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Theory overview on Lepton Flavour Violation

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Why is Flavour Physics important?

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SM flavour puzzle

- Why three families?
- Why the hierarchies?

  (m_t/m_e = 3.4 x 10^5)

Why is Flavour Physics important?

SM flavour puzzle

- Why three families?
- Why the hierarchies?

  ($m_t/m_e = 3.4 \times 10^5$)

We need to find the scale of New Physics!

- LHC found a SM-like Higgs
- No sign of new phenomena
- Do we need to go beyond SM at all?

Do we really need New Physics?

- Hierachy Problem (?)
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses
- Baryon asymmetry
- Origin of flavor hierarchies

...

Do we really need New Physics?

- Hierachy Problem (?) → TeV-scale New Physics?
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses → See-saw?
- Baryon asymmetry → Leptogenesis?
- Origin of flavor hierarchies → Symmetries of flavor?

...

Testable through leptonic Flavor/CP Violation?

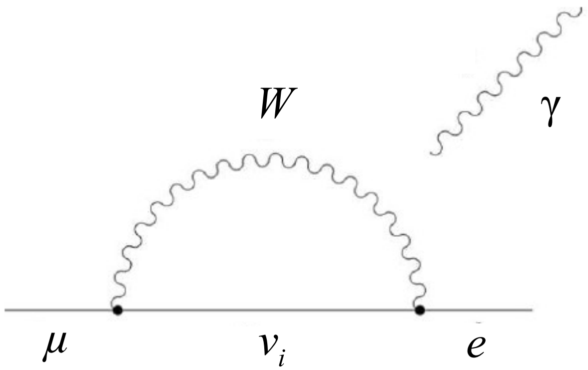
Clean example: charged Lepton Flavour Violation

- Neutrinos oscillate → Lepton family numbers are not conserved!

- Can we observe LFV in charged leptons decays?

- In the SM + massive neutrinos:

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



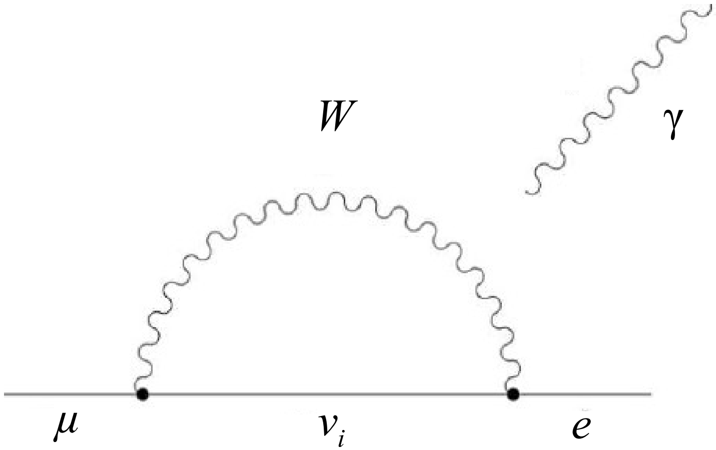
⇨ $\mathrm{BR}(\mu \to e\gamma) \lesssim \mathcal{O}(10^{-50})$

Suppression due to small neutrino masses

Cheng Li '77, '80; Petcov '77

⇨ In presence of NP at the TeV we can expect large effects!

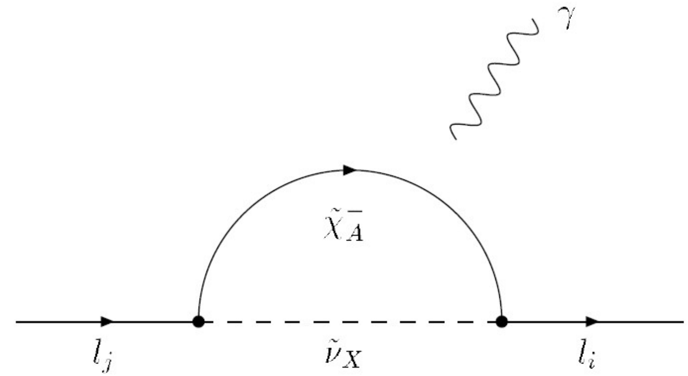
Clean example: charged Lepton Flavour Violation

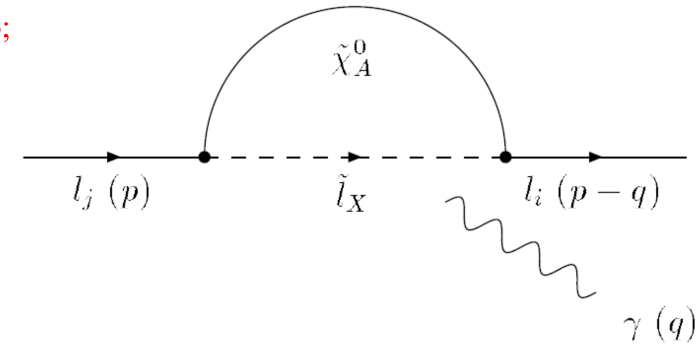


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_i U_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W}\right|^2$$

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

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

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

Process	Relevant operators	Present Bound on Λ (TeV) $C = 1/16\pi^2$	Present Bound on Λ (TeV) $C = 1$	Future Bound on Λ (TeV) $C = 1/16\pi^2$	Future Bound on Λ (TeV) $C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	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

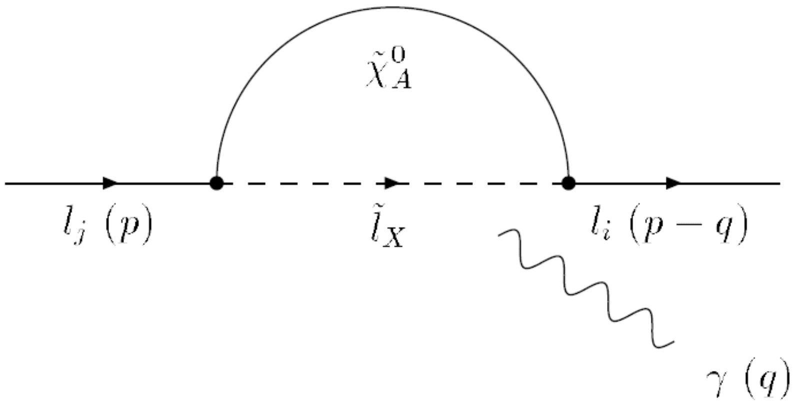
updated from LC Lalak Pokorski Ziegler '12

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

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

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

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

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

Hisano et al. '95

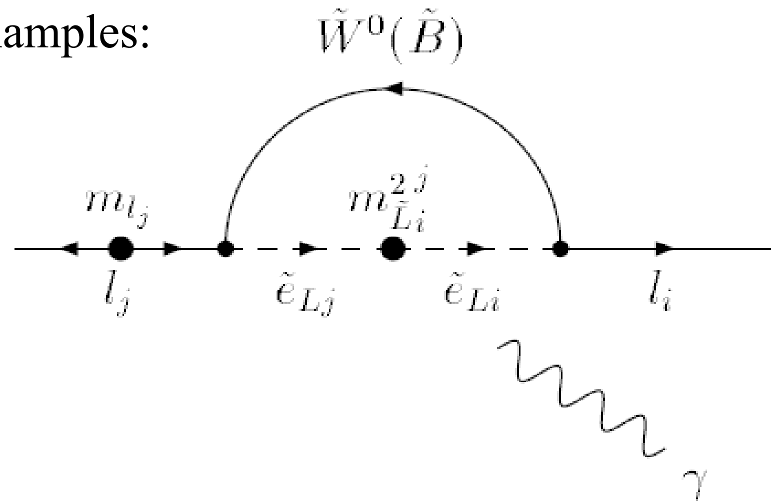
Mass Insertion Approximation

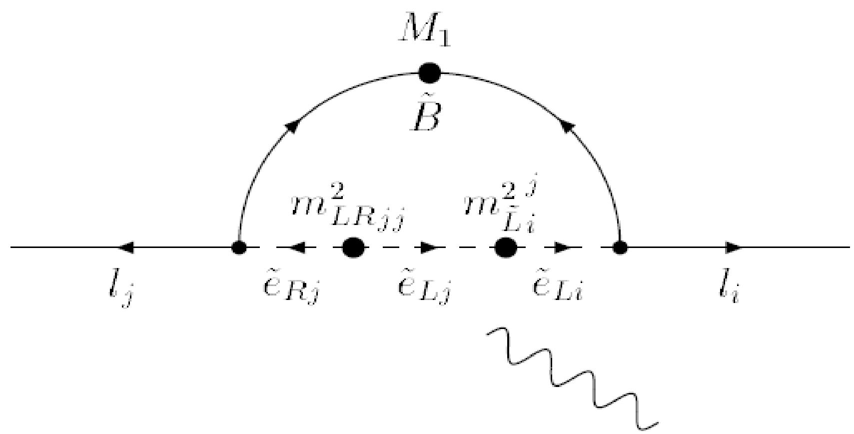
Hall Kostelecky Raby '86
Pokorski Rosiek Savoy '99

Slepton mass matrix:

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

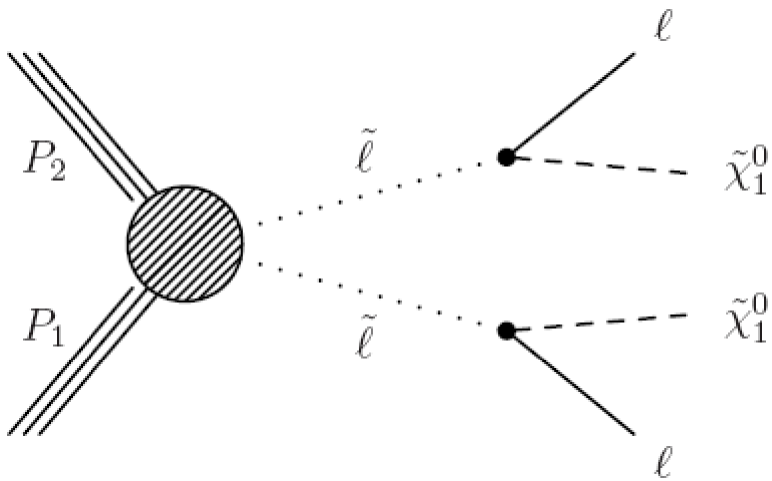
Examples:

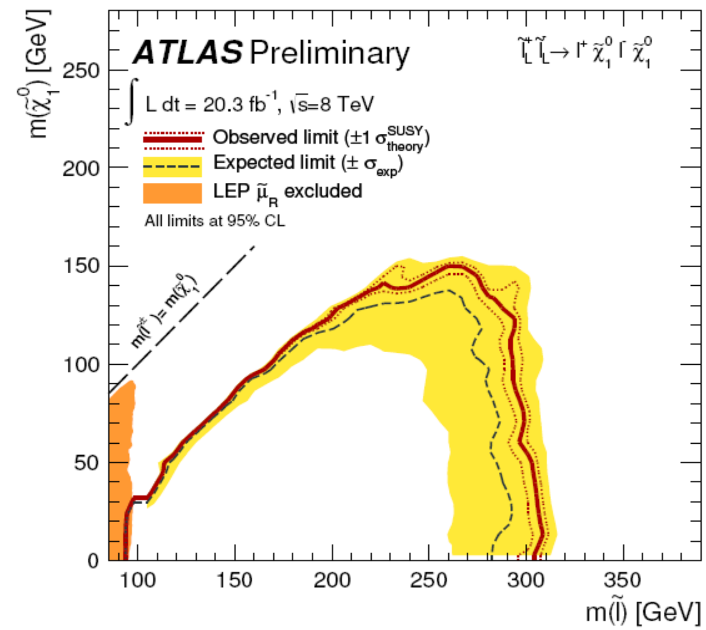




$\Rightarrow$ $$\frac{BR(l_i \to l_j \gamma)}{BR(l_i \to l_j \nu_i \bar{\nu}_j)} \propto \frac{\delta_{ij}^2}{\tilde{m}^2}$$ $\Rightarrow$ Limits on δ's

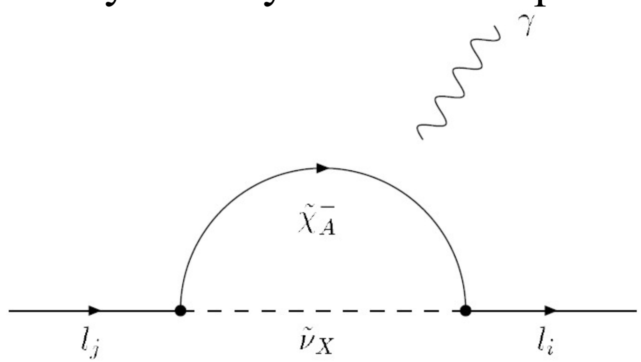
Gabbiani Masiero '89
Gabbiani et al. '96
Masina Savoy '02
Paradisi '05 ...

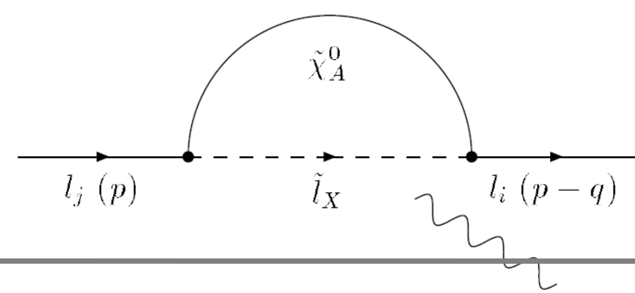




EW-searches at the LHC started to go considerably beyond the limits set by LEP

They directly look for the particles that can induce LFV transitions!

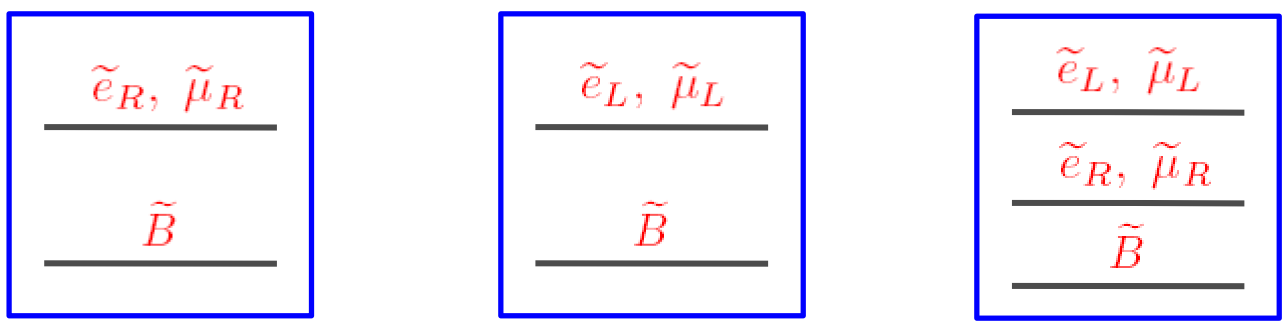




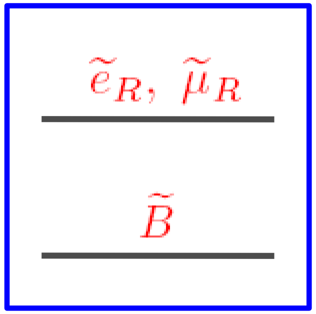
What is the impact of direct searches for SUSY particles at the LHC on the discovery prospects of LFV processes at low-energy experiments?

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

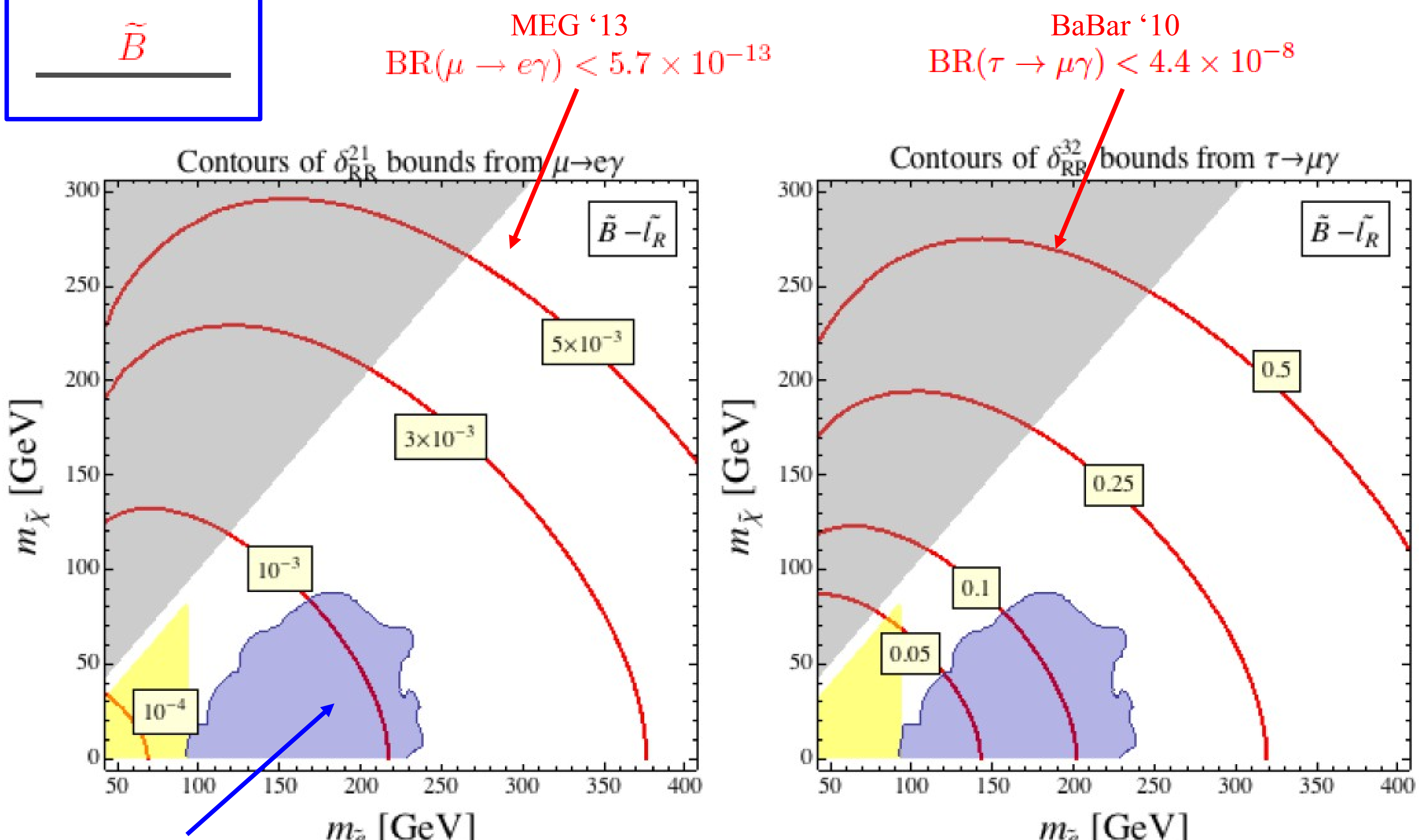
Examples:



LFV vs LHC bounds within simplified models

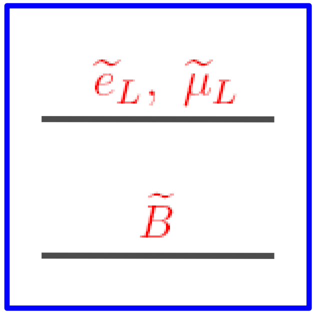


LC, Galon, Masiero, Shadmi, Paradisi, to appear



ATLAS-CONF-2013-049

LFV vs LHC bounds within simplified models



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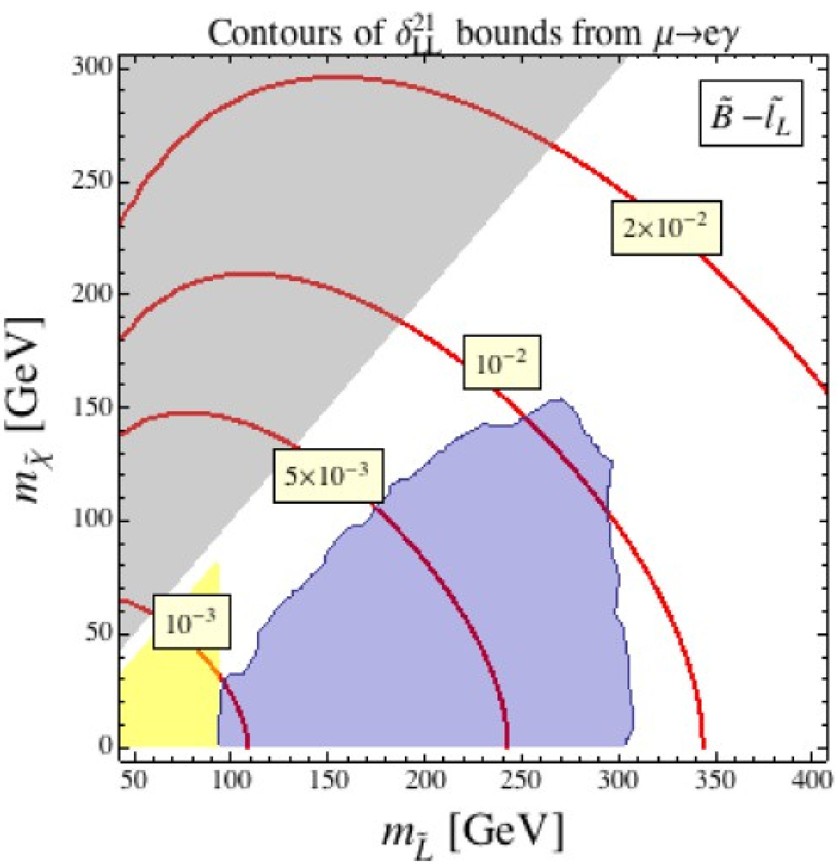

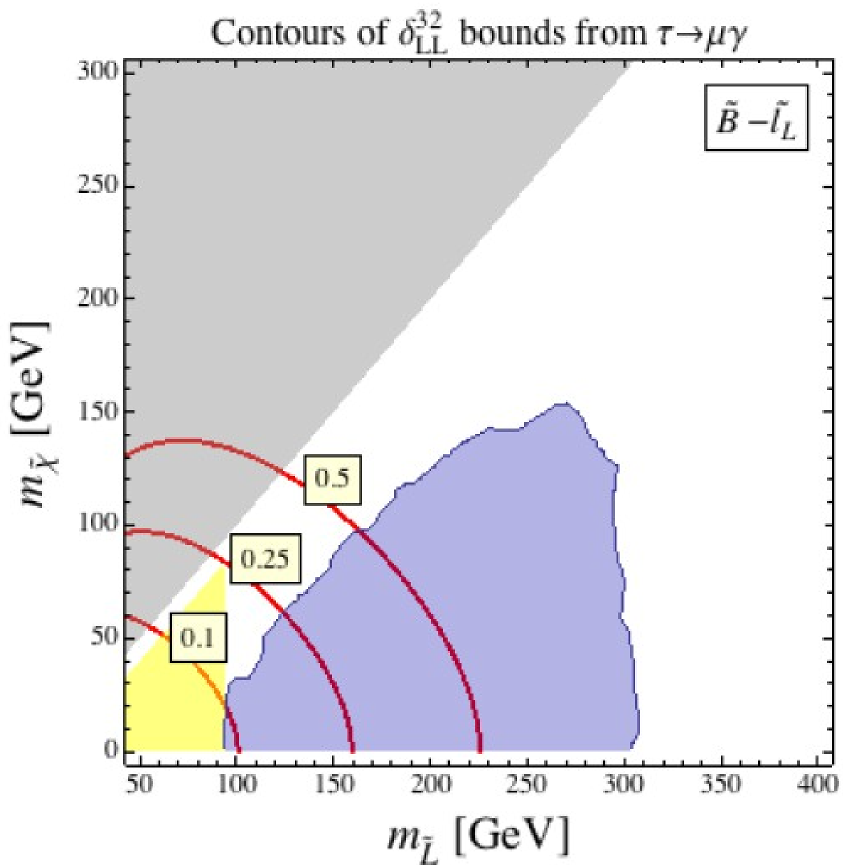

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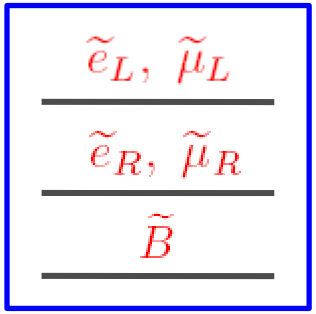
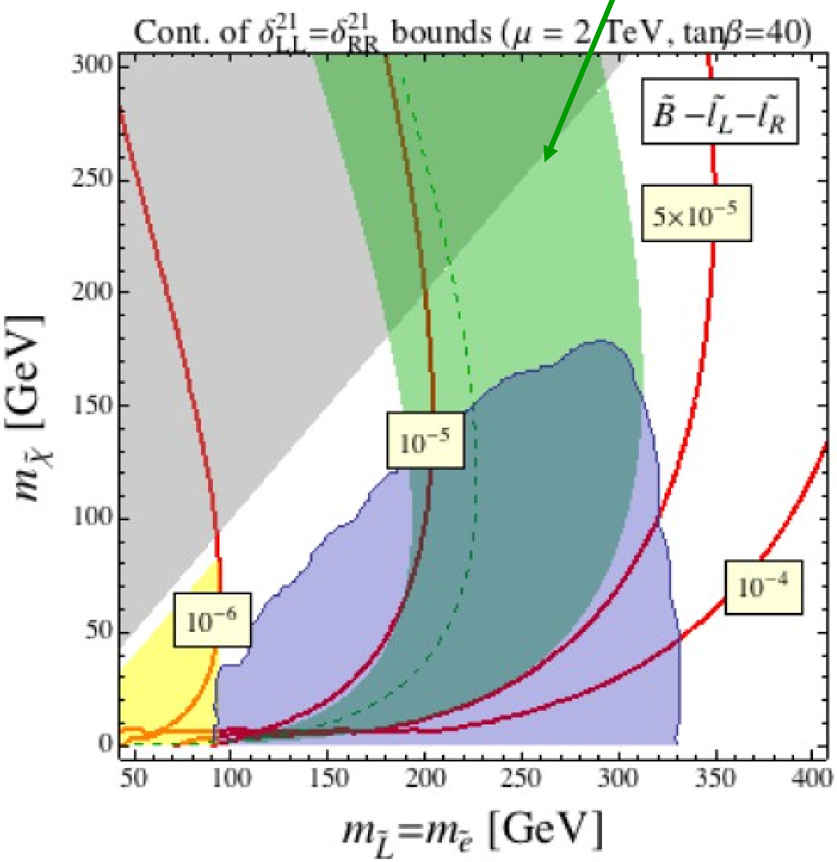
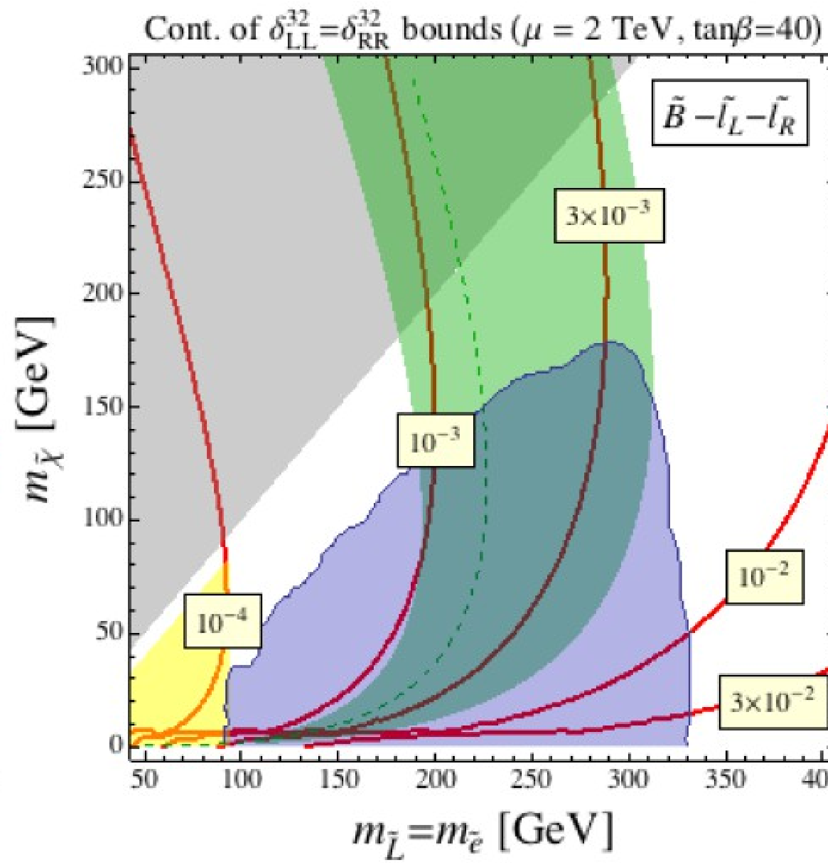


LC, Galon, Masiero, Shadmi, Paradisi, to appear

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





Anatomy of LFV in SUSY models

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

Overall suppression given by slepton and neutralino/chargino masses:

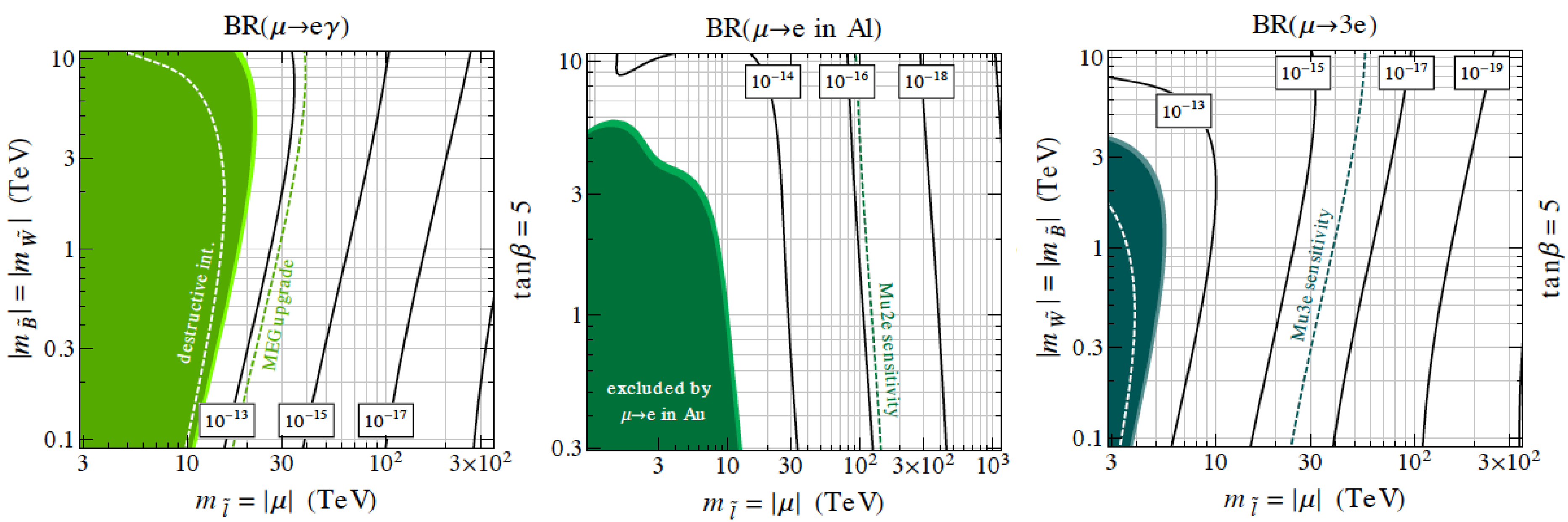
- LHC constraints (e.g. slepton masses > 200÷300 GeV)
- SUSY solution of $(g-2)_\mu$ requires sleptons etc. below 1 TeV

The flavor structure of slepton mass matrices might be:

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

Degenerate SUSY spectrum with O(1) flavour mixing:

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

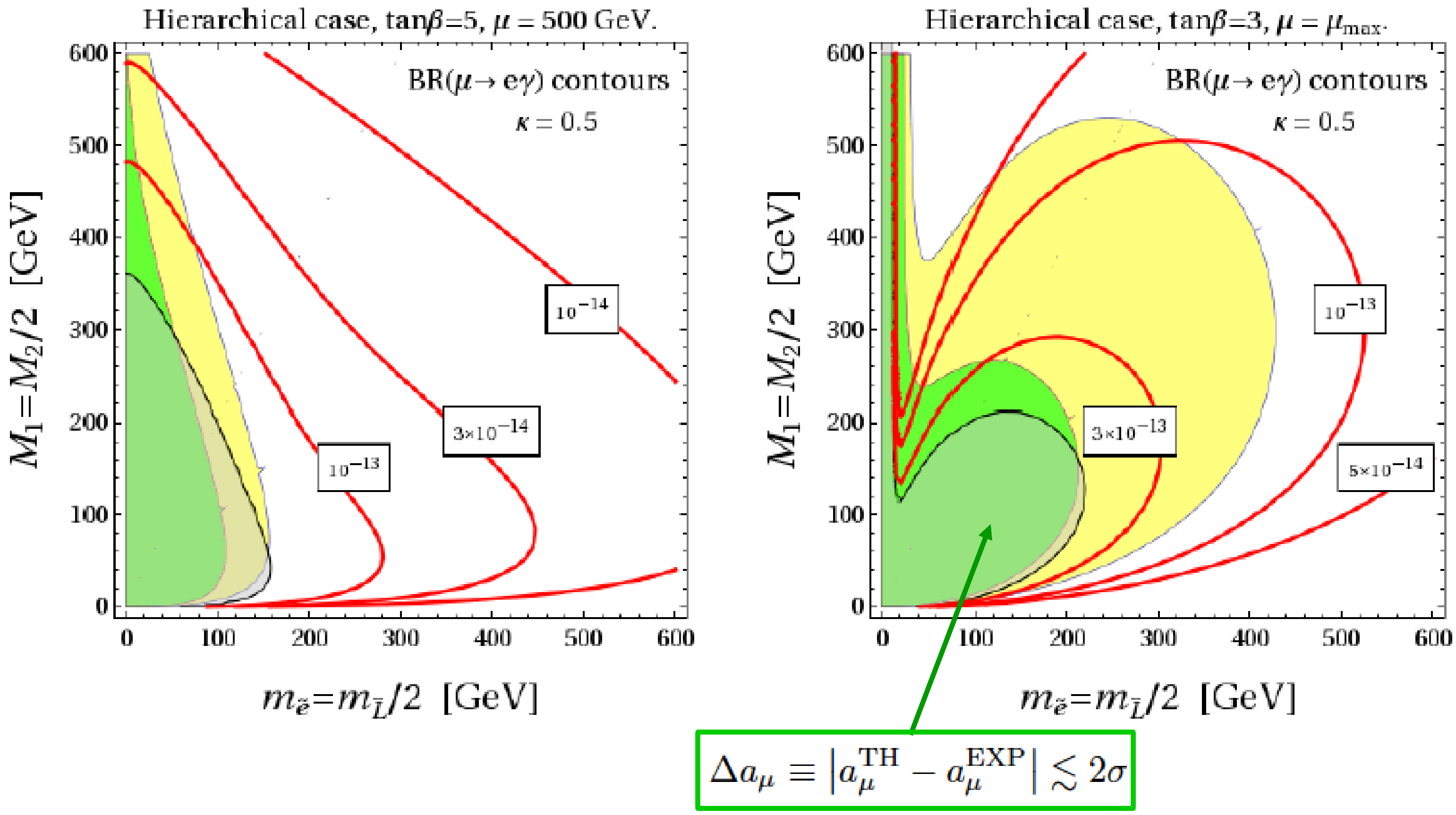


$$|\delta^L_{ij}| = |\delta^R_{ij}| = 0.3$$

Altmannshofer, Harnik, Zupan '13

Example: gauge-mediated SUSY breaking with U(1) flavour symmetry

LC, Paradisi, Ziegler '14



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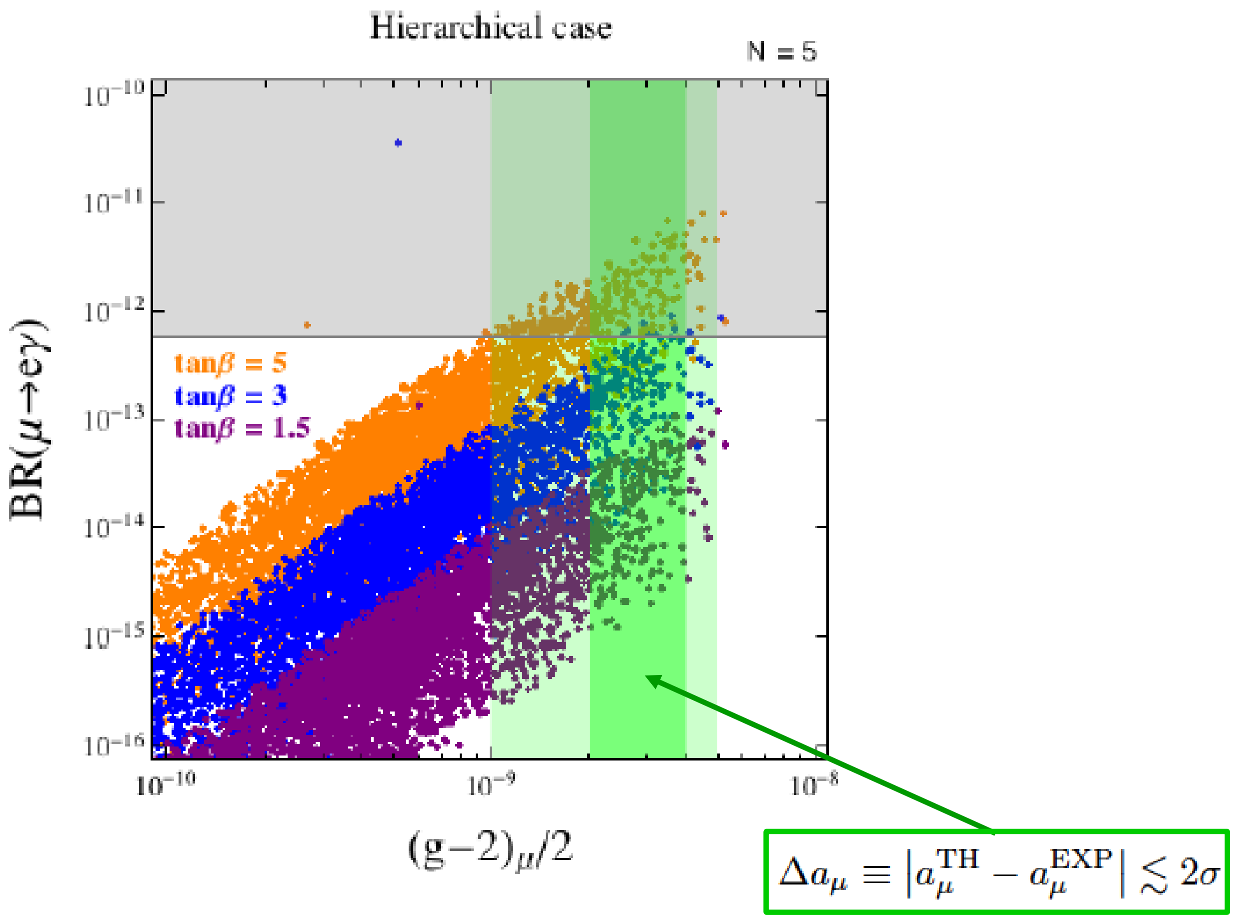


In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

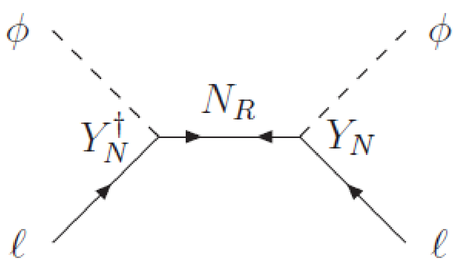
Hall Kostelecky Raby ‘86

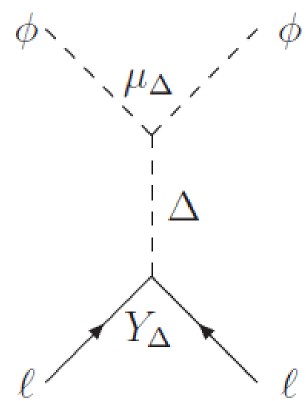
⇨ Example: seesaw mechanism. LFV generically induced in the slepton mass matrix!

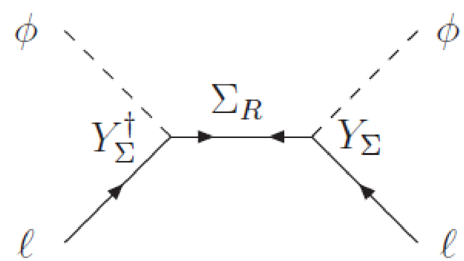
Borzumati Masiero ‘86

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

Heavy fermionic singlets (RH neutrinos)

Type II

Heavy scalar triplet

Type III

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

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

Type II

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

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

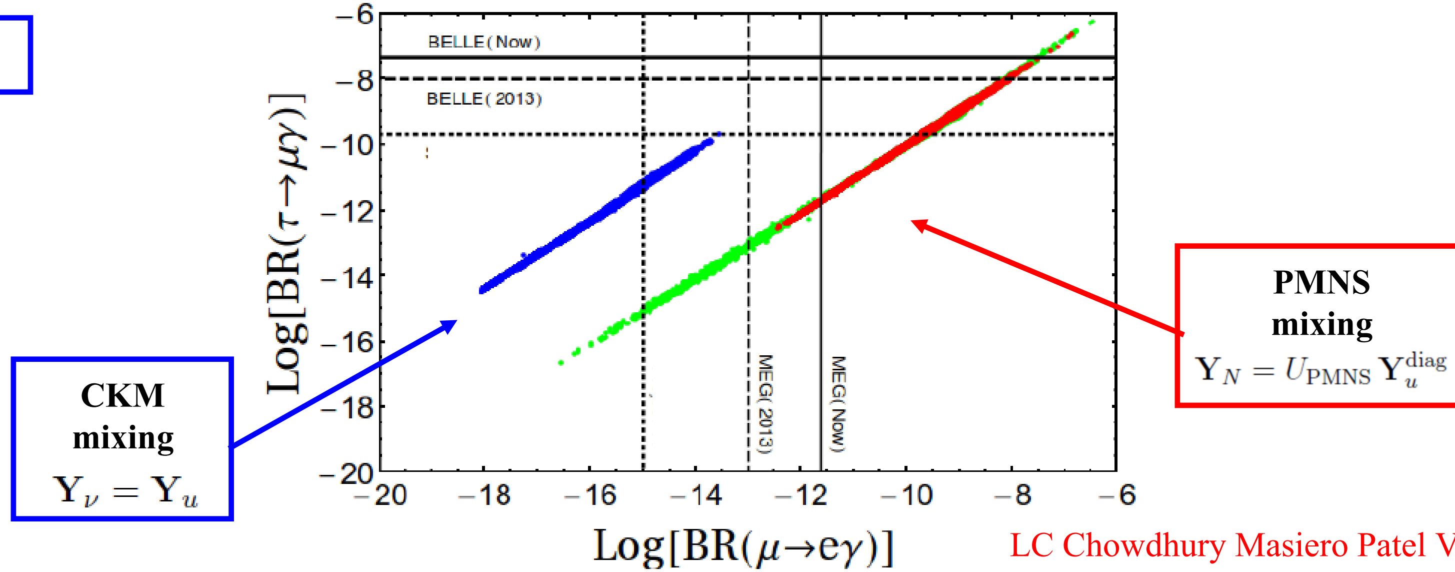
A. Rossi '02; Rossi Joaquim '06

Type III

Similar to type I

Biggio LC '10; Esteves et al. '10

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 $\theta_{13} \sim O(0.1)$

Random variation of matrix R and neutrino parameters:

Type I

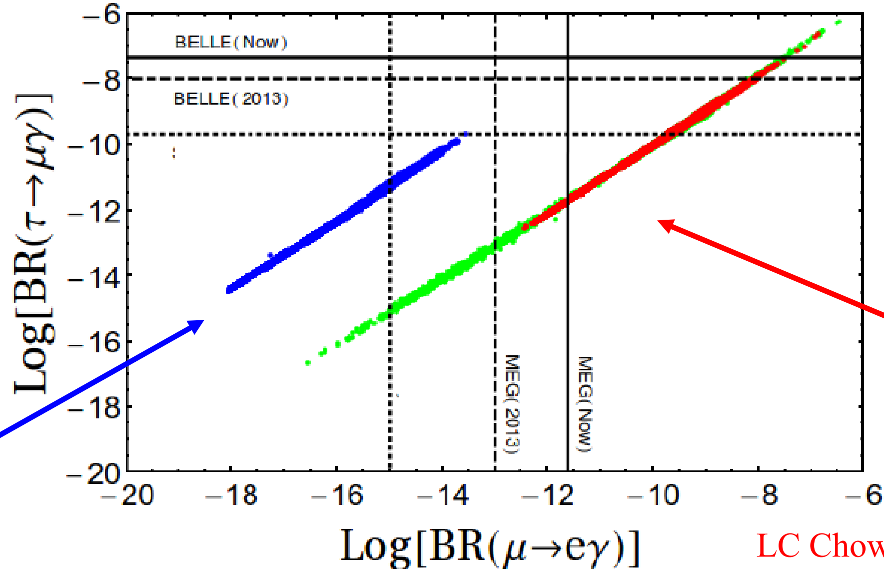
$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \lesssim \mathcal{O}(1000) \Rightarrow \mathrm{BR}(\tau\to\mu\gamma) \lesssim \mathcal{O}(10^{-9})$$

Type II

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

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 $\mu\to e$ 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

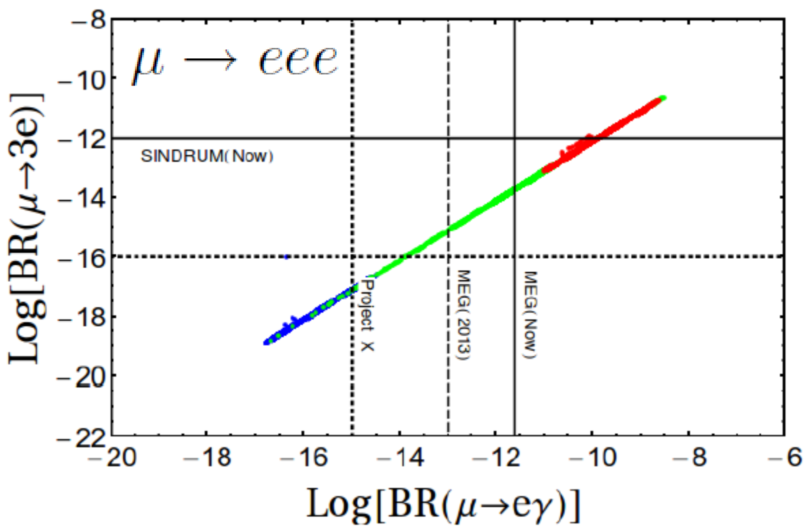
In SUSY (with R_P) $\mu \to eee$ and $\mu \to e$ conversion dominated by the dipole $\mu \to e\gamma$*

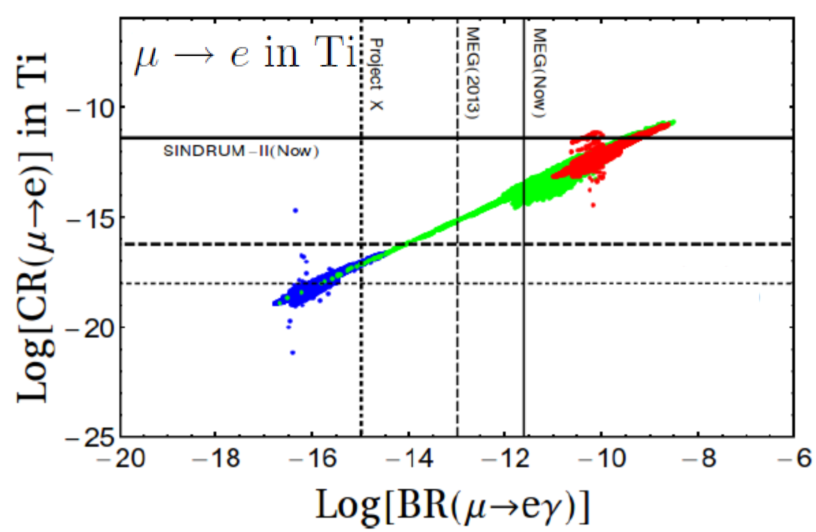
Strong correlations:

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

not only seesaw models!

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





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- Sensitivities < 10^{-15} would go beyond MEG
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In fact, there are models where $\mu\to eee$ and/or $\mu\to e$ conv. arise at tree-level.

Examples:

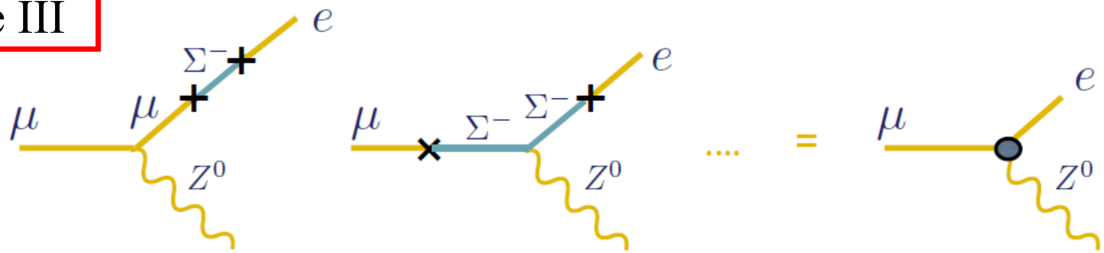
- SUSY with R-parity violation — e.g. Dreiner Kramer O'Leary '06
- Low-energy seesaw models — Abada et al '07
- Low-energy flavor models — LC Lalak Pokorski Ziegler '12

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

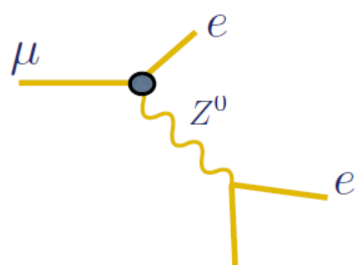
Example of enhanced μ→eee / $\mu\to e$: low-energy seesaw

crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states

Type III



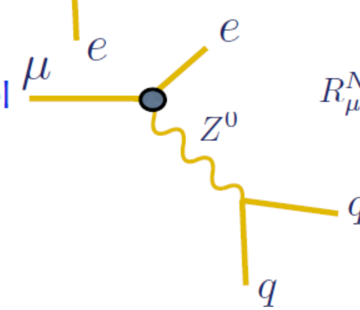
⇒ $\mu \to eee$: tree level



$$\Gamma(\mu \to eee) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot d^2$$

Abada, Biggio, Bonnet, Gavela, TH 07', 08'

$\mu \to e$ conversion : tree level



$$R^N_{\mu\to e} = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^\dagger_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot (b^N)^2$$

$\mu \to e\gamma$: still at one loop

⇒ ratios of 2 processes with same flavour transition: totally fixed!

$$Br(\mu \to e\gamma) = 1.3 \cdot 10^{-3} \cdot Br(\mu \to eee) = 3.1 \cdot 10^{-4} \cdot R^{\mu\to e}_{Ti}$$

from T. Hambye's talk at the 1st Conference on CLFV, Lecce 2013

Concluding remarks

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'