Lepton flavour violation: introduction

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- status of lepton flavour violation
- theoretical expectations/predictions
- lepton flavour violation at colliders

[extensive use of the WG3 report of the "Flavour in the Era of the LHC" workshop]

Working Group on the Interplay between Collider and Flavour Physics
2nd meeting, CERN, March 17, 2009

Status of lepton flavour violation

So far lepton flavour violation has been observed only in the neutrino sector (oscillations). Experimental upper bounds on LFV processes involving charged leptons:

Table 1.1: Present limits on rare μ decays.

mode	limit (90% C.L.)	year	Exp./Lab.
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	2002	MEGA / LAMPF
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	1988	SINDRUM I / PSI
$\mu^+e^- \leftrightarrow \mu^-e^+$	8.3×10^{-11}	1999	PSI
$\mu^-\ \mathrm{Ti} \to e^-\mathrm{Ti}$	6.1×10^{-13}	1998	SINDRUM II / PSI
$\mu^-\ \mathrm{Ti} \to e^+\mathrm{Ca}^*$	3.6×10^{-11}	1998	SINDRUM II / PSI
$\mu^-\ \mathrm{Pb} \to e^-\mathrm{Pb}$	4.6×10^{-11}	1996	SINDRUM II / PSI
$\mu^-\ \mathrm{Au} \to e^-\mathrm{Au}$	7×10^{-13}	2006	SINDRUM II / PSI

[WG3 report]

Table 1.2: 90% C.L. upper limits on selected LFV tau decays by Babar and BELLE.

Channel	Babar $\mathcal{L}$ (fb^{-1})	Babar $\mathcal{B}_{\text{UL}}$ (10^{-8})	BELLE $\mathcal{L}$ (fb^{-1})	BELLE $\mathcal{B}_{\text{UL}}$ (10^{-8})
$\tau^\pm \to e^\pm\gamma$	232	11	535	12
$\tau^\pm \to \mu^\pm\gamma$	232	6.8	535	4.5
$\tau^\pm \to \ell^\pm\ell^\mp\ell^\pm$	92	11 - 33	535	2 - 4
$\tau^\pm \to e^\pm\pi^0$	339	13	401	8.0
$\tau^\pm \to \mu^\pm\pi^0$	339	11	401	12
$\tau^\pm \to e^\pm\eta$	339	16	401	9.2
$\tau^\pm \to \mu^\pm\eta$	339	15	401	6.5
$\tau^\pm \to e^\pm\eta'$	339	24	401	16
$\tau^\pm \to \mu^\pm\eta'$	339	14	401	13

[WG3 report]

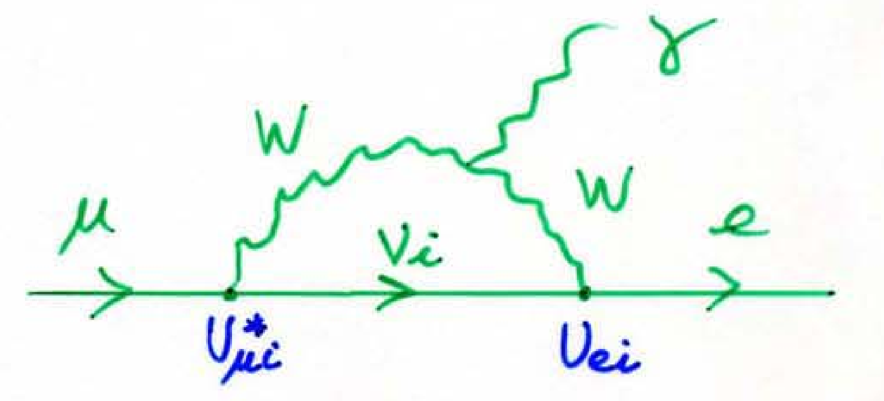
Also strong constraints on LFV rare decays of mesons:

$$\text{BR}\left(K_L^0 \to \mu e\right) < 4.7 \times 10^{-12}$$

$$\text{BR}\left(B_d^0 \to \mu e\right) < 1.7 \times 10^{-7} \qquad \text{[Belle]}$$

$$\text{BR}\left(B_s^0 \to \mu e\right) < 6.1 \times 10^{-6} \qquad \text{[CD]}$$

This is consistent with the Standard Model, in which LFV processes involving charged leptons are suppressed by the tiny neutrino masses



e.g. μ → e γ :

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

Using known oscillations parameters (U = PMNS lepton mixing matrix) and $|U_{e3}| < 0.2$, this gives $\mathrm{BR}\,(\mu \to e\gamma) \;\lesssim\; 10^{-54}$: inaccessible to experiment!

This makes LFV a unique probe of new physics: the observation of e.g. μ → e γ would be an unambiguous signal of new physics (no SM background)

→ very different from the hadronic sector

Conversely, the present upper bounds on LFV processes already put strong constraints on new physics (same as hadronic sector)

In terms of effective Lagrangian operators:

μ → e γ :

$$\frac{C_{\mu e\gamma}}{\Lambda_{NP}^2}\langle H^0\rangle\,\bar{e}\ \ ^{\mu\nu}\mu_R\,F_{\mu\nu}\ +\ \text{h.c.}$$

The exp. upper bound $\mathrm{BR}\,(\mu\to e\gamma)\ <\ 1.2\times 10^{-11}$ translates into

$$\Lambda_{NP}\ >\ \begin{cases}1.7\times 10^{14}\,\text{TeV} & (C=1)\\ 860\,\text{TeV} & (C=\frac{\alpha_W}{4\pi})\end{cases}$$

μ → e e e :

$$\frac{C_{eee\mu}^{MN}}{\Lambda_{NP}^2}\ (\bar{e}\gamma^\mu P_M e)\,(\bar{e}\gamma^\mu P_N\mu)\ +\ \text{h.c.}$$

(P,M = L,R)

The exp. upper bound $\mathrm{BR}\,(\mu\to eee)\ <\ 10^{-12}$ translates into

$$\Lambda_{NP}\ >\ \begin{cases}210\,\text{TeV} & (C=1)\\ 11\,\text{TeV} & (C=\frac{\alpha_W}{4\pi})\end{cases}$$

→ strong constraint on new physics at the TeV scale

Indeed, many new physics scenarios predict “large” LFV rates

Prospects for LFV experiments

<u>$\mu \to e\gamma$:</u>

- the experiment MEG at PSI has started taking data in sept. 2008
- first results expected in summer 2009
- expects to reach a sensitivity of a few 10^{-13} (factor of 100 improvement) in 3 years of acquisition time

<u>$\mu \to e$ conversion :</u>

- the project mu2e is under study at FNAL - aims at $\mathcal{O}(10^{-16})$
- the project PRISM/PRIME at J-PARC aims at $\mathcal{O}(10^{-18})$

<u>τ decays :</u>

- LHC experiments limited to $\tau \to \mu\mu\mu$ – comparable to existing B fact.
- superB factories will probe the $10^{-9} - 10^{-10}$ level

Theoretical expectations/predictions

Many new physics scenarios predict "large" LFV rates: supersymmetry, extra dimensions, little Higgs models, ...

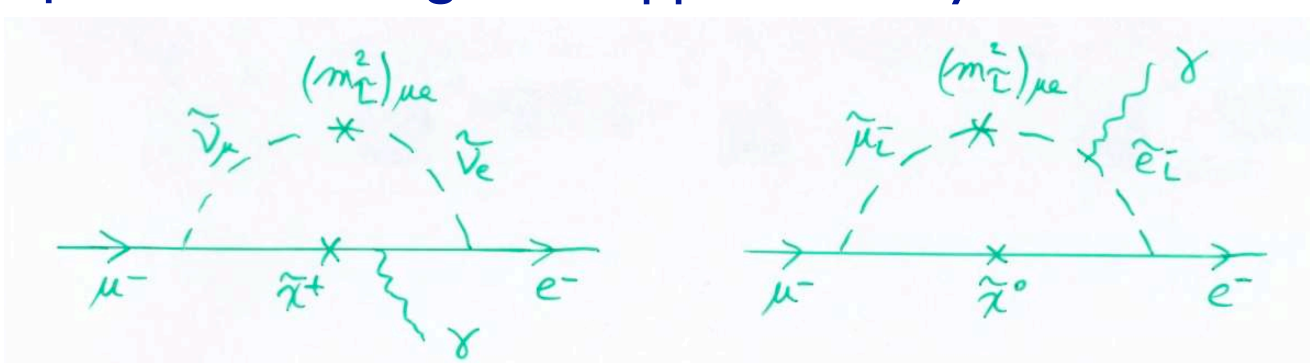
In (R-parity conserving) supersymmetry extensions of the Standard Model, LFV is induced by a misalignment between the lepton and slepton mass matrices, parametrized by the mass insertion parameters ($\alpha \neq \beta$):

$$\delta^{LL}_{\alpha\beta} \equiv \frac{(m^2_{\tilde{L}})_{\alpha\beta}}{m^2_L}, \qquad \delta^{RR}_{\alpha\beta} \equiv \frac{(m^2_{\tilde{e}})_{\alpha\beta}}{m^2_R}, \qquad \delta^{RL}_{\alpha\beta} \equiv \frac{A^e_{\alpha\beta} v_d}{m_R m_L}$$

In the mass insertion approximation, the branching ratio for $\mu \to e\,\gamma$ reads

$$\mathrm{BR}\,(\mu \to e\gamma) = \frac{3\pi\alpha^3}{4G_F^2 \cos^4\theta_W} \left\{ \left| f_{LL}\, \delta^{LL}_{12} + f_{LR}\, \delta^{LR}_{12} \right|^2 + \left| f_{RR}\, \delta^{RR}_{12} + f^\star_{LR}\, \delta^{LR\star}_{21} \right|^2 \right\} \tan^2\beta$$

with f_L, f_R functions of the superpartner masses and of tan β. For moderate to large tan β, the branching ratio approximately scales as $\tan^2\beta$



[Masina, Savoy]

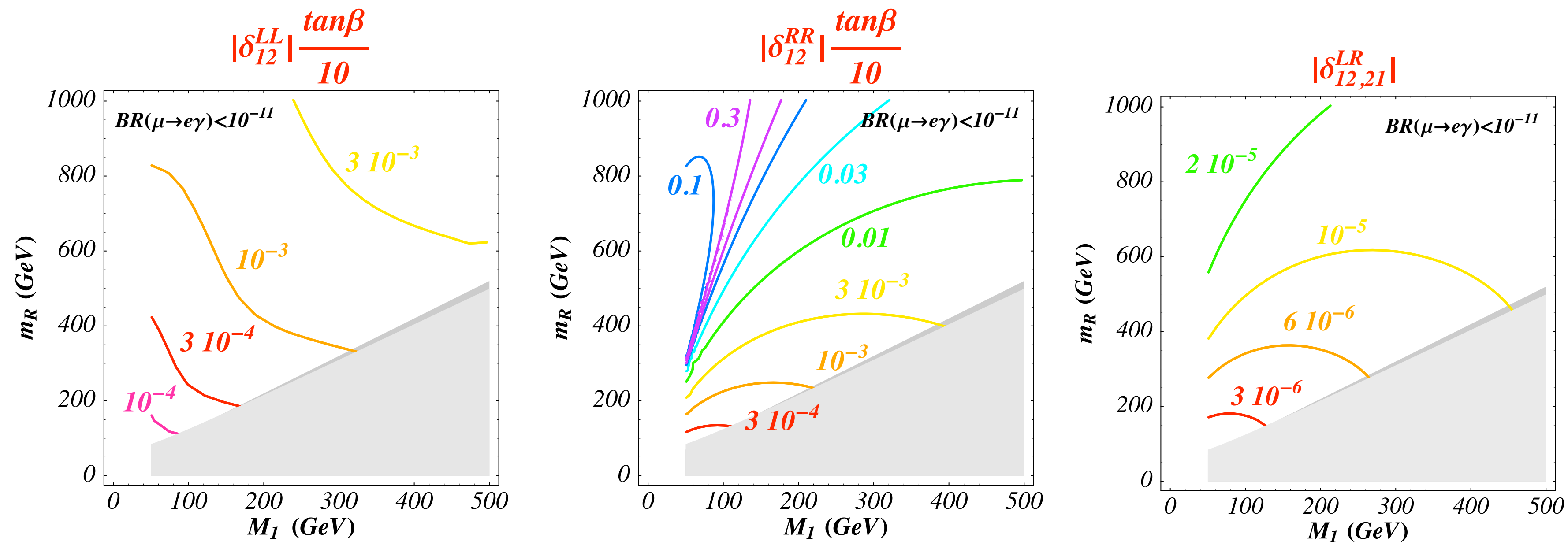


Fig. 5.3: Upper limits on δ_{12}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

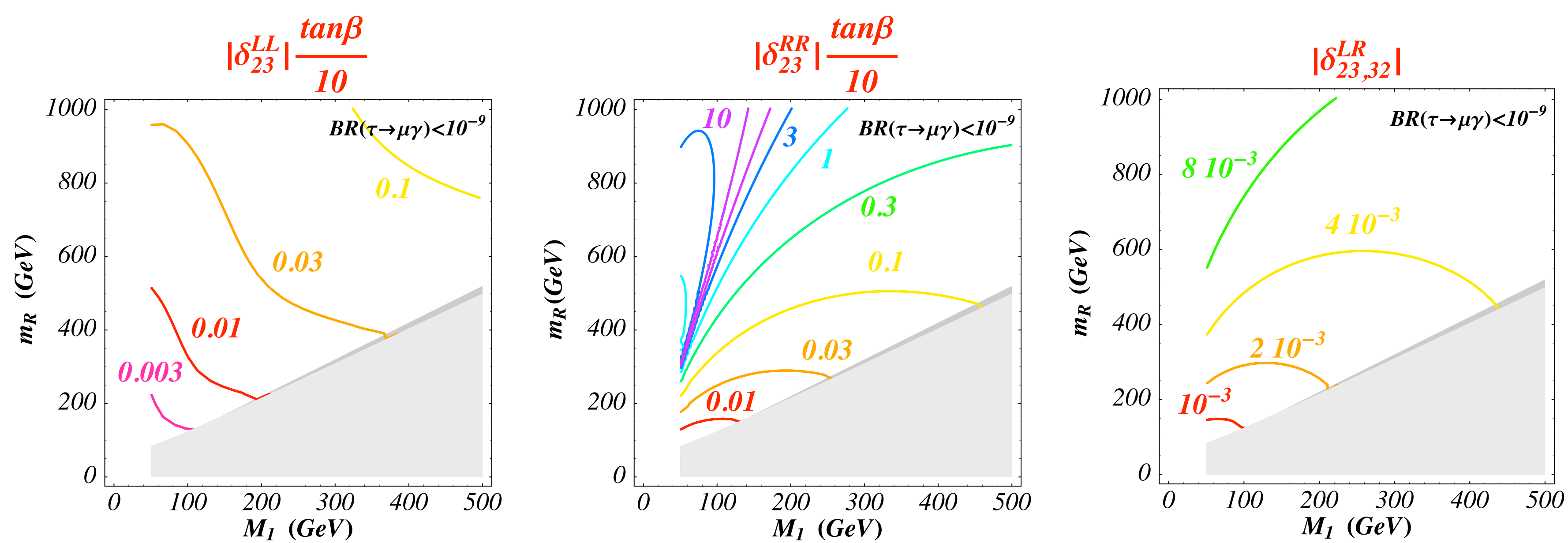


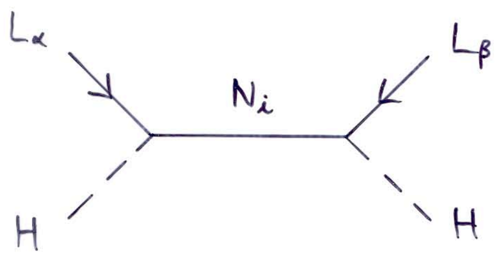
Fig. 5.4: Upper limits on δ_{23}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

Important difference with the quark sector: even if slepton soft terms are flavour universal at some high scale, radiative corrections may induce large LFV [quark sector: controlled by CKM, pass most flavour constraints]

Such large corrections are due to heavy states with FV couplings to SM leptons, whose presence is suggested by $m_\nu << m_l$ [Borzumati, Masiero]

Most celebrated example: (type I) seesaw mechanism

$$\mathcal{L}_{seesaw} = -\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{N}_i Y_{i\alpha} L_\alpha H + \text{h.c.}\right)$$



$$\Rightarrow \qquad (M_\nu)_{\alpha\beta} = -\sum_i \frac{Y_{i\alpha} Y_{i\beta}}{M_i} v^2 \quad (v = \langle H \rangle)$$

Assuming universal slepton masses at M_U, one obtains at low energy:

$$(m^2_{\tilde{L}})_{\alpha\beta} \simeq -\frac{3m_0^2 + A_0^2}{8\pi^2} C_{\alpha\beta}\,, \quad (m^2_{\tilde{e}})_{\alpha\beta} \simeq 0\,, \quad A^e_{\alpha\beta} \simeq -\frac{3}{8\pi^2} A_0 y_{e\alpha} C_{\alpha\beta}$$

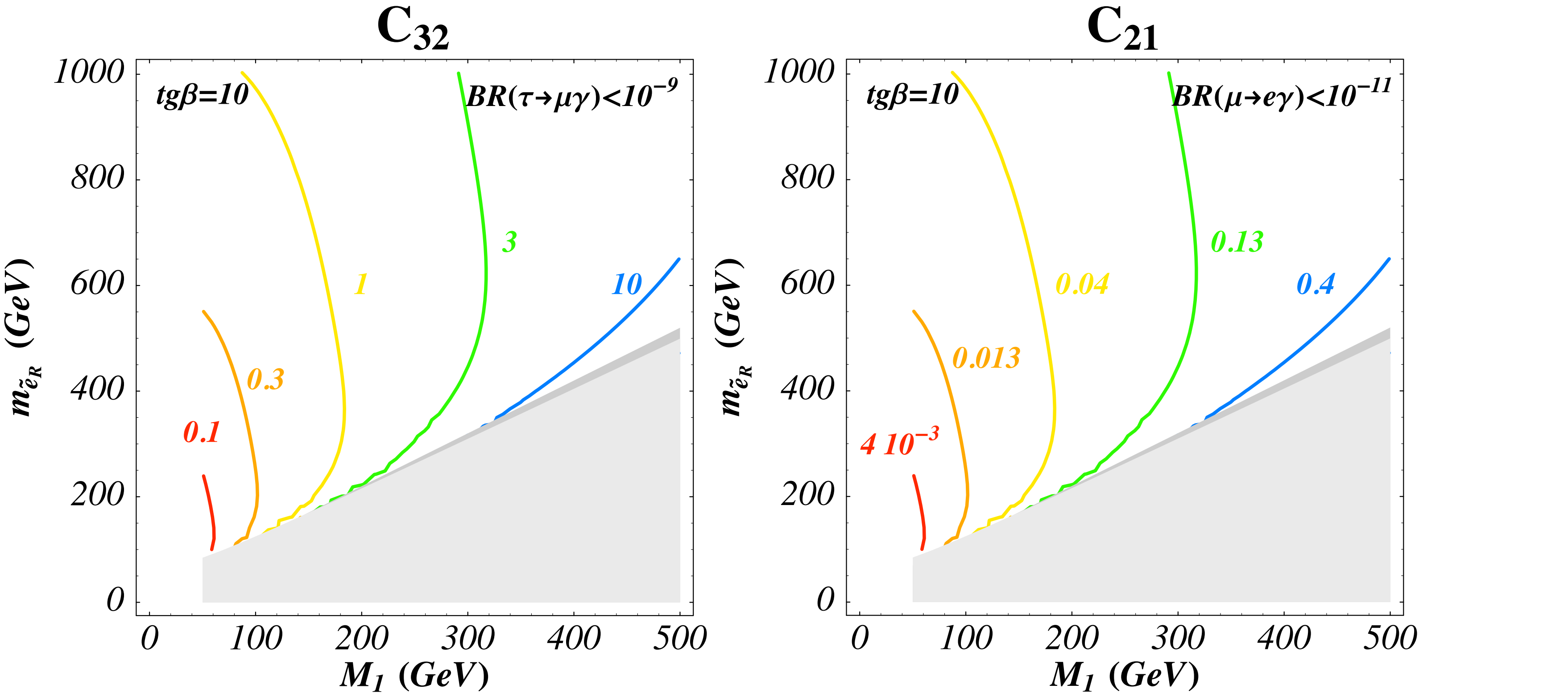
where $C_{\alpha\beta} \equiv \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$ encapsulates all the dependence on the seesaw parameters

$$\text{BR}\left(l_\alpha \to l_\beta \gamma\right) \propto |C_{\alpha\beta}|^2$$

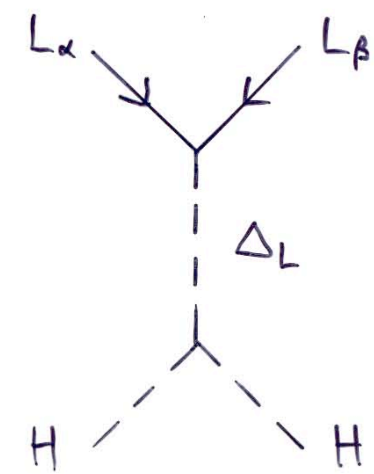
$$\mathrm{BR}\left(l_\alpha \to l_\beta \gamma\right) \ \propto \ |C_{\alpha\beta}|^2$$

$$C_{\alpha\beta} \ \equiv \ \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$$

[SL, Masina, Savoy]



Other example: type II seesaw mechanism [A. Rossi]



= heavy scalar SU(2)L triplet exchange

$$\frac{1}{\sqrt{2}} Y_T^{ij} L_i T L_j + \frac{1}{\sqrt{2}} \lambda H_u \bar{T} H_u + M_T T \bar{T}$$

$$\Rightarrow \quad M_\nu^{ij} = \lambda Y_T^{ij} \frac{v_u^2}{M_T}$$

The radiative corrections to soft slepton masses are now controlled by

$$(Y_T^\dagger Y_T)_{\alpha\beta} \ln(M_U/M_T) \ \propto \ \sum_i m_{\nu_i}^2 U_{i\alpha} U_{i\beta}^*$$

$\Rightarrow$ predictive (up to an overalll scale) and leads to correlations between LFV observables (correlations controlled by the neutrino parameters)

[A. Rossi]

$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left|\frac{(m_{\tilde{L}}^2)_{\tau\mu}}{(m_{\tilde{L}}^2)_{\mu e}}\right|^2 \frac{\mathrm{BR}(\tau\to\mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 300 & [s_{13}=0] \\ 2\ (3) & [s_{13}=0.2] \end{cases}$$

$$\frac{\mathrm{BR}(\tau\to e\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left|\frac{(m_{\tilde{L}}^2)_{\tau e}}{(m_{\tilde{L}}^2)_{\mu e}}\right|^2 \frac{\mathrm{BR}(\tau\to e\nu_\tau\bar{\nu}_e)}{\mathrm{BR}(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 0.2 & [s_{13}=0] \\ 0.1\ (0.3) & [s_{13}=0.2] \end{cases}$$

In the context of Grand Unification, other heavy states may induce flavour violation in the slepton (and in the squark) sector [Barbieri, Hall, Strumia]

e.g. minimal SU(5) with type I seesaw: coloured Higgs triplets couple to RH quarks and leptons with the same Yukawa couplings as the Higgs doublets

$$\frac{1}{2} Y^u_{ij} Q_i Q_j H_c + Y^u_{ij} \overline{U}_i \overline{E}_j H_c + Y^d_{ij} Q_i L_j \overline{H}_c + Y^d_{ij} \overline{U}_i \overline{D}_j \overline{H}_c + Y^\nu_{ij} \overline{D}_i \overline{N}_j H_c$$

$\Rightarrow$ potentially large radiative corrections to the soft terms of the singlet squarks and sleptons (absent in the MSSM at leading order); in particular, comtributions to $(m^2_{\tilde{e}})_{ij}$ controlled by the top Yukawa:

$$(m^2_{\tilde{e}})_{ij} \simeq -\mathrm{e}^{i\varphi_{d_{ij}}} V_{3i} V^\star_{3j} \frac{3Y_t^2}{(4\pi)^2} (3m_0^2 + A_0^2) \log\left(\frac{M_G^2}{M_{H_c}^2}\right)$$

and contributions to $(m^2_{\tilde{d}})_{ij}$ controlled by the RHN couplings $\Rightarrow$ correlation between leptonic and hadronic flavour violations [Hisano, Shizimu - Ciuchini et al.]

$$(m^2_{\tilde{d}})_{23} \simeq \mathrm{e}^{i\varphi_{d_{23}}} (m_{\tilde{L}^2})^*_{23} \left(\log\frac{M_G^2}{M_{H_c}^2} / \log\frac{M_G^2}{M_{N_3}^2}\right)$$

Similar effects (although of different origin) in SO(10) models with type II seesaw [Calibbi, Frigerio, SL, Romanino, in progress]

Since radiative corrections to slepton soft terms are large, interfere with possible non-universal contributions from supersymmetry breaking (different from quark sector)

$\Rightarrow$ difficult to disentangle them, unless correlations characteristic of a given scenario are observed

An interesting scenario: type II seesaw with the triplet [extended to a (15, 15*) of SU(5)] mediating supersymmetry breaking [Joaquim, Rossi]

$$W_{(15,\overline{15})} \;=\; \frac{1}{\sqrt{2}}(Y_{15}\,\bar{5}\,15\,\bar{5} + \lambda\,5_H\,\overline{15}\,5_H) + \xi\,X\,15\,\overline{15}$$

$$\langle X \rangle \;=\; \langle S_X \rangle + \langle F_X \rangle \theta^2 \quad \Rightarrow \quad \xi \langle X \rangle \;=\; M_{15} - B_{15} M_{15} \theta^2$$

$\Rightarrow$ gauge and Yukawa-mediated supersymmetry breaking (controlled by gauge couplings and $Y_{15} = Y_T$)

$\Rightarrow$ soft terms determined by M_{15}, B_{15} [the F_X / X of gauge mediation], Y_{15} and λ : predictive scenario (can trade Y_{15} for the neutrino mass matrix)

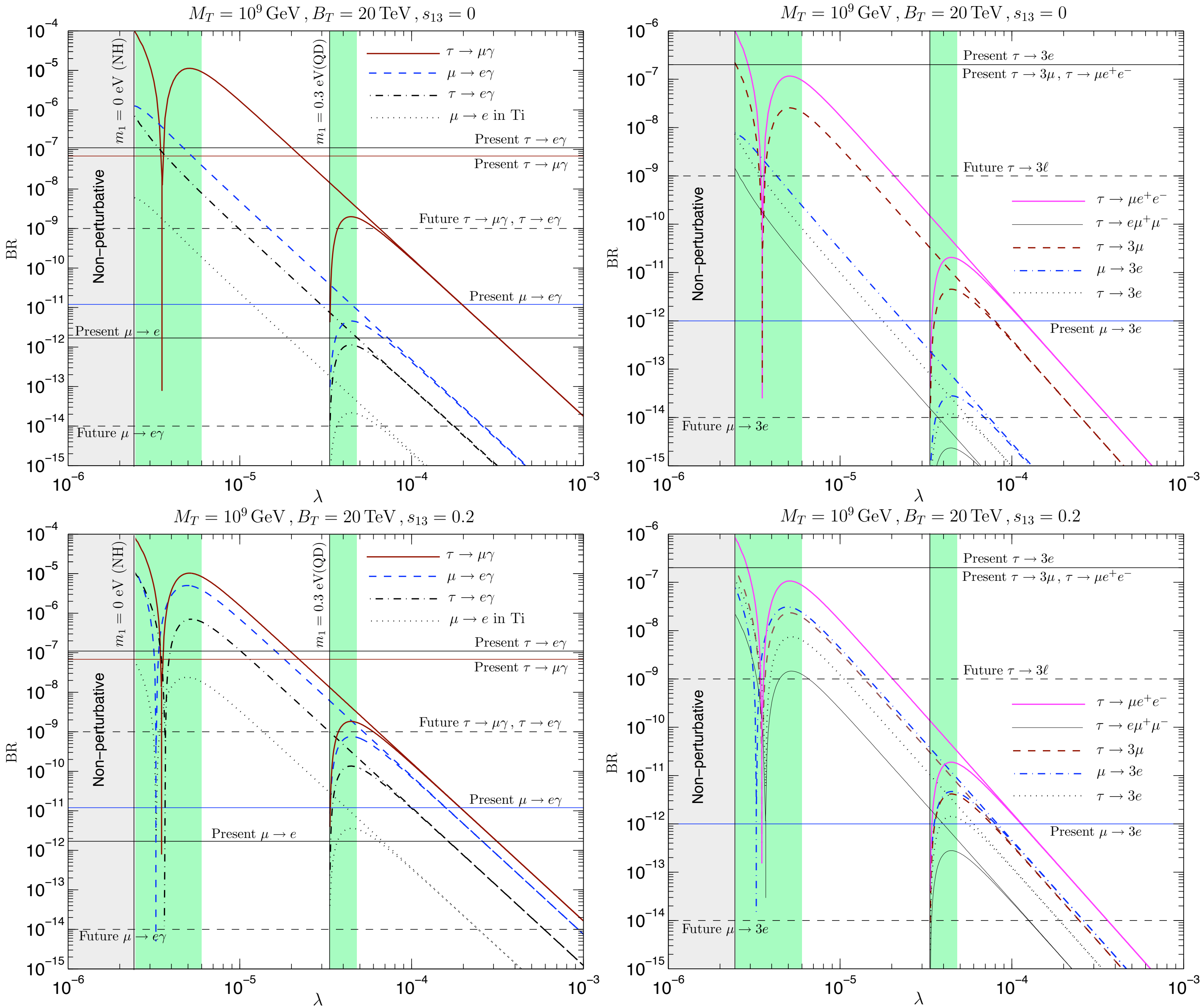


Fig. 5.28: Branching ratios of several LFV processes as a function of λ. The left (right) vertical line indicates the lower bound on λ imposed by requiring perturbativity of the Yukawa couplings $Y_{T,S,Z}$ when $m_1 = 0\,(0.3)$ eV [normal-hierarchical (quasi-degenerate) neutrino mass spectrum]. The regions in green (grey) are excluded by the $m_{\tilde{\ell}_1} > 100$ GeV constraint (perturbativity requirement when $m_1 = 0$).

[Joaquim, Rossi]

LFV in extra-dimensional scenarios

[Cf. talks by G. Perez, A. Buras, A. Weiler and A. Falkowski]

Yesterday's talks: in warped models in which the fermion mass hierarchies are accounted for by different fermion localizations in extra dimensions, a "RS-GIM" mechanism softens the FCNC problem

[Gherghetta, Pomarol - Huber, Shafi - Agashe, Perez, Soni]

Still a milder FCNC problem remains which can be cured e.g. with a bulk Higgs [Agashe, Azatov, Zhu] or with approximate bulk flavour symmetries [Fitzpatrick, Perez, Randall - Santiago - Csaki, Falkowski, Weiler]

Only few studies of LFV in extra dimensions

Agashe, Blechman, Petriello: RS model with Higgs propagating in the bulk ($l_i \to l_j \gamma$ UV sensitive if Higgs localized on the IR brane)

Present bounds on LFV processes compatible with O(1 TeV) KK masses, with however some tension between loop-induced $l_i \to l_j \gamma$ and tree-level $\mu \to e$ conversion [can be improved with different lepton reps (2009)]

[Agashe, Blechman, Petriello]

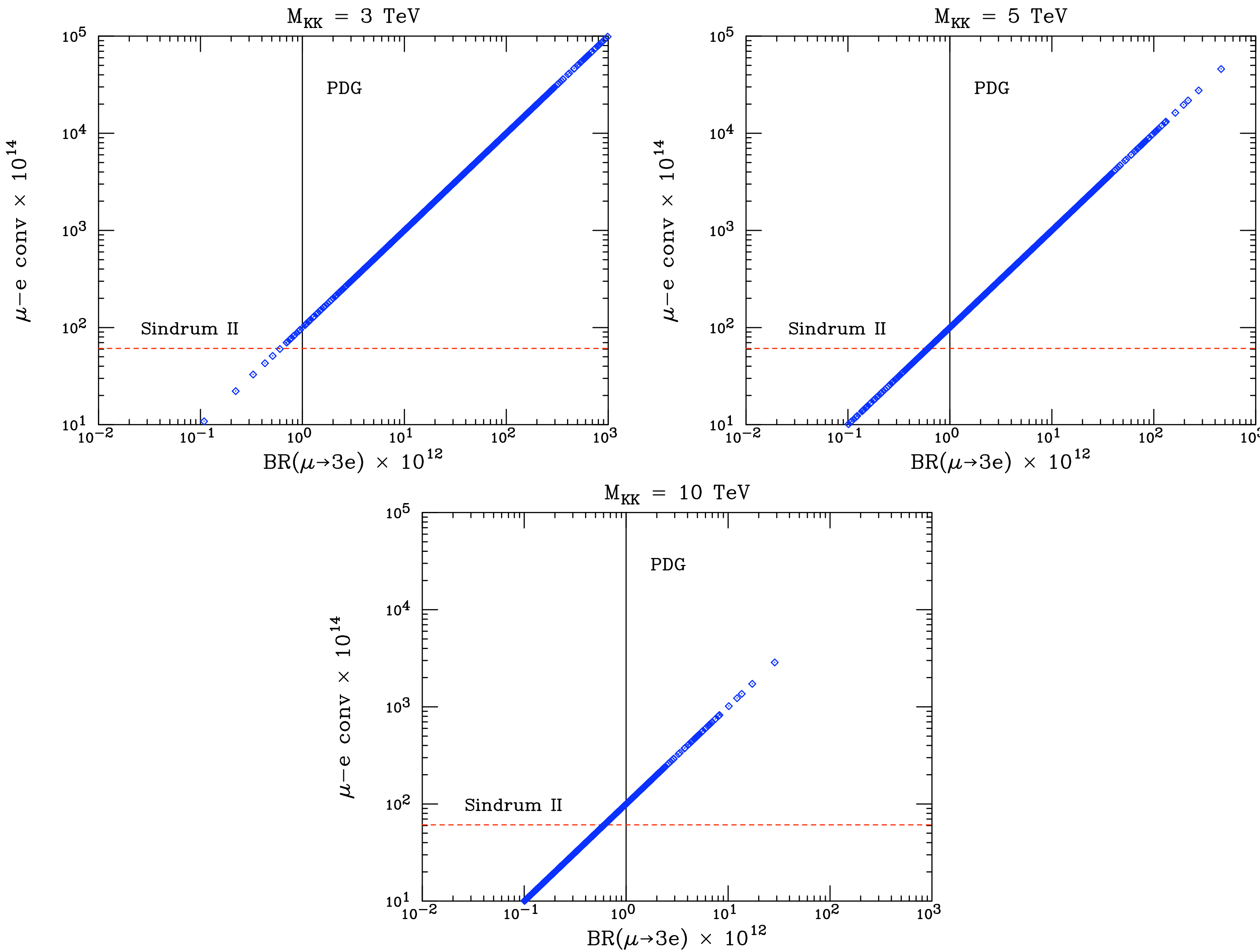


FIG. 4: Scan of the $\mu \to 3e$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV. The solid and dashed lines are the PDG and SINDRUM II limits, respectively.

[Agashe, Blechman, Petriello]

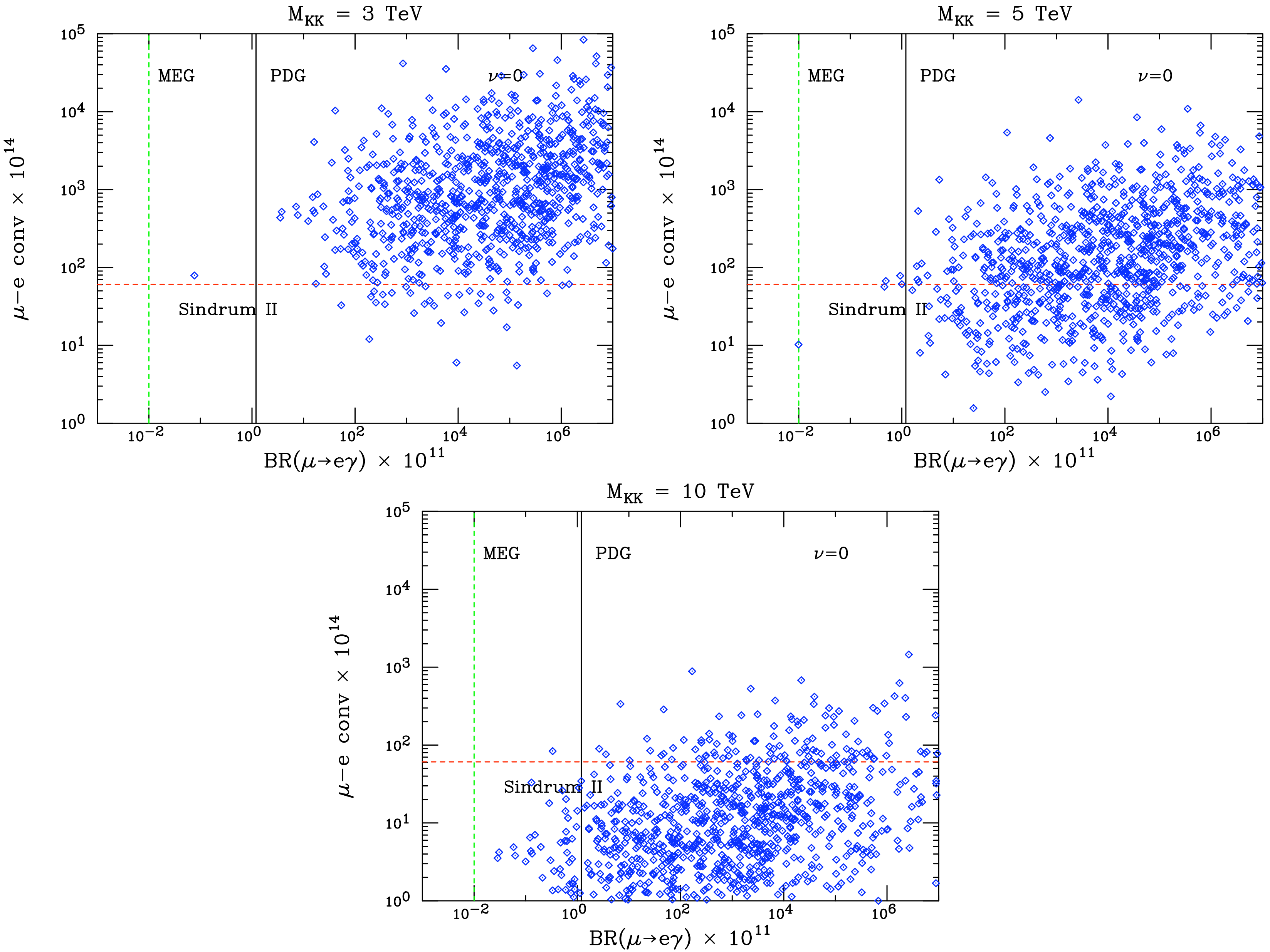


FIG. 6: Scan of the $\mu \to e\gamma$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \to e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to $BR(\mu \to e\gamma)$.

LFV in the littlest Higgs model with T-parity

[Cf. talks by M. Blanke and Y. Okada]

LFV in the littlest Higgs model with T-parity (LHT) has already been covered by M. Blanke yesterday

The origin of LFV is the FV couplings of the mirror leptons to the SM leptons (via the heavy gauge bosons) = new flavour mixing matrices $V_{H\nu}$ and V_{Hl}, related by the PMNS matrix

Generally find large rate ⇒ constraints on the mirror lepton parameters

After imposing these constraints, find correlations between LFV processses that differ from the MSSM expectations

Ratios of LFV Branching Ratios

BBDRT, 0903.xxxx

	LHT	MSSM
$\frac{Br(\mu^-\to e^- e^+ e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^- e^+ e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^- \mu^+ \mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$ ❇
$\frac{Br(\tau^-\to e^- \mu^+ \mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$ ❇
$\frac{Br(\tau^-\to \mu^- e^+ e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$

❇ can be significantly enhanced by Higgs contributions

Paradisi, hep-ph/0508054, hep-ph/0601100

Lepton flavour violation at colliders

The measurement of a few LFV observables in the charged lepton sector will not be enough to identify the new physics

$\Longrightarrow$ searches for LFV at colliders are complementary

Here concentrate on RPC Susy: LFV in neutralino/slepton decays at the LHC

LHC: squark and gluino production followed by cascade decays via the second lightest neutralino

$$\begin{aligned} pp &\rightarrow \tilde{q}\tilde{q},\ \tilde{g}\tilde{q},\ \tilde{g}\tilde{g} \\ \tilde{q} &\rightarrow \tilde{\chi}_2^0 q \\ \tilde{\chi}_2^0 &\rightarrow l_i^{\pm}\tilde{l}_k^{\mp} \rightarrow l_i^{\pm} l_j^{\mp}\tilde{\chi}_1^0 \end{aligned}$$

(Drell-Yan production of slepton pairs also possible)

benefits from good lepton flavour identification and small backgrounds

(LL) slepton mass matrix in the charged lepton mass eigenstate basis (real case, 2 flavours):

$$\begin{pmatrix} (m^2_{\tilde{L}})_{11} & (m^2_{\tilde{L}})_{12} \\ (m^2_{\tilde{L}})_{12} & (m^2_{\tilde{L}})_{22} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}} & \sin\theta_{\tilde{l}} \\ -\sin\theta_{\tilde{l}} & \cos\theta_{\tilde{l}} \end{pmatrix} \begin{pmatrix} m^2_{\tilde{l}_1} & 0 \\ 0 & m^2_{\tilde{l}_2} \end{pmatrix} \begin{pmatrix} \cos\theta_{\tilde{l}} & -\sin\theta_{\tilde{l}} \\ \sin\theta_{\tilde{l}} & \cos\theta_{\tilde{l}} \end{pmatrix}$$

$$\Delta\tilde{m}^2 \equiv m^2_{\tilde{l}_2} - m^2_{\tilde{l}_1} \qquad\qquad \tan 2\theta_{\tilde{l}} = \frac{2\,(m^2_{\tilde{L}})_{12}}{(m^2_{\tilde{L}})_{22} - (m^2_{\tilde{L}})_{11}}$$

LFV in charged lepton processes is controlled by $\delta^{LL}_{12} \equiv (m^2_{\tilde{L}})_{12}/\bar{m}^2$:

$$\mathrm{BR}\,(\mu \to e\gamma) \sim \left|(m^2_{\tilde{L}})_{12}\,/\,\bar{m}^2\right|^2$$

$\bar{m}^2$ = average slepton mass

Slepton mixing also implies slepton oscillations, which are controlled by $\Delta\tilde{m}^2$ and $\sin 2\theta_{\tilde{l}}$ (cf. neutrino oscillations). As a result of the competition between oscillations and decay, the probability that a selectron decays into a muon is:

$$P\,(\tilde{e} \to f_\mu) = \frac{1}{2}\,\sin^2 2\theta_{\tilde{l}}\,\frac{(\Delta\tilde{m}^2)^2}{4\bar{m}^2\Gamma^2_{\tilde{l}} + (\Delta\tilde{m}^2)^2}\,\mathrm{BR}\,(\tilde{\mu} \to f_\mu)$$

It is large if $\sin 2\theta_{\tilde{l}} \sim 1$ and $\Delta\tilde{m}^2 \gtrsim \Gamma_{\tilde{l}}\,\bar{m}$

Arkani-Hamed, Cheng, Feng, Hall

At first sight, a large $\sin 2\theta_{\tilde{l}}$ seems to be incompatible with a small μ → e γ rate. Actually it is not if $(m^2_{\tilde{L}})_{11} \simeq (m^2_{\tilde{L}})_{22}$

→ large LFV effects at colliders are possible even if μ → e γ is very small: complementarity of low-energy and collider experiments

Hisano, Kitano, Nojiri: compare 5σ contours for LFV discovery at the LHC in $\tilde{\chi}^0_2 \to e^\pm \mu^\mp \tilde{\chi}^0_1$ with $\mathrm{BR}\,(\mu \to e\gamma)$ for different MSSM parameters:

[2-flavour mixing in the $(\tilde{e}_R,\, \tilde{\mu}_R)$ sector parametrized by $\sin 2\theta_{\tilde{l}}$ and $\Delta\tilde{m}^2$]

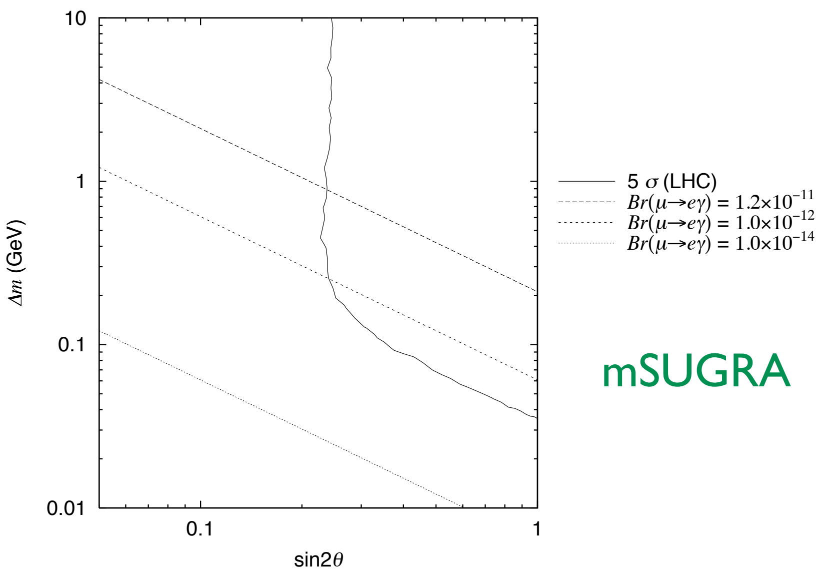


Figure 8: The LHC reach and the line of the constant $Br(\mu \to e\gamma)$ in the MSUGRA model are shown. Here, $\tan\beta = 10$, $A = 0$, $m = 100$ GeV, and $M = 300$ GeV.

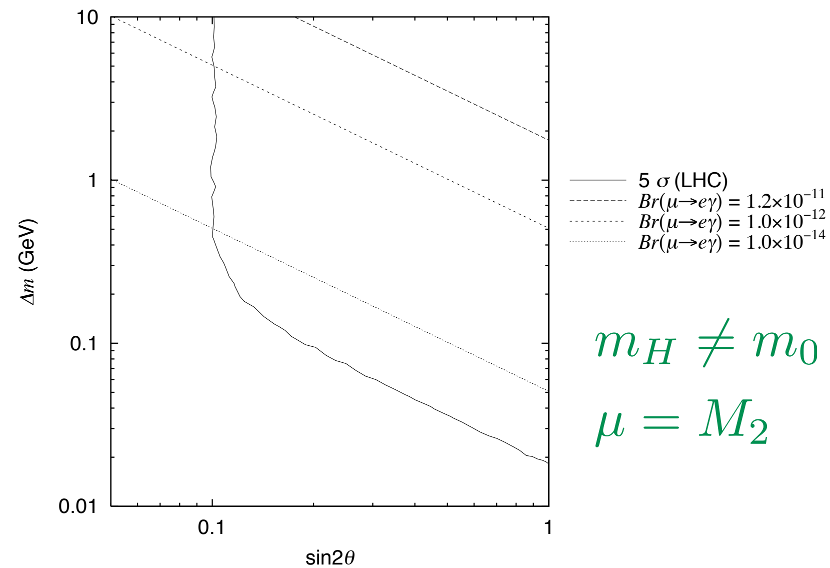


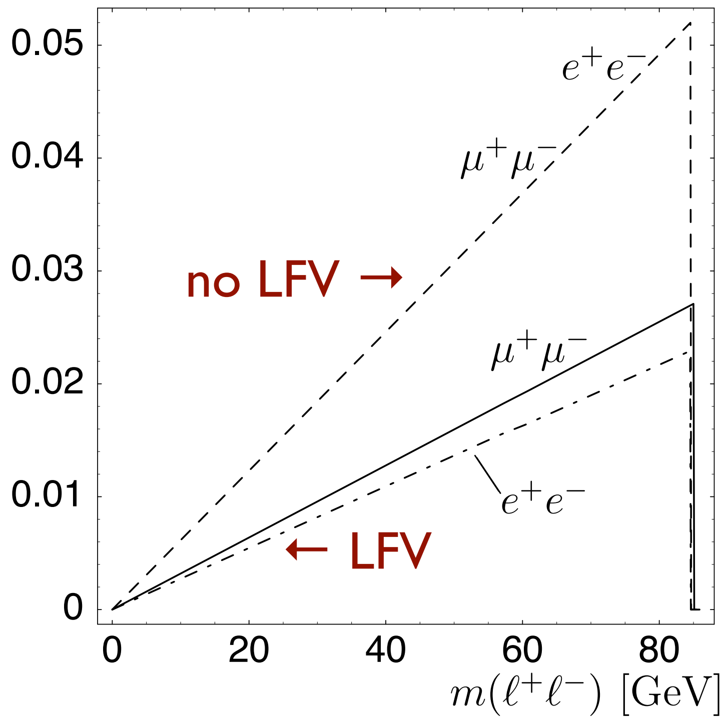
Figure 9: The LHC reach and the line of the constant $Br(\mu \to e\gamma)$ in the cMSSM are shown. Here, $\mu = M_2$, $\tan\beta = 10$, $A = 0$, $m_{16} = 100$ GeV, and $M = 300$ GeV.

Information from the distribution of the di-lepton invariant mass (consider first the case with no LFV, i.e. ll = ee or μμ):

$$\frac{d\Gamma_{l^- l^+}}{dm_{ll}} \propto \begin{cases} m_{ll} & (0 \leq m_{ll} \leq m_{ll}^{\max}) \\ 0 & (m_{ll}^{\max} < m_{ll}) \end{cases} \qquad (m_{ll}^{\max})^2 = \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}}}$$

⇒ kinematical edge in the di-lepton invariant mass distribution:

$(100/\Gamma_{tot})\, d\,\Gamma(\tilde{\chi}^0_2 \to \ell^+\ell^-\tilde{\chi}^0_1)/d\,m(\ell^+\ell^-)$ [GeV^{-1}]



[Bartl et al.]

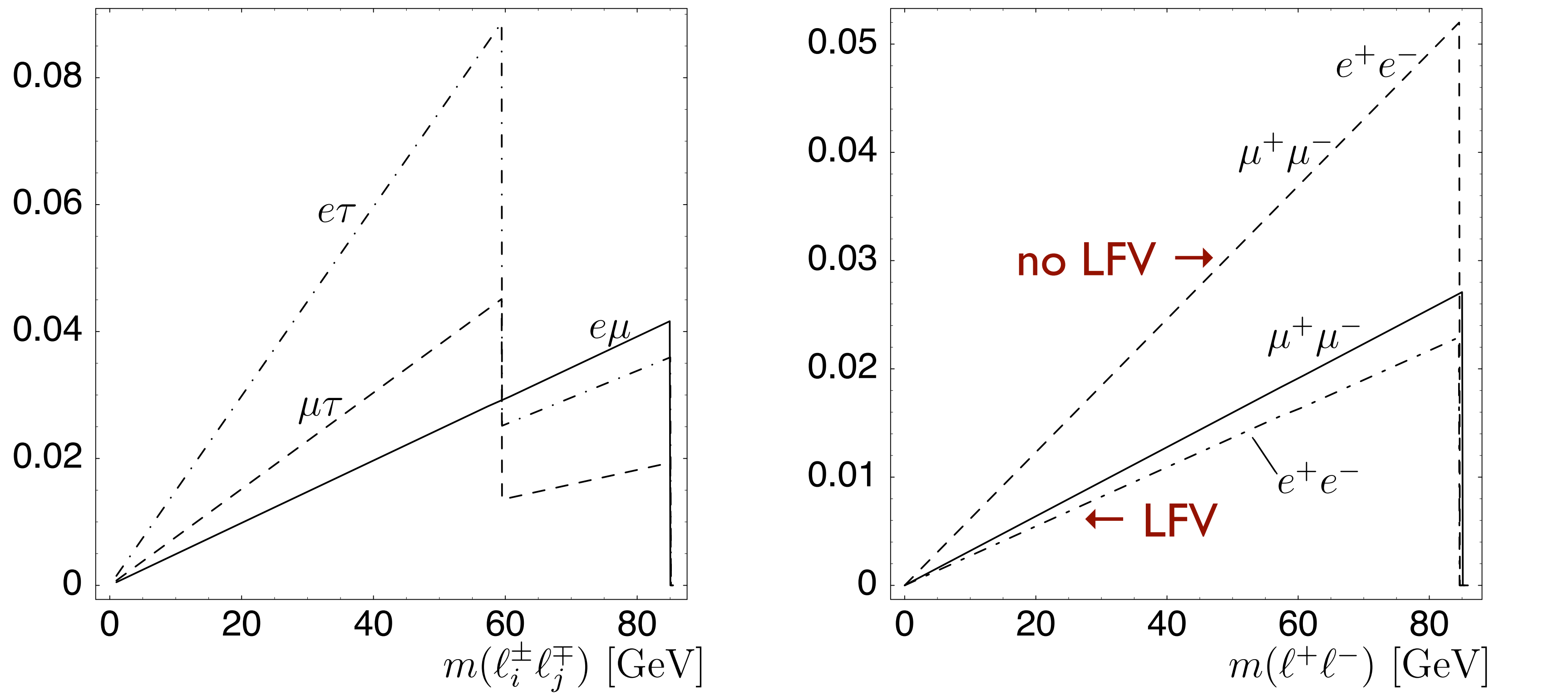
[mSUGRA SPS1a' – LFV in $\tilde{l}_R$ sector]

background does not have an edge structure ⇒ easily subtracted

can identify decay chains and measure masses of superpartners

LFV case: mSUGRA SPS1a' – LFV in $\tilde{l}_R$ sector [Bartl et al.]

(a) $(100/\Gamma_{tot})\, d\Gamma(\tilde{\chi}^0_2 \to \ell^\pm_i \ell^\mp_j \tilde{\chi}^0_1)/d\,m(\ell^\pm_i \ell^\mp_j)$ **(b)** $(100/\Gamma_{tot})\, d\Gamma(\tilde{\chi}^0_2 \to \ell^+ \ell^- \tilde{\chi}^0_1)/d\,m(\ell^+ \ell^-)$



A double-edge structure arises if 2 intermediate sleptons with a sizeable mass difference and the corresponding decay chains are open (i.e. $m_{\tilde{\chi}^0_1} < m_{\tilde{l}} < m_{\tilde{\chi}^0_2}$ for each slepton)

In this example, $m_{\tilde{\chi}^0_1} < m_{\tilde{\tau}_R} < m_{\tilde{e}_R} \simeq m_{\tilde{\mu}_R} < m_{\tilde{\chi}^0_2}$ and no double-edge structure for the eμ channel, since the BR's of $\tilde{\chi}^0_2 \to e\,\tilde{\tau}_R,\ \mu\,\tilde{\tau}_R$ are tiny

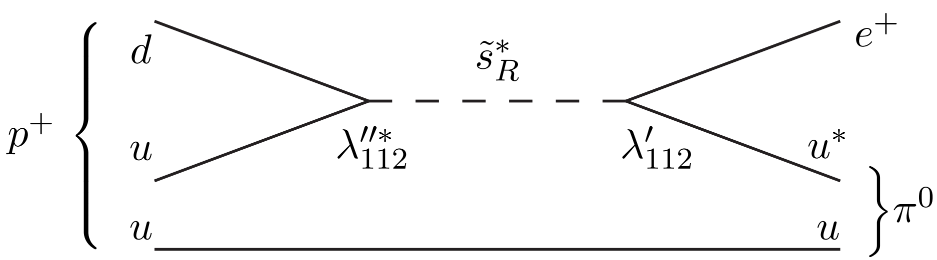
LFV in LSP decays (R-parity violating scenarios)

R-parity = discrete symmetry defined as:

$$R_P \;=\; (-1)^{3B+L+2S} \;=\; \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for superpartners} \end{cases}$$

Introduced in the MSSM in order to avoid fast proton decay from supersymmetric baryon and lepton number violating interactions:

$$W_{RPV} \;=\; \frac{1}{2}\,\lambda_{ijk}\,L_i L_j \bar{e} \,+\, \lambda'_{ijk} L_i Q_j \bar{d}_k \,+\, \frac{1}{2}\,\lambda''_{ijk}\bar{u}_i \bar{d}_j \bar{d}_k \,+\, \mu_i H_u L_i$$



$$\Longrightarrow \quad |\lambda'\lambda''| \;\lesssim\; 10^{-25}\left(\frac{m_{\tilde{d}_R}}{1\,\mathrm{TeV}}\right)^2$$

Consequences of R-parity: proton stability; superpartners produced in pairs; stable LSP (dark matter, missing energy signals at colliders)

However, R-parity is not unavoidable: forbidding the λ” couplings is enough to ensure proton stability

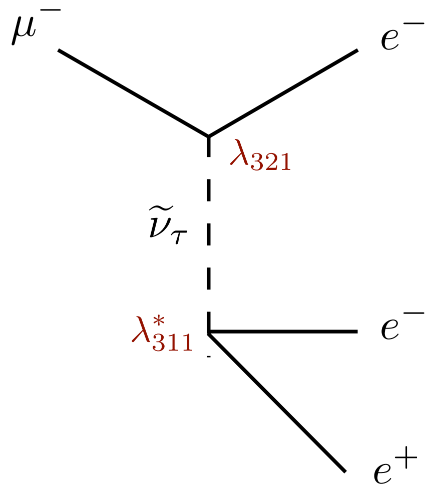
→ scenario where R-parity is violated by the lepton number violating couplings λ and λ’ only (and possibly also μ_i)

→ rich phenomenology at colliders, depending on the size of λ and λ’ (LSP decays and displaced vertices / RPV sparticle decays, single sparticle production...)

→ possibility of generating neutrino masses

- tree-level neutrino mass from μ_i-induced neutrino/higgsino mixing
- 1-loop neutrino masses induced by λ and λ’ (need $\lambda, \lambda' \sim 10^{-4} - 10^{-3}$)

→ LFV decays of charged leptons ($l \to l' l' l''$ at tree level)



$$|\lambda_{321}\lambda^*_{311}|,\ |\lambda^*_{i12}\lambda_{i11}| < 7 \times 10^{-7} \left(\frac{m_{\tilde{\nu}}}{100\,\mathrm{GeV}}\right)^2$$

→ LFV decays of the LSP (from bilinear RPV):

$$\begin{array}{rcl} \tilde{\chi}_1^0 & \rightarrow & W^{\pm} l^{\mp},\ Z\nu \\ \tilde{\chi}_1^0 & \rightarrow & l^{\pm} q \bar{q}',\ q\bar{q}\nu,\ l^+ l^- \nu \end{array}$$

A particulary predictive scenario: bilinear R-parity breaking

(only $\epsilon_i L_i H_u$ present in WRP, and the corresponding soft terms $B_i \epsilon_i \tilde{L}_i H_u$ in the scalar potential)

Parameters: $\epsilon_i, \Lambda_i \ (i = 1, 2, 3)$

where $B_i \ \rightarrow \ v_i \equiv \langle \tilde{\nu}_i \rangle$ (sneutrino vevs) $\rightarrow \ \Lambda_i \equiv \mu v_i + v_d \epsilon_i$

⇒ neutrino masses generated at tree + 1-loop level, with in particular

$$\tan^2\theta_{23} \simeq \left(\frac{\Lambda_2}{\Lambda_3}\right)^2 \qquad \sin^2\theta_{13} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2 + \Lambda_3^2}} \qquad \tan^2\theta_{12} \sim \left|\frac{\epsilon_1}{\epsilon_2}\right|$$

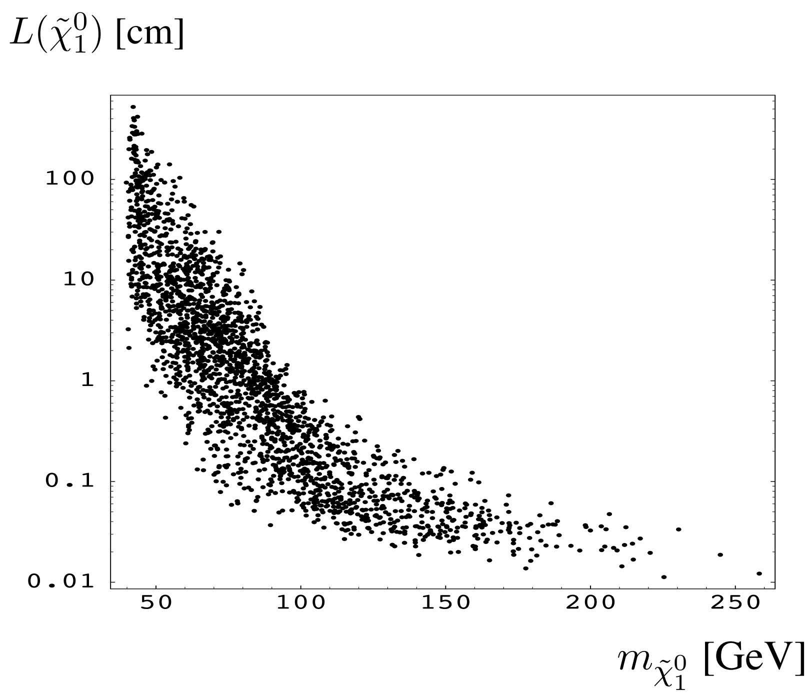
→ the BR's of the LFV decays of the LSP are correlated with the measured oscillation parameters, e.g. [Mukhopadhyaya, Roy Vissani – Hirsch, Porod, Romao, Valle]

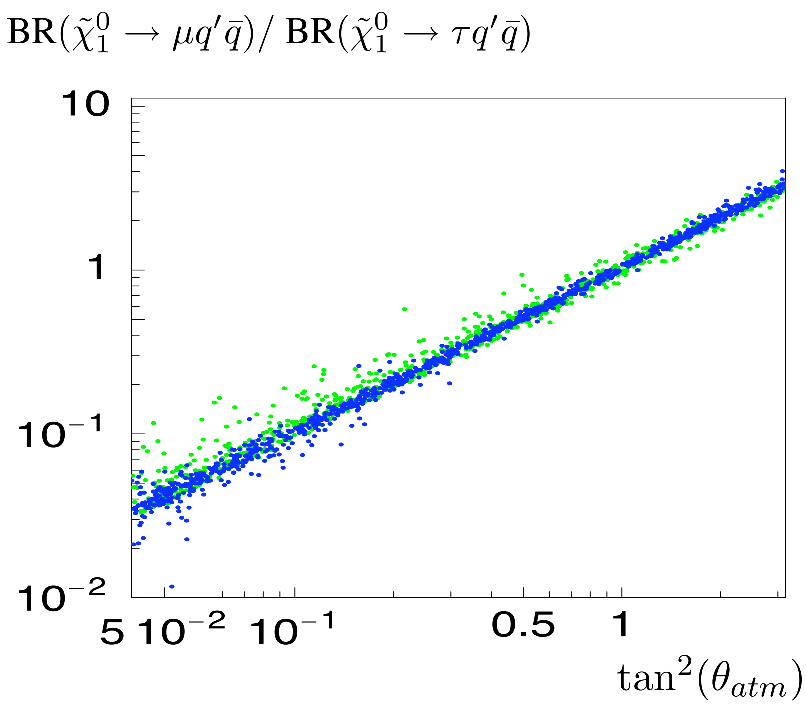
$$\frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \mu^{\pm} W^{\mp})}{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \tau^{\pm} W^{\mp})} \simeq \frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \mu^{\pm} \bar{q} q')}{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \tau^{\pm} \bar{q} q')} \simeq \tan^2\theta_{23}$$

<u>Note</u>: meutrio data requires small R-parity violating couplings

$\Rightarrow$ superpartner production and decays as in the MSSM with R-parity; only difference = LSP decay with a potentially measurable decay length, allowing to identify its decay products

<u>Scan over the MSSM parameters</u>: [Hirsch, Porod, Romao, Valle]





$$L(\tilde{\chi}_1^0) \sim (0.01 - 100)\,\mathrm{cm}$$

$$\frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \to \mu^\pm q' \bar{q})}{\mathrm{BR}\,(\tilde{\chi}_1^0 \to \tau^\pm q' \bar{q})} \approx \tan^2\theta_{23}$$

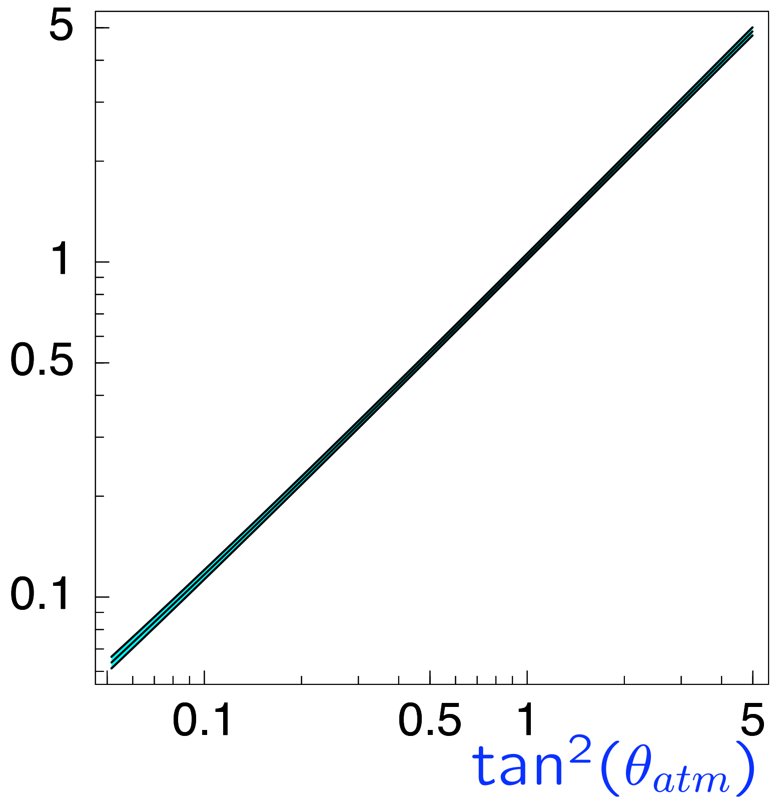
Assume MSSM spectrum known within 10% : [Hirsch, Porod, Romao, Valle]

Parameters: $m_0 = 500\,\mathrm{GeV}, \quad M_2 = 120\,\mathrm{GeV}, \quad \mu = 500\,\mathrm{GeV}$

$A_0 = -500\,\mathrm{GeV}, \quad \tan\beta = 5$

Statistical error: $10^5\ \tilde{\chi}^0_1$

$BR(\tilde{\chi}^0_1 \to \mu q q')/BR(\tilde{\chi}^0_1 \to \tau q q')$



$BR(\tilde{\chi}^0_1 \to e\tau\nu)/BR(\tilde{\chi}^0_1 \to \mu\tau\nu)$