

The lepton flavor violation road to new physics

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Pedestrian Seminar
Valencia

Coincidence problem!



Próximos Coloquios

Viernes, 20 Febrero, 2015 - 12:30

Desde el laboratorio a la aplicación industrial

Prof. Corma, Avelino

Salón de Actos



Próximos Seminarios

Martes, 17 Febrero, 2015 - 11:30

Trobada: QUAerere AXion, a proposal in a search for Galactic axions

Carugno, Giovanni

Seminar Room, 1.1.1

Jueves, 19 Febrero, 2015 - 16:30

Student Seminar: The lepton flavor violation road to new physics

Dr. Vicente, Avelino

Paterna Seminario

Miércoles, 25 Febrero, 2015 - 11:30

Trobada: Flavoured Conspiracies and Conundrums

Virto, Javier

Seminar Room, 1.1.1



Noticias

<http://webific.ific.uv.es/>

Conferencia de Juan José Gómez Cadenas: "Paisaje con neutrinos/Paisaje sin neutrinos"

Enviado por Isidoro.Garcia@ific.uv.es en Mié, 04/02/2015 - 09:48

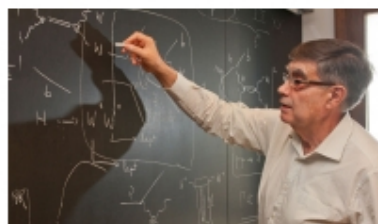


El investigador del Instituto de Física Corpuscular (IFIC, CSIC-UV) y director del experimento NEXT ofrece una conferencia el jueves 5 de febrero, en el Salón de Actos de la Biblioteca de Ciencias *Eduard Boscà*, Campus de Burjassot, a las 13:00 horas, con entrada libre. Los neutrinos fueron definidos en su día como "un pedazo diminuto de realidad". Carecen de carga eléctrica, casi no tienen masa y apenas interactúan con la materia.

[Leer más](#)

José Bernabéu Alberola ingresa en la Real Academia de Ciencias

Enviado por Isidoro.Garcia@ific.uv.es en Lun, 02/02/2015 - 09:57



El catedrático de la Universidad de Valencia e investigador del Instituto de Física Corpuscular (IFIC, CSIC-UV) José Bernabéu Alberola, ha sido nombrado de forma unánime Académico Correspondiente Nacional de la Real Academia de Ciencias de España. El nombramiento se produjo en el último pleno de la prestigiosa institución académica celebrado el pasado 28 de

Outline of the talk

- Introduction: the lepton sector
- Lepton flavor violation
- Hot topics
 - LFV in low-scale seesaw models
 - Higgs LFV decays
- Final remarks



Introduction: the lepton sector

Introduction

Before the LHC started operating we all hoped for **great discoveries...**

A lush, dense tropical forest scene with sunlight filtering through the canopy. The image is used as a background for a presentation slide. The text is overlaid on the image in white. The forest is filled with various types of trees and plants, including large palm leaves and thick tree trunks. The lighting is bright, with sunlight creating a dappled effect on the foliage.

Microscopic
black holes

Extra dimensions

Supersymmetry

Compositeness

LHC expectations

LHC results...

**125 GeV
palm tree**

Introduction

Do we have a good reason to go **Beyond the Standard Model?**

Introduction

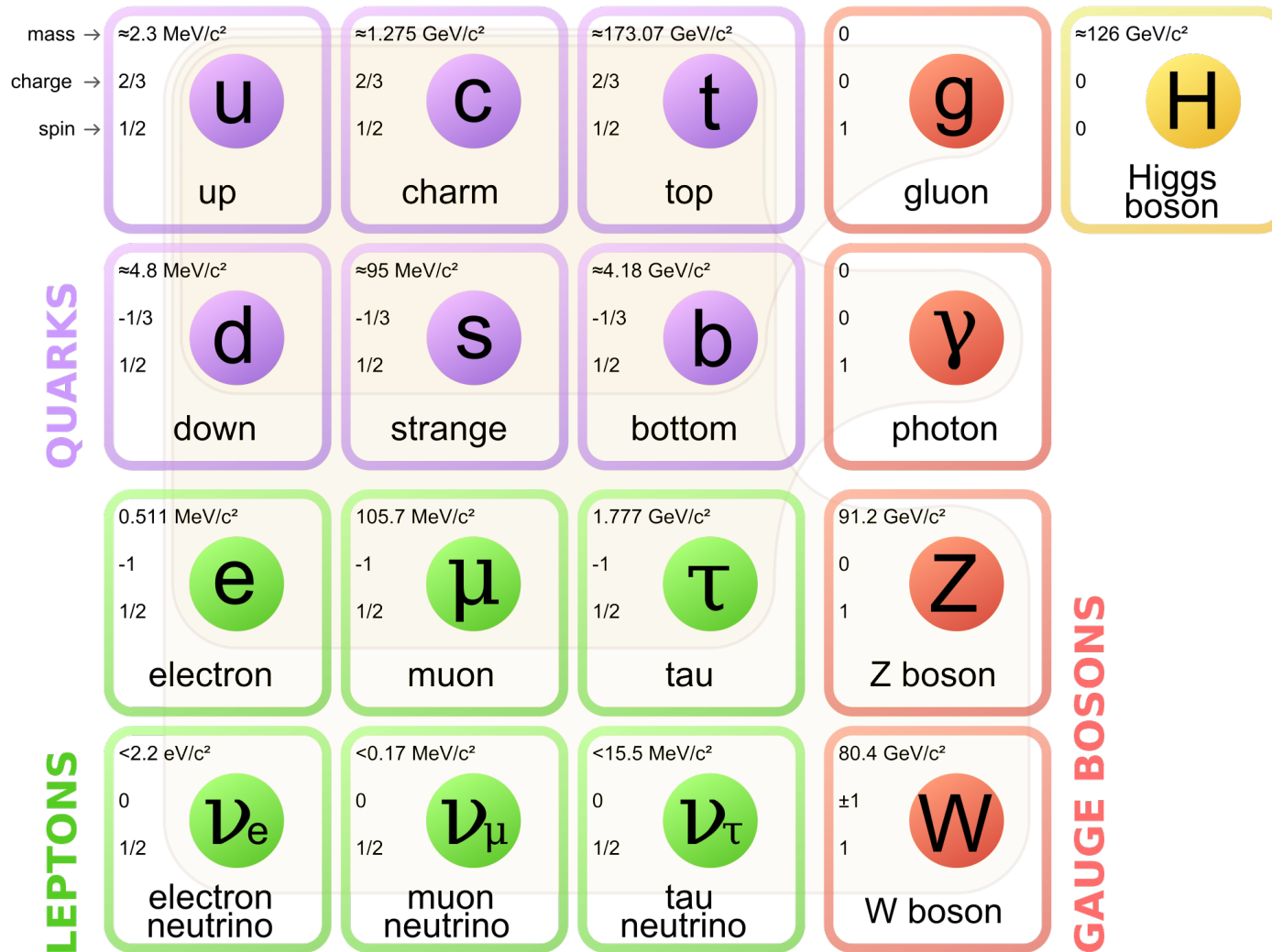
Do we have a good reason to go **Beyond the Standard Model?**



Neutrinos!

The lepton sector is still
to be understood!

The Standard Model



Neutrinos and the lepton sector

Dear radioactive Ladies and Gentlemen...

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich herzlichst anzuheissen bitte, Ihnen das näher auseinanderzusetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin $1/2$ haben und das Ausschlussprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta-Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



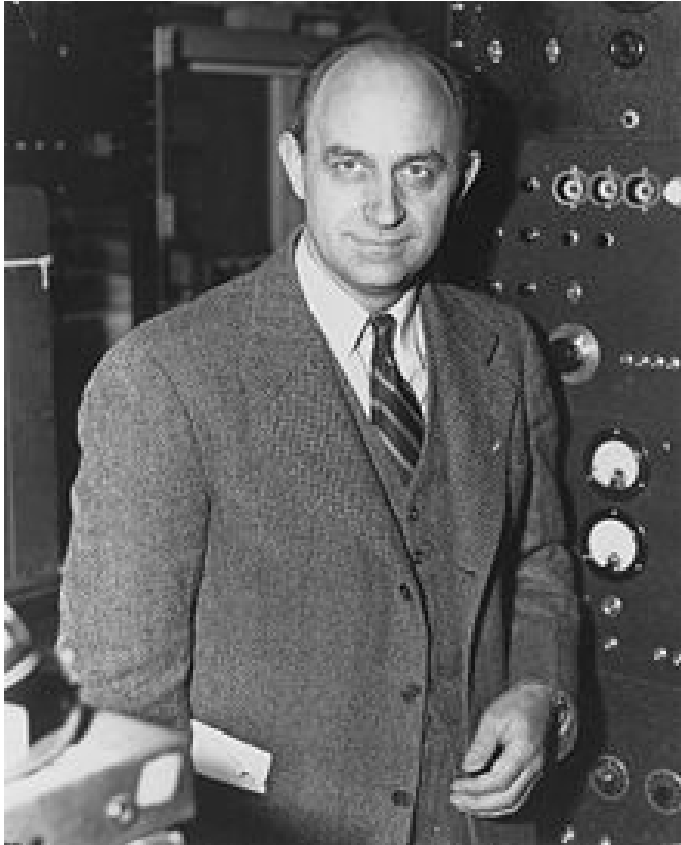
December 4th, 1930

Letter to his colleagues in Tübingen

1930

Pauli's neutrino hypothesis

Neutrinos and the lepton sector

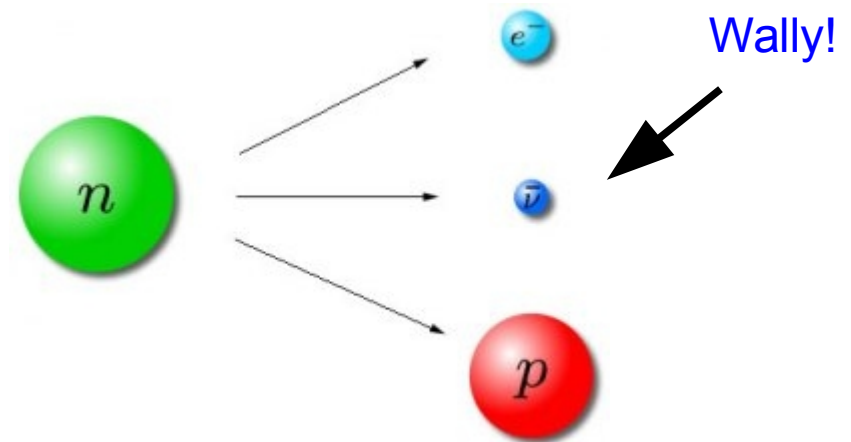


1934

Fermi's theory

Weak interactions and beta decay

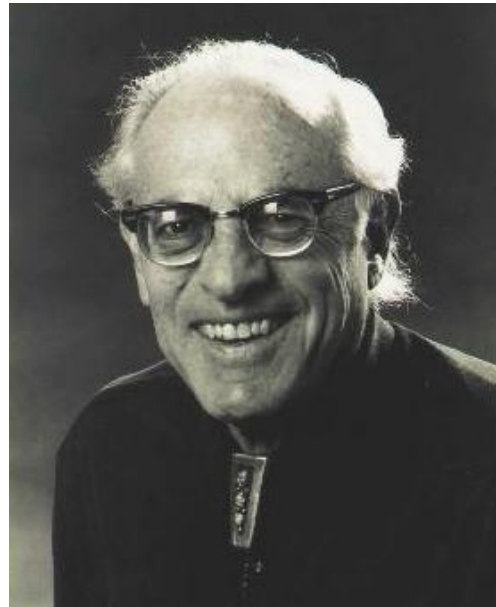
First application of Pauli's invention



$$\mathcal{L} = \frac{G_F}{\sqrt{2}} (\bar{\psi}_p \gamma_\mu \psi_n) (\bar{\psi}_e \gamma^\mu \psi_\nu)$$

He also introduced the name 'neutrino'!

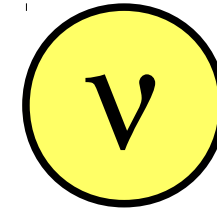
Neutrinos and the lepton sector



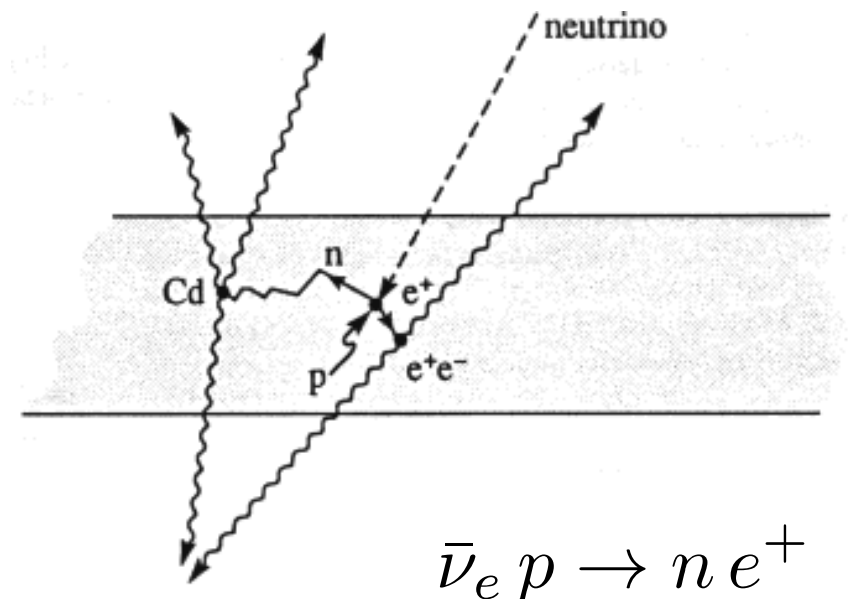
1956

C. Cowan and F. Reines
Discovery of the neutrino

The first of many neutrino experiments...



They exist!



Neutrinos in the SM

The Standard Model was built with the **assumption** of **massless neutrinos**

$$m_\nu(\text{SM}) = 0$$

- No **right-handed neutrinos**, and then no Dirac mass $\cancel{\nu_R}$
- Minimal lepton sector
- Accidental **lepton number (L)** conservation

Our dear friends
Salam, Weinberg and Glashow



Where are my neutrinos??

Solar neutrino problem



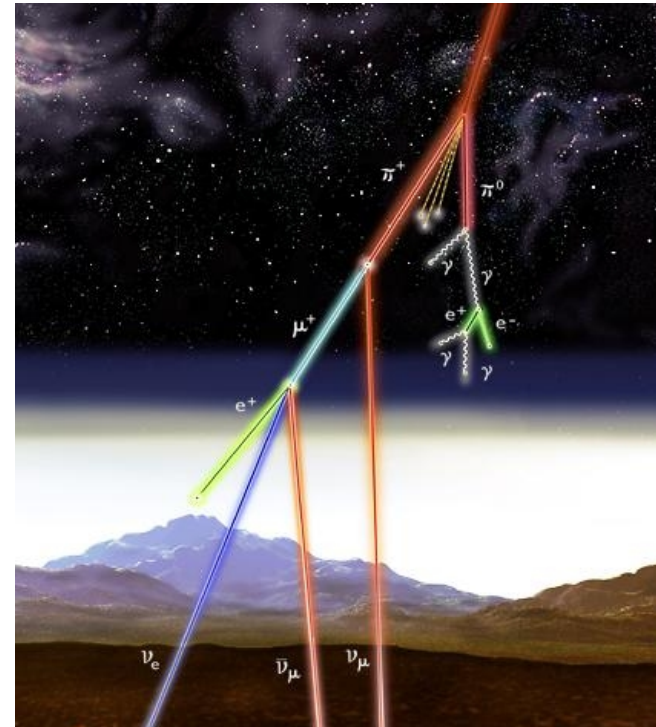
Not to scale!
(obviously...)

$$N_{\text{observed}} \simeq \frac{1}{3} N_{\text{expected}}$$

Where are the missing
neutrinos?



Atmospheric neutrino problem



$$\frac{N_\mu}{N_e} < 2$$

Neutrino oscillations

Nowadays there is a well established solution to these puzzles:

Neutrino oscillation

Idea: If neutrinos with definite flavor (ν_e, ν_μ, ν_τ) are not **mass eigenstates** they oscillate in their propagation

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

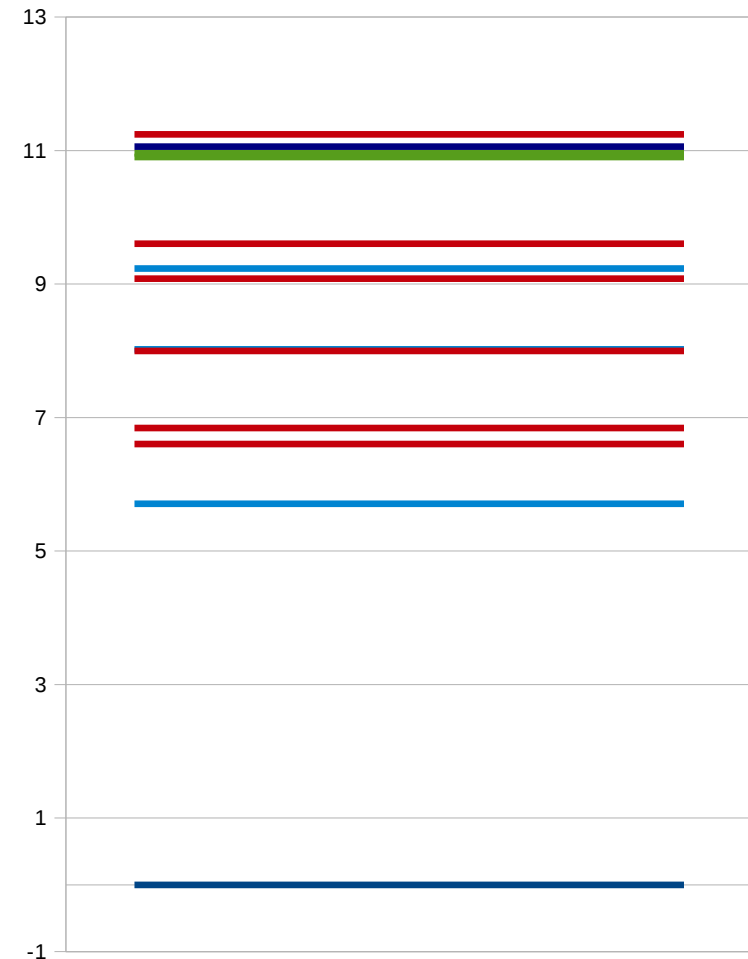
And then, when one does a measurement, the probability of finding a given flavor is

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

$\Rightarrow$ Neutrinos must have non-zero masses and mixing angles!

SM particle masses

Particle	Log10 (m eV)
neutrino	0
electron	5,71
muon	8,02
tau	9,23
u quark	6,6
d quark	6,85
s quark	8
c quark	9,08
b quark	9,6
t quark	11,24
W boson	10,9
Z boson	10,96
Higgs	11,06



The neutrino looks special, right?

Open questions

What is the origin of neutrinos masses?

Are they Dirac or Majorana?

What is the absolute scale of neutrino masses?

What is the mass ordering?

Are there more than three neutrinos? Maybe sterile?

Is there CP violation in the lepton sector?

The Introduction is over!



Lepton flavor violation

Lepton flavor violation

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

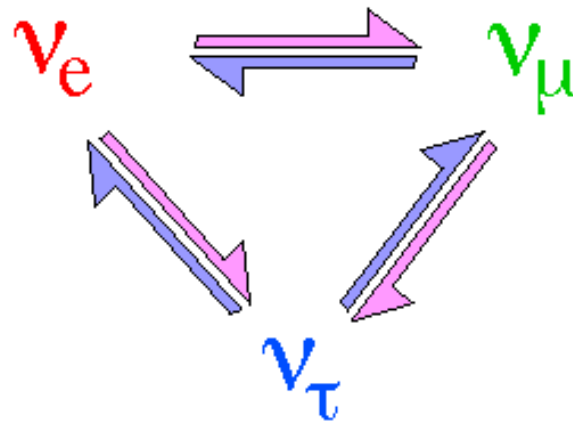
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{array}{c} \updownarrow \\ \text{Gauge and} \\ \text{Yukawa} \\ \text{interactions} \end{array}$$


Is **lepton flavor** a conserved quantity?

Neutrino oscillations: LFV

We already know the answer: **NO**

Neutrino flavor oscillations: flavor violating process!



Then... is this
process a sign of
BSM physics?

Yes it is!



What about cLFV?

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

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

$$\mu^- \rightarrow e^- \gamma$$

$$h \rightarrow \mu^- \tau^+$$

$$\tau^- \rightarrow \mu^- \mu^+ \mu^-$$

$$\pi^0 \rightarrow e^- \mu^+$$

$$K_L^0 \rightarrow \pi^0 e^- \mu^+$$

...

Never observed...

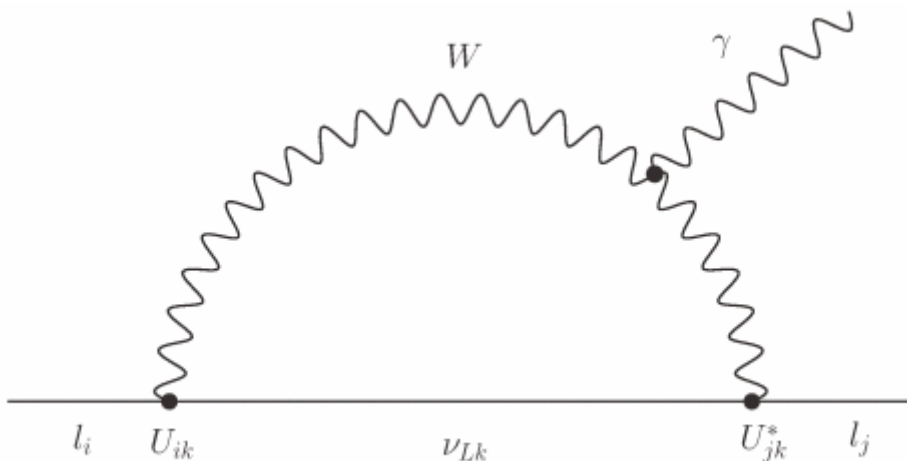
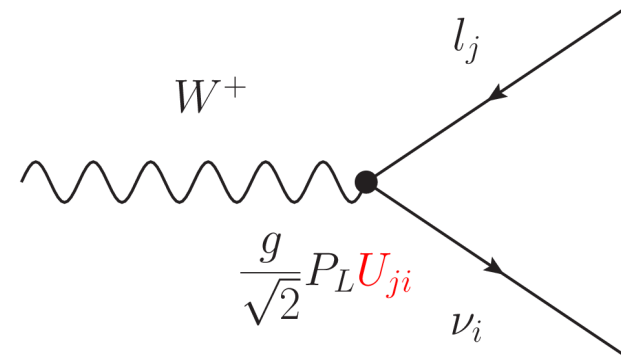
What about cLFV?

SM + Dirac neutrino masses

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} U_{ji} \bar{l}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

U : lepton mixing matrix

[analog of the CKM matrix in the lepton sector]



$$\text{Br}(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_k U_{ek} U_{\mu k}^* \frac{m_{\nu k}^2}{m_W^2} \right|^2 \lesssim 10^{-54}$$

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 (non-trivial) **physics beyond the Standard Model**

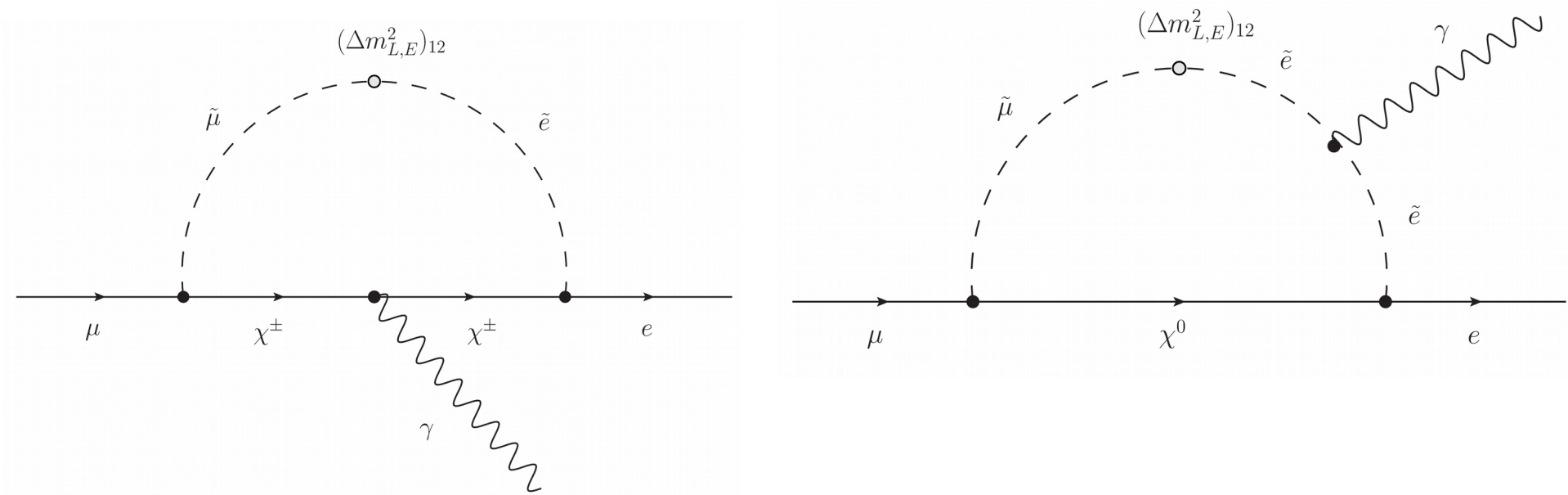
In fact, most **BSM models** predict **large cLFV rates**

We can probe **very high energy scales!**

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

Why do we care about LFV?

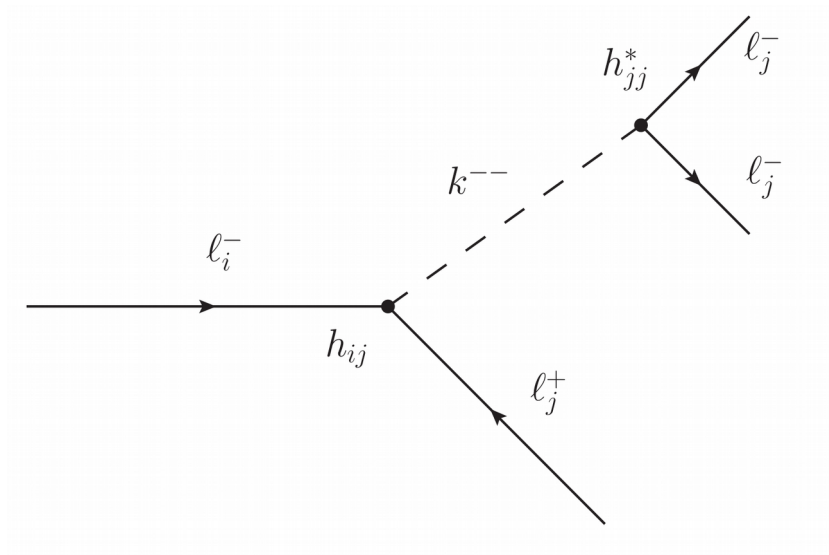
Example 1: Supersymmetric models



Sleptons: a whole new sector coupled to the **SM leptons**
Strong constraints on the **off-diagonal** soft terms

Why do we care about LFV?

Example 2: Babu-Zee model



$$\text{BR} \sim \left| \frac{h_{ij} h_{jj}^*}{m_k^2} \right|^2$$

Small **off-diagonal h couplings** and/or **heavy k's** are required

Experimental projects

Great experimental perspectives!

LFV Process	Present Bound	Future Sensitivity
$\mu \rightarrow e\gamma$	5.7×10^{-13}	6×10^{-14} (MEG)
$\tau \rightarrow e\gamma$	3.3×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\tau \rightarrow \mu\gamma$	4.4×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\mu \rightarrow 3e$	1.0×10^{-12}	$\sim 10^{-16}$ (Mu3e)
$\tau \rightarrow 3e$	2.7×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
$\tau \rightarrow 3\mu$	2.1×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
$\mu^-, \text{Au} \rightarrow e^-, \text{Au}$	7.0×10^{-13}	—
$\mu^-, \text{SiC} \rightarrow e^-, \text{SiC}$	—	2×10^{-14} (DeeMe)
$\mu^-, \text{Al} \rightarrow e^-, \text{Al}$	—	$10^{-15} - 10^{-17}$ (COMET)
$\mu^-, \text{Ti} \rightarrow e^-, \text{Ti}$	4.3×10^{-12}	$10^{-17} - 10^{-18}$ (Mu2e)
		$\sim 10^{-18}$ (PRISM/PRIME)

Experimental projects

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

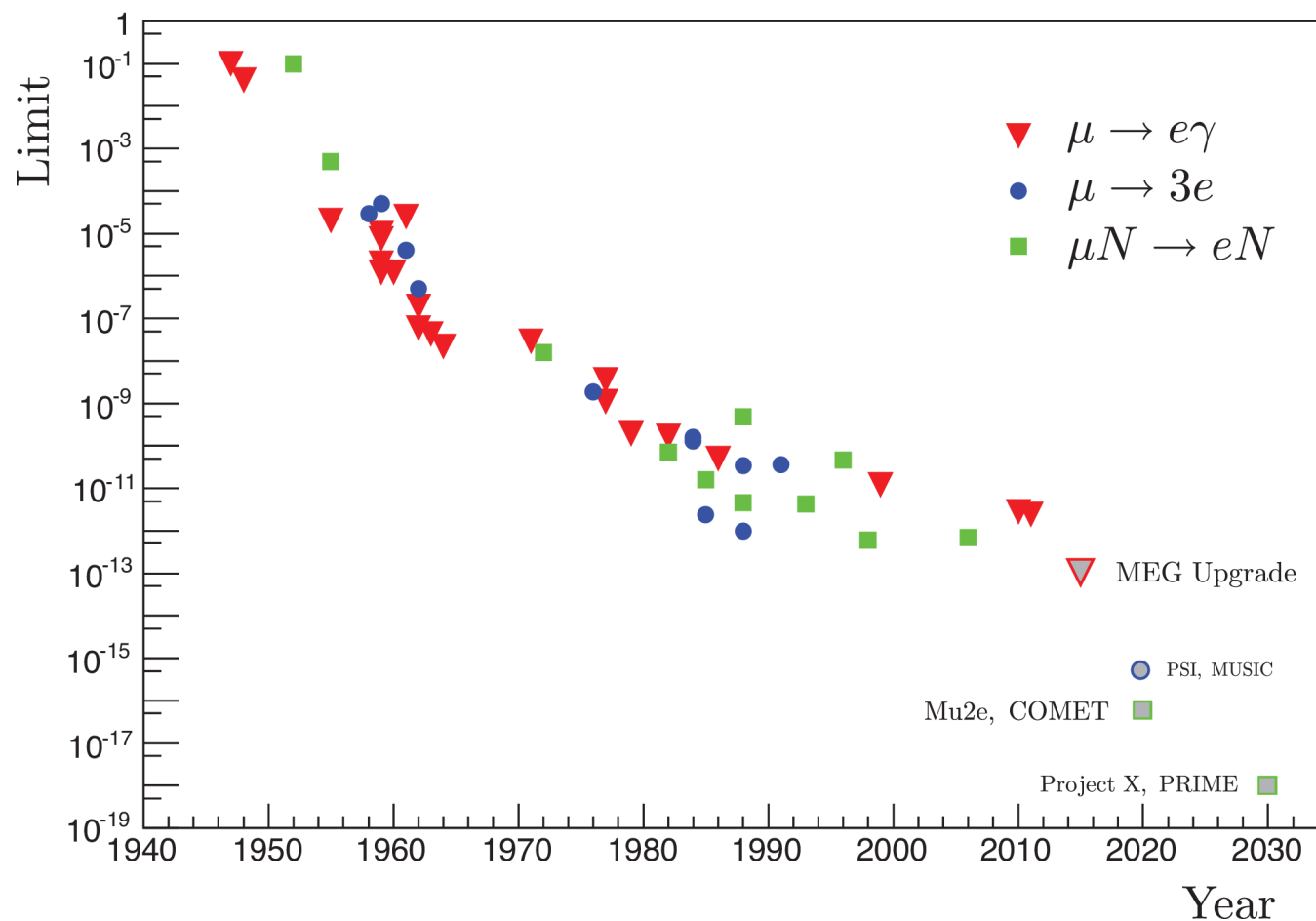
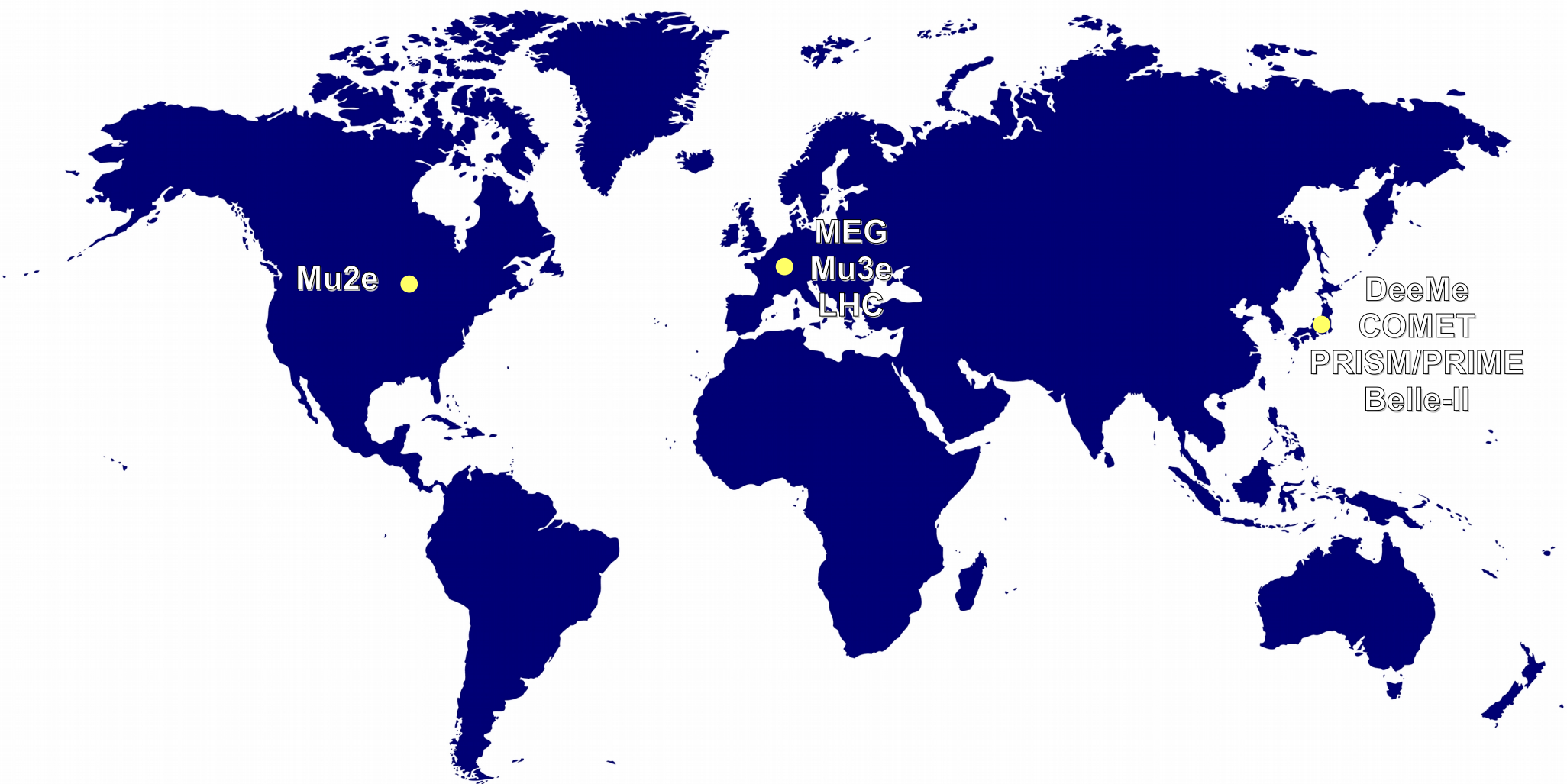


Figure taken from Bernstein & Cooper [arXiv:1307.5787]

Experimental projects



Experimental projects

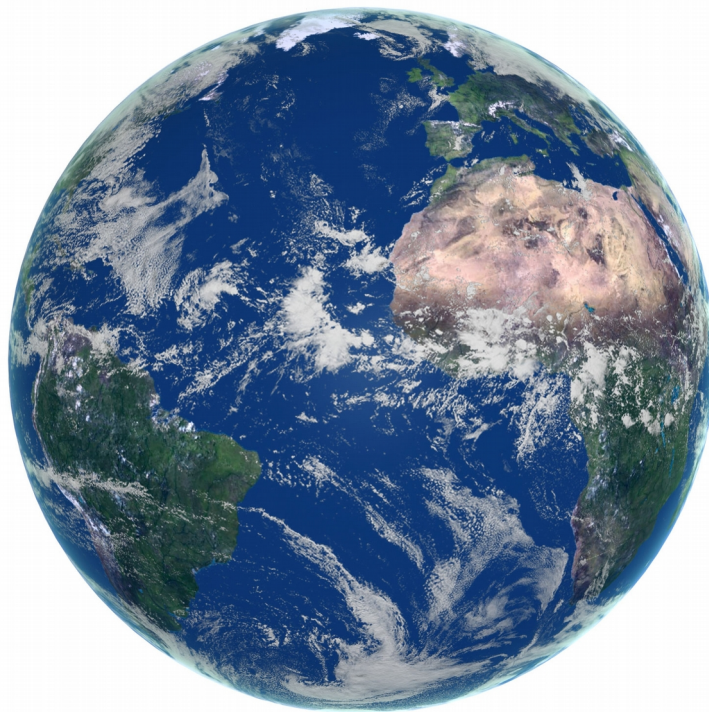
What is the meaning of 10^{-18} ?

Experimental projects

What is the meaning of 10^{-18} ?

There are about 5000 rice grains in one portion of paella

[Source: lapaella.net]



Imagine
finding a rice
grain here!



10.000 km

[Source: my own extrapolation]

LFV : Where to look for?

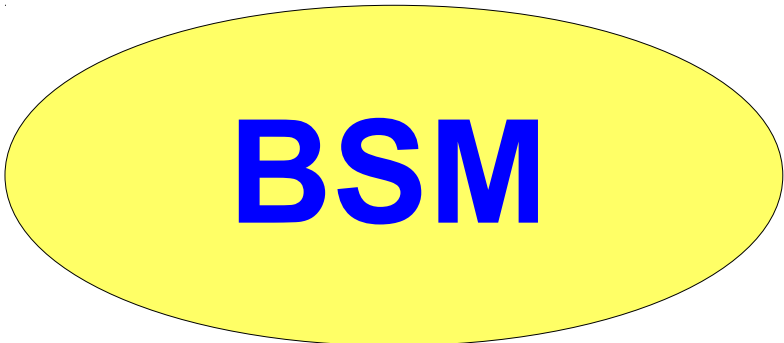
$$\ell_i \rightarrow \ell_j \gamma$$

$$\ell_i \rightarrow 3 \ell_j$$

$$\mu - e$$

conversion in nuclei

$$\ell_i \rightarrow \ell_j \ell_k \ell_k$$



BSM

LFV at colliders

$$M \rightarrow \ell_i \ell_j$$

LFV : Where to look for?

Everywhere!

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

Table taken from Buras et al [arXiv:1006.5356]

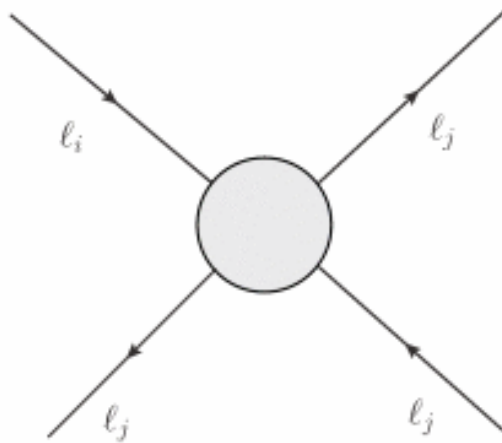
$$\ell_i \rightarrow 3 \ell_j \text{ vs } \ell_i \rightarrow \ell_j \gamma$$

What contribution dominates $\ell_i \rightarrow 3 \ell_j$?

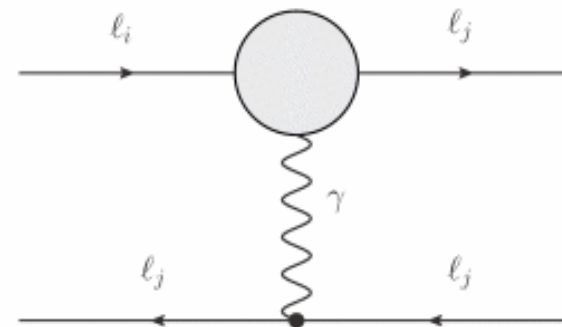
In many models of interest: **Photonic dipole contributions**

Most popular example: MSSM

[Hisano et al 1996; Arganda, Herrero 2006]



$\simeq$



**Dipole
dominance**

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

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

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

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

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

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

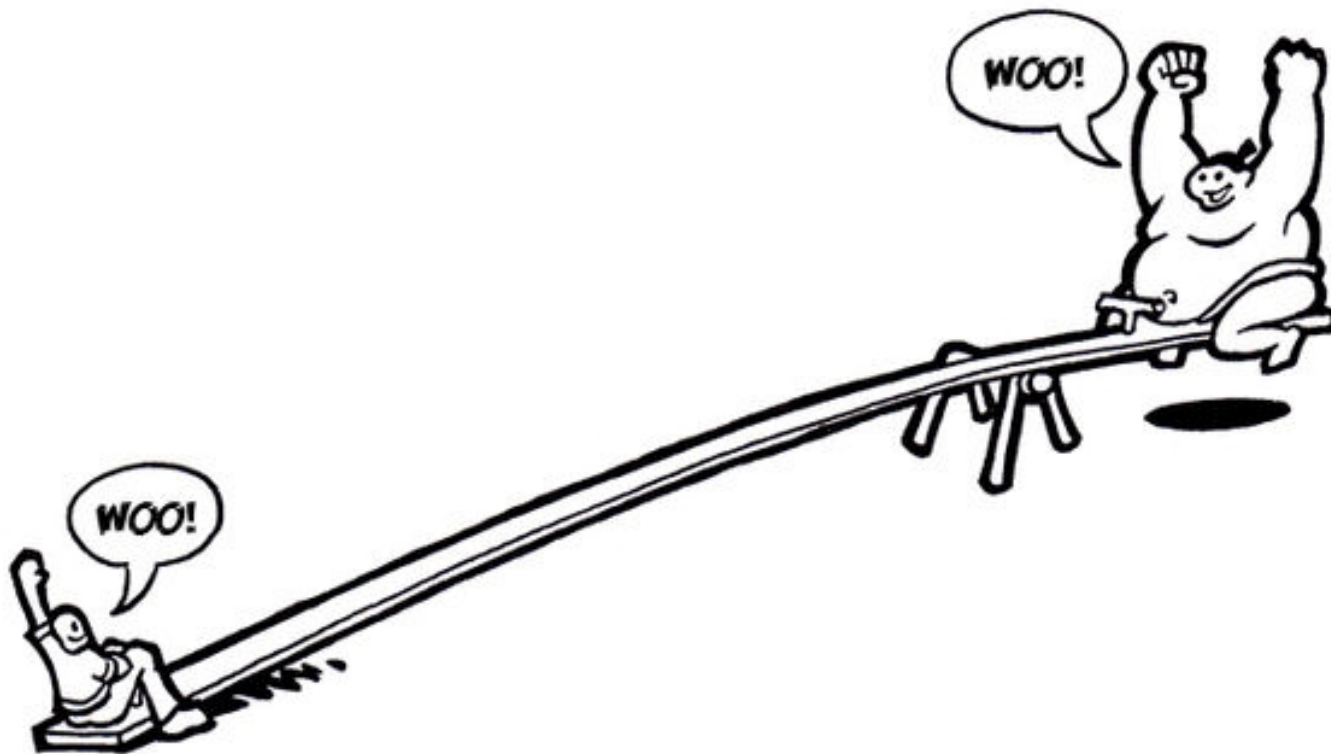
Standard vs Inverse Seesaw

Standard Seesaw



Standard vs Inverse Seesaw

Inverse Seesaw

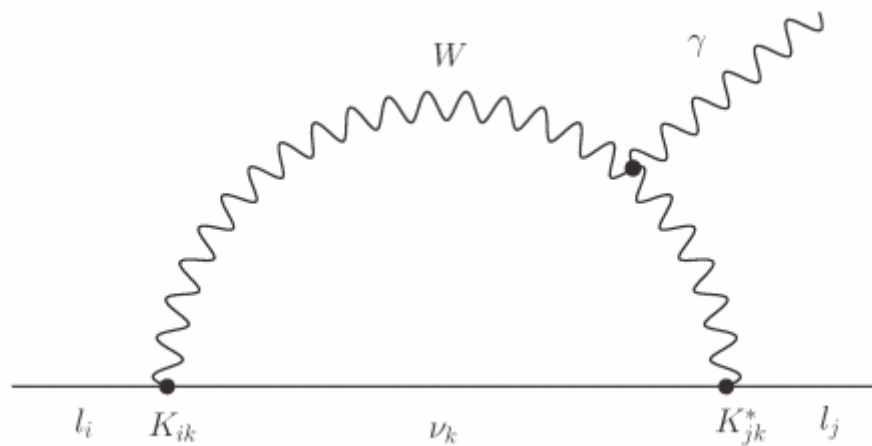


Penguins in the inverse seesaw

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

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

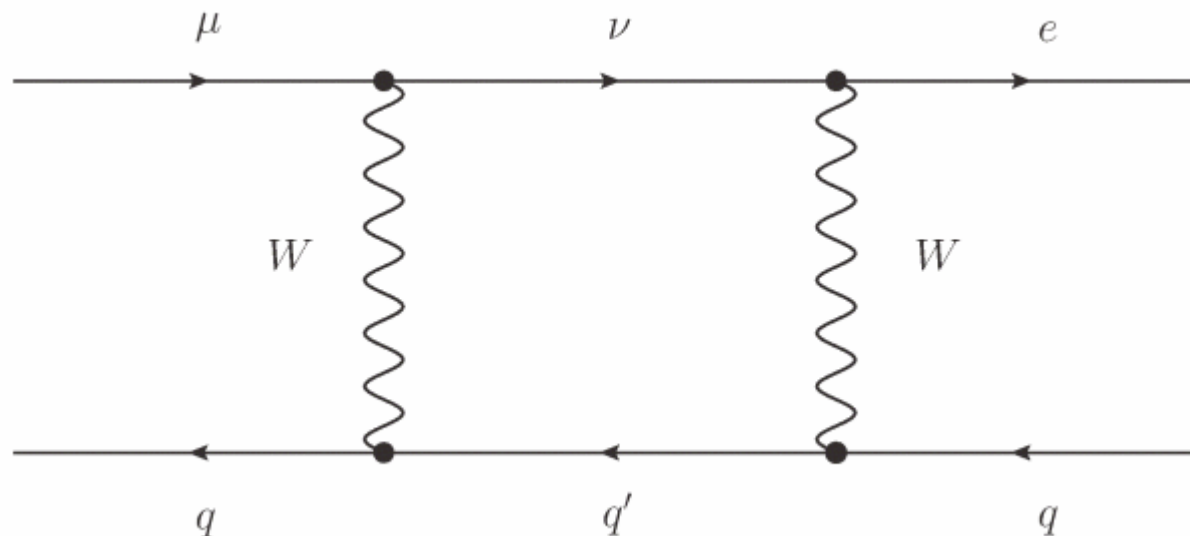
$$\text{Br}(\mu \rightarrow e\gamma)_{\text{MEG}} < 5.7 \cdot 10^{-13} \quad \begin{array}{l} \text{MEG limit} \\ 1303.0754 \end{array}$$



The **GIM** suppression is spoiled by the sterile neutrinos

Boxes in the inverse seesaw

Furthermore, for $\mu - e$ conversion in nuclei and $\ell_i \rightarrow 3 \ell_j \dots$



[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!

- Analytical and numerical study of

$$\ell_i \rightarrow \ell_j \gamma$$

$$\ell_i \rightarrow \ell_j \ell_k \ell_k$$

$\mu - e$ conversion in nuclei

- All contributions included
- A few hundred Feynman diagrams



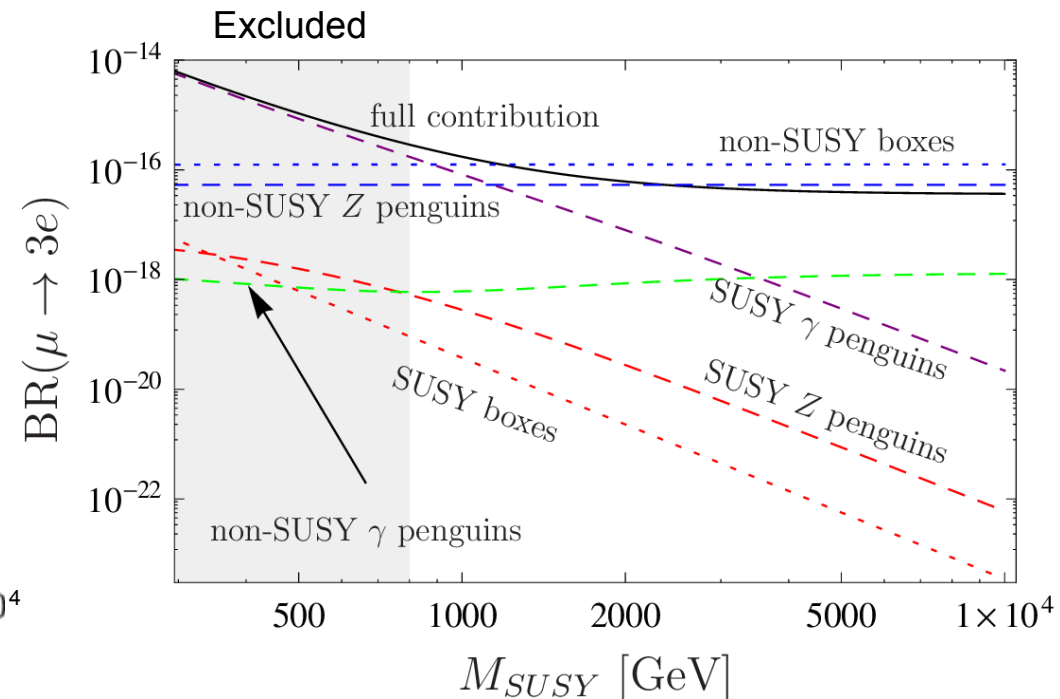
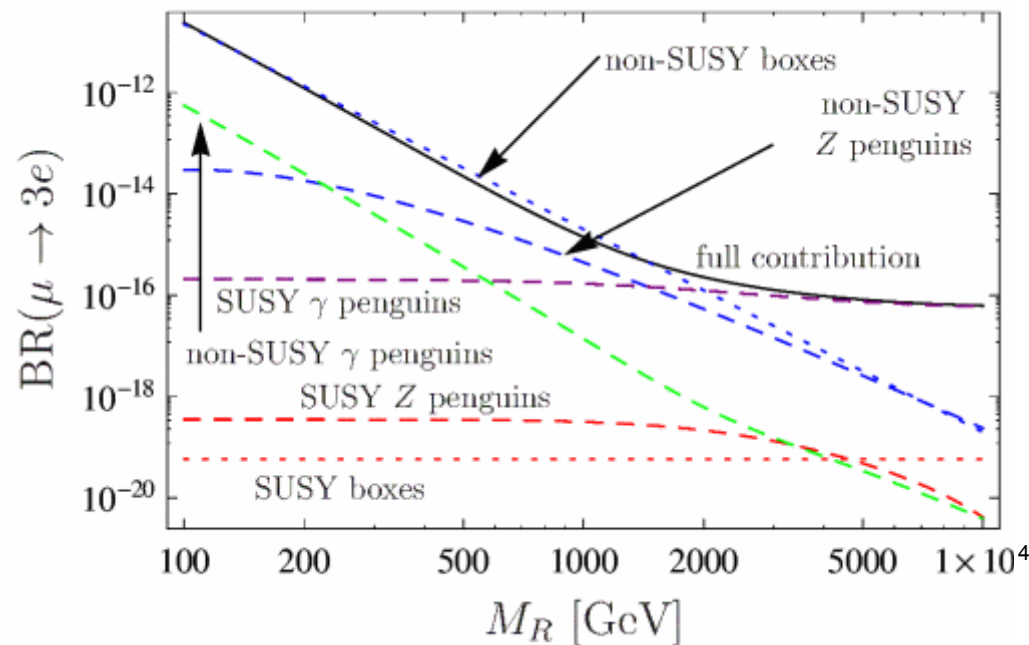
How were they
computed?

Later...

Low-scale seesaw models

$$\ell_i \rightarrow 3 \ell_j$$

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



The anatomy of LFV strongly depends on M_R and M_{SUSY}

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

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!

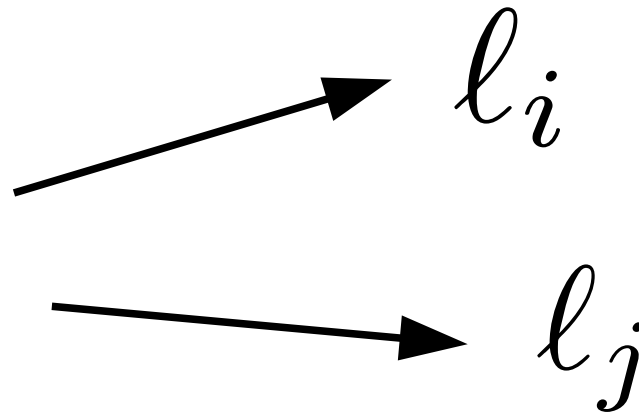
Manual: [arXiv:1405.1434](https://arxiv.org/abs/1405.1434)

Website: <http://sarah.hepforge.org/FlavorKit.html>

Higgs LFV decays

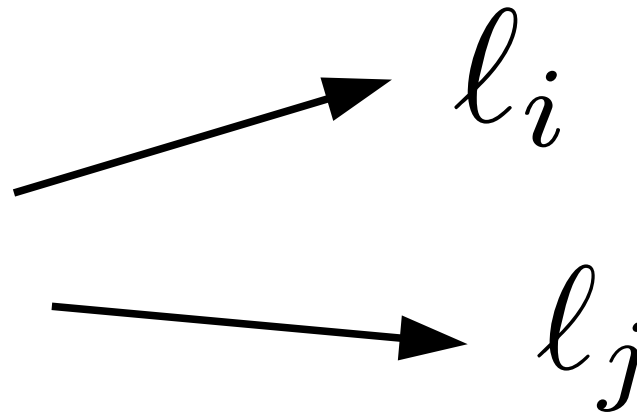
Higgs LFV decays

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



Higgs LFV decays

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



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

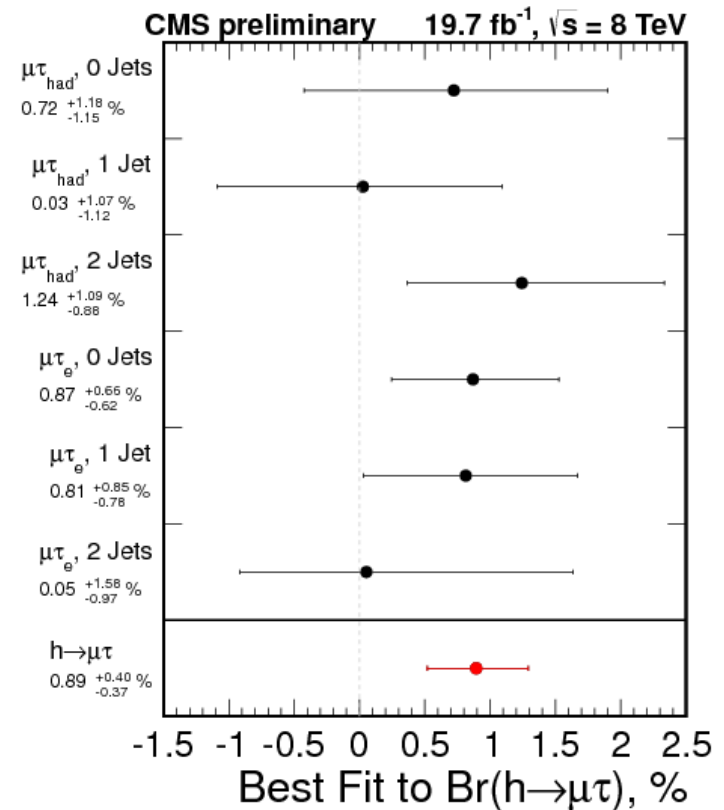
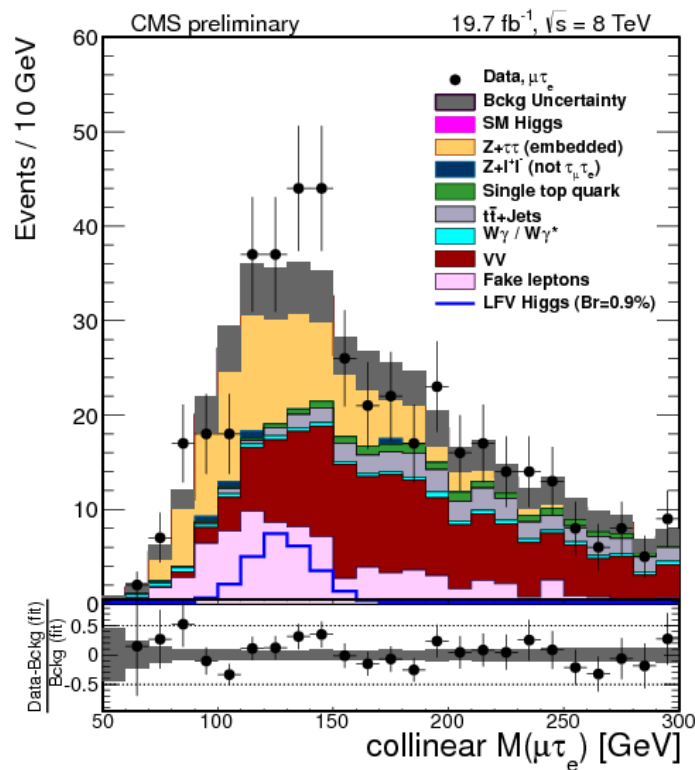
LHC sensitivity: $\text{Br} \sim 10^{-3}$ [Davidson, Verdier, 2012]
 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$

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

A hint from CMS?

A 2.5σ excess in $h \rightarrow \tau\mu$

[CMS-PAS-HIG-14-005, July 2014]



$$\text{BR}(h \rightarrow \tau\mu) = (0.89^{+0.40}_{-0.37})\%$$

A hint from CMS?

$$\text{BR}(h \rightarrow \tau\mu) = (0.89^{+0.40}_{-0.37})\%$$

- **Large** LFV branching ratio

$$\text{BR}(h \rightarrow \tau\bar{\tau})_{\text{SM}} \sim 6\%$$

- Needs more **statistics** and confirmation from **ATLAS**
- If taken seriously, any **model**?

Any model?

Flavor constraints seem to preclude any explanation for the CMS excess...



MSSM [Arana-Catania et al, 2013]

$$\text{BR}(h \rightarrow \tau\mu) \lesssim 10^{-4}$$

RPV Supersymmetry [Arhrib et al, 2013]

$$\text{BR}(h \rightarrow \tau\mu) \lesssim 10^{-5}$$

Vector-like leptons [Falkowski et al, 2014]

$$\text{BR}(h \rightarrow \tau\mu) \lesssim 10^{-5}$$

Inverse Seesaw [Arganda et al, 2014]

$$\text{BR}(h \rightarrow \tau\mu) \lesssim 10^{-5}$$

No hope?



A new hope: Type-III 2HDM

[Davidson, Grenier, 2010; Harnik et al, 2013; Kopp, Nardecchia, 2014]

A model! **Type-III 2HDM**

[**Type-III** = most general case]

$$\mathcal{L}_Y = m_i \bar{f}_L^i f_R^i - \rho_{ij} (\bar{f}_L^i f_R^j + \text{h.c.}) h$$



General 3x3 matrix



In *principle*... it is possible to account for the **CMS excess**!

A new hope: Type-III 2HDM

[Aristizabal Sierra, AV, 2014]

Explicit *proof of validity* including the relevant constraints

- Direct searches
- Indirect constraints from flavor
- $\tau \rightarrow \mu \gamma$
- Higgs couplings to fermions
- T parameter
- Perturbativity and boundedness from below

Higgs LFV decays in the Type-III 2HDM

[Aristizabal Sierra, AV, 2014]

$$m_H \subset [200, 1000] \text{ GeV}$$

$$m_A \subset [400, 1000] \text{ GeV}$$

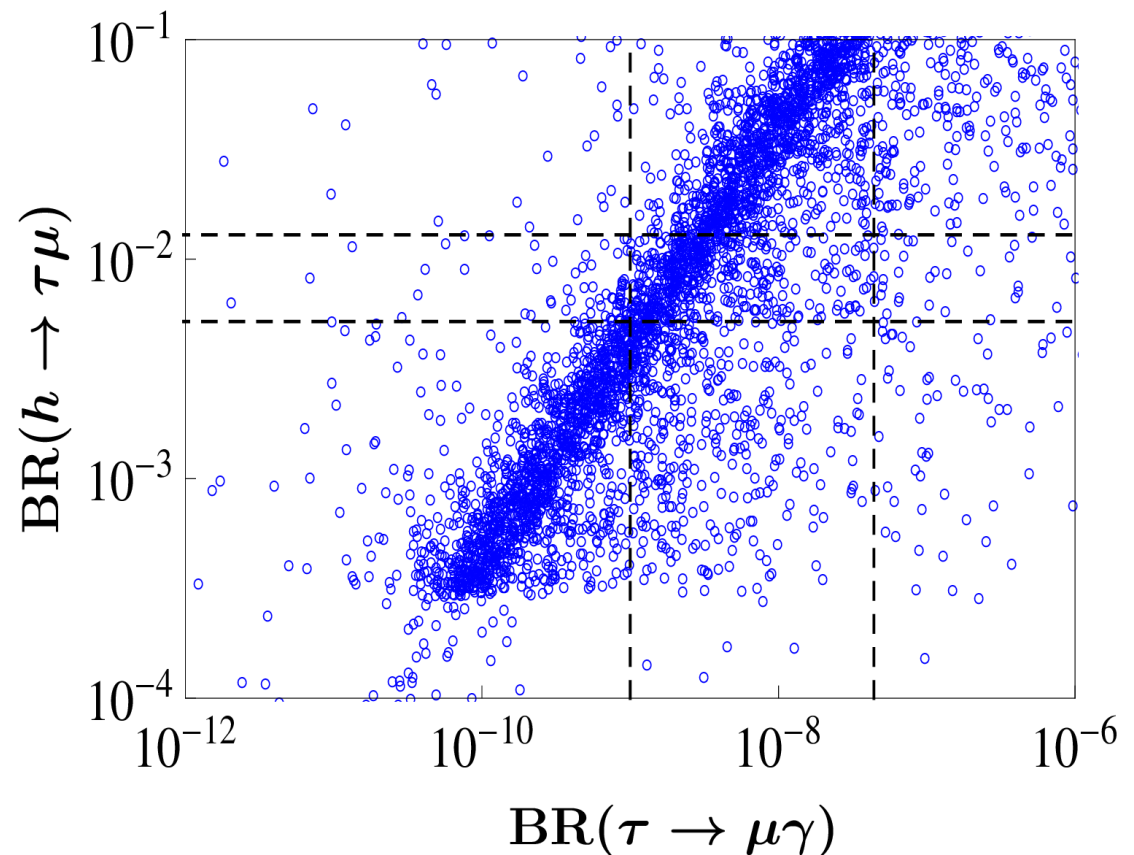
$$m_{H^\pm} = m_A + \delta m$$

$$\text{with } \delta m \subset [-5, 5] \text{ GeV}$$

$$\sin(\beta - \alpha) \subset [0.7, 1.0]$$

$$\tan \beta_\tau \subset [0.1, 40]$$

$$|\kappa_{\tau\mu}| \subset [0.1, 3]$$



Unfortunately, no prediction for $\text{BR}(\tau \rightarrow \mu\gamma)$

Higgs LFV decays in the Type-III 2HDM

[Aristizabal Sierra, AV, 2014]

Some *comments*:

The signal is consistent with the **Sher-Cheng ansatz**

$$\rho_{\tau\mu} \simeq \frac{\sqrt{m_\tau m_\mu}}{\langle H \rangle}$$

A **flavor symmetry** at work?

In this model $\text{BR}(\tau \rightarrow 3\mu) \simeq 2 \cdot 10^{-3} \text{BR}(\tau \rightarrow \mu\gamma)$

The observation of $\tau \rightarrow 3\mu$ would **exclude** this explanation!

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

$$\ell_i \rightarrow 3 \ell_j \text{ vs } \ell_i \rightarrow \ell_j \gamma$$

A brief détour...

Experimental limits

$$\ell_i \rightarrow \ell_j \gamma$$

$$\text{Br}(\mu \rightarrow e \gamma) < 0.57 \cdot 10^{-12}$$

$$\text{Br}(\tau \rightarrow e \gamma) < 3.3 \cdot 10^{-8}$$

$$\text{Br}(\tau \rightarrow \mu \gamma) < 4.4 \cdot 10^{-8}$$

$$\ell_i \rightarrow 3 \ell_j$$

$$\text{Br}(\mu \rightarrow 3e) < 1.0 \cdot 10^{-12}$$

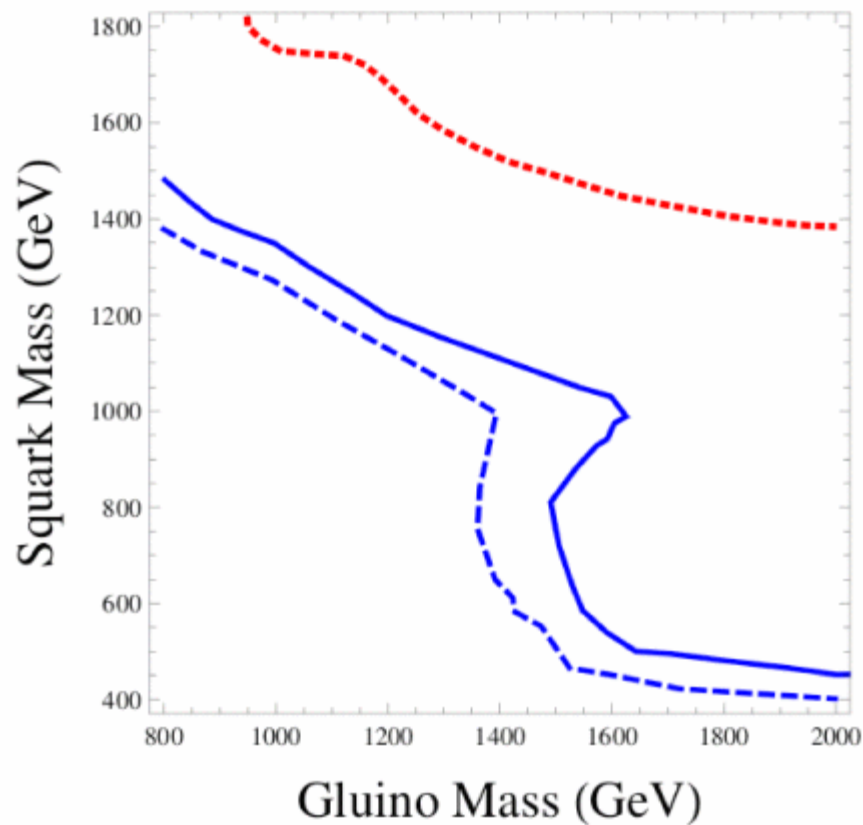
$$\text{Br}(\tau \rightarrow 3e) < 2.7 \cdot 10^{-8}$$

$$\text{Br}(\tau \rightarrow 3\mu) < 2.1 \cdot 10^{-8}$$

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



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

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

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

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

LFV at LHCb

Lepton flavor violating decays at



$$B_{d,s}^0 \rightarrow \ell_i \ell_j$$

[Aaij et al, LHCb collaboration, 2013]

$$\tau \rightarrow 3 \mu$$

[Aaij et al, LHCb collaboration, 2014]

1409.8548, last month!

Limits **improved** with respect to **CDF**

$$\text{BR}(B^0 \rightarrow e \mu) < 2.8 \cdot 10^{-9}$$

$$\text{BR}(B_s^0 \rightarrow e \mu) < 1.1 \cdot 10^{-8}$$

Large production of τ 's, clean **final state**

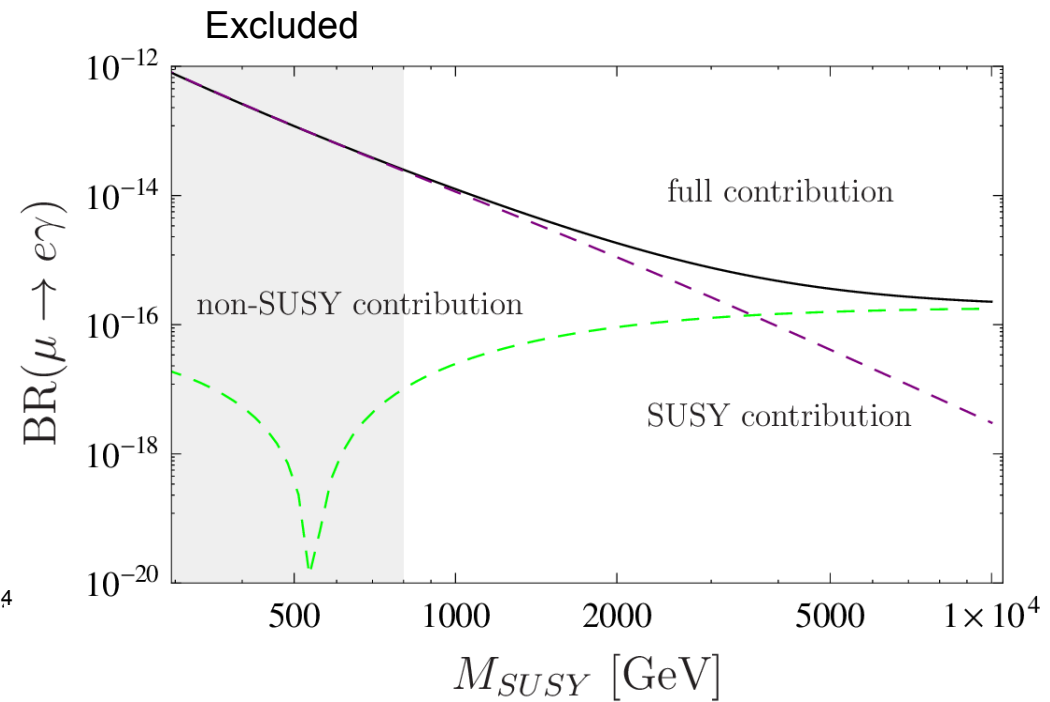
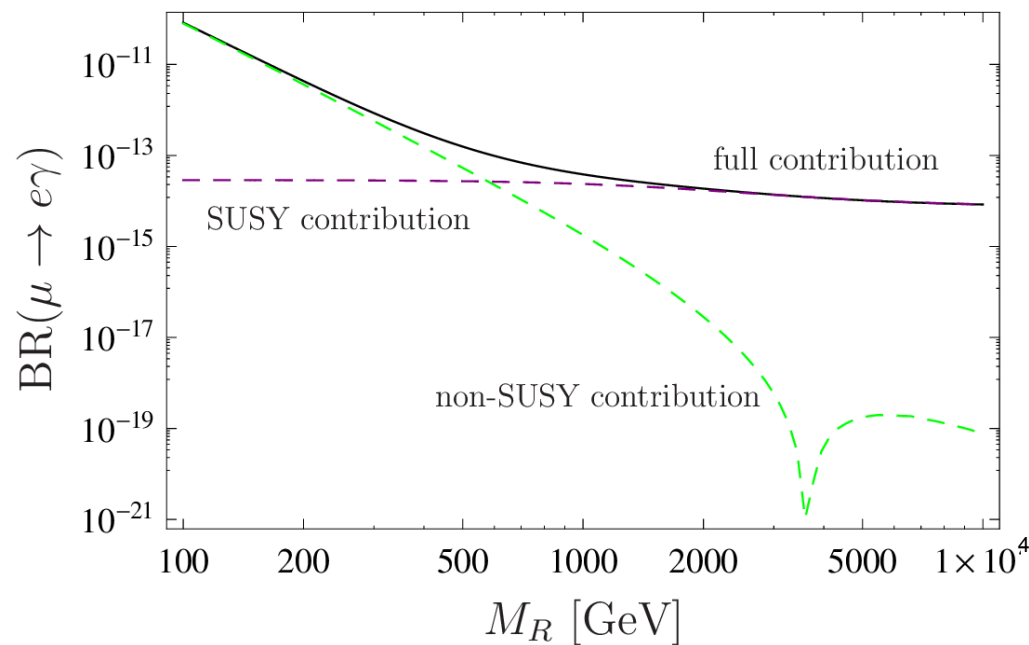
$$\text{BR}(\tau \rightarrow 3 \mu) < 4.6 \cdot 10^{-8} \text{ (at 90\% CL)}$$

To be compared with $2.1 \cdot 10^{-8}$ (**Belle**)

Low-scale seesaw models

$$\ell_i \rightarrow \ell_j \gamma$$

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

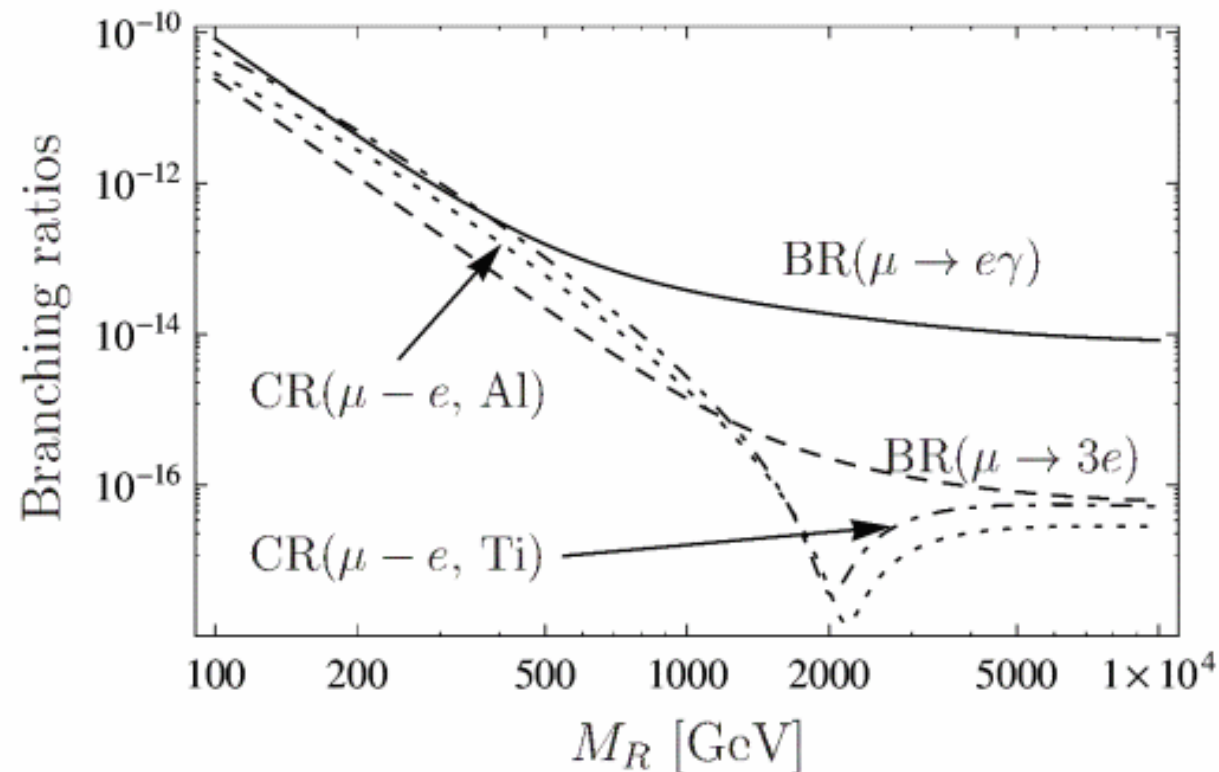


The anatomy of LFV strongly depends on M_R and M_{SUSY}

Low-scale seesaw models

$$\ell_i \rightarrow 3 \ell_j$$

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

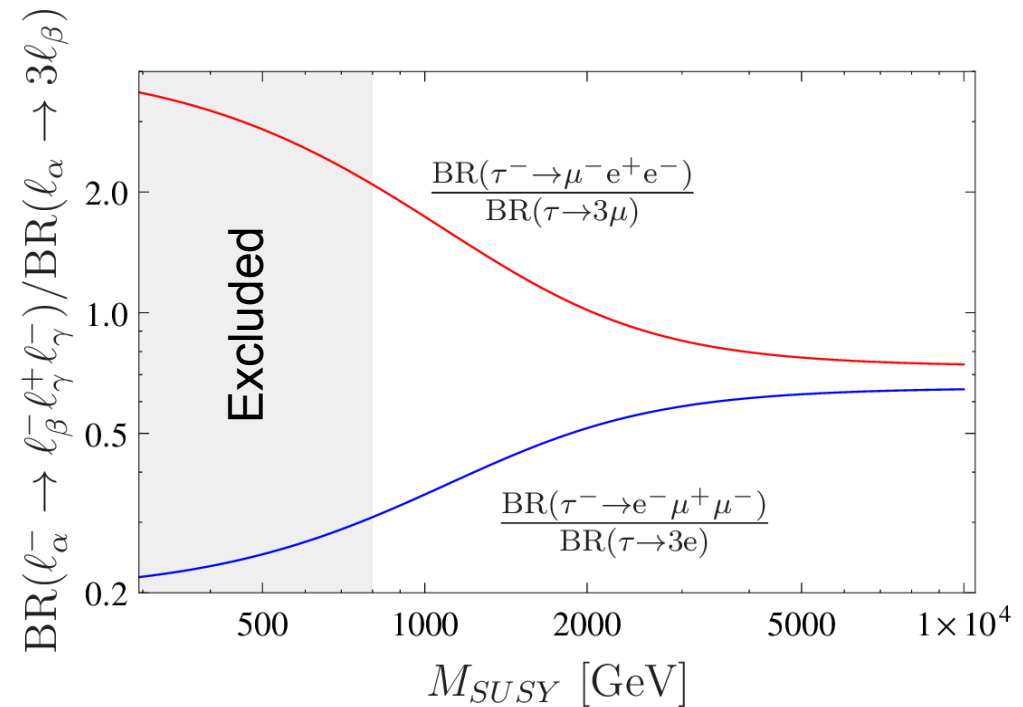
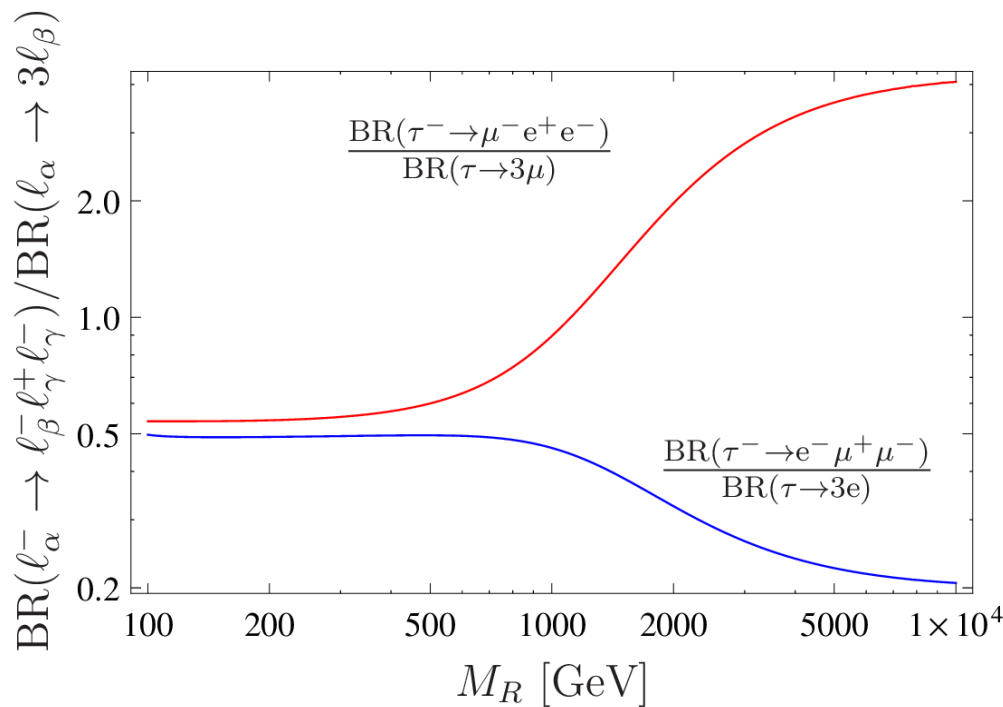


The **dipole dominance** is **broken** for low RH neutrino masses

Low-scale seesaw models

$$\ell_i \rightarrow \ell_j \ell_k \ell_k$$

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



Tau LFV decay ratios provide information on the **mass scales**

Vector-like leptons

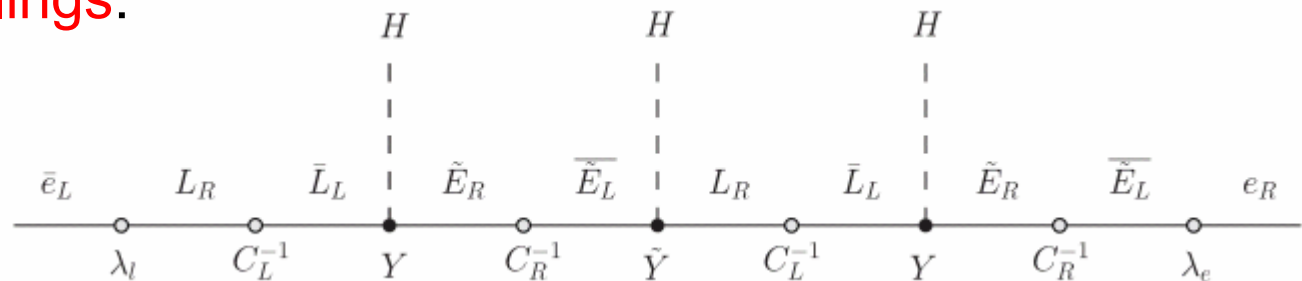
[Falkowski, Straub, AV, 2014]

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:

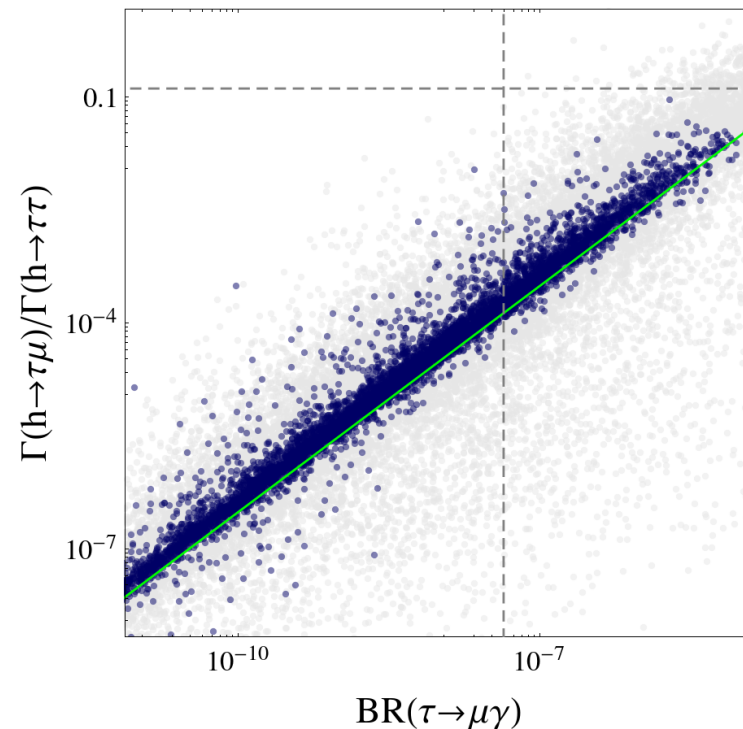
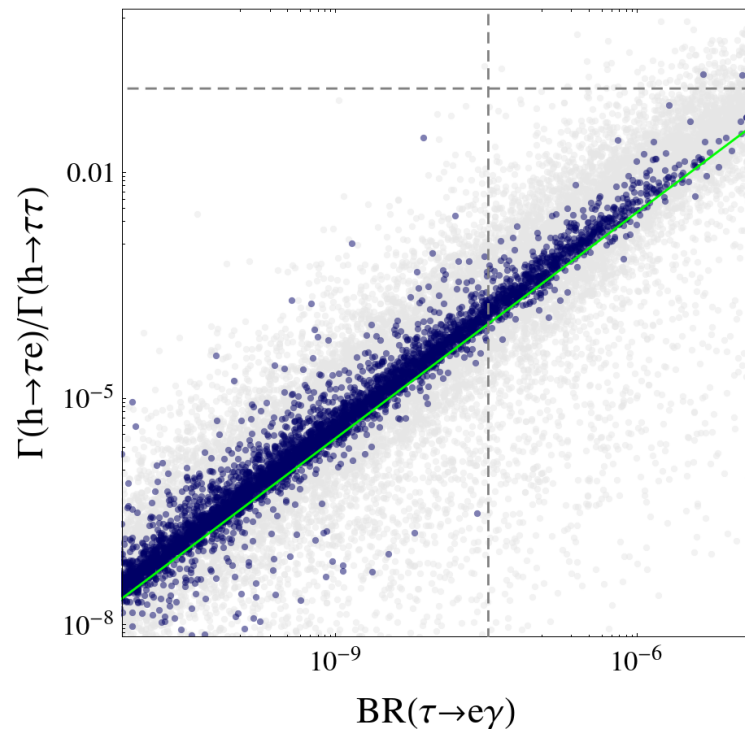


$$\mathcal{L}_{\text{eff}} = -\frac{h}{\sqrt{2}} \bar{e}_L \mathbf{c}_{\text{eff}} e_R + \text{h.c.} \quad \mathbf{c}_{\text{eff}} = Y_{\text{eff}} + \frac{v^2}{M^2} \lambda_l C_L^{-1} Y C_R^{-1} \tilde{Y} C_L^{-1} Y C_R^{-1} \lambda_e$$

Vector-like leptons

[Falkowski, Straub, AV, 2014]

$$\Rightarrow \text{BR's} \lesssim 10^{-5}$$



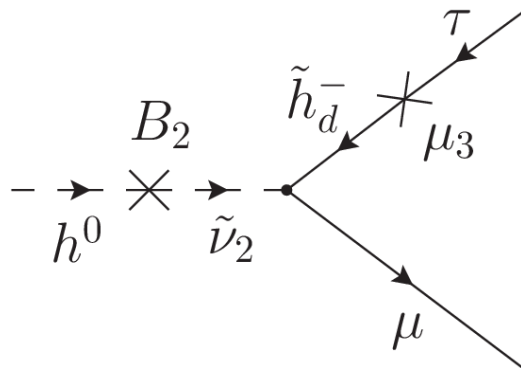
Unfortunately... **unobservable at the LHC**



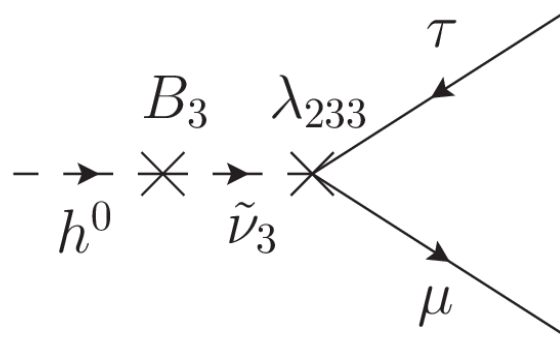
$H \rightarrow \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]

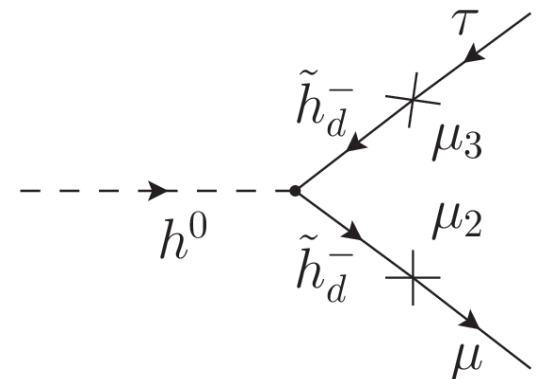
The **particles-sparticles mixing** induced by RPV lead to **tree-level LFV Higgs decays**



$B\epsilon$ contribution



$B\lambda$ contribution

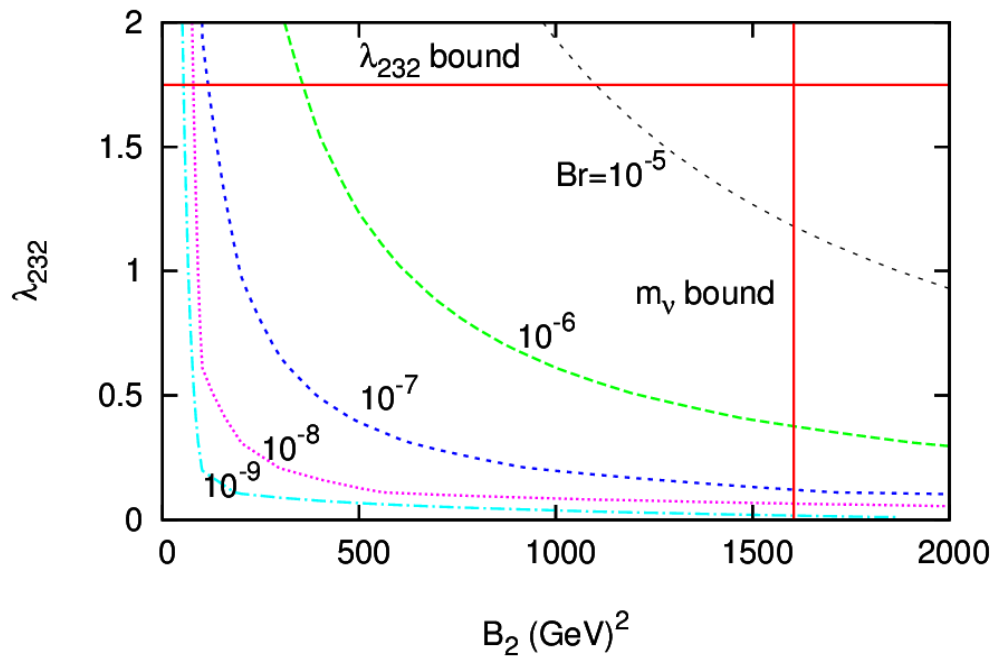


ϵ^2 contribution

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

$H \rightarrow \mu\tau$ 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}
$B_1 A_{123}^\lambda$	5×10^{-11}
$B_1 A_{132}^\lambda$	5×10^{-11}
$B_2 A_{232}^\lambda$	5×10^{-11}
$B_3 A_{233}^\lambda$	5×10^{-11}

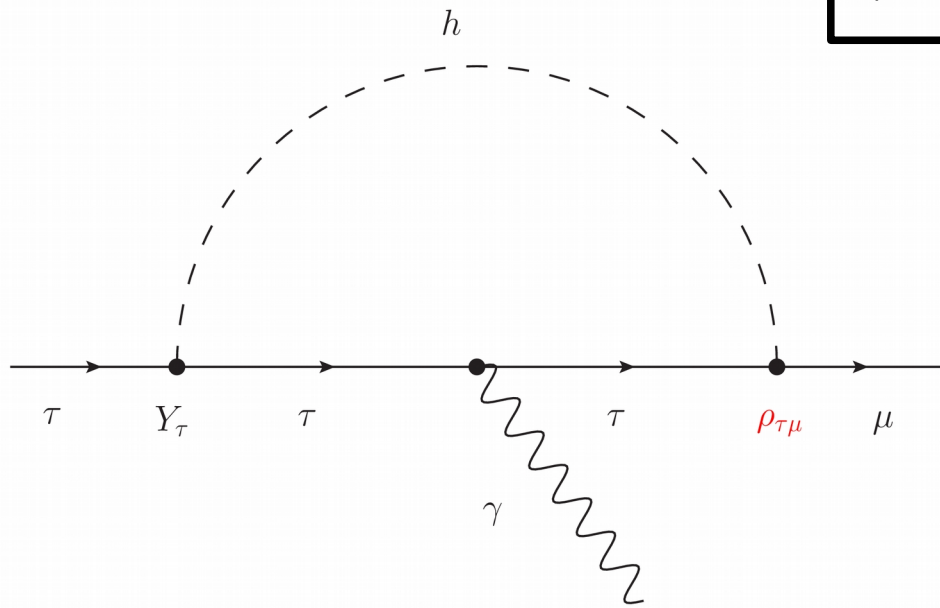
Again... **unobservable at the LHC**



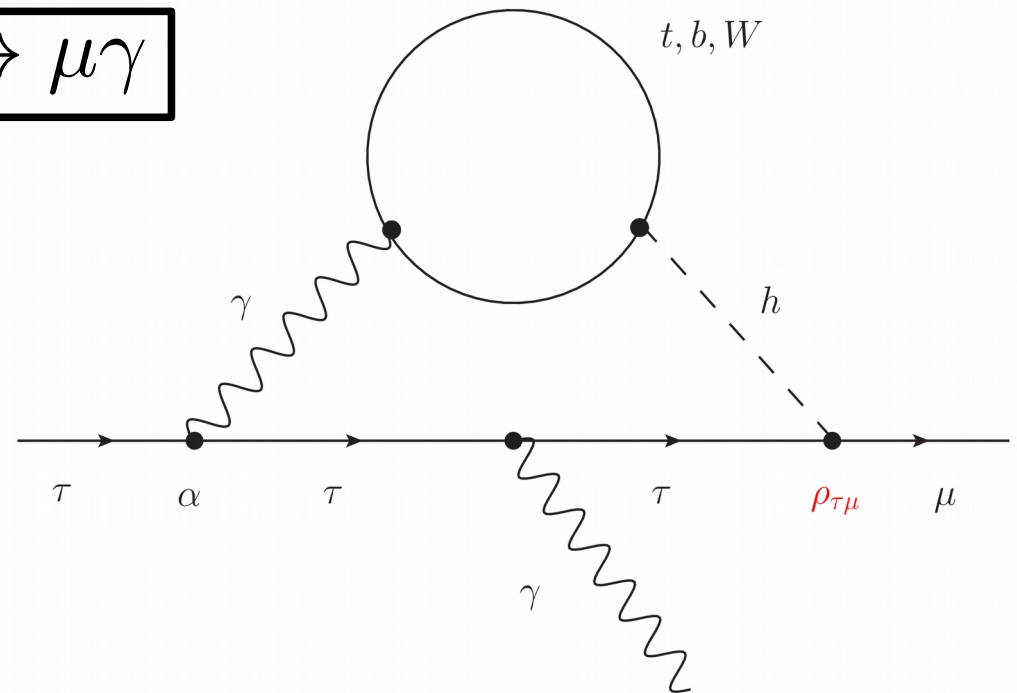
A new hope: Type-III 2HDM

[Davidson, Grenier, 2010; Harnik et al, 2013; Kopp, Nardecchia, 2014]

$$\tau \rightarrow \mu \gamma$$



1-loop



2-loop
Barr-Zee

The Type-III 2HDM

[Lee, 1973; Branco, 1980]

[Davidson, Grenier, 2010; Aristizabal Sierra, AV, 2014]

In **Higgs Basis** for the Higgs doublets and the **mass basis** for the fermions:

$$-\mathcal{L}_Y = \sqrt{2} \left(\overline{q}_{Lj} \tilde{H}_1 \frac{K_{ij}^* m_i^U}{v} u_{Ri} + \overline{q}_{Li} H_1 \frac{m_i^D}{v} d_{Ri} + \overline{\ell}_{Li} H_1 \frac{m_i^E}{v} e_{Ri} \right) \\ + \overline{q}_{Li} \tilde{H}_2 \rho_{ij}^U u_{Rj} + \overline{q}_{Li} H_2 \rho_{ij}^D d_{Rj} + \overline{\ell}_{Li} H_2 \rho_{ij}^E e_{Rj} + \text{h.c.}$$

ρ^E : general 3x3 matrix

Type-III = most general case

The Type-III 2HDM

[Lee, 1973; Branco, 1980]

[Davidson, Grenier, 2010; Aristizabal Sierra, AV, 2014]

Higgs couplings to fermions

$$g_{hff'} = \frac{m_f}{v} s_{\beta-\alpha} \delta_{ff'} + \frac{\rho_{ff'}}{\sqrt{2}} c_{\beta-\alpha}$$

Parameterization inspired in the Sher-Cheng ansatz

$$\rho_{ij}^E = -\kappa_{ij} \tan \beta_\tau \frac{\sqrt{2m_i m_j}}{v}$$

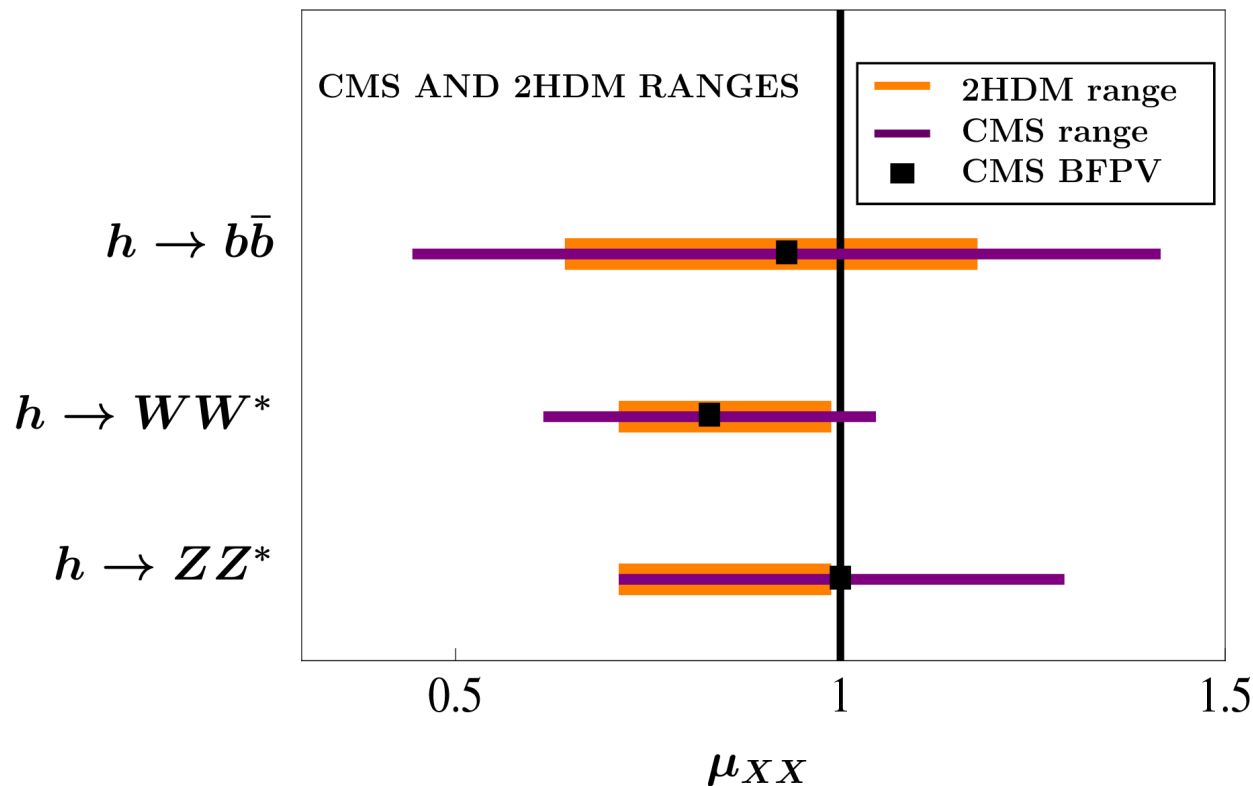
$$\tan \beta_\tau = \frac{-\rho_{\tau\tau}}{\sqrt{2}m_\tau/v}$$

Type-II values are assumed
for the quark couplings

Reminder: no unique
definition of $\tan \beta$
in the type-III 2HDM

Higgs LFV decays in the Type-III 2HDM

[Aristizabal Sierra, AV, 2014]



Signal strengths

$$\mu_{XX} = \left(\frac{g_{htt}}{g_{htt}^{\text{SM}}} \right)^2 \left(\frac{g_{hXX}}{g_{hXX}^{\text{SM}}} \right)^2$$

Gluon fusion is assumed!

Signal strengths ranges in the 2HDM
Compatible with all constraints and the CMS signal for $h \rightarrow \tau\mu$