Neutrino masses from new generations

(in coll. with A. Aparici, N. Rius, A. Santamaría)

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Neutrinos: new physics is needed (better testable)

- Neutrino masses ($\sum m_\nu \lesssim 1$ eV) $\Rightarrow$ first hint of PBSM.
- From oscillation experiments, the possible hierarchies are:

1. NH: $m_3 \approx \sqrt{|\triangle m^2_{23}|} \approx 0.05$ eV & $m_2 \approx \sqrt{\triangle m^2_{12}} \approx 0.01$ eV.
2. IH: $m_2 \approx m_1 \approx \sqrt{|\triangle m^2_{23}|} \approx 0.05$ eV.
3. Quasi-degenerate: $m_1 \simeq m_2 \simeq m_3$.

- Lepton mixing is compatible with TBM (hint of $\theta_{13} \neq 0$):

$$U^{TBM} = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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Simple explanation: RH nus and high-scale seesaw, but...

- Hierarchy problem for $O(1)$ Yukawas ($\delta m_H^2 \simeq m_R^2/(4\pi)^2$).
- Difficult to test it (sterile ν_R with $m_R \sim 10^{15}\,\mathrm{GeV}$).

Natural SM extension: new families

- Theoretically: $\beta_{QCD} < 0 \Longrightarrow n_{gen} \leq 8$.
- EW fits (always with assumptions) allow 2 extra at most.

$\rightarrow$ A heavy Higgs would fit better with extra families.
$\rightarrow$ Removes tension with LEP II bound.
$\rightarrow$ Need further studies for the new LHC data.

- Baryogenesis: more CPV.
- DM: hadrons, heavy ν /singlets if stable enough.
- Composite Higgs & dynamical EW symm. breaking:

$\rightarrow$ solution to hierarchy problem.

- Might solve flavor discrepancies.
- Tight connection with the LHC...

Severe bounds on extra families

- Direct detection, with assumptions:
- $m_{t'} > 450$ GeV (new LHC bound, assumes $t' \to Wb$)
- $m_{b'} > 385$ GeV (assumes $b' \to Wt$)

with $|m_{t'} - m_{b'}| \lesssim 80$ GeV from EW fits.

- $m_E > 100.8$ GeV

with $|m_E - m_{\nu'}| \lesssim 140$ GeV from EW fits.

- $m_{\nu'}$:

1. unstable (LEP II): 80.5 (M), 90.3 (D), 63 GeV (both).
2. stable (inv. Z width): $m_4 > 39.5\,(M),\ 45\,(D)$ GeV.

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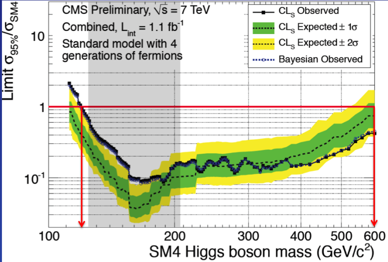
Neutrinos at the EW scale shouldn't surprise anyone!

What seem unnatural are neutrinos with masses 13 orders of magnitude smaller than the EW scale!

New very stringent limits on a 4G Higgs

- H-G-G vertex enhanced by 3 (5) for a fourth (fifth) family.
- $B_r^{4/5\,G}$ can be very different from B_r^{SM} & change the results.



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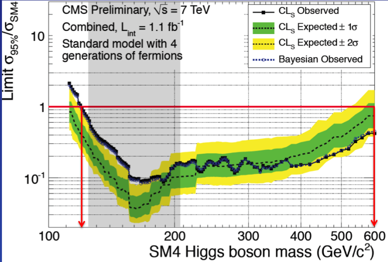


New families with simple Higgs are really being pushed...

- $120 < m_H^{4G} < 600\,\mathrm{GeV}$ excl. (95% C.L.). Combined result soon. $114.4 - 120$, $\gtrsim 600$ GeV still allowed.
- If H_{4G} excluded, are there ways out? Extended scalar sector? Strongly coupled? Composite? Exotic B_r?

A new SM family and a ν_R with Majorana mass m_R

(Petcov et al., Babu et al., Grimus et al., Choudhury et al.)

- New generation leptons E, ν_E and a singlet ν_R:

$$\mathcal{L} \supset \bar{\ell} Y_e e_R \phi + \bar{\ell} Y_\nu \nu_R \tilde{\phi} + \frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \mathrm{H.c.}$$

with:

$$Y_\nu = \begin{pmatrix} y_e \epsilon & y_\mu \epsilon & y_\tau \epsilon & y_E \end{pmatrix}^T \text{ where } \epsilon \ll 1$$

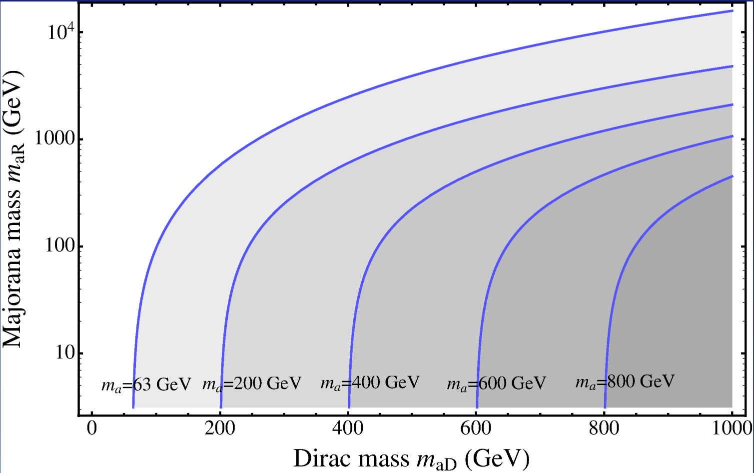
- We rotate to mass basis:

$\rightarrow \nu_\alpha = \sum_i V_{\alpha i} \nu'_i$, with $i = 1, .., 4$, $\alpha = e, .., E$.

- Two massive states at tree level ($m_D \approx y_E v$):

$$m_{4,\bar{4}} = \tfrac{1}{2}\left(\sqrt{m_R^2 + 4 m_D^2} \mp m_R\right) \gtrsim 63\,\text{GeV} \longrightarrow y_E \approx \mathcal{O}(1)$$

Lepton number violating scale so $m_4 > 63$ GeV



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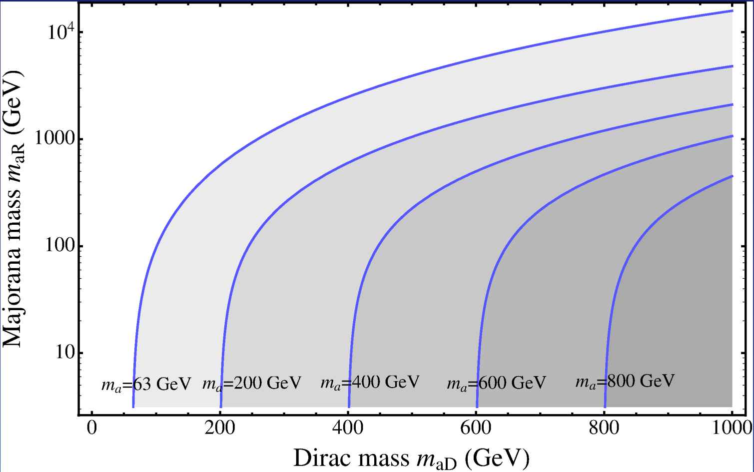
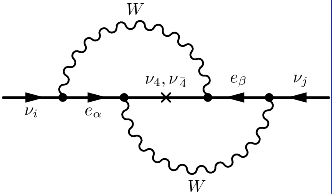


So the Majorana mass is bounded from above:

$m_R < 20$ TeV

The two-loop contribution to m_ν

- Automatically, at tree level $m_\nu = 0$.
- However, at two loops light neutrino masses are generated:



$$M_{ij} = \frac{g^4}{M_W^4} m_D^2\, m_R \sum_\alpha V_{i\alpha} V_{4\alpha} m_\alpha^2 \sum_\beta V_{j\beta} V_{4\beta} m_\beta^2 \,(-I_{\alpha\beta})$$

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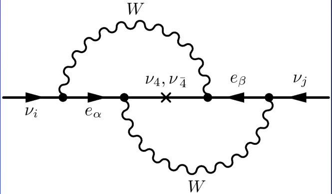

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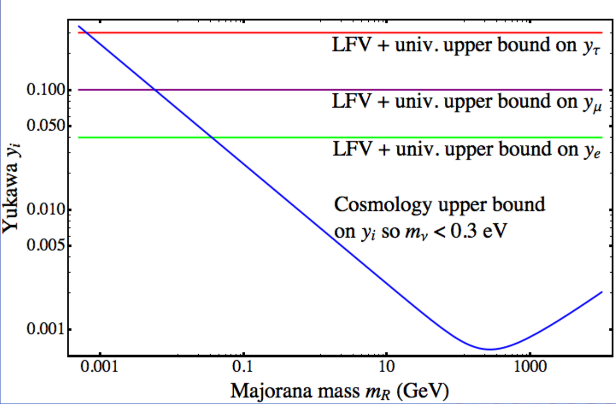
Huge hierarchies between masses:

$$\frac{m_2}{m_3} \lesssim \frac{1}{4y_E^2}\left(\frac{m_\tau}{m_E}\right)^2 \left(\frac{m_\tau}{m_{\bar{4}}}\right)^2 \lesssim 10^{-7}$$: ruled-out as main mech.

The two-loop contribution is relevant

- When a new gen. and a ν_R with $m_R \leq \mathcal{O}(10)$ TeV is added to the SM, the two-loop cont. to m_ν, although by itself it cannot explain the neutrino spectrum, is always present.
- In general, it places an important constraint in the $y_i - m_R$ plane so $m_{\nu i} \lesssim 0.3$ eV.



Why is a fourth Majorana neutrino natural?

- In a 4 gen. plus a ν_{Ri} per gen. context ...

$\rightarrow$ Majorana masses to SM light ν via a high-scale see-saw (type I) seems a natural explanation.

- If ν_{Ri} (with $i \neq 4$) have large Majorana masses M, even if we set at tree level $m_{4R} \equiv m_R = 0$ so ν_E is Dirac, m_R is gen. at two loops: $m_R \approx \epsilon^2 M/(2^7\pi^4)$, in the TeV range for natural values (must be < 20 TeV, so $m_4 > 63$ GeV).
- Therefore, it is not natural that if SM ν are Majorana via see-saw, ν_E is Dirac.
- So, again, the constraint in the $y_i - m_R$ plane is present, so the tree level + two-loop + ... contribution correctly reproduces the spectrum.

The five generation model (two new complete gens.)

$$Y_\nu = \begin{pmatrix} y_E\,\epsilon & y_E\,\epsilon & -y_E\,\epsilon & y_E & 0 \\ 0 & y_F\,\epsilon' & y_F\,\epsilon' & 0 & y_F \end{pmatrix}^T \quad \text{with } \epsilon,\, \epsilon' \ll 1.$$

Rotation to mass basis in NH (now $m_{4D} \approx y_E v$ & $m_{5D} \approx y_F v$):

$$V \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 & \epsilon & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & \epsilon & \epsilon' \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & -\epsilon & \epsilon' \\ 0 & -\sqrt{3}\epsilon & 0 & 1 & 0 \\ 0 & 0 & -\sqrt{2}\epsilon' & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2) \to \text{TBM}$$

At tree level: $m_{4,\bar{4}\,(5,\bar{5})} = \frac{1}{2}\left(\sqrt{m^2_{4R(5R)} + 4m^2_{4D(5D)}} \mp m_{4R(5R)}\right)$.

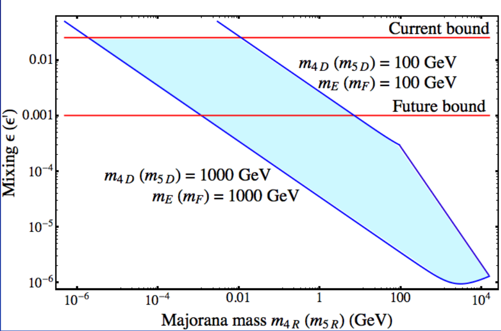
At two loops:

$$m_{2(3)} \approx \frac{g^4 \epsilon^2(')}{(4\pi)^4 M_W^4} m^2_{4D(5D)}\; m_{4R(5R)}\; m^2_{E(F)} \log\left(\frac{m_{E(F)}}{m_{\bar{4}(\bar{5})}}\right)$$

Parameter space for correct mass scale & ratio

$$\text{NH} \rightarrow \frac{m_2}{m_3} \approx \frac{\epsilon^2 m_{4D}^2 m_{4R} m_E^2}{\epsilon'^2 m_{5D}^2 m_{5R} m_F^2}$$

Degenerate scenario not viable. Bounds by $\mu e \gamma$ & μe conv.



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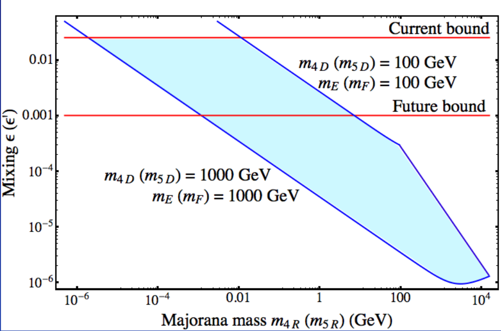


To have right neutrino masses and testability in LFV exp.:

Better PD, with $m_R < \mathcal{O}(1)$ GeV. Otherwise, same-sign leptons.

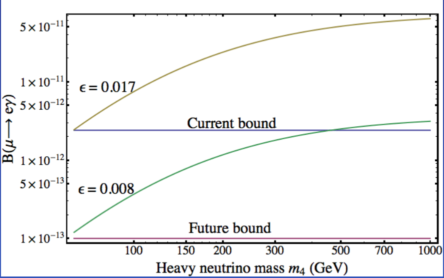
Universality and LFV

- Universality. For example, pion decay, gives:

$$\frac{\Gamma(\pi \to e\nu_e)}{\Gamma(\pi \to \mu\nu_\mu)} \approx \frac{m_e^2(m_\pi^2 - m_e^2)^2}{m_\mu^2(m_\pi^2 - m_\mu^2)^2} \frac{1 - |V_{e4}|^2 - |V_{e5}|^2}{1 - |V_{\mu 4}|^2 - |V_{\mu 5}|^2} (1 + \delta R_{e,\mu}) =$$

$$= (1.23 \pm 0.004) \cdot 10^{-4} \longrightarrow \epsilon' < 0.04 \, (\mathrm{NH}) \; (90\% \text{ C.L.})$$

- LFV: new MEG bound $B(\mu \to e\gamma) < 2.4 \cdot 10^{-12}$.



Currently $\epsilon \lesssim 0.02$. Future μe conv. at $\sim 10^{-16}$: $\epsilon \approx \mathcal{O}(10^{-3})$.

- $0\nu\beta\beta$ current bounds constrain $\langle M_N \rangle > 10^8\,\mathrm{GeV}$:

$$\langle M_N \rangle^{-1} = \sum_N U_{eN}^{T\,2} M_N^{-1} = \epsilon^2 \frac{m_{4R}}{m_{4D}^2}$$

$$\longrightarrow \epsilon^2 m_{4R}/m_{4D}^2 \lesssim 10^{-8}\,\mathrm{GeV}^{-1}$$

$\rightarrow$ However, having the right m_ν is a stronger bound. Not relevant new heavy contribution.

- Same-sign leptons at colliders, for instance:
- $q\bar{q} \rightarrow Z \rightarrow \nu_4\nu_4$ and then $\nu_4 \rightarrow W^\mp \ell^\pm$, for $\epsilon,\ \epsilon' < 10^{-4}$ and $m_R > 1$ GeV: complementary to LFV.
- $q\bar{q}' \rightarrow W^\pm \rightarrow \nu_{4,\bar{4}} E^\pm \rightarrow E^\pm E^\pm W^\mp$ for $m_E < m_4$.
- $gg \rightarrow H \rightarrow \nu_4\nu_4 \rightarrow \ell^\pm\ell^\pm W^\mp W^\mp$. Unusual H signal.

$\rightarrow$ For $\ell_i^\pm \ell_j^\pm$, no missing E_T. For $m_E < m_4$ and $E^\pm E^\pm$, depending on τ_E: same-sign light di-leptons, displaced vertex...

Summary & conclusions

- Important connection between ν & new families.
- **LHC will confirm or exclude.**
- Small m_ν are natural with new **complete families** (with ν_R). $m_R < 20$ TeV necessary.
- ν mass-less at tree level, **acquire masses at two loops.**
- Simplest **4 family model cannot reproduce spectrum.**
- However, **important constraint on 4 gen. models from the two-loop contribution so $m_{\nu i} \lesssim 0.3\,$eV.**
- m_{4R} is generated if $m_{iR} \neq 0$, so ν_E **is naturally Majorana.**
- Model with **five generations:**

$\longrightarrow$ **Predict NH or IH. TBM** can be accommodated **easily.**
$\longrightarrow$ **Model is being tested:** ν sector, LFV, $0\nu\beta\beta$, same-sign leptons & specially at the LHC new particles & Higgs physics.

New families... dead or alive?

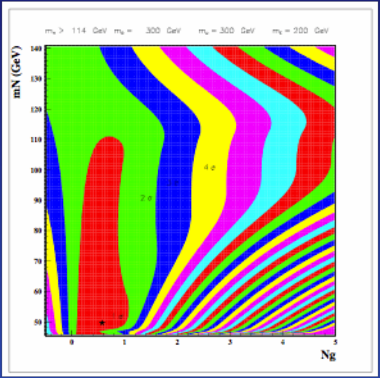
- Terrific performance of the LHC $\Longrightarrow$ **stringent limits:**

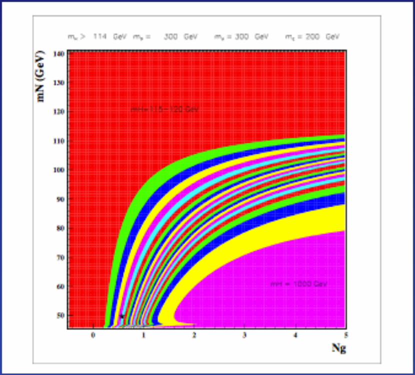
$\rightarrow$ excluded range for a 4G Higgs: $120 < m_{4G} < 600$ GeV!
$\rightarrow$ new quarks (assuming $t' \rightarrow Wb$): $m_{t'} > 450$ GeV!

- In addition "intriguing fluctuations" (R. Heuer) for low mass SM Higgs... without 4G enhancement ($\sigma^H_{4G} \approx 9\, \sigma^H_{SM}$).
- **The situation is really tight,** in particular with a Higgs.
- **If new families exist & a H_{4G} is excluded... extended scalar sector? new strong &/or composite EWSB sector? Need further studies.**
- *Just extra SM-like families with the minimal Higgs content of the SM seem to be sick... (but not yet dead).*

BACK-UP SLIDES

How many extra families are allowed?





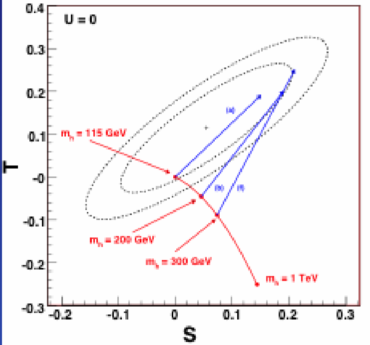
(Novikov et al.)

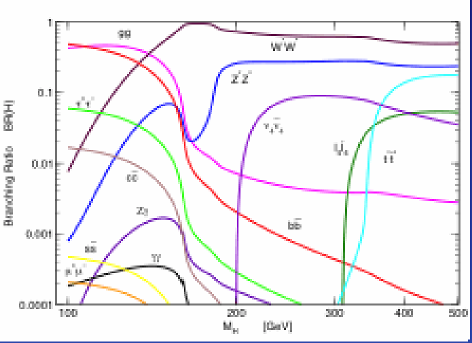
Need new fits with new Higgs & t', b' data.

They are model-dependent: mixing, ν nature, degenerate new particles, only SM Higgs (no condensate)...

More on electroweak fits (Kribs et al.)

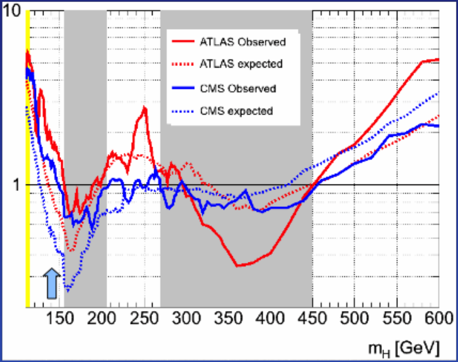
Higher Higgs mass allowed with extra generations!





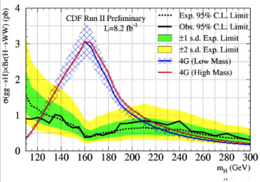
$m_\nu = 100$, $m_E = 155$	m_U	m_D	ΔS	ΔT
a	310	260	0.15	0.19
b	320	260	0.19	0.20
f	400	325	0.21	0.25

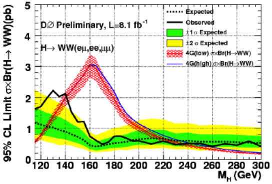
New SM data bounds from LHC



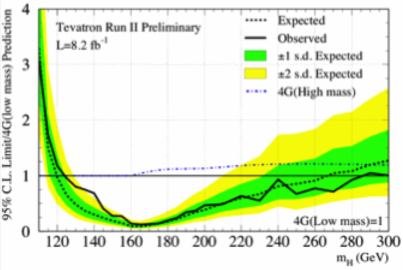
- Looking forward to seeing the combined result...

New 4G data bounds from Tevatron





CDF only 8.2 fb^{-1} (summer 11) $123<m_H<215$ GeV @95%CL
DØ only 8.1 fb^{-1} (summer 11) $140<m_H<240$ GeV @95%CL



- $124 < m_h^{4G} < 286$ GeV excluded.

The neutrino mass two-loop integral

$$I_{kn} = \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{p\cdot q}{(p^2-m_k^2)(q^2-m_n^2)((p+q)^2-m_1^2)((p+q)^2-m_2^2)} \times$$

$$\times \left[\frac{1}{p^2q^2} - \frac{3}{4}\frac{1}{(p^2-M_W^2)(q^2-M_W^2)} \right]$$

If we take $m_{E,F} \gg m_{\bar{4},\bar{5}} > m_W$, we obtain:

$$I_0 \approx -\frac{1}{2^{10}\pi^4 m_{\bar{4}}^2} \ln \frac{m_{\bar{4}}^2}{m_4^2}, \qquad k,n = e,\mu,\tau$$

$$I_E \approx -\frac{1}{2^{10}\pi^4 m_E^2} \ln \frac{m_E^2}{m_{\bar{4}}^2}, \qquad k \text{ and/or } n = E$$

$$I_F \approx -\frac{1}{2^{10}\pi^4 m_F^2} \ln \frac{m_F^2}{m_{\bar{5}}^2}, \qquad k \text{ and/or } n = F$$

Yukawa structure in IH

$$Y_\nu = \begin{pmatrix} -2y_E\epsilon & y_E\,\epsilon & -y_E\,\epsilon & y_E & 0 \\ y_F\,\epsilon' & y_F\,\epsilon' & -y_F\,\epsilon' & 0 & y_F \end{pmatrix}^T$$

$\epsilon, \epsilon' \ll 1$, so $m_{4D} \approx y_E v$ & $m_{5D} \approx y_F v$. Rot. to mass basis (IH):

$$V \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 & -2\epsilon & \epsilon' \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & \epsilon & \epsilon' \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & -\epsilon & -\epsilon' \\ \sqrt{6}\epsilon & 0 & 0 & 1 & 0 \\ 0 & -\sqrt{3}\epsilon' & 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2) \to \text{TBM!}$$

Light neutrino masses are:

$$m_{1(2)} \approx \frac{g^4 \epsilon^{2}(')}{(4\pi)^4 M_W^4}\, m^2_{4D(5D)}\, m_{4R(5R)}\, m^2_{E(F)} \log\left(\frac{m_{E(F)}}{m_{\tilde{4}(\tilde{5})}}\right)$$