Higgs lepton flavor violating decays

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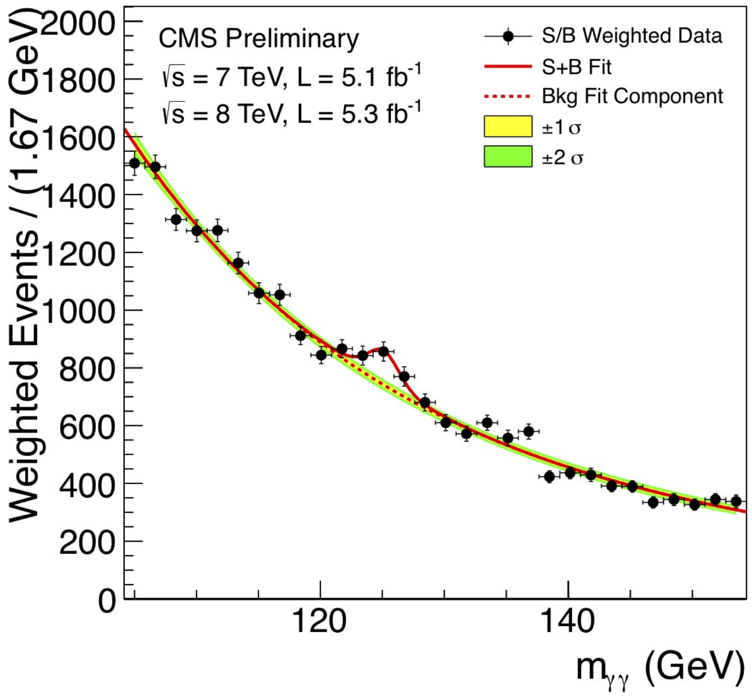
WIN 2023

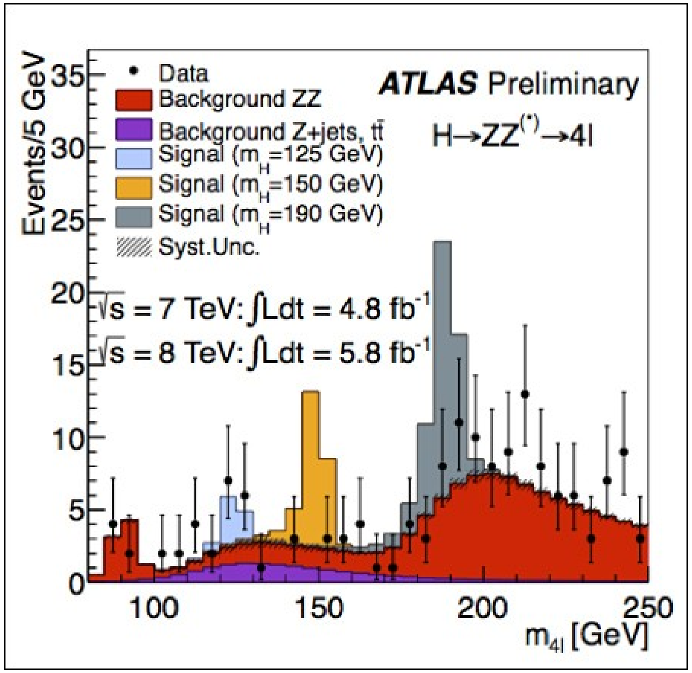
Zhuhai

The Higgs boson discovery

- July 4th, 2012:

The Higgs boson discovered by ATLAS and CMS!





$$\text{CMS} : (125.3 \pm 0.6)\,\text{GeV} \qquad \text{ATLAS} : 126.5\,\text{GeV}$$

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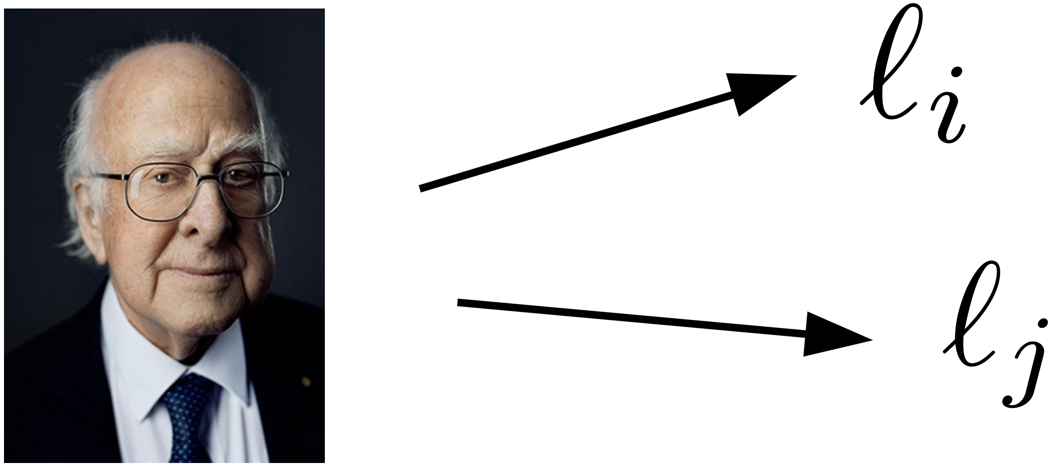
Higgs LFV decays

We have discovered the Higgs

However, is there room for non-standard decays?



ℓ_i

ℓ_j

$\boxed{h \to \mu\, e}$ $\boxed{h \to \tau\, e}$ $\boxed{h \to \tau\, \mu}$

Outline of the talk

- Introduction
- General considerations
- Example model: the 2HDM
- Final comments

General considerations

EFT preliminaries

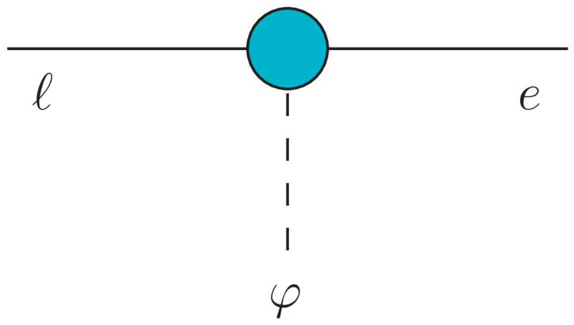
[Diaz-Cruz, Toscano, 2000]

[Harnik, Kopp, Zupan, 2012]

[Herrero-Garcia, Rius, Santamaria, 2016]

[AV, 2019]

$$-\mathcal{L}_{\rm SM}^{Y} = \bar{\ell}\,\Gamma_e\,e\,\varphi + \text{h.c.}$$



EFT preliminaries

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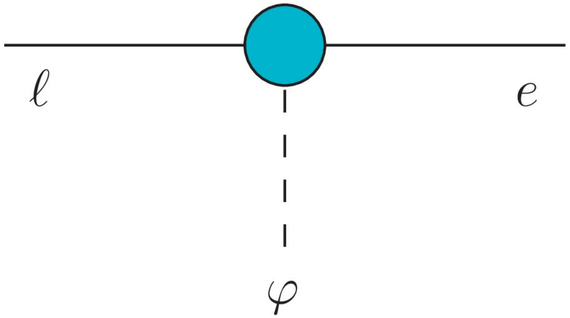
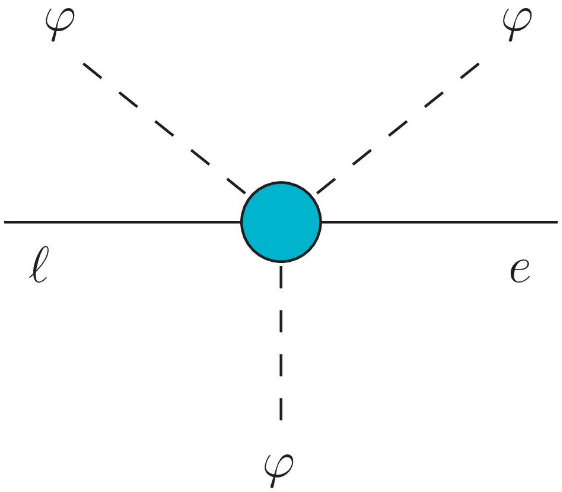


$$\mathcal{L}_{\rm EFT} = \frac{C_i}{\Lambda^{d-4}}\,Q_i + \text{h.c.}$$



$$Q_{e\varphi} = \left(\varphi^\dagger\varphi\right)\,\left(\bar{\ell}\,e\,\varphi\right)$$

EFT preliminaries

[Diaz-Cruz, Toscano, 2000]

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[Harnik, Kopp, Zupan, 2012]

[AV, 2019]

After EW symmetry breaking:

Lepton doublet

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

Scalar doublet

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h + i\, G^0 + v) \end{pmatrix}$$

The Higgs boson!

EFT preliminaries

[Diaz-Cruz, Toscano, 2000]

[Herrero-Garcia, Rius, Santamaria, 2016]

[Harnik, Kopp, Zupan, 2012]

[AV, 2019]

After EW symmetry breaking:

$$\mathcal{L}_{\mathrm{SM}}^{Y} + \mathcal{L}_{\mathrm{EFT}} \supset$$

$$-\,\bar{e}_L \left[\frac{v}{\sqrt{2}} \left(\Gamma_e - C_{e\varphi}\,\frac{v^2}{2\Lambda^2} \right) + \frac{h}{\sqrt{2}} \left(\Gamma_e - 3\,C_{e\varphi}\,\frac{v^2}{2\Lambda^2} \right) \right] e_R + \mathrm{h.c.}$$

$$= -\,\bar{e}_L \left[\mathcal{M}_e + h\,\mathcal{Y}_e \right] e_R + \mathrm{h.c.}$$

Charged leptons mass matrix

Higgs coupling to charged leptons

EFT preliminaries

In general, the matrices $\mathcal{M}_e$ and $\mathcal{Y}_e$ are <u>not diagonal in the same basis</u>

$$V_{e_L}^\dagger \mathcal{M}_e V_{e_R} = \widehat{\mathcal{M}}_e = \text{diag}(m_e, m_\mu, m_\tau)$$

$$g_{h\ell\ell} = V_{e_L}^\dagger \mathcal{Y}_e V_{e_R} = \frac{1}{v} \widehat{\mathcal{M}}_e - \frac{v^2}{\sqrt{2}\Lambda^2} V_{e_L}^\dagger C_{e\varphi} V_{e_R}$$

$$\Downarrow$$

Higgs LFV decays

$$\text{BR}(h \to \ell_i \ell_j) = \frac{m_h}{8\pi\Gamma_h} \left(|g_{h\ell_i\ell_j}|^2 + |g_{h\ell_j\ell_i}|^2 \right)$$

EFT preliminaries

However, this is not all there is...

$$Q_{eW} = \left(\bar{\ell}\sigma^{\mu\nu}e\right)\tau^I\varphi\,W_{\mu\nu}^I \qquad Q_{eB} = \left(\bar{\ell}\sigma^{\mu\nu}e\right)\varphi\,B_{\mu\nu}$$

$$\mathcal{L}_{\text{EFT}}^{\text{low}} = \frac{L_{e\gamma}}{v}\,\mathcal{O}_{e\gamma} + \text{h.c.}$$

$$\boxed{\mathcal{O}_{e\gamma} = \bar{e}_L\sigma^{\mu\nu}e_R\,F_{\mu\nu}}$$

$$\Downarrow$$

Charged LFV decays ⚠

$$\text{BR}(\ell_i \to \ell_j\gamma) = \frac{m_i^3}{4\pi v^2\,\Gamma_i}\left(|\left(L_{e\gamma}\right)_{ij}|^2 + |\left(L_{e\gamma}\right)_{ji}|^2\right)$$

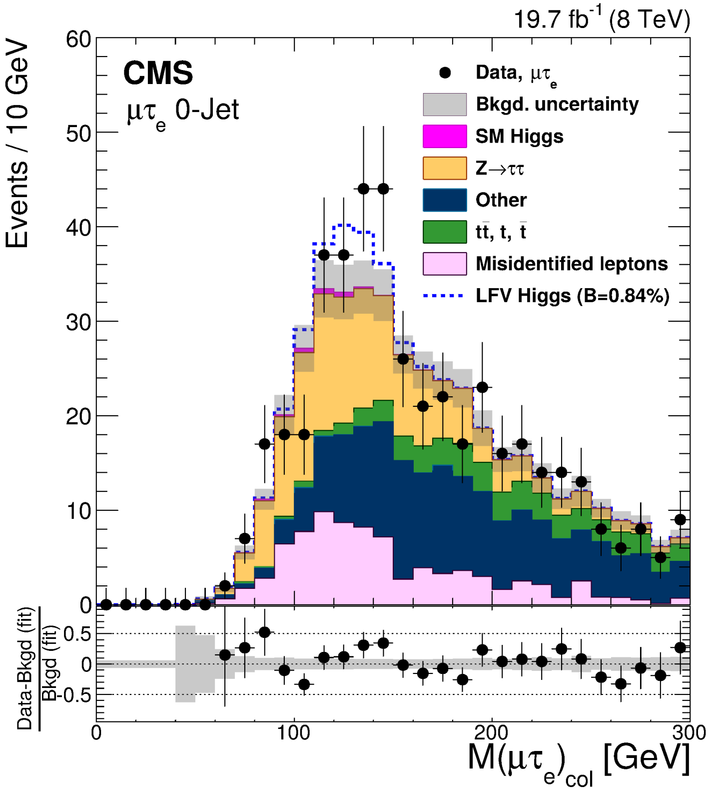
OK, fine...
But can this be measured?

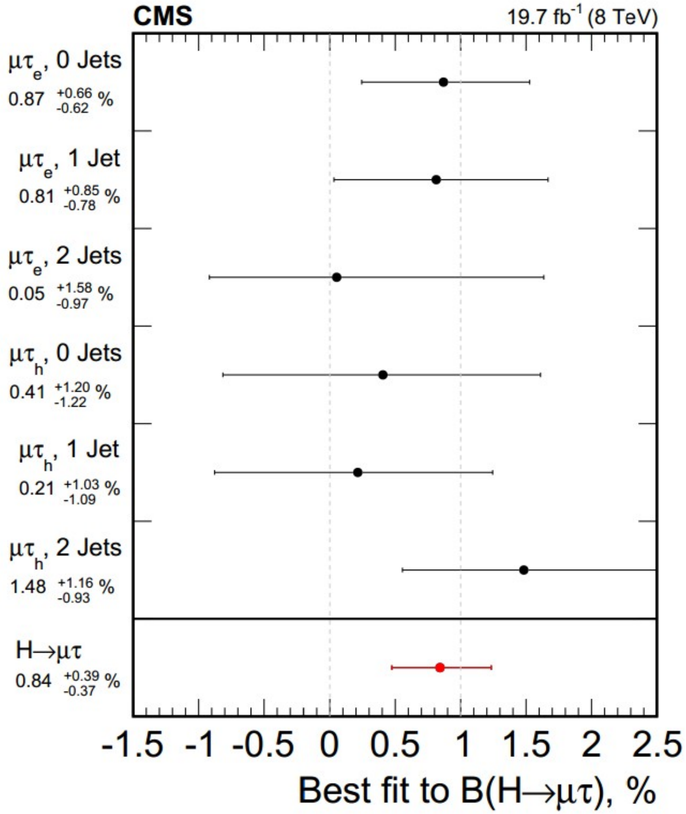
A hint from CMS?

A 2.4σ excess in $h \to \tau\mu$

[PLB 749 (2015) 337, arXiv:1502.07400]

First public note
in July 2014





$$\mathrm{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

Too good to be true

Run-2 data did not confirm the excess

The first analysis by CMS of their run-2 data collected in 2015...

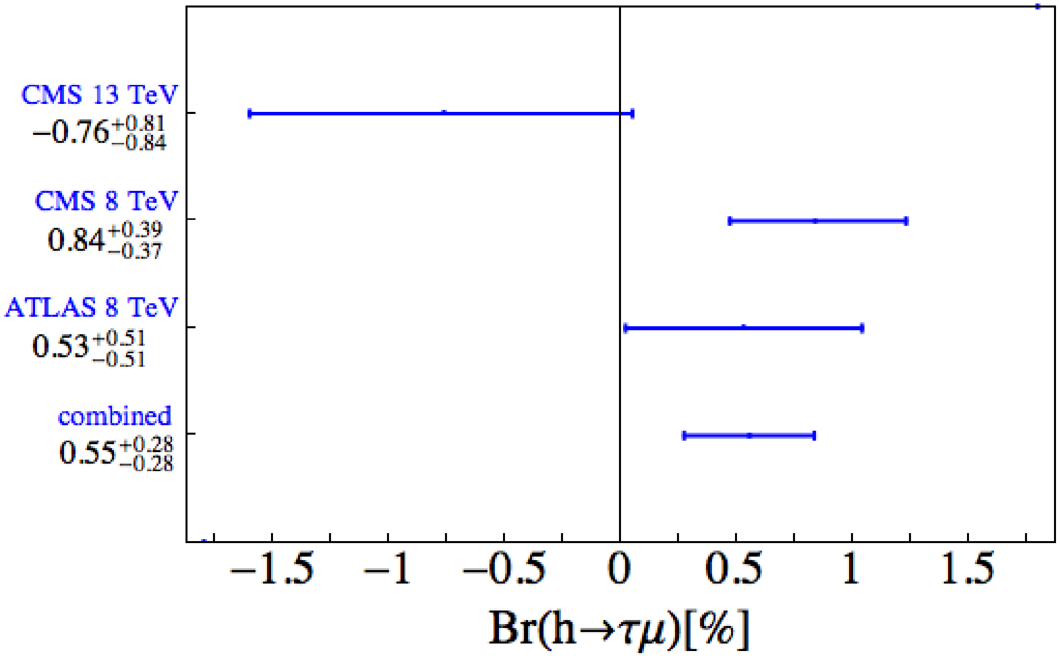
... killed the excitement

Current limits

$$\mathrm{BR}(h \to \tau\,\mu)_{\mathrm{CMS}} \lesssim 1.5 \cdot 10^{-3}$$

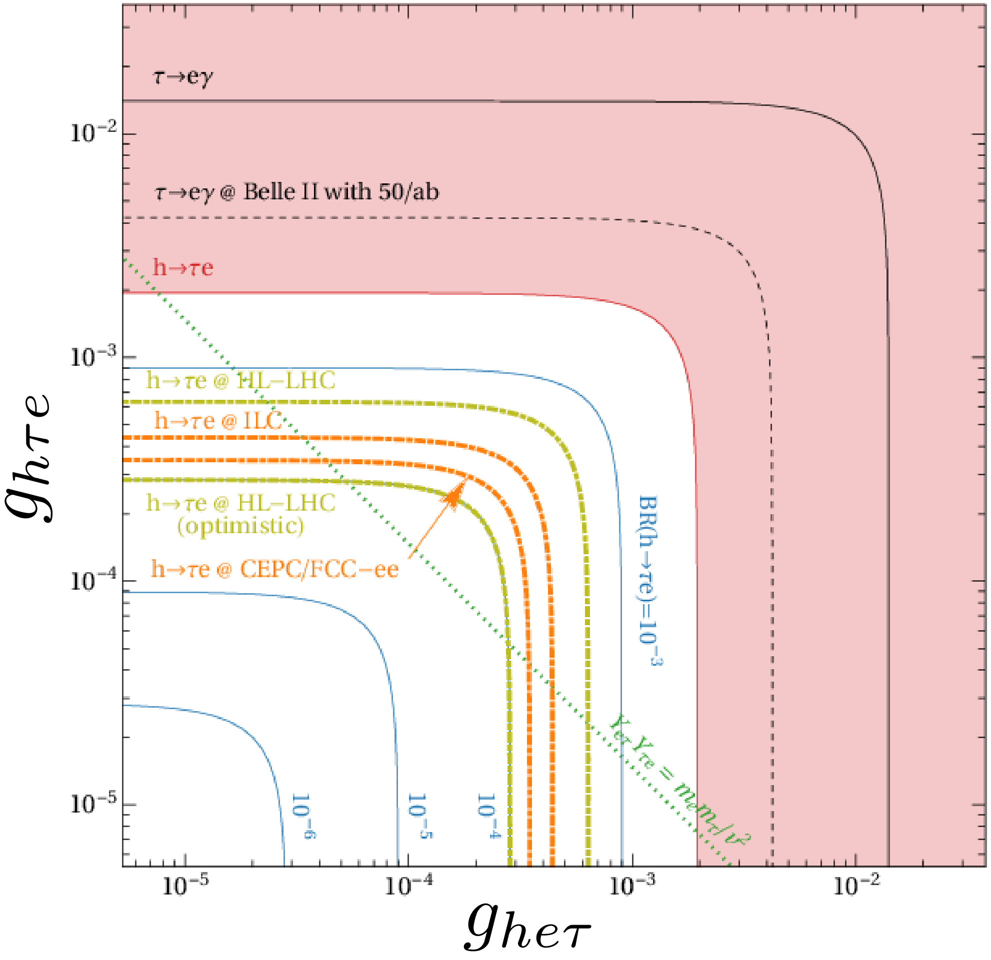
$$\mathrm{BR}(h \to \tau\,\mu)_{\mathrm{ATLAS}} \lesssim 1.8 \cdot 10^{-3}$$

[Figure from the Resonaances blog]

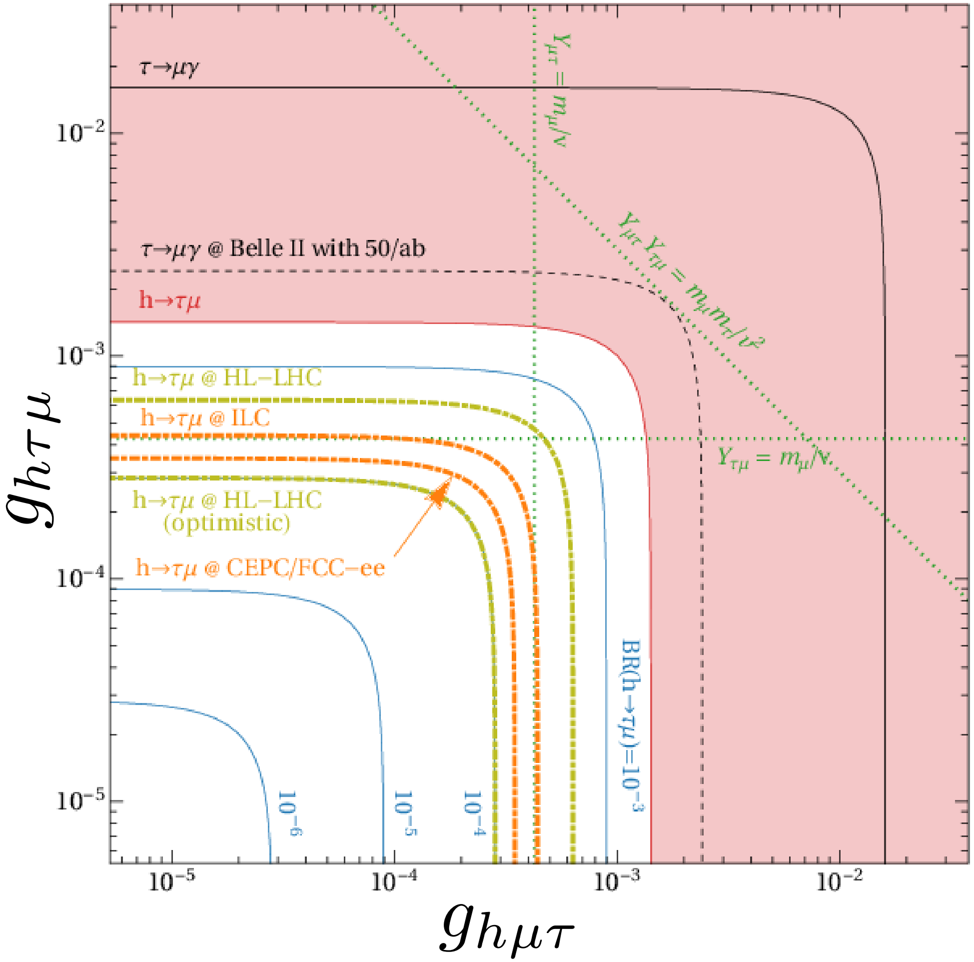


Nevertheless, we learned a lot about Higgs LFV decays

$\tau\ e$



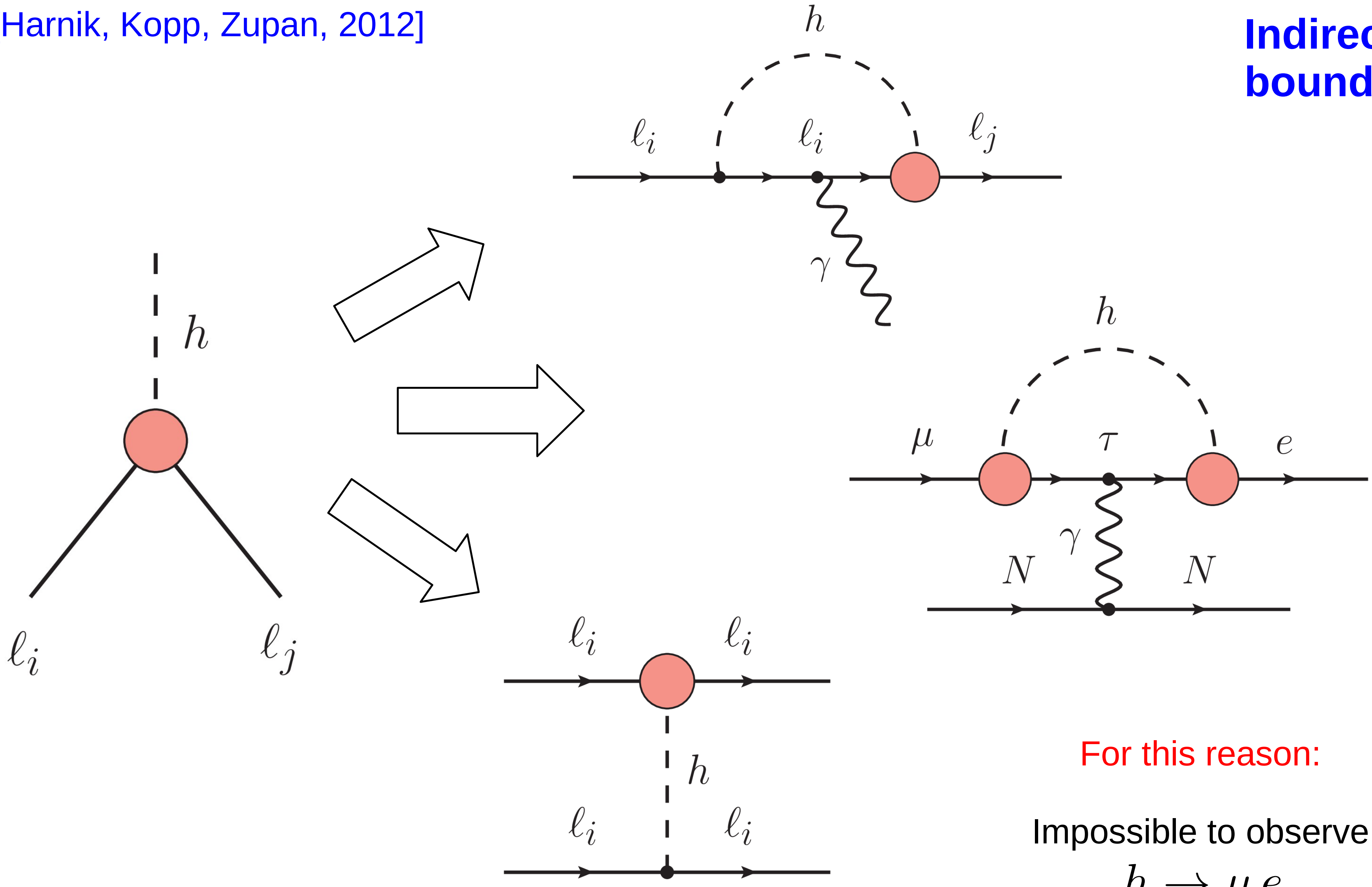
$\tau\ \mu$



[Figures from Altmannshofer et al, 2205.10576]

[Harnik, Kopp, Zupan, 2012]

Indirect bounds



For this reason:

Impossible to observe

$$h \to \mu\, e$$

$h \to \tau\mu$ in the 2HDM

A new hope: Type-III 2HDM

[Diaz-Cruz, Toscano, 2000]

[Davidson, Grenier, 2010]

[Harnik et al, 2013]

[Kopp, Nardecchia, 2014]

Type-III 2HDM

[Type-III = most general case]

Introduce two identical Higgs doublets: $\{\varphi_1, \varphi_2\}$

- Both doublets are allowed to couple to all fermions
- One can perform arbitrary $U(2)$ transformations in the doublet space

$$\varphi_1 = \left(\begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}} \left(v + \phi_1^0 + i\, G^0 \right) \end{array} \right) \quad \varphi_2 = \left(\begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}} \left(\phi_2^0 + i\, A \right) \end{array} \right)$$

Technical note: I work in the *Higgs basis*

A new hope: Type-III 2HDM

[Diaz-Cruz, Toscano, 2000]

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[Kopp, Nardecchia, 2014]

Type-III 2HDM

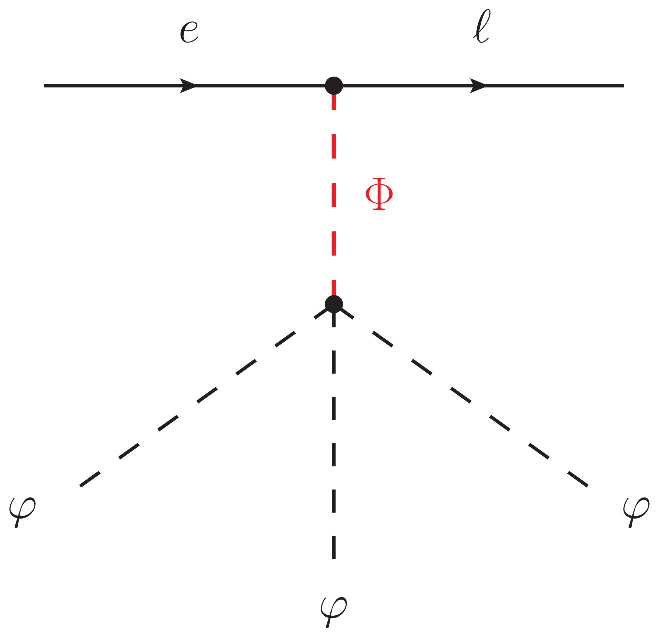
[Type-III = most general case]

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} s_{\beta-\alpha} & c_{\beta-\alpha} \\ c_{\beta-\alpha} & -s_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

$$-\mathcal{L}_{2\mathrm{HDM}}^{Y} \supset \bar{e}_L \left(\frac{1}{v} \widehat{\mathcal{M}}_e \, s_{\beta-\alpha} + \frac{1}{\sqrt{2}} \underset{\substack{\uparrow \\ \text{General 3x3 matrix}}}{\rho_e} \, c_{\beta-\alpha} \right) e_R \, h + \mathrm{h.c.}$$

EFT motivation

Suppressed $\mathcal{O}_{e\gamma}$



UV completion of

$$Q_{e\varphi} = \left(\varphi^\dagger \varphi\right) \left(\bar{\ell}\, e\, \varphi\right)$$

- Induced at 1-loop
- Closing the loop introduces a charged lepton mass insertion
- A necessary chirality flip introduces another charged lepton mass insertion

$$\left(L_{e\gamma}\right)_{ij} \sim \left(\frac{m_i}{v}\right)^2 \frac{1}{16\,\pi^2} \left(C_{e\varphi}\right)_{ij} \ll \left(C_{e\varphi}\right)_{ij}$$

This estimate is known to be poor...

but it gives us hope!

A new hope: Type-III 2HDM

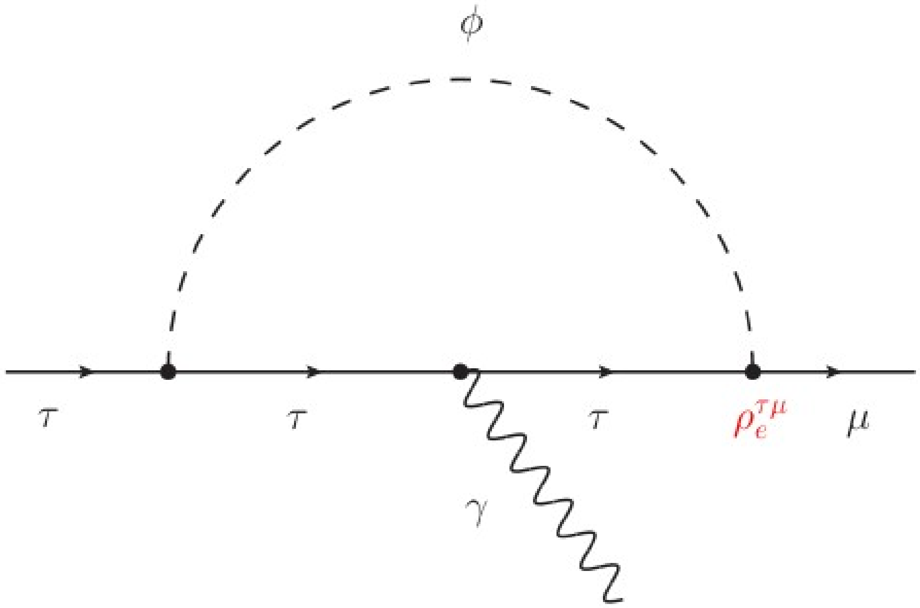
[Aristizabal Sierra, AV, 2014]

Explicit *proof* including the relevant constraints

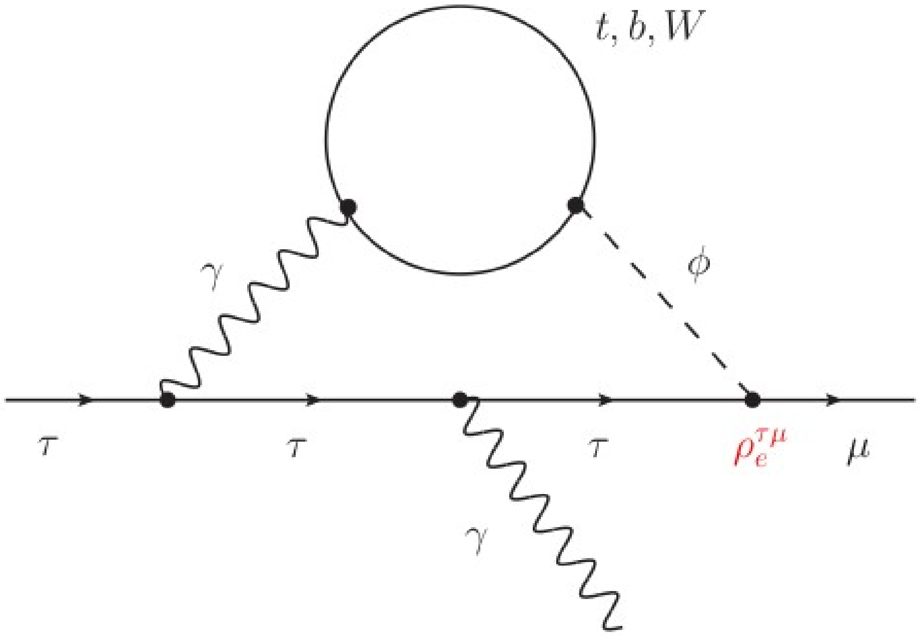
- Direct searches
- Indirect constraints from flavor
- $\tau \to \mu\gamma$
- Higgs couplings to fermions
- T parameter
- Perturbativity and boundedness from below

A new hope: Type-III 2HDM

$\tau \to \mu\gamma$ in the type-III 2HDM

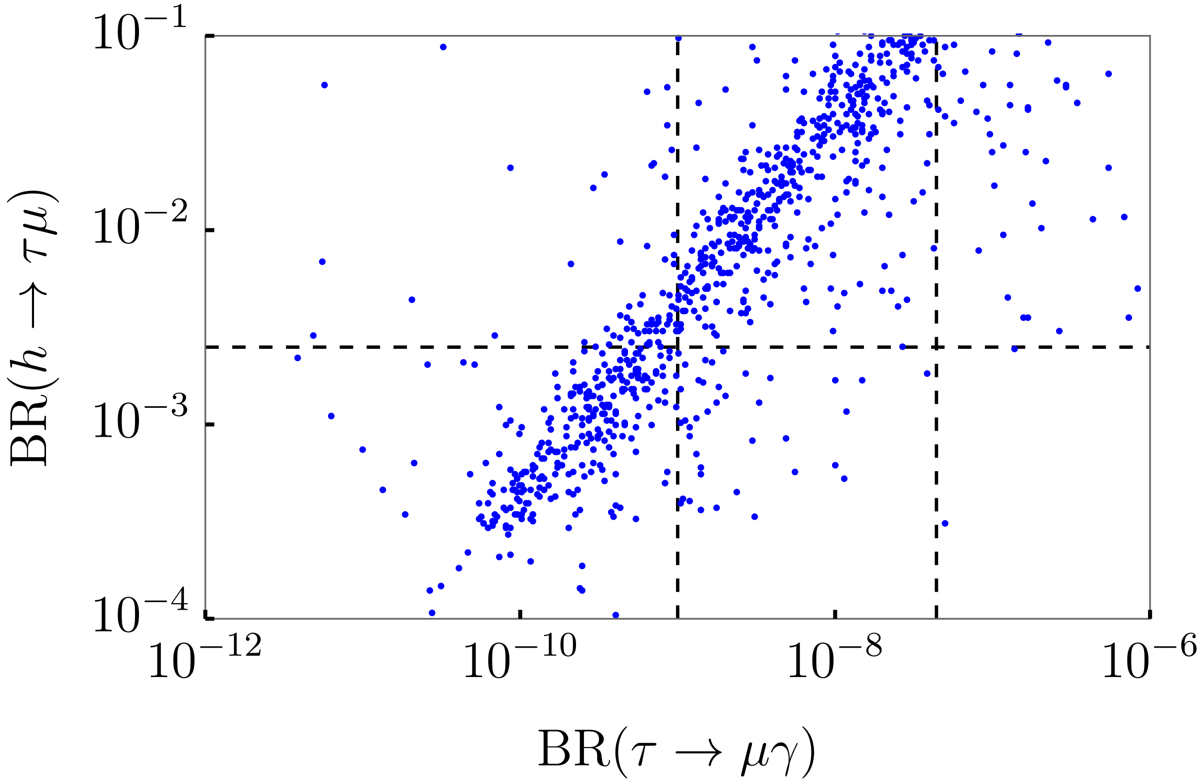


1-loop diagrams



2-loop Barr-Zee diagrams

A new hope: Type-III 2HDM



[Aristizabal Sierra, AV, 2014]

Updated in

[AV, 2019]

The correlation is not exact due to the multiple contributions to $\tau \to \mu\gamma$

The 2-loop Barr-Zee contributions usually dominate

Main conclusion:

the model leads to observable Higgs LFV in parts of the parameter space

Some final comments

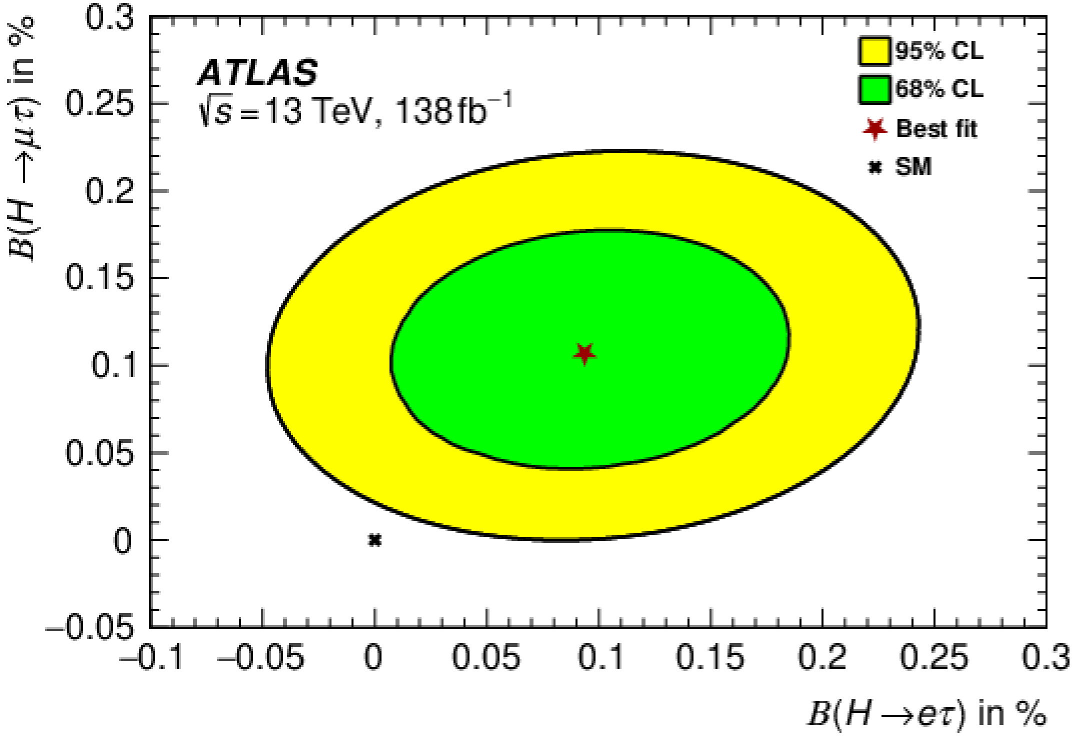
- Recent results by ATLAS

  2302.05225

  “ $2.1\,\sigma$ tension”

  or

  “Agreement at $2.1\,\sigma$”



- Additional information in polarization: 2302.08489, talk by Takeuchi-san
- Higgs LFV @ future colliders: 2305.05386, 2306.17520

The real final comments

The Higgs boson has been already discovered but it may hide many valuable secrets

On general grounds, one expects Higgs LFV decays in many new physics scenarios

Constraints from other LFV observables imply that in most models one finds very low rates, unobservable at the LHC

Scalar extensions (such as the general type-III 2HDM) are the most promising scenarios

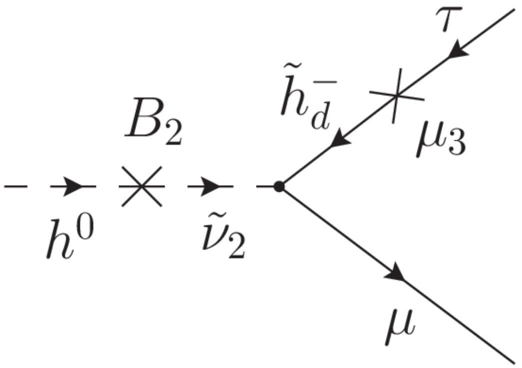
Thank you for your attention!

Backup slides

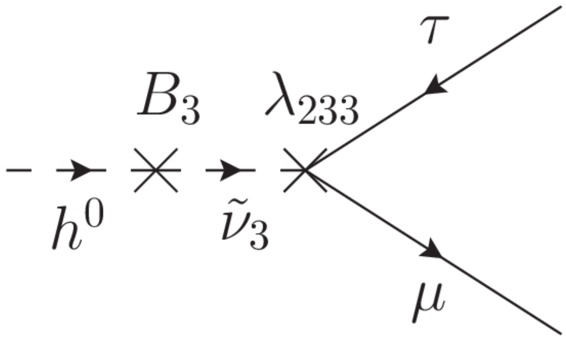
$H \to \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]

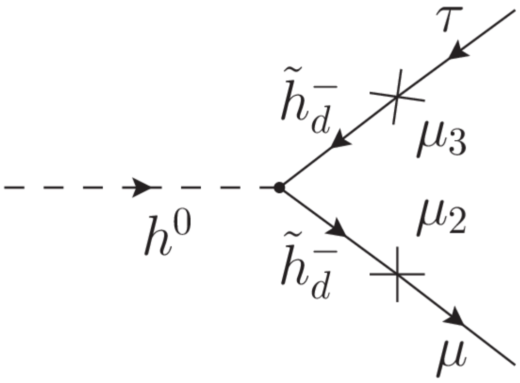
The particles-sparticles mixing induced by RPV lead to
tree-level LFV Higgs decays



$B\epsilon$ contribution



$B\lambda$ contribution

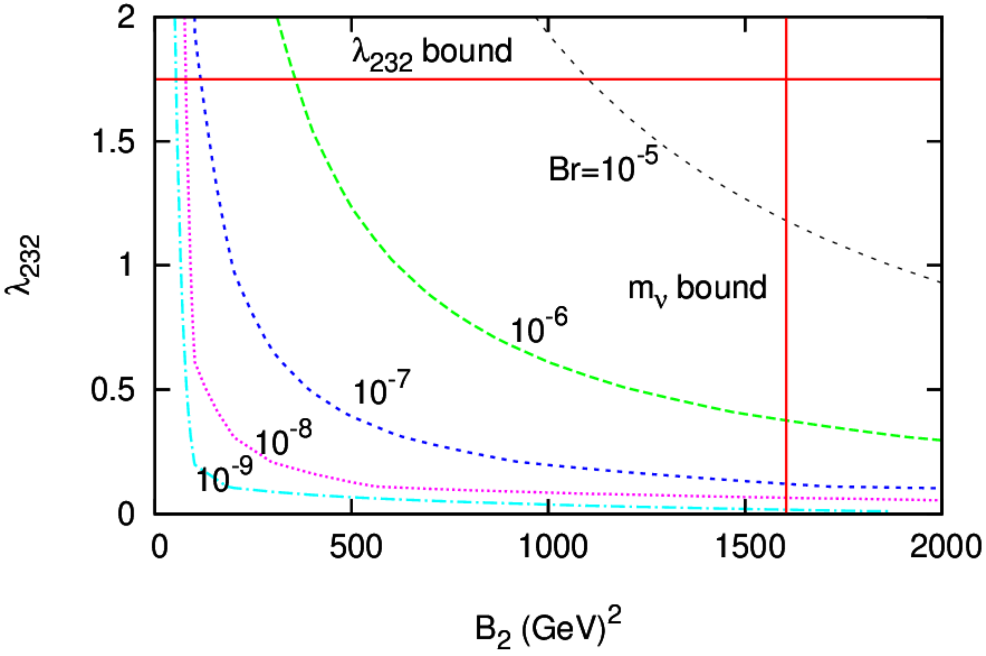


ϵ^2 contribution

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

Vector-like leptons

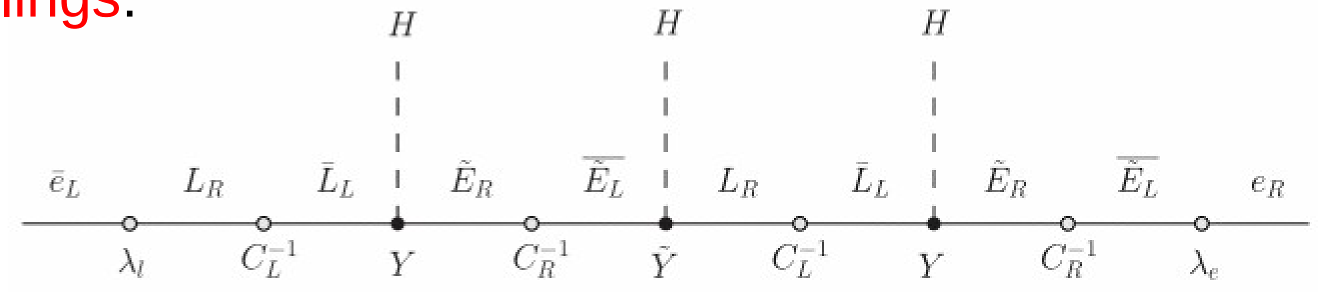
[Falkowski, Straub, AV, 2014]

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:

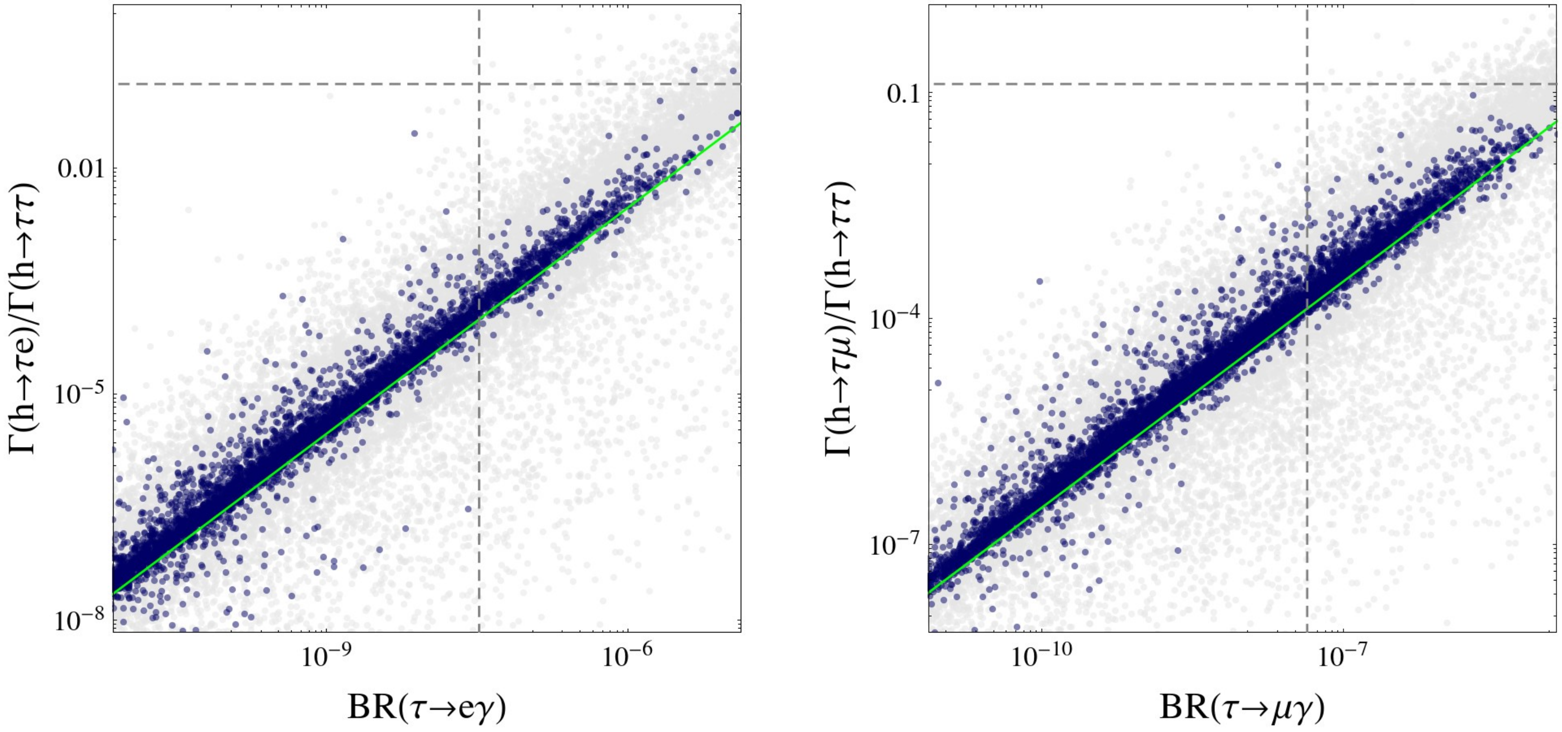


$$\mathcal{L}_{\text{eff}} = -\frac{h}{\sqrt{2}} \bar{e}_L c_{\text{eff}} e_R + \text{h.c.} \qquad c_{\text{eff}} = Y_{\text{eff}} + \frac{v^2}{M^2} \lambda_l C_L^{-1} Y C_R^{-1} \tilde{Y} C_L^{-1} Y C_R^{-1} \lambda_e$$

Vector-like leptons

[Falkowski, Straub, AV, 2014]

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



Unfortunately... unobservable at the LHC

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