Higgs lepton flavor violation: UV completions and connection to neutrino masses

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Outline

Introduction

Higgs lepton flavor violation

- CMS [ATLAS] at 8 TeV observes hint of a signal at $2.4\,[1]\sigma$:

$$\mathrm{BR}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\,\%\,[(0.53 \pm 0.51)\,\%]\,.$$

- If interpreted as upper bounds, at $95\,\%$ CL, we have:

$$\mathrm{BR}(H \to \mu\tau) < 1.51\,(1.43) \cdot 10^{-2}\ \text{CMS}\,(\text{ATLAS})\,.$$

- 2015 data: $\mathrm{BR}(H \to \mu\tau) = (-0.76^{+0.81}_{-0.84})\,\%$. Doesn't exclude 8 TeV.
- If not confirmed, $H \to \mu\tau$ will still be a very sensitive BSM probe.

We want to ask:

1. What are the UV completions and their expected HLFV rates?
2. Could HLFV be connected to neutrino masses, i.e., $\Lambda_{\mathrm{LNV}} \sim \Lambda_{\mathrm{LFV}}$?
   - LFV observed in ν oscillations, and is expected in charged leptons.
   - For Dirac ν or in seesaws HLFV and CLFV rates are unobservable.

NP is needed for HLFV

- SM Higgs couplings are diagonal, so NP required for HLFV:

$$\mathcal{L} = -\overline{e_{\mathrm{Li}}}\, M_{\mathrm{i}}\, e_{\mathrm{Ri}} - H\, \overline{e_{\mathrm{Li}}}\, y_{\mathrm{ij}}\, e_{\mathrm{Rj}} + \mathrm{H.c.}$$

giving:

$$\mathrm{BR}(H \to \tau\mu) = \frac{m_H}{8\pi\, \Gamma_H^{\mathrm{total}}} \left(|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2\right),$$

or for quick estimates, using $\mathrm{BR}(H \to \tau\tau) = 0.065$:

$$\mathrm{BR}(H \to \tau\mu) \approx 0.065\, \frac{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2}{2\, |y_{\tau\tau}|^2}\, .$$

- To explain the excess we need at $\sim 1\sigma$, for $\Gamma_H^{\mathrm{total}} = \Gamma_H^{\mathrm{SM}} + \Gamma_H^{\mathrm{new}}$:

$$0.002 \lesssim \sqrt{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2} \lesssim 0.003.$$

UV completions from EFT

The *Yukawa* and *Derivative operators*

- SM + EFT [Buchmuller, Grzadkowski, Harnik...]:

$$\mathcal{L}_{\rm leptons} = \overline{L} i \not{D} L + \overline{e_{\rm R}} i \not{D} e_{\rm R} - (Y_{\rm e} \overline{L} e_{\rm R} \Phi + \sum_a \frac{C_a}{\Lambda^2} \mathcal{O}_a + {\rm H.c.})$$

$$D = 6: \qquad \mathcal{O}_{\rm Y} = \overline{L}\, C_Y\, e_{\rm R} \Phi (\Phi^\dagger \Phi)\,, \quad \mathcal{O}_{\rm D\,i} = (\overline{e_{\rm R}} \Phi^\dagger)\, C_{D\,i}\, i \not{D} (e_{\rm R}\, \Phi)\,.$$

- $\mathcal{O}_{\rm D\,i}$ related by EOM to $\mathcal{O}_{\rm Y}+$ plus other non-HLFV operators.
- After SSB, $\langle \Phi_0 \rangle = (H + v)/\sqrt{2}$, diagonalize M_e:

$$(M_{\rm e})_{ii} \equiv \text{diag}(m_e, m_\mu, m_\tau) = \frac{1}{\sqrt{2}} V_{\rm L}^\dagger \Big(Y_{\rm e} + C_Y \frac{v^2}{2\Lambda^2} \Big) V_{\rm R} v.$$

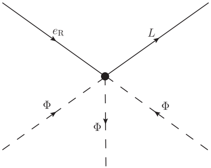
- Yukawas are no longer diagonal ($V_{\rm L}^\dagger\, C_Y\, V_{\rm R} \approx C_Y$):

$$(y_{\rm e})_{ij} = \frac{m_i}{v} \delta_{ij} + (C_Y)_{ij} \frac{v^2}{\sqrt{2}\Lambda^2}\,, \qquad \overline{C}_Y \equiv \sqrt{|(C_Y)_{\tau\mu}|^2 + |(C_Y)_{\mu\tau}|^2}\,.$$

HLFV scales and models

- NP scales necessary to explain the CMS excess as a function of $\overline{C}_Y$:

$\overline{C}_Y$	Λ (TeV)
1	5
m_τ/v	0.4
$1/(4\pi)^2$	0.4
$m_\tau/v/(4\pi)^2$	0.04



- Clearly preferred at tree level and without chirality suppression.
- Strongest constraint from $\tau \to \mu\gamma$:

$$\frac{ev}{16\pi^2\Lambda^2\sqrt{2}}\bar{\mu}\sigma_{\mu\nu}\left(C^{\gamma}_{\mu\tau}P_R + C^{\gamma *}_{\tau\mu}P_L\right)\tau F^{\mu\nu}\,,$$

which leads to

$$\mathrm{BR}(\tau\to\mu\gamma) \approx 0.03\,(\mathrm{TeV}/\Lambda)^4\,\overline{C}^2_\gamma < 4.4\times 10^{-8}\;.$$

$$\overline{C}_\gamma/\Lambda^2 \equiv \sqrt{|C^{\gamma}_{\mu\tau}|^2 + |C^{\gamma}_{\tau\mu}|^2}/\Lambda^2 \lesssim 10^{-3}\ \mathrm{TeV}^{-2}\,.$$

First rough classification of models

For each type of $\overline{C}_\gamma$, using the lower bound on Λ from $\tau \to \mu\gamma$, we can predict an upper bound on $\mathrm{BR}(H \to \tau\mu)$ for different $\overline{C}_Y$:

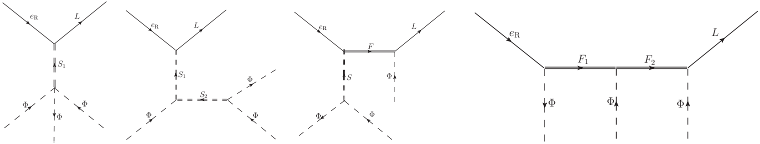
$\overline{C}_Y$ \ $\overline{C}_\gamma$	m_τ^2/v^2	m_τ/v	1
1 ($\mathcal{O}_Y$)	1	0.04	10^{-6}
m_τ/v ($\mathcal{O}_{1,2}$)	0.04	10^{-6}	10^{-10}
$1/(4\pi)^2$ ($\mathcal{O}_Y$)	0.03	10^{-6}	10^{-10}
$m_\tau/((4\pi)^2 v)$ ($\mathcal{O}_{1,2}$)	10^{-6}	10^{-10}	10^{-14}

In red excluded models as an explanation (unless cancellations in $\tau \to \mu\gamma$).

Systematically study all tree level topologies

(see also [del Aguila, de Blas...])

- Many studies with EFT and models: Iltan, Diaz, Pilaftsis, Diaz Cruz, Sher, Blankenburg, Harnik, Dorsner, Crivellin, Goudelis, Arhrib, Nir, Davidson, Aristizabal, Falkowski, Celis, Arganda, Campos, Dery, Arana-Catania, Kearney, Bhattacharyya, Omura, Dorsner, de Lima, Altmannshofer...
- **Our approach: we start by systematically listing the HLFV UV models opening EFT and impose constraints from CLFV.**

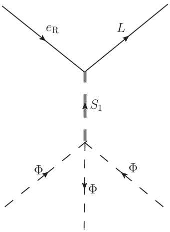


(A) (B) (C) (D)

- The topologies follow a hierarchy:

$$\overline{C}_Y \sim \frac{1}{m^2}\left(\lambda Y \,:\, Y \,:\, Y^2 \,:\, Y^3\right).$$

Opening the *Yukawa operator*: scalars. Topologies A.



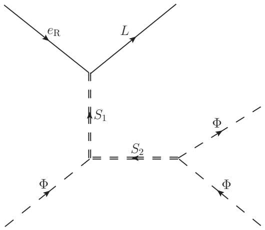
Top.	Particles	Representations $(\mathrm{SU}(2)_\mathrm{L}, \mathrm{U}(1)_\mathrm{Y})$	H$e_\alpha e_\beta$
A	1 S	$S = (2, -1/2)$	$Y\lambda/m_{S_1}^2$

- HLFV is given by ($\tan\beta = v_2/v_1$, α CP-even mixing angle):

$$\mathrm{BR}(H \to \mu\tau) = \frac{m_H}{8\pi\Gamma_H}\left(\frac{c_{\beta-\alpha}}{\sqrt{2}\,c_\beta}\right)^2 \left(|Y_2^{\tau\mu}|^2 + |Y_2^{\mu\tau}|^2\right).$$

- **A:** General 2HDM can explain it after considering all constraints. [Davidson, Aristizabal, Dorsner, Iltan, Diaz, Kanemura...].

Opening the *Yukawa operator*: scalars. Topology B.



Top.	Particles	Representations $(\mathrm{SU}(2)_\mathrm{L}, \mathrm{U}(1)_\mathrm{Y})$	$\mathrm{H}e_\alpha e_\beta$
B	2 S	$(2,-1/2)_S \oplus (1,0)_S, (3,0)_S, (3,1)_S$	$\frac{Y\mu_1\mu_2}{m^2_{S_1} m^2_{S_2}}$

- The vevs v_T of the scalar triplets $(3,0)_S$ and $(3,1)_S$ contribute as:

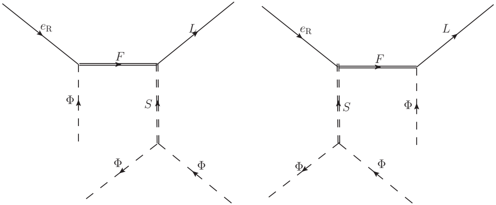
$$\rho_{(3,0)} = 1 + 4v_T^2/v^2 > 1\,, \qquad \rho_{(3,1)} = (v^2 + 2\,v_T^2)/(v^2 + 4\,v_T^2) < 1\,.$$

- **B**: Their vevs are $v_T \sim \mu_2\, v^2/(v\, M^2_{S_2}) \lesssim (5\,\mathrm{GeV})/v$, so:

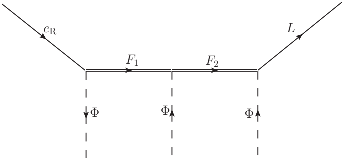
$$\mathrm{BR}(H \to \mu\tau) \sim 0.06 \left(Y_{S_1} \frac{\mu_1 v}{M^2_{S_1}} \frac{\mu_2 v^2}{v M^2_{S_2}} \frac{1}{y_\tau} \right)^2 \lesssim 0.6\, \frac{Y^2_{S_1} v^2}{M^2_{S_1}}\,.$$

Opening the *Yukawa operator*: fermions. Topologies C, D.

- Both scalars and VL fermions (**C**):



-Only VL fermions (**D**):



Top.	Particles	Representations $(\mathrm{SU}(2)_\mathrm{L}, \mathrm{U}(1)_\mathrm{Y})$	H$e_\alpha e_\beta$
$\mathbf{C_1}$	1 F,1 S	$(2,-1/2)_F \oplus (1,0)_S, (3,0)_S$	$\frac{Y_L Y_e \mu}{m_F m_S^2}$
$\mathbf{C_2}$	1 F,1 S	$(2,-3/2)_F \oplus (3,1)_S$	$\frac{Y_L Y_e \mu}{m_F m_S^2}$
$\mathbf{C_3}$	1 F,1 S	$(1,-1)_F \oplus (1,0)_S$, $(3,-1)_F \oplus$ $(3,0)_S$	$\frac{Y_L Y_e \mu}{m_F m_S^2}$
$\mathbf{C_4}$	1 F,1 S	$(3,0)_F \oplus (3,1)_S$	$\frac{Y_L Y_e \mu}{m_F m_S^2}$
$\mathbf{D_1}$	2 F	$(2,-1/2)_F \oplus (1,0)_F, (3,0)_F$	$\frac{Y_L Y_e Y_F}{m_{F_1} m_{F_2}}$
$\mathbf{D_2}$	2 F	$(2,-1/2)_F \oplus (1,-1)_F, (3,-1)_F$	$\frac{Y_L Y_e Y_F}{m_{F_1} m_{F_2}}$
$\mathbf{D_3}$	2 F	$(2,-3/2)_F \oplus (1,-1)_F, (3,-1)_F$	$\frac{Y_L Y_e Y_F}{m_{F_1} m_{F_2}}$

Bounds on HLFV models

- Several constraints on them from universality, ρ, naturality, perturbativity, stability, $h \to \gamma\gamma$... etc.
- Strongest limits from CLFV ($\tau \to \mu\gamma$). Different contributions:

  a) From EFT with SM Higgs (Yukawa op.) $\propto m_\tau^2$ [Blankenburg, Harnik].

  b) From EFT operators NOT giving HLFV (*Derivative* op.).

  c) With at least one heavy particle (from matching with EFT):

  c1) Closing the Higgs in the HLFV topologies and attaching a photon.

  c2) From only heavy particles running in the loop.

Upper bounds on HLFV models from CLFV.

We can classify the contributions in two types:

1. *Robust*: a), b), c1).
   Can NOT decouple HLFV from CLFV.
   For instance, in 2HDM diagrams with light and heavy Higgs (c1).
2. *Natural*: c2).
   Can decouple HLFV from CLFV.
   For instance, heavy Higgs cont. in 2HDM would vanish if $Y_{\tau\tau} = 0$.

We get for the different topologies:

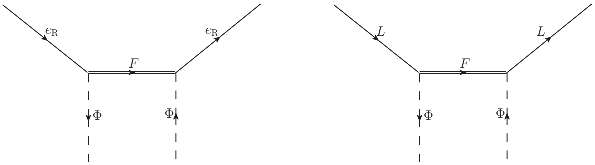
- Topologies A and B:

$$\mathrm{BR}(H \to \mu\tau) \lesssim 0.1\,(0.2)\,, \qquad \text{for } \textit{robust } (\textit{natural}).$$

- Topologies C and D:

$$\mathrm{BR}(H \to \mu\tau) \lesssim 2 \cdot 10^{-6}\,(2 \cdot 10^{-2})\,, \qquad \text{for } \textit{robust } (\textit{natural}).$$

The *Derivative operator*. Topologies E with VLL, $\propto m_\tau$.



- Z:$\kappa_{\tau\mu} e/(2 c_w s_w)$,W:$\kappa_{\tau\mu} e/(2\sqrt{2} s_w)$,H:$y_{\tau\mu} \sim y_\tau \kappa_{\tau\mu}$ $(\kappa_{\tau\mu} \sim Y_{\tau F} Y_{\mu F} v^2/m_F^2)$.
- Tree-level ZLFV $\mathrm{BR}(\tau \to 3\mu) < 2.1 \cdot 10^{-8} \;\longrightarrow\; |\kappa_{\tau\mu}| \lesssim \mathcal{O}(10^{-3})$:

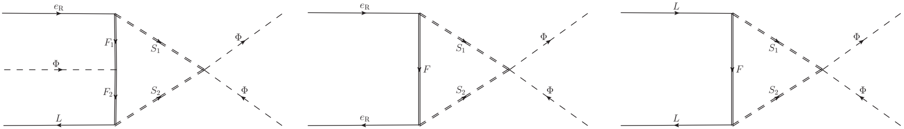
$$\mathrm{BR}(h \to \mu\tau) \sim 1200 |y_{\tau\mu}|^2 \lesssim 10^{-7} \,.$$

- As for the Yukawa op., also $\tau \to \mu\gamma$: contributions a, b and c1.

Operator	Topology	Particles	Z $\nu_\alpha \nu_\beta$	Z $e_\alpha e_\beta$	W $e_\alpha \nu_\beta$	H $e_\alpha e_\beta$
$(\overline{e_R}\Phi^\dagger) i\not{D} (e_R\,\Phi)$	E_1	$(2,-1/2)_F$		-1		1
$(\overline{e_R}\Phi^T) i\not{D} (e_R\,\Phi^*)$	E_2	$(2,-3/2)_F$		$+1$		1
$(\overline{L}\tilde{\Phi}) i\not{D} (\tilde{\Phi}^\dagger L)$	E_{3a}	$(1,0)_F$	-1		-1	
$(\overline{L}\vec{\sigma}\tilde{\Phi}) i\not{D} (\tilde{\Phi}^\dagger \vec{\sigma} L)$	E_{3b}	$(3,0)_F$	-1	-2	$+1$	2
$(\overline{L}\Phi) i\not{D} (\Phi^\dagger\, L)$	E_{4a}	$(1,-1)_F$		$+1$	-1	1
$(\overline{L}\vec{\sigma}\Phi) i\not{D} (\Phi^\dagger\,\vec{\sigma} L)$	E_{4b}	$(3,-1)_F$	$+2$	$+1$	$+1$	2

Connection to neutrino masses

Neutrino mass models typically give HLFV at one loop



Top.	Part.	Representations	Neutrino mass models
LR	S, F	$(1,0)_F, (3,0)_F$	Dirac, SSI/III (ISS)
RR	S	$(1,2)_S$	ZB (doubly-charged)
LL	S	$(1,1)_S, (3,1)_S$	ZB (singly-charged), SSII
LL (Z_2)	$S \oplus F$	$(1,1/2)_S \oplus (1,0)_F, (3,0)_F$	Scotogenic Model

Neutrino mass models giving HLFV at one loop

- We estimate that all neutrino mass models give:

$$\mathrm{BR}(H \to \mu\tau) \sim 0.06 \, \frac{\lambda_{iH}^2}{(4\pi)^4} \left(\frac{v}{\mathrm{TeV}}\right)^4 \left(\frac{Y}{M_i/\mathsf{TeV}}\right)^4 .$$

- $\tau \to \mu\gamma$ typically give the constraint:

$$\left(\frac{Y}{M_i/\mathsf{TeV}}\right)^4 \lesssim \mathcal{O}(0.01 - 1) \quad \longrightarrow \quad \mathrm{BR}(H \to \mu\tau) \lesssim 10^{-8} .$$

Is $\mathrm{BR}(H \to \mu\tau) \sim 0.01$ possible, overcoming the loop $\sim 1/(4\pi)^4$?

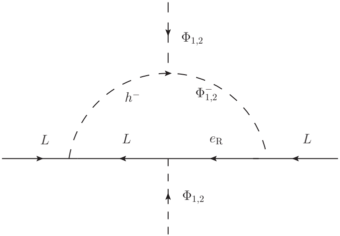
- Evade cLFV? No, some of the new F and S in the loop are charged. One expects cLFV at the same level as HLFV [Dorsner].
- Large Yukawas with special textures: $\lesssim 10^{-5}$ [ISS, Arganda].
- But: large Y, λ lead to instabilities/non-perturbative and $H \to \gamma\gamma$.

Neutrino masses for HLFV at tree level: The Zee Model.

[Zee, Cheng, Babu, Wolfenstein, Petcov, Smirnov, Frampton, Kanemura, Aristizabal, Koide, He..]

- The Zee model (type III version):

$$\mathcal{L}_Y = -\overline{L}\,(Y_1^\dagger \Phi + Y_2^\dagger \Phi_2) e_{\mathrm{R}} - \overline{\tilde{L}} f\, L h^+ + \mathrm{H.c.}$$



$$M_\nu \propto \Big(f\, m_f^2 + m_f^2 f^T - \\ - v/\sqrt{2 c_\beta} (f\, m_f\, Y_2 + Y_2^T\, m_f\, f^T) \Big)$$

$$M_\nu \propto \begin{pmatrix} -2 f^{e\tau}\, Y_2^{\tau\, e} & -f^{e\tau}\, Y_2^{\tau\, \mu} - f^{\mu\tau}\, Y_2^{\tau\, e} & \frac{\sqrt{2}\, c_\beta\, m_\tau}{v}\, f^{e\tau} - f^{e\tau}\, Y_2^{\tau\, \tau} \\ - & -2 f^{\mu\tau}\, Y_2^{\tau\, \mu} & \frac{\sqrt{2}\, c_\beta\, m_\tau}{v}\, f^{\mu\tau} - f^{\mu\tau}\, Y_2^{\tau\, \tau} \\ - & - & 0 \end{pmatrix}$$

The Zee Model

$$\mathrm{BR}(H \to \mu\tau) = \frac{m_H}{8\pi\Gamma_H} \left(\frac{s_{\beta-\alpha}}{\sqrt{2}\, s_\beta} \right)^2 \left(|Y_2^{\tau\mu}|^2 + |Y_2^{\mu\tau}|^2 \right).$$

- Mixing angles imply $Y_2^{e\tau}$, $Y_2^{\mu\tau} \neq 0$ so $\mathrm{BR}_{H\to\mu\tau} \times \mathrm{BR}_{H\to e\tau} > \#$.
- Upper bound from $\mu \to e\gamma$ plus μe conversion [Dorsner]:

$$\mathrm{BR}_{H\to\mu\tau} \times \mathrm{BR}_{H\to e\tau} \lesssim 10^{-8}.$$

- For $\mathrm{BR}_{H\to\mu\tau} \sim 0.01$ we get $\mathrm{BR}_{H\to\tau e} \lesssim 10^{-6}$.
- Compatibility under study doing a MCMC [In preparation].

LR models. [Mohapatra, Senjanovic, Keung...]

- LR models based on $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{B-L}}$ and restore parity:

$$\mathrm{Q} = \mathrm{T}_{3\mathrm{L}} + \mathrm{T}_{3\mathrm{R}} + (\mathrm{B}-\mathrm{L})/2\,.$$

- $\mathrm{B}-\mathrm{L} = 2$ triplets, $\Delta_\mathrm{R}(1,3,2)$ and $\Delta_\mathrm{L}(3,1,2)$. Bi-doublet $(2,2,0)$:

$$\Sigma = \begin{pmatrix} \Phi_1^0 & \Phi_2^+ \\ \Phi_1^- & \Phi_2^0 \end{pmatrix}, \qquad \tilde{\Sigma} = \tau_2\,\Sigma^*\,\tau_2 = \begin{pmatrix} \Phi_2^{0*} & -\Phi_1^+ \\ -\Phi_2^- & \Phi_1^{0*} \end{pmatrix}.$$

- The Yukawa Lagrangian is a Type III 2HDM at low energies:

$$\mathcal{L}_Y \subset \overline{L}_L(Y_1\Sigma + Y_2\tilde{\Sigma})L_\mathrm{R} \to \overline{e_L}\,\left(Y_1(v_1 + H_1^0) + Y_2(v_2 + H_2^0)\right)e_\mathrm{R}.$$

- Need $v_\mathrm{L} \ll v_1 \sim v_2 \ll v_\mathrm{R}$. FCNC imply $m_{H_2^0} \gtrsim 15$ TeV.
- Extended models with $m_{W_R} \sim 2$ TeV for di-boson anomaly (and no excess in SS leptons) may explain both [Mohapatra, Liu, Dobrescu, Gluza...].

Summary and conclusions

Summary and conclusions

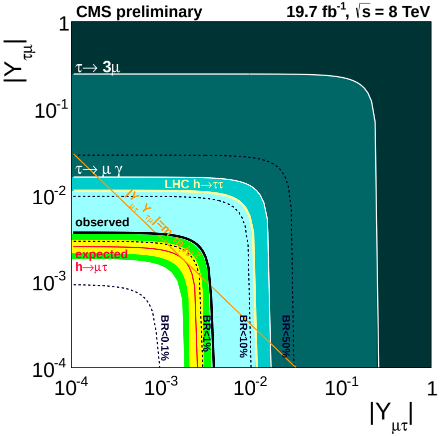
- HLFV would imply BSM physics, maybe related to neutrino masses.
- All tree level topologies from *Yukawa* and *Derivative* operators.
- Contributions to $\tau \to \mu\gamma$ from both EFT and UV. Robust/natural (HLFV doesn't/does decouple from CLFV) upper limits on $H \to \tau\mu$.
- All VL models are excluded as an explanation. Some generate the *Derivative operator* giving tree-level ZLFV.
- Type III 2HDM works due to CLFV suppression wrt VL (cont. with only heavy Higgs could be made zero if $Y_{\tau\tau} \to 0$).
- All models with HLFV at 1 loop (typical neutrino mass models) yield too low BR, typically $\lesssim 10^{-9}$, and in the best case $\lesssim 10^{-5}$.
- We find that the best-motivated scenarios (also neutrino masses) are:
  1. The Zee model [detailed study in preparation].
  2. LR symmetric models, which may also explain di-boson anomaly.

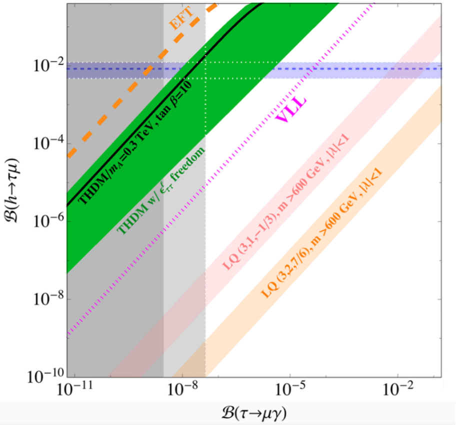
Back-up slides

Summary of EFT [left, CMS] and models [right, Dorsner]

- 2HDM work because $\tau \to \mu\gamma$ is suppressed wrt VL:

$$\mathrm{BR}^{\mathrm{2HDM}}_{\tau\to\mu\gamma} \sim 10^{-3}\,\mathrm{BR}^{\mathrm{VL}}_{\tau\to\mu\gamma}.$$





LFV at $D = 6$

- In general cLFV like $\tau \to \mu\,\gamma$ is given by ($\vec{\tau} = (\tau_1, \tau_2, \tau_3)$):

$$\overline{L}\,\Phi\, c_B\ \sigma^{\mu\,\nu} e_{\rm R} B_{\mu\,\nu} + \overline{L}\,\Phi\, c_W\ \sigma^{\mu\,\nu} e_{\rm R}\,(\vec{\tau}\cdot\vec{W}_{\mu\,\nu})\,.$$

- Four lepton operators generate $\tau \to 3\mu$, for instance, via:

$$c_{4F}\,\overline{e_{\rm R}}\,\overline{e_{\rm R}}\,e_{\rm R}\,e_{\rm R}\,.$$

- Other ones give rise to FCNC and FCCC:

$$(\overline{L}\,c_{D1}\gamma_\mu L + \overline{e_R}\,c_{D2}\,\gamma_\mu e_R)\,(\Phi^\dagger i\overleftrightarrow{D}^\mu\Phi) + (\overline{L}\,c_{D3}\,\gamma_\mu\,\vec{\tau}\,L)\,(\Phi^\dagger\,\vec{\tau}\,i\overleftrightarrow{D}^\mu\Phi)\,,$$

  where $\Phi^\dagger\,\overleftrightarrow{D}^\mu\,\Phi \equiv \Phi^\dagger\,iD^\mu\Phi - (iD^\mu\Phi^\dagger)\Phi$.
- These last ones do NOT generate HLFV.
- HLFV is given by the *Yukawa* and the *Derivative operators*.

The *Derivative operator*

- Using EOM, the *Yukawa operator* becomes $C_Y = C'\, Y_e + Y_e\, C''$:

$$\frac{1}{\Lambda^2}(\overline{L}\, C'\, i\gamma_\mu D^\mu L)\,(\Phi^\dagger\Phi)+\text{H.c.}\,, \qquad \frac{1}{\Lambda^2}(\overline{e_{\rm R}}\, C''^\dagger\, i\gamma_\mu D^\mu e_{\rm R})\,(\Phi^\dagger\Phi)+\text{H.c.}$$

- These change kinetic terms, so we need to redefine wave functions:

$$L'_k = L_i\left(1 + 2\, C'_{ki}\,\frac{\Phi^\dagger\Phi}{\Lambda^2}\right)^{1/2} = L_i\left(1 + C'_{ki}\,\frac{\Phi^\dagger\Phi}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\Phi^\dagger\Phi}{\Lambda^2}\right)^2.$$

- The SM Yukawa gives the *Yukawa op.*, and kinetic terms become:

$$\frac{1}{\Lambda^2}(\overline{L}\, C'\, \gamma_\mu L)\,(\Phi^\dagger i\overleftrightarrow{D}^\mu\Phi)\,,$$

which does not give HLFV, but sizable FCNC and FCCC (VL models).

SM + relevant EFT operators

- Φ SM Higgs, $L\,(e_{\rm R})$ lepton doublet (singlet), $Y_{\rm e}$ Yukawa matrix:

$$\mathcal{L}_{\rm SM} = \overline{L} i \not{D} L + \overline{e_{\rm R}} i \not{D} e_{\rm R} + Y_{\rm e} \overline{L} e_{\rm R} \Phi + {\rm H.c.}$$

- At $D = 5$ only the Weinberg operator, which gives neutrino masses:

$$\mathcal{L}_5 = \frac{1}{2} \frac{c_{\alpha\beta}}{\Lambda} (\overline{\ell_\alpha} \tilde{\Phi}) \, (\Phi^\dagger \tilde{\ell}_\beta) + {\rm H.c.} \qquad \longrightarrow m_\nu = c \, \frac{v^2}{\Lambda} \, .$$

- At $D = 6$ many operators, but only a few are relevant for HLFV.
- The following renormalize H and v and can be easily absorbed:

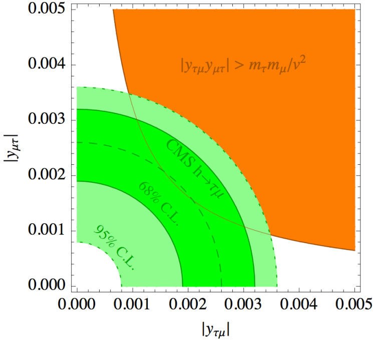
$$c_H \, \partial^\mu (\Phi^\dagger \Phi) \, \partial_\mu (\Phi^\dagger \Phi) + c_\lambda \, (\Phi^\dagger \Phi)^3 \, .$$

Naturality: OK with large $H \to \tau\mu$. Figure from Dorsner.

- $|\det M| = |M_{\mu\mu} M_{\tau\tau} - M_{\tau\mu} M_{\mu\tau}| = m_\mu m_\tau$.
- To avoid avoid fine-tuning we can require $|M_{\tau\mu} M_{\mu\tau}| < m_\mu m_\tau$.
- We get for $y_{\tau\mu} = y_{\mu\tau}$:

$$\overline{y} \equiv \sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} \lesssim 0.005\,.$$

- This is compatible with the CMS preferred range.



Bounds on VLL from the *Derivative operator*

- Universality.

$$\mu_\ell \equiv \frac{\mathrm{BR}_\ell}{\mathrm{BR}_\ell^{SM}} = \frac{(g_L^{SM} + \delta g_{\ell L}^{NP})^2 + (g_R^{SM} + \delta g_{\ell R}^{NP})^2}{(g_L^{SM})^2 + (g_R^{SM})^2}$$
$$\approx 1 + 2\,\frac{g_L^{SM}\delta g_{\ell L}^{NP} + g_R^{SM}\delta g_{\ell R}^{NP}}{(g_L^{SM})^2 + (g_R^{SM})^2}\,.$$

From $\mu_\tau = 1.0036 \pm 0.0025$ (similarly for $\mu\mu$, ee):

$$\kappa_{\ell\ell} < \kappa_{\tau\tau} < 0.005 \qquad \text{at } 95\,\%\ \text{C.L.}$$

Opening the *Derivative operator* with VL: example

- Example: vector-like lepton $E = (1, -1)_{\mathrm{F}}$ of bare mass M_{E}:

$$\mathcal{L} = i\overline{L}\,\not{D}\,L + i\overline{e_{\mathrm{R}}}\,\not{D}\,e_{\mathrm{R}} + \overline{E}\,(i\not{D} - M_{\mathrm{E}})\,E + (\overline{L}Y_e e_{\mathrm{R}}\Phi + \overline{L}Y_E E_{\mathrm{R}}\Phi + \mathrm{H.c.})\,.$$

- Take $M_{\mathrm{E}} > v$, so we can integrate-out the E:

$$\mathcal{L}_{\mathrm{EFT}} = -(\overline{L}\,\Phi)\,\frac{Y_E\,Y_E^\dagger}{i\not{D} - M_{\mathrm{E}}}(\Phi^\dagger\,L) = (\overline{L}\,\Phi)\,\frac{Y_E Y_E^\dagger}{M_{\mathrm{E}}^2} i\not{D}\,(\Phi^\dagger\,L) + \mathcal{O}\left(\frac{1}{M_{\mathrm{E}}^4}\right)$$

- Using $C_E/\Lambda^2 = 1/2 Y_E M_E^{-2} Y_E^\dagger$ and $\Phi\Phi^\dagger = \frac{1}{2}(\Phi^\dagger\Phi) + \frac{1}{2}\vec{\tau}(\Phi^\dagger\vec{\tau}\Phi)$:

$$\begin{aligned}\mathcal{L}_{\mathrm{EFT}}^{D\leq 6} = \quad & \frac{i}{2\Lambda^2}\Big[(\overline{L}\,C_E\,\overleftrightarrow{\not{D}}\,L)\;(\Phi^\dagger\,\Phi) + (\overline{L}\,C_E\,\vec{\tau}\,\overleftrightarrow{\not{D}}\;L)\;(\Phi^\dagger\,\vec{\tau}\,\Phi) - \\ & - (\overline{L}\,C_E\,\gamma^\mu\,L)\,(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \;(\overline{L}\,C_E\,\gamma^\mu\,\vec{\tau}\,L)\,(\Phi^\dagger\,\vec{\tau}\,\overleftrightarrow{D}_\mu \Phi)\Big]\,.\end{aligned}$$

- **Both HLFV (1st line) and FCNC (2nd line) at same level!**

General VL models explicitly: "matching" with EFT

- Z FCNC, where ℓ run only on doublets and a, b on all charged leptons:

$$\mathcal{L}_Z = \frac{g}{2c_W}\left(\bar{E}_L\gamma^\mu X_L E_L + \bar{E}_R\gamma^\mu X_R E_R + 2s_W^2 J^\mu_{EM}\right) Z^\mu,$$

$$(X_L)_{ba} = \left(V_L^\dagger\right)_{b\ell}(V_L)_{\ell a} \ , (X_R)_{ba} = \left(V_R^\dagger\right)_{b\ell}(V_R,)_{\ell a} \ ,$$

- H FCNC:

$$-\mathcal{L}_h \to \bar{E}_L V_L^\dagger Y_E V_R E_R h + \text{h.c.}\,.$$

- The HLFV Yukawa coupling is (similarly for $y_{\tau\mu}$):

$$v y_{\mu\tau} = (v V_L^\dagger Y_E V_R)_{\mu\tau} = (X_L D_E + D_E X_R - 2X_L D_E X_R)_{\mu\tau}$$

$$= (X_L)_{\mu\tau} m_\tau + m_\mu (X_R)_{\mu\tau} - 2(X_L D_E X_R)_{\mu\tau}$$

$$\approx \frac{Y_{\mu F_1} v}{m_{F_1}}\frac{(Y^\dagger)_{F_1\tau} v}{m_{F_1}} m_\tau + \frac{Y_{\mu F_2} v}{m_{F_2}}\frac{(Y^\dagger)_{F_2\tau} v}{m_{F_2}} m_\mu - 2\frac{Y_{\mu F_1} v}{m_{F_1}} Y_{12} v \frac{(Y^\dagger)_{F_2\tau} v}{m_{F_2}}\,.$$

- *Derivative op.* + *Yukawa op.*, top. D: dominates unless $Y_{12} v < m_\tau$.

$\tau \to \mu\gamma$ in VL models

- 1-loop VL Higgs contributions to $\tau \to \mu\gamma$ go as (Z subdominant):

$$((X_L D_E + D_E X_R - 2X_L D_E X_R)\tilde{D}_E^{-1}(X_L D_E + D_E X_R - 2X_L D_E X_R))_{\mu\tau}$$

$$\approx \left(\frac{Y_{\mu S} Y_{SD} Y_{D\tau} v^3}{M_{S,D}^2}\right) \approx (X_L D_E X_R)_{\mu\tau} \propto v y_{\mu\tau}.$$

- In VL enhanced $\tau \to \mu\gamma$ rate wrt to 2HDM:

$$A_R^{\mathrm{VL}} \sim \frac{y_{\mu\tau}}{(4\pi)^2 v m_\tau} \qquad \text{vs} \qquad A_R^{\mathrm{2HDM}} \sim \frac{y_{\mu\tau}\, m_\tau}{(4\pi)^2 v m_H^2}.$$

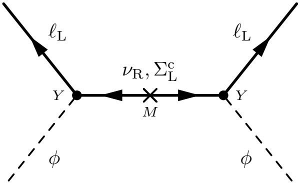
- Note: 2HDM 2 loops (Barr-Zee) dominate [Davidson, Harnik, Aristizabal...].
- $\tau \to \mu\gamma$ excludes VL in composite scenarios [Falkowski].

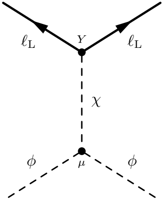
Opening the Weinberg operator at tree level: seesaws

- Rewriting the Weinberg operator:

$$\left(\overline{\ell_\alpha}\tilde{\phi}\right)\,\left(\phi^\dagger\tilde{\ell}_\beta\right) = -\left(\overline{\ell_\alpha}\,\vec{\sigma}\tilde{\phi}\right)\,\left(\phi^\dagger\,\vec{\sigma}\tilde{\ell}_\beta\right) = \frac{1}{2}\left(\overline{\ell_\alpha}\,\vec{\sigma}\,\tilde{\ell}_\beta\right)\,\left(\phi^\dagger\,\vec{\sigma}\,\tilde{\phi}\right),$$

where α and β are family indices and $\vec{\sigma} \equiv (\sigma_1, \sigma_2, \sigma_3)$.





- 3 different particles can generate Weinberg op. at tree level:
  - a $Y = 0$ heavy fermion singlet (triplet), type I (III) seesaw.
  - a $Y = 1$ heavy scalar triplet, type II seesaw.
- Explains why ν's are light: they couple to high scale fields.
- Drawbacks: typically difficult to test, problem of hierarchies.

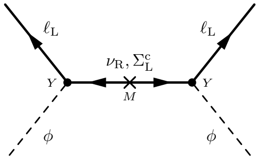
Adding right-handed neutrinos: seesaw type I

$$\mathcal{L}_{\nu_\mathrm{R}} = i\,\overline{\nu_\mathrm{R}}\gamma^\mu\partial_\mu\nu_\mathrm{R} - \left(\overline{\ell}\,\tilde{\phi}\,Y\,\nu_\mathrm{R} + \frac{1}{2}\overline{\nu_\mathrm{R}^\mathrm{c}}m_\mathrm{R}\nu_\mathrm{R} + \mathrm{H.c.}\right)\,,$$

where m_R is a $n \times n$ symmetric matrix. After SSB:

$$\mathcal{L}_{\nu\,\mathrm{mass}} = -\frac{1}{2}\,\begin{pmatrix}\overline{\nu_\mathrm{L}} & \overline{\nu_\mathrm{R}^\mathrm{c}}\end{pmatrix}\begin{pmatrix}0 & m_\mathrm{D}\\ m_\mathrm{D}^\mathrm{T} & m_\mathrm{R}\end{pmatrix}\begin{pmatrix}\nu_\mathrm{L}^\mathrm{c}\\ \nu_\mathrm{R}\end{pmatrix} + \mathrm{H.c.}\,,$$

where $m_\mathrm{D} = Y\frac{v}{\sqrt{2}}$.



If $m_\mathrm{R} \gg m_\mathrm{D}$, one gets n m_R leptons (mainly singlets) and

$$m_\nu \simeq -m_\mathrm{D}\,m_\mathrm{R}^{-1}\,m_\mathrm{D}^\mathrm{T}.$$

Seesaw type II

- Add to the SM one scalar triplet with hypercharge $Y = 1$ and LN -2. In the doublet representation of $SU(2)_{\rm L}$ the triplet is a 2×2 matrix:

$$\chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi_0 & -\chi^+/\sqrt{2} \end{pmatrix}$$

Gauge invariance allows a Yukawa coupling of the scalar triplet to 2 lepton doublets,

$$\mathcal{L}_\chi = -\left((Y_\chi)_{\alpha\beta}\, \bar{\tilde{\ell}}_\alpha \chi \ell_\beta + \text{H.c.} \right) - V(\phi, \chi)\,,$$

where Y_χ is a symmetric matrix and $\tilde{\ell} = i\tau_2\, \ell^{\rm c}$. The scalar potential has the following terms:

$$V(\phi, \chi) = m_\chi^2\, \text{Tr}[\chi\chi^\dagger] + \left(\mu\, \tilde{\phi}^\dagger \chi^\dagger \phi + \text{H.c.} \right) + \ldots$$

Seesaw type II

- The μ coupling violates LN and induces a VEV for the triplet via v_ϕ, even if $m_\chi > 0$. In the limit $m_\chi \gg v_\phi$:

$$m_\nu = 2Y_\chi v_\chi = 2Y_\chi \frac{\mu v_\phi^2}{m_\chi^2}$$

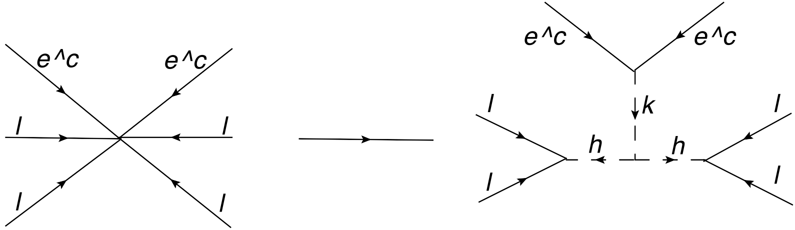
- m_ν are thus proportional to both Y_χ and μ, since the breaking of LN results from their simultaneous presence.
- If m_χ^2 is positive and large,v_χ will be small, in agreement with the ρ parameter, $v_\chi \lesssim 6 \text{ GeV}$.
- Moreover, μ can be naturally small, because in its absence LN is recovered, increasing the symmetry.

Example: the Zee-Babu model [Cheng and Li, Zee, Babu...]

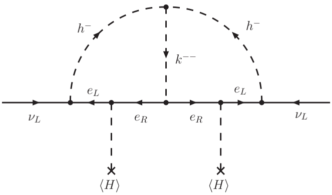
The D= 9 $\Delta L = 2$ effective operator $\ell\ell\ell\ell e^c e^c$ generates the Weinberg operator at two loops (and therefore m_ν). By NDA:

$$m_\nu \sim \frac{c}{(4\pi)^4}\frac{y_e^2 v^2}{\Lambda}$$

One can open this operator with a singly- and a doubly-charged scalar $h^{\pm}, k^{\pm\pm}$ with $Y_h = \pm 1$ and $Y_k = \pm 2$.



$$\mathcal{L}_Y = \overline{\ell}\, Y e\phi + \overline{\tilde{\ell}} f \ell h^+ + \overline{e^c} g\, e\, k^{++} + \mu h^2 k^{++} + \text{H.c.}$$



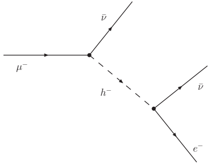
$$\mathcal{M}_\nu = \frac{v^2 \mu}{48\pi^2 M^2} \tilde{I}\, f\, Y\, g^\dagger Y^T f^T\,,$$
$$M \equiv \max(m_h, m_k)\,.$$

- f is AS $\rightarrow \det f = 0 \rightarrow \det \mathcal{M}_\nu = 0$, so one ν is massless.
- We can estimate the amplitude of $H \rightarrow \mu\tau$ to be:

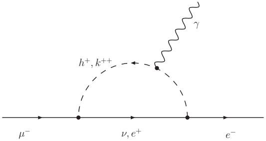
$$A_{\text{ZB}} \sim \frac{m_\tau v}{(4\pi)^2} \left(\frac{\lambda_{hH}}{m_h^2} (f_{e\mu}^* f_{e\tau}) + \frac{\lambda_{kH}}{m_k^2} (g_{e\mu}^* g_{e\tau} + g_{\mu\mu}^* g_{\mu\tau} + g_{\mu\tau}^* g_{\tau\tau}) \right),$$

where $\lambda_{hH}|h|^2 H^\dagger H + \lambda_{kH}|k|^2 H^\dagger H + \text{h.c.}$.

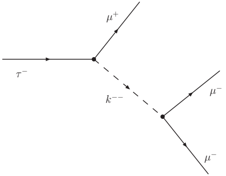
Strongest onstraints: cLFV and universality



- $|V_{ud}^{exp}|^2 + |V_{us}^{exp}|^2 + |V_{ub}^{exp}|^2 = 0.9999 \pm 0.0006$
  $\approx 1 - \frac{\sqrt{2}}{G_F m_h^2} |f_{e\mu}{}^2| \longrightarrow |f_{e\mu}|^2 < 0.007 \left(\frac{m_h}{\text{TeV}}\right)^2$
- τ/μ universality: $\frac{G_\tau^{exp}}{G_\mu^{exp}} = 0.9998 \pm 0.0013$
  $||f_{e\tau}|^2 - |f_{e\mu}|^2| < 0.035 \left(\frac{m_h}{\text{TeV}}\right)^2$

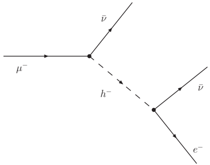


- $\text{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
  $\frac{|f_{e\tau}^* f_{\mu\tau}|^2}{(m_h/\text{TeV})^4} + \frac{16|g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau}|^2}{(m_k/\text{TeV})^4} < 0.7$

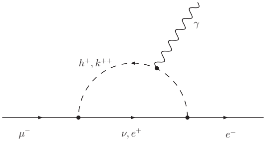


- $\text{BR}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$
  $|g_{\mu\tau} g_{\mu\mu}^*| < 0.008 \left(\frac{m_k}{\text{TeV}}\right)^2$

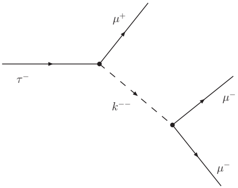
Universality and LFV constraints



- $|V_{ud}^{exp}|^2 + |V_{us}^{exp}|^2 + |V_{ub}^{exp}|^2 = 0.9999 \pm 0.0006$
  $\approx 1 - \frac{\sqrt{2}}{G_F m_h^2} |f_{e\mu}{}^2| \longrightarrow |f_{e\mu}|^2 < 0.007 \left(\frac{m_h}{\text{TeV}}\right)^2$



- $\text{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$
  $\frac{|f_{e\tau}^* f_{\mu\tau}|^2}{(m_h/\text{TeV})^4} + \frac{16|g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau}|^2}{(m_k/\text{TeV})^4} < 1.6 \cdot 10^{-6}$



- $\text{BR}(\mu^- \to e^+ e^- e^-) < 1.0 \times 10^{-12}$
  $\longrightarrow |g_{e\mu} g_{ee}^*| < 2.3 \cdot 10^{-5} \left(\frac{m_k}{\text{TeV}}\right)^2$