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

Juan Herrero García

University of Adelaide, CoEPP

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Outline

1. Introduction to neutrino mass models
2. The new observable: Higgs lepton flavor violation
3. Parameter scan of the Zee model
4. Summary and conclusions

Introduction to neutrino mass models

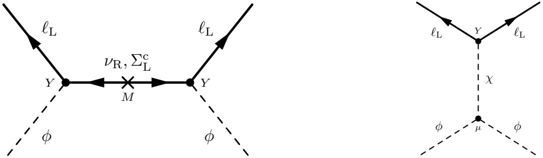
The Weinberg operator: tree level completions– seesaws

- There is only one dimension 5 EFT operator, which violates ΔL in 2.
- It generates Majorana neutrino masses (α, β flavour indices):

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

- Rewriting it, with $\vec{\sigma} \equiv (\sigma_1, \sigma_2, \sigma_3)$:

$$\left(\overline{L_\alpha}\tilde{\phi}\right)\,\left(\phi^\dagger \tilde{L}_\beta\right) = -\left(\overline{L_\alpha}\,\vec{\sigma}\tilde{\phi}\right)\,\left(\phi^\dagger\,\vec{\sigma}\tilde{L}_\beta\right) = 1/2\left(\overline{L_\alpha}\,\vec{\sigma}\,\tilde{L}_\beta\right)\,\left(\phi^\dagger\,\vec{\sigma}\,\tilde{\phi}\right),$$



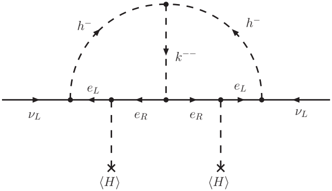
- Left) a $Y = 0$ heavy fermion singlet (triplet), type I (III) seesaw.
- Right) a $Y = 1$ heavy scalar triplet, type II seesaw.
- Drawbacks: typically difficult to test, problem of hierarchies.

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:

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

- 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.

The new observable: Higgs lepton flavor violation

HLFV as a test of new physics beyond the SM

- HLFV is a new observable to study, with upper limits:

Observable	ATLAS	CMS
$\mathrm{Br}(h \to \tau\mu)$	$1.43\ \%$	$1.20\ \%$
$\mathrm{Br}(h \to \tau e)$	$1.04\ \%$	$0.69\ \%$

- In the SM, Higgs couplings to the charged leptons are diagonal.
- HLFV implies NP beyond the SM, parameterized by EFT operators:

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

- HLFV occurs at $D = 6$:

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

- $\mathcal{O}_{\mathrm{D\,i}}$ related by EOM to $\mathcal{O}_{\mathrm{Y}} +$ plus other non-HLFV operators.

$h \to \tau\mu$ 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 ($V_\mathrm{L}^\dagger \, C_Y \, V_\mathrm{R} \approx C_Y$):

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

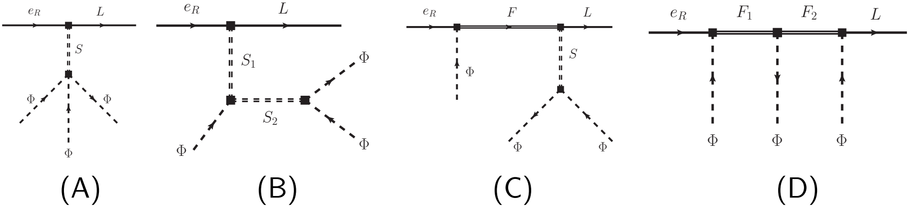
- HLFV is given by:

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

HLFV UV completions at tree level

[Rius, Santamaria and JHG, arXiv: 1605.06091]

Opening $\mathcal{O}_{\rm Y} = \overline{L}\, C_{Y}\, e_{\rm R} \Phi(\Phi^\dagger \Phi)$ at tree level we obtain:

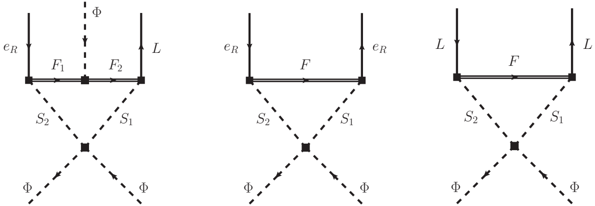


- Topology A (also B) is a two-Higgs doublet, with possible large HLFV.
- Topology C and D with VLL predict very small HLFV, $< 10^{-6}$.

We know that lepton flavor is violated in the neutrino sector, so:

What are the HLFV rates in popular neutrino mass models?

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:

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

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

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

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: $\mathrm{BR} \lesssim 10^{-5}$ [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?**

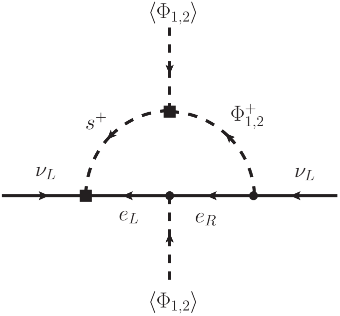
Parameter scan of the Zee model

arXiv: 1701.05345

- The Zee model (most general version), $\Delta L = 2$ in the μ term:

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

- Neutrino masses are generated via the one-loop diagram:



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

HLFV in the Zee Model

- The mass matrix (neglecting terms $\propto m_e$) reads:

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

- HLFV is given by:

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

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

- We expect a lower bound on HLFV and CLFV.
- Need full parameter scan to test if they can be observable.

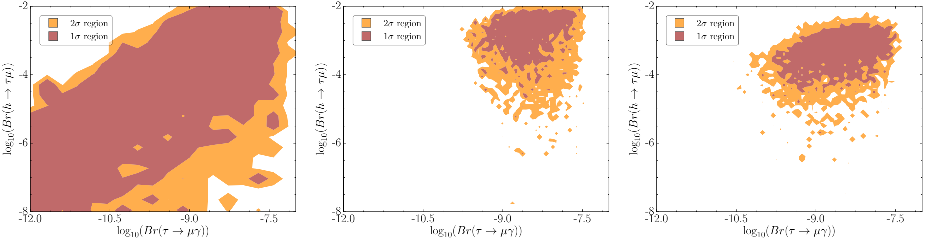
Full parameter scan of Zee model [with Multinest, Superplot]

[T. Ohlsson, S. Riad, J. Wiren and JHG, arXiv: 1701.05345]

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)

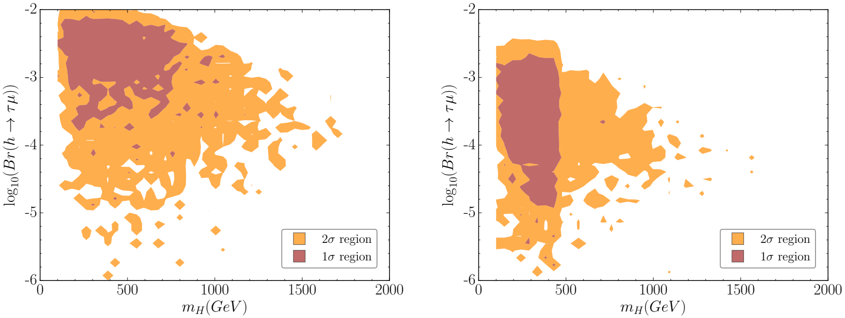
$\mu = 0$ **NO** **IO**



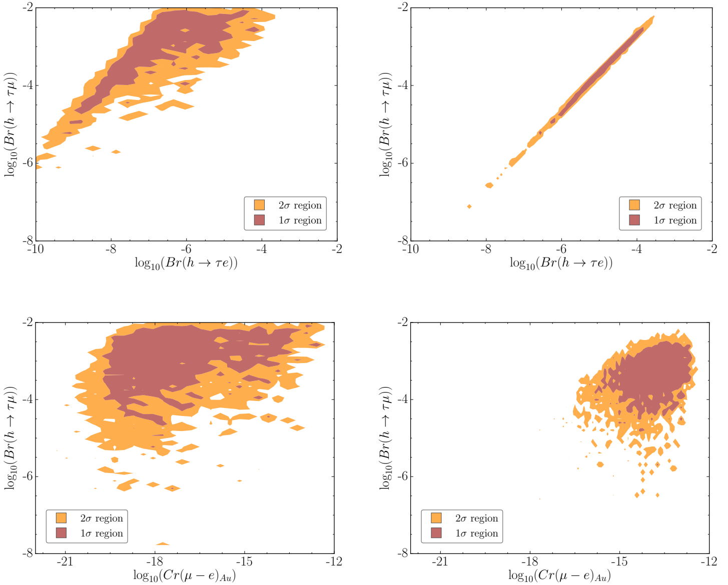
Decoupling of $h \to \tau\mu$ with m_H (NO left, IO right)

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

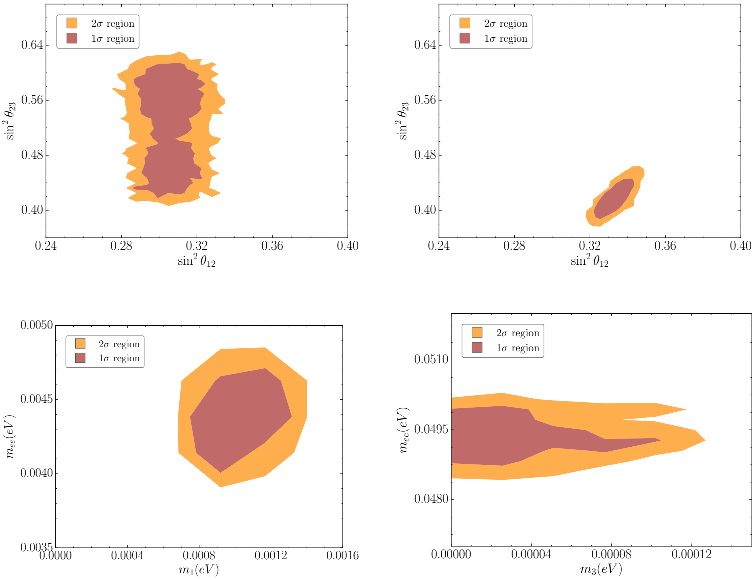
$$\mathrm{Br}(h \to \tau\mu) \simeq \frac{m_h}{16\pi\Gamma_h} \frac{\lambda_6^2 v^4}{c_\beta^2 m_H^4} \left(|Y_2^{\tau\mu}|^2 + |Y_2^{\mu\tau}|^2 \right).$$



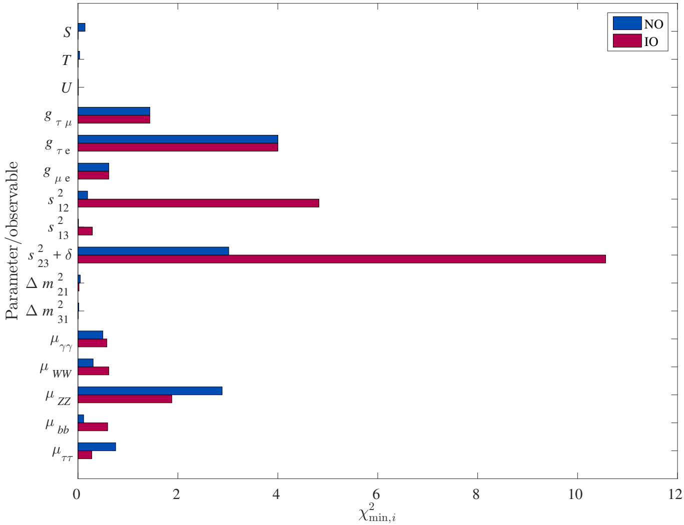
Other HLFV and CLFV processes (NO left, IO right)



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



Individual contributions to the χ^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	$\kappa = 1$	$\kappa = 10$	$\kappa = 1$	$\kappa = 10$
$\chi^2_{\rm min}$	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

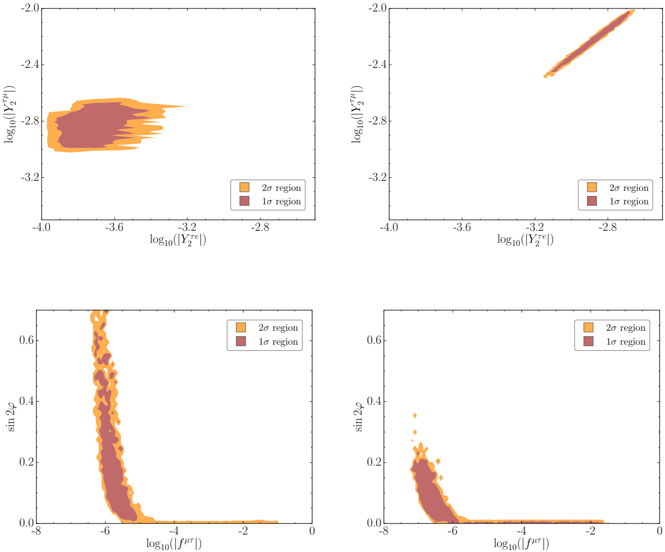
Summary and conclusions

1. Radiative models are a simple explanation for the lightness of neutrino masses, they do not have large hierarchies and are testable.
2. HLFV implies BSM physics, maybe related to neutrino masses.
3. However, most neutrino models generate one-loop suppressed HLFV.
4. On the other hand, the Zee model generates HLFV at tree level:

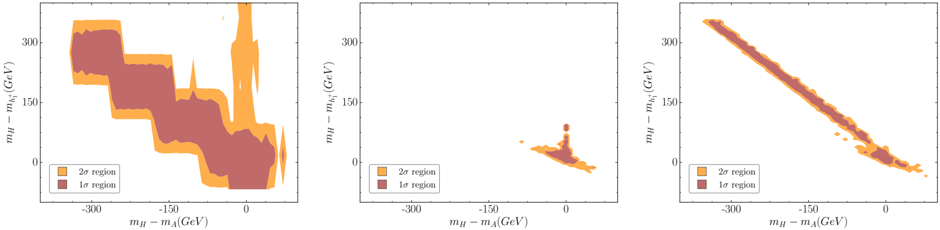
- Large $h \to \tau\mu$ is possible.
- NO gives a good fit, IO is disfavoured.
- If θ_{23} happens to be in the second octant, then IO will be excluded.
- Lightest neutrino compatible with massless only in IO.
- Scalar masses have to be below ~ 2 TeV.
- Future $\tau \to \mu\gamma$ (μe conversion) completely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

Back-up slides

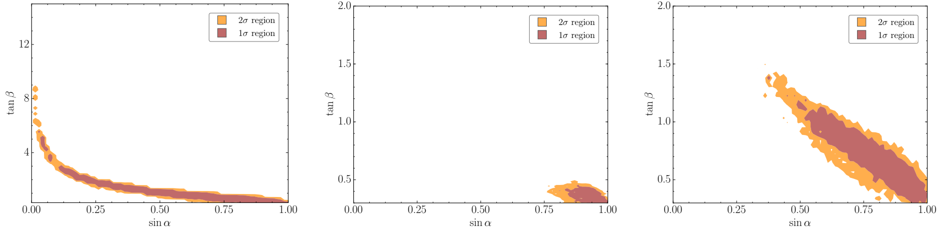
Yukawa couplings (NO left, IO right)



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



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



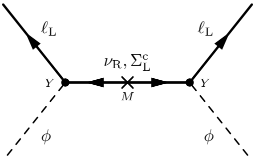
Adding right-handed neutrinos: seesaw type I

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

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

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

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

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

Adding a $Y = 1$ scalar triplet: seesaw type II

- The triplet is a 2×2 matrix:

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

- Yukawa coupling to the lepton doublets:

$$\mathcal{L}_\chi = -\Big((Y_\chi)_{\alpha\beta} \, \overline{\tilde{L}}_\alpha \chi L_\beta + \text{H.c.} \Big) - V(\phi, \chi) \, ,$$

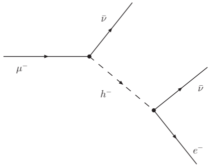
where Y_χ is a symmetric matrix and $\tilde{L} = i\tau_2 \, L^c$. The scalar potential:

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

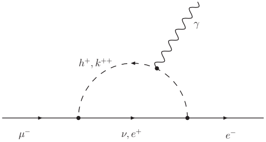
- μ induces v_ϕ, even if $m_\chi > 0$. From the ρ parameter, $v_\chi \lesssim 5$ GeV.
- Y_χ and μ violate LN. In the limit $m_\chi \gg v_\phi$, we get:

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

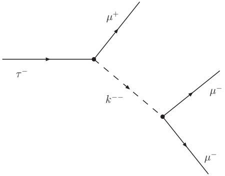
Zee-Babu strongest constraints: cLFV and universality



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

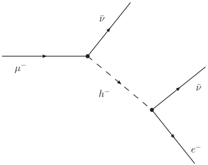


- $\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
  $\frac{|f_{e\tau}^* f_{\mu\tau}|^2}{(m_h/\mathrm{TeV})^4} + \frac{16|g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau}|^2}{(m_k/\mathrm{TeV})^4} < 0.7$

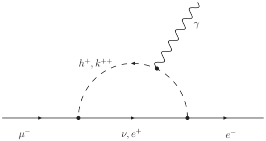


- $\mathrm{BR}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$
  $|g_{\mu\tau} g_{\mu\mu}^*| < 0.008 \left(\frac{m_k}{\mathrm{TeV}}\right)^2$

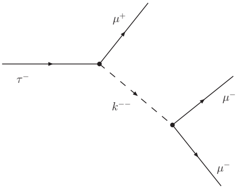
Zee Babu universality and LFV constraints



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



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



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