Flavor Violation at the LHC

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Sixth Workshop on Theory, Phenomenology and Experiments in Flavour Physics - FPCapri2016, June 13th, 2016

Outline

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**

LHC status…

➔ Higgs search results, m_h : 126 GeV

- in the tight MSSM window <135 GeV

➔ $m_{\tilde{q}}$ (1st gen.) ~ $m_{\tilde{g}} \geq$ 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 ΔM 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/μ

Standard SUSY searches

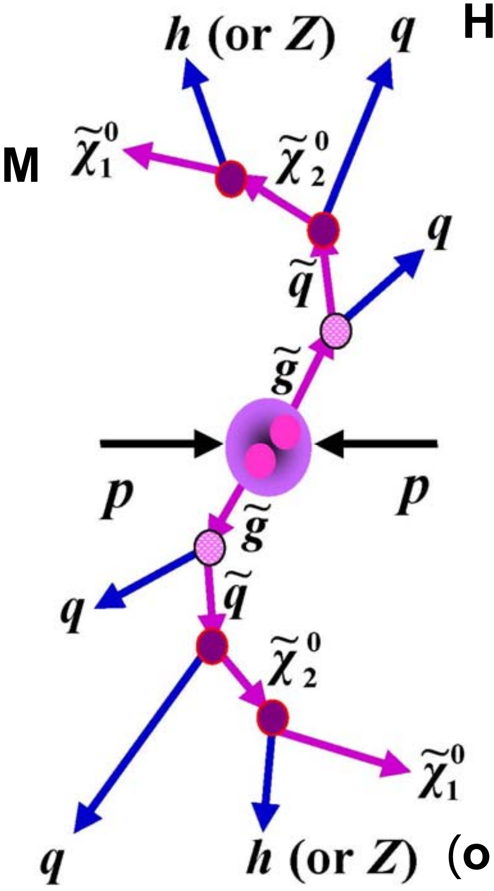
Colored particles can be produced and they decay into the weakly interacting stable particle

(or l^+l^-, $\tau+\tau-$)

High P_T jet

[mass difference is large]

DM



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

DM

R-parity conserving

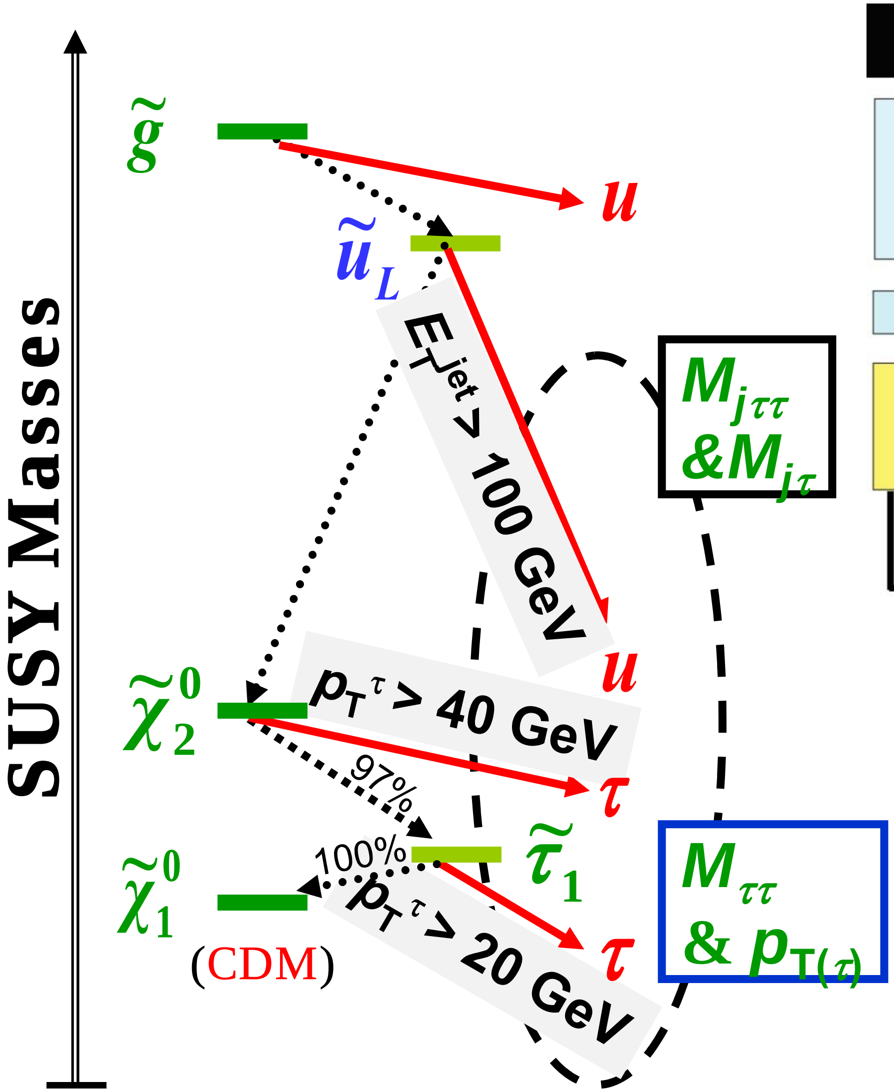
High P_T jet

(or l^+l^-, $\tau+\tau-$)

The signal :

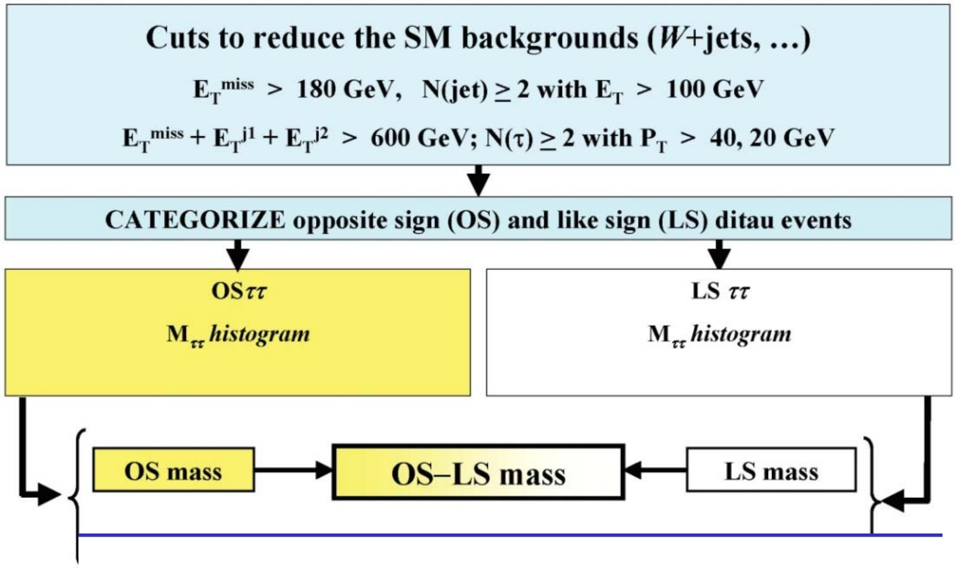
jets + leptons+ t’s +W’s+Z’s+H’s + missing E_T

Non-colored in cascade



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

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



Cuts to reduce the SM backgrounds (*W*+jets, …)

$E_T^{\text{miss}} > 180$ GeV, $N(\text{jet}) \geq 2$ with $E_T > 100$ GeV

$E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600$ GeV; $N(\tau) \geq 2$ with $P_T > 40, 20$ GeV

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

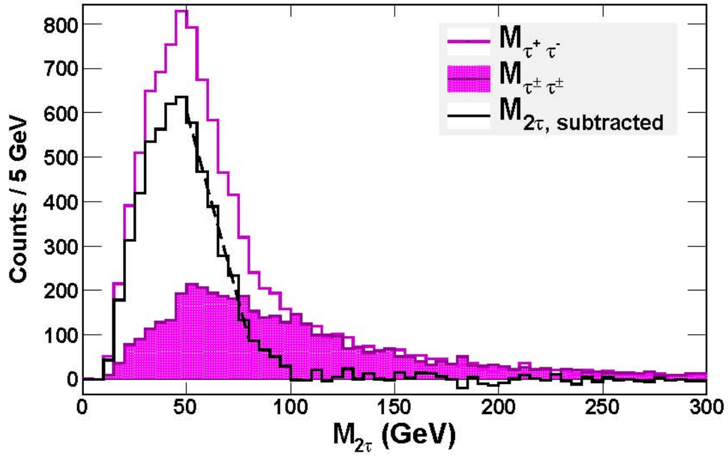
OS$\tau\tau$

$M_{\tau\tau}$ *histogram*

LS $\tau\tau$

$M_{\tau\tau}$ *histogram*

OS mass → OS–LS mass ← LS mass



Arnowitt, Dutta, Gurrola, Kamon, Krislock and Toback'06,07,08,09

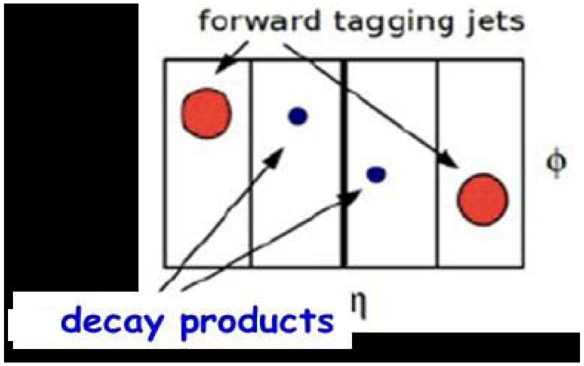
Non-Colored sector: LHC

Challenge:

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

- **Not so large ΔM($\equiv m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$)➔ Smaller Missing energy**

- **VBF topology: Tagging VBF jets**



- **ISR+ missing E_T + e, μ, τ, b, t etc.**

Monojet+Leptons: Sleptons

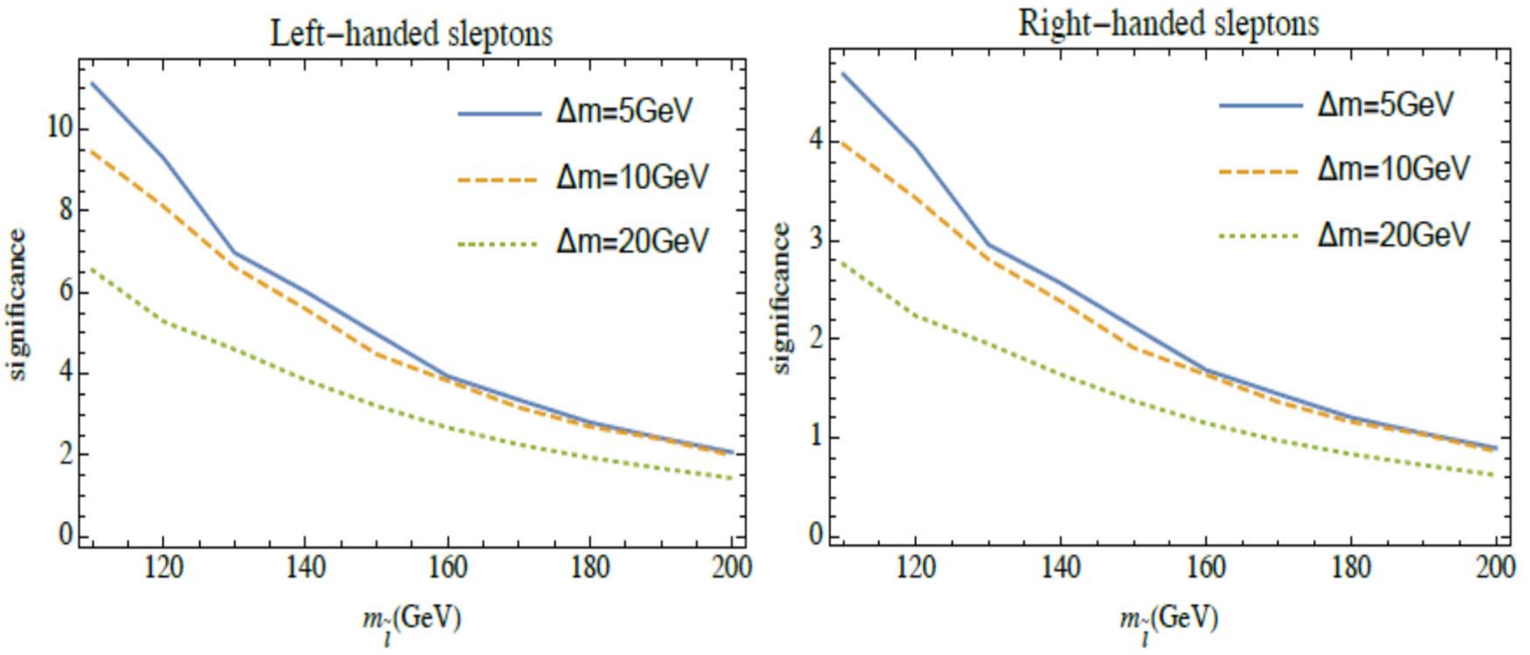


FIG. 5. The statistical significance ($S/\sqrt{B}$) after all cuts, as a function of the slepton mass, for three mass splittings (denoted Δm). An integrated luminosity of 100 fb^{-1} at LHC 14 is assumed. Left: left-handed slepton; right: right-handed slepton. Two generations of sleptons (selectons and smuons) of degenerate masses are included.

Han, Liu, 2015

VBF: Sleptons

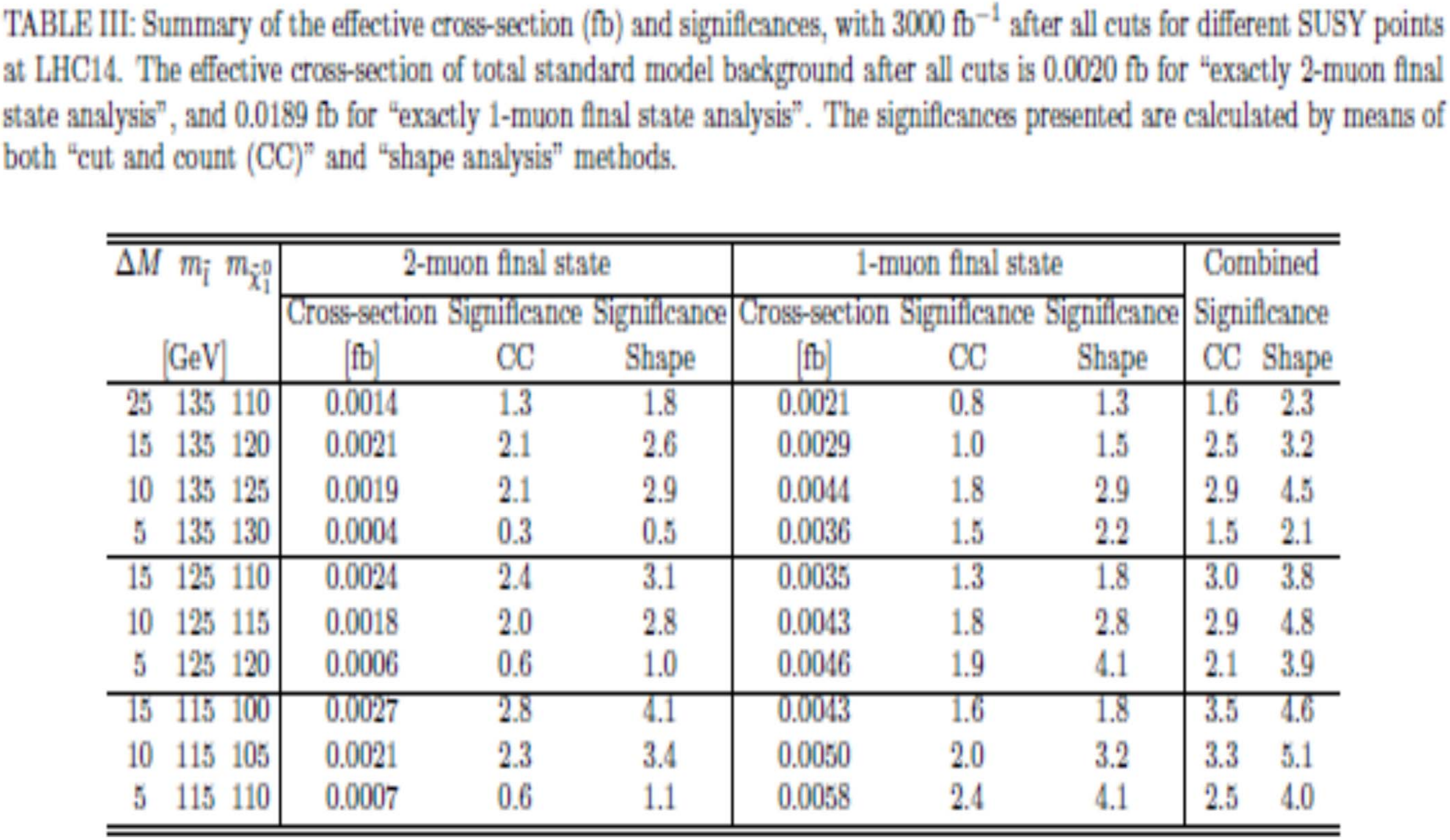


TABLE III: Summary of the effective cross-section (fb) and significances, with 3000 fb^{-1} after all cuts for different SUSY points at LHC14. The effective cross-section of total standard model background after all cuts is 0.0020 fb for "exactly 2-muon final state analysis", and 0.0189 fb for "exactly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

ΔM	$m_{\tilde{l}}$	$m_{\tilde{\chi}_1^0}$	2-muon final state			1-muon final state			Combined	
			Cross-section	Significance	Significance	Cross-section	Significance	Significance	Significance	
	[GeV]		[fb]	CC	Shape	[fb]	CC	Shape	CC	Shape
25	135	110	0.0014	1.3	1.8	0.0021	0.8	1.3	1.6	2.3
15	135	120	0.0021	2.1	2.6	0.0029	1.0	1.5	2.5	3.2
10	135	125	0.0019	2.1	2.9	0.0044	1.8	2.9	2.9	4.5
5	135	130	0.0004	0.3	0.5	0.0036	1.5	2.2	1.5	2.1
15	125	110	0.0024	2.4	3.1	0.0035	1.3	1.8	3.0	3.8
10	125	115	0.0018	2.0	2.8	0.0043	1.8	2.8	2.9	4.8
5	125	120	0.0006	0.6	1.0	0.0046	1.9	4.1	2.1	3.9
15	115	100	0.0027	2.8	4.1	0.0043	1.6	1.8	3.5	4.6
10	115	105	0.0021	2.3	3.4	0.0050	2.0	3.2	3.3	5.1
5	115	110	0.0007	0.6	1.1	0.0058	2.4	4.1	2.5	4.0

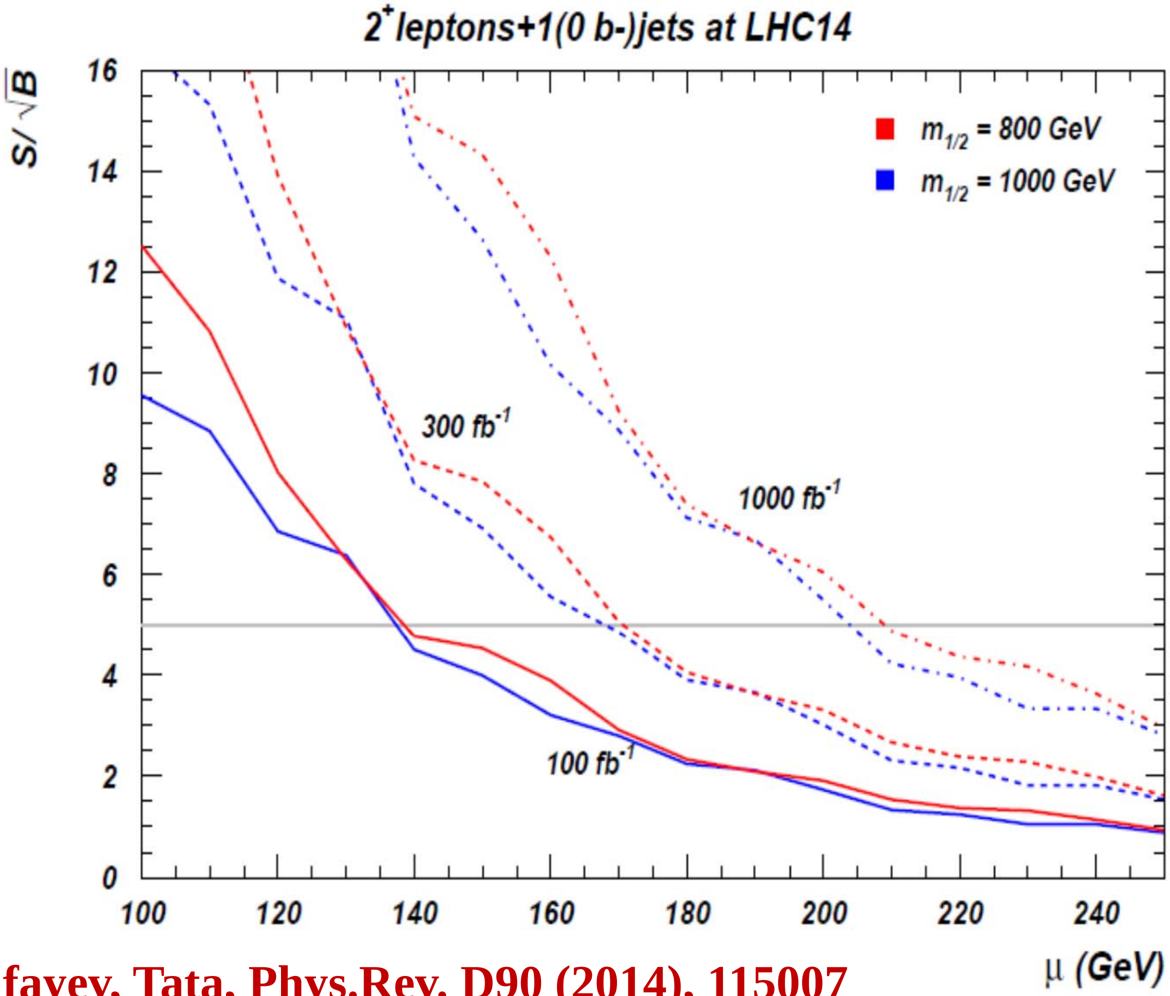
Dutta, Ghosh, Gurrola, Kamon, Sheldon, Sinha, Wang, Wu, 2015

Monojet+Leptons: Higgsinos

Higgsino type $\chi^0_{1,2}$ (cosmologically interesting):

The mass difference between χ^0_1 and χ^0_2, $\chi^\pm_1$: 10 GeV

ISR+missing E_T+Leptons

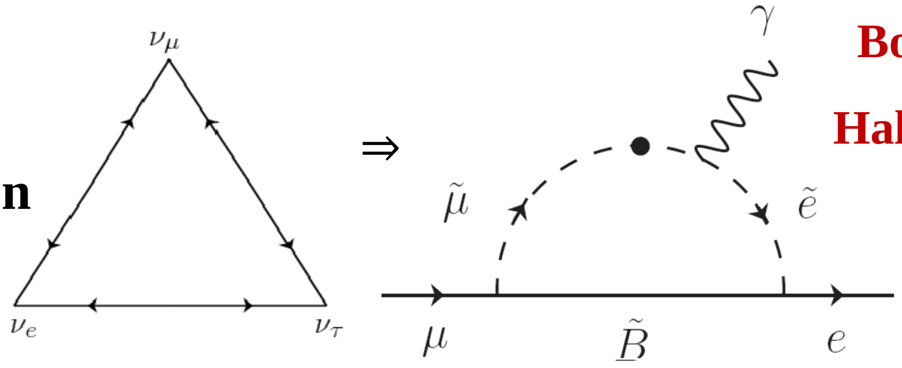


Baer, Mustafayev, Tata, Phys.Rev. D90 (2014), 115007

LFV in SUSY Models

- **LFV can be quite natural in SUSY models**

Neutrino flavor Oscillations have been observed



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.**

LFV and Neutrino

Seesaw mechanism naturally explains small ν-mass.

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

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

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond,
Slansky (1979)
Mohapatra, Senjanovic
(1980)

Current Neutrino data suggest

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

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 $(Y_\nu \ell \nu^c H_u)$. $M_D = Y_\nu v_u$

Majorana neutrino coupling : $f\nu^c\nu^c\Delta$

$M_R = f v_{B-L}$ Where $\langle\Delta\rangle = v_{B-L}$

Flavor violation may reside entirely in f and/or entirely in Y_ν

One can express the RGE induced off-diagonal elements of SUSY breaking in terms of f and Y_ν

LFV in SUSY Models

- **When flavor violation occurs only in *f* (Majorana LFV)**

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

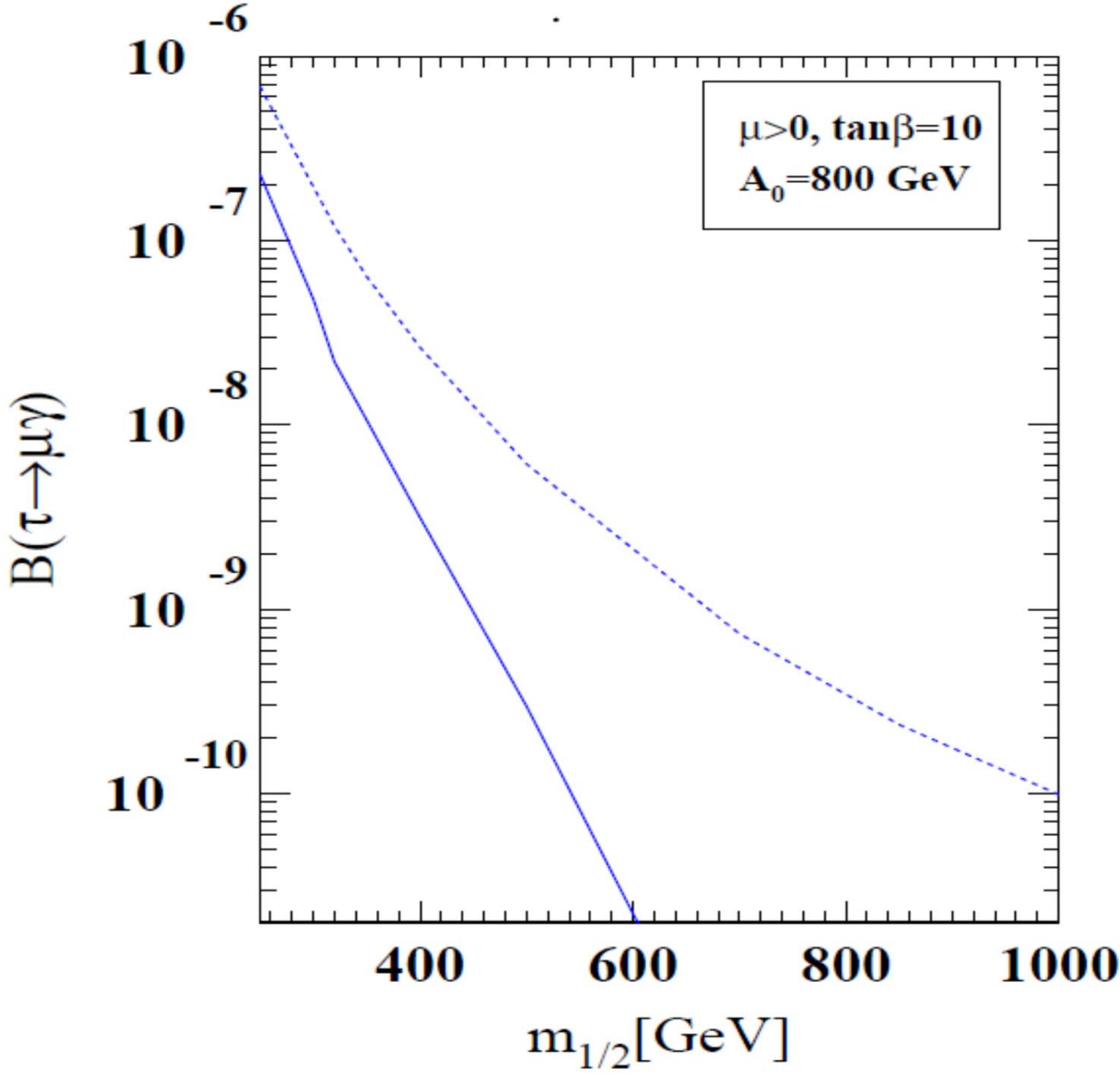
$$A_{\ell ij}(i \neq j) \;\simeq\; \frac{-3}{64\pi^4}[A_\ell(Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger f Y_\nu^\dagger Y_\nu)]_{ij}\left(\ell n \frac{M_{P\ell}}{M_{B-L}}\right)^2$$

- **When flavor violation occurs only in Dirac Yukawa Y_ν**

  (with mSUGRA)

$$\Delta m^2_{ij}(i \neq j) \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\left(\ell n \frac{M_{Pl}}{M_{B-L}}\right)$$

LFV in SUSY Models



Dashed line: Dirac
Solid line Majorana

Babu, Dutta, Mohapatra, 200

LFV in SUSY Models

LFV also occurs without neutrino couplings in SUSY GUTS

$$(m^2_{\tilde{e}_R})_{ij} \simeq -\frac{3}{8\pi^2} V_{3i} V^*_{3j} |Y_t|^2 \left(3m_0^2 + |A_0|^2\right) \ln\left(\frac{M_P}{M_G}\right)$$

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

Barbieri, Hall, Strumia, 1995
Hisano et al, 1997

LFV in SUSY Models

The charged slepton mass matrix: 6x6

$$\mathcal{M}^2_{\tilde{l}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ \mathcal{M}^2_{LR} & \mathcal{M}^2_{RR} \end{pmatrix},$$

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

In mSUGRA/CMSSM $\mathcal{M}^2_{LL} = \mathcal{M}^2_{RR} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$, A_l=0

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

- **Constraints from** $\boldsymbol{\tau \to \mu\gamma, \mu \to e\gamma\ etc}$

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,**

  $\tilde{\chi}_2^0 \rightarrow \tilde{l}^* l \rightarrow l^{\pm} l^{\mp} \tilde{\chi}_1^0$ **where l=e, μ, τ**

  - **Neutralinos can arise fron the squark deacys:**

    $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{l}^* l \rightarrow q l^{\pm} l^{\mp} \tilde{\chi}_1^0$

  - **Direct production of $\tilde{\chi}_2^0$ is also possible**

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

$$\tilde{\chi}_2^0 - \tilde{l} - \tilde{\chi}_1^0$$

LFV at the LHC

In the non-LFV scenario

$$\tilde{\chi}_2^0 \to \tilde{l}^* l \to l^{\pm} l^{\mp} \tilde{\chi}_1^0$$ where l=e, μ, τ

In the LFV scenario, we have in addition

$$\tilde{\chi}_2^0 \to \tau\mu, e\mu, \tau e + \tilde{\chi}_1^0$$

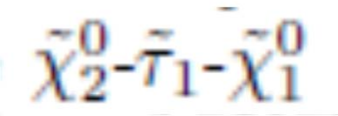
We consider a nonzero 2-3 element and we define

$$\delta_{RR,LFV} = \frac{[\mathcal{M}_{RR}^2]_{23}}{[\mathcal{M}_{RR}^2]_{33}}$$

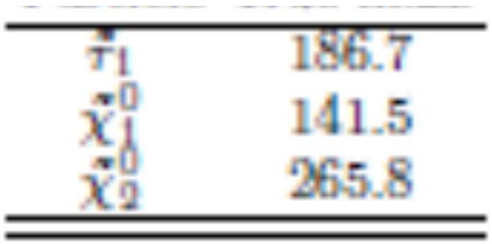
This LFV will enter into $\tilde{\chi}_2^0$, $\tilde{l}$ decay modes and $\tau \to \mu\gamma$ amplitudes

Allahverdi, Dutta, Kamon, 2012

LFV at the LHC



$\tilde{\chi}_2^0$-$\tilde{\tau}_1$-$\tilde{\chi}_1^0$



$\tilde{\tau}_1$	186.7
$\tilde{\chi}_1^0$	141.5
$\tilde{\chi}_2^0$	265.8

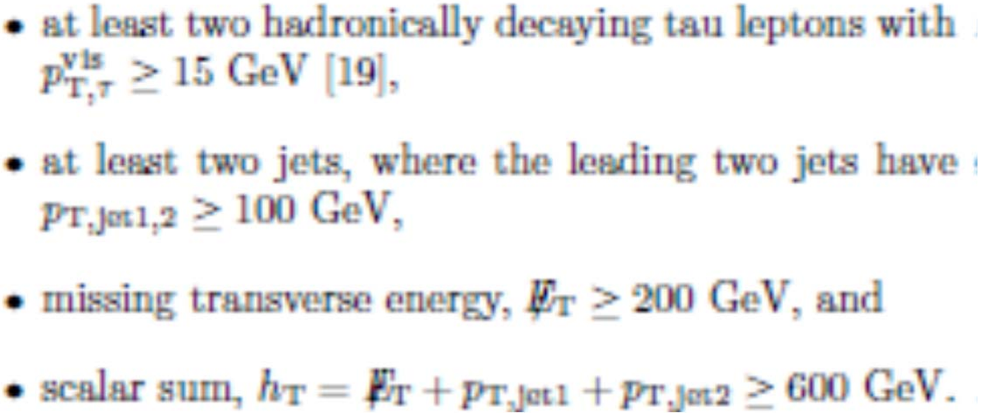
Masses in GeV

The whole analysis can be scaled by $\boldsymbol{\sigma(\tilde{q}_L, \tilde{g})\mathcal{B}(\tilde{q}_L, \tilde{g} \rightarrow \tilde{\chi}_2^0)}$

- **However, the technique remains the same**

$\boldsymbol{\sigma(\tilde{q}_L, \tilde{g})\mathcal{B}(\tilde{q}_L, \tilde{g} \rightarrow \tilde{\chi}_2^0)}$ **~ 0.1 pb at 13 TeV LHC**

Analysis:



- at least two hadronically decaying tau leptons with $p_{\mathrm{T},\tau}^{\mathrm{vis}} \geq 15$ GeV [19],
- at least two jets, where the leading two jets have $p_{\mathrm{T,jet1,2}} \geq 100$ GeV,
- missing transverse energy, $\not{E}_\mathrm{T} \geq 200$ GeV, and
- scalar sum, $h_\mathrm{T} = \not{E}_\mathrm{T} + p_{\mathrm{T,jet1}} + p_{\mathrm{T,jet2}} \geq 600$ GeV.

- **The final states are characterized by LS and OS tau pair**
- **We perform OS-LS to remove background**

LFV at the LHC

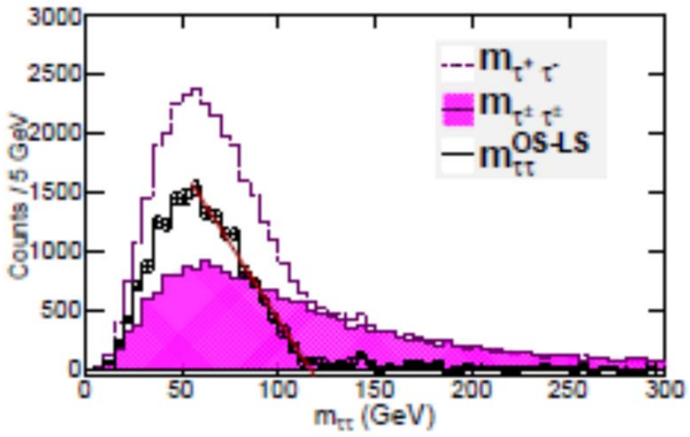


FIG. 1: The $\tau_h\tau_h$ invariant mass distribution for our benchmark point, shown in Table I. A linear fit finds the endpoint of the distribution. This distribution represents an integrated luminosity of 1000 fb^{-1}. However, we also report the situation for a lower luminosity of 300 fb^{-1} in this paper.

4 observables

$$m_{\tau\tau}^{max} = f(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})$$

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

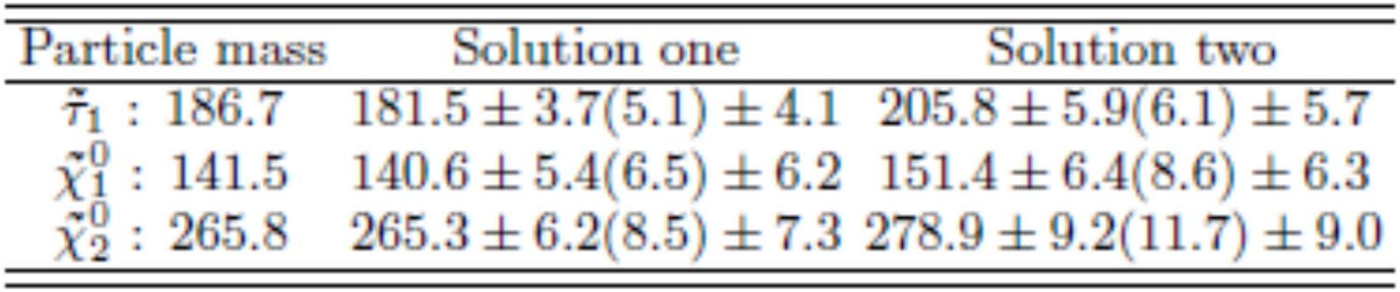
$$slope(p_{T,\tau}^{vis}) = f_3\left(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}\right)$$ **which include the average of low and high $p_{T,\tau}^{vis}$)**

$$slope(p_{T,+}^{vis}) = f_4(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})$$**: slope of transverse momentum sum distribution**

LFV at the LHC

Using the observables, we solve for the masses.

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



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	$265.3 \pm 6.2(8.5) \pm 7.3$	$278.9 \pm 9.2(11.7) \pm 9.0$

- **The statistical uncertainties are for $\boldsymbol{\mathcal{L} = 1000(300)\ fb^{-1}}$**
- **The systematic uncertainties are due to a jet energy scale mismeasurement of 3%**
- **Two solutions due to non-linear equations**

LFV at the LHC

We now investigate the effect of $\boldsymbol{\delta_{RR,LFV}}$

The presence of this term allows:

$\boldsymbol{\widetilde{\chi}_2^0} \rightarrow \boldsymbol{\widetilde{l_1}}\,\tau,\quad \boldsymbol{\tilde{l}_1} \rightarrow \boldsymbol{\mu\widetilde{\chi}_1^0}$

➔ $\boldsymbol{\widetilde{\chi}_2^0} \rightarrow \boldsymbol{\bar{\mu}}\tau$ **+ missing E$_T$, where missing E$_T$:** $\boldsymbol{\widetilde{\chi}_1^0}$

So the final states contain muons

- **However the tau decays also contain muons:** $\boldsymbol{\tau = \nu_\tau \bar{\nu}_\mu \mu}$

$\boldsymbol{\widetilde{\chi}_2^0} \rightarrow \boldsymbol{\tau\bar{\tau}} + \boldsymbol{\widetilde{\chi}_1^0} \rightarrow \boldsymbol{\bar{\mu}}\tau$**+ missing E$_{T,}$** **E$_T$:** $\boldsymbol{\widetilde{\chi}_{1,}^0\, \nu_\tau \bar{\nu}_\mu}$

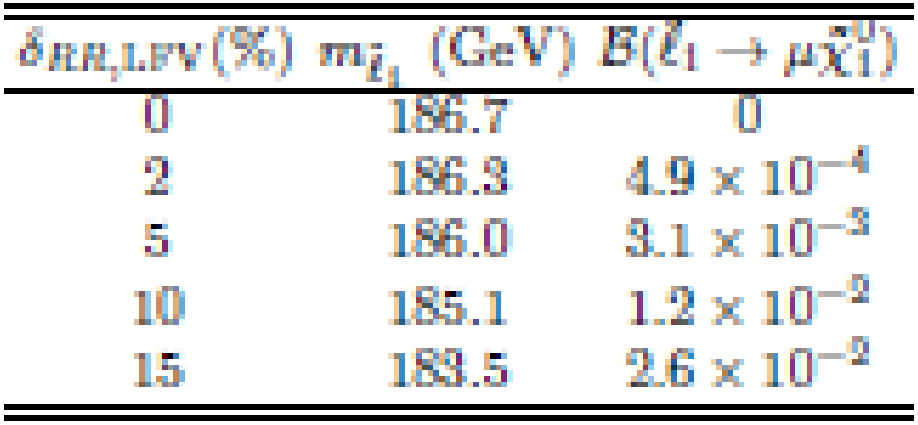
➔ **Missing E$_T$ in the background**

- **We need to separate these extra muons from the tau decays**

➔ **complicated analysis**

LFV at LHC

The effect of $\delta_{RR,LFV}$ on our benchmark points



$\delta_{RR,\mathrm{LFV}}(\%)$	$m_{\tilde{\tau}_1}$ (GeV)	$B(\tilde{\ell}_1 \to \mu\tilde{\chi}_1^0)$
0	186.7	0
2	186.3	4.9×10^{-4}
5	186.0	3.1×10^{-3}
10	185.1	1.2×10^{-2}
15	183.5	2.6×10^{-2}

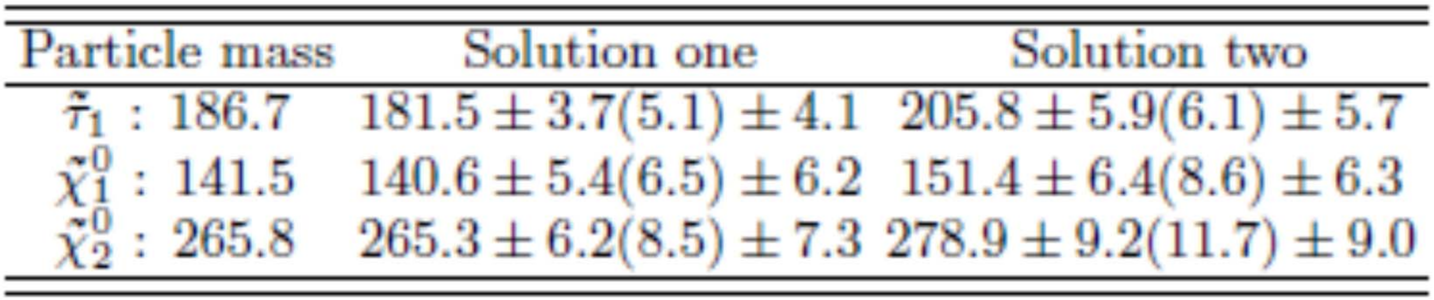
- **The values of $\delta_{RR,LFV}$ larger than 15% violate the $\mathrm{B}(\tau \to \mu\gamma) \leq 4.4 \times 10^{-8}$ for our benchmark point**

- **The change in the stau mass is very small**

LFV at the LHC

Analysis plan:

- **Take one of the mass points**



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- **Determine the $\tilde{\chi}_2^0 . \tilde{\tau}_1, \tilde{\chi}_1^0$ masses by using various observables**

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

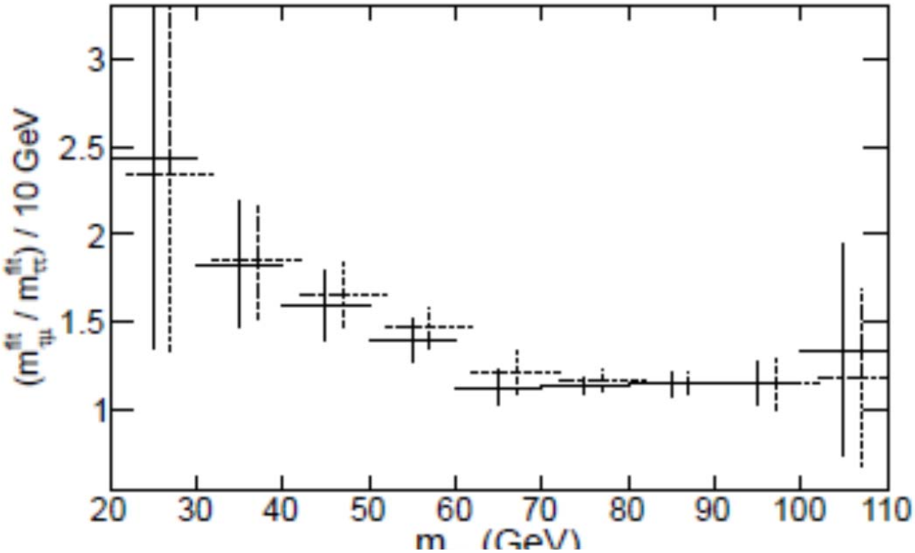
- **Subtract the determined $m_{\tau\mu}$ and from the observed $m_{\tau\mu}$ distributions**

- **Determine the amount of flavor violation**

LFV at the LHC

- The ττ (left) and τμ (right)invariant mass distribution for the LHC simulated $\delta_{RR,LFV}$=0 point (first solution)

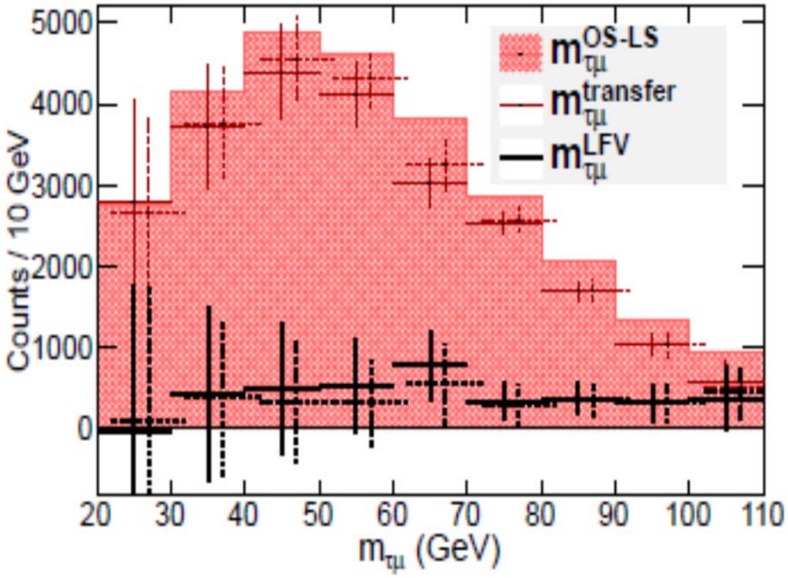
- The distribution is for an integrated luminosity of 1000 fb^{-1}

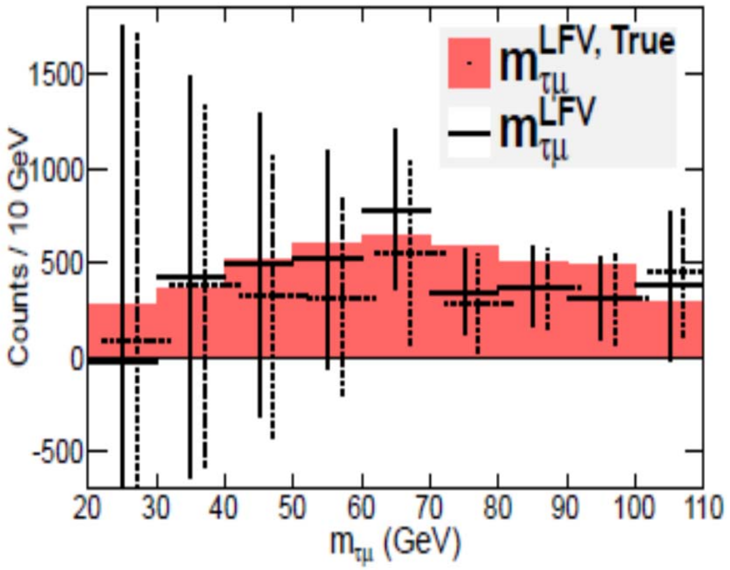


Transfer function for both masses

LFV at LHC

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



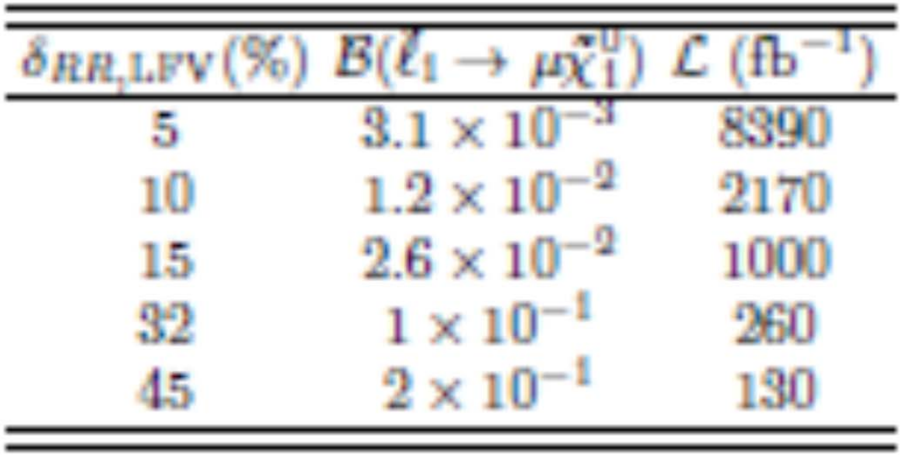


- **The τ−μ mass distribution for $\delta_{RR,LFV}$=0.15.**
- **Dashed is the second solution**

- **Comparison of the determined $m_{\tau\mu}$ with true $m_{\tau\mu}$**

LFV at the LHC

Keeping $\boldsymbol{\sigma(\tilde{q}_L, \tilde{g})\mathcal{B}(\tilde{q}_L, \tilde{g} \rightarrow \tilde{\chi}_2^0)}$ **same:**



$\delta_{RR,\mathrm{LFV}}(\%)$	$\mathcal{B}(\tilde{\ell}_1 \rightarrow \mu\tilde{\chi}_1^0)$	$\mathcal{L}$ (fb^{-1})
5	3.1×10^{-3}	8390
10	1.2×10^{-2}	2170
15	2.6×10^{-2}	1000
32	1×10^{-1}	260
45	2×10^{-1}	130

For more than 2σ 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**