Flavor Violation at the LHC

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1. Colored, Non colored particles bounds and possible search strategies, cascade decays, VBF, monojet etc.

2. Lepton Flavor Violation and Sources in Models

3. Establishing LFV at the LHC
Higgs search results, $m_h : 126$ GeV

- in the tight MSSM window $< 135$ GeV

$m_{\tilde{q}}$ (1st gen.) $\sim m_{\tilde{g}} \geq 1.7$ TeV

$\tilde{t}_1$ produced from $\tilde{g}$, $m_{\tilde{t}_1} \geq 700$ GeV

$\tilde{t}_1$ produced directly, $m_{\tilde{t}_1} \geq 660$ GeV (special case)

$\tilde{e} / \tilde{\mu}$ excluded between 110 and 280 GeV for a mass-less $\tilde{\chi}_1^0$ or for a mass difference $> 100$ GeV, small $\Delta M$ is associated with small missing energy

$\tilde{\chi}_1^\pm$ masses between 100 and 600 GeV are excluded for mass-less $\tilde{\chi}_1^0$ for $\tilde{\chi}_1^\pm$ or for the mass difference $> 40$ GeV decaying into $e/\mu$
The signal:

jets + leptons + t’s + W’s + Z’s + H’s + missing $E_T$

Colored particles can be produced and they decay into the weakly interacting stable particle.

The $p_T$ of jets and leptons depend on the sparticle masses which are given by models.

High $p_T$ jet

[Mass difference is large]
Non-colored in cascade

\[ \varepsilon_\tau = 50\%, \ f_{\text{fake}} = 1\% \text{ for } p_T^{\text{vis}} > 20 \text{ GeV} \]

\( E_T^{\text{miss}} + 2j + 2\tau \) Analysis Path

- Cuts to reduce the SM backgrounds (W+jets, ...)
  \[ E_T^{\text{miss}} > 180 \text{ GeV}, \ N(\text{jet}) \geq 2 \text{ with } E_T > 100 \text{ GeV} \]
  \[ E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600 \text{ GeV}; \ N(\tau) \geq 2 \text{ with } p_T^{\tau} > 40, 20 \text{ GeV} \]

- CATEGORIZE opposite sign (OS) and like sign (LS) ditau events

- OS\(\tau\) \(M_\tau\) histogram
- LS \(\tau\) \(M_\tau\) histogram

Arnowitt, Dutta, Gurrola, Kamon, Krislock and Toback’06,07,08,09
Non-Colored sector: LHC

Challenge:

- How can we probe the colorless SUSY sector if the first two generations are heavy?

- Not so large $\Delta M(\equiv m_\tilde{l} - m_\tilde{\chi}_1^0) \Rightarrow$ Smaller Missing energy

- VBF topology: Tagging VBF jets

- ISR+ missing $E_T + e, \mu, \tau, b, t$ etc.
FIG. 5. The statistical significance ($S/\sqrt{B}$) after all cuts, as a function of the slepton mass, for three mass splittings (denoted $\Delta m$). An integrated luminosity of 100 fb$^{-1}$ at LHC 14 is assumed. Left: left-handed slepton; right: right-handed slepton. Two generations of sleptons (selectrons and smuons) of degenerate masses are included.

Han, Liu, 2015
TABLE III: Summary of the effective cross-section (fb) and significances, with 3000 fb$^{-1}$ after all cuts for different SUSY points at LHC14. The effective cross-section of total standard model background after all cuts is 0.0020 fb for “exactly 2-muon final state analysis”, and 0.0189 fb for “exactly 1-muon final state analysis”. The significances presented are calculated by means of both “cut and count (CC)” and “shape analysis” methods.

<table>
<thead>
<tr>
<th>$\Delta M$</th>
<th>$m_{\tilde{\ell}}$</th>
<th>$m_{\tilde{\chi}_1^0}$</th>
<th>2-muon final state</th>
<th>1-muon final state</th>
<th>Combined Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[GeV]</td>
<td></td>
<td>Cross-section</td>
<td>Significance</td>
<td>CC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[fb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>135</td>
<td>110</td>
<td>0.0014</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td>15</td>
<td>135</td>
<td>120</td>
<td>0.0021</td>
<td>2.1</td>
<td>2.6</td>
</tr>
<tr>
<td>10</td>
<td>135</td>
<td>125</td>
<td>0.0019</td>
<td>2.1</td>
<td>2.9</td>
</tr>
<tr>
<td>5</td>
<td>135</td>
<td>130</td>
<td>0.0004</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>125</td>
<td>110</td>
<td>0.0024</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>10</td>
<td>125</td>
<td>115</td>
<td>0.0018</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>125</td>
<td>120</td>
<td>0.0006</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>115</td>
<td>100</td>
<td>0.0027</td>
<td>2.8</td>
<td>4.1</td>
</tr>
<tr>
<td>10</td>
<td>115</td>
<td>105</td>
<td>0.0021</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>115</td>
<td>110</td>
<td>0.0007</td>
<td>0.6</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Higgsino type \( \chi_{1,2}^0 \) (cosmologically interesting):

The mass difference between \( \chi_1^0 \) and \( \chi_2^0, \chi_1^\pm \): 10 GeV

ISR+missing \( E_T + \text{Leptons} \)

Baer, Mustafayev, Tata, Phys.Rev. D90 (2014), 115007
LFV in SUSY Models

- LFV can be quite natural in SUSY models

  Neutrino flavor
  Oscillations have been observed

  ![Diagram showing neutrino oscillations](image)

  Borzumati, Masiero (1986)
  Hall, Kostelecky, Raby (1986)
  Hisano, Moroi, Tobe, Yamaguchie (1995)

- The grand unified models, e.g., SU(5), SO(10), intermediate scale models can provide LFV even when the flavor diagonal masses are assumed at high scale

- LFV can be radiatively induced by flavor violating terms in the slepton masses arising from CKM and MNSP.
Seesaw mechanism naturally explains small $\nu$-mass.

$$\mathcal{L} = \bar{\nu}_L M_D \nu_R + \frac{1}{2} \nu_R^T M_R \nu_R + h.c.$$  

$$M_\nu = -M_D M_R^{-1} M_D^T$$

Current Neutrino data suggest

$$M_R \sim (10^{12} - 10^{15}) \text{ GeV}$$

Flavor Change in the neutrino sector to explain the data

Flavor change in the charged slepton sector
LFV in SUSY Models

LFV using neutrino couplings:

Dirac neutrino coupling \((Y_\nu \ell \nu^c H_u)\). \(M_D = Y_\nu \nu_u\)

Majorana neutrino coupling : \(f \nu^c \nu^c \Delta\)

\[
M_R = f \nu_{B-L} \quad \text{Where} \quad <\Delta> = \nu_{B-L}
\]

Flavor violation may reside entirely in \(f\) and/or entirely in \(Y_\nu\)

One can express the RGE induced off-diagonal elements of SUSY breaking in terms of \(f\) and \(Y_\nu\)
When flavor violation occurs only in $f$ (Majorana LFV)

$$\Delta m_{ij}^2 (i \neq j) \simeq -\frac{3(m_0^2 + A_0^2)}{32\pi^4}[Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger Y_\nu^\dagger Y_\nu]_{ij} \left(\ln\frac{M_{Pl}}{M_{B-L}}\right)^2$$

$$A_{\ell ij} (i \neq j) \simeq -\frac{3}{64\pi^4}[A_\ell (Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger Y_\nu^\dagger Y_\nu)]_{ij} \left(\ln\frac{M_{Pl}}{M_{B-L}}\right)^2$$

When flavor violation occurs only in Dirac Yukawa $Y_\nu$

(with mSUGRA)

$$\Delta m_{ij}^2 (i \neq j) \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger Y_\nu)_{ij} \left(\ln\frac{M_{Pl}}{M_{B-L}}\right)$$
LFV in SUSY Models

Dashed line: Dirac
Solid line Majorana

Babu, Dutta, Mohapatra, 2002
LFV in SUSY Models

LFV also occurs without neutrino couplings in SUSY GUTS

\[(m_{\tilde{e}_R}^2)_{ij} \approx -\frac{3}{8\pi^2} V_{3i} V_{3j}^* |Y_t|^2 (3m_0^2 + |A_0|^2) \ln\left(\frac{M_P}{M_G}\right)\]

Top quarks and anti-tau leptons are grouped together in SU(5)

Barbieri, Hall, Strumia, 1995
Hisano et al, 1997
The charged slepton mass matrix: 6x6

\[ \mathcal{M}_\ell^2 = \begin{pmatrix} \mathcal{M}_{LL}^2 & \mathcal{M}_{LR}^2 \\ \mathcal{M}_{LR}^2 & \mathcal{M}_{RR}^2 \end{pmatrix} \]

\( \mathcal{M}_{LL(RR)}^2 \): 3x3 matrix for the left(right) sleptons soft masses
\( \mathcal{M}_{LR}^2 \): 3x3 matrix for the soft masses: \( m_l(A_l+\mu \tan \beta) \)

In mSUGRA/CMSSM

\[ \mathcal{M}_{LL}^2 = \mathcal{M}_{RR}^2 = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

The off–diagonal elements arising from the radiative corrections produce flavor violation

- Constraints from \( \tau \rightarrow \mu \gamma, \mu \rightarrow e \gamma \) etc
LFV at the LHC

We need to produce charged sleptons at the LHC to measure LFV

- Charged slepton production cross sections are small

- We use the neutralinos and their decays,

\[ \tilde{\chi}_2^0 \to \tilde{l}^* l \to l^\pm l^\mp \tilde{\chi}_1^0 \text{ where } l=e, \mu, \tau \]

  - Neutralinos can arise from the squark decays:

\[ \tilde{q}_L \to q \tilde{\chi}_2^0 \to q \tilde{l}^* l \to q l^\pm l^\mp \tilde{\chi}_1^0 \]

  - Direct production of \( \tilde{\chi}_2^0 \) is also possible

- We need to have the following subsystem presence in the signal

\[ \tilde{\chi}_2^0 - \tilde{l} - \tilde{\chi}_1^0 \]
In the non-LFV scenario
\[ \tilde{\chi}^0_2 \rightarrow \tilde{l}^* l \rightarrow l^\pm l^\mp \tilde{\chi}^0_1 \] where l=e, μ, τ

In the LFV scenario, we have in addition
\[ \tilde{\chi}^0_2 \rightarrow \tau \mu, e \mu, \tau e + \tilde{\chi}^0_1 \]

We consider a nonzero 2-3 element and we define
\[ \delta_{RR,LFV} = \frac{[M^2_{RR}]_{23}}{[M^2_{RR}]_{33}} \]

This LFV will enter into \( \tilde{\chi}^0_2 \), \( \tilde{l} \) decay modes and \( \tau \rightarrow \mu \gamma \) amplitudes

Allahverdi, Dutta, Kamon, 2012
The whole analysis can be scaled by \( \sigma(\tilde{q}_L, \tilde{g})B(\tilde{q}_L, \tilde{g} \rightarrow \tilde{\chi}_2^0) \)

- However, the technique remains the same

\[ \sigma(\tilde{q}_L, \tilde{g})B(\tilde{q}_L, \tilde{g} \rightarrow \tilde{\chi}_2^0) \sim 0.1 \text{ pb at 13 TeV LHC} \]

Analysis:

- The final states are characterized by LS and OS tau pair
- We perform OS-LS to remove background
\[ m_{\tau\tau}^{\text{max}} = f(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}) \]

\[
slope(p_{T,\tau}^{\text{vis high}}) = f_2(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})
\]

\[
slope(p_{T,\tau}^{\text{vis}}) = f_3(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}) \text{ which include the average of low and high } p_{T,\tau}^{\text{vis}} \]

\[
slope(p_{T,\tau}^{\text{vis}}) = f_4(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}) : \text{ slope of transverse momentum sum distribution}
\]
Using the observables, we solve for the masses.

Mass measurements for the chosen benchmark point:
\[ m_0 = 250 \text{ GeV}, \ m_{1/2} = 350 \text{ GeV}, \ A_0 = 0, \ \tan\beta = 40, \ \mu > 0. \]

<table>
<thead>
<tr>
<th>Particle mass</th>
<th>Solution one</th>
<th>Solution two</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\tau}_1 ) : 186.7</td>
<td>181.5 ± 3.7(5.1) ± 4.1</td>
<td>205.8 ± 5.9(6.1) ± 5.7</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 ) : 141.5</td>
<td>140.6 ± 5.4(6.5) ± 6.2</td>
<td>151.4 ± 6.4(8.6) ± 6.3</td>
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<tr>
<td>( \tilde{\chi}_2^0 ) : 265.8</td>
<td>265.3 ± 6.2(8.5) ± 7.3</td>
<td>278.9 ± 9.2(11.7) ± 9.0</td>
</tr>
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- The statistical uncertainties are for \( \mathcal{L} = 1000(300) \ fb^{-1} \)

- The systematic uncertainties are due to a jet energy scale mismeasurement of 3%

- Two solutions due to non-linear equations
We now investigate the effect of $\delta_{RR,LFV}$

The presence of this term allows:

$$\tilde{\chi}_2^0 \rightarrow \tilde{l}_1\tau, \quad \tilde{l}_1 \rightarrow \mu\tilde{\chi}_1^0$$

$\Rightarrow \tilde{\chi}_2^0 \rightarrow \mu\tau + \text{missing } E_T$, where missing $E_T: \tilde{\chi}_1^0$

So the final states contain muons

- However the tau decays also contain muons: $\tau = \nu_\tau \bar{\nu}_\mu \mu$
  $$\tilde{\chi}_2^0 \rightarrow \tau\bar{\tau} + \tilde{\chi}_1^0 \rightarrow \mu\tau + \text{missing } E_T, \quad E_T: \tilde{\chi}_1^0, \nu_\tau \bar{\nu}_\mu$$
  $\Rightarrow$ Missing $E_T$ in the background

- We need to separate these extra muons from the tau decays
  $\Rightarrow$ complicated analysis
The effect of $\delta_{RR,LFV}$ on our benchmark points

<table>
<thead>
<tr>
<th>$\delta_{RR,LFV}$ (%)</th>
<th>$m_{\tilde{\ell}_1}$ (GeV)</th>
<th>$B(\ell_1 \to \mu \chi_1^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>186.7</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>186.3</td>
<td>$4.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>5</td>
<td>186.0</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>10</td>
<td>185.1</td>
<td>$1.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>15</td>
<td>183.5</td>
<td>$2.6 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

- The values of $\delta_{RR,LFV}$ larger than 15% violate the $B(\tau \to \mu \gamma) \leq 4.4 \times 10^{-8}$ for our benchmark point

- The change in the stau mass is very small
Analysis plan:

- Take one of the mass points

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<td>$\tilde{\chi}^0_2$</td>
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<td>$278.9 \pm 9.2(11.7) \pm 9.0$</td>
</tr>
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- Determine the $\tilde{\chi}^0_2, \tilde{\tau}_1, \tilde{\chi}^0_1$ masses by using various observables

- Generate the $m_{\tau\mu}$ distribution from $m_{\tau\tau}$ by using a transfer function

- Subtract the determined $m_{\tau\mu}$ and from the observed $m_{\tau\mu}$ distributions

- Determine the amount of flavor violation
The $\tau\tau$ (left) and $\tau\mu$ (right) invariant mass distribution for the LHC simulated $\delta_{RR,LFV}=0$ point (first solution)

The distribution is for an integrated luminosity of 1000 fb$^{-1}$
LFV at LHC

- Use the transfer function to transform the \( m_{\tau\tau}^{Non-LFV} \) distribution into a \( m_{\tau\mu}^{Non-LFV} \) shape
- Subtract the distribution from the \( m_{\tau\tau}^{data} \) distribution

- The \( \tau-\mu \) mass distribution for \( \delta_{RR,LFV}=0.15 \).
- Dashed is the second solution

- Comparison of the determined \( m_{\tau\mu} \) with true \( m_{\tau\mu} \)
Keeping \( \sigma(\bar{q}_L, \bar{g})B(\bar{q}_L, \bar{g} \rightarrow \tilde{\chi}_2^0) \) same:

<table>
<thead>
<tr>
<th>( \delta_{RR, L_{LFV}} ) (%)</th>
<th>( B(\ell_1 \rightarrow \mu \tilde{\chi}_1^0) )</th>
<th>( \mathcal{L} ) (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>( 3.1 \times 10^{-3} )</td>
<td>8390</td>
</tr>
<tr>
<td>10</td>
<td>( 1.2 \times 10^{-2} )</td>
<td>2170</td>
</tr>
<tr>
<td>15</td>
<td>( 2.6 \times 10^{-2} )</td>
<td>1000</td>
</tr>
<tr>
<td>32</td>
<td>( 1 \times 10^{-1} )</td>
<td>260</td>
</tr>
<tr>
<td>45</td>
<td>( 2 \times 10^{-1} )</td>
<td>130</td>
</tr>
</tbody>
</table>

For more than 2\( \sigma \) significance
Conclusion

- Search for LFV requires the production of non-colored particles
- If the colored particles are within reach then the non colored particles can be probed from the cascade decays
- When colored particles are heavy, the non-colored states need to be produced directly, VBF, ISR + missing $E_T + X$
- SUSY models have many sources to produce LFV
- Establishing LFV at the LHC can be possible