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

Juan Herrero García

Royal Institute of Technology (KTH)

In collaboration with Arcadi Santamaría and Nuria Rius

arXiv:1605.06091

**Planck 2016**

Valencia, 25$^{\text{th}}$ of May 2016

# 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:

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

- 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 $\nu$ oscillations, and is expected in charged leptons.
   - For Dirac $\nu$ or in seesaws HLFV and CLFV rates are unobservable.

# NP is needed for HLFV

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

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

giving:

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

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 $\Gamma_H^{\rm total} = \Gamma_H^{\rm SM} + \Gamma_H^{\rm new}$:

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

# UV completions from EFT

# The *Yukawa* and *Derivative operators*

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

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

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

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

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

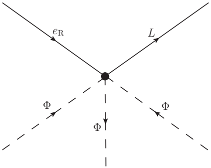
- Yukawas are no longer diagonal ($V_{\rm L}^\dagger\, C_Y\, V_{\rm R} \approx C_Y$):

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

# HLFV scales and models

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

| $\overline{C}_Y$ | $\Lambda$ (TeV) |
|---|---|
| 1 | 5 |
| $m_\tau/v$ | 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

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

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

# First rough classification of models

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

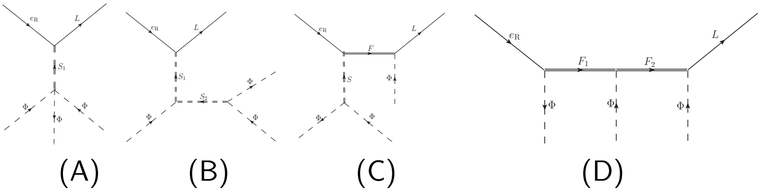
| $\overline{C}_Y$ \ $\overline{C}_\gamma$ | $m_\tau^2/v^2$ | $m_\tau/v$ | 1 |
|---|---|---|---|
| 1 $(\mathcal{O}_Y)$ | $1$ | $0.04$ | $10^{-6}$ |
| $m_\tau/v$ $(\mathcal{O}_{1,2})$ | $0.04$ | $10^{-6}$ | $10^{-10}$ |
| $1/(4\pi)^2$ $(\mathcal{O}_Y)$ | $0.03$ | $10^{-6}$ | $10^{-10}$ |
| $m_\tau/((4\pi)^2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

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...])

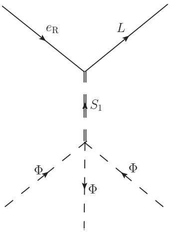
- Many studies with EFT and models: Iltan, Diaz, Pilaftsis, Diaz Cruz, Akeroyd, Sher, Blankenburg, Harnik, Dorsner, Crivellin, Goudelis, Arhrib, Nir, Davidson, Aristizabal-Sierra, Falkowski, Celis, Arganda, Campos, Dery, Arana-Catania, Kearney, Bhattacharyya, Alvarado, Omura, Nebot, Dorsner, Huitu, Lami, Bizot, Belusca-Maito, Cheung, Banerjee, Buschmann, Das, de Lima, Baek, Aloni, Altmannshofer, Yue...
- **Our approach: we start by systematically listing the HLFV UV models opening EFT and impose constraints from CLFV.**




- Hierarchy:

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

# Opening the *Yukawa operator*: scalars. Topology A.



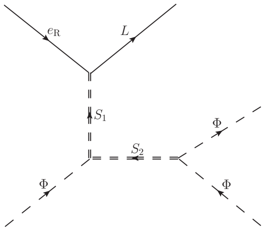

| Top. | Particles | Representations $(\mathrm{SU}(2)_\mathrm{L}, \mathrm{U}(1)_\mathrm{Y})$ | H$e_\alpha e_\beta$ |
|---|---|---|---|
| **A** | 1 S | $S = (2, -1/2)$ | $Y\lambda/m_{S_1}^2$ |

- HLFV is given by ($\tan\beta = v_2/v_1$, $\alpha$ 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 | $(2,-1/2)_S \oplus (1,0)_S, (3,0)_S, (3,1)_S$ | $\frac{Y\mu_1\mu_2}{m_{S_1}^2 m_{S_2}^2}$ |

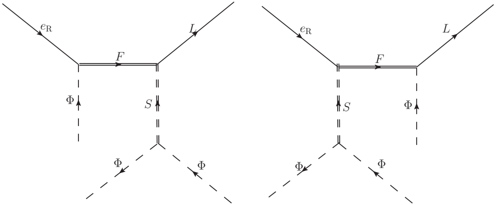
- The vevs $v_T$ of the scalar triplets $(3,0)_S$ and $(3,1)_S$ contribute as:

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

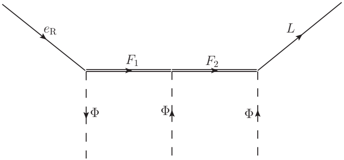
- **B**: Their vevs are $v_T \sim \mu_2\, v^2/(v\, M_{S_2}^2) \lesssim (5\,\mathrm{GeV})/v$, so:

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

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




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




| Top. | Particles | Representations $(\mathrm{SU}(2)_L, \mathrm{U}(1)_Y)$ | $\mathrm{H}e_\alpha e_\beta$ |
|---|---|---|---|
| $\mathbf{C_1}$ | 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 | $(2,-3/2)_F \oplus (1,-1)_F, (3,-1)_F$ | $\frac{Y_L Y_e Y_F}{m_{F_1} m_{F_2}}$ |

# Bounds on HLFV models

- Several constraints on them from universality, $\rho$, 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:

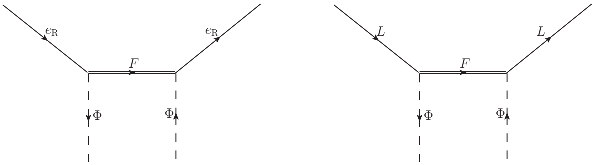
- Topologies A and B:

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

- 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:$\kappa_{\tau\mu} e/(2c_w s_w)$,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 $\mathrm{BR}(\tau \to 3\mu) < 2.1 \cdot 10^{-8} \;\longrightarrow\; |\kappa_{\tau\mu}| \lesssim \mathcal{O}(10^{-3})$:

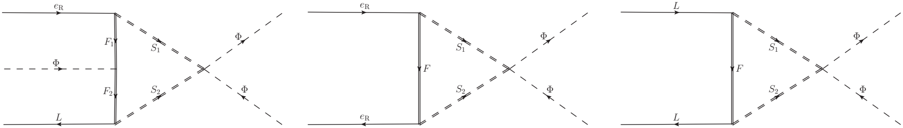
$$\mathrm{BR}(h \to \mu\tau) \sim 1200 |y_{\tau\mu}|^2 \lesssim 10^{-7}\,.$$

- 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 $\sim 1/(4\pi)^4$?

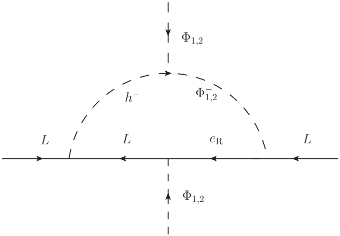
- Evade cLFV? No, some of the new F and S in the loop are charged. One expects cLFV at the same level as HLFV [Dorsner].
- Large Yukawas with special textures: $\lesssim 10^{-5}$ [ISS, Arganda].
- But: large $Y, \lambda$ lead to instabilities/non-perturbative and $H \to \gamma\gamma$.

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

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

- The Zee model (type III version):

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




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

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

# 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 $\mu e$ 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 $\mathrm{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$ and restore parity:

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

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

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

- 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

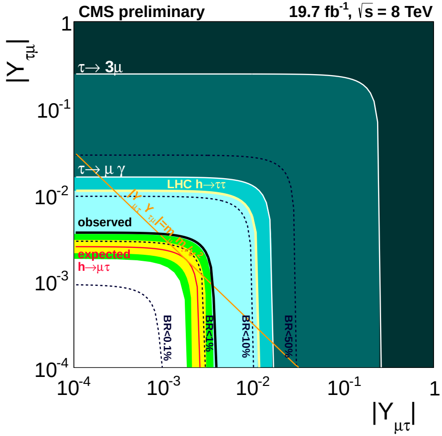
- HLFV would imply BSM physics, maybe related to neutrino masses.
- All tree level topologies from *Yukawa* and *Derivative* operators.
- Contributions to $\tau \to \mu\gamma$ from both EFT and UV. Robust/natural (HLFV doesn't/does decouple from CLFV) upper limits on $H \to \tau\mu$.
- All VL models 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.

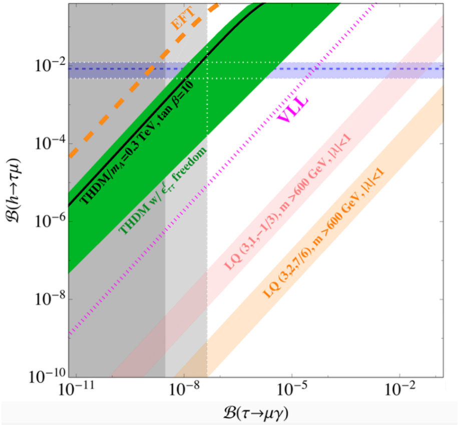
# Back-up slides

# 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 $C_Y = C' \, Y_e + Y_e \, C''$:

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

- 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).

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

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

- 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:

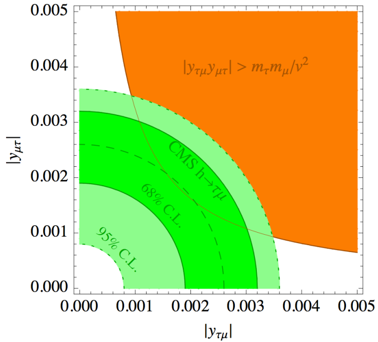
$$c_H\,\partial^\mu(\Phi^\dagger\Phi)\,\partial_\mu(\Phi^\dagger\Phi) + c_\lambda\,(\Phi^\dagger\Phi)^3\,.$$

# 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 $E = (1, -1)_{\rm F}$ of bare mass $M_{\rm E}$:

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

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

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

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

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

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

# General VL models explicitly: "matching" with EFT

- Z FCNC, where $\ell$ 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 $y_{\tau\mu}$):

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

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

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

- *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:

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

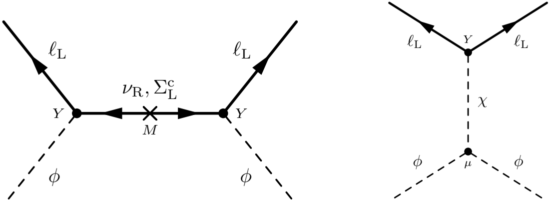
- Note: 2HDM 2 loops (Barr-Zee) dominate [Davidson, Harnik, Aristizabal...].
- $\tau \to \mu\gamma$ excludes VL in composite scenarios [Falkowski].

# 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 $\alpha$ and $\beta$ 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 $\nu$'s are light: they couple to high scale fields.
- Drawbacks: typically difficult to test, problem of hierarchies.

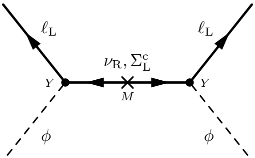
# Adding right-handed neutrinos: seesaw type I

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

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

$$\mathcal{L}_{\nu\,\text{mass}} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D\\ m_D^T & m_R\end{pmatrix}\begin{pmatrix}\nu_L^c\\ \nu_R\end{pmatrix} + \text{H.c.}\,,$$

where $m_D = Y\frac{v}{\sqrt{2}}$.




If $m_R \gg m_D$, one gets $n$ $m_R$ leptons (mainly singlets) and

$$m_\nu \simeq -m_D\,m_R^{-1}\,m_D^T.$$

# Seesaw type II

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

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

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

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

# Seesaw type II

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

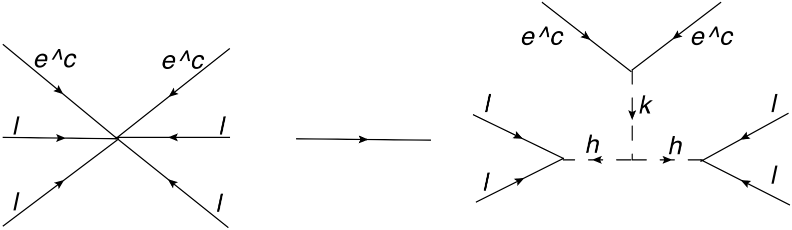
$$m_\nu = 2Y_\chi v_\chi = 2Y_\chi \frac{\mu v_\phi^2}{m_\chi^2}$$

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

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 $m_\nu$). By NDA:

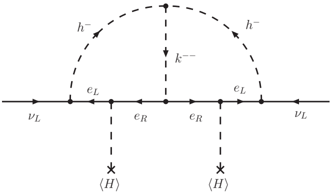
$$m_\nu \sim \frac{c}{(4\pi)^4} \frac{y_e^2 v^2}{\Lambda}$$

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



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

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




$$\mathcal{M}_\nu = \frac{v^2 \mu}{48\pi^2 M^2} \tilde{I}\, f\, Y\, g^\dagger Y^T f^T\,,$$

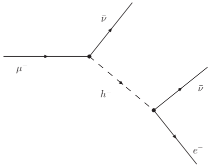
$$M \equiv \max(m_h, m_k)\,.$$

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

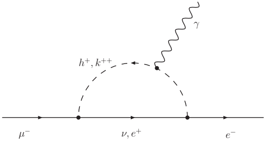
$$A_{\text{ZB}} \sim \frac{m_\tau v}{(4\pi)^2} \left( \frac{\lambda_{hH}}{m_h^2} \left( f^*_{e\mu} f_{e\tau} \right) + \frac{\lambda_{kH}}{m_k^2} \left( g^*_{e\mu} g_{e\tau} + g^*_{\mu\mu} g_{\mu\tau} + g^*_{\mu\tau} g_{\tau\tau} \right) \right),$$

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

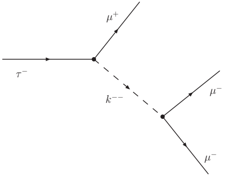
# Strongest onstraints: cLFV and universality



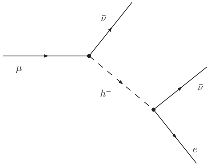

- $|V_{ud}^{exp}|^2 + |V_{us}^{exp}|^2 + |V_{ub}^{exp}|^2 = 0.9999 \pm 0.0006$
  $\approx 1 - \frac{\sqrt{2}}{G_F m_h^2} |f_{e\mu}{}^2| \longrightarrow |f_{e\mu}|^2 < 0.007 \left(\frac{m_h}{\text{TeV}}\right)^2$
- $\tau/\mu$ universality: $\frac{G_\tau^{exp}}{G_\mu^{exp}} = 0.9998 \pm 0.0013$
  $||f_{e\tau}|^2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



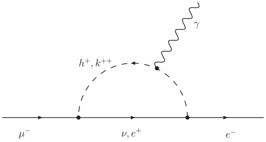

- $\text{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
  $\frac{|f_{e\tau}^* f_{\mu\tau}|^2}{(m_h/\text{TeV})^4} + \frac{16|g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau}|^2}{(m_k/\text{TeV})^4} < 0.7$



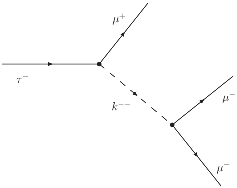

- $\text{BR}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$
  $|g_{\mu\tau} g_{\mu\mu}^*| < 0.008 \left(\frac{m_k}{\text{TeV}}\right)^2$




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




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




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