NuFact 2012

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Lepton Flavor Violation vs. θ_{13}

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MAX-PLANCK-GESELLSCHAFT

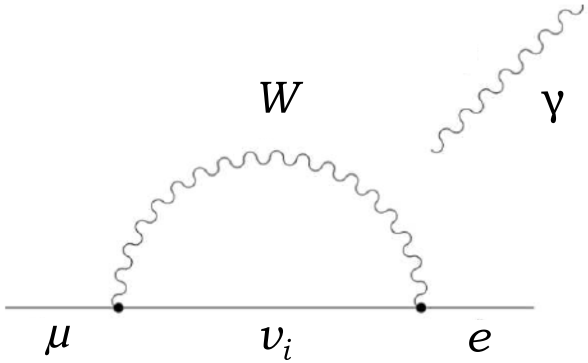
Why LFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!

- Can we observe LFV in charged leptons decays?

- In the SM :

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



⇒ $\mathcal{O}(10^{-55}) \lesssim \mathrm{BR}(\mu \to e\gamma) \lesssim \mathcal{O}(10^{-48})$
(2σ ranges of ν param.)

Suppression due to small neutrino masses

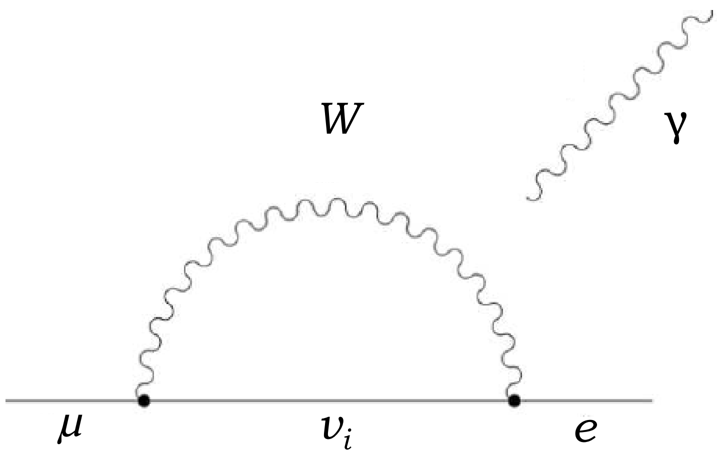
Cheng Li '77, '80; Petcov '77

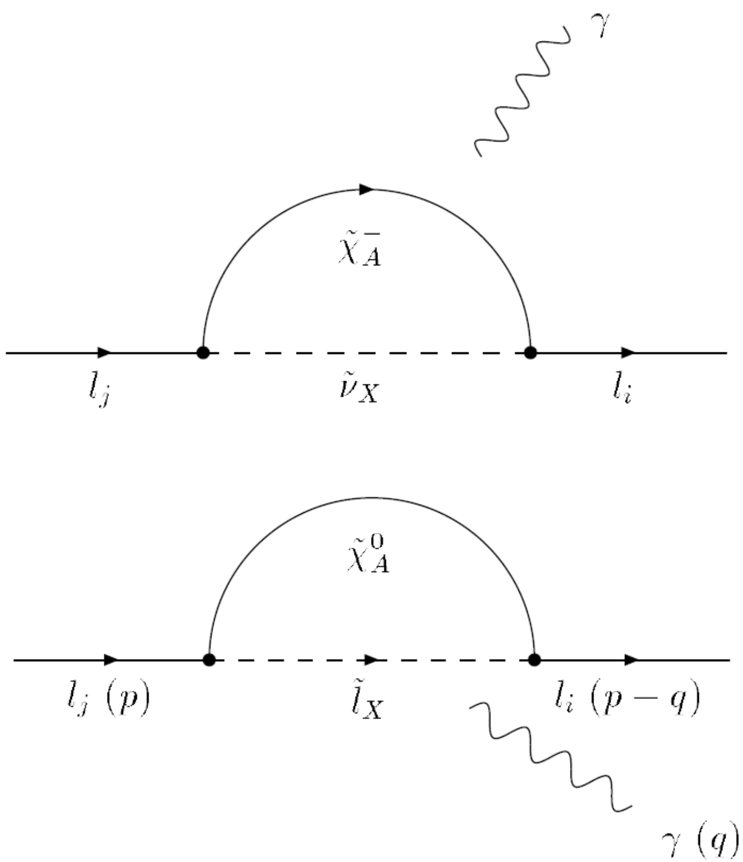
⇒ In presence of NP at the TeV we can expect large effects!

Introduction

Example: SUSY

Borzumati Masiero '86;
Hisano et al. '95





Flavour violation induced by misalignment between leptons and sleptons

Example: SUSY

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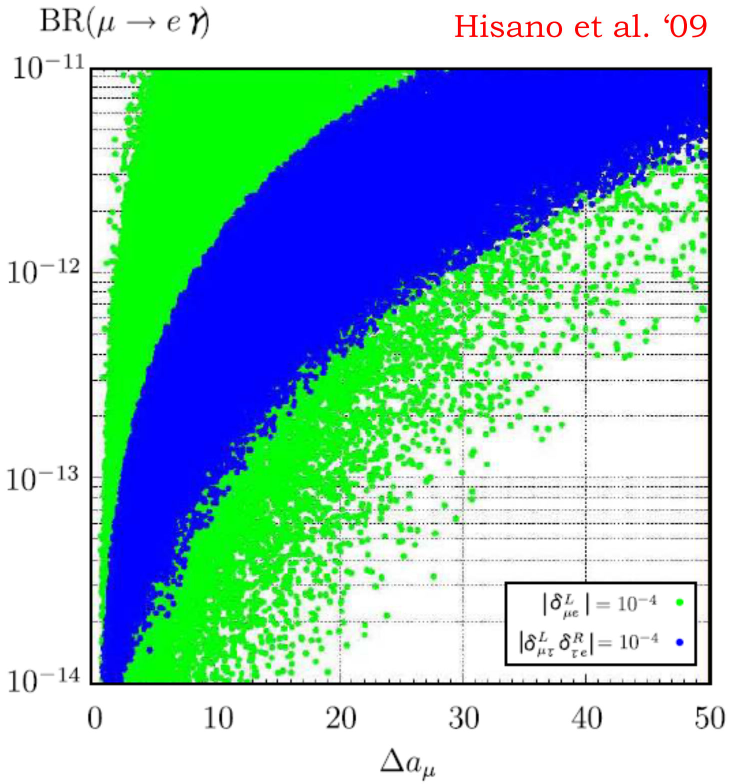
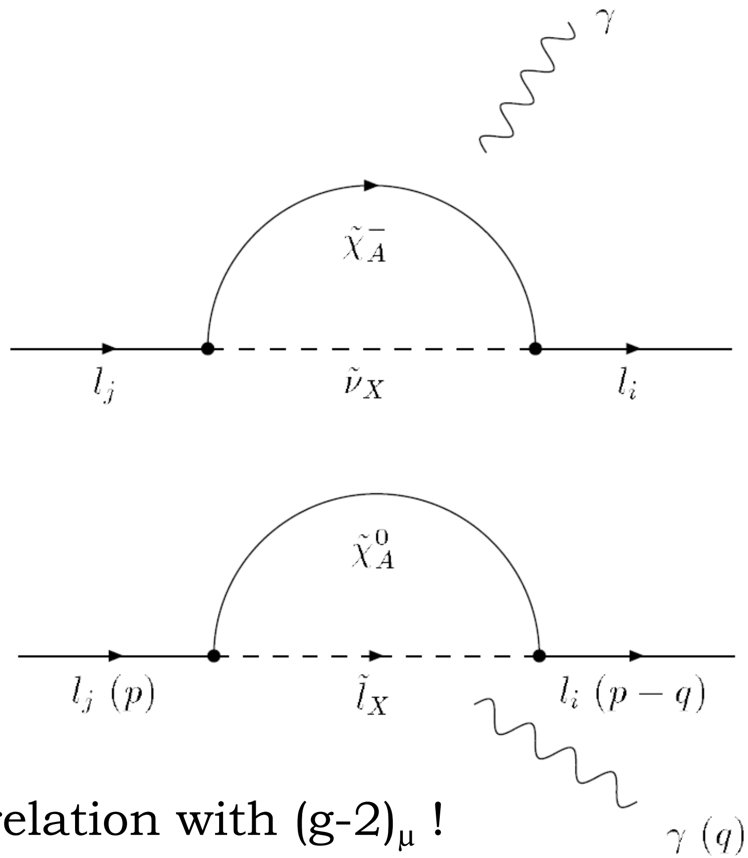
Hisano et al. '09





Similar dipole operator: correlation with $(g\text{-}2)_\mu$!

$$\mathrm{BR}(\mu \to e\gamma) \approx 2 \times 10^{-12} \left[\frac{\Delta a_\mu^{\mathrm{SUSY}}}{3 \times 10^{-9}}\right]^2 \left|\frac{\delta^L_{\mu e}}{10^{-4}}\right|^2$$

Hisano Nagai Paradisi Shimizu '09

Why LFV?

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

Process	Relevant operators	Pres. Bound on Λ $(c=1)$	Fut. Bound on Λ $(c=1)$
$\mu \to e\gamma$	$\frac{c}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	48 TeV	107 TeV
$\mu \to eee$	$\frac{c}{16\pi^2\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17 TeV	166 TeV
	$\frac{c}{16\pi^2\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10 TeV	98 TeV
$\mu \to e$ in Ti	$\frac{c}{16\pi^2\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	33 TeV	577 TeV
	$\frac{c}{16\pi^2\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	59 TeV	1000 TeV

LC Lalak Pokorski Ziegler ‘12

Why LFV?

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

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

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$\mu \to eee$	$\frac{c}{\Lambda^2}(\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_L \gamma^\mu e_L)$	208 TeV	2085 TeV
	$\frac{c}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	124 TeV	1230 TeV
$\mu \to e$ in Ti	$\frac{c}{\Lambda^2}(\overline{\mu}_L \gamma^\mu e_L)(\overline{d}_L \gamma^\mu d_L)$	419 TeV	7254 TeV
	$\frac{c}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	745 TeV	12600 TeV

LC Lalak Pokorski Ziegler '12

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

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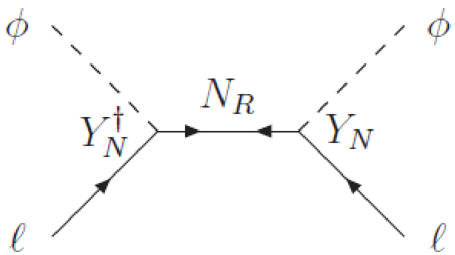
(SUSY) Seesaw Mechanism

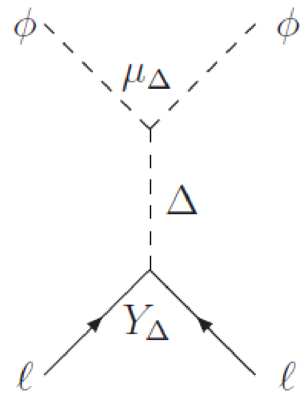
Tree level generation of the neutrino mass operator $\boxed{\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right)}$:



Type I

Heavy fermionic singlets (RH neutrinos)

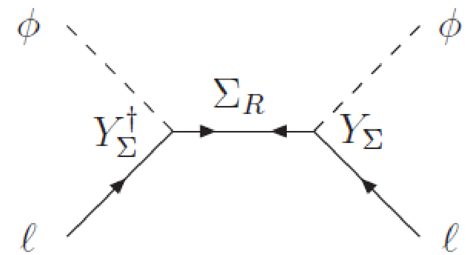
Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, ...



Type II

Heavy scalar triplet

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, ...



Type III

Heavy fermionic triplets

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez, ...

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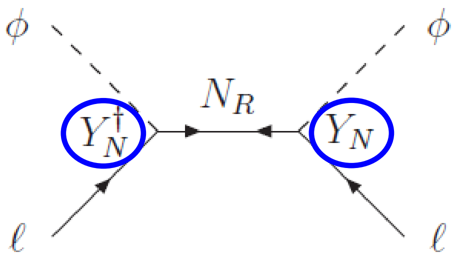

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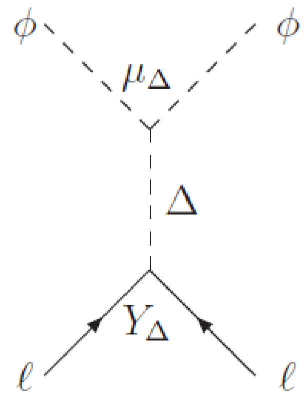

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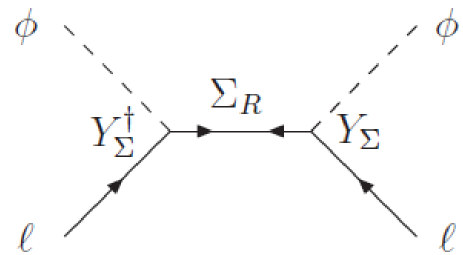

Type III

Heavy fermionic
triplets

Type I (SUSY):

$$W_{\rm I} = W_{\rm MSSM} + (\mathbf{Y}_N)_{ij}\, N_i L_j H_u - \frac{1}{2}(\mathbf{M}_R)_{kk}\, N_k N_k$$

$$\Rightarrow \quad \mathbf{m}_\nu = {\mathbf{Y}_N}^T {\mathbf{M}_R}^{-1} \mathbf{Y}_N v_u^2 \qquad \boxed{\mathbf{Y}_N = \frac{1}{v_u}\sqrt{\mathbf{M}_R}\,\mathbf{R}\,\sqrt{\hat{\mathbf{m}}_\nu}\, U^\dagger_{\rm PMNS}}$$

Mismatch between low and high-energy params.

Casas Ibarra '01

(SUSY) Seesaw Mechanism

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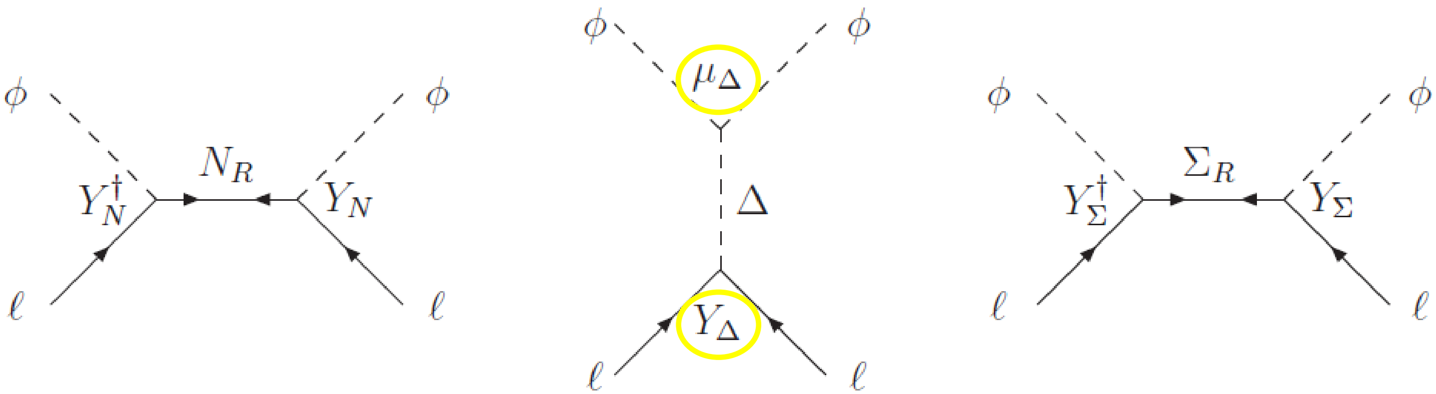

Type I	Type II	Type III
Heavy fermionic singlets (RH neutrinos)	Heavy scalar triplet	Heavy fermionic triplets

Type II (SUSY): $$W_{\rm II} = W_{\rm MSSM} + \frac{1}{\sqrt{2}}(\mathbf{Y}_\Delta)_{ij}\, L_i \Delta L_j + \frac{1}{\sqrt{2}}\lambda\, H_u \Delta H_u + M_\Delta\, \Delta\bar{\Delta}$$

$$\Rightarrow \quad \mu_\Delta = \lambda \frac{M_\Delta}{\sqrt{2}} \qquad\qquad \boxed{(\mathbf{m}_\nu)_{ij} = \frac{\lambda v_u^2}{M_\Delta}\,(\mathbf{Y}_\Delta)_{ij}}$$

Direct link to the light neutrino mass matrix! In principle all parameters known

LFV in SUSY seesaw

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

Hall Kostelecky Raby '86

⇨ This applies to the new seesaw interactions: generically induce LFV in the slepton mass matrix!

Borzumati Masiero '86

Type I

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

Borzumati Masiero '86

Type II

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

$$\boxed{U \hat{\mathbf{m}}_\nu^2 U^\dagger}$$

A. Rossi '02; Rossi Joaquim '06

Type III

Similar to type I

Biggio LC '10; Esteves et al. '10

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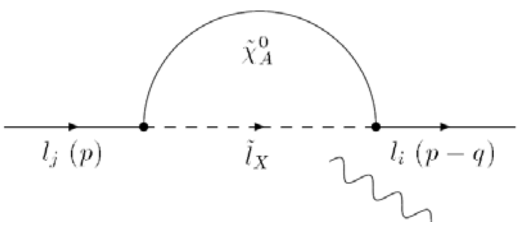

$$m^2_{\tilde\ell} = \begin{pmatrix} (\tilde{m}^2_L)_{ij} + (m^2_\ell)_{ij} - m_Z^2(\frac{1}{2} - \sin^2\theta_W)\delta_{ij} & A^{\ell\,*}_{ji} v_d - (m_\ell)_{ji}\mu\tan\beta \\ A^\ell_{ij} v_d - (m_\ell)_{ij}\mu^*\tan\beta & (\tilde{m}^2_E)_{ij} + (m^2_\ell)_{ij} - m_Z^2\sin^2\theta_W\delta_{ij} \end{pmatrix}$$

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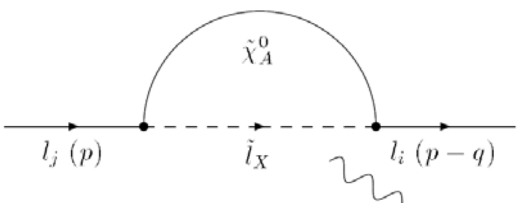


⇨ $$BR(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha_{\rm em}}{G_F^2} \left(|C_L^{ij}|^2 + |C_R^{ij}|^2 \right) BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)$$

Hisano et al. '95

$$C_L^{ij} \sim \frac{g^2}{16\pi^2} \frac{(\tilde{m}^2_L)_{ij}}{\tilde{m}^4} \tan\beta$$

$\boxed{\text{Type II}}$: direct connection between seesaw couplings and the PMNS.

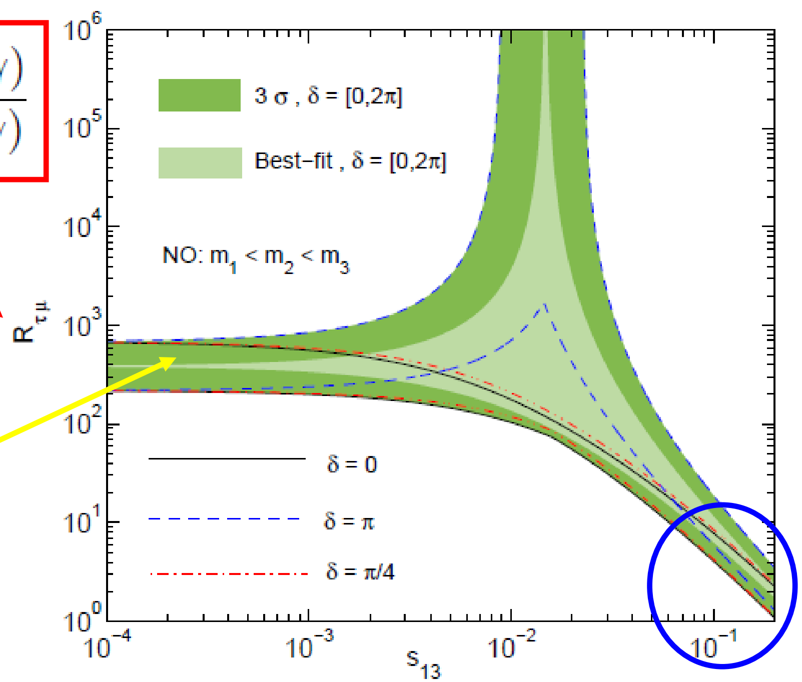
Hierarchical neutrinos normal ordering (IO similar):

$$\mathrm{BR}(\mu \to e\gamma) \propto \left|\Delta m^2_{31}\, s_{\theta_{13}} c_{\theta_{13}} s_{\theta_{23}} + \Delta m^2_{21}\, s_{\theta_{12}} c_{\theta_{13}} (c_{\theta_{12}} c_{\theta_{23}} - s_{\theta_{12}} s_{\theta_{13}} s_{\theta_{23}})\right|^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \propto \left|\Delta m^2_{31}\, c^2_{\theta_{13}} c_{\theta_{23}} s_{\theta_{23}} + \mathcal{O}(\Delta m^2_{12})\right|^2$$

$$\boxed{R_{\tau\mu} \equiv \frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\mu \to e\gamma)}}$$

$$\boxed{\left(\frac{\Delta m^2_{31}}{\Delta m^2_{21}}\right)^2}$$



Joaquim '09

Taking the 2σ ranges of Forero Tortola Valle '12 we get:

$$\boxed{R_{\tau\mu} \lesssim 6}$$

MEG '11 limit implies:

$$\mathrm{BR}(\tau \to \mu\gamma) \lesssim 10^{-11}$$

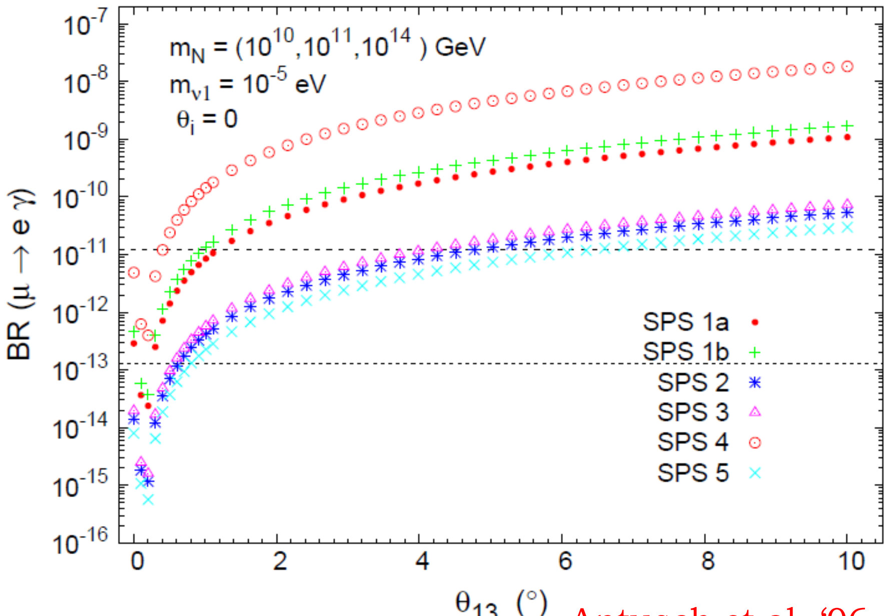
beyond the reach of foreseeable experiments!

$\boxed{\text{Type I}}$: in general the connection between seesaw couplings and the PMNS is 'washed out' by the matrix R Casas et al '10

However, theoretically motivated examples where the correlation is there:

- Trivial mixing from RHν (i.e. R~**1**) :

$$\Rightarrow \quad \mathrm{BR}(\mu \to e\gamma) \propto \left|(y_k^N)^2\, U_{\mu k} U^*_{ek}\right|^2 \quad \text{(hierarchical RH}\nu \to k{=}3\text{)}$$



Antusch et al. '06

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However, theoretically motivated examples where the correlation is there:

- SO(10) GUT ('PMNS mixing' case): Chang Masiero Murayama '02; Masiero Vives Vempati '02

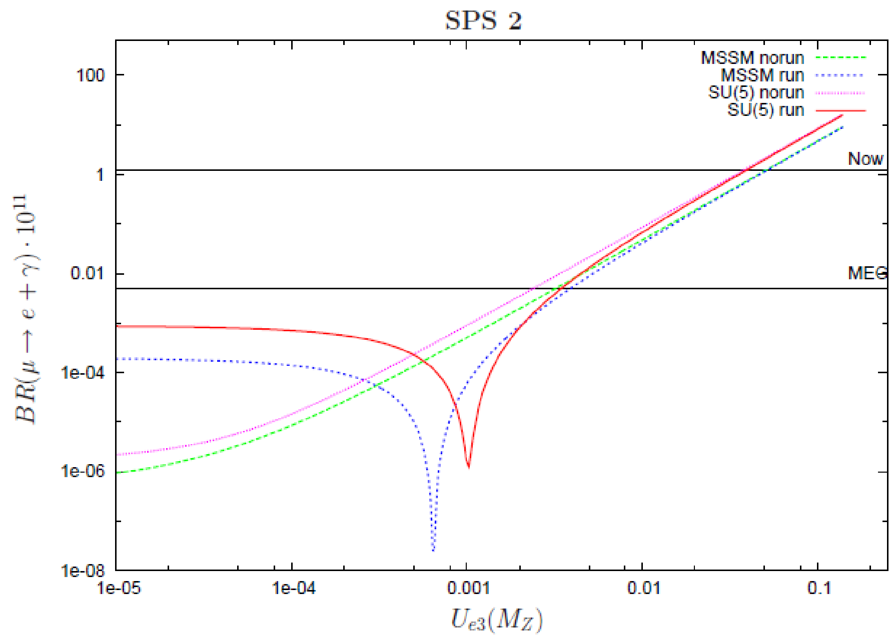
$$W = \frac{1}{2}(Y_u)_{ij}16_i16_j10_u + \frac{1}{2}(Y_d)_{ij}16_i16_j\frac{\langle 45\rangle}{M_{Pl}}10_d$$

$$Y_d = \Theta_L V^*_{CKM} Y_d^D \Theta_R U_{MNS} \Theta_\nu$$

$$\Downarrow \ \mathbf{Y}^{\rm diag}_{d,e}$$

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

$$\mathrm{BR}(\mu \to e\gamma) \propto \left| y_t^2 U_{\mu 3} U^*_{e3}\right|^2$$



LC Faccia Masiero Vempati '06

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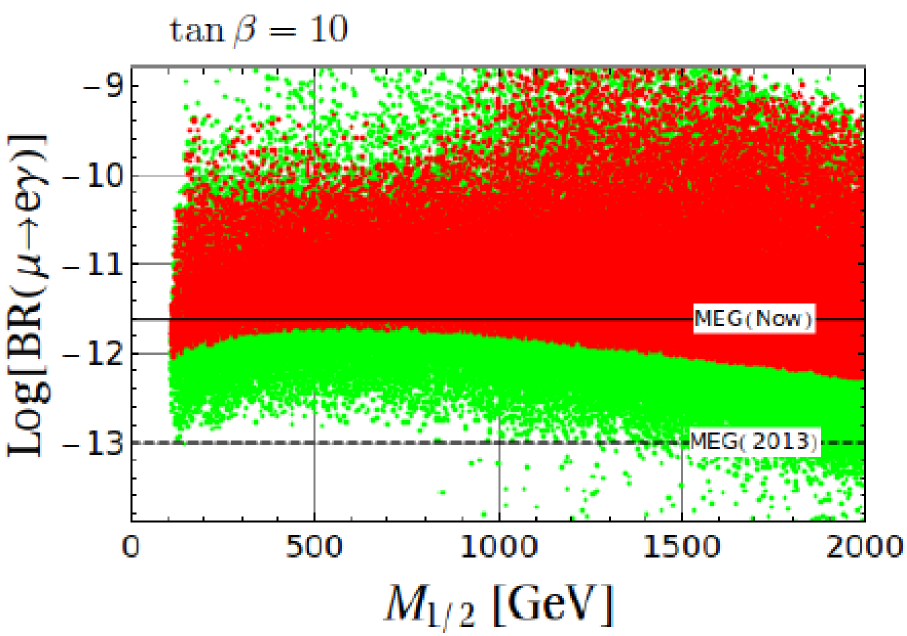

$$m_0 \in [0,\ 5]\ \mathrm{TeV}$$

$$\Delta m_H \in \begin{cases} 0 & \text{for mSUGRA} \\ [0,\ 5] & \text{for NUHM1} \end{cases}$$

$$m_{1/2} \in [0.1,\ 2]\ \mathrm{TeV}$$

$$A_0 \in [-3m_0,\ +3m_0]$$

$$\mathrm{sgn}(\mu) \in \{-,+\}$$

LC Chowdhury Masiero Patel Vempati, to appear

$$\boxed{|U_{e3}| = 0.11}$$

$$\boxed{124.5\ \mathrm{GeV} \lesssim m_h \lesssim 126.5\ \mathrm{GeV}}$$

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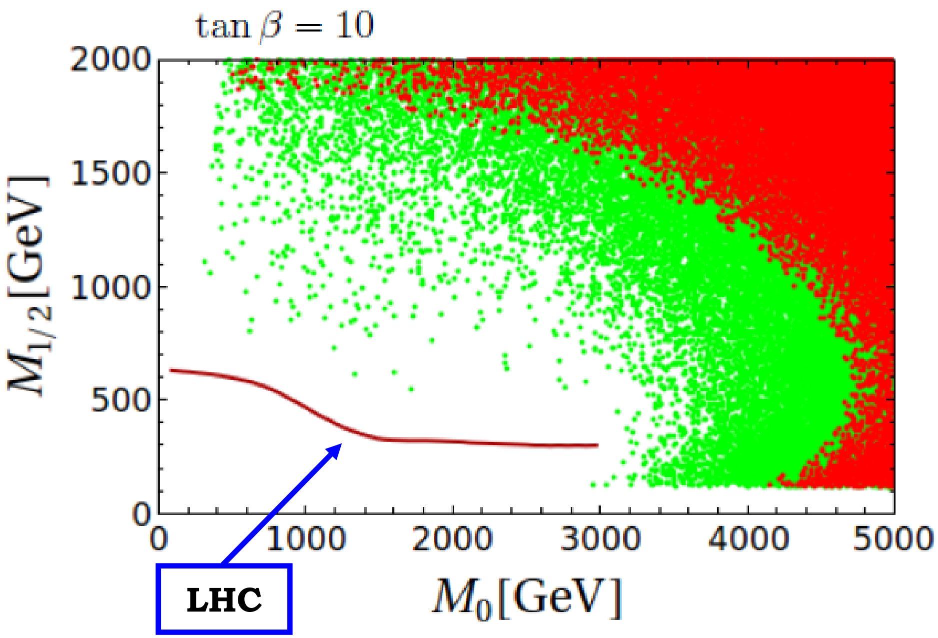

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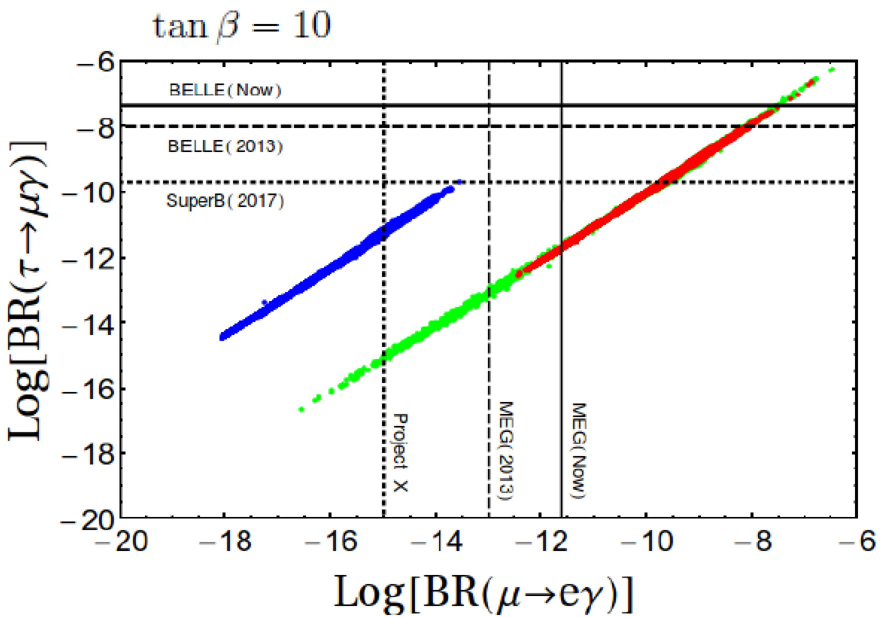

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θ_{13} dependence

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- SO(10) GUT ('PMNS mixing' case)

Such scenarios (hierarchical RHν and θ_{13} << 1) could 'naturally' suppress $\mu \to e$ transitions relative to $\tau \to \mu$

This cannot be realized with $\theta_{13} \sim O(0.1)$

Random variation of matrix R and neutrino parameters:

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

DayaBay/Reno measurements imply that SUSY seesaw(s) can be preferably tested through $\mu \to e$ transitions

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Possible exception: 1st and 2nd generation sleptons much heavier than 3rd generation

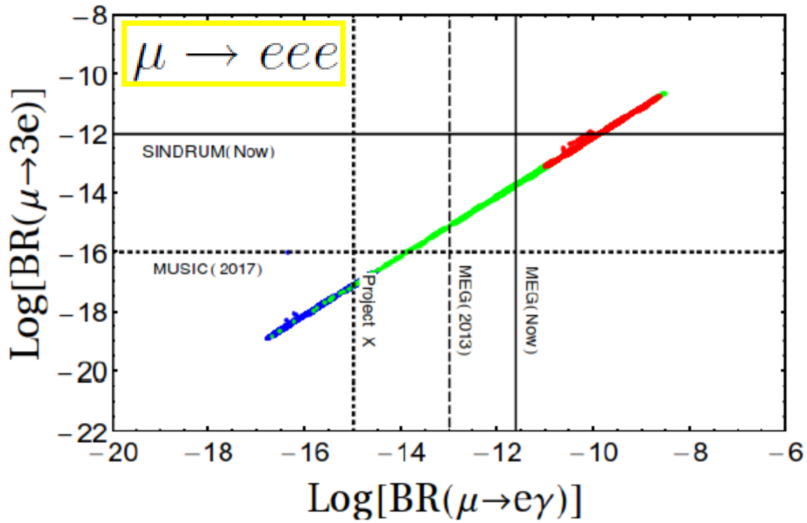
In SUSY (with R_P) $\mu \to eee$ and $\mu \to e$ conversion dominated by the dipole $\mu \to e\gamma^*$

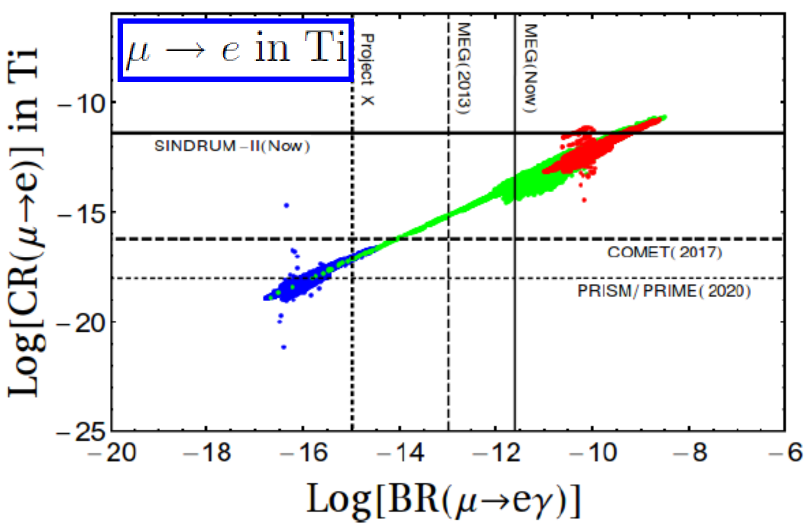
Strong correlations:

not only seesaw models!

$$\boxed{\begin{aligned} \mathrm{BR}(\mu \to eee) &\sim \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma) \\ \mathrm{CR}(\mu \to \text{ in N}) &\sim \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma) \end{aligned}}$$

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





LC Chowdhury Masiero Patel Vempati, to appear

Correlations in the μ-e sector

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!

$$\boxed{\begin{aligned} \mathrm{BR}(\mu \to eee) &\sim \alpha_{\mathrm{em}} \times \mathrm{BR}(\mu \to e\gamma) \\ \mathrm{CR}(\mu \to \text{ in N}) &\sim \alpha_{\mathrm{em}} \times \mathrm{BR}(\mu \to e\gamma) \end{aligned}}$$

- 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 type III seesaw — Abada et al '07
- Low-energy flavor models with Higgs-like messengers — LC Lalak Pokorski Ziegler '12

$\boxed{\text{Rates enhanced wrt. } \mu \to e\gamma\,!}$

TeV scale seesaw fields with large Yukawa couplings are possible (cancellations, flavor symmetry, inverse seesaw...)

Potentially large LFV coupling to gauge bosons are induced (e.g. lepton-W-RHν)

Abada Biggio Bonnet Gavela Hambye '07

Type I

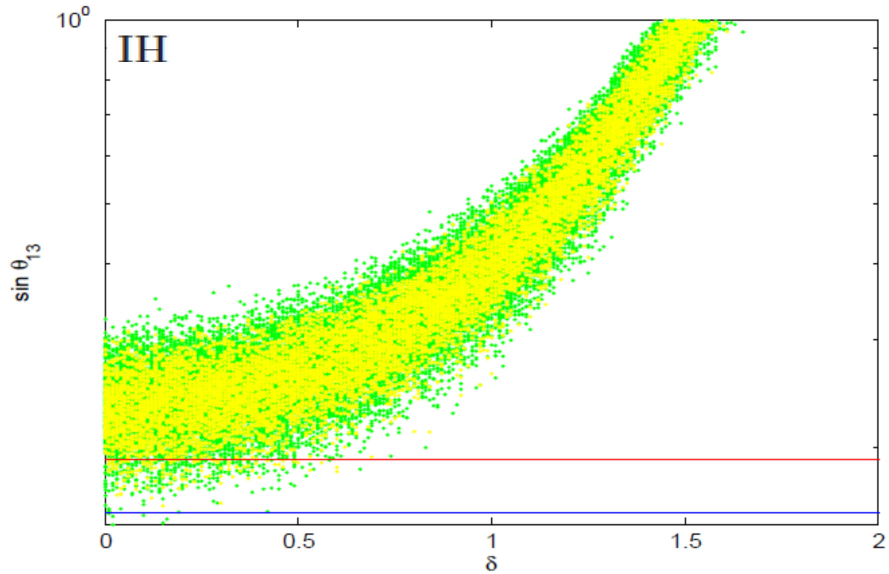
$$\mathbf{NH}: \quad \mathrm{BR}(\mu \to e\gamma) \cong \frac{3\alpha_{\rm em}}{32\pi}\left(\frac{y^2 v^2}{M_1^2}\frac{m_3}{m_2+m_3}\right)^2 \left|U_{\mu 3} + i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}\right|^2 \left|U_{e3} + i\sqrt{\frac{m_2}{m_3}}U_{e2}\right|^2 \left[G(X) - G(0)\right]^2$$

$$\mathbf{IH}: \quad \mathrm{BR}(\mu \to e\gamma) \cong \frac{3\alpha_{\rm em}}{32\pi}\left(\frac{y^2 v^2}{M_1^2}\frac{1}{2}\right)^2 \left|U_{\mu 2} + iU_{\mu 1}\right|^2 \left|U_{e2} + iU_{e1}\right|^2 \left[G(X) - G(0)\right]^2 .$$

Dinh Ibarra Molinaro Petcov '12

- Possibly suppressed rates

Dinh et al. '12



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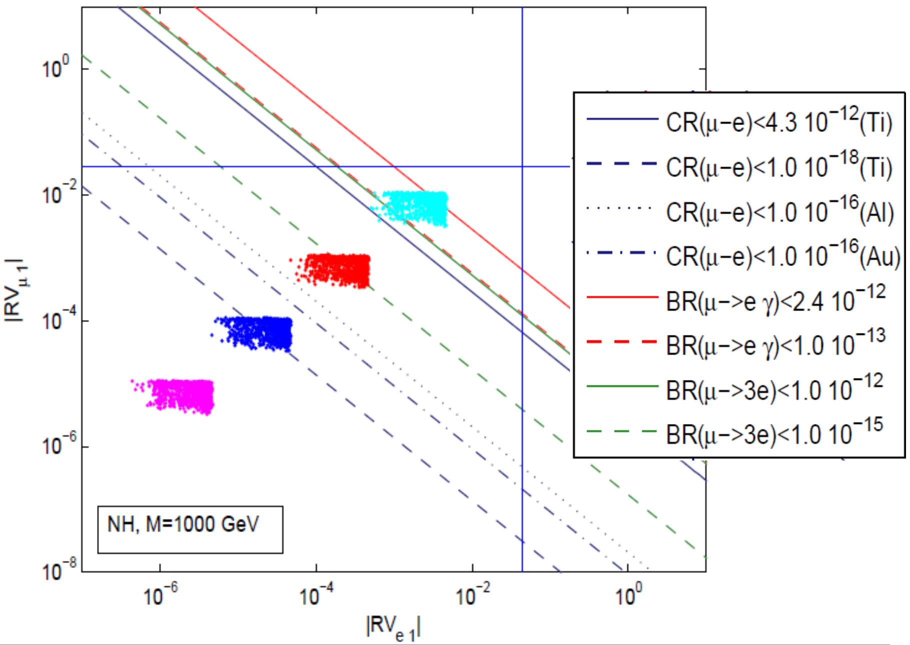
Dinh Ibarra Molinaro Petcov '12

- Possibly suppressed rates
- $\mu \to e$ conversion strongest constraint (loop function enhancement)



Dinh et al. '12

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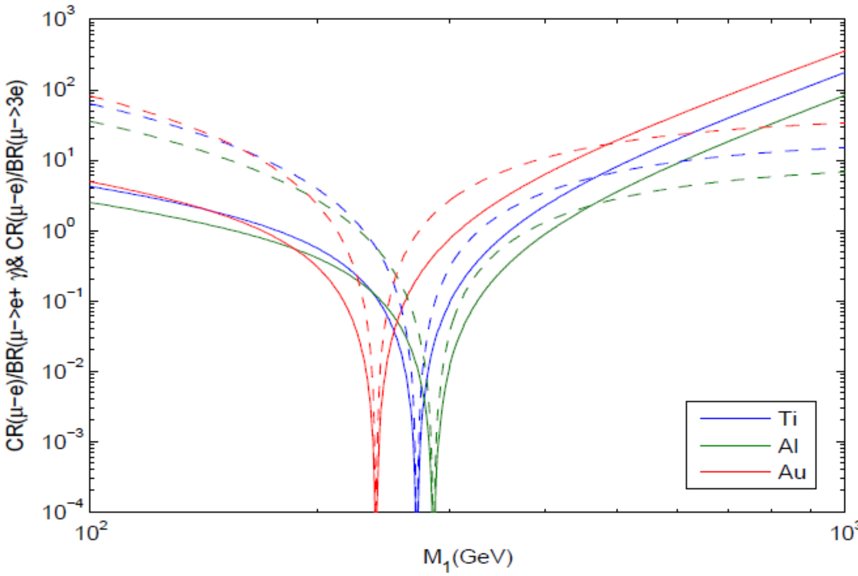
Dinh Ibarra Molinaro Petcov '12

- Possibly suppressed rates
- $\mu \to e$ conversion strongest constraint (loop function enhancement)
- Correlations: parameters can be determined through diff. channels

Dinh et al. '12



LFV in SUSY flavor models

- SU(3) — LC Jones-Perez Vives '07; LC Jones-Perez Masiero Park Vives '09; LC Hodgkinson Jones-Perez Masiero Vives '09
- $U(2)_l x U(2)_e$ — Blankenburg Isidori Jones-Perez '12
- A_4 — Feruglio Hagedorn Lin Merlo '08, '09; Altarelli Feruglio Merlo Stamou '09
- Model independent discussion — LC Lalak Pokorski Ziegler '12

Structure of slepton mass matrices determined by the flavor symmetry

Same dynamics explain fermion masses and mixing and controls LFV

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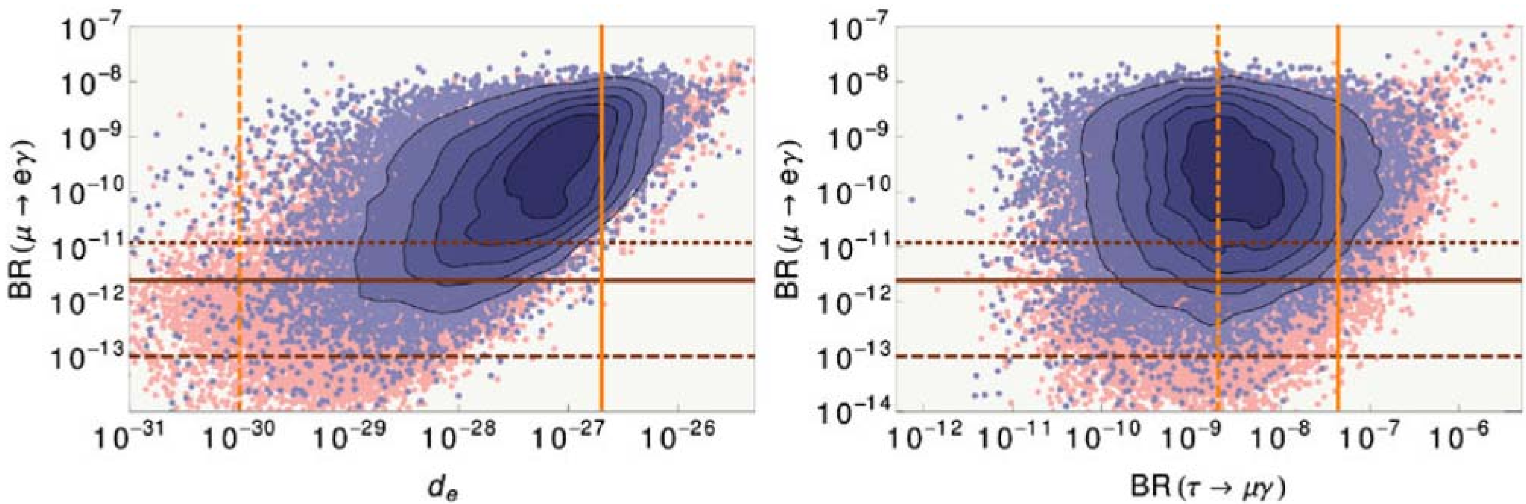
SU(3) with light SUSY spectrum:



LC Hodgkinson Jones-Perez Masiero Vives '09

LFV in SUSY flavor models

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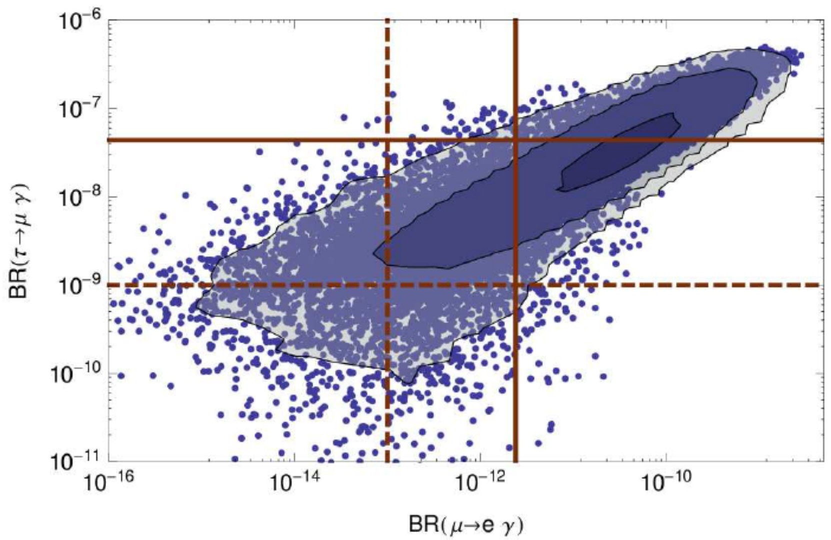
$U(2)_l x U(2)_e$ with heavy first generations sleptons

Stau masses < 1 TeV



Blankenburg Isidori Jones-Perez '12

LFV in SUSY flavor models

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- $U(2)_l \mathrm{x} U(2)_e$

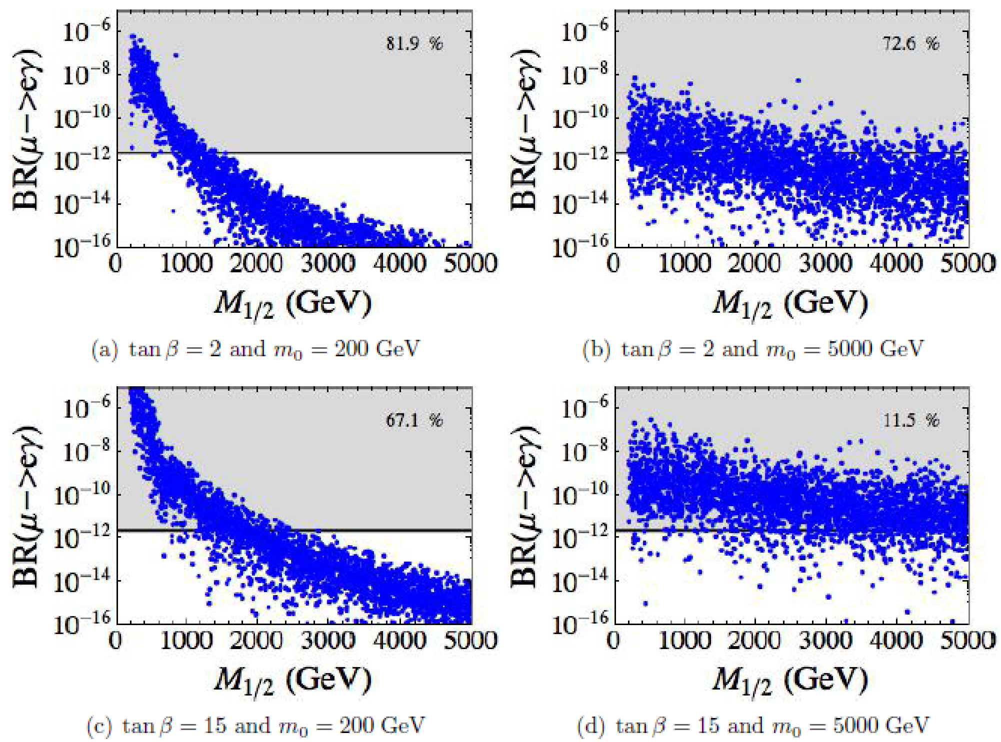
Blankenburg Isidori Jones-Perez '12

- A_4

Feruglio Hagedorn Lin Merlo '08, '09;
Altarelli Feruglio Merlo Stamou '12

A_4 predictes:

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\mu \to e\nu\bar{\nu})} \approx \frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}$$



(a) $\tan\beta = 2$ and $m_0 = 200$ GeV
(b) $\tan\beta = 2$ and $m_0 = 5000$ GeV
(c) $\tan\beta = 15$ and $m_0 = 200$ GeV
(d) $\tan\beta = 15$ and $m_0 = 5000$ GeV

Altarelli Feruglio Merlo Stamou '12

Conclusions

• LFV processes among the stringest constraints/tests of new physics

• In (SUSY) seesaw, $\theta_{13} \sim O(0.1)$ favours $\mu \to e$ transitions

• MEG already constrain some SUSY seesaw/GUT models far beyond LHC

• Searches for $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\mu \to eee$ and $\mu \to e$ conv. (in different nuclei) would give complementar information crucial for model discrimination

Thanks for your attention!