Understanding neutrino properties in a 2HDM see-saw

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Outline

Neutrino masses and the see-saw

Puzzles

- Existence
- Smallness
- mild hierarchy $\sqrt{\Delta m^2_{\mathrm{sol}}}/\sqrt{\Delta m^2_{\mathrm{atm}}}$
- large mixing angles θ_{12}, θ_{23}, small θ_{13}

The see-saw

$$\mathcal{L} \supset \Phi^* \bar{L} \mathbf{Y}_{\boldsymbol{\nu}} \nu_R - \frac{1}{2} \nu_R^T \mathbf{M_R} \nu_R + \mathrm{h.c.}$$

yielding at low scales

$$\mathcal{M}_\nu = \frac{v^2}{2} \mathbf{Y}_{\boldsymbol{\nu}} \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^T$$

If $\mathbf{Y}_{\boldsymbol{\nu}}$ hierarchical, expect naively $\sqrt{\Delta m^2_{\mathrm{atm}}} \gg \sqrt{\Delta m^2_{\mathrm{sol}}}$
[cf. Casas, Ibarra, Jimenez-Alburquerque, '07]

Benefits and drawbacks

The see-saw

New particles	ν-puzzles solved	New problems	Signatures
≥ 2 r.h. neutrinos	• Existence • Smallness	(Hierarchy problem)	None

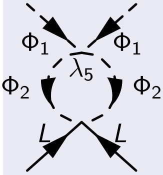
The general (=type III) 2HDM see-saw

- $\mathcal{L} \supset \Phi_a^* \bar{L} \mathbf{Y}_{\boldsymbol{\nu}}^a \nu_R - \frac{1}{2} \nu_R^T \mathbf{M_R} \nu_R + \text{h.c.}$ $a = 1, 2$
- Basis $\langle \Phi_1^0 \rangle = v$, $\langle \Phi_2^0 \rangle = 0$

Tree level mass generation

$$\mathcal{M}_\nu = \frac{v^2}{2} \mathbf{Y}_{\boldsymbol{\nu}}^1 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{1\,T}$$

One loop mass generation [Grimus, Neufeld, '89]



$$m_2 = \frac{v^2}{2} \frac{2\lambda_5}{16\pi^2} \log \frac{M_R}{m_{\Phi_2}} \mathrm{Tr}(\mathbf{Y}_{\boldsymbol{\nu}}^2 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{2\,T}) \times P$$

where $P = 1 - \dfrac{\mathrm{Tr}(\mathbf{Y}_{\boldsymbol{\nu}}^2 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{2\dagger} \mathbf{Y}_{\boldsymbol{\nu}}^1 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{1\dagger})}{\mathrm{Tr}(\mathbf{Y}_{\boldsymbol{\nu}}^1 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{1\dagger}) \mathrm{Tr}(\mathbf{Y}_{\boldsymbol{\nu}}^2 \mathbf{M_R}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}^{2\dagger})}$

Generation of a mild hierarchy

Assuming m_3 to be generated at tree, m_2 at loop level

$$\frac{m_2}{m_3} = \frac{2\lambda_5}{16\pi^2} \log \frac{M_R}{m_{\Phi_2}} \times \frac{\mathrm{Tr}(\mathbf{Y}_\nu^2 \mathbf{M}_\mathbf{R}^{-1} \mathbf{Y}_\nu^{2T})}{\mathrm{Tr}(\mathbf{Y}_\nu^1 \mathbf{M}_\mathbf{R}^{-1} \mathbf{Y}_\nu^{1T})} \times P$$

Reasonable values

- $\lambda_5 \sim 1$
- $\log(M_R/m_{\Phi_2}) \sim 30$
- $\mathrm{Tr}(\mathbf{Y}_\nu^2 \mathbf{M}_\mathbf{R}^{-1} \mathbf{Y}_\nu^{2T}) \sim \mathrm{Tr}(\mathbf{Y}_\nu^1 \mathbf{M}_\mathbf{R}^{-1} \mathbf{Y}_\nu^{1T})$
- $P \sim 0.5$

$$\Rightarrow \boxed{\frac{m_2}{m_3} \sim 0.2}$$

Therefore

$\rightarrow$ Obtain naturally mild neutrino mass hierarchy [Grimus, Neufeld, '00]

$\rightarrow$ Mild dependence on m_{Φ_2}

$\rightarrow$ Relies on flavour violation in neutrino sector

Benefits and drawbacks

The see-saw

New particles	ν-puzzles solved	New problems	Signatures
≥ 2 r.h. neutrinos	• Existence • Smallness	(Hierarchy problem)	None

The 2HDM see-saw

New particles	ν-puzzles solved	New problems	Signatures
≥ 1 r.h. neutrino ≥ 2 Higgs doublets	• Existence • Smallness • Mild hierarchy	?	?

The 2HDM in the decoupling limit

Problems associated with the 2HDM

- Charge breaking minima
- Large contributions to oblique parameters S, T, U
- FCNC, LFV
- CP violation

All these problems disappear in the decoupling limit!

where the new Higgs fields are much heavier than the electroweak scale, $m_{\Phi_2} \gg v$.

Benefits and drawbacks

The see-saw

New particles	ν-puzzles solved	New problems	Signatures
≥ 2 r.h. neutrinos	• Existence • Smallness	(Hierarchy problem)	None

The 2HDM see-saw

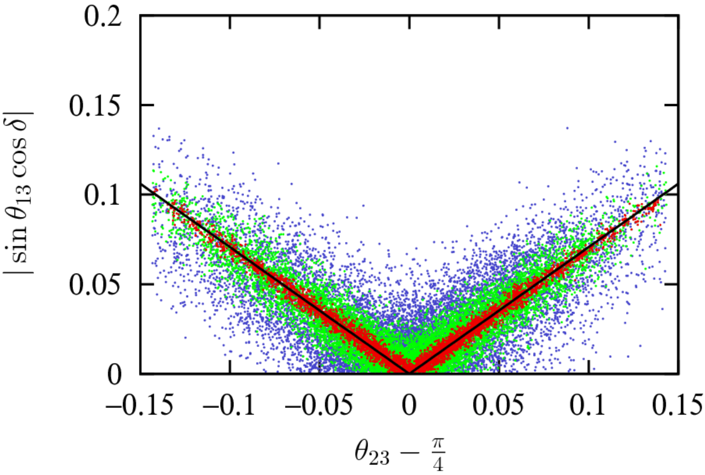
New particles	ν-puzzles solved	New problems	Signatures
≥ 1 r.h. neutrino ≥ 2 Higgs doublets	• Existence • Smallness • Mild hierarchy	In decoupling limit only hierarchy problem	Maybe

A correlation $\theta_{13} \leftrightarrow \theta_{23}$

- Assume $\mathbf{U}_{i3}(M_R) = 1/\sqrt{2} \times (0,1,1)^T$ at the Majorana mass scale M_R
- RGE running of $\mathcal{M}_\nu \Rightarrow \mathbf{U}_{i3} = \mathbf{U}_{i3}(M_R) + \epsilon \mathbf{U}_{i2}(M_R)$
- Obtain correlation $\theta_{23} - \pi/4 = \sqrt{2} \sin\theta_{13} \cos\delta$
- This correlation is perturbed by the re-diagonalization of $\mathbf{Y}^1_\mathbf{e}$:

  Even if $\mathbf{Y}^1_\mathbf{e}$ is diagonal at M_R this must not be the case at m_{Φ_2},
  $\beta_{\mathbf{Y}^1_\mathbf{e}} \supset \mathrm{Tr}\left(3\mathbf{Y}^{1\dagger}_\mathbf{u}\mathbf{Y}^2_\mathbf{u} + 3\mathbf{Y}^1_\mathbf{d}\mathbf{Y}^{2\dagger}_\mathbf{d} + \mathbf{Y}^1_\mathbf{e}\mathbf{Y}^{2\dagger}_\mathbf{e}\right)\mathbf{Y}^2_\mathbf{e} + \mathbf{Y}^1_\mathbf{e}\mathbf{Y}^{2\dagger}_\mathbf{e}\mathbf{Y}^2_\mathbf{e} + \frac{1}{2}\mathbf{Y}^2_\mathbf{e}\mathbf{Y}^{2\dagger}_\mathbf{e}\mathbf{Y}^1_\mathbf{e}$
  Define unitary matrix $\mathbf{V}^\mathbf{L}_\mathbf{e}$ by $\mathbf{Y}^1_\mathbf{e}\mathbf{Y}^{1\dagger}_\mathbf{e} = \mathbf{V}^\mathbf{L}_\mathbf{e}\mathrm{diag}(y^2_{e1}, y^2_{e2}, y^2_{e3})\mathbf{V}^{\mathbf{L}\dagger}_\mathbf{e}$
  Then $\mathbf{U} \to \mathbf{V}^\mathbf{L}_\mathbf{e}\mathbf{U}$

A correlation $\theta_{13} \leftrightarrow \theta_{23}$



$\mathbf{U}_{i3}(M_R) = (0,1,1)^T,\ M_R = 10^{14}\ \mathrm{GeV},\ |\lambda_5| = 0.5$

$|\mathbf{V}^{\mathbf{L}}_{\mathbf{e}\,i\neq j}| < 0.06\ (0.03/0.01)$ for blue (green/red) points

Conclusions

If neutrino mass has contributions from several Higgses

$\rightarrow$ Mild hierarchy $\sqrt{\Delta m^2_{\mathrm{sol}}}/\sqrt{\Delta m^2_{\mathrm{atm}}}$ natural

$\rightarrow$ New opportunity to understand mixing angles

$\rightarrow$ For 2HDM, $\theta_{23} = \pi/4$, $\sin\theta_{13} = 0$ at the Majorana scale and $\mathbf{V_e^L} \approx \mathbb{1}$
$\Rightarrow \theta_{23} - \pi/4 \approx \sqrt{2}\sin\theta_{13}\cos\delta$

$\rightarrow$ New Higgs fields do not lead to problems if decoupled