Lepton flavour violation and leptogenesis

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- (charged) lepton flavour violation
- neutrinos and the matter-antimatter asymmetry of the Universe : leptogenesis

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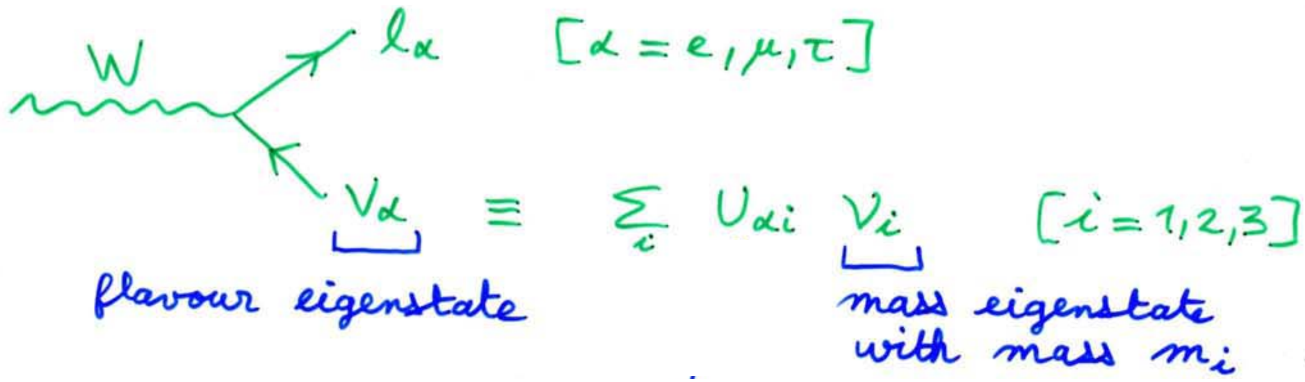
Lepton flavour violation (LFV)

We know that flavour is violated in the lepton sector, since neutrinos oscillate ($\nu_\mu \leftrightarrow \nu_e$ violates both Le and Lμ)



Since the PMNS matrix U appears in charged lepton current, would naively expect strong flavour-violating effects in the charged lepton sector too (i.e. processes such as $\mu \to e\,\gamma$ and $\mu \to 3e$ should be observed).

This is not the case due to a GIM mechanism: LFV is strongly suppressed (and in practice unobservable) in the Standard Model

But we have good reasons to believe that there is new physics beyond the SM (neutrino masses, dark matter...) $\Rightarrow$ generally new sources of LFV

Indeed, many well-motivated new physics scenarios predict large flavour violations in the charged lepton sector:

- supersymmetry
- low-scale neutrino mass models
- extra dimensions / composite Higgs models
- ...

→ the absence of sizeable SM contributions makes LFV a unique probe of new physics

<u>Further motivation:</u> connection with neutrino physics

The smallness of neutrino masses suggests a specific mechanism of mass generation ⇒ new particles with flavour violating couplings to leptons

→ LFV could tell us something about the origin of neutrino masses

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:

[S. Davidson, talk at Planck 2022]

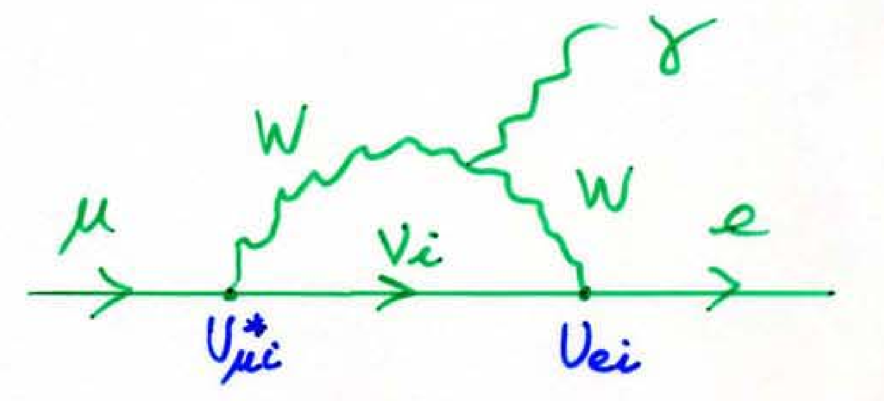
some processes	current constraints on BR	future sensitivities
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$	6×10^{-14} (MEG)
$\mu \to e\bar{e}e$	$< 1.0 \times 10^{-12}$ (SINDRUM)	10^{-16} (202x, Mu3e)
$\mu A \to eA$	$< 7 \times 10^{-13}$ Au, (SINDRUMII)	$10^{-(16\to?)}$ (Mu2e,COMET)
		$10^{-(18\to?)}$ (PRISM/PRIME/ENIGMA)
$K^+ \to \pi^+\bar{\mu}e$	$< 1.3 \times 10^{-11}$ (E865)	10^{-12} (NA62)
...		
$B^+ \to \bar{\mu}\nu$	$< 1.0 \times 10^{-6}$ (Belle)	$\sim 10^{-7}$ (BelleII)

$\mu A \to eA \equiv \mu$ in $1s$ state of nucleus A converts to e

some processes	current constraints on BR	future sensitivities
$\tau \to \ell\gamma$	$< 3.3, 4.4 \times 10^{-8}$	few$\times 10^{-9}$ (Belle-II)
$\tau \to 3\ell$	$< 1.5 - 2.7 \times 10^{-8}$	few$\times 10^{-9}$(Belle-II, LHCb?)
$\tau \to \ell\{\pi, \rho, \phi, K, ...\}$	$\lesssim$ few $\times 10^{-8}$	few$\times 10^{-9}$ (Belle-II)
$\tau \to ...$		
$h \to \tau^{\pm}\ell^{\mp}$	$< 1.5, 2.2 \times 10^{-3}$(ATLAS/CMS)	
$h \to \mu^{\pm}e^{\mp}$	$< 6.1 \times 10^{-5}$(ATLAS/CMS)	
$Z \to e^{\pm}\mu^{\mp}$	$< 7.5 \times 10^{-7}$(ATLAS)	

[S. Davidson, talk at Planck 2022]

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), 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)

Theoretical expectations/predictions

Many new physics scenarios predict "large" LFV rates: supersymmetry, low-scale neutrino mass models, extra dimensions / composite Higgs models…

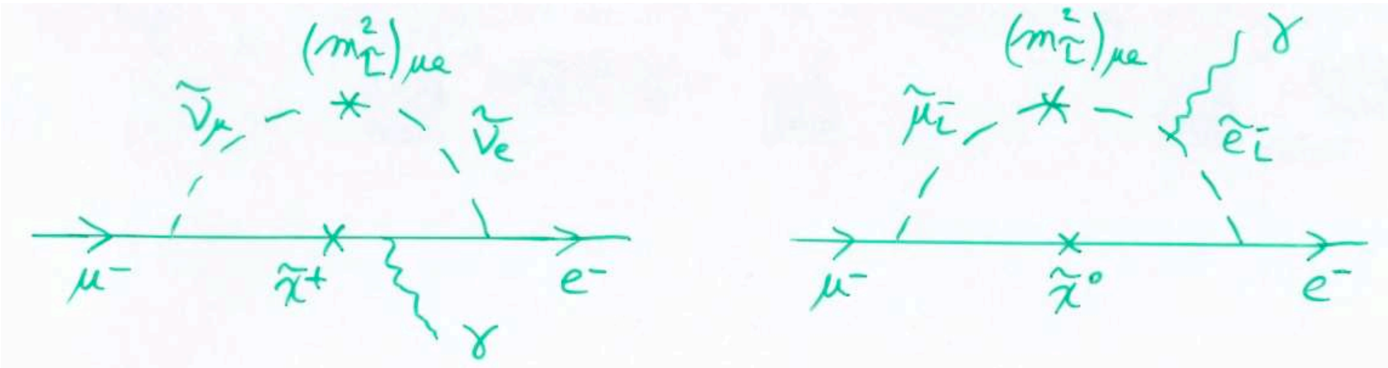
In (R-parity conserving) supersymmetric extensions of the Standard Model, LFV is induced by a misalignment between the lepton and slepton mass matrices, parametrized by the mass insertion parameters ($\alpha \neq \beta$):

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

(can be viewed as supersymmetric lepton mixing angles)

$\Rightarrow$ typical $\mu \to e\,\gamma$ rate: $B(\mu \to e\gamma) \sim 10^{-5}\, \frac{M_W^4}{M_{SUSY}^4}\, |\delta^{LL}_{12}|^2 \tan^2\beta$

where $\tan\beta \equiv \langle H^0_u \rangle / \langle H^0_d \rangle$



Bounds on LFV processes translate into upper limits on the slepton mass insertion parameters as a function of superpartner masses

Case of supersymmetric seesaw mechanism : even if slepton mass matrices are flavour diagonal at some high scale (« flavour-blind » supersymmetry breaking), radiative corrections induced by the heavy Majorana neutrinos may induce large LFV [Borzumati, Masiero]

To a good approximation, these corrections are proportional to the combinations of seesaw parameters $C_{\alpha\beta} \equiv \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$ (assuming universal slepton masses at M_U)

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

In general, however, cannot disentangle the seesaw-induced LFV from the LFV induced by supersymmetry breaking. In addition, there is no direct relation between the measured neutrino parameters and the seesaw-induced LFV, due to the degeneracy of seesaw parameters

It is therefore fair to say that there is no model-independent prediction of the supersymmetric (type I) seesaw mechanism for LFV processes

The supersymmetric seesaw mechanism often predicts large LFV rates

Example [Masiero, Vempati, Vives]: SO(10)-motivated ansätze for the seesaw parameters

“minimal case”: CKM-like mixing in the Dirac couplings Yij

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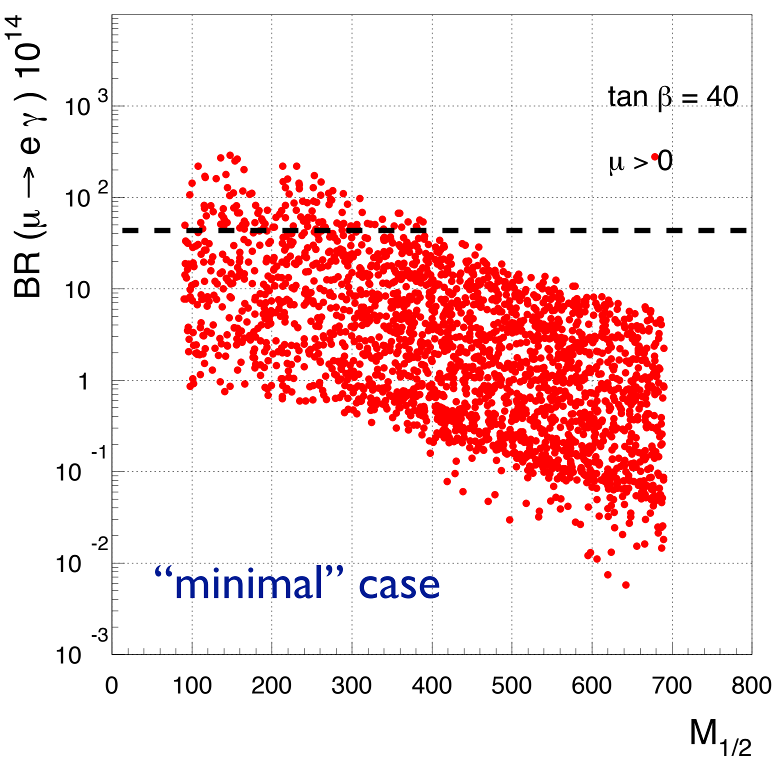
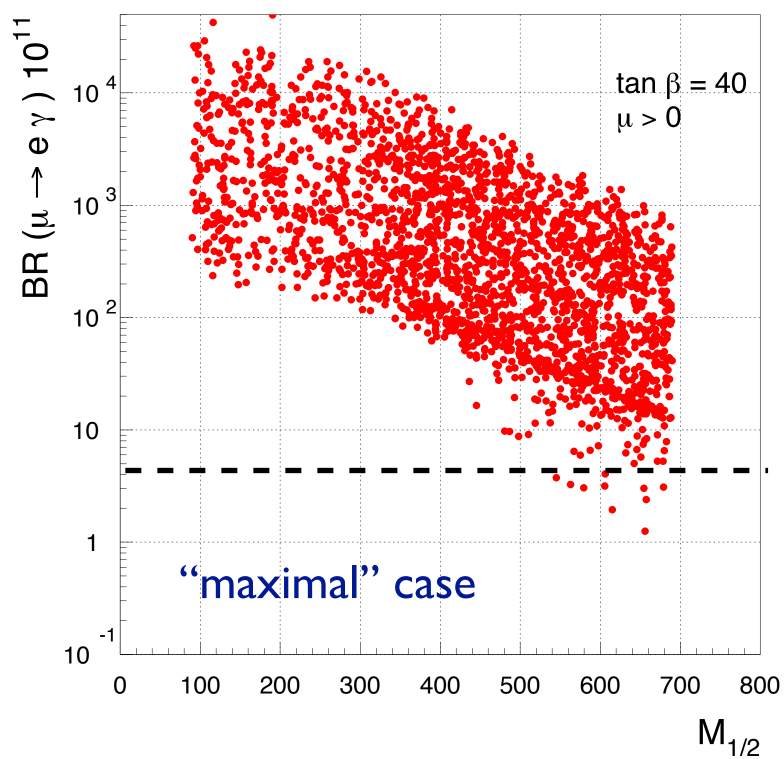
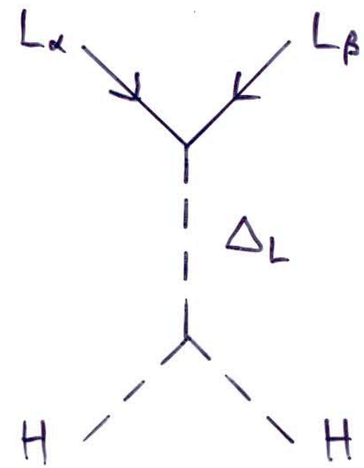




More predictive version of the seesaw mechanism:

Type II seesaw [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 overall scale) and leads to correlations between LFV observables (correlations controlled by the neutrino parameters)

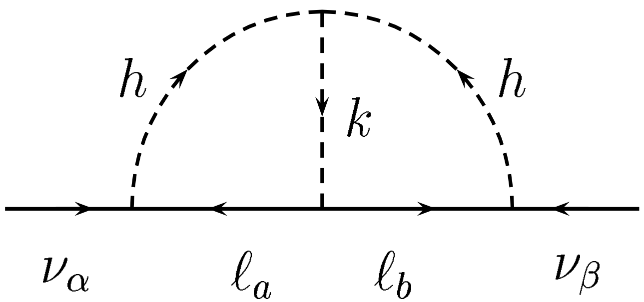
[A. Rossi]

LFV in non-supersymmetric mechanisms of neutrino mass generation

<u>Example of a radiative model: Zee-Babu model</u>

introduce 2 charged SU(2) singlet scalars, h^+ and k^{++}, with couplings to leptons:

$$f_{\alpha\beta}\, L_\alpha^T C i\sigma^2 L_\beta h^+ + h'_{\alpha\beta} e_{R\alpha}^T C e_{R\beta} k^{++} + \text{h.c.}$$



Lepton number is violated by scalar couplings: $\mu\, h^+ h^+ k^{--} + \text{h.c.}$

Neutrino mass matrix: $(M_\nu)_{\alpha\beta} \sim \dfrac{8\mu}{(16\pi^2)^2 m_h^2}\, f_{\alpha\gamma} m_{e_\gamma} h_{\gamma\delta} m_{e_\delta} f_{\delta\beta}$

In addition to new exotic scalars, this mechanism predicts flavour-violating processes involving charged leptons, such as $\mu \to e\,\gamma$:

$$Br(\mu \to e\gamma) \simeq 4.5 \cdot 10^{-10} \left(\frac{\varepsilon^2}{h_{\mu\mu}^2 \mathscr{I}(r)^2}\right)\left(\frac{m_\nu}{0.05\ \text{eV}}\right)^2 \left(\frac{100\ \text{GeV}}{m_h}\right)^2$$

$\epsilon \equiv f_{e\tau}/f_{\mu\tau}$

$\mathcal{J}(r)$ = loop function

Example of a low-scale seesaw model: inverse seesaw

Conventional type I seesaw: loop contribution of the heavy Majorana neutrinos to $\mu \to e\,\gamma$ are suppressed by the large Majorana masses and/or by the small Dirac couplings

$$m_\nu \sim Y_N \frac{1}{M_N} Y_N^T v^2 \qquad \Gamma(\mu \to e\gamma) \propto Y_N^4 \frac{m_\mu^5}{M_N^4} \text{ very suppressed!!}$$

Inverse seesaw :

$$\begin{array}{c|ccc} & \nu_L & N_1 & N_2 \\ \hline \nu_L & & & \\ N_1 & & \left(\begin{array}{ccc} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & \mu \end{array}\right) & \\ N_2 & & & \end{array} \qquad L_{N_1} = +1\,,\ L_{N_2} = -1$$

soft L breaking

$$m_\nu = -Y_N^T \frac{\mu}{M_N^2} Y_N\, v^2 \sim 0.1\,\mathrm{eV}$$

can have Y large and M not too high

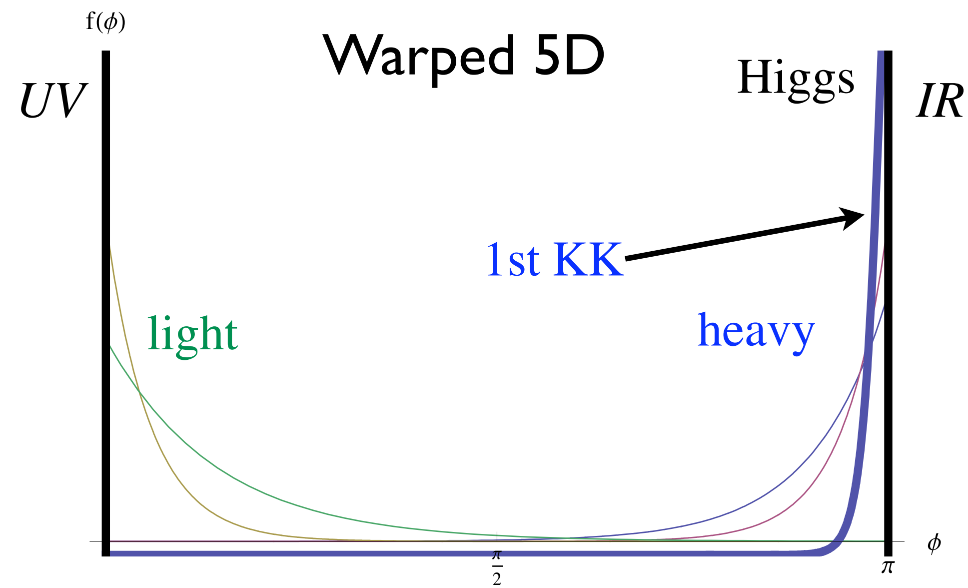
thanks to the small L-violating μ

$Br(\mu \to e\gamma)$ unsuppressed by Y_N nor M_N

[Abada, Biggio, Bonnet, Gavela, Hambye '07]

LFV in extra-dimensional scenarios

Source of flavour violation = couplings of light fermions to Kaluza-Klein excitations

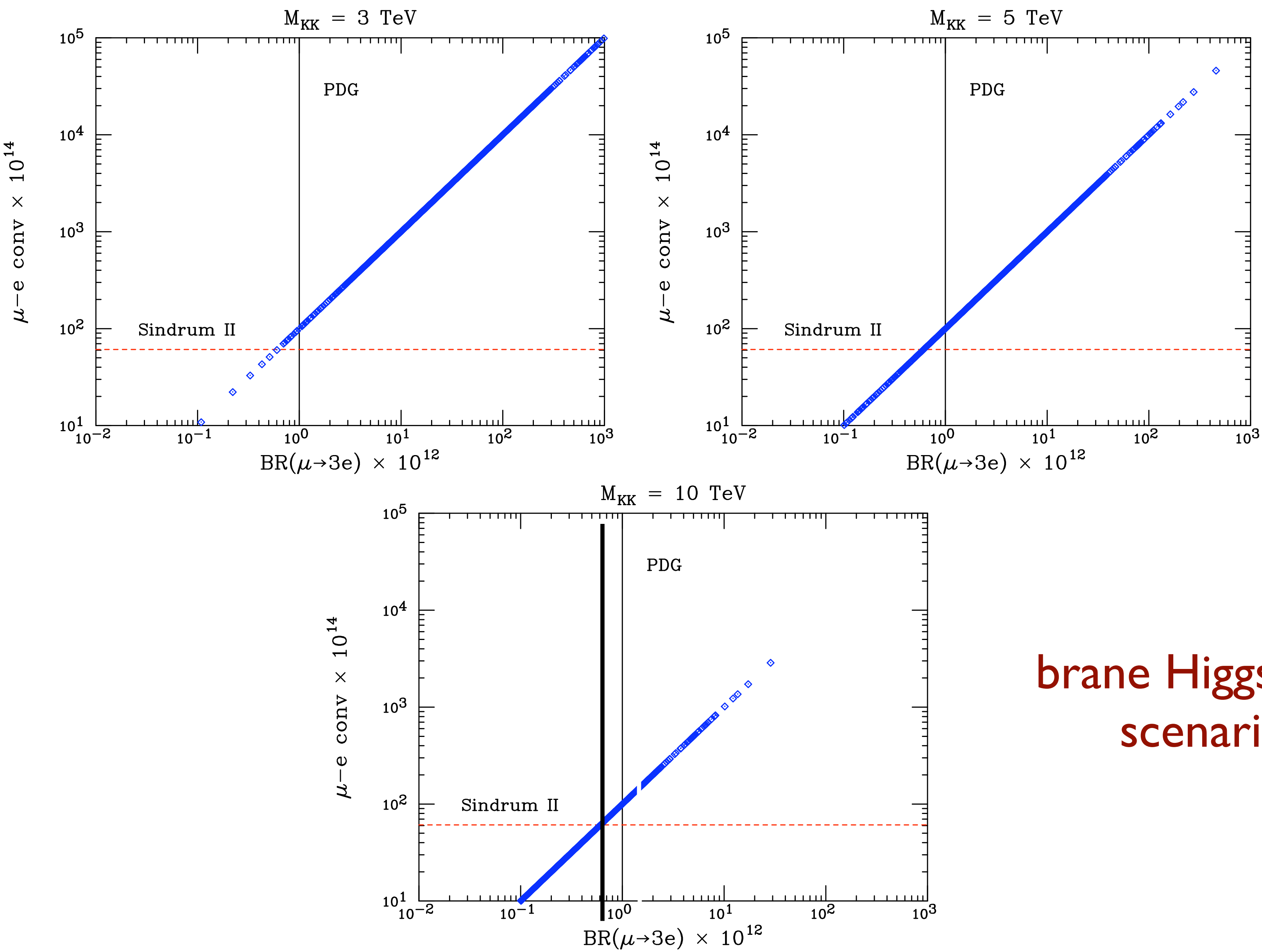


Milder flavour violation in warped (Randal-Sundrum) models in which the fermion mass hierarchies are accounted for by different fermion localizations in extra dimensions (small overlap with KK wavefunction)

Agashe, Blechman, Petriello: RS model with Higgs propagating in the bulk or localized on the IR brane (li → lj γ UV sensitive if Higgs localized on the IR brane)

Present bounds on LFV processes compatible with O(1 TeV) KK masses if Higgs localized on the IR brane, essentially excluded by μ → e γ up to 10 TeV KK masses if propagates in the bulk

[Agashe, Blechman, Petriello]



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.