# Higgs lepton flavor violation

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# Outline

# Motivation

# NP is needed for HLFV

- CMS: $BR(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%\ (2.4\sigma)$, or $< 1.51\%\ (95\%\text{CL})$.
- Also LFV already seen in neutrino oscillations.
- SM Higgs couplings are diagonal, so NP required if excess is confirmed

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

giving:

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

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

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

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

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

# An EFT approach

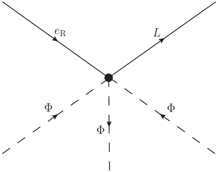
# The *Yukawa operator*

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

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

- HLFV, the EFT *Yukawa operator* [Harnik]:

$$\mathcal{L}^{D=6}_{\rm HLFV} = \frac{1}{\Lambda^2} \overline{L}\, C\, e_{\rm R} \Phi (\Phi^\dagger \Phi) + \text{H.c.}$$



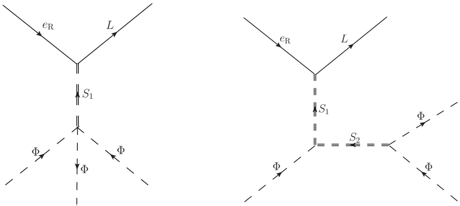

- After SSB, $\langle \Phi_0 \rangle = (H+v)/\sqrt{2}$, diagonalize $M_e$:

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

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

$$(Y_{\rm e})_{ij} = \frac{m_i \sqrt{2}}{v} \delta_{ij} + C_{ij} \frac{v^2}{\Lambda^2}.$$

# Opening the *Yukawa operator*: scalars. Topologies A, B.



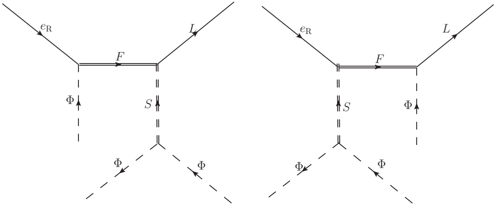

| Top. | Particles | Representations $(\mathrm{SU}(2)_\mathrm{L}, \mathrm{U}(1)_\mathrm{Y})$ | $\mathrm{H}e_\alpha e_\beta$ |
|---|---|---|---|
| **A** | 1 S | $S = (2, -1/2)$ | $\frac{Y\lambda}{m_{S_1}^2}$ |
| **B** | 2 S | $(2, -1/2)_S \oplus (1,0)_S, (3,0)_S, (3,1)_S$ | $\frac{Y\mu_1\mu_2}{m_{S_1}^2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

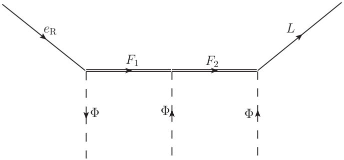
- **A:** 2HDM can explain it [Iltan, Diaz, Kanemura, Davidson, Aristizabal, Dorsner...].. We give two motivated examples from neutrino masses.
- **B**: Triplets have strong bounds from $\rho$: $\mu_2 v^2/(v M_{S_2}^2) \lesssim (5\,\mathrm{GeV})/v$:

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

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

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

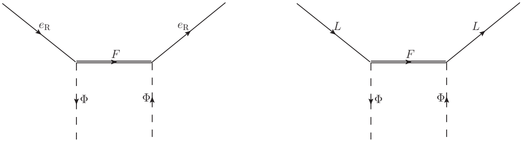



| Top. | Particles | Representations $(\mathrm{SU(2)_L, U(1)_Y})$ | $\mathrm{H}e_\alpha e_\beta$ |
|---|---|---|---|
| $\mathbf{C_1}$ | 1 F,1 S | $(2,-1/2)_F \oplus (1,0)_S, (3,0)_S$ | $\frac{Y_L Y_e \mu}{m_F m_S^2}$ |
| $\mathbf{C_2}$ | 1 F,1 S | $(2,-3/2)_F \oplus (3,1)_S$ | $\frac{Y_L Y_e \mu}{m_F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

# The *Derivative operator*. Topologies E.

- Explicit UV completions with VL generate *Derivative operator*.
- Related by EOM to the *Yukawa operator*, but bounds are different!
- Tree-level FCNC, 1-loop cLFV. $Z : c\,e/(2c_W s_W)$, $W : c\,e/(2\sqrt{2}s_W)$.

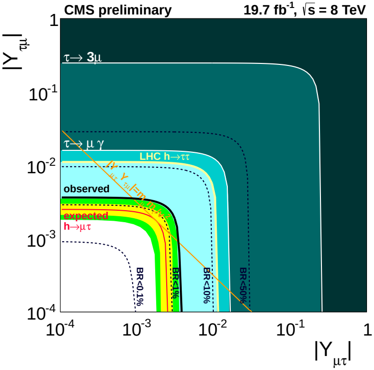


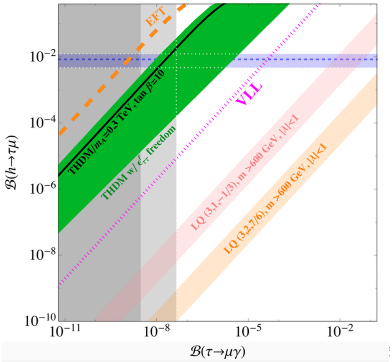

| Operator | Top. | Particles | $Z\nu_\alpha\nu_\beta$ | $Ze_\alpha e_\beta$ | $We\nu$ | $He_\alpha e_\beta$ |
|---|---|---|---|---|---|---|
| $(\overline{e_R}\Phi^\dagger)\gamma_\mu D^\mu(e_R\,\Phi)$ | $E_1$ | $(2,-1/2)_F$ | | -1 | | $\frac{YYy_\tau v^2}{m_F^2}$ |
| $(\overline{e_R}\Phi^T)\gamma_\mu D^\mu(e_R\,\Phi^*)$ | $E_2$ | $(2,-3/2)_F$ | | +1 | | $\frac{YYy_\tau v^2}{m_F^2}$ |
| $(\overline{L}\tilde{\Phi})\gamma_\mu D^\mu(\tilde{\Phi}^\dagger L)$ | $E_{3a}$ | $(1,0)_F$ | -1 | | -1 | No |
| $(\overline{L}\vec{\tau}\tilde{\Phi})\gamma_\mu D^\mu(\tilde{\Phi}^\dagger\vec{\tau}L)$ | $E_{3b}$ | $(3,0)_F$ | -1 | -2 | +1 | $\frac{YYy_\tau v^2}{m_F^2}$ |
| $(\overline{L}\Phi)\gamma_\mu D^\mu(\Phi^\dagger\,L)$ | $E_{4a}$ | $(1,-1)_F$ | | +1 | -1 | $\frac{Y_\mu Y_\tau y_\tau v^2}{m_F^2}$ |
| $(\overline{L}\vec{\tau}\Phi)\gamma_\mu D^\mu(\Phi^\dagger\,\vec{\tau}L)$ | $E_{4b}$ | $(3,-1)_F$ | +2 | +1 | +1 | $\frac{YYy_\tau v^2}{m_F^2}$ |

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

- Strongest constraints: $\tau \to \mu\gamma$, $e\, m_\tau/(8\pi^2\Lambda^2)\,\overline{\mu}\sigma^{\mu\nu}P_{L,R}\tau F_{\mu\nu}$.
- At 1 loop 2HDM have $\sim m_\tau^2$ wrt VL, one from vertex, other from helicity flip. 2HDM dominant contributions from 2 loops.
- 2HDM work because $\tau \to \mu\gamma$ is suppressed wrt VL:

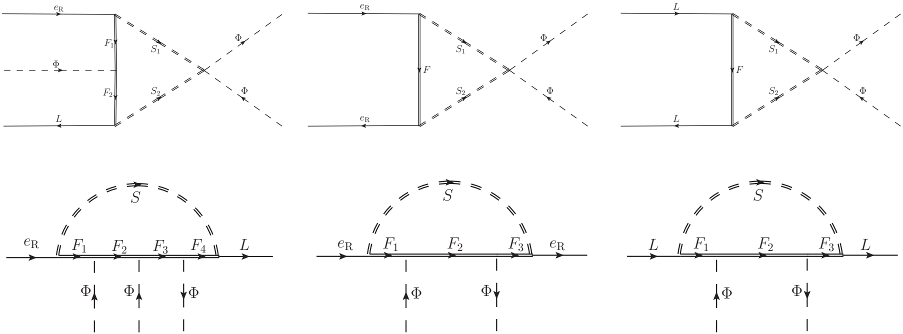
$$BR^{\mathrm{2HDM}}_{\tau\to\mu\gamma} \sim 10^{-3}\, BR^{\mathrm{VL}}_{\tau\to\mu\gamma}.$$



# Neutrino mass models

# Neutrino mass models giving HLFV at one loop




| Top. | Part. | Representations | Neutrino mass models |
|---|---|---|---|
| LR | S, F | $(2,-1/2)_S$, $(1,0)_F,(3,1)_F$ | 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 $(Z_2)$ | $S \oplus F$ | $(1,-2)_S \oplus (1,0)_F,(3,0)_F$ | Scotogenic Model |

# Neutrino mass models giving HLFV at one loop

- We estimate that all neutrino mass models give:

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

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

$$\left(\frac{Y}{M_i/\mathsf{TeV}}\right)^4 \lesssim \mathcal{O}(0.01 - 1) \qquad \longrightarrow \qquad BR(H \to \mu\tau) \lesssim 10^{-9} .$$

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

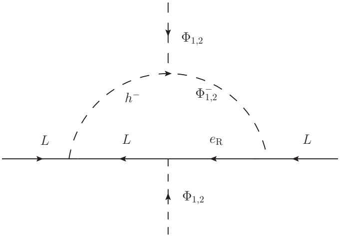
- Evade cLFV? No, some of the new F and S in the loop are charged. One expects cLFV at the same level as HLFV [Dorsner].
- Large Yukawas with special textures: $\lesssim 10^{-5}$ [ISS, Arganda].
- But: large $Y, \lambda$ lead to instabilities/non-perturbative and $H \to \gamma\gamma$.

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

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

- The Zee model, a Type III 2HDM:

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




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

$$BR(H \to \mu\tau) = \frac{m_H}{8\pi\Gamma_H}\left(\frac{Y_2^{\tau\mu}\, s_{\beta-\alpha}}{\sqrt{2}\, s_\beta}\right)^2 \sim 0.01?$$ [JHG, in preparation]

# Neutrino mass models for HLFV at tree level. LR models.

[Mohapatra, Senjanovic, Keung...]

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

$$\mathrm{Q = T_{3L} + T_{3R} + \frac{B-L}{2}}.$$

- $\mathrm{B-L=2}$ 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:

$$\mathcal{L}_Y \subset \overline{L}_L(Y_1\Sigma + Y_2\tilde{\Sigma})L_\mathrm{R} \to \frac{\overline{e_L}}{\sqrt{2}}\left(Y_1(v_1+H_1^0)+Y_2(v_2+H_2^0)\right)e_\mathrm{R}.$$

- 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

- We have systematically check all tree level topologies for $H \to \tau\mu$.
- All VL models generate the *Derivative operator* (FCNC) and they are excluded as an explanation from cLFV constraints.
- 2HDM work due to cLFV suppression wrt VL.
- 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 are:
  1. The Zee model [detailed study in preparation to check its viability].
  2. LR symmetric models [may also explain di-boson LHC hint].

# Back-up slides

# HLFV

- Many studies in the literature: Iltan, Diaz, Pilaftsis, DiazCruz, Sher, Blankenburg, Harnik, Dorsner, Goudelis, Arhrib, Davidson, Aristizabal, Falkowski, Celis, Arganda, Sierra, Campos, Dery, Arana-Catania, Kearney, Bhattacharyya, Omura, Dorsner, de Lima...
- Specific UV models are much more constrained (e.g., VL) than EFT (e.g, see Harnik et al). We further investigate this fact via EFT, and in particular using the *Derivative operator*.

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

- The mass matrix after including the EFT operator looks like

$$\mathcal{M} = \begin{pmatrix} y_\mu & y_{\mu\tau} \\ y_{\tau\mu} & y_\tau \end{pmatrix} v \longrightarrow \quad m_\mu \sim \frac{|y_{\tau\mu} y_{\mu\tau}|\, v}{y_\tau}, \quad m_\tau \sim y_\tau v.$$

- To avoid fine-tuning we need: $\sqrt{|y_{\tau\mu} y_{\mu\tau}|} \lesssim \frac{\sqrt{m_\mu m_\tau}}{v} \sim 2 \cdot 10^{-3}.$