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

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PASCOS 2017

Madrid, 20th of June 2017

THE UNIVERSITY of ADELAIDE

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Outline

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

Brief introduction to radiative neutrino masses

Radiative models. An example, the Zee model

[Zee, Cheng, Babu, Wolfenstein, Petcov, Kanemura, Farzan, Cai, Aristizabal, He, JHG...]

- ν are much lighter than all the other fermions: $m_\nu / m_e < 10^{-6}$.
- Possible explanation: ν are massless at tree level, m_ν generated radiatively. Generate the Weinberg operator at n-loop order:

$$\mathcal{O}_5 = \frac{c_{\alpha\beta}}{\Lambda} (\overline{L_\alpha} \tilde{\Phi}) (\Phi^\dagger \tilde{L}_\beta) \longrightarrow m_\nu = c \frac{v^2}{\Lambda}, \quad \text{with} \quad c \propto \left(\frac{1}{4\pi}\right)^{2n}.$$

- LNV scale Λ can be TeV: no large hierarchies, testable.
- Review by Cai, Schmidt, Vicente, Volkas & JHG to appear very soon.
- An example: the Zee model, which adds to the SM content an extra Higgs doublet Φ_2 and a new singly-charged SU(2) singlet h^+:

$$\mathcal{L}_Y \subset -\overline{L} (Y_1^\dagger \Phi_1 + Y_2^\dagger \Phi_2) e_R - \overline{\tilde{L}} f L h^+ + \mu \epsilon_{\alpha\beta} \Phi_1^\alpha \Phi_2^\beta h^- + \text{H.c.}$$

The Zee model and its connection to HLFV

Leptonic Yukawa Lagrangian in the mass basis

Scalar spectrum: 2 CP-even scalars $(h,\, H)$, 1 CP-odd (A), and 2 charged scalars $h^+_{1,\,2}$ which mix via the μ term, subject to naturality constraints:

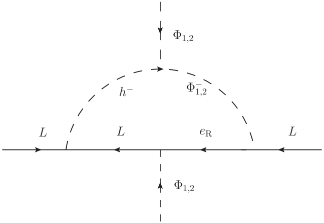
$$s_{2\varphi} = \frac{\sqrt{2} v \mu}{m^2_{h_2^+} - m^2_{h_1^+}}\,, \qquad \text{with} \qquad \mu \lesssim \frac{4\pi\, m_h}{s_{\beta-\alpha}} \simeq 1.5\,\mathrm{TeV}\,.$$

In the mass basis, the most general leptonic Lagrangian reads

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

Neutrino masses, mixings and LFV

$\Delta L = 2$ by simultaneous presence of Y_1 (or m_E), Y_2, f, & μ:



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

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

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: $h \to \tau\mu$, $\tau \to \mu\gamma$.

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:

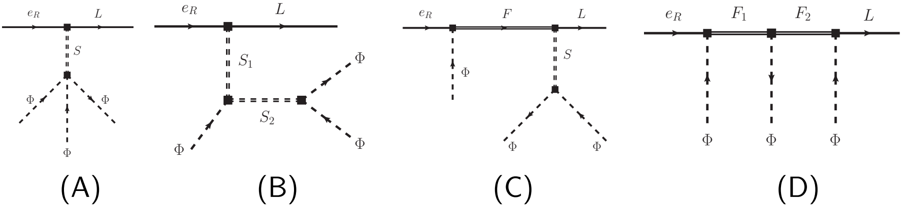
$$(y_\mathrm{e})_{ij} = \frac{m_i}{v}\delta_{ij} + (C_Y)_{ij}\frac{v^2}{\sqrt{2}\Lambda^2}\,, \qquad \overline{C}_Y \equiv \sqrt{|(C_Y)_{\tau\mu}|^2 + |(C_Y)_{\mu\tau}|^2}\,.$$

- 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]



- 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

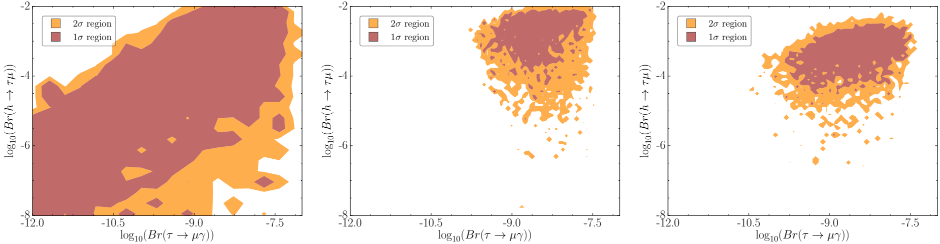
Results of parameter scan no ν masses, NO and IO

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

We show the one and two sigma profile likelihoods using MULTINEST for:

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

$\mu = 0$ **NO** **IO**



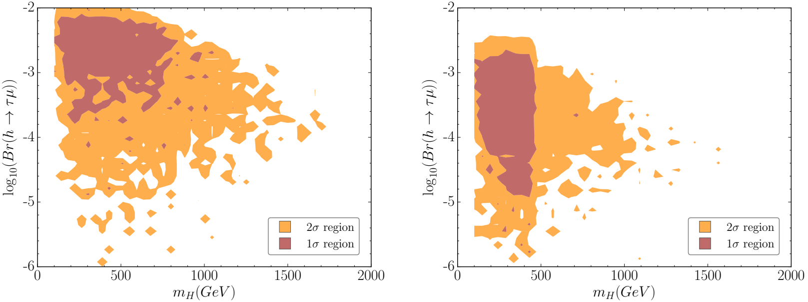
Decoupling of $h \to \tau\mu$ with m_H (NO left, IO right)

Having a sufficiently SM-like Higgs as observed demands CP-even mixing:

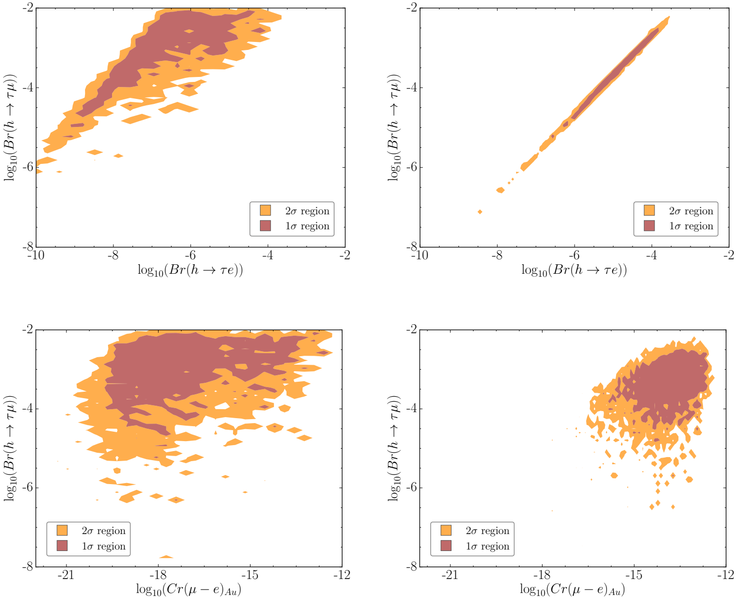
$$s_{2(\beta-\alpha)} = -\frac{2\lambda_6 v^2}{m_H^2 - m_h^2} \longrightarrow 0\,, \qquad \text{with} \quad \lambda_6 \left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right)\,,$$

in the Higgs basis ($\langle H_1^0 \rangle = v/\sqrt{2}$, $\langle H_2^0 \rangle = 0$). Expanding on $\beta - \alpha \approx \pi/2$:

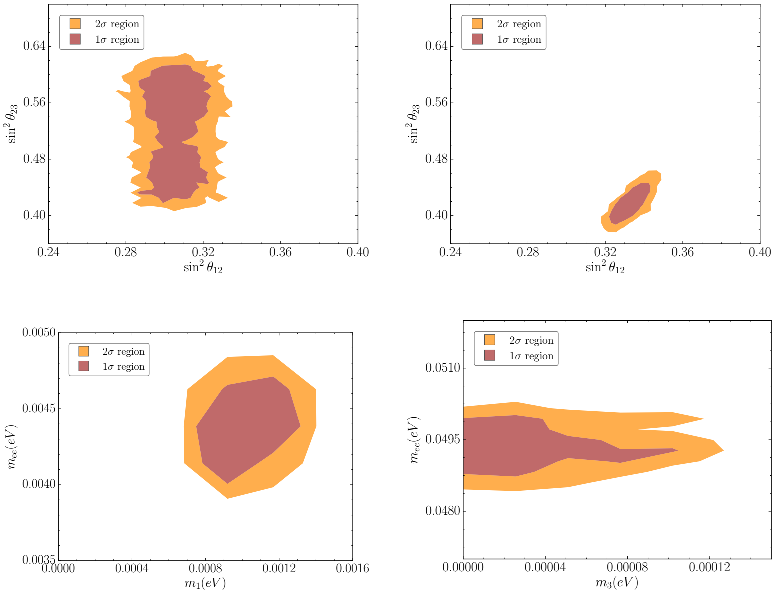
$$\mathrm{Br}(h \to \tau\mu) \simeq \frac{m_h}{16\pi\Gamma_h}\frac{\lambda_6^2 v^4}{c_\beta^2 m_H^4}\left(|Y_2^{\tau\mu}|^2 + |Y_2^{\mu\tau}|^2\right).$$



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



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



Summary and conclusions

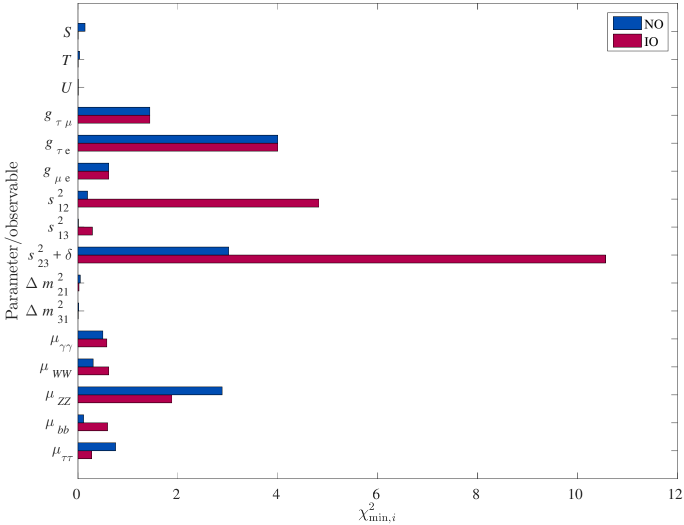
Summary and conclusions

1. Radiative models are a simple explanation for the lightness of neutrino masses, with no large hierarchies, and testable.
2. In fact, many sets of BSM fields have $\Delta L = 2$ and thus generate m_ν.
3. HLFV implies BSM physics, maybe related to neutrino masses.
4. The Zee model is a simple example with HLFV at tree level. The main results of 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

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 $\delta m_h / m_h \lesssim \kappa$:

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

- $\kappa = 1\,(10)$ 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
$\text{Br}_{h\to\tau\mu}$	$[1\cdot10^{-6}, 1\cdot10^{-2}]$	$[1\cdot10^{-6}, 1\cdot10^{-2}]$	$[2\cdot10^{-7}, 4\cdot10^{-3}]$	$[1\cdot10^{-7}, 5\cdot10^{-3}]$
$\text{Br}_{h\to\tau e}$	$[1\cdot10^{-10}, 2\cdot10^{-4}]$	$[1\cdot10^{-10}, 2\cdot10^{-4}]$	$[6\cdot10^{-9}, 3\cdot10^{-4}]$	$[3\cdot10^{-9}, 3\cdot10^{-4}]$
$\text{Br}_{\tau\to\mu\gamma}$	$[8\cdot10^{-10}, 3\cdot10^{-8}]$	$[1\cdot10^{-10}, 3\cdot10^{-8}]$	$[3\cdot10^{-11}, 3\cdot10^{-8}]$	$[3\cdot10^{-11}, 4\cdot10^{-8}]$
$\text{Br}_{\mu\to e\gamma}$	$[10^{-21}, 6\cdot10^{-13}]$	$[3\cdot10^{-22}, 6\cdot10^{-13}]$	$[1\cdot10^{-31}, 1\cdot10^{-12}]$	$[1\cdot10^{-34}, 1\cdot10^{-12}]$
$\text{Cr}_{\mu\to e}$	$[10^{-21}, 4\cdot10^{-13}]$	$[1\cdot10^{-21}, 4\cdot10^{-13}]$	$[3\cdot10^{-17}, 3\cdot10^{-13}]$	$[3\cdot10^{-17}, 3\cdot10^{-13}]$
$m_{H,A}$	< 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
$s_{\beta-\alpha}$	$[0.98, 1.0]$	$[0.98, 1.0]$	$[0.97, 1.0]$	$[0.97, 1.0]$

The scalar sector

- Most general potential in the Higgs basis ($\langle H_1^0 \rangle = v/\sqrt{2}$, $\langle H_2^0 \rangle = 0$):

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

- 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:

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

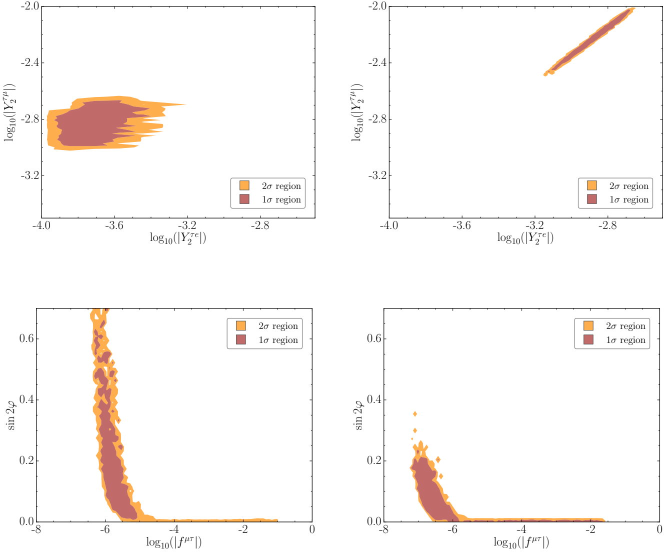
Free parameters of the scan

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

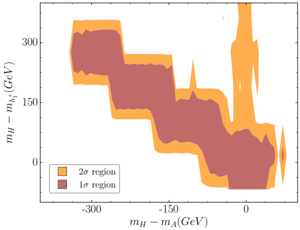
We used MultiNest to scan over the 19 free parameters of the model:

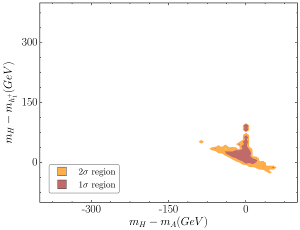
Parameter	Prior
Complex: $Y_2^{\tau\tau}$, $Y_2^{\tau\mu}$, $Y_2^{\tau e}$, $Y_2^{\mu\tau}$	$[10^{-12}, 10^{-1}]$
Real: $f^{\mu\tau}$, $f^{e\tau}$, $Y_2^{e\tau}$	$[10^{-12}, 10^{-1}]$
$\tan\beta$	$[0.3, 50]$
λ_1, λ_2, $\|\lambda_3\|$, $\|\lambda_5\|$	$[10^{-5}, \sqrt{4\pi}]$
μ_h, μ_2 [GeV]	$[1, 10^7]$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

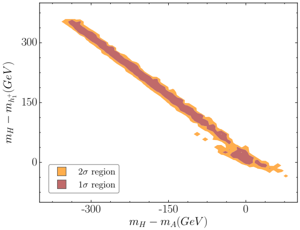
Yukawa couplings, charged mixing angle (NO left, IO right)



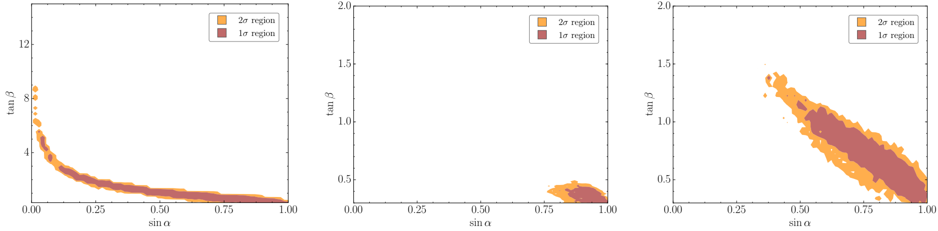
Splittings of the scalar masses ($\mu = 0$, NO left, IO right)







$\sin\alpha$ 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:

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

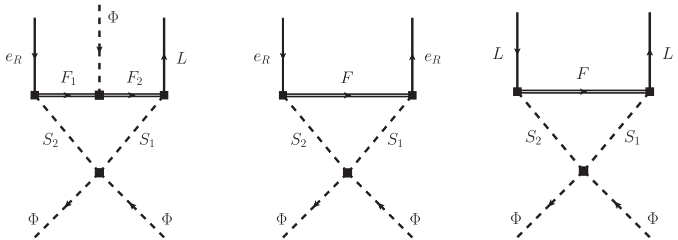
- Yukawas are no longer diagonal ($V_{\rm L}^\dagger \, C_Y \, V_{\rm R} \approx C_Y$):

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

- HLFV is given by:

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

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 $\lambda_{h\Phi}|h^+|^2\Phi^\dagger\Phi + \lambda_{k\Phi}|k|^2\Phi^\dagger\Phi + \mathrm{h.c.}$):

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

HLFV rates at one loop

- We can estimate HLFV in previous neutrino mass models:

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

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

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

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 $h \to \gamma\gamma$.

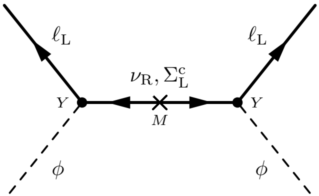
$\longrightarrow$ **Does any neutrino mass model generate HLFV at tree level?**

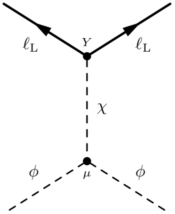
The Weinberg operator: tree level completions– seesaws

- 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.





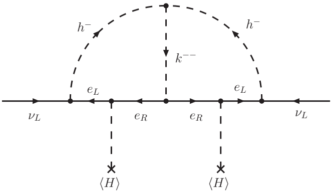
1. Positive points: SO(10) embedding, Leptogenesis.
2. Drawbacks: typically difficult to test, problem of hierarchies.

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:

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

- Neutrino masses are generated at two loops:

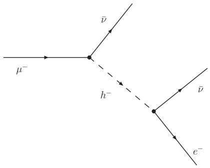


$$\mathcal{M}_\nu = \frac{v^2 \mu}{48\pi^2 M^2} \tilde{I}\, f\, Y\, g^\dagger Y^T f^T ,$$
$$M \equiv \max(m_h, m_k)\,.$$

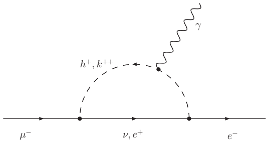
Clear predictions:

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

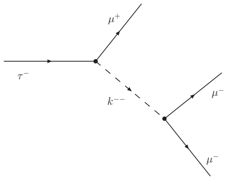
Zee-Babu strongest constraints: CLFV and universality



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



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



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