CLFV model constraints from MEG, BELLE/BaBar and LHCb

Stéphane Lavignac (IPhT Saclay)

- introduction
- experimental status of charged lepton flavour violation
- model-independent constraints
- constraints on supersymmetric models
- other examples: warped models, little Higgs

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Introduction

There are good reasons to believe that the Standard Model is an incomplete theory, and to expect New Physics around the TeV scale (dark matter, baryon asymmetry of the universe, hierarchy problem...)

Flavour physics observables are indirectly sensitive to new particles (through their couplings to quarks and leptons) and are therefore complementary to direct searches at colliders:

- provide some information about the flavour structure of new physics (couplings and mixing patterns of new particles which hopefully will be produced some day in a collider)
- sensitive to new physics scales / regions of new physics parameter space that may not be accessible at the LHC

In the quark sector, the data accumulated by K physics experiments and B factories do not show any clear signal of departure from the Standard Model, and put strong constraints on the flavour structure of its extensions

The lepton sector is different from the quark sector in many respects:

1) so far lepton flavour violation (LFV) has been observed only in the neutrino sector ($\nu_\mu \leftrightarrow \nu_e$ violates both Le and Lμ)

2) the SM predicts no observable flavour violation in the charged lepton sector. The observation of any LFV process, e.g. μ → e γ, would be an unambiguous signal of new physics beyond the SM

[one cannot overestimate this advantage - compare with $(g-2)_\mu$]

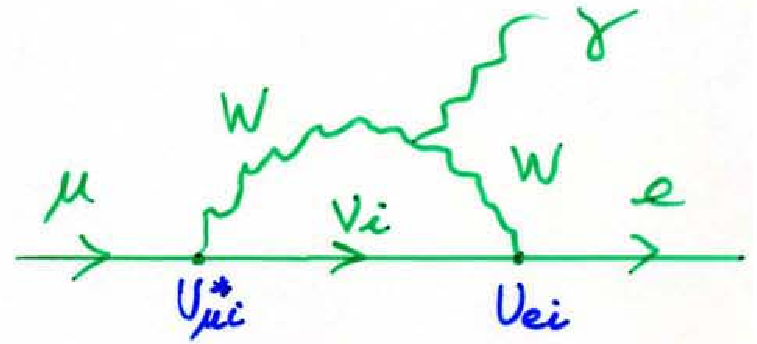
3) if neutrinos are Majorana particles, their masses must be generated by a specific mechanism involving new particles with flavour-violating couplings to leptons. This represents a new source of LFV with respect to the PMNS matrix (assumed to be the only source of LFV in the SM)

This makes lepton flavour violation a good probe of physics beyond the Standard Model (and of the mechanism of neutrino mass generation)

In the Standard Model, the violation of lepton flavour by the charged current does not imply large CLFV rates as a consequence of the GIM mechanism

e.g. $\mu \rightarrow e \gamma$:

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



The m_{ν_i} - independent piece in the loop integral $f(x_i),\ x_i = m^2_{\nu_i}/M^2_W$ drops by virtue of the unitarity of the PMNS matrix: $\sum_i U^*_{\mu i} U_{ei} = 0$

Same mechanism as for hadronic FCNCs, but $m^2_{\nu_i}/M^2_W$ is much smaller than m^2_c/M^2_W in Δm_K

Using known oscillations parameters gives $\mathrm{BR}\,(\mu \to e\gamma) \;\lesssim\; 10^{-54}$: inaccessible to experiment!

Experimental status of CLFV

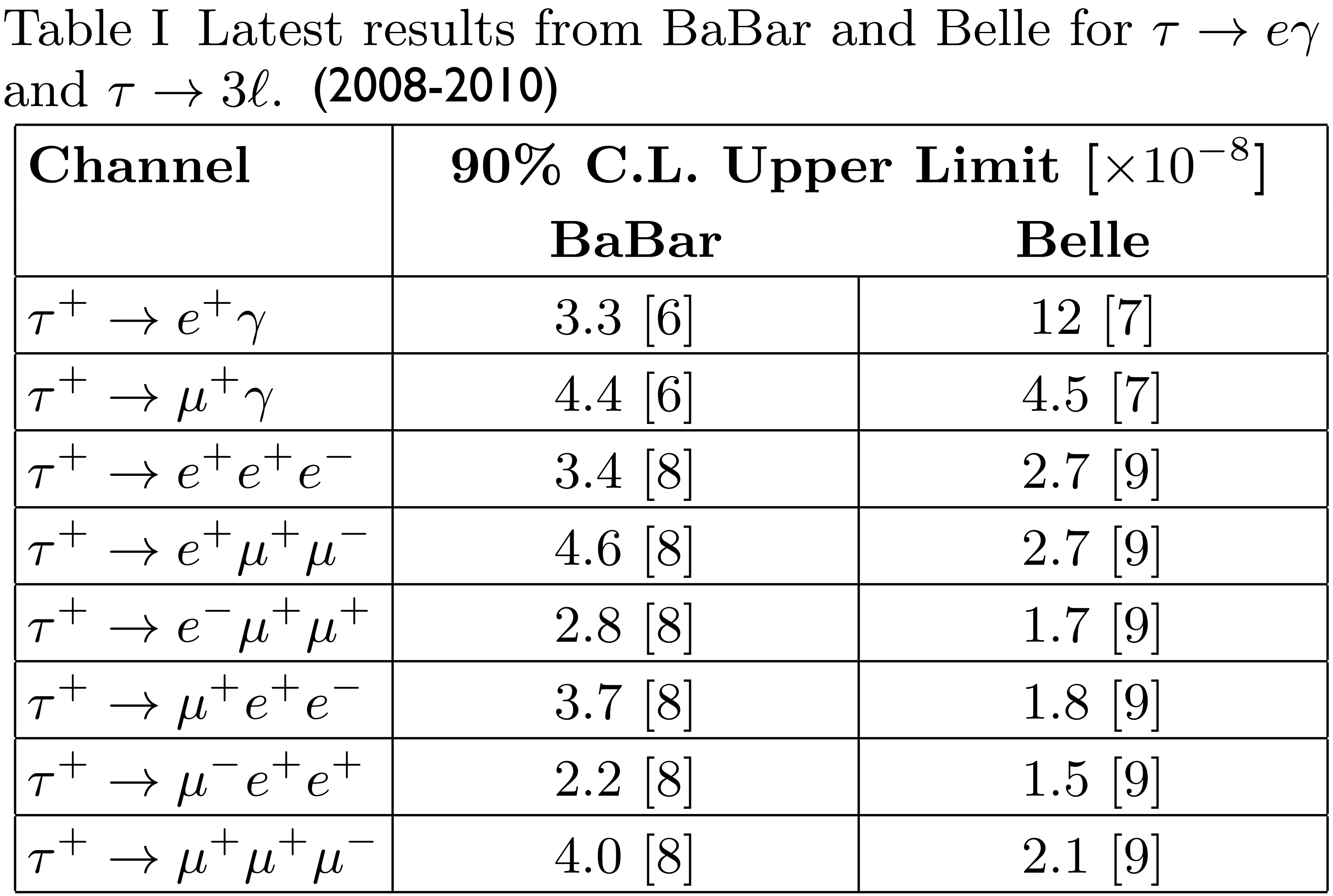


Table I Latest results from BaBar and Belle for $\tau \to e\gamma$ and $\tau \to 3\ell$. (2008-2010)

Channel	**90% C.L. Upper Limit** $[\times 10^{-8}]$	
	BaBar	**Belle**
$\tau^+ \to e^+\gamma$	3.3 [6]	12 [7]
$\tau^+ \to \mu^+\gamma$	4.4 [6]	4.5 [7]
$\tau^+ \to e^+e^+e^-$	3.4 [8]	2.7 [9]
$\tau^+ \to e^+\mu^+\mu^-$	4.6 [8]	2.7 [9]
$\tau^+ \to e^-\mu^+\mu^+$	2.8 [8]	1.7 [9]
$\tau^+ \to \mu^+e^+e^-$	3.7 [8]	1.8 [9]
$\tau^+ \to \mu^-e^+e^+$	2.2 [8]	1.5 [9]
$\tau^+ \to \mu^+\mu^+\mu^-$	4.0 [8]	2.1 [9]

[F. Renga at FPCP 2012, 21-25 May 2012, Heifei, China]

Table II Best available limits on $\tau \to \ell h^0$ decays. **(2009-2011)**

Channel	**90% C.L.** **Upper Limit** $[\times 10^{-8}]$	**Ref.**
$\tau^- \to \mu^- \rho^0$	1.2	Belle [10]
$\tau^- \to e^- \rho^0$	1.8	Belle [10]
$\tau^- \to \mu^- \phi$	8.4	Belle [10]
$\tau^- \to e^- \phi$	3.1	Belle [10]
$\tau^- \to \mu^- \omega$	4.7	Belle [10]
$\tau^- \to e^- \omega$	4.8	Belle [10]
$\tau^- \to \mu^- K^{*0}$	7.2	Belle [10]
$\tau^- \to e^- K^{*0}$	3.2	Belle [10]
$\tau^- \to \mu^- \overline{K}^{*0}$	7.0	Belle [10]
$\tau^- \to e^- \overline{K}^{*0}$	3.4	Belle [10]
$\tau^- \to \mu^- \eta$	3.8	Belle [11]
$\tau^- \to e^- \eta$	3.6	Belle [11]
$\tau^- \to \mu^- \pi^0$	2.2	Belle [11]
$\tau^- \to \mu^- K^0_S$	3.3	BaBar [12]
$\tau^- \to e^- K^0_S$	4.0	BaBar [12]

[F. Renga at FPCP 2012]

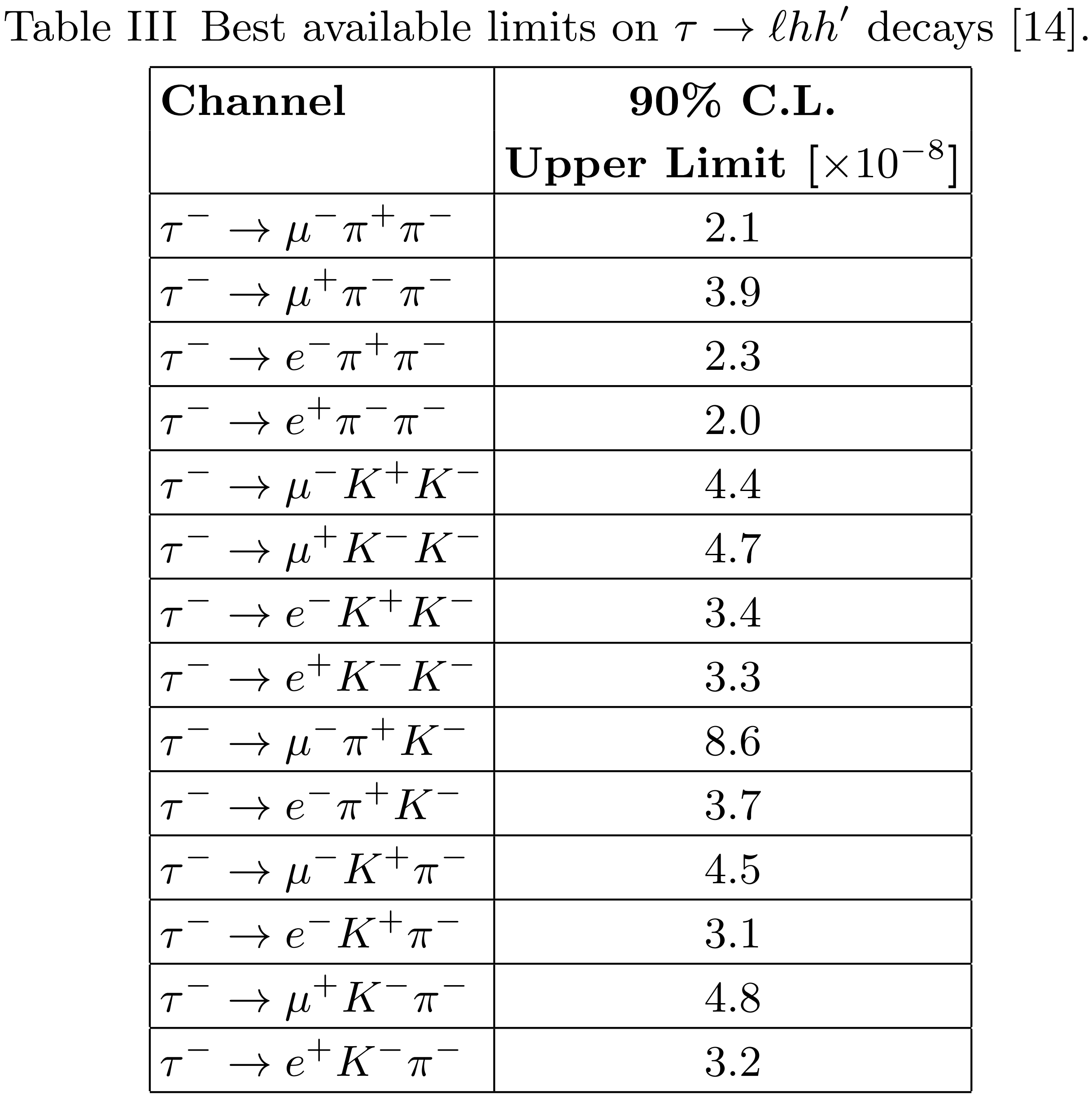


Table III Best available limits on $\tau \to \ell h h'$ decays [14].

Channel	**90% C.L. Upper Limit** $[\times 10^{-8}]$
$\tau^- \to \mu^- \pi^+ \pi^-$	2.1
$\tau^- \to \mu^+ \pi^- \pi^-$	3.9
$\tau^- \to e^- \pi^+ \pi^-$	2.3
$\tau^- \to e^+ \pi^- \pi^-$	2.0
$\tau^- \to \mu^- K^+ K^-$	4.4
$\tau^- \to \mu^+ K^- K^-$	4.7
$\tau^- \to e^- K^+ K^-$	3.4
$\tau^- \to e^+ K^- K^-$	3.3
$\tau^- \to \mu^- \pi^+ K^-$	8.6
$\tau^- \to e^- \pi^+ K^-$	3.7
$\tau^- \to \mu^- K^+ \pi^-$	4.5
$\tau^- \to e^- K^+ \pi^-$	3.1
$\tau^- \to \mu^+ K^- \pi^-$	4.8
$\tau^- \to e^+ K^- \pi^-$	3.2

BELLE at FPCP2012

Searches for tau LFV at LHCb

$$BR(\tau^- \to \mu^+\mu^-\mu^-) < 7.8\,(6.3) \times 10^{-8} \qquad 95\%\,(90\%)\,\mathrm{C.L.}$$

best upper limit at a hadron collider, still less sensitive than BELLE:

$$BR(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8} \qquad (90\%\,\mathrm{C.L.})$$

The upgraded LHCb experiment should reach a few 10^{-9}

Ongoing sensitivity studies for $B_s \to e^-\mu^+,\ D^0 \to e^-\mu^+$

should reach the sensitivity of current B factories

["Implications of LHCb measurements and future prospects", arXiv:1208.3355]

Muon LFV

Table 8.1: Present limits on rare μ decays.

mode	upper 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 of the "Flavour in the Era of the LHC" workshop, arXiv:0801.1826]

updated by MEG (see next slide)

Also strong constraints on LFV rare decays of mesons:

$$
\begin{aligned}
\mathrm{BR}\,(K_L^0 \to \mu e) &< 4.7 \times 10^{-12} \qquad [\mathrm{BNL\ E871}] \\
\mathrm{BR}\,(B_d^0 \to \mu e) &< 1.7 \times 10^{-7} \qquad [\mathrm{Belle}] \\
\mathrm{BR}\,(B_s^0 \to \mu e) &< 6.1 \times 10^{-6} \qquad [\mathrm{CDF}]
\end{aligned}
$$

Latest MEG result (Moriond EW 2013)

Fit results on branching ratio

	Best fit	Upper limit (90% C.L.)	Sensitivity
2009-2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

- ☑ **Upper limit from all combined dataset:**
  - ☑ **$\mathcal{B}<5.7\times10^{-13}$ (90%C.L.)**
- ☑ **×4 more stringent than the present upper limit**

Prospects:

Taking data until summer 2013

MEG upgrade approved in January 2013: expect 5×10^{-14} in 3 years

Prospects for CLFV experiments

μ → e γ :

MEG update should reach 5×10^{-14} in 3 years of acquisition time

μ → eee :

Mu3e proposal at PSI aims at $\mathcal{O}(10^{-16})$ (improvement by 4 orders of magn.)

μ → e conversion in nuclei :

The projects mu2e at FNAL and COMET aim at a sensitivity below 10^{-16}
More ambitious projects under study at FNAL and J-PARC $\mathcal{O}(10^{-18})$

τ decays :

The upgraded LHCb experiment should reach a few 10^{-9} on $\tau \longrightarrow \mu\mu\mu$
Future B factories (KEKB, SuperB) should probe the $10^{-9} - 10^{-10}$ level

Model-independent constraints

Effective Lagrangian approach: add to the SM Lagrangian higher-dimensional LFV operators and constrain their coefficients:

$$\mathcal{O}_{eB}^{ij} = \bar{\ell}_i \sigma^{\mu\nu} e_{Rj} H B_{\mu\nu}, \qquad \mathcal{O}_{eW}^{ij} = \bar{\ell}_i \sigma^{\mu\nu} \tau^I e_{Rj} H W_{\mu\nu}^I.$$

$$\mathcal{O}_{(1)\ell\ell}^{ijkl} = (\bar{\ell}_i \gamma^\mu \ell_j)(\bar{\ell}_k \gamma_\mu \ell_l), \qquad \mathcal{O}_{(3)\ell\ell}^{ijkl} = (\bar{\ell}_i \tau^I \gamma^\mu \ell_j)(\bar{\ell}_k \tau^I \gamma_\mu \ell_l),$$

$$\mathcal{O}_{ee}^{ijkl} = (\bar{e}_i \gamma^\mu P_R e_j)(\bar{e}_k \gamma_\mu P_R e_l), \qquad \mathcal{O}_{\ell e}^{ijkl} = (\bar{\ell}_i e_j)(\bar{e}_k \ell_l).$$

(+ operators involving quarks and leptons)

The most stringent constraints come from $l_i \to l_j \gamma$ (especially $\mu \to e \gamma$), $\mu \to eee$, μ−e conversion and $K_L^0 \to e^- \mu^+$

Examples of constraints:

$\underline{\mu \rightarrow e\, \gamma :}$

$$\frac{C^{M}_{\mu e\gamma}}{\Lambda^2_{NP}} \langle H^0 \rangle\, \bar{e}\sigma^{\mu\nu} P_M \mu\, F_{\mu\nu} \; + \; \text{h.c.}$$

(M = L,R)

The exp. upper bound $\text{BR}\,(\mu \to e\gamma) \; < \; 5.7 \times 10^{-13}$ translates into

$$\Lambda_{NP} \; > \; \begin{cases} 7.8 \times 10^4\, \text{TeV} & (C = 1) \\ 400\, \text{TeV} & (C = \frac{\alpha_W}{4\pi}) \end{cases}$$

$\underline{\mu \rightarrow e\, e\, e :}$

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

(M,N = L,R)

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

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

→ CLFV starts to be sensitive to scales comparable to kaon physics:

$$\Lambda_{\text{NP}} \; \gtrsim \; \begin{cases} 2 \times 10^4\, \text{TeV} & (C = 1) \\ 2 \times 10^3\, \text{TeV} & (C = \frac{\alpha_S}{4\pi}) \end{cases} \qquad \frac{C}{\Lambda^2_{\text{NP}}}\, (\bar{s}d)(\bar{s}d)$$

Impressive constraints but not very informative: the coefficients of the effective operators are combinations of couplings, new particle masses and possible loop factors

Also in a given model cancellations between different contributions may arise (e.g. due to a symmetry)

→ need to consider more explicit theoretical scenarios to fully exploit the experimental data

Constraints on supersymmetric models

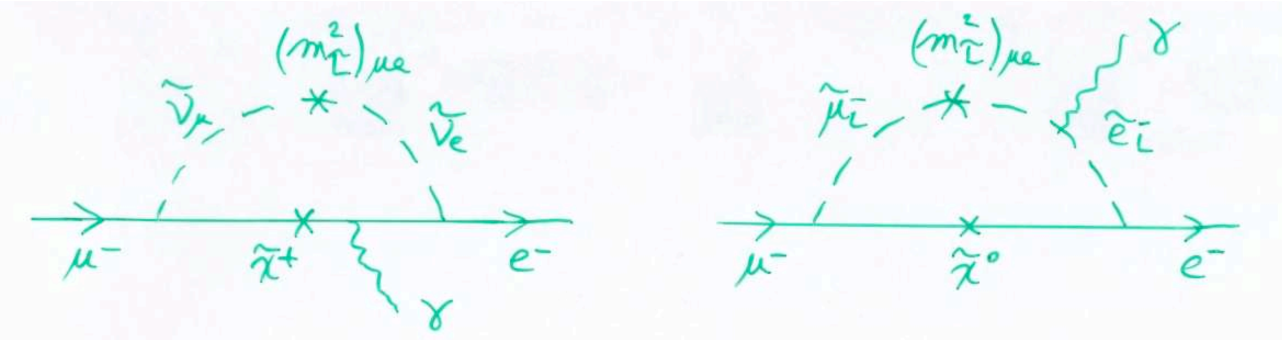
In (R-parity conserving) supersymmetric extensions of the Standard Model, LFV is induced by a misalignment between the lepton and slepton mass eigenstate bases, which can be parametrized by the mass insertion parameters ($\alpha \neq \beta$):

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

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

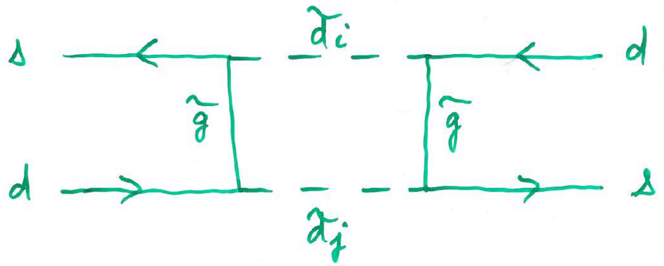
$$\mathrm{BR}\,(\mu \to e\gamma) = \frac{3\pi\alpha^3}{4G_F^2 \cos^4\theta_W} \left\{ \left| f_{LL}\, \delta^{LL}_{12} + f_{LR}\, \delta^{LR}_{12} \right|^2 + \left| f_{RR}\, \delta^{RR}_{12} + f^{\star}_{LR}\, \delta^{LR\star}_{21} \right|^2 \right\} \tan^2\beta$$

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 $\tan^2\beta$



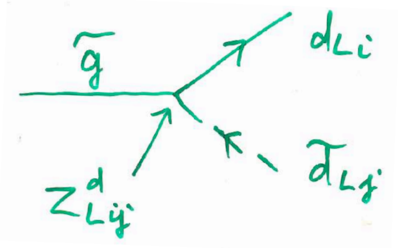
Digression on the mass insertion approximation

In (R-parity conserving) supersymmetric extensions of the Standard Model, potentially large FCNCs are induced by a misalignment between the fermion and sfermion mass eigenstate bases - e.g. for $K^0 - \bar{K}^0$ mixing:



$$\frac{\Delta m_K^{\rm SUSY}}{m_K} \sim \frac{g_S^4}{16\pi^2} \frac{f_K^2}{m_{\tilde g}^2} \sum_{i,j} Z_{is} Z_{id}^* Z_{js} Z_{jd}^* \, g(x_i, x_j) \qquad x_i \equiv \frac{m_{\tilde d_i}^2}{m_{\tilde g}^2}$$

Z = unitary matrix, e.g. $Z_L^d \equiv R_L^d (\tilde R_L^d)^\dagger$, where $R_L^d (\text{resp. } \tilde R_L^d)$ brings the LH down quarks (squarks) to their mass eigenstate basis



$\sum_i Z_{is} Z_{id}^* = 0 \;\Rightarrow\; \Delta m_K^{\rm SUSY} = 0$ for equal squark masses

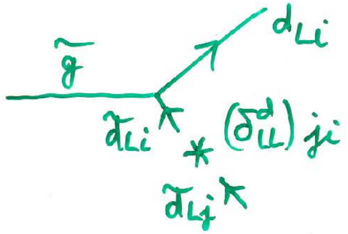
GIM suppression only effective for approximately degenerate squark masses (unless strong squark/gluino mass hierarchy), or small off-diagonal Z entries (”alignement”) [Nir, Seiberg ’93]

Instead of working with flavour off-diagonal gluino couplings, work in the basis in which these couplings are diagonal, but the squark mass matrices are not

Then the FCNC diagrams involve off-diagonal squark propagators, which can be expanded around the diagonal (assuming small off-diagonal masses)

$$\left(\frac{1}{k^2-M^2}\right)_{ij} = \frac{1}{k^2-m_i^2}\delta_{ij} + \frac{1}{k^2-m_i^2} M^2_{ij} \frac{1}{k^2-m_j^2} + \cdots$$

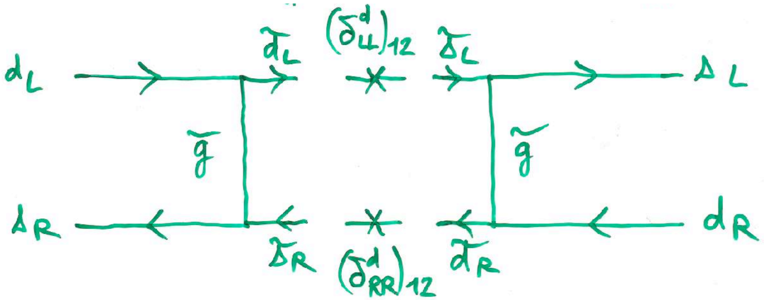
If the m_i are close, one can expand around an average squark mass and introduce mass insertion parameters:



← flavour-violating mass insertion

$$\delta_{ij} \equiv \frac{M^2_{ij}}{\bar m^2}$$

e.g. $K^0 - \bar K^0$ mixing



[Masina, Savoy '02]

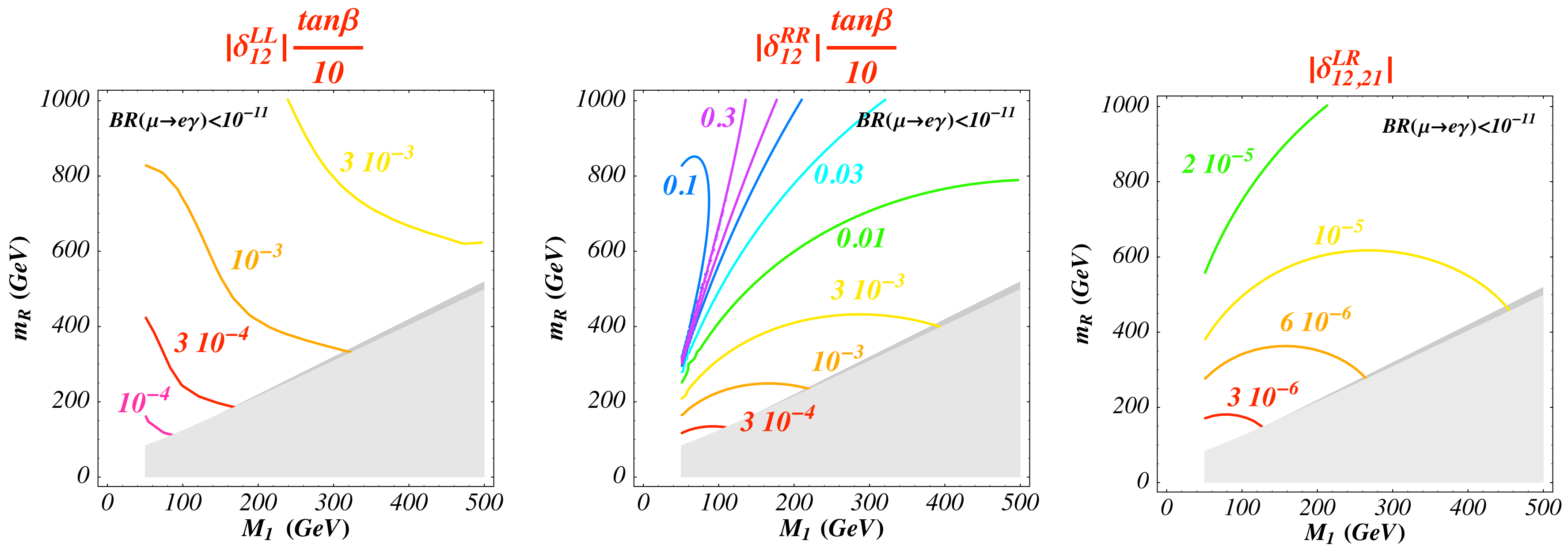


Fig. 5.3: Upper limits on δ_{12}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

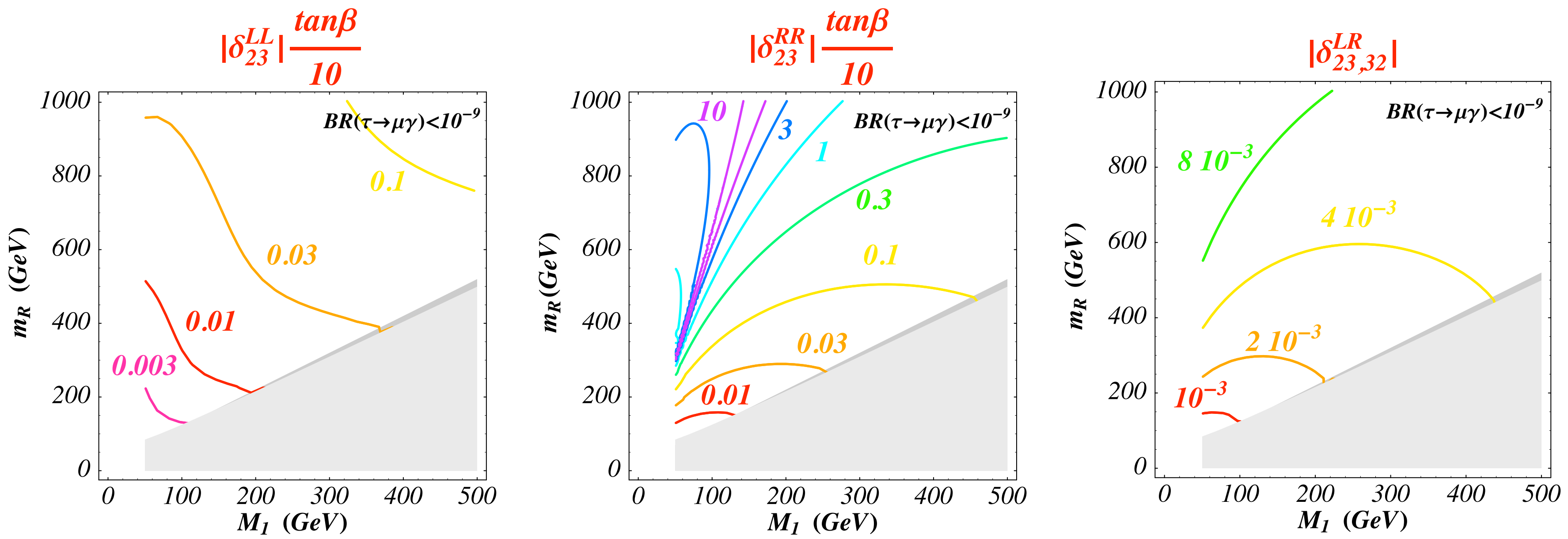


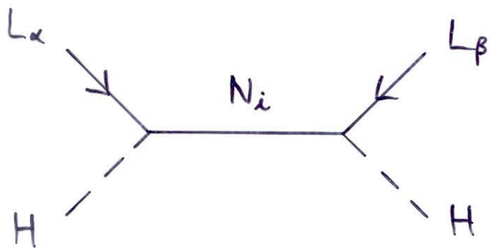
Fig. 5.4: Upper limits on δ_{23}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

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_ν << m_l [Borzumati, Masiero '86]

Most celebrated example: (type I) seesaw mechanism

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



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

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

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

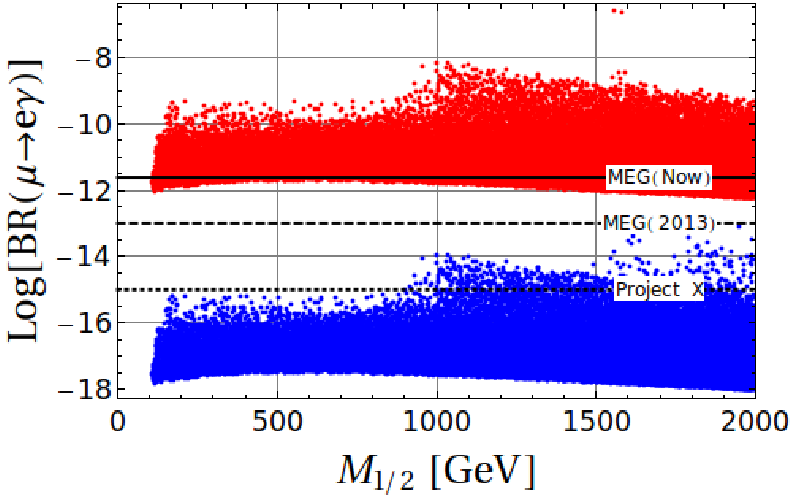
However, due to the large number of (type I) seesaw parameters (18 parameters for 9 physical quantities in the light neutrino sector), there are no generic predictions for CLFV from the supersymmetric seesaw

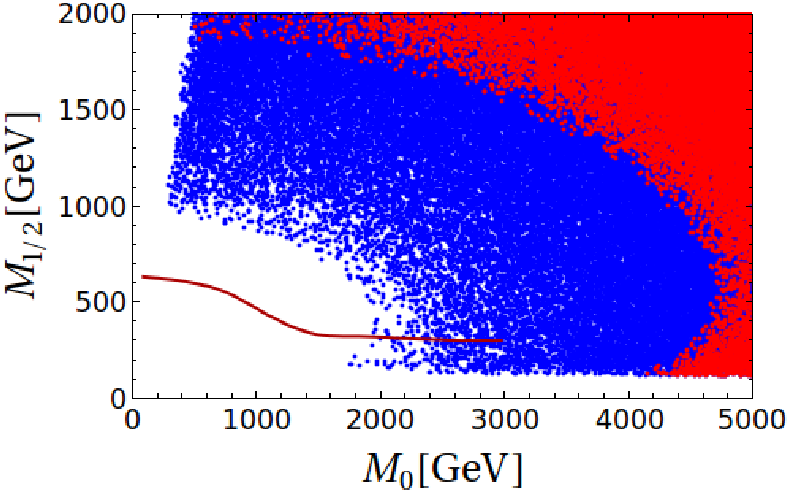
Rather predictions from specific model, e.g. when the seesaw mechanism is embedded in a Grand Unified Theory, or in the presence of flavour symmetries that constrain

Example: SO(10)-inspired mass relations Y = Yu [Calibbi et al., arXiv:1207.7227]

assume equal eigenvalues
but allow different mixings

$$\mathbf{Y}_\nu = \mathbf{Y}_u \qquad \text{(CKM Case)}$$
$$\mathbf{Y}_\nu = \mathbf{Y}_u^{\text{diag}}\,\mathbf{U}_{\text{PMNS}} \qquad \text{(PMNS Case)},$$

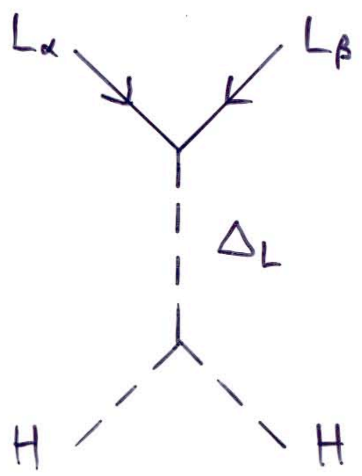




scan over mSUGRA parameters, tan β = 10, $U_{e3} = 0.11$

Other example: type II seesaw mechanism

= heavy scalar SU(2)L triplet exchange



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

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

The radiative corrections to soft slepton masses are now controlled by

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

⇒ predictive (up to an overall scale) and leads to correlations between LFV observables (correlations controlled by the neutrino parameters)

[A. Rossi '02]

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

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

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

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

⇒ 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:

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

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

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

Similar effects (although of different origin) in SO(10) models with type II seesaw [Calibbi, Frigerio, SL, Romanino ’09]

Type II seesaw in non-standard SO(10) unification [Calibbi, Frigerio, SL, Romanino ’09]

Triplet seesaw realized by non-standard embedding of the SM fermions into SO(10) representations:

$$\begin{aligned} 16_i &= 10_i \oplus \;.\; \oplus 1_i \\ 10_i &= \;.\; \oplus \bar{5}_i^{10} \end{aligned}$$

$(5_i^{10}, \bar{5}_i^{16})$ form a (heavy) vector-like pair of matter fields

Triplets contained in a 54-dimensional representation

The squark and slepton soft terms receive flavour-violating radiative corrections from:

- the heavy triplets and their SO(10) partners (components of the 54)
  ⇒ controlled by the fij’s ($f_{ij} 10_i 10_j 54$)
- the heavy quarks and leptons (heavy components of the 16_i and 10_i)
  ⇒ controlled by the up-quark Yukawa couplings ($y_{ij} 16_i 16_j 10$)

→ flavour structure of the radiative corrections predicted in terms of low-energy parameters [up quark and neutrino masses, quark and lepton mixing]

Assuming universal soft terms at the GUT scale, we obtain in the leading-log approximation (in matrix form):

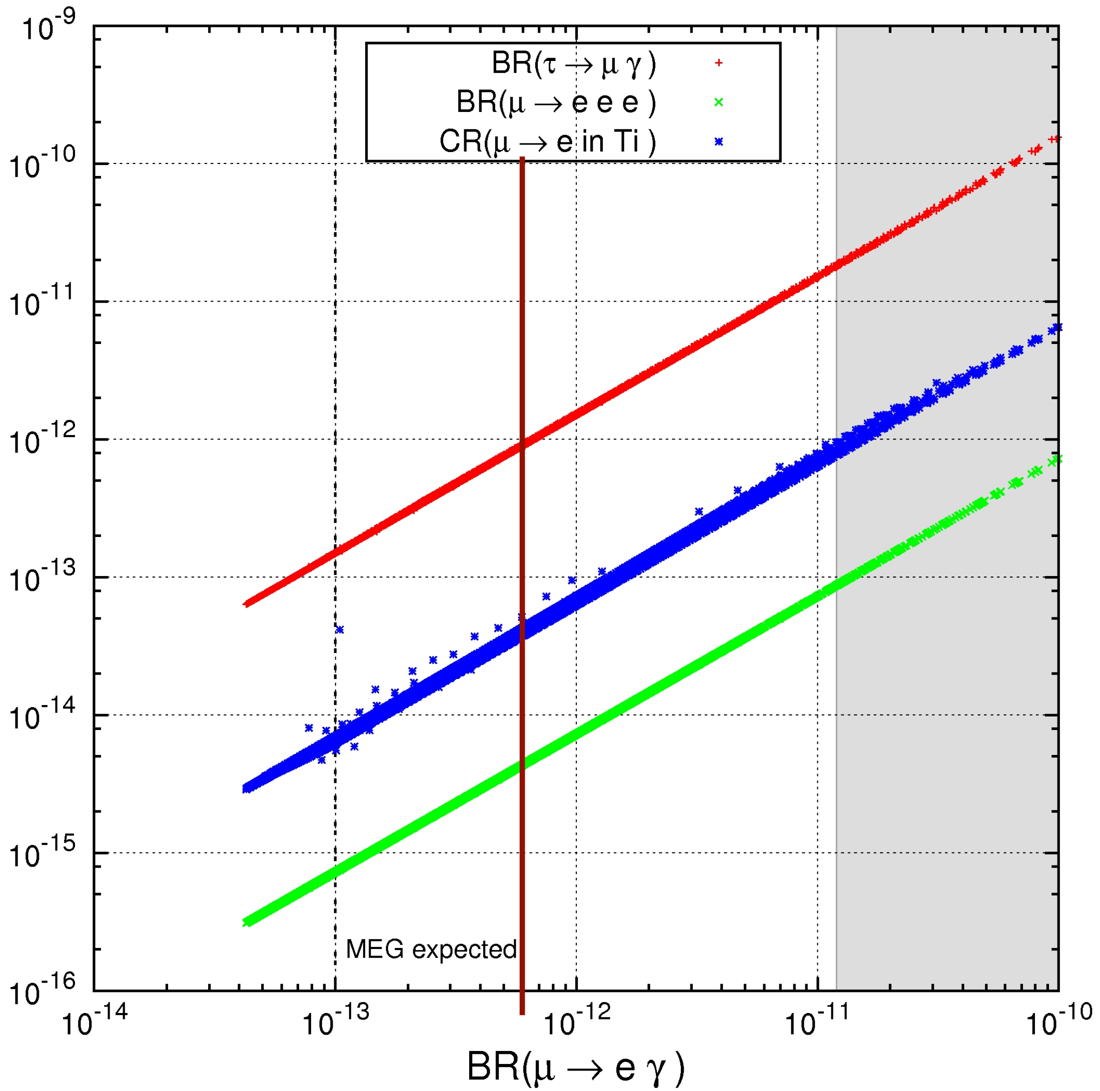
$$
\begin{aligned}
\delta m_L^2 &= -\frac{3m_0^2+A_0^2}{16\pi^2}\, f^\dagger \left(3\ln\frac{M_{\rm GUT}^2}{M_{15}^2} + \frac{9}{10}\ln\frac{M_{\rm GUT}^2}{M_{24}^2+M_{L^c}^T M_{L^c}^*} + \frac{3}{2}\ln\frac{M_{\rm GUT}^2}{M_{24}^2+M_D^T M_D^*}\right) f \\
\delta m_{d^c}^2 &= -\frac{3m_0^2+A_0^2}{16\pi^2}\, f^\dagger \left(3\ln\frac{M_{\rm GUT}^2}{M_{15}^2} + \ln\frac{M_{\rm GUT}^2}{M_{24}^2+M_{L^c}^\dagger M_{L^c}} + \frac{7}{5}\ln\frac{M_{\rm GUT}^2}{M_{24}^2+M_D^\dagger M_D}\right) f
\end{aligned}
$$

The first term in the bracket is present in the SU(5) version of the type II seesaw [A. Rossi], the next two are due to the presence of the heavy quarks and leptons

Contrary to the standard type II seesaw, flavour violation is also induced in the singlet slepton and doublet squark sectors:

$$
\begin{aligned}
\delta m_{e^c}^2 &= -\frac{3m_0^2+A_0^2}{16\pi^2}\,\cos^2\theta_H\, y^\dagger \left(2\ln\frac{M_{\rm GUT}^2}{M_{L^c}^* M_{L^c}^*}\right) y \\
\delta m_Q^2 &= -\frac{3m_0^2+A_0^2}{16\pi^2}\,\cos^2\theta_H\, y^\dagger \left(\ln\frac{M_{\rm GUT}^2}{M_D M_D^\dagger}\right) y
\end{aligned}
$$

δm_Q^2 has the same flavour structure as the MSSM radiative corrections



— τ → μ γ

— μ Ti → e Ti

— μ → e e e

Correlations between μ → e γ and other LFV processes

(triplet parameters fixed, scan over $m_0 < 3\,\mathrm{TeV},\ M_{1/2} < 2\,\mathrm{TeV}$,

$A_0 = 0, \tan\beta = 10, \mu > 0$)

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

⇒ 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]

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

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

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

⇒ 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)

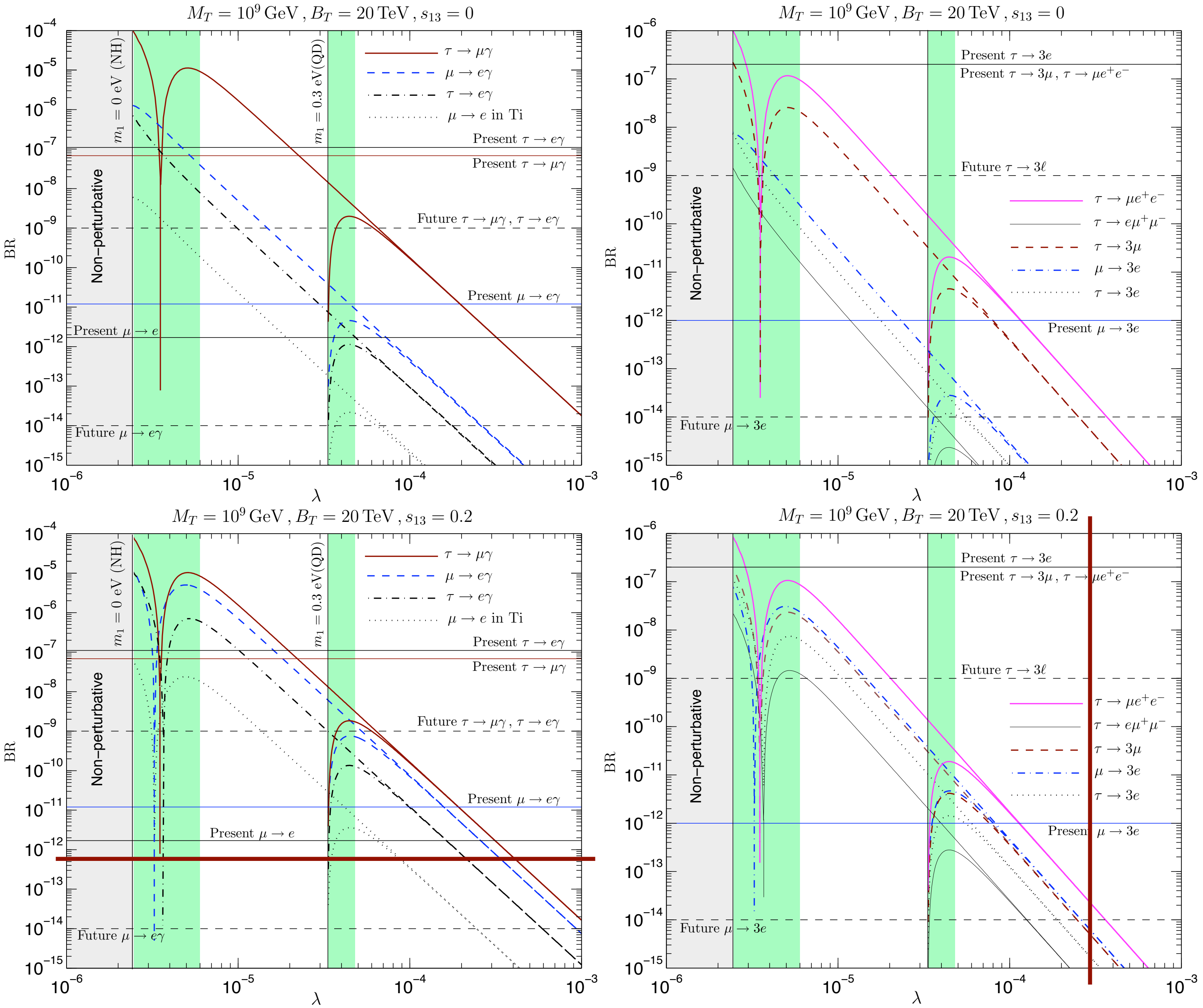
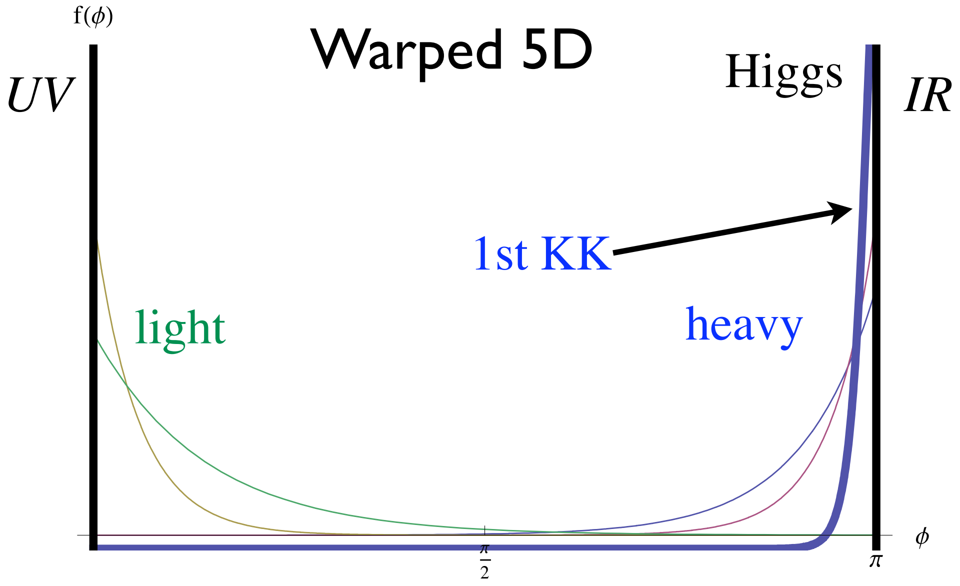


Fig. 5.28: Branching ratios of several LFV processes as a function of λ. The left (right) vertical line indicates the lower bound on λ imposed by requiring perturbativity of the Yukawa couplings $Y_{T,S,Z}$ when $m_1 = 0\,(0.3)$ eV [normal-hierarchical (quasi-degenerate) neutrino mass spectrum]. The 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



Flavour-violating couplings of light fermions to Kaluza-Klein excitations of neutral gauge bosons ⇒ tree-level FCNCs

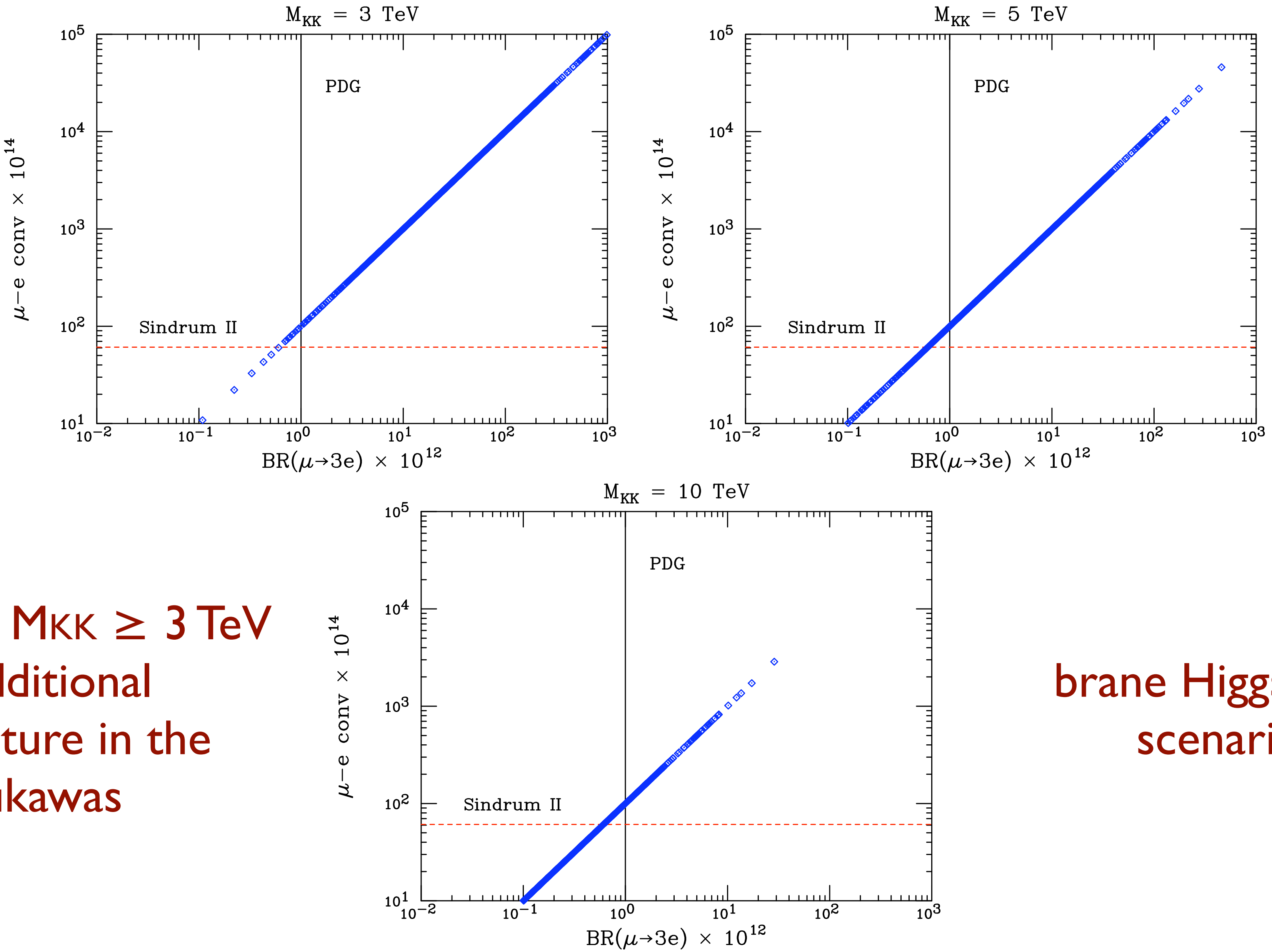
Milder flavour violation in warped (Randal-Sundrum) models in which the fermion mass hierarchies are accounted for by different profiles in the extra dimension (small overlap of light fermions with gauge boson KK wavefunction) → "RS-GIM" mechanism

Agashe, Blechman, Petriello '06: 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)]

scan over 5d Yukawa couplings :

[Agashe, Blechman, Petriello]

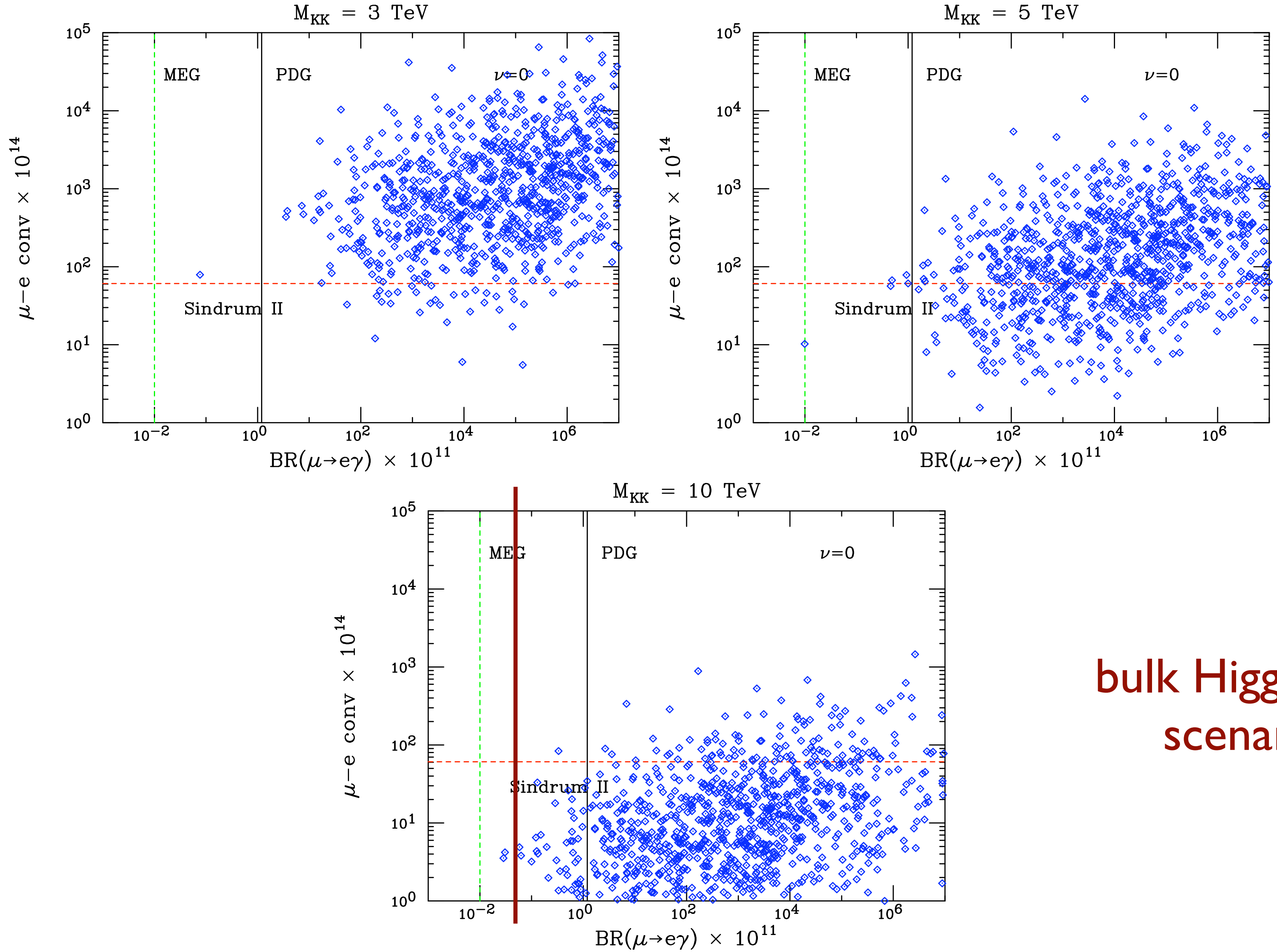


need MKK ≥ 3 TeV or additional structure in the 5d Yukawas

brane Higgs field scenario

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]



bulk Higgs field scenario

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 (LHT)

Blanke, Buras, Duling, Recksiegel, Tarantino ’07

Higgs boson as a pseudo-Goldstone boson of a spontaneously broken global symmetry

- global symmetry breaking SU(5) → SO(5) at 1 TeV
- enlarged gauge symmetry $[SU(2)xU(1)]^2 \Rightarrow$ new heavy gauge bosons
- 3 generation of heavy (TeV) mirror leptons
- T-parity protects EW precision observables

Origin of LFV: flavour-violating 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

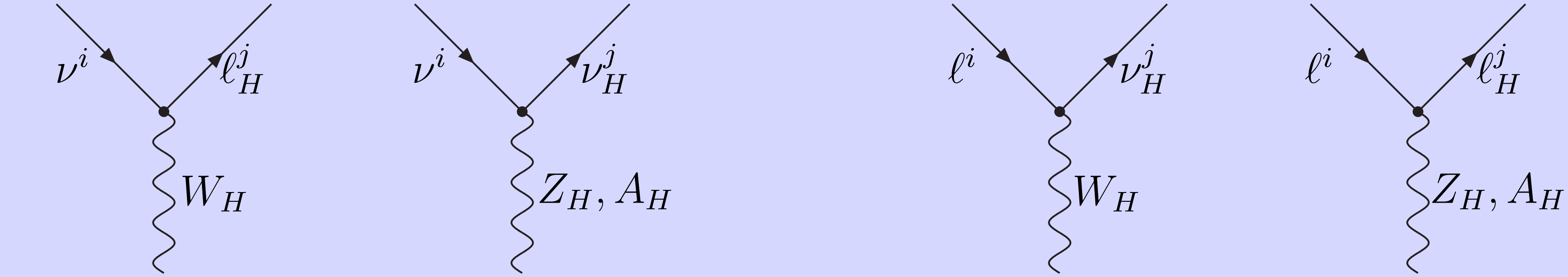
Generally find large rate ⇒ constraints on the mirror lepton parameters (quasi-degenerate masses or hierarchical V_{Hl})

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

[Monika Blanke]

Hubisz, Lee, Paz, hep-ph/0512169
Choudhury et al., hep-ph/0612327
MB, Buras, Duling, Poschenrieder, Tarantino, hep-ph/0702136

new **flavour mixing matrices $V_{H\nu}$, $V_{H\ell}$** parameterize **mirror lepton interactions with SM ν, ℓ**



$$\sim (V_{H\nu})_{ji}\gamma^\mu P_L \qquad \sim (V_{H\nu})_{ji}\gamma^\mu P_L \qquad \sim (V_{H\ell})_{ji}\gamma^\mu P_L \qquad \sim (V_{H\ell})_{ji}\gamma^\mu P_L$$

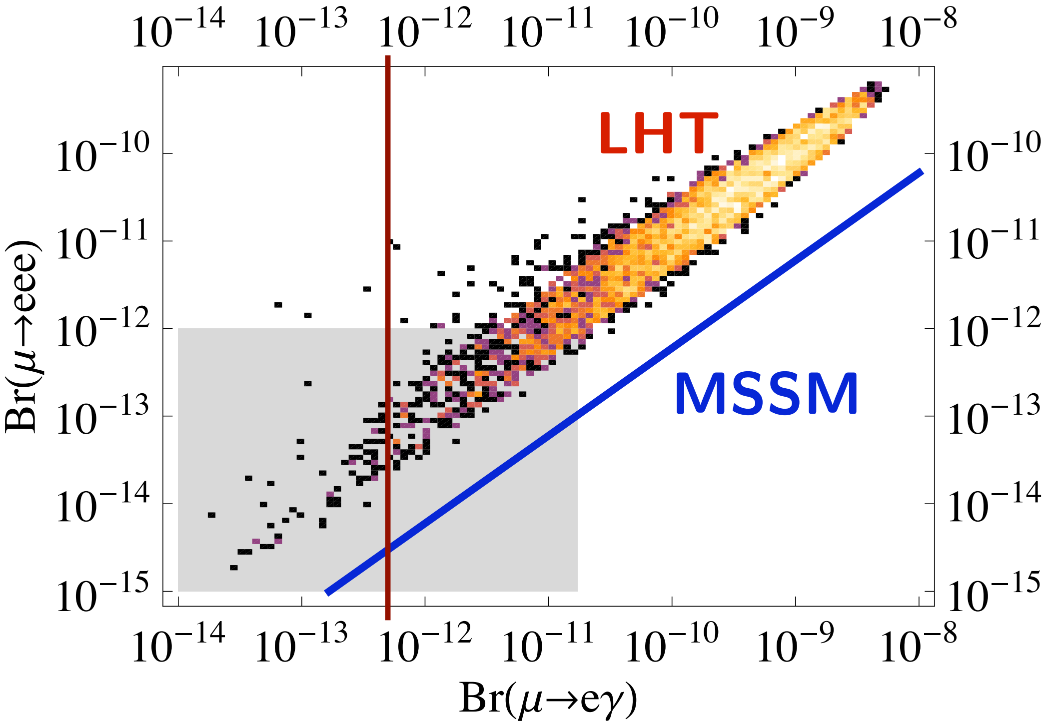
new source of flavour and CP violation!

flavour mixing matrices related through

$$\boxed{V^\dagger_{H\nu} V_{H\ell} = V^\dagger_{\text{PMNS}}}$$

[Monika Blanke]

Blanke, Buras, Duling, Recksiegel, Tarantino ’07



- most points exceed experimental bounds : $\sim$ **10% fine-tuning** in mirror lepton parameters required

  DEL AGUILA, ILLANA, JENKINS, 0811.2891

- **strong correlation** between $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$
- **dipole contribution** fully negligible $\neq$ **MSSM**

Blanke, Buras, Duling, Recksiegel, Tarantino ’07

Ratios of LFV Branching Ratios

BBDRT, 0903.xxxx

	LHT	**MSSM**
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$ ❇
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$ ❇
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$

❇ can be significantly enhanced by Higgs contributions

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

Conclusions

- lepton flavour violation in the charged lepton sector is a unique probe of new physics: the observation of CLFV processes would definitely testify for physics beyond the Standard Model
- present experimental data already severely constrain many theoretical scenarii, in particular extra-dimensional models (KK masses beyond 10 TeV or some structure in the 5d Yukawas)
- supersymmetry suffers from the supersymmetric flavour problem. Assuming supersymmetry breaking is flavour blind, radiative corrections from heavy states are strongly constrained