ZPW2015: The flavour of new physics

University of Zurich, January 9th 2015

Lepton Flavour Violation in SUSY models

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ULB

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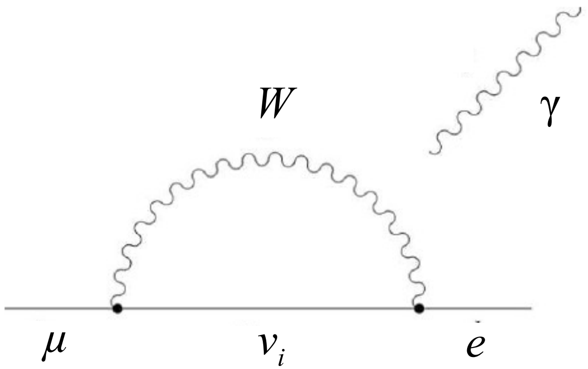
Why charged Lepton Flavour Violation?

- Neutrinos oscillate → Lepton family numbers are not conserved!

- Can we observe LFV in charged leptons decays?

- In the SM + massive neutrinos:

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{em}}}{32\pi} \left| \sum_i U_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2$$



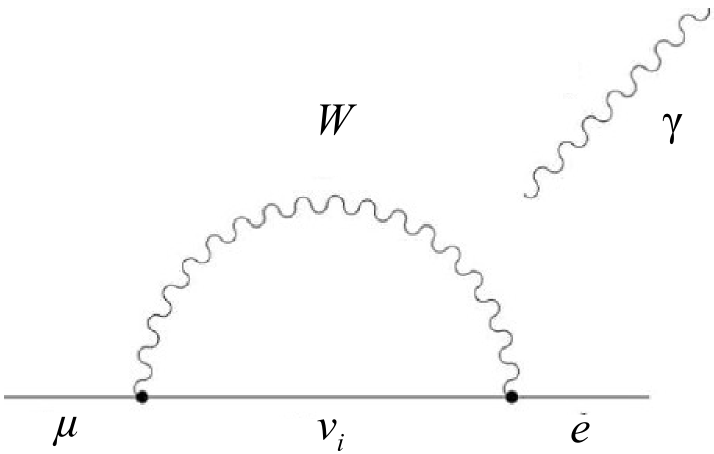
⇨ $\mathrm{BR}(\mu \to e\gamma) \lesssim \mathcal{O}(10^{-50})$

Suppression due to small neutrino masses

Cheng Li '77, '80; Petcov '77

⇨ In presence of New Physics at 'low' scales we can expect large effects!

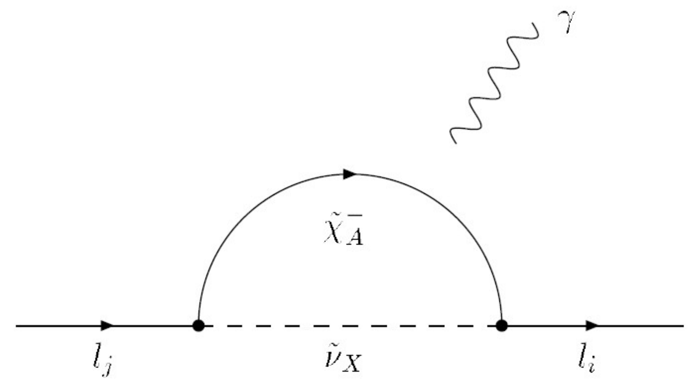
Why charged Lepton Flavour Violation?

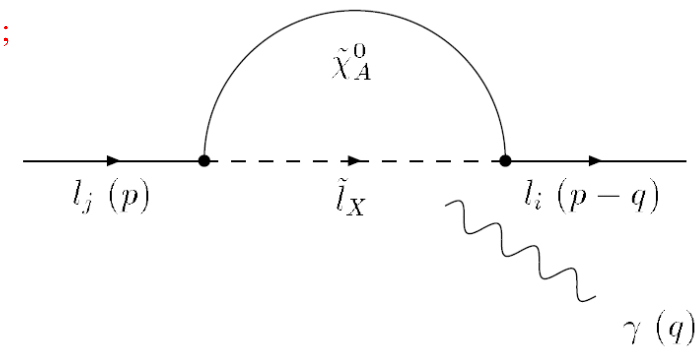


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi} \left| \sum_i U_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2$$

SUSY ⇨

Borzumati Masiero '86;
Hisano et al. '95





- Unambiguous signal of New Physics
- Stringent test of NP models
- It probes scales far beyond the LHC reach

Probing high-energy scales

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{C_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

$\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}$

Process	Relevant operators	Present Bound on Λ (TeV)		Future Bound on Λ (TeV)	
		$C = 1/16\pi^2$	$C = 1$	$C = 1/16\pi^2$	$C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	50	—	90	—
$\mu \to eee$	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17	210	170	2100
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10	120	100	1200
$\mu \to e$ in Ti	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	30	420	580	7300
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	60	750	1000	13000

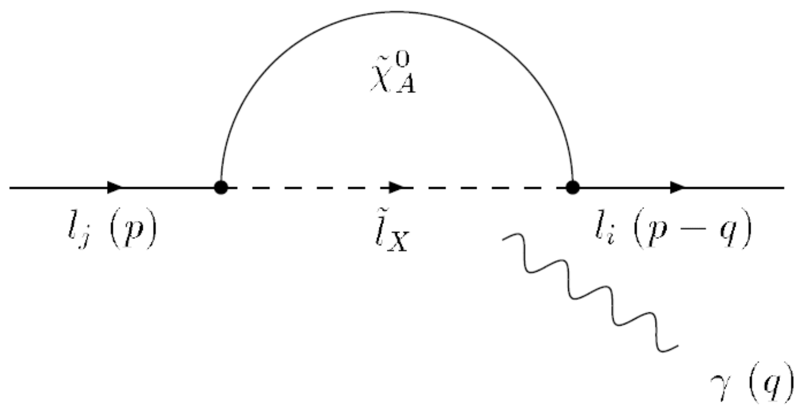
updated from LC Lalak Pokorski Ziegler '12

$\mathrm{BR}(\mu \to eee) < 10^{-16}$

$\mathrm{CR}(\mu \to e \text{ in Ti}) < 5 \times 10^{-17}$

Slepton mass matrix:

$$m^2_{\tilde{\ell}} = \begin{pmatrix} (\tilde{m}^2_L)_{ij} + (m^2_\ell)_{ij} - m^2_Z(\frac{1}{2} - \sin^2\theta_W)\delta_{ij} & A^{\ell\,*}_{ji} v_d - (m_\ell)_{ji}\mu\tan\beta \\ A^\ell_{ij} v_d - (m_\ell)_{ij}\mu^*\tan\beta & (\tilde{m}^2_E)_{ij} + (m^2_\ell)_{ij} - m^2_Z\sin^2\theta_W\delta_{ij} \end{pmatrix}$$



If flavour conserving:

g-2, EDMs

$$T = m_{l_i}\epsilon^\lambda \overline{u}_j(p-q)[iq^\nu\sigma_{\lambda\nu}(A_L P_L + A_R P_R)]u_i(p)$$

$\Rightarrow$

$$\frac{BR(l_i \to l_j\gamma)}{BR(l_i \to l_j\nu_i\bar{\nu_j})} = \frac{48\pi^3\alpha}{G_F^2}(|A_L^{ij}|^2 + |A_R^{ij}|^2)$$

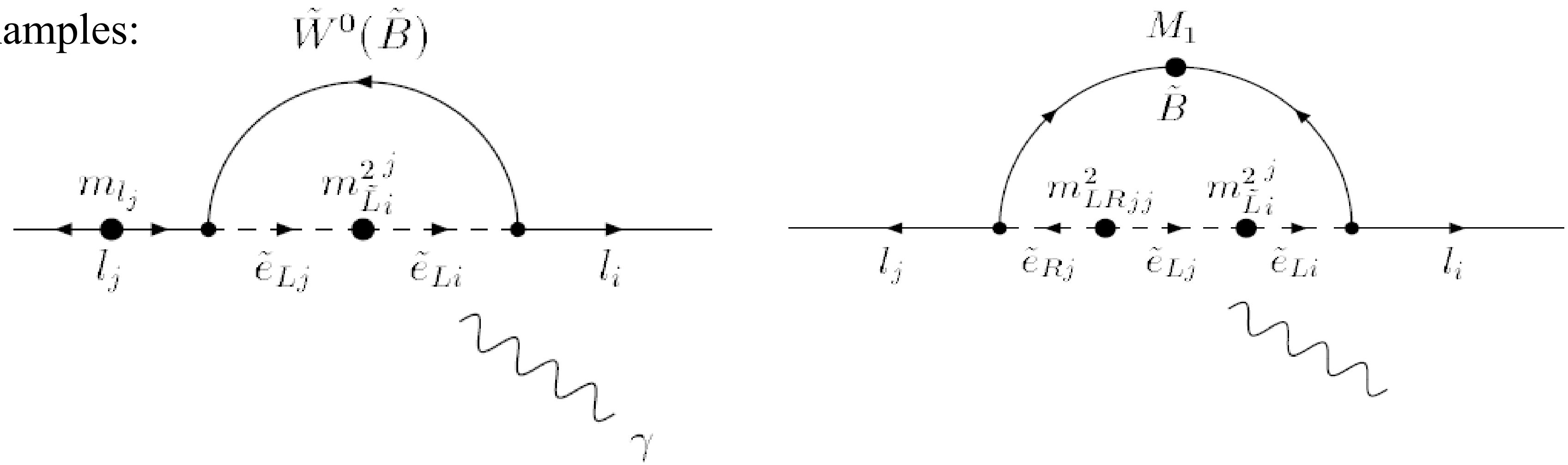
Hisano et al. '95

Slepton mass matrix:

Hall Kostelecky Raby '86
Pokorski Rosiek Savoy '99

$$(\tilde{l}_L^\dagger \tilde{l}_R^\dagger)\begin{pmatrix} m_L^2(1+\delta_{LL}) & (A-\mu\tan\beta)m_l + m_L m_R \delta_{LR} \\ (A-\mu\tan\beta)m_l + m_L m_R {\delta_{LR}}^\dagger & m_R^2(1+\delta_{RR}) \end{pmatrix}\begin{pmatrix} \tilde{l}_L \\ \tilde{l}_R \end{pmatrix}$$

Examples:

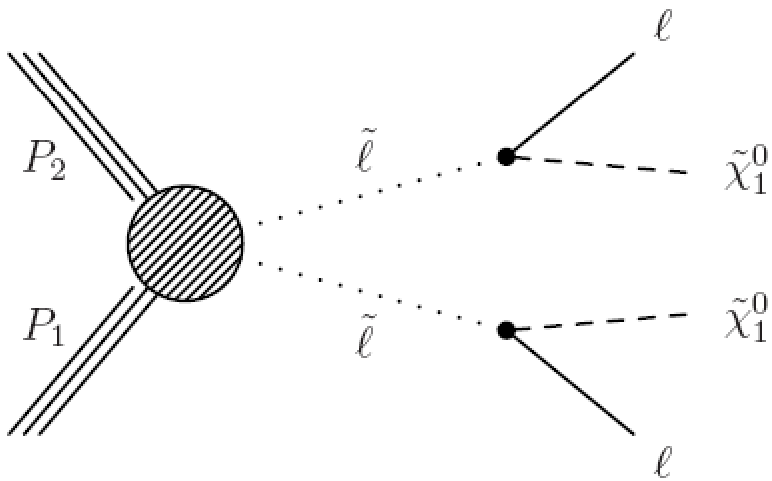


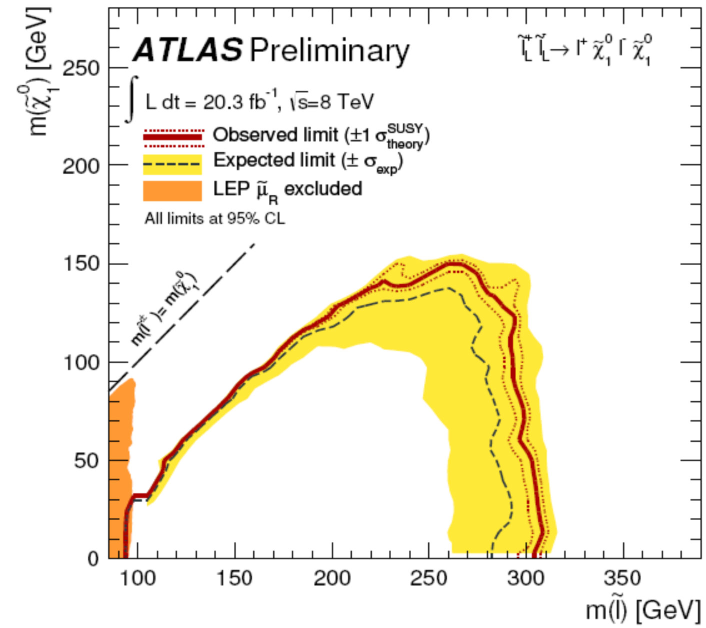
$$\Rightarrow \quad \frac{BR(l_i \to l_j\gamma)}{BR(l_i \to l_j \nu_i \bar{\nu}_j)} \propto \frac{\delta_{ij}^2}{\tilde{m}^2} \quad \Rightarrow$$

Limits on δ's

Gabbiani Masiero '89
Gabbiani et al. '96
Masina Savoy '02
Paradisi '05 ...

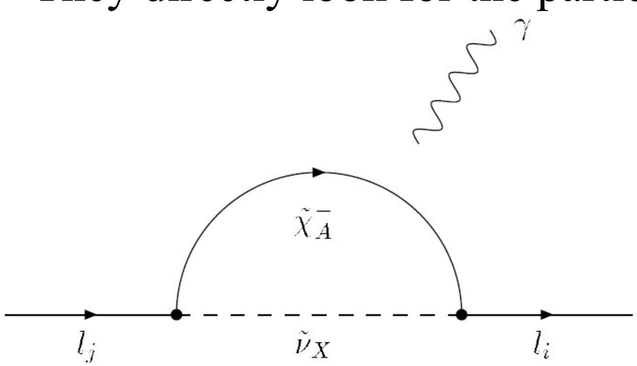
Comparing LFV and LHC bounds

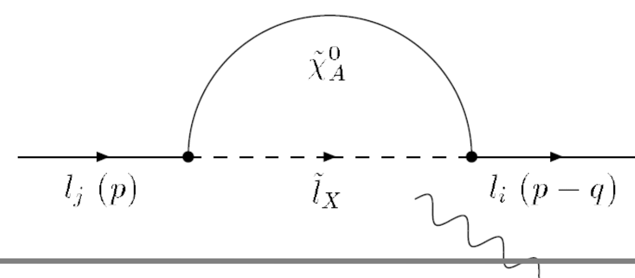


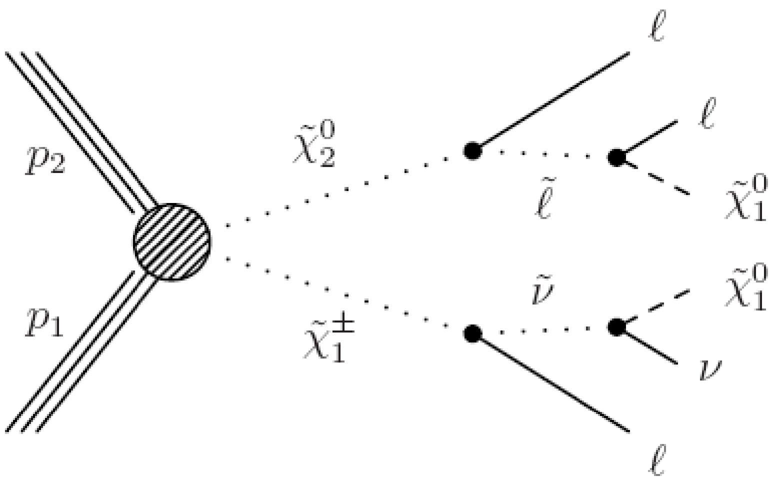


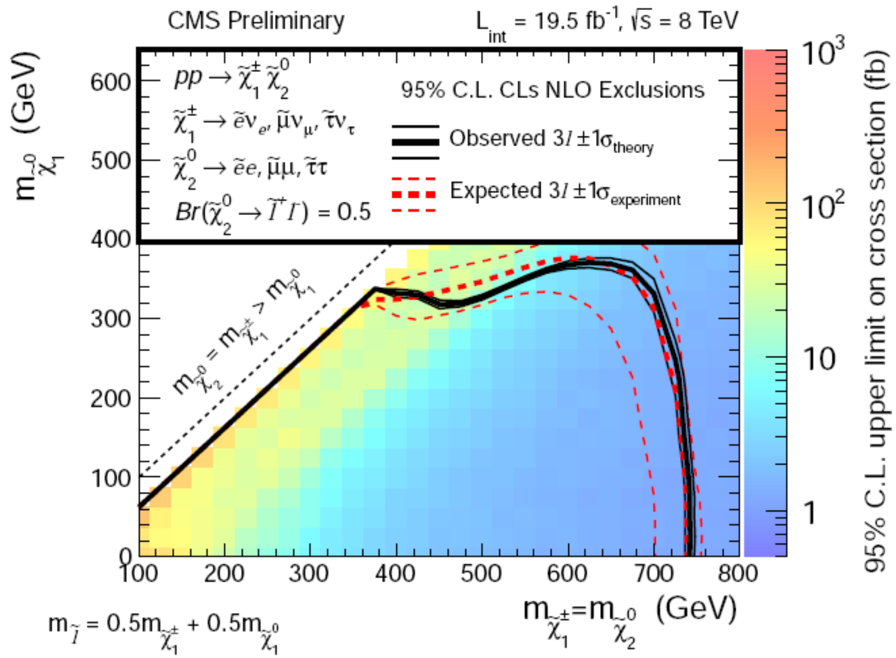
EW-searches at the LHC started to go considerably beyond the limits set by LEP

They directly look for the particles that can induce LFV transitions









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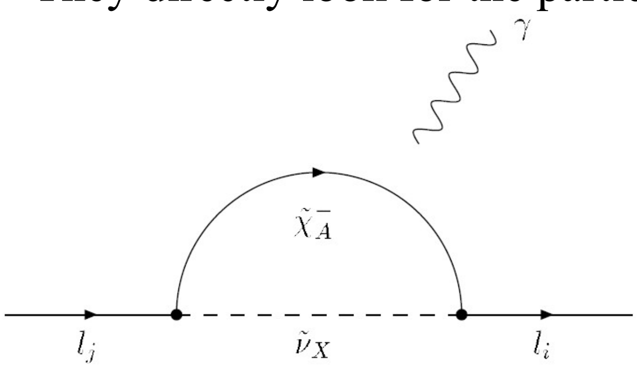
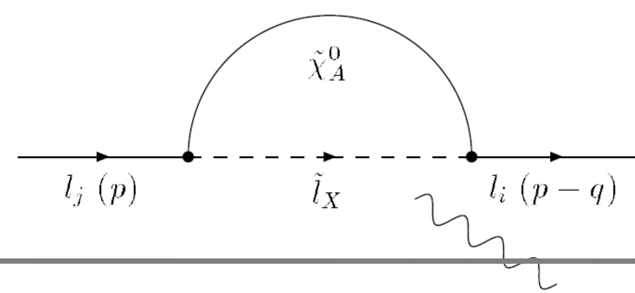


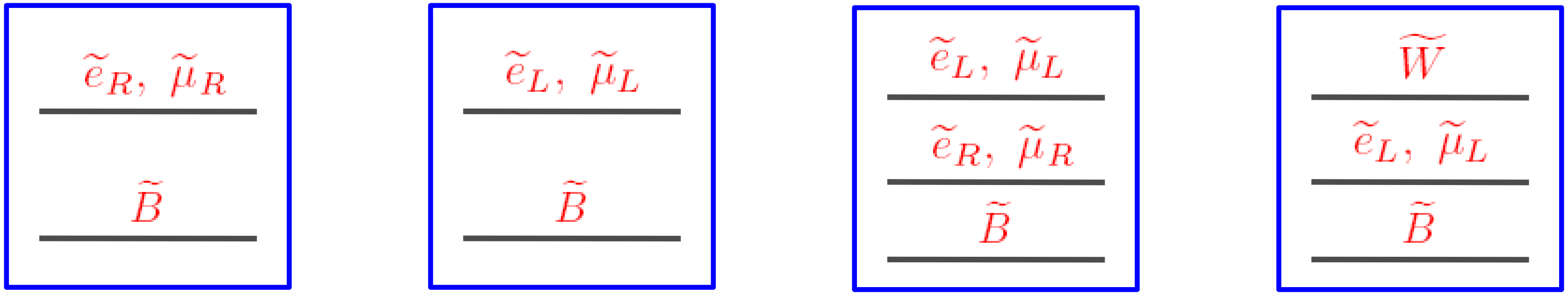


Comparing LFV and LHC bounds

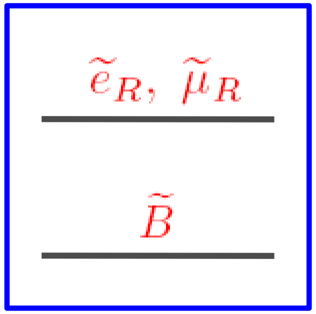
What is the impact of direct searches for SUSY particles at the LHC on the discovery prospects of LFV processes at low-energy experiments?

We can study LFV/LHC complementarity within the same simplified models used by the collaborations for the interpretation of the searches

Examples:



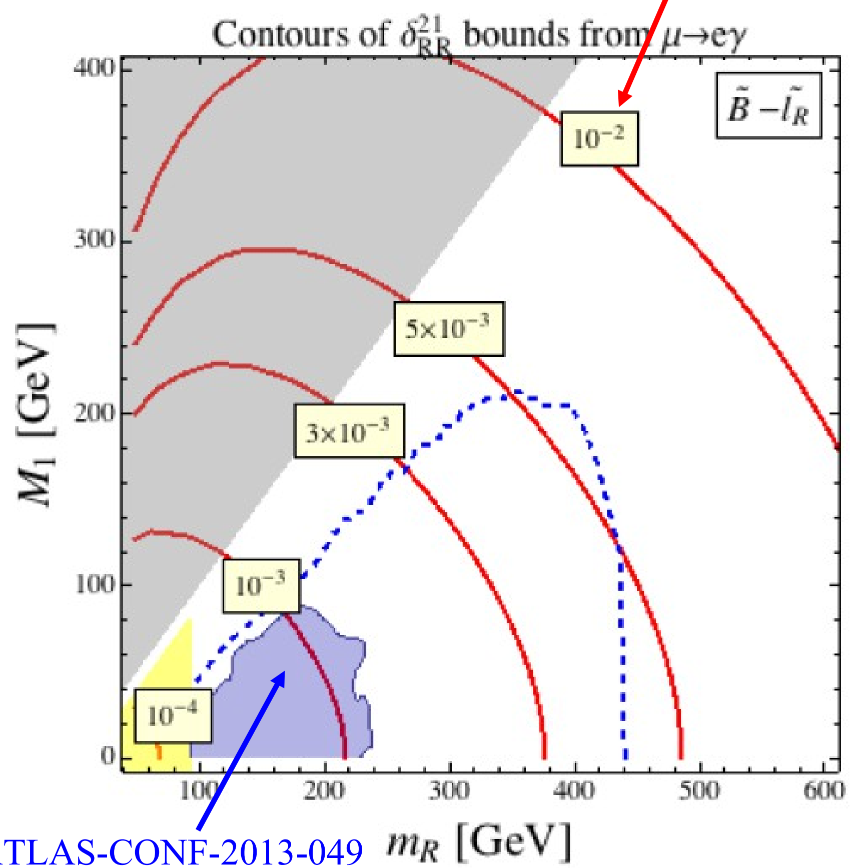
LFV vs LHC bounds within simplified models



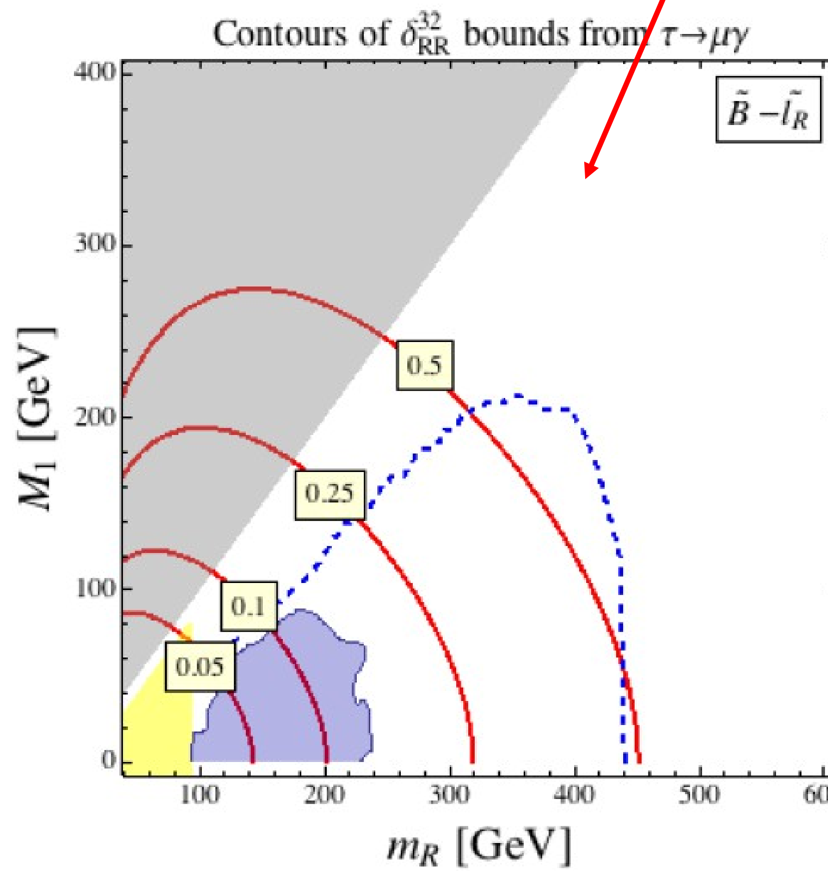
LC, Galon, Masiero, Shadmi, Paradisi, to appear

MEG '13
$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

BaBar '10
$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$



ATLAS-CONF-2013-049



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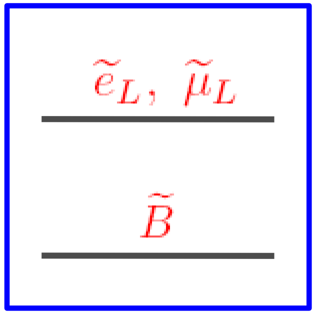

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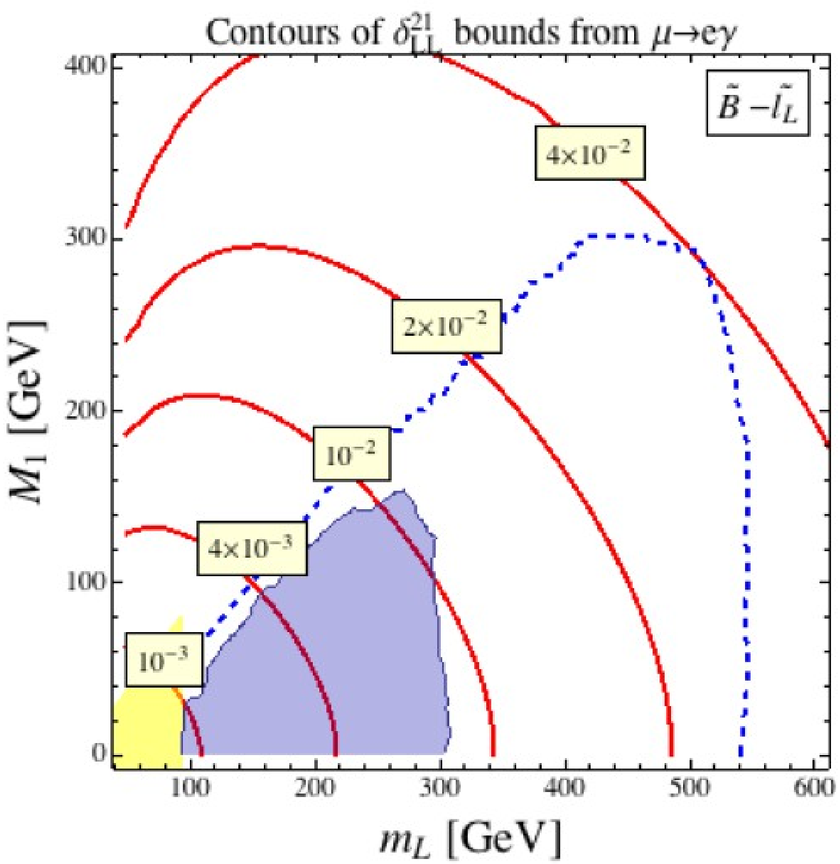
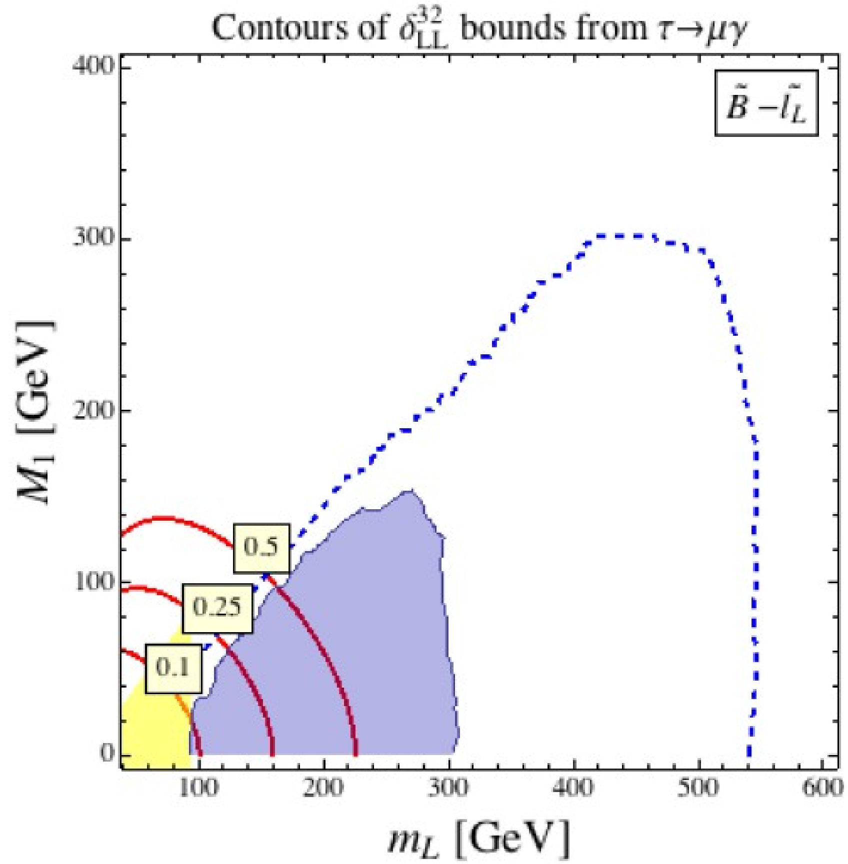
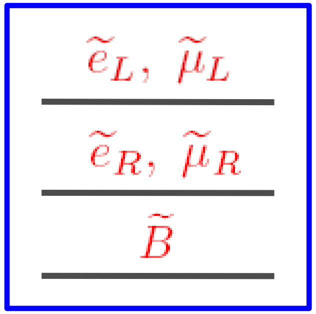


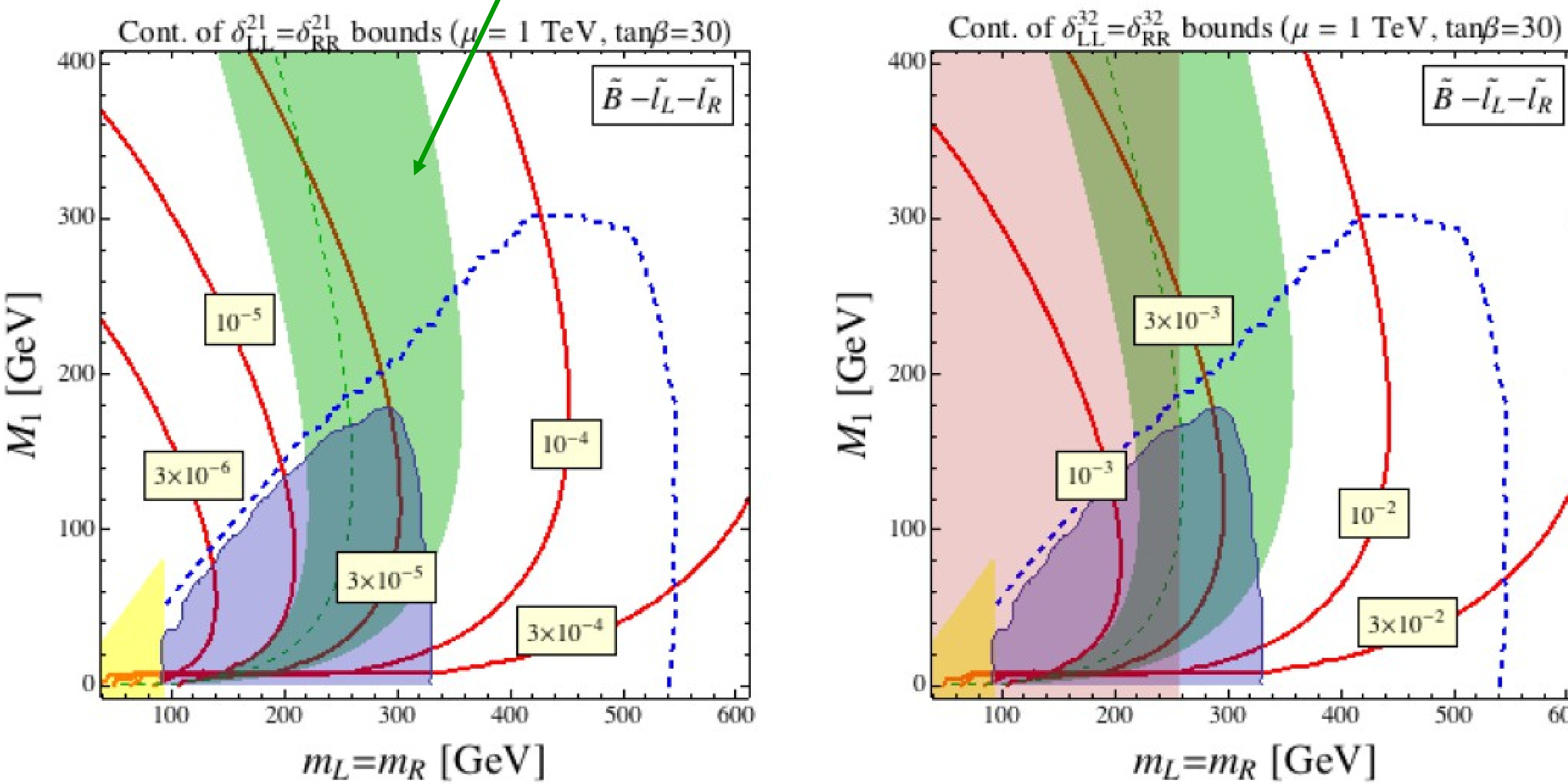


LFV vs LHC bounds within simplified models

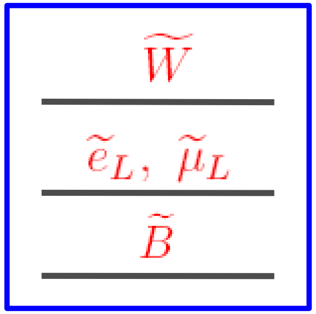


LC, Galon, Masiero, Shadmi, Paradisi, to appear

$$\Delta a_\mu \equiv \left|a_\mu^{\rm TH} - a_\mu^{\rm EXP}\right| \lesssim 2\sigma$$



LFV vs LHC bounds within simplified models



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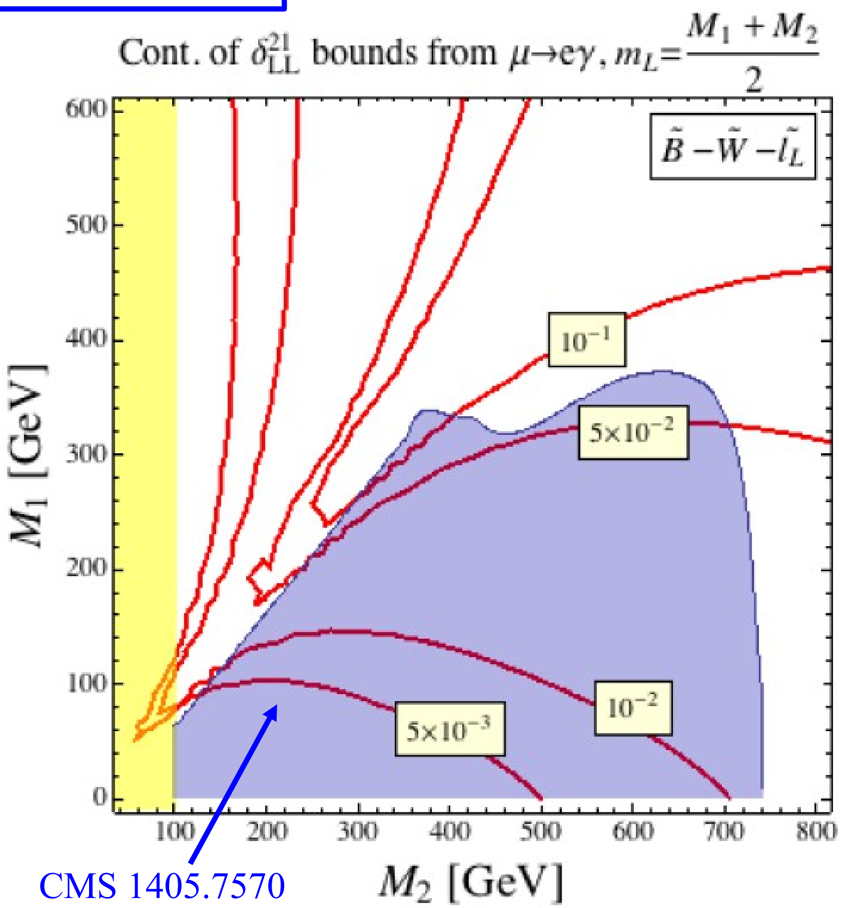
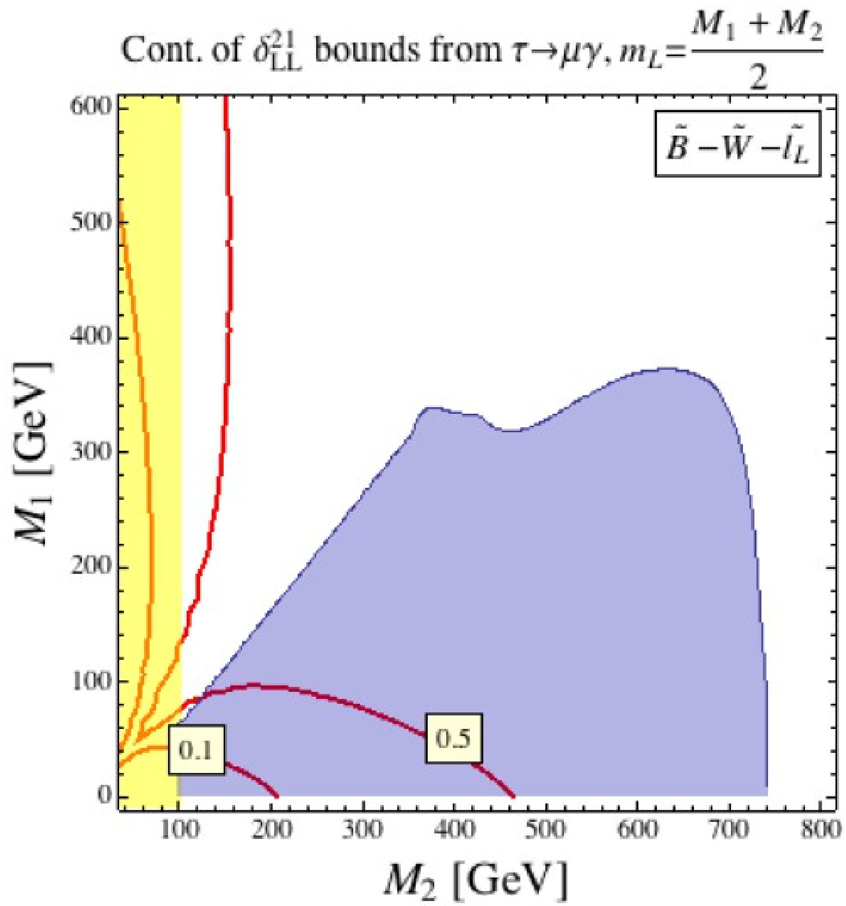
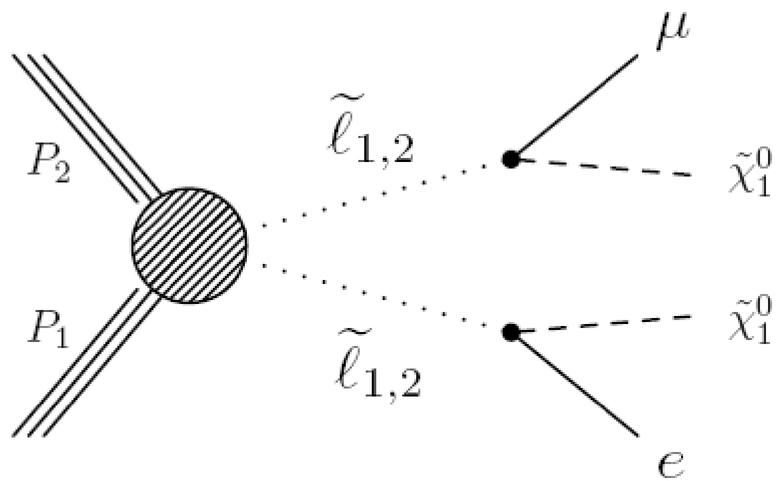






$$\tilde{\ell}_1 = \cos\theta_{\tilde{\ell}}\,\tilde{\mu} + \sin\theta_{\tilde{\ell}}\,\tilde{e}$$
$$\tilde{\ell}_2 = -\sin\theta_{\tilde{\ell}}\,\tilde{\mu} + \cos\theta_{\tilde{\ell}}\,\tilde{e}$$

Fraction of LFV events:

$$R_{e\mu} \equiv \frac{N(e^+\mu^-) + N(\mu^+e^-)}{N(e^+e^-) + N(\mu^+\mu^-)} = \frac{S_{e\mu}}{1 - S_{e\mu}} \qquad S_{e\mu} \equiv \frac{\sin^2 2\theta}{2}\,\frac{x^4 + 3x^2}{(1+x^2)^2}, \qquad x \equiv \frac{\Delta m_{\tilde{\ell}}}{\Gamma_{\tilde{\ell}}}$$

Arkani-Hamed et al. ’96. '97

For maximal smuon-selectron mixing, one has $R_{e\mu} \approx 50\%$ if $\Delta m_{\tilde{\ell}} > \Gamma_{\tilde{\ell}}$!

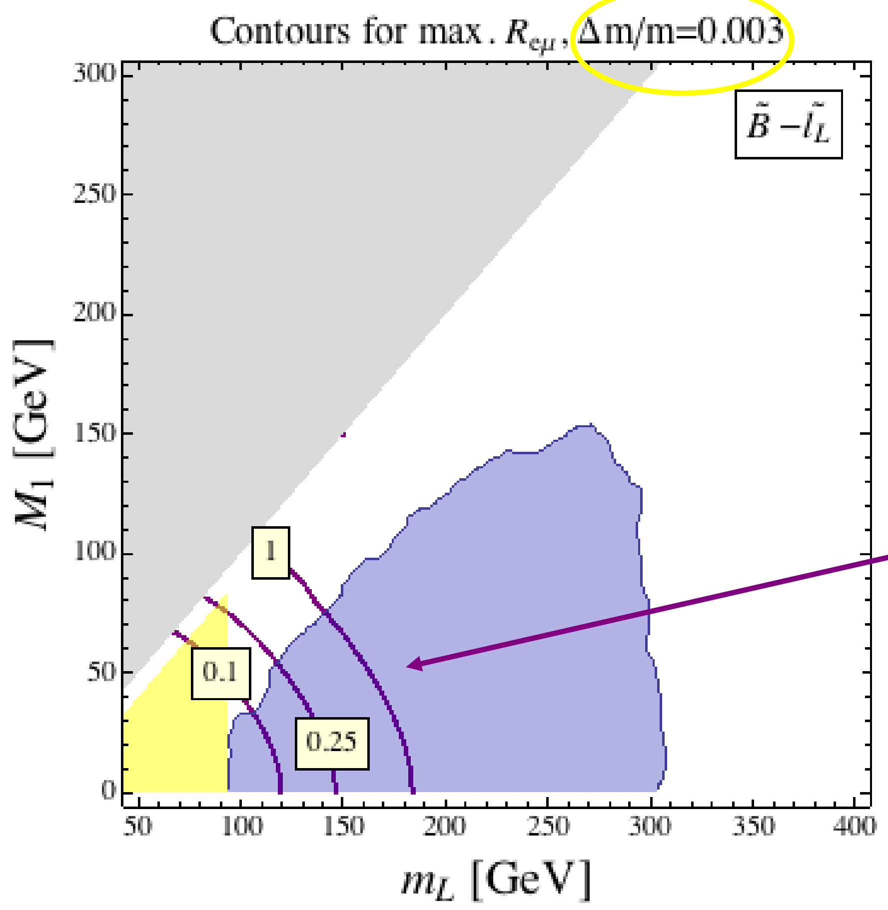
(if $\Delta m_{\tilde{\ell}} < \Gamma_{\tilde{\ell}}$, decay is faster than oscillation) $\Gamma_{\tilde{\ell}_L} \approx 10^{-3} m_{\tilde{\ell}_L}$

$\widetilde{e}_L,\ \widetilde{\mu}_L$

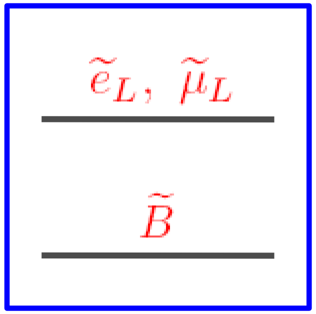
$\widetilde{B}$

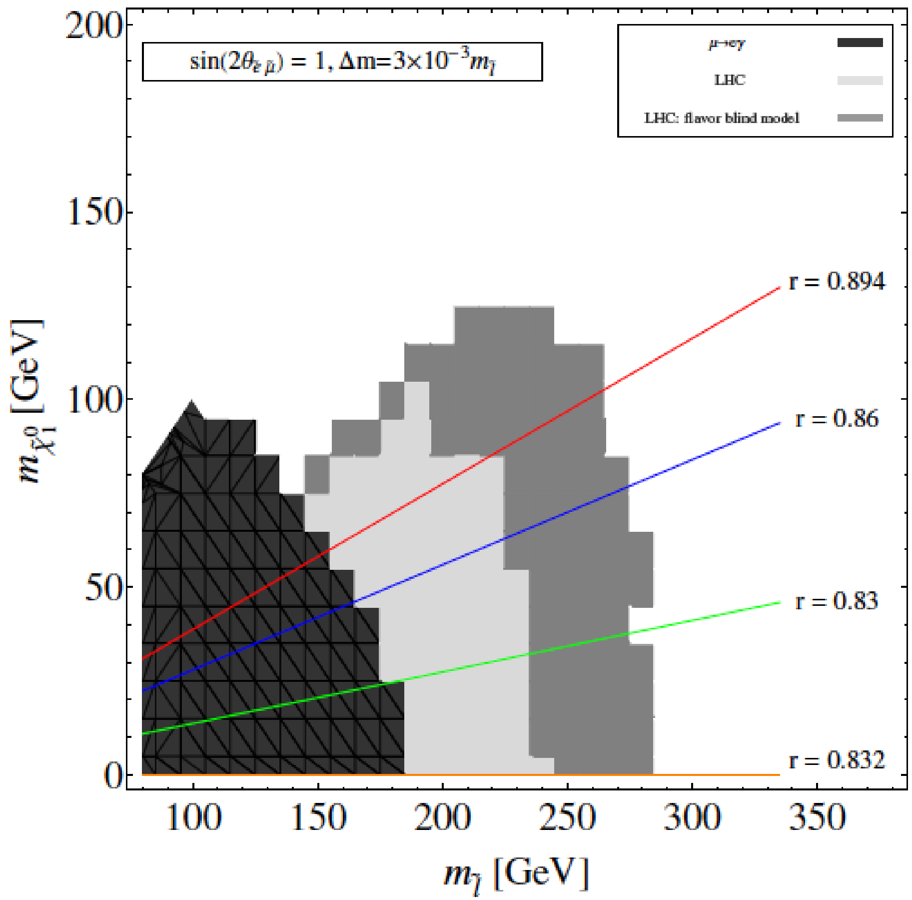
$$\delta \approx 2\sin\theta_{\widetilde{\ell}}\cos\theta_{\widetilde{\ell}}\ \frac{\Delta m_{\widetilde{\ell}}}{m_{\widetilde{\ell}}}$$

$$\Gamma_{\widetilde{\ell}_L} \approx 10^{-3} m_{\widetilde{\ell}_L}$$



50% of e-μ events still compatible with MEG!





(c) $\frac{\Delta m}{m} = 3 \times 10^{-3},\ \sin 2\theta = 1$

⇨ LHC bound relaxed down to 250 GeV (with 50% of e-μ events) !

Anatomy of LFV in SUSY models

Two ingredients: flavour structure of soft terms & the SUSY mass-scale

Overall suppression given by slepton and neutralino/chargino masses:

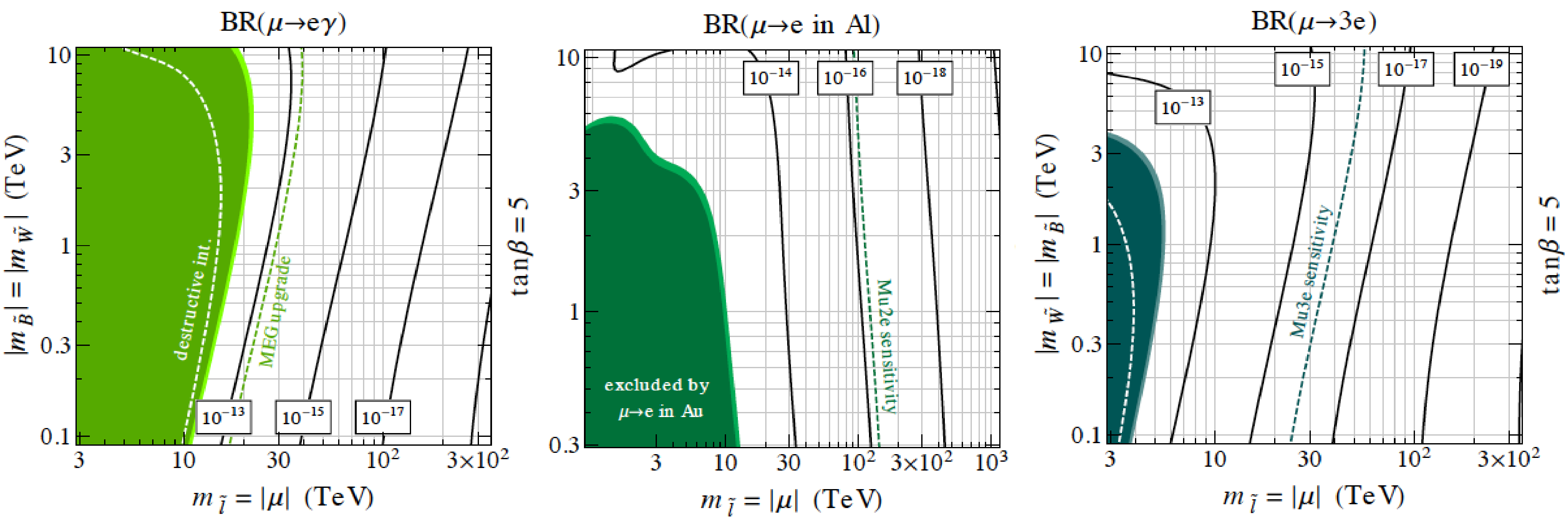
- LHC constraints (e.g. slepton masses > 200÷300 GeV)
- SUSY solution of $(g-2)_\mu$ requires sleptons etc. below 1 TeV

The flavor structure of slepton mass matrices might be:

- anarchical (MEG constraint → super-heavy sleptons)
- controlled by the same dynamics generating the fermion masses (*e.g.* a flavour symmetry)
- trivial (no mixing): high-energy physics induced radiative corrections can give LFV

Degenerate SUSY spectrum with O(1) flavour mixing:

$$\mathrm{BR}(\mu \to e\gamma) \;\sim\; 5 \times 10^{-13} \left(\frac{10\ \mathrm{TeV}}{\tilde{m}}\right)^4 \tan^2\beta$$



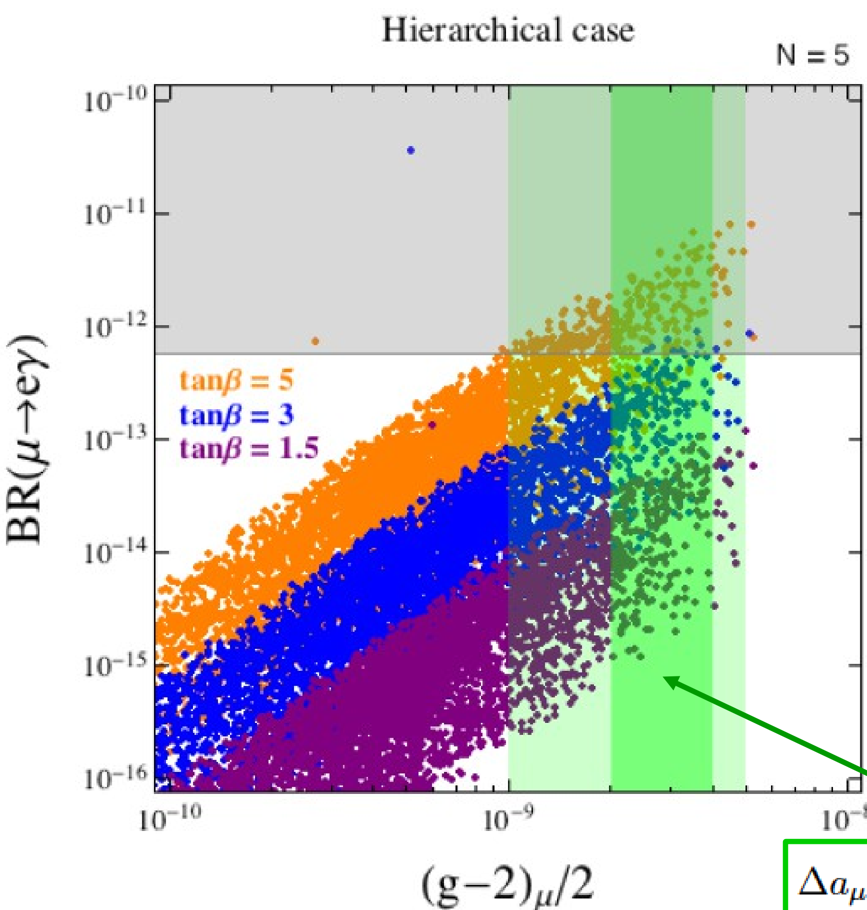
$$|\delta^L_{ij}| = |\delta^R_{ij}| = 0.3$$

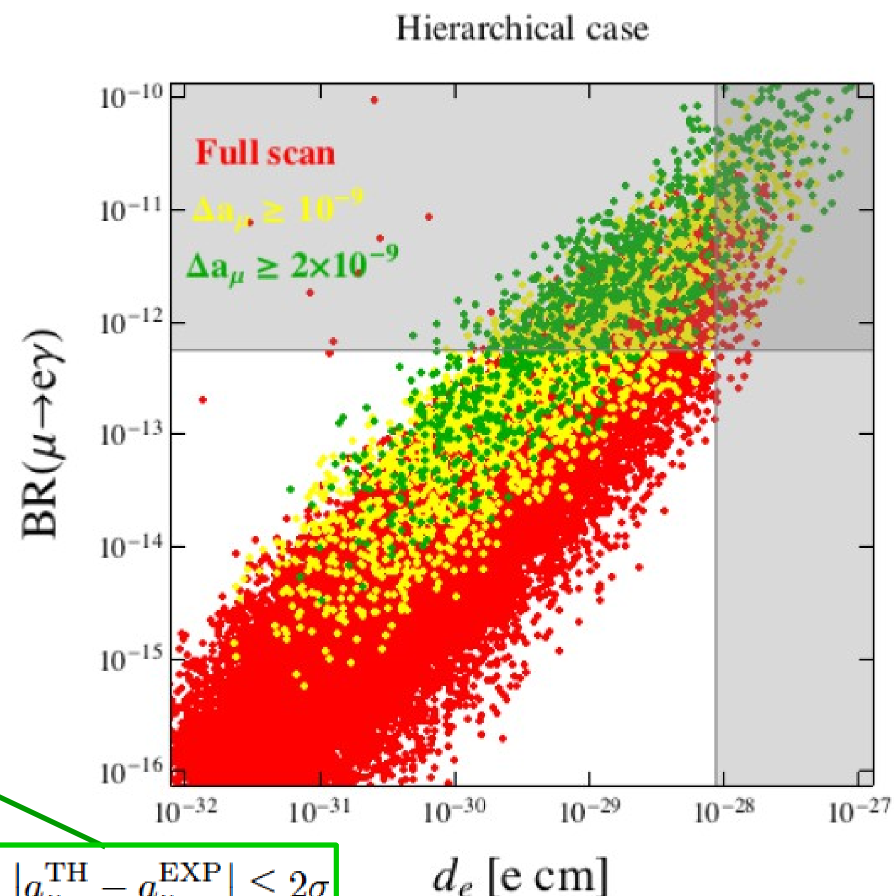
Altmannshofer, Harnik, Zupan '13

Flavour structure controlled by a flavour symmetry

Example: gauge-mediated SUSY breaking with matter-messenger couplings
(controlled by a U(1) FN flavour symmetry) LC, Paradisi, Ziegler '14

$$W = W_{\mathrm{(N)MSSM}} + X\overline{\Phi}\Phi + (\lambda_E)_{ij} E_i L_j \Phi_D$$





$$\Delta a_\mu \equiv \left| a_\mu^{\mathrm{TH}} - a_\mu^{\mathrm{EXP}} \right| \lesssim 2\sigma$$

In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

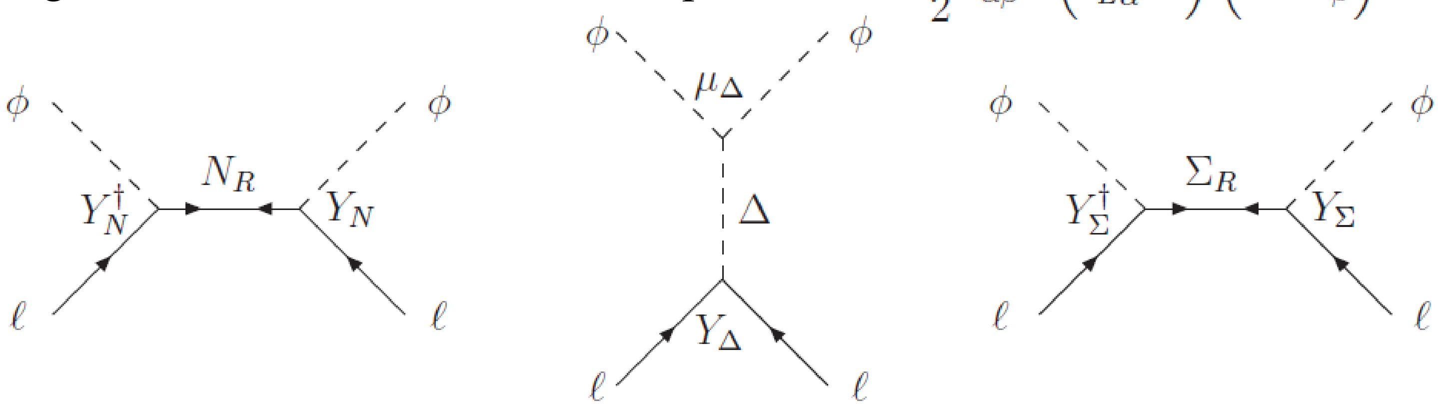
Hall Kostelecky Raby '86

⇨ Example: seesaw mechanism. LFV generically induced in the slepton mass matrix!

Borzumati Masiero '86

Seesaw models

Tree level generation of the neutrino mass operator: $\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\, \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right)$



Type I	Type II	Type III
Heavy fermionic singlets (RH neutrinos)	Heavy scalar triplet	Heavy fermionic triplets

In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

Hall Kostelecky Raby '86

⇨ Example: seesaw mechanism. LFV generically induced in the slepton mass matrix!

Borzumati Masiero '86

Seesaw models

Type I

$$(\tilde{m}_L^2)_{ij} \propto m_0^2 \sum_k (\mathbf{Y}_N^*)_{ki} (\mathbf{Y}_N)_{kj} \ln\left(\frac{M_X}{M_{R_K}}\right)$$

Borzumati Masiero '86

$$\mathbf{Y}_N = \frac{1}{v_u}\sqrt{\mathbf{M}_R}\,\mathbf{R}\,\sqrt{\hat{\mathbf{m}}_\nu}\,U_{\mathrm{PMNS}}^\dagger$$

Type II

$$(\tilde{m}_L^2)_{ij} \propto m_0^2 (\mathbf{Y}_\Delta{}^\dagger \mathbf{Y}_\Delta)_{ij} \ln\left(\frac{M_X}{M_\Delta}\right) \propto m_0^2 (\mathbf{m}_\nu{}^\dagger \mathbf{m}_\nu)_{ij} \ln\left(\frac{M_X}{M_\Delta}\right)$$

$$\mathbf{Y}_\Delta = \mathbf{m}_\nu \frac{M_\Delta}{\lambda v_u^2}$$

A. Rossi '02; Rossi Joaquim '06

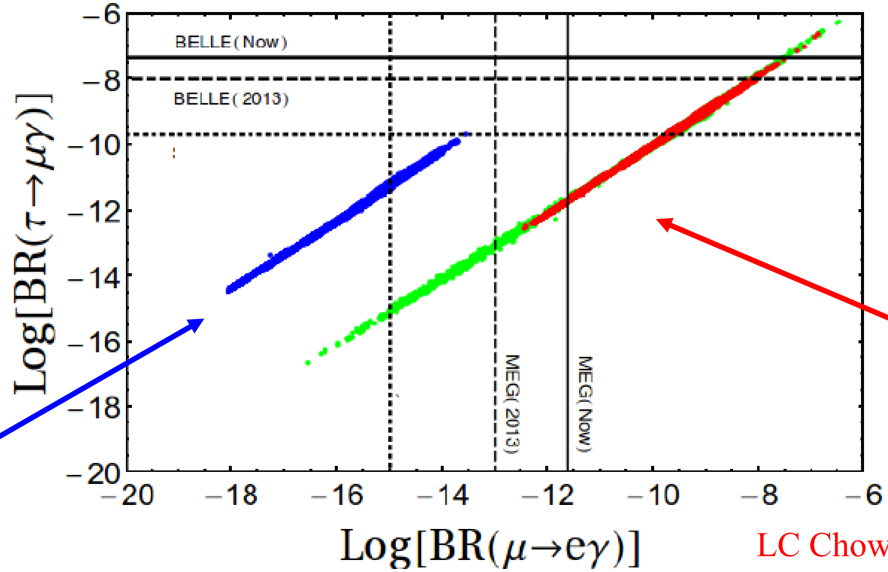
Type III

Similar to type I

Biggio LC '10; Esteves et al. '10

τ-μ vs. μ-e transitions

Type I



CKM mixing
$\mathbf{Y}_\nu = \mathbf{Y}_u$

PMNS mixing
$\mathbf{Y}_N = U_{\rm PMNS}\,\mathbf{Y}_u^{\rm diag}$

LC Chowdhury Masiero Patel Vempati '12

Scenarios that could 'naturally' suppress $\mu\rightarrow e$ transitions relative to $\tau\rightarrow\mu$ cannot be realized with $\theta_{13} \sim O(0.1)$

Random variation of matrix R and neutrino parameters:

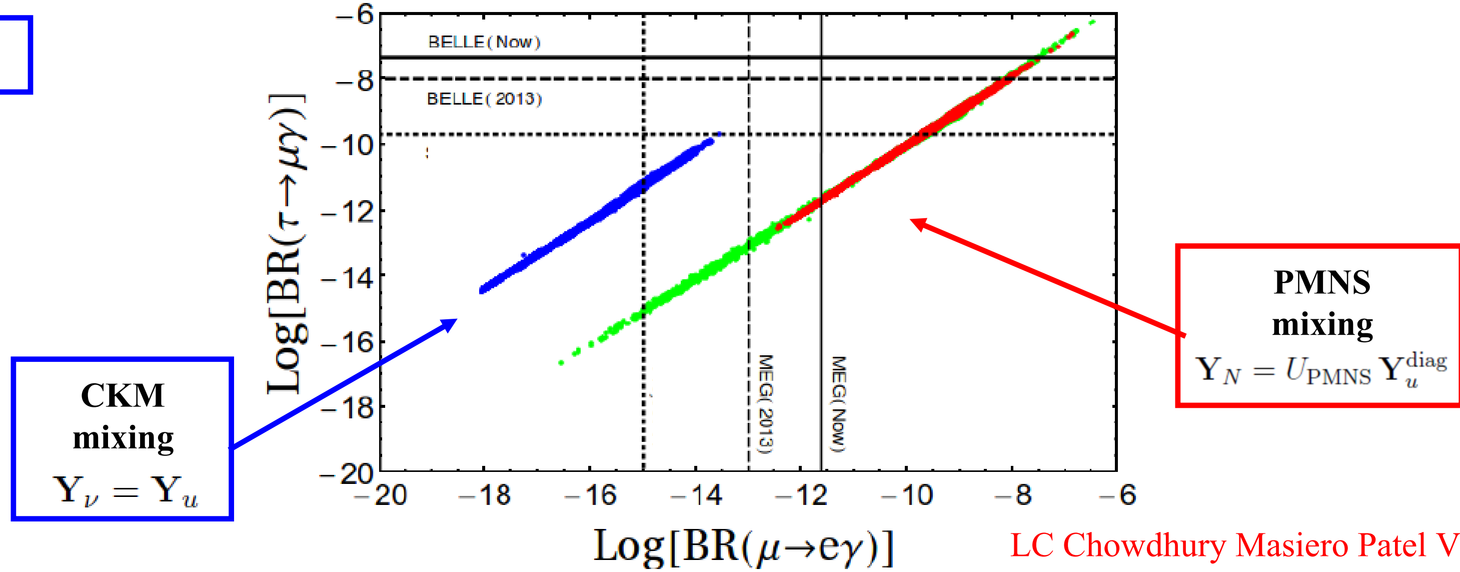
Type I

$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \lesssim \mathcal{O}(1000) \;\Rightarrow\; \mathrm{BR}(\tau\to\mu\gamma) \lesssim \mathcal{O}(10^{-9})$$

Type II

$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \lesssim 6 \;\Rightarrow\; \mathrm{BR}(\tau\to\mu\gamma) \lesssim 4\times 10^{-12}$$

Type I



LC Chowdhury Masiero Patel Vempati '12

Scenarios that could 'naturally' suppress $\mu \to e$ transitions relative to $\tau \to \mu$ cannot be realized with $\theta_{13} \sim O(0.1)$

θ_{13} measurements imply that SUSY seesaw(s) can be preferably tested through $\mu \to e$ transitions

In SUSY (with R_P) $\mu\to eee$ and $\mu\to e$ conversion dominated by the dipole $\mu\to e\gamma$*
Strong correlations:

not only seesaw models!

$$\begin{aligned} \mathrm{BR}(\mu\to eee) &\simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2}-3\right)\mathrm{BR}(\mu\to e\gamma) , \\ \mathrm{CR}(\mu\to e \text{ in N}) &\simeq \alpha\times\mathrm{BR}(\mu\to e\gamma) , \end{aligned}$$

- Sensitivities < 10^{-15} would go beyond MEG
- Crucial model discriminators

In fact, there are models where $\mu\to eee$ and/or $\mu\to e$ conv. arise at tree-level.

Examples:

- SUSY with R-parity violation — e.g. Dreiner Kramer O'Leary '06
- Low-energy seesaw models — Abada et al '07
- Low-energy flavor models — LC Lalak Pokorski Ziegler '12

Rates enhanced wrt. $\mu\to e\gamma$!

There is New Physics out there
but we don't know the scale!

LFV processes are a unique laboratory
to search for New Physics beyond the LHC reach

LFV and LHC highly complementary in testing
TeV-scale New Physics

Exploring different channels is crucial
to cover the full 'theory space'