Lepton Flavor Violation
(Theory)

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Introduction

In the **Standard Model**, three copies of the leptonic SU(2) doublet are introduced

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Gauge and Yukawa interactions

✘

Is lepton flavor a conserved quantity?

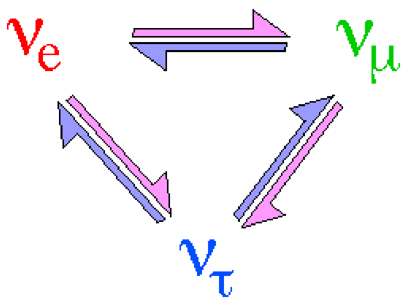
Neutrino oscillations: LFV

We already know the answer: NO

Neutrino oscillations: If neutrinos with definite flavor are not mass eigenstates, they oscillate in their propagation

$$|i\rangle = |\nu_e\rangle \quad \to \text{ Propagation } \to \quad |f\rangle = C_e|\nu_e\rangle + C_\mu|\nu_\mu\rangle + C_\tau|\nu_\tau\rangle$$

$$P(\nu_e \to \nu_i) \simeq \sin^2\theta_{ei}\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



What about cLFV?

Note: LFV ≠ Lepton Flavor in Vienna

In conclusion, lepton flavor is **not** conserved: there is **lepton flavor violation (LFV)**

However... what about **charged lepton flavor violation (cLFV)**?

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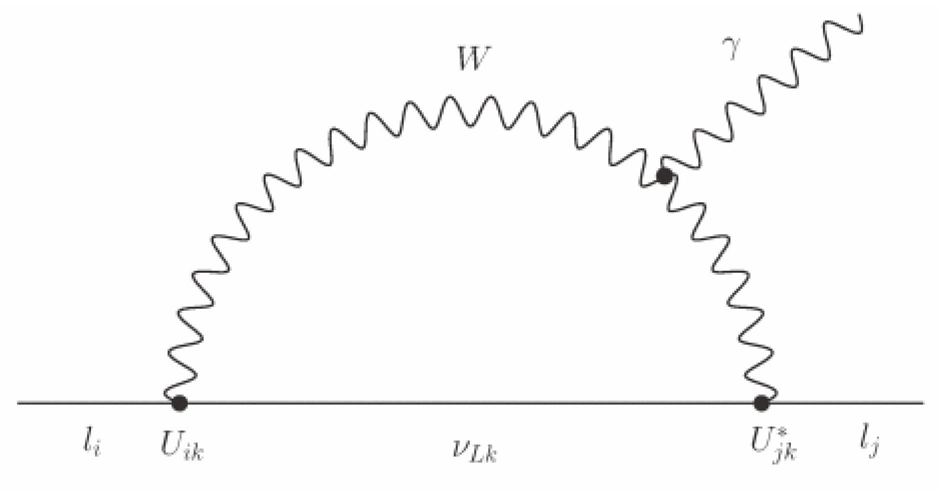
SM + neutrino masses



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_k U_{ek} U^*_{\mu k} \frac{m^2_{\nu k}}{m^2_W} \right|^2 \lesssim 10^{-54}$$

Since neutrino masses are the only source of LFV, all cLFV amplitudes are strongly suppressed (in fact, GIM suppressed)

Why do we care about LFV?

The observation of cLFV would be a clear signal of physics beyond the Standard Model

In fact, most BSM models predict large cLFV rates

$$\mathcal{O} = \frac{c_{e\mu}}{\Lambda^2}\,\bar{\mu}e\bar{e}e \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{c_{e\mu}}} \gtrsim 100\,\text{TeV}$$

The emphasis is put on the discovery, rather than on the accuracy of the predictions

A few exceptions...

[Crivellin et al 2014; Pruna, Signer 2014]

LFV : Where to look for?

$\ell_i \to \ell_j \gamma$

$\ell_i \to 3\,\ell_j$

$\ell_i \to \ell_j \ell_k \ell_k$

$\mu - e$

conversion in nuclei

BSM

LFV at colliders

$M \to \ell_i \ell_j$

LFV : Where to look for?

Everywhere!

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	$0.06 \ldots 2.2$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.07 \ldots 2.2$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$	$0.06 \ldots 2.2$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$	$0.03 \ldots 1.3$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.04 \ldots 1.4$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2$	~ 5	$0.3 \ldots 0.5$	$1.5 \ldots 2.3$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$	$1.4 \ldots 1.7$
$\frac{R(\mu Ti \to e Ti)}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$	$10^{-12} \ldots 26$

Table taken from Buras et al [arXiv:1006.5356]

The LFV program

In order to unravel the physics behind LFV (and perhaps neutrino masses!) we must:

- Search for LFV in as many observables as possible: they might have information about different sectors of the theory

- Study the relations among different observables (ratios, correlations, hierarchies...)

- Understand the origin of such relations: what is the underlying physics?

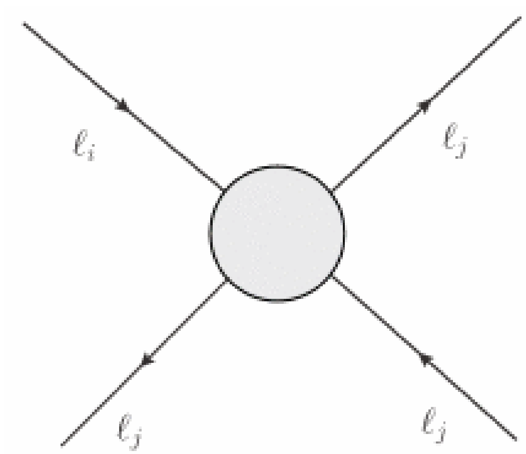
LFV in low-scale seesaw models

What contribution dominates $\ell_i \to 3\,\ell_j$?

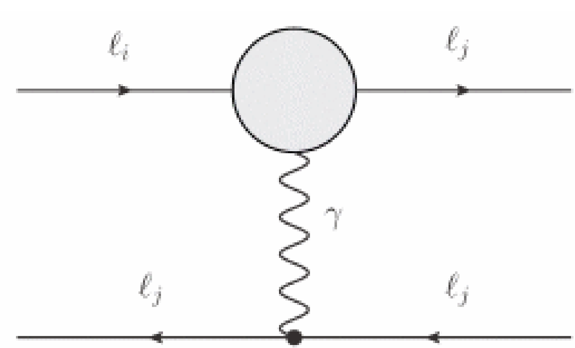
In many models of interest: Photonic dipole contributions

Most popular example: MSSM

[Hisano et al 1996; Arganda, Herrero 2006]



$\simeq$



Dipole dominance

$$\frac{BR(\ell_i \to 3\,\ell_j)}{BR(\ell_i \to \ell_j \gamma)} = \frac{\alpha}{3\pi}\left(\log \frac{m_{\ell_i}^2}{m_{\ell_j}^2} - \frac{11}{4}\right) \Rightarrow \quad BR(\ell_i \to \ell_j \gamma) \gg BR(\ell_i \to 3\,\ell_j)$$

Low-scale seesaw models

[Mohapatra, Valle, 1986]

The Inverse Seesaw

$$-\mathcal{L}_{IS} \supset Y_\nu^{ij} \nu_i^c L_j \tilde{H} + M_{R_{ij}} \nu_i^c S_j + \frac{1}{2} \mu_{S_{ij}} S_i S_j$$

6 additional singlet states: 3 generations of ν^c and 3 generations of S

However, more minimal models are also possible
[Malinsky et al, 2009; Hirsch et al, 2010; Bhupal Dev, Pilaftsis, 2012]

Neutrino masses

[Gonzalez-Garcia, Valle, 1989]

$$\mathcal{M} = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} Y_\nu^T v & 0 \\ \frac{1}{\sqrt{2}} Y_\nu v & 0 & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix}$$

- Non-zero neutrino masses. In the limit $\mu_S \ll Y_\nu v \ll M_R$:

$$m_\nu \simeq \frac{v^2}{2} Y_\nu^T (M_R^T)^{-1} \mu_S M_R^{-1} Y_\nu$$

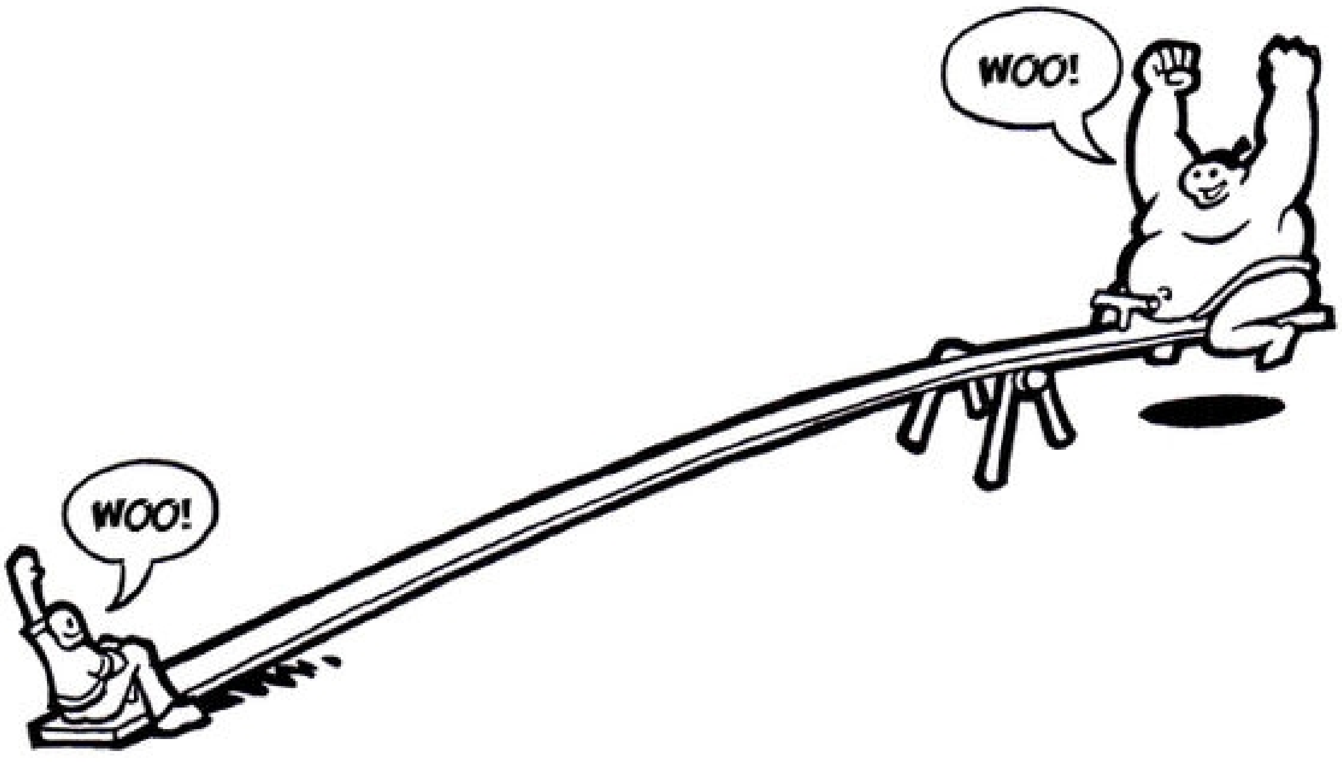
- The suppression by μ_S allows to have $Y_\nu \sim \mathcal{O}(1)$ and, at the same time, light singlets.
- Technically natural in the 't Hooft sense: $\mu_S \to 0$ restores lepton number.

Standard vs Inverse Seesaw

Standard Seesaw

Standard vs Inverse Seesaw

Inverse Seesaw



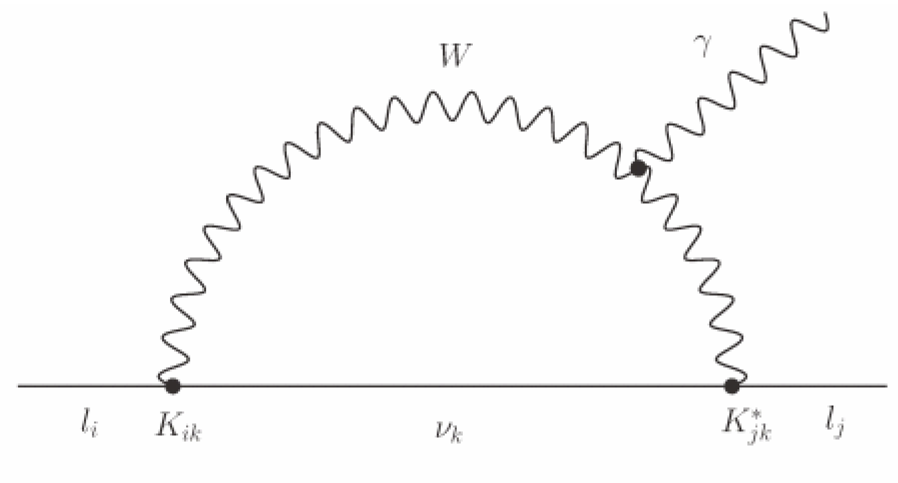
Penguins in the inverse seesaw

[Ilakovac, Pilaftsis, 1995; Deppisch, Valle, 2005]

$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2 m_\mu^5}{256\pi^2 m_W^4 \Gamma_\mu} \left| \sum_k K_{ek} K_{\mu k}^* G_\gamma \left(\frac{m_{\nu k}^2}{m_W^2} \right) \right|^2$$

$$\mathrm{Br}(\mu \to e\gamma)_{\mathrm{MEG}} < 5.7 \cdot 10^{-13}$$

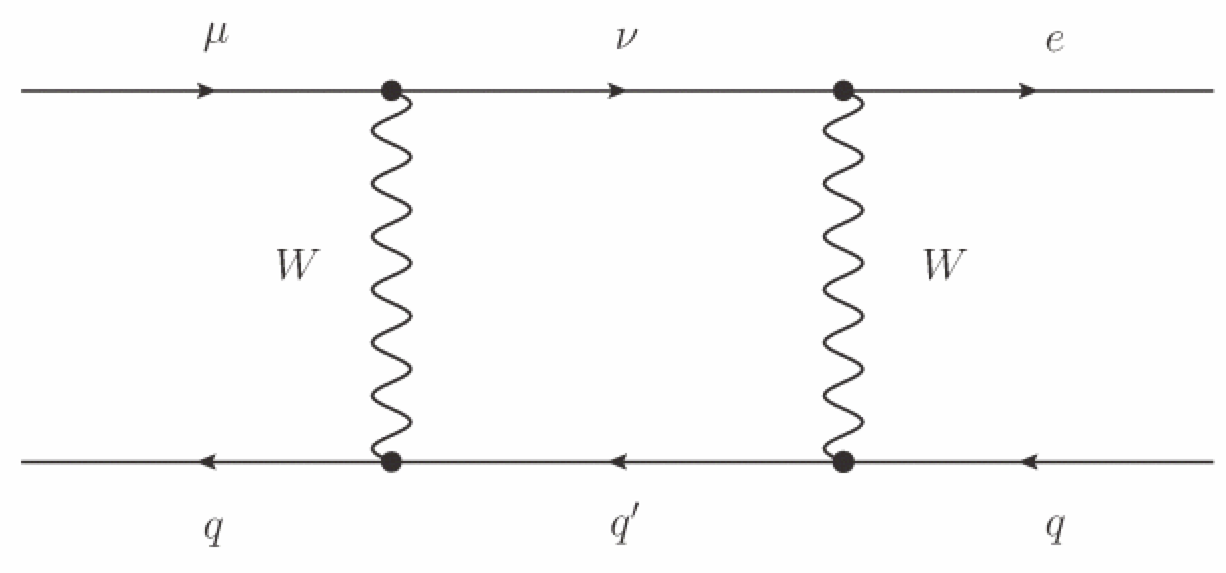
MEG limit
1303.0754



The GIM suppression is spoiled by the sterile neutrinos

Boxes in the inverse seesaw

Furthermore, for $\mu - e$ conversion in nuclei and $\ell_i \to 3\,\ell_j$ ...



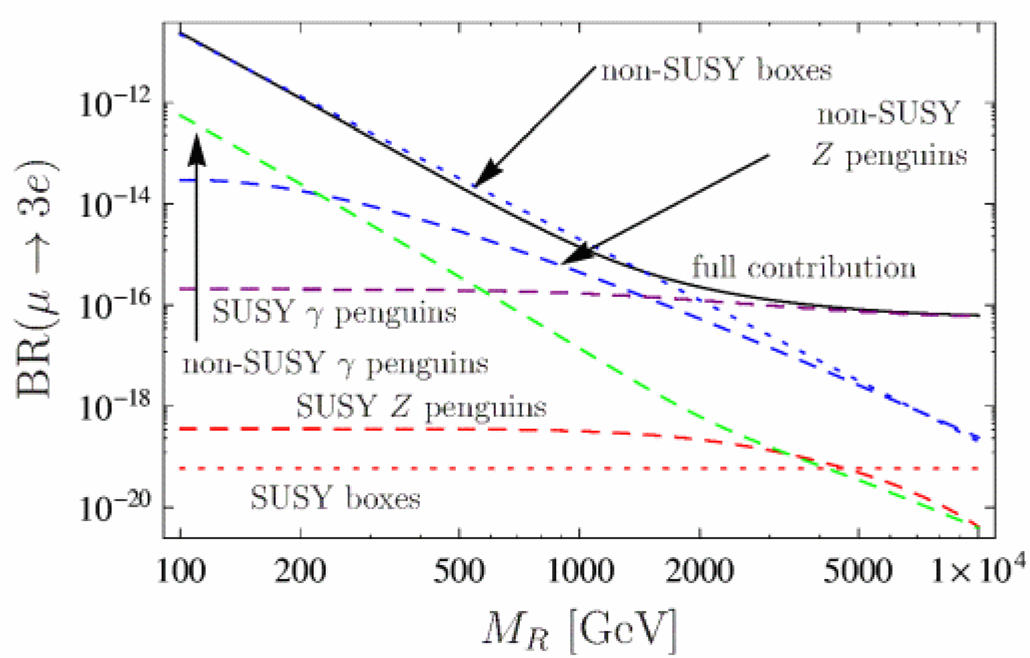
[Ilakovac, Pilaftsis, 2009; Dinh, Ibarra, Molinaro, Petcov, 2012; Alonso, Dhen, Gavela, Hambye, 2013; Ilakovac, Pilaftsis, Popov, 2012]

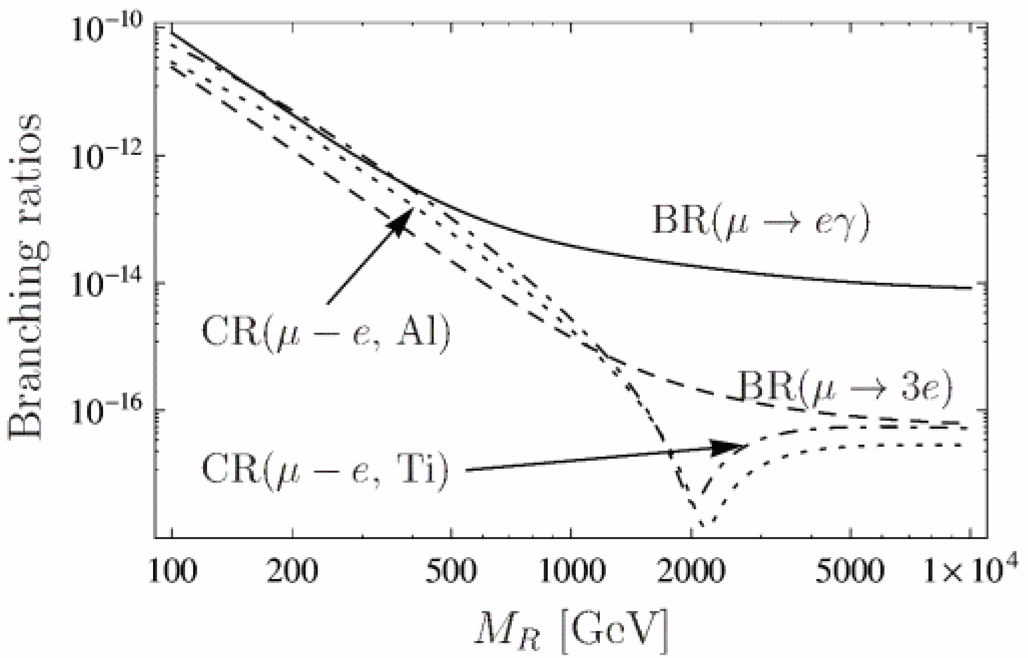
- Non-supersymmetric contribution
- Relevant for light singlet neutrinos
- Large non-dipole contributions

Low-scale seesaw models

[Abada, Krauss, Porod, Staub, AV, Weiland, 2014]

75 pages paper
First complete study of all SUSY and non-SUSY contributions!





The dipole dominance is broken for low RH neutrino masses

FlavorKit

[Porod, Staub, AV, 2014]

A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

Lepton flavor	Quark flavor
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

Not limited to a single model: use it for the model of your choice

Easily extendable

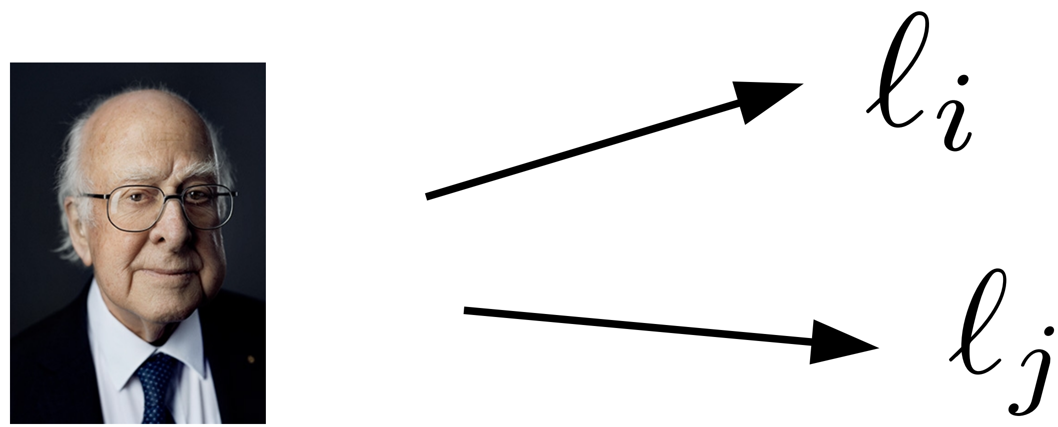
Many observables ready to be computed in your favourite model!

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

Higgs LFV decays

Higgs LFV decays

We have discovered the Higgs
However, is there room for non-standard decays?



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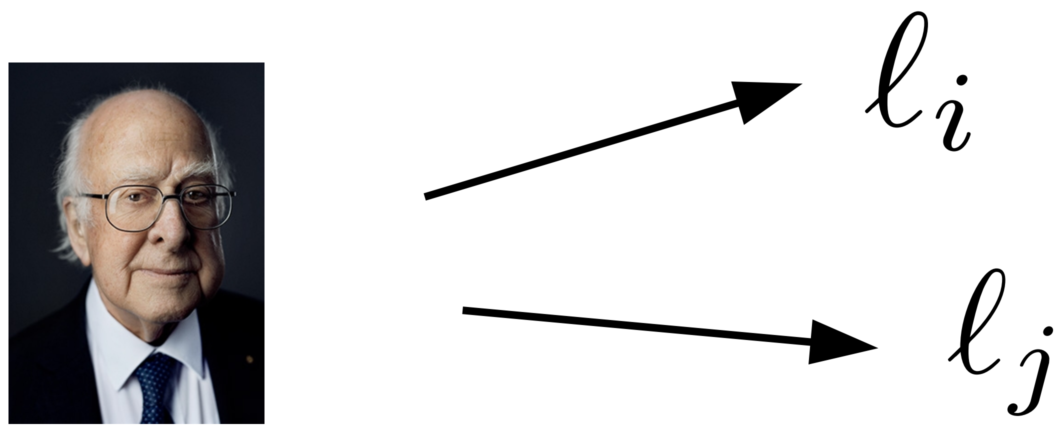


Current limits: $\mathrm{Br} \lesssim 0.1$ [Blankenburg et al, 2013; Harnik et al, 2013]

LHC sensitivity: $\mathrm{Br} \sim 10^{-3}$ [Davidson, Verdier, 2012]

$20 fb^{-1}$ at $\sqrt{s} = 8$ TeV

Early works: [Pilaftsis, 1992; Diaz-Cruz, Toscano, 2000]

Vector-like leptons

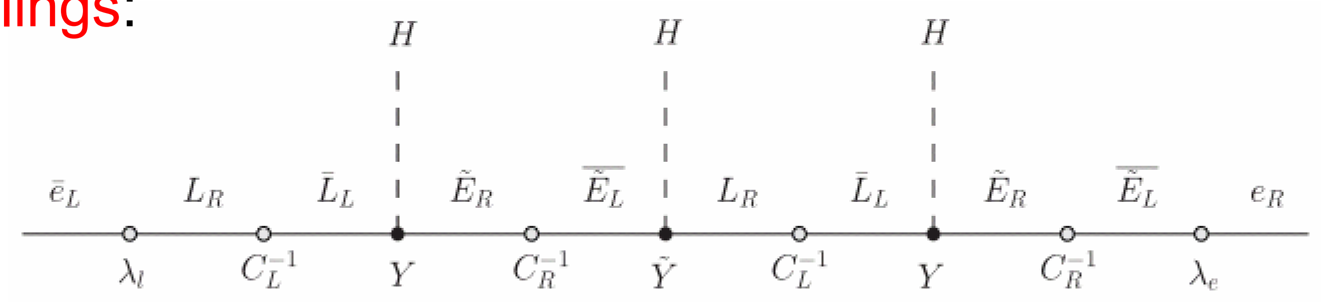
[Falkowski, Straub, AV, 2014]

Model with vector-like leptons
"Composite Higgs inspired"

$$\mathcal{L}_{F,c} = -M\left(\bar{L}C_L L + \tilde{E}C_R\tilde{E}\right) - \left(\bar{L}_L Y\tilde{E}_R H + \bar{L}_R\tilde{Y}\tilde{E}_L H + \text{h.c.}\right)$$

$$\mathcal{L}_{\text{mix}} = M\left(\bar{l}_L\lambda_l L_R + \tilde{E}_L\lambda_e e_R\right) + \text{h.c.}$$

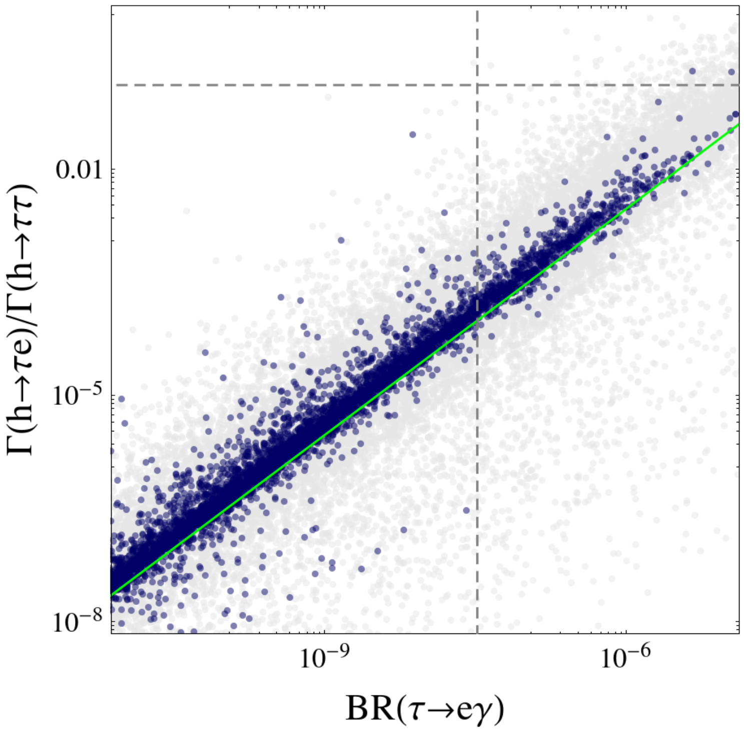
Higgs LFV couplings:

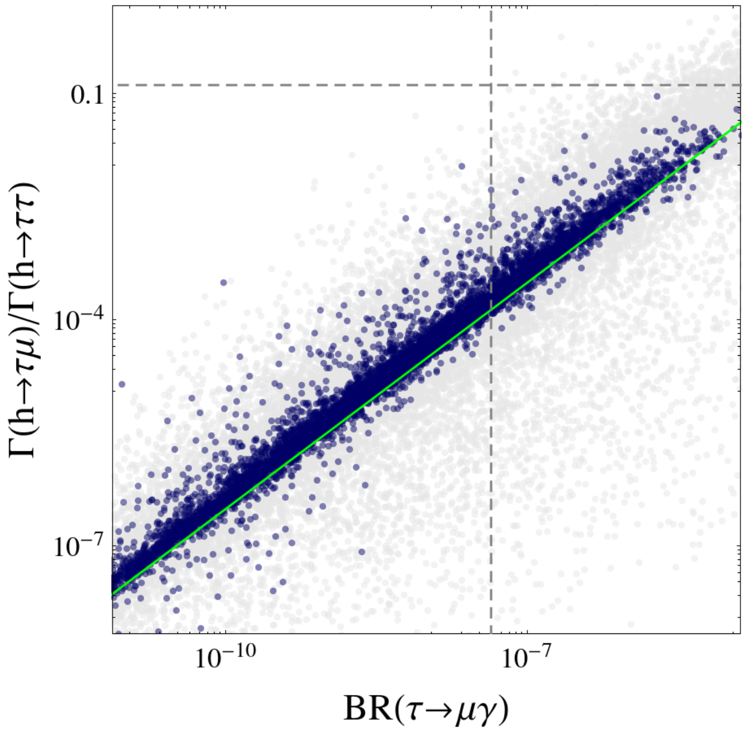


$$\mathcal{L}_{\text{eff}} = -\frac{h}{\sqrt{2}}\bar{e}_L c_{\text{eff}} e_R + \text{h.c.} \qquad c_{\text{eff}} = Y_{\text{eff}} + \frac{v^2}{M^2}\lambda_l C_L^{-1} Y C_R^{-1}\tilde{Y} C_L^{-1} Y C_R^{-1}\lambda_e$$

Vector-like leptons

[Falkowski, Straub, AV, 2014]



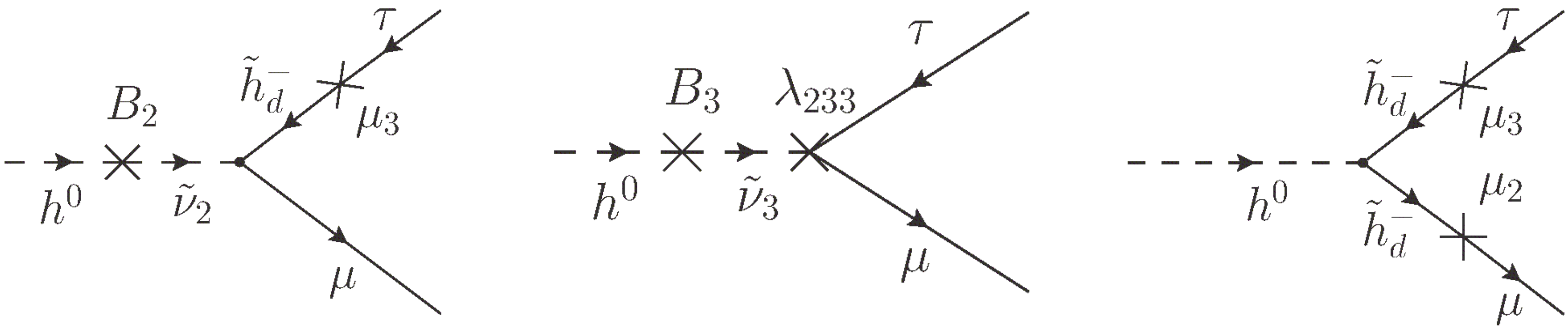


Unfortunately... unobservable at the LHC

$H \to \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]

The particles-sparticles mixing induced by RPV lead to
tree-level LFV Higgs decays

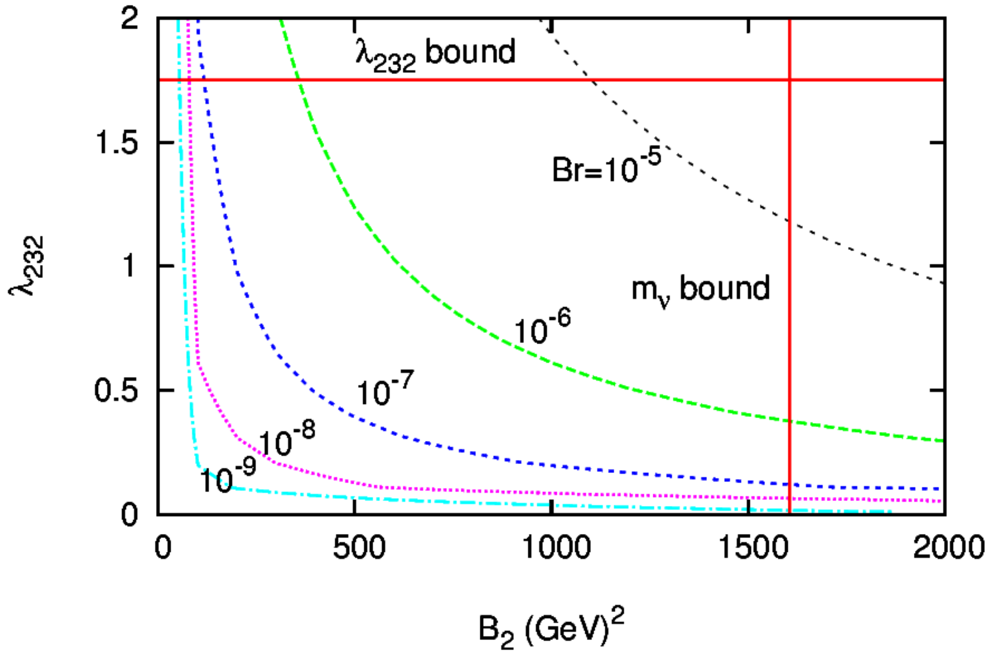


$B\epsilon$ contribution $\quad B\lambda$ contribution $\quad \epsilon^2$ contribution

Note: $\mathcal{L}_{soft} \supset B\tilde{L}H_u$

$H \to \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]



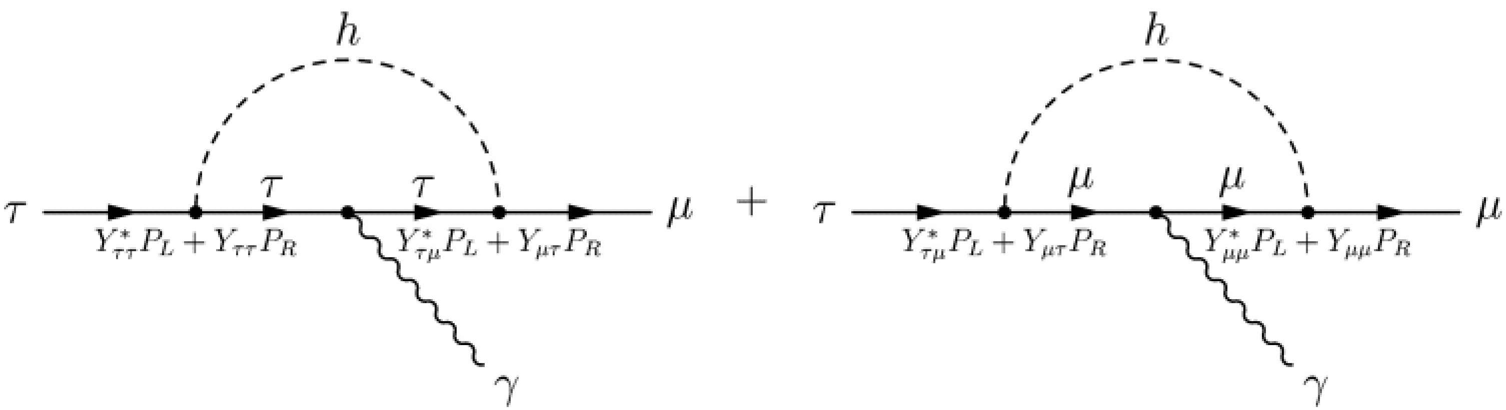
RPV Parameter Combinations	Br with Neutrino Mass $\lesssim 1$ eV Constraint
$B_2\,\mu_3$	1×10^{-15}
$B_3\,\mu_2$	1×10^{-13}
$B_1\,\lambda_{123}$	1×10^{-5}
$B_1\,\lambda_{132}$	3×10^{-5}
$B_2\,\lambda_{232}$	3×10^{-5}
$B_3\,\lambda_{233}$	3×10^{-5}
$\mu_2\,\mu_3$	2×10^{-18}
$B_1\,A^{\lambda}_{123}$	5×10^{-11}
$B_1\,A^{\lambda}_{132}$	5×10^{-11}
$B_2\,A^{\lambda}_{232}$	5×10^{-11}
$B_3\,A^{\lambda}_{233}$	5×10^{-11}

Again... unobservable at the LHC

A new hope...

[Harnik et al, 2013; Kopp, Nardecchia, 2014]

$$\mathcal{L}_Y = m_i \bar{f}^i_L f^i_R - Y_{ij} (\bar{f}^i_L f^j_R + \text{h.c.})$$



[Figure from Harnik et al, arXiv:1209.1397]

A model!

2HDM type III

In principle... observable Higgs LFV decays at the LHC!

Higgs LFV couplings and other LFV processes: [Celis et al, 2014]

See also some recipes for model builders: [Dery et al, 2014]

Final remarks

Final remarks

LFV is going to live a golden age

Many LFV observables. Correlations are not only possible, but in fact expected!

We must be ready: understand the LFV anatomy, patterns, correlations, hierarchies...

Thank you!

Backup slides

$\ell_i \to 3\,\ell_j$ vs $\ell_i \to \ell_j \gamma$

A brief détour...

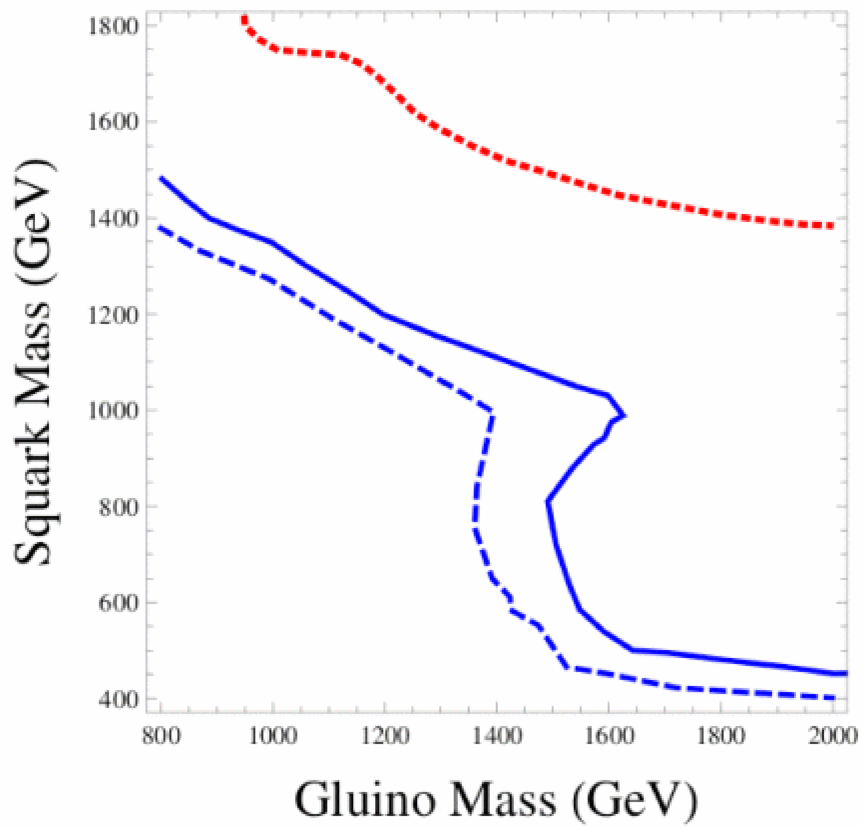
Experimental limits

$\ell_i \to \ell_j \gamma$	$\ell_i \to 3\,\ell_j$
$\text{Br}(\mu \to e\gamma) < 0.57 \cdot 10^{-12}$	$\text{Br}(\mu \to 3e) < 1.0 \cdot 10^{-12}$
$\text{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8}$	$\text{Br}(\tau \to 3e) < 2.7 \cdot 10^{-8}$
$\text{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$	$\text{Br}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$

RPV and LHC bounds

Less missing energy...
less stringent constraints!

P. W. Graham et al, JHEP 1207 (2012) 149
M. Hanussek, J. S. Kim, PRD 85 (2012) 115021



$m(\tilde{\chi}_1^0) = 50\,\mathrm{GeV}$

Blue: $\tilde{\chi}_1^0 \to \nu b\bar{b}$

Red: stable $\tilde{\chi}_1^0$

Plot taken from P. W. Graham et al, JHEP 1207 (2012) 149