The Zee model: connecting neutrino masses to Higgs lepton flavor violation

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Outline

1. Brief introduction to neutrino mass models
2. The Zee model and its connection to HLFV
3. Results from a parameter scan
4. Summary and conclusions

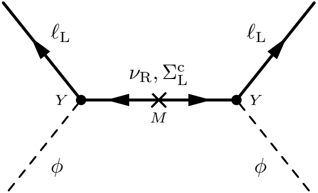
Brief introduction to neutrino masses

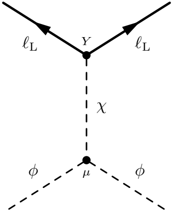
The Weinberg operator: tree level completions– seesaws

- There is only one dimension 5 EFT operator, with $\Delta L = 2$.
- It generates Majorana neutrino masses (α, β flavour indices):

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

- Left) a $Y = 0$ heavy fermion singlet (triplet), type I (III) seesaw.
- Right) a $Y = 1$ heavy scalar triplet, type II seesaw.





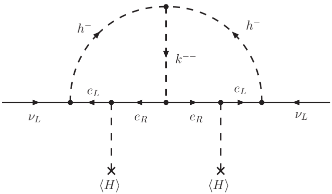
1. Positive points: SO(10) embedding, Leptogenesis.
2. Drawbacks: typically difficult to test, problem of hierarchies.

Loop level $\mathcal{O}_5$ completions: radiative models [Zee, Cheng, Babu...]

- Prototype example: the Zee-Babu model, which adds a singly- and a doubly-charged scalar $h^\pm, k^{\pm\pm}$. $\Delta L = 2$ in the μ term:

$$\mathcal{L}_{\rm ZB} \subset \overline{L}\, Y e_{\rm R} \Phi + \overline{\tilde{L}} f L h^+ + \overline{e^c_{\rm R}} g\, e_{\rm R}\, k^{++} + \left(\mu h^2 k^{++} + \text{H.c.}\right).$$

- Neutrino masses are generated at two loops:



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

Clear predictions:

- f is AS $\to \det f = 0 \to \det \mathcal{M}_\nu = 0$, so one ν is massless.
- k^{++} can be light enough to be searched for at the LHC.

[Review to appear soon by Cai, JHG, Schmidt, Vicente, Volkas.]

The Zee model and its connection to HLFV

The Zee Model [Zee, Cheng, Babu, Wolfenstein, Petcov, Kanemura, Aristizabal, He..]

- The Zee model adds to the SM content an extra Higgs doublet Φ_2 and a new singly-charged SU(2) singlet h^+.
- The most general Yukawa Lagrangian reads (f is AS, $Y_{1,2}$ general):

$$\mathcal{L}_Y = -\overline{L}\,(Y_1^\dagger \Phi_1 + Y_2^\dagger \Phi_2) e_{\mathrm{R}} - \overline{\tilde{L}} f\, L h^+ + \mathrm{H.c.}$$

- Charged lepton masses are given by ($t_\beta = v_2/v_1$):

$$m_E = \frac{v}{\sqrt{2}} \left(c_\beta Y_1^\dagger + s_\beta Y_2^\dagger \right) .$$

- Convenient to go to the Higgs basis ($\langle H_1^0 \rangle = v/\sqrt{2}$, $\langle H_2^0 \rangle = 0$):

$$-\mathcal{L}_Y = \overline{L} \left[\frac{\sqrt{2} m_E}{v} H_1 + \left(\frac{Y_2^\dagger}{c_\beta} - \frac{\sqrt{2} m_E t_\beta}{v} \right) H_2 \right] e_{\mathrm{R}} + \overline{\tilde{L}} f L h^+ + \mathrm{H.c.}$$

The scalar sector

- The most general potential in the Higgs basis reads:

$$
\begin{aligned}
V = {} & \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 - \left(\mu_3^2 H_2^\dagger H_1 + \text{H.c.}\right) + \frac{1}{2}\lambda_1 \left(H_1^\dagger H_1\right)^2 \\
& + \frac{1}{2}\lambda_2 \left(H_2^\dagger H_2\right)^2 + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) \\
& + \left\{\frac{1}{2}\lambda_5 \left(H_1^\dagger H_2\right)^2 + \left[\lambda_6 \left(H_1^\dagger H_1\right) + \lambda_7 \left(H_2^\dagger H_2\right)\right] H_1^\dagger H_2 + \text{H.c.}\right\} \\
& + \mu_h^2 \left|h^+\right|^2 + \lambda_h \left|h^+\right|^4 + \lambda_8 \left|h^+\right|^2 H_1^\dagger H_1 + \lambda_9 \left|h^+\right|^2 H_2^\dagger H_2 \\
& + \lambda_{10} \left|h^+\right|^2 \left(H_1^\dagger H_2 + \text{H.c.}\right) + \left(\mu \epsilon_{\alpha\beta} H_1^\alpha H_2^\beta h^- + \text{H.c.}\right)
\end{aligned}
$$

- The spectrum consists of two CP-even scalars (h, H), one CP-odd (A), and two charged scalars $h_{1,2}^+$ which mix via the μ term:

$$
s_{2\varphi} = \frac{\sqrt{2} v \mu}{m_{h_2^+}^2 - m_{h_1^+}^2} .
$$

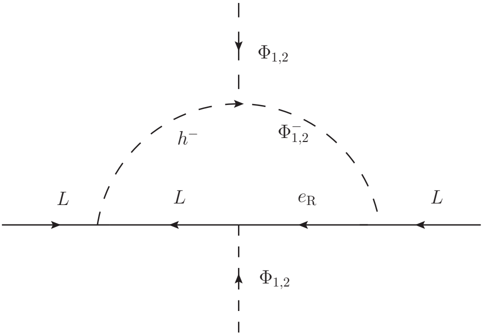
Leptonic Yukawa Lagrangian in the mass basis

In the mass basis, the most general leptonic Lagrangian reads

$$
\begin{aligned}
-\mathcal{L}_Y = {} & \overline{\nu_{\mathrm{L}}}\, U^\dagger \left(\frac{-\sqrt{2} m_E t_\beta}{v} + \frac{Y_2^\dagger}{c_\beta} \right) e_{\mathrm{R}} \left(c_\varphi h_1^+ - s_\varphi h_2^+ \right) \\
& + 2\, \overline{\nu_{\mathrm{L}}^c}\, U^T f e_{\mathrm{L}} \left(-s_\varphi h_1^+ - c_\varphi h_2^+ \right) \\
& + \overline{e_{\mathrm{L}}} \left(\frac{-m_E s_\alpha}{v c_\beta} + c_{\beta-\alpha} \frac{Y_2^\dagger}{\sqrt{2} c_\beta} \right) e_{\mathrm{R}} h \\
& + \overline{e_{\mathrm{L}}} \left(\frac{m_E c_\alpha}{v c_\beta} - s_{\beta-\alpha} \frac{Y_2^\dagger}{\sqrt{2} c_\beta} \right) e_{\mathrm{R}} H \\
& + i \overline{e_{\mathrm{L}}} \left(-\frac{m_E t_\beta}{v} + \frac{Y_2^\dagger}{\sqrt{2} c_\beta} \right) e_{\mathrm{R}} A + \mathrm{H.c.}
\end{aligned}
$$

Neutrino masses at one loop

- $\Delta L = 2$ by the simultaneous presence of Y_1, Y_2, f, and μ.
- Majorana neutrino masses are generated at one loop:



- The neutrino mass matrix reads:

$$\mathcal{M}_\nu = \frac{s_{2\varphi}\, t_\beta}{8\sqrt{2}\pi^2\, v}\left(f\, m_f^2 + m_f^2\, f^T - \frac{v}{\sqrt{2 s_\beta}}\left(f\, m_f\, Y_2 + Y_2^T\, m_f\, f^T\right)\right) \ln \frac{m^2_{h_2^+}}{m^2_{h_1^+}}$$

Neutrino mixings and LFV

Neglecting terms proportional to the electron mass, $\mathcal{M}_\nu$ reads:

$$\mathcal{M}_\nu \propto \begin{pmatrix} -2f^{e\tau}Y_2^{\tau e} & -f^{e\tau}Y_2^{\tau\mu} - f^{\mu\tau}Y_2^{\tau e} & \frac{\sqrt{2}s_\beta\, m_\tau}{v}f^{e\tau} - f^{e\tau}Y_2^{\tau\tau} \\ -f^{e\tau}Y_2^{\tau\mu} - f^{\mu\tau}Y_2^{\tau e} & -2f^{\mu\tau}Y_2^{\tau\mu} & \frac{\sqrt{2}s_\beta m_\tau}{v}f^{\mu\tau} - f^{\mu\tau}Y_2^{\tau\tau} \\ \frac{\sqrt{2}s_\beta\, m_\tau}{v}f^{e\tau} - f^{e\tau}Y_2^{\tau\tau} & \frac{\sqrt{2}s_\beta m_\tau}{v}f^{\mu\tau} - f^{\mu\tau}Y_2^{\tau\tau} & 2\frac{m_\mu}{m_\tau}f^{\mu\tau}Y_2^{\mu\tau} \end{pmatrix}.$$

Reproducing correctly neutrino mixings implies $Y_2^{e\tau}$, $Y_2^{\mu\tau} \neq 0$, so:

- We expect sizable LFV rates mediated by Y_2.
- This is expected, as LF is violated by neutrino oscillations.
- In particular, HLFV rates like $\mathrm{Br}(h \to \tau\mu)$ could be large.

HLFV as a test of new physics beyond the SM

Observable	ATLAS	CMS
$\mathrm{Br}(h \to \tau\mu)$	$1.43\ \%$	$0.25\ \%$
$\mathrm{Br}(h \to \tau e)$	$1.04\ \%$	$0.61\ \%$

- In the SM, Higgs couplings to charged leptons are diagonal. HLFV occurs at $D = 6$ via (also derivative ops. like $(\overline{e_{\mathrm{R}}}\Phi^\dagger)\, C_{D\,i}\, i\not{D}(e_{\mathrm{R}}\,\Phi)$):

$$\mathcal{O}_{\mathrm{Y}} = \overline{L}\, C_Y\, e_{\mathrm{R}}\Phi(\Phi^\dagger\Phi)\,.$$

- Yukawas to leptons are not diagonal in the mass basis:

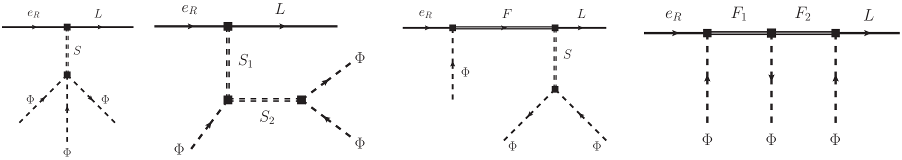
$$(y_{\mathrm{e}})_{ij} = \frac{m_i}{v}\delta_{ij} + (C_Y)_{ij}\frac{v^2}{\sqrt{2}\Lambda^2}\,, \qquad \overline{C}_Y \equiv \sqrt{|(C_Y)_{\tau\mu}|^2 + |(C_Y)_{\mu\tau}|^2}\,.$$

- HLFV is given by:

$$\mathrm{BR}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h}\bar{y}^2, \qquad \bar{y} \equiv \overline{C}_Y\,\frac{v^2}{\sqrt{2}\Lambda^2}.$$

HLFV UV completions of $\mathcal{O}_{\mathrm{Y}}$ at tree level

[Rius, Santamaria and JHG, JHEP 1611 (2016) 084, arXiv: 1605.06091]



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

- Topology A (also B) is a two-Higgs doublet, with possible large HLFV.
- Topology C and D with VLL predict very small HLFV, $< 10^{-6}$.

HLFV in 2HDM (topology A) like for the Zee model is given by:

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

$\longrightarrow$ Need parameter scan of the Zee model to predict HLFV and CLFV.

Results from a parameter scan

JHEP 1704 (2017) 130, arXiv: 1701.05345

Free parameters of the scan

[T. Ohlsson, S. Riad, J. Wiren and JHG, JHEP 1704 (2017) 130, arXiv: 1701.05345]

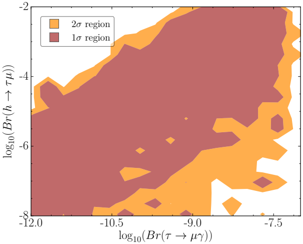
We used MultiNest to scan over the 19 free parameters of the model:

Parameter	Prior
Complex: $Y_2^{\tau\tau}$, $Y_2^{\tau\mu}$, $Y_2^{\tau e}$, $Y_2^{\mu\tau}$	$[10^{-12}, 10^{-1}]$
Real: $f^{\mu\tau}$, $f^{e\tau}$, $Y_2^{e\tau}$	$[10^{-12}, 10^{-1}]$
$\tan\beta$	$[0.3, 50]$
λ_1, λ_2, $\lvert\lambda_3\rvert$, $\lvert\lambda_5\rvert$	$[10^{-5}, \sqrt{4\pi}]$
μ_h, μ_2 [GeV]	$[1, 10^7]$
μ [GeV]	$[1, 10^7]$

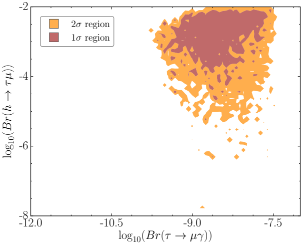
We show the one and two sigma profile likelihoods for:

- no neutrino masses ($\mu = 0$)
- neutrino masses ($\mu \neq 0$) in:
  1. Normal Ordering (NO)
  2. Inverted Ordering (IO)

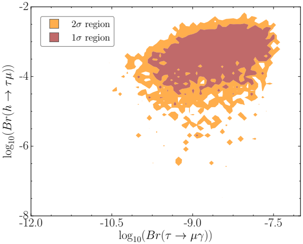
$\mu = 0$



NO



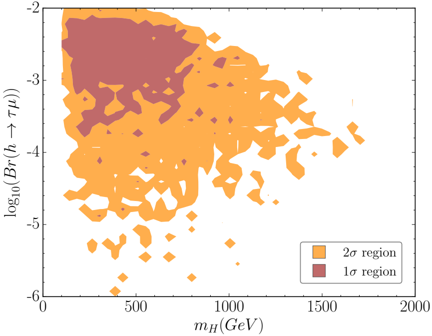
IO

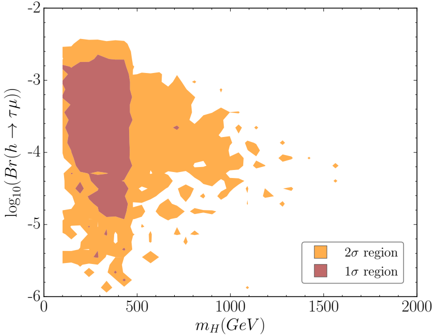


Decoupling of $h \to \tau\mu$ with m_H (NO left, IO right)

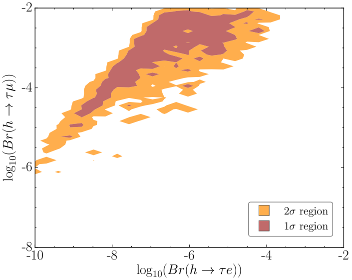
Having a sufficiently SM-like Higgs boson as observed demands $s(\beta - \alpha) \approx 1$ (alignment limit). Expanding around $\beta - \alpha \approx \pi/2$:

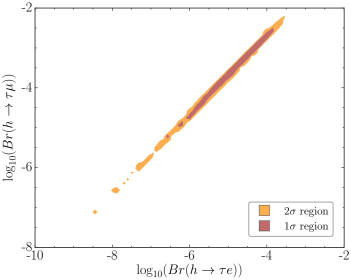
$$\mathrm{Br}(h \to \tau\mu) \simeq \frac{m_h}{16\pi\Gamma_h} \frac{\lambda_6^2 v^4}{c_\beta^2 m_H^4} (|Y_2^{\tau\mu}|^2 + |Y_2^{\mu\tau}|^2) \,.$$

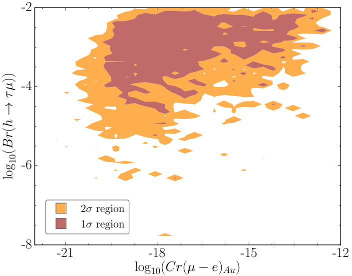


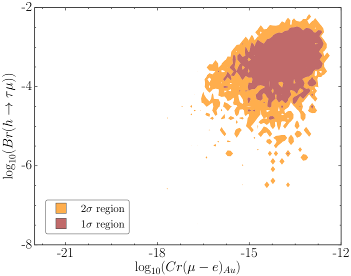


Other HLFV and CLFV processes (NO left, IO right)

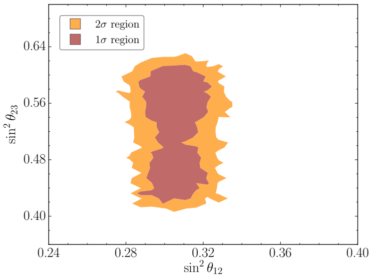


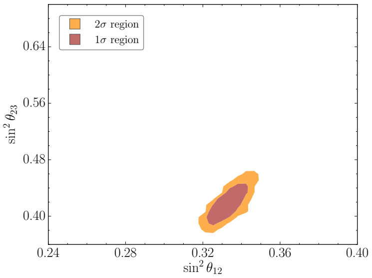


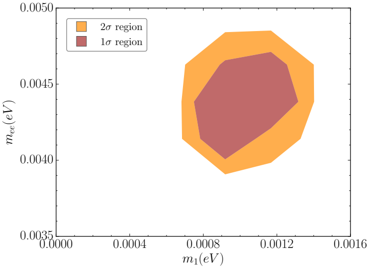


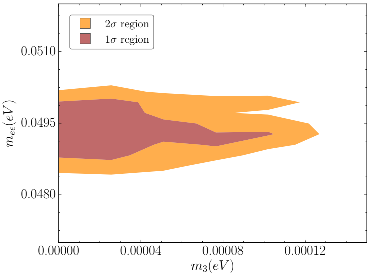


Neutrino mixings, lightest mass, m_{ee} (NO left, IO right)

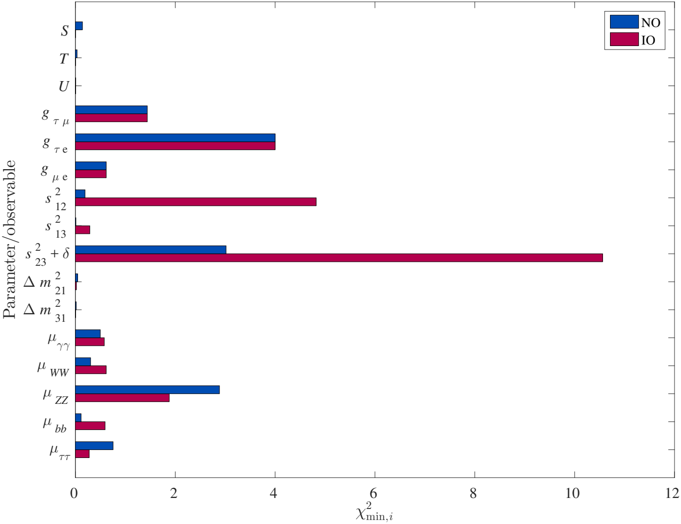








Individual contributions to the $\Delta\chi^2$



Naturality limits from the Higgs mass. 95 % C.L. results

- m_h gets a correction $\delta m_h \propto \mu$. Demanding $\delta m_h/m_h \lesssim \kappa$:

$$\mu \lesssim \kappa \, \frac{4\pi \, m_h}{s_{\beta-\alpha}} \simeq 1.5 \left(\frac{\kappa}{s_{\beta-\alpha}} \right) \mathrm{TeV} \, .$$

- $\kappa = 1\,(10)$ corresponds to *no* (10 %) fine-tuning.

	NO		IO	
Quantity	$\kappa = 1$	$\kappa = 10$	$\kappa = 1$	$\kappa = 10$
χ^2_{min}	10.7	11.0	21.7	24.0
$\text{Br}_{h\to\tau\mu}$	$[1\cdot 10^{-6}, 1\cdot 10^{-2}]$	$[1\cdot 10^{-6}, 1\cdot 10^{-2}]$	$[2\cdot 10^{-7}, 4\cdot 10^{-3}]$	$[1\cdot 10^{-7}, 5\cdot 10^{-3}]$
$\text{Br}_{h\to\tau e}$	$[1\cdot 10^{-10}, 2\cdot 10^{-4}]$	$[1\cdot 10^{-10}, 2\cdot 10^{-4}]$	$[6\cdot 10^{-9}, 3\cdot 10^{-4}]$	$[3\cdot 10^{-9}, 3\cdot 10^{-4}]$
$\text{Br}_{\tau\to\mu\gamma}$	$[8\cdot 10^{-10}, 3\cdot 10^{-8}]$	$[1\cdot 10^{-10}, 3\cdot 10^{-8}]$	$[3\cdot 10^{-11}, 3\cdot 10^{-8}]$	$[3\cdot 10^{-11}, 4\cdot 10^{-8}]$
$\text{Br}_{\mu\to e\gamma}$	$[10^{-21}, 6\cdot 10^{-13}]$	$[3\cdot 10^{-22}, 6\cdot 10^{-13}]$	$[1\cdot 10^{-31}, 1\cdot 10^{-12}]$	$[1\cdot 10^{-34}, 1\cdot 10^{-12}]$
$\text{Cr}_{\mu\to e}$	$[10^{-21}, 4\cdot 10^{-13}]$	$[1\cdot 10^{-21}, 4\cdot 10^{-13}]$	$[3\cdot 10^{-17}, 3\cdot 10^{-13}]$	$[3\cdot 10^{-17}, 3\cdot 10^{-13}]$
$m_{H,A}$	< 1.7 TeV	< 2.5 TeV	< 1.1 TeV	< 1.5 TeV
m_{h^+}	< 1.7 TeV	< 2.5 TeV	< 1.1 TeV	< 1.5 TeV
$s_{\beta-\alpha}$	$[0.98, 1.0]$	$[0.98, 1.0]$	$[0.97, 1.0]$	$[0.97, 1.0]$

Summary and conclusions

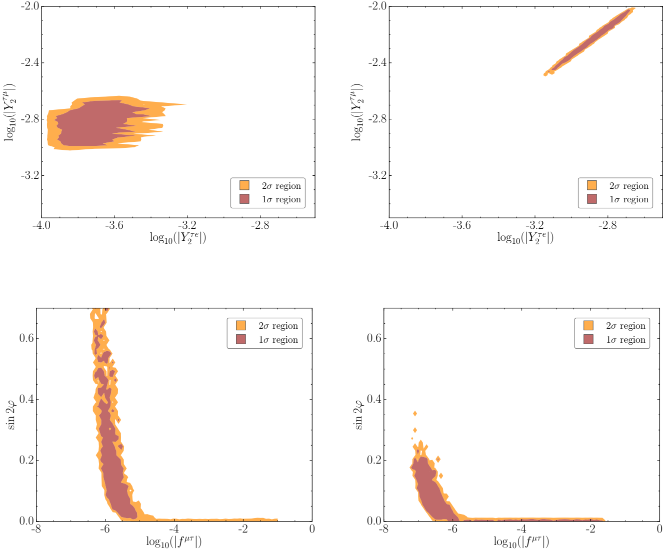
Summary and conclusions

1. Radiative models are a simple explanation for the lightness of neutrino masses, with no large hierarchies, and testable.
2. HLFV implies BSM physics, maybe related to neutrino masses.
3. The Zee model is a simple explanation for neutrino masses with HLFV at tree level. The main results from the parameter scan are:

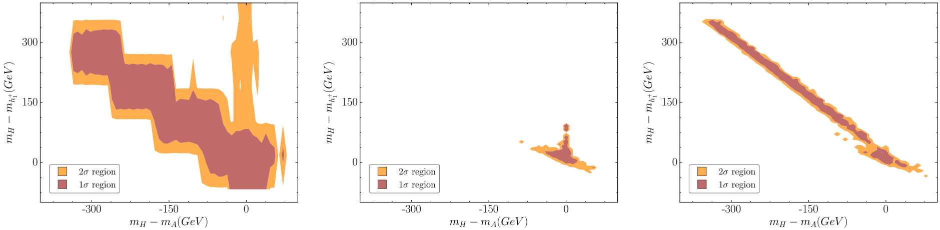
- Large $h \to \tau\mu$ is possible.
- NO gives a good fit, IO is disfavoured.
- If θ_{23} happens to be in the second octant, then IO will be excluded.
- One massless neutrino only compatible with IO.
- Scalar masses have to be below ~ 2 TeV, accessible at the LHC.
- Future $\tau \to \mu\gamma$ (μe conversion) can test NO (IO).

Back-up slides

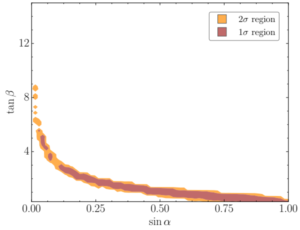
Yukawa couplings, charged mixing angle (NO left, IO right)

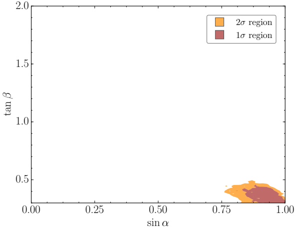


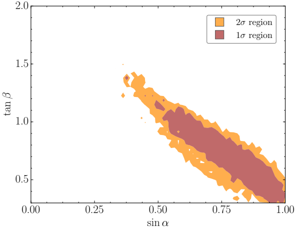
Splittings of the scalar masses ($\mu = 0$, NO left, IO right)



$\sin\alpha$ and $\tan\beta$ ($\mu = 0$, NO left, IO right)







$h \to \tau\mu$ in EFT

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

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

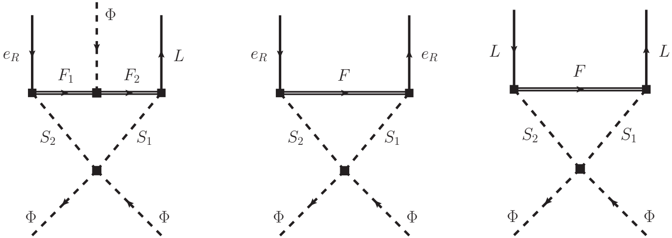
- Yukawas are no longer diagonal ($V_\mathrm{L}^\dagger \, C_Y \, V_\mathrm{R} \approx C_Y$):

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

- HLFV is given by:

$$\mathrm{BR}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h} \bar{y}^2, \qquad \bar{y} \equiv \overline{C}_Y \, \frac{v^2}{\sqrt{2}\Lambda^2}.$$

Neutrino mass models typically generate 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 k^{++})
LL	S	$(1,1)_S, (3,1)_S$	ZB (singly-charged h^+), SSII
LL (Z_2)	$S \oplus F$	$(1,1/2)_S \oplus (1,0)_F, (3,0)_F$	Scotogenic Model

$\longrightarrow$ In the Zee-Babu (with $\lambda_{h\Phi}|h^+|^2\Phi^\dagger\Phi + \lambda_{k\Phi}|k|^2\Phi^\dagger\Phi + \mathrm{h.c.}$):

$$A_{\rm ZB}^{h\to\tau\mu} \sim \frac{m_\tau v}{(4\pi)^2}\left(\frac{\lambda_{h\Phi}}{m_{h^+}^2}\left(f_{e\mu}^* f_{e\tau}\right) + \frac{\lambda_{k\Phi}}{m_k^2}\left(g_{e\mu}^* g_{e\tau} + g_{\mu\mu}^* g_{\mu\tau} + g_{\mu\tau}^* g_{\tau\tau}\right)\right).$$

HLFV rates at one loop

- We can estimate HLFV in previous neutrino mass models:

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

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

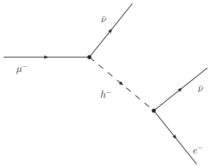
$$\left(\frac{Y}{M_i/\mathsf{TeV}}\right)^4 \lesssim \mathcal{O}(0.01-1) \quad \longrightarrow \quad \mathrm{BR}(h \to \mu\tau) \lesssim 10^{-8}.$$

Can $\mathrm{BR}(h \to \mu\tau)$ be large, overcoming the loop $\sim 1/(4\pi)^4$?

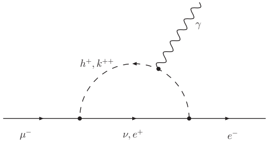
- Evade CLFV? NO, some of the new F and S in the loop are charged. One expects CLFV at the same level as HLFV [Dorsner].
- Large Yukawas with special textures: $\mathrm{BR} \lesssim 10^{-5}$ [ISS, Arganda].
- But: large Y, λ lead to instabilities/non-perturbative and $h \to \gamma\gamma$.

$\longrightarrow$ **Does any neutrino mass model generate HLFV at tree level?**

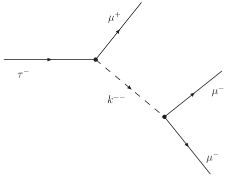
Zee-Babu strongest constraints: CLFV and universality



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



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



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