Lepton Flavor Violation at the Large Hadron Collider

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Phenomenology Symposium 2012

Outline

LFV Motivation
mSUGRA is flavor unified...
...but neutrinos oscillate, which motivates LFV!

LFV @ LHC
Considerations
Mass Measurements
Transfer Function

Conclusions

mSUGRA

SUSY

- Flavor Problem:
  SUSY breaking terms can induce FCNC's
- Simplest assumption to solve it:
  SUSY breaking masses are flavor diagonal

mSUGRA

Minimal Supergravity model

- m_0, $m_{1/2}$, A_0, $\tan\beta$, sign(μ)
- 3rd generation sfermions split from others
- Typically: $m_{\tilde{\tau}_1} < m_{\tilde{\mu}} \sim m_{\tilde{e}}$
- No LFV...

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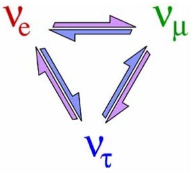
Neutrino Oscillation



$$\Delta m^2_{21} = (7.59{+}{-}0.21) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$$

Seesaw masses

- Massive right handed neutrinos (ν^c) have masses: $\mathcal{M}_\nu = \mathcal{M}_D^T(\mathcal{M}_R)^{-1}\mathcal{M}_D$
- Flavor mixings in $\mathcal{M}_R$ and $\mathcal{M}_D$
- Right handed neutrino mass $\sim v_{B-L} \sim 10 - 15\ \mathrm{GeV}$
- ν^c active at large momentum scale $\geq v_{B-L}$
- Above v_{B-L} slepton mass terms feel effect of ν^c

$\Rightarrow$ Generates LFV!!

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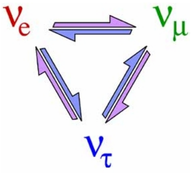

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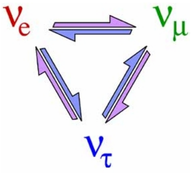

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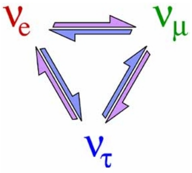

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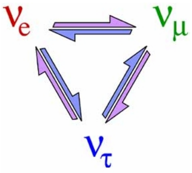

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LFV Implementation

Slepton Mass Matrix — **mSUGRA**

$$\mathcal{M}^2_{\tilde{\ell}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ \mathcal{M}^2_{LR} & \mathcal{M}^2_{RR} \end{pmatrix} \qquad \mathcal{M}^2_{LL} = \mathcal{M}^2_{RR} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{M}^2_{LR} = \mathrm{diag}\left[m_\ell(A_\ell + \mu \tan\beta)\right] \qquad A_\ell = A_0$$

Introduce LFV in the $(2,3) = (\tilde{\mu}, \tilde{\tau})$ component of $\mathcal{M}^2_{RR}$.

$$\delta_{RR,\mathrm{LFV}} = \frac{\left[\mathcal{M}^2_{RR}\right]_{23}}{\left[\mathcal{M}^2_{RR}\right]_{33}} = \frac{m^2_{LFV,23}}{m^2_{\tilde{\tau}_R}}$$

Lightest slepton, $\tilde{\ell}_1$, is an admixture of $\tilde{\mu}$ and $\tilde{\tau}$ states.

LFV Implementation

Abram Krislock
May 5
Pheno 2012

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LFV signal and background

Decay Chain subsystem: $\tilde{\chi}_2^0$-$\tilde{\ell}_1$-$\tilde{\chi}_1^0$

- Mostly $\tau\tau$ final states
- Small amount of LFV $\tau\mu$ final states
- $\tau\mu$ final states also arise from leptonic τ decay

Use a General Technique: Any LFV!

$$\mu\tau \quad e\tau \quad \cdots$$

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Battle Plan

1) Understand the $\tilde{\chi}_2^0$-$\tilde{\ell}_1$-$\tilde{\chi}_1^0$ subsystem very well.

- mass measurements of $\tilde{\chi}_2^0$, $\tilde{\ell}_1$, and $\tilde{\chi}_1^0$

2) Model the $\tau\mu$ BG from leptonic τ decay.

- new technique: transfer function

3) Extract the LFV $\tau\mu$ signal.

Study by simulating $\sqrt{s} = 14$ TeV LHC.

- Use SPheno, PYTHIA, PGS4

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2 Jets + 2 τ + $\not{E}_T$ Signal

Dominant production at LHC is $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, or $\tilde{q}\tilde{q}$

$\tilde{q}_L$

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$$\begin{array}{ccc} \tilde{q}_L & \rightarrow & q \\ & \searrow & \\ & & \tilde{\chi}_2^0 \end{array}$$

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Dominant production at LHC is $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, or $\tilde{q}\tilde{q}$

$\tilde{q}_L \rightarrow q$ Hard Jet (2)

$\searrow$

$\tilde{\chi}_2^0$

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$$
\begin{array}{llllll}
\tilde{q}_L & \rightarrow & q & & & \text{Hard Jet (2)} \\
 & \searrow & & & & \\
 & & \tilde{\chi}_2^0 & \rightarrow & \tau^{\mp} & \\
 & & & \searrow & & \\
 & & & & \tilde{\tau}_1^{\pm} &
\end{array}
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$$\searrow \tilde{\chi}^0_1$$

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$\tilde{q}_L \rightarrow$	q			Hard Jet (2)
$\searrow$				
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2 Jets + 2 τ + $\not\!\!E_{\mathrm{T}}$ Signal

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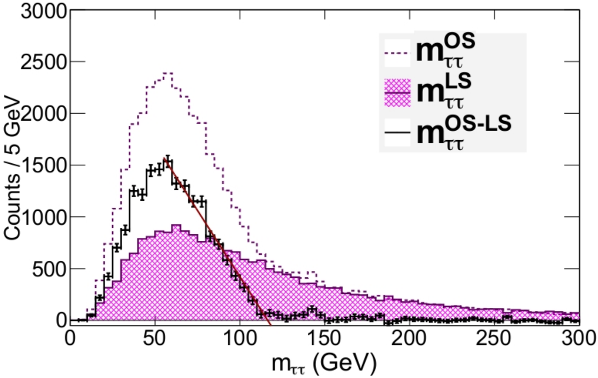
Cuts:

- $\geq 2\tau_{\mathrm{h}}$ with $p_{\mathrm{T},\tau_{\mathrm{h}}}^{\mathrm{vis}} \geq 15\ \mathrm{GeV}$
- ≥ 2 jets, with $p_{\mathrm{T,jet1,2}} \geq 100\ \mathrm{GeV}$
- $\not\!\!E_{\mathrm{T}} \geq 200\ \mathrm{GeV}$
- $h_{\mathrm{T}} = \not\!\!E_{\mathrm{T}} + p_{\mathrm{T,jet1}} + p_{\mathrm{T,jet2}} \geq 600\ \mathrm{GeV}$

Ditau Invariant Mass



Mass Measurement from LHC Data

- Functional Form: $m_{\tau\tau}^{\text{end}} = f(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})$
- Combine with $p_{\mathrm{T},\tau}$ observables.
- Invert Functional Forms to solve: $m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$

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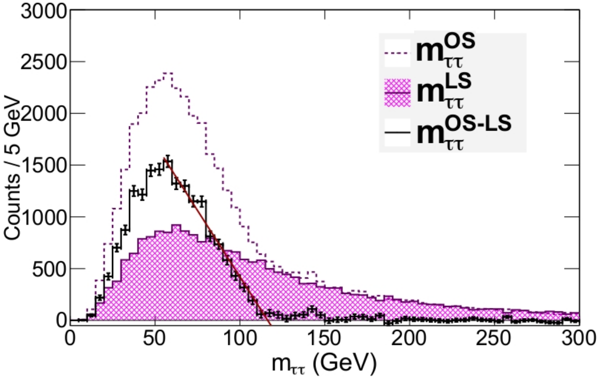

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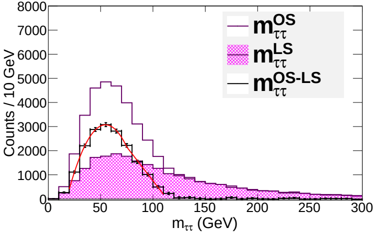
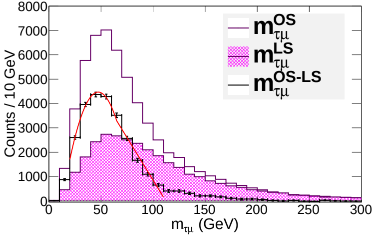
Di-Tau and Tau-Mu Invariant Mass

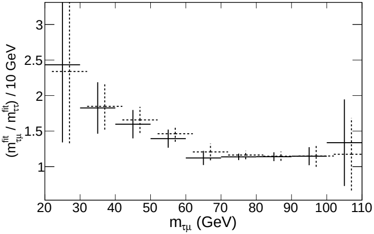
Using $m_{\tilde{\tau}_1}$, $m_{\tilde{\chi}_1^0}$, and $m_{\tilde{\chi}_2^0}$:
compare the shapes with an LHC simulation.





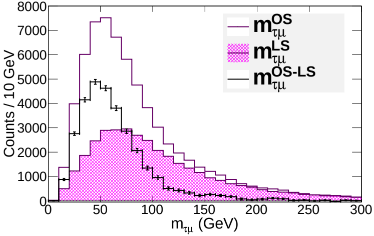
Divide

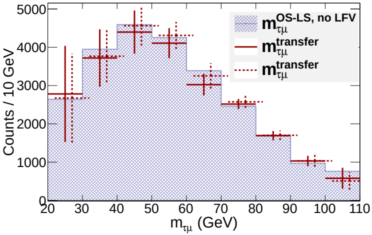
$\Rightarrow$



LFV signal

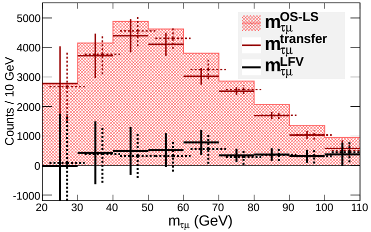
Back to the LHC Data:
Use the transfer function, convert $m_{\tau\tau}$ to $m_{\tau\mu}^{\text{transfer}}$.





Subtract

$\Rightarrow$



Conclusions

New Technique: Transfer Function

- $\delta_{RR,\mathrm{LFV}} = 15\% \Rightarrow$ Excess
- Ruled out mSUGRA benchmark:
  - $\mathcal{L} = 1000~\mathrm{fb}^{-1} \Rightarrow \sim 2\sigma$ with systematics.
  - Same significance at $\mathcal{L} = 300~\mathrm{fb}^{-1}$ without systematics.
  - Let's reduce those systematics!!!
- Doesn't have to be mSUGRA!

arXiv:1203.3276

Extra Numbers

- $m_0 = 250$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 40$, and $\mu > 0$.
- Statistical @ $\mathcal{L} = 1000(300)\ \mathrm{fb}^{-1}$.
- Systematic: Jet Energy Scale $\pm 3\%$.

Particle Mass	Solution One	Solution Two
$\tilde{\tau}_1$: 186.7	$181.5 \pm 3.7(5.1) \pm 4.1$	$205.8 \pm 5.9(6.1) \pm 5.7$
$\tilde{\chi}_1^0$: 141.5	$140.6 \pm 5.4(6.5) \pm 6.2$	$151.4 \pm 6.4(8.6) \pm 6.3$
$\tilde{\chi}_2^0$: 265.8	$265.3 \pm 6.2(8.5) \pm 7.3$	$278.9 \pm 9.2(11.7) \pm 9.0$
$\delta_{RR,\mathrm{LFV}} = 15\%$	2.2σ (1.7σ) excess	1.6σ (1.2σ) excess

OS−LS

Making use of Opposite Sign(OS)−Like Sign(LS) subtraction:

$$\tilde{q}_L \rightarrow q$$
$$\searrow \tilde{\chi}_2^0 \rightarrow \tau^{\mp}$$
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$\tau^{\pm}$

Background OS

$m_{\tau\tau}^{\mathrm{OS}}$

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Background LS

$m_{\tau\tau}^{\mathrm{OS}}$ $m_{\tau\tau}^{\mathrm{LS}}$

OS−LS

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 & & & & & \searrow & \\
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$$

OS−LS
Eats BG

$$m_{\tau\tau}^{\mathrm{OS}} - m_{\tau\tau}^{\mathrm{LS}} = m_{\tau\tau}^{\mathrm{OS-LS}}$$