Lepton Flavor Violation at LHC

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In collaboration with J. Hisano and M. M. Nojiri, arXiv:0812.4496
Introduction & Motivation

- The LFV processes are important discovery channels of BSM.
- Current experimental upper bounds on LFV processes:

\[
\begin{align*}
  Br(\mu \to e\gamma) &< 1.2 \times 10^{-11} & \text{MEGA}, \\
  Br(\tau \to \mu\gamma) &< 4.5(6.8) \times 10^{-8} & \text{Belle(BaBar),} \\
  Br(\tau \to e\gamma) &< 1.2(1.1) \times 10^{-7} & \text{Belle(BaBar).}
\end{align*}
\]

- Prospects:

\[
\begin{align*}
  Br(\mu \to e\gamma) &\sim 10^{-13} & \text{MEG}, \\
  Br(\tau \text{ decay}) &\sim 10^{-9} - 10^{-10} & \text{superB factory.}
\end{align*}
\]

- LHC plays a complementary role to identify new physics and determine LFV parameters. \(\leftarrow\) esp. in light slepton scenario
\[ \mu \rightarrow e\gamma \]

Right-handed LFV ⇒ Cancellation among dominant diagrams

At the cancellation point,

\[
\frac{1}{2m_{\tilde{l}_L}^2} - \frac{1}{m_{\tilde{l}_R}^2} f_1 \left( \frac{\mu^2}{m_{\tilde{l}_R}^2} \right) \sim 0. \tag{6}
\]

In the plot,

i) \( m_{1/2} = 300 \text{ GeV}, \tan \beta = 10 \)

ii) mSUGRA-like relations are assumed among \( M_1, M_2 \), and slepton masses

iii) \( \mu \) is free (NUHM)

\[\mu \sim m_{\tilde{l}_L} \text{ along the cancellation line}\]

\[\mu \text{ is smaller as } m_0 \text{ decreases } \Rightarrow \text{ DM relic density is small}\]

and \( \tilde{\chi}_4^0 \rightarrow \tilde{e}_L \) and \( \tilde{\chi}_2^0 \rightarrow \tilde{e}_R \) are always kinematically allowed.
We took $m_{H_U} > m_{H_D} = m_0$, particularly with $M_1 < M_2 < \mu \sim m_{1/2}$ and dark matter relic density consistent with observations.

Moreover, we took the choice $m_{\tilde{\chi}^0_1} < m_{\tilde{e}_R} < m_{\tilde{\chi}^0_2} < m_{\tilde{e}_L} < m_{\tilde{\chi}^0_4}$ when both left- and right-handed sleptons can be directly produced via neutralino decay.
Consider a horizontal $U(1) \times U(1)$ symmetry where each $U(1)$ is explicitly broken by a scalar singlet spurion carrying the corresponding charge -1.

⇒ Slepton masses:

$$M_{\tilde{L}}^2 = m_{\tilde{L}}^2 + \epsilon m_0 X_{\tilde{L}}' , \quad M_{\tilde{e}}^2 = m_{\tilde{e}}^2 + \epsilon m_0 X_{\tilde{e}}' ,$$  \hspace{1cm} (7)

where

$$X_{\tilde{L}}' \sim \begin{pmatrix} 0 & \epsilon^4 & \epsilon^8 \\ \epsilon^4 & 0 & \epsilon^4 \\ \epsilon^8 & \epsilon^4 & 0 \end{pmatrix} , \quad X_{\tilde{e}}' \sim \begin{pmatrix} 0 & \epsilon^2 & \epsilon^4 \\ \epsilon^2 & 0 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 0 \end{pmatrix} ,$$  \hspace{1cm} (8)

and $\epsilon = $ symmetry breaking parameter $\sim |V_{\text{us}}| \sim 0.2$
Contents

1. A model point with correct DM relic density $\Rightarrow$ the cancellation point
2. Sparticle masses and parameters determination from endpoint information
3. Flipping solution exercises
   
   Key observables:
   
   ▶ 2 jets + missing $E_T$
   ▶ relative edge heights
   ▶ charge asymmetry
4. LFV and DM density
MC Study

ISAJET v7.75 + HERWIG 6.5 + AcerDet

# of generated events = \(5 \times 10^6\) \(\rightarrow\) \(~300\) fb\(^{-1}\) of integrated luminosity

<table>
<thead>
<tr>
<th>point A:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>(m_0)</td>
<td>100</td>
<td>(m_{1/2})</td>
<td>300</td>
</tr>
<tr>
<td>(m_{HD})</td>
<td>100</td>
<td>(m_{HU})</td>
<td>380</td>
</tr>
<tr>
<td>(A_0)</td>
<td>0</td>
<td>(\tan \beta)</td>
<td>10</td>
</tr>
</tbody>
</table>

\[\mu = 271\ \text{GeV}\]

\[\Omega_{DM} h^2 = 0.1179\]

(\(\mu = 397.3\ \text{GeV}\) for mSUGRA point)

\[\Rightarrow\] For point A, \(\tilde{\chi}^0_4\) and \(\tilde{\chi}^+_2\) have more Wino component.

\[\Rightarrow\] Enhancement in \(Br(\tilde{u}_L \rightarrow \tilde{\chi}^0_4/\tilde{\chi}^+_2)\) by at least factor 6.
OSSF dilepton invariant mass distribution

\[ \tilde{\chi}_2 \to \tilde{\nu}_L \to \tilde{\chi}_1^+ \]

\[ \tilde{\chi}_4 \to \tilde{\nu}_R \to \tilde{\chi}_1^0 \]

\[ \tilde{\chi}_4 \to \tilde{\nu}_L \to \tilde{\chi}_1^0 \]

- Including \( m_{jll}^{\text{max}}, m_{jl}^{\text{max}}, m_{jl}^{\text{min}} \), one can resolve \( m_{\tilde{q}_L}, m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}, m_{\tilde{\nu}_L}, m_{\tilde{\nu}_R} \).

- A study of four-lepton (2OSSF) events reveals \( m_{ll}^{\text{max}}(\tilde{\chi}_4^0 \to \tilde{\nu}_L \to \tilde{\chi}_2^0) \).

- \( m_{\tilde{\nu}_L} - m_{\tilde{\chi}_1^0} = 124.92^{+0.65}_{-0.65} \text{ GeV}, \quad m_{\tilde{\nu}_R} - m_{\tilde{\chi}_1^0} = 15.68^{+0.45}_{-0.49} \text{ GeV} \)
Flipping Solutions

(1) \( M_1 < M_2 < \mu \) (point A)

(2) \( M_1 < \mu < M_2 \) (point A2)

(3) \( \mu < M_1 < M_2 \) (point A3)

\[
\begin{align*}
&\{ m_{\tilde{\mu}_L}, m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_2^0} (m_{\tilde{\chi}_3^0} \text{ for A3}), m_{\tilde{\chi}_1^0}, m_{\tilde{\epsilon}_L}, m_{\tilde{\epsilon}_R} \} \\
&\text{are degenerate between three points} \\
&\Rightarrow \text{endpoints from their cascade decay} \\
&\text{will be the same}
\end{align*}
\]

We investigate whether three solutions can be discriminated @ the LHC.

For point A2,

- \( \tilde{\chi}_4^0 \) and \( \tilde{\chi}_2^+ \) have more Wino component \( \Leftarrow \) Branching ratios
- \( \tilde{\chi}_2^0 \) has less Wino component \( \Leftarrow \) Charge asymmetry

For point A3,

- \( \tilde{\chi}_1^0 \) is Higgsino-like \( \Leftarrow \) 2 jets + missing \( E_T \)
2 jets + missing $E_T$


$$\text{Br}(\tilde{q}_R \rightarrow \tilde{\chi}_1^0) = \begin{cases} 
0.94 & \text{point A} \\
0.89 & \text{point A2} \\
0.16 & \text{point A3}
\end{cases}$$

For $pp \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$ events, their signature is two high-$p_T$ jets + large $E_T$.

$$m_{T2}(p^j_T, p^\alpha_T, p^\beta_T; m_{\text{test}}) \equiv \min_{p^\alpha_T+p^\beta_T=p^{\text{miss}}_T} \left[ \max \left\{ m_T(p^j_T, p^\alpha_T; m_{\text{test}}), m_T(p^j_T, p^\beta_T; m_{\text{test}}) \right\} \right]$$

$$m_T^2(p_T; m_{\text{test}}) \equiv m_j^2 + m_{\text{test}}^2 + 2 \left( E_T E_T^{\alpha} - p_T^j \cdot p_T^\alpha \right).$$

$$m_{T2}(m_{\text{test}} = m_{\chi_1^0}) \leq m_{\tilde{q}_R}$$

<table>
<thead>
<tr>
<th>Point</th>
<th>No. of Signal</th>
<th>No. of SM Background</th>
<th>$S/B_{SM}$</th>
<th>$S/\sqrt{B_{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1341</td>
<td>180</td>
<td>7.5</td>
<td>100.0</td>
</tr>
<tr>
<td>A3</td>
<td>133</td>
<td>180</td>
<td>0.7</td>
<td>9.9</td>
</tr>
</tbody>
</table>

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\[ \mu \rightarrow e \gamma \]

\[ x = 0.3 \]

- Point A and A2 have \( Br(\mu \rightarrow e \gamma) \) differ by two orders of magnitude.
- Only point A is in the cancellation region and then gives \( Br(\mu \rightarrow e \gamma) \) below the current experimental upper bound.
- A precise determination of \( \mu \) parameter is important for determination of flavor mixing parameter.
OSSF Dilepton Invariant Mass Distribution

A2: $\tilde{\chi}_0^0$ and $\tilde{\chi}_2^+$ have more Wino component

$\Rightarrow$ Enhancement in edges from

$\tilde{\chi}_2^+ \rightarrow \tilde{\nu}_L \rightarrow \tilde{\chi}_1^0$ (factor 2) and

$\tilde{\chi}_4^0 \rightarrow \tilde{e}_L \rightarrow \tilde{\chi}_1^0$ (factor 4)

relative to edge of $\tilde{\chi}_2^+ \rightarrow \tilde{\nu}_R \rightarrow \tilde{\chi}_1^0$.
Charge Asymmetry


Example

\[ \theta = \text{angle between quark and lepton in the } \tilde{\chi}_2^0 \text{ rest frame} \]

⇒ positive charge asymmetry

The difference between $m_{j_hl^+}$ and $m_{j_hl^-}$ distributions as a function of $m_{j_hl}$
($j_h$ is defined by $m_{j_hll} \equiv \max(m_{j_1ll}, m_{j_2ll})$)

Assuming that L-R slepton mixing is negligible, the flatness of charge asymmetry distribution suggests the contribution from $\tilde{q}_R \rightarrow \tilde{\chi}_2^0$ decay.

$\Rightarrow$ $\tilde{\chi}_2^0$ for point A2 must have smaller Wino component.

$\Rightarrow M_1 < \mu < M_2$
The ratio $R$ depends on $\mu/M_1$ stronger than on $M_2/M_1$.

As $\mu/M_1$ is smaller, mixing between neutralino states is larger and the charge asymmetry receives more $\tilde{q}_R$ contribution.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Resolving Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu &lt; M_1, M_2$</td>
<td>$m_{T2}$ method</td>
</tr>
<tr>
<td>$M_1 &lt; \mu &lt; M_2$</td>
<td>charge asymmetry + branching ratio</td>
</tr>
<tr>
<td>$m_{\tilde{e}<em>L} \leftrightarrow m</em>{\tilde{e}_R}$</td>
<td>charge asymmetry</td>
</tr>
</tbody>
</table>
Recall $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0} = 124.92^{+0.65}_{-0.65} \text{ GeV}$, $m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} = 15.68^{+0.45}_{-0.49} \text{ GeV}$.

- The mass difference of order one percent, corresponding to $1 \sim 2 \text{ GeV}$, is allowed by MEGA bound ($Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$).
The $\mu \rightarrow e$ conversion rate shows strong sensitivity to the SUSY parameters at different $\mu$ values from $Br(\mu \rightarrow e\gamma)$ and $Br(\mu \rightarrow 3e)$.

$\mu = 271.33^{+6.89}_{-6.81}$ GeV
Finally, precise SUSY parameter determination is also important for the
determination of DM density and DM scattering cross section.

<table>
<thead>
<tr>
<th></th>
<th>$\Omega_{DM} h^2$</th>
<th>$\sigma^{SI}_{p\chi} \left(10^{-8} \text{ pb}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1179</td>
<td>1.6</td>
</tr>
<tr>
<td>A2</td>
<td>0.0817</td>
<td>3.2</td>
</tr>
<tr>
<td>A3</td>
<td>0.0096</td>
<td>17.5</td>
</tr>
<tr>
<td>observation/exp. upper bound</td>
<td>0.122 (WMAP &amp; SDSS)</td>
<td>4.6 (CDMS)</td>
</tr>
</tbody>
</table>

Uncertainties in $\sigma^{SI}_{p\chi}$:

- nucleon matrix element of strange quark
- $\sigma^{SI}_{p\chi}|A-$exchange $\propto \left(\frac{\tan^2 \beta}{m_A^4}\right)$
Conclusions

- We studied the one-parameter-extended NUHM, $m_{H_U} \neq m_{H_D} = m_0$, particularly with $M_1 < M_2 < \mu \sim m_{1/2}$ and dark matter relic density consistent with cosmological and astrophysical observations.

- We are also interested in the region where cancellation among leading contributions to $Br(\mu \to e\gamma)$ occurs in the models with right-handed LFV masses. Therefore, we took the choice $m_{\tilde{\chi}^0_1} < m_{\tilde{e}_R} < m_{\tilde{\chi}^0_2} < m_{\tilde{e}_L} < m_{\tilde{\chi}^0_4}$ when both left- and right-handed sleptons can be directly produced via neutralino decay.

- In the region when $M_1 < M_2 < \mu \sim m_{1/2}$, $\tilde{\chi}^0_4$ and $\tilde{\chi}^+_2$ are a mixed states with rather large Wino component and their various decay patterns are expectable at the LHC.

- When the relation $M_1 < M_2, \mu$ is kept, we showed three solutions with similar mass spectrum but different ordering of $M_1, M_2$ and $\mu$. We showed that by looking into 2 jets + missing $E_T$ signature, relative height of $m_{ll}$ edges and charge asymmetry, the degeneracy can be lifted.

- We emphasized that a precise $\mu$ parameter determination is an important key for resolving cancellation point of LFV processes, determination of the LFV parameter and determination of DM density and DM scattering cross section.
# Mass Spectrum (point A)

<table>
<thead>
<tr>
<th>$m_{\tilde{g}}$</th>
<th>719.67</th>
<th>$m_{\tilde{\nu}}$</th>
<th>224.37</th>
<th>$m_{\tilde{\chi}^+}$</th>
<th>321.62</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{u}_L}$</td>
<td>665.19</td>
<td>$m_{\tilde{e}_L}$</td>
<td>239.62</td>
<td>$m_{\tilde{\chi}^+}$</td>
<td>196.30</td>
</tr>
<tr>
<td>$m_{\tilde{d}_L}$</td>
<td>670.29</td>
<td>$m_{\tilde{e}_R}$</td>
<td>130.38</td>
<td>$m_{\tilde{\chi}^0}$</td>
<td>323.23</td>
</tr>
<tr>
<td>$m_{\tilde{u}_R}$</td>
<td>648.85</td>
<td>$m_{\tilde{\tau}_2}$</td>
<td>238.89</td>
<td>$m_{\tilde{\chi}^0}$</td>
<td>278.87</td>
</tr>
<tr>
<td>$m_{\tilde{d}_R}$</td>
<td>642.47</td>
<td>$m_{\tilde{\tau}_1}$</td>
<td>128.07</td>
<td>$m_{\tilde{\chi}^0}$</td>
<td>197.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$m_{\tilde{\chi}^0}$</td>
<td>114.70</td>
</tr>
</tbody>
</table>
Selection criteria:

- an OSSF dilepton pair where both leptons have $p_T^l > 10$ GeV and $|\eta| < 2.5$.
- more than 4 jets with $p_T^{j,1} > 100$ GeV, $p_T^{j,2,3,4} > 50$ GeV.
- $M_{\text{eff}} \equiv p_T,1 + p_T,2 + p_T,3 + p_T,4 + E_T > 400$ GeV.
- $E_T > \max(100, 0.2M_{\text{eff}})$. 
Estimated error of sparticle masses and SUSY parameters

<table>
<thead>
<tr>
<th>Sparticle Mass</th>
<th>Central value</th>
<th>Estimated error (1-σ)</th>
</tr>
</thead>
</table>
| $m_{\tilde{\chi}^0_1}$ | 114.70 | +6.7  
|               |          | −6.3  |
| $m_{\tilde{\bar{e}}_R} - m_{\tilde{\chi}^0_1}$ | 15.68 | +0.45  
|               |          | −0.49 |
| $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ | 83.12 | +0.75  
|               |          | −0.62 |
| $m_{\tilde{\bar{e}}_L} - m_{\tilde{\chi}^0_1}$ | 124.92 | +0.65  
|               |          | −0.65 |
| $m_{\tilde{\chi}^0_4} - m_{\tilde{\chi}^0_1}$ | 208.53 | +0.77  
|               |          | −0.64 |
| $m_{\tilde{q}_L} - m_{\tilde{\chi}^0_1}$ | 551.19 | +4.64  
|               |          | −4.47 |
| $m_{\tilde{\bar{e}}_R} - m_{\tilde{\mu}_R}$ | 1.00 | +0.04  
|               |          | −0.04 |
| $m_{\tilde{\bar{e}}_L} - m_{\tilde{\mu}_L}$ | 2.00 | +0.48  
|               |          | −0.49 |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Central value</th>
<th>Estimated error (1-σ)</th>
</tr>
</thead>
</table>
| $\mu$     | 271.33       | +6.89  
|           |              | −6.81 |
| $M_1$     | 122.49       | +7.16  
|           |              | −7.17 |
| $M_2$     | 230.89       | +6.57  
|           |              | −6.54 |
| $\mu/M_1$ | 2.215        | +0.084  
|           |              | −0.078 |
| $M_2/M_1$ | 1.885        | +0.063  
|           |              | −0.057 |