Neutrino masses from extra generations

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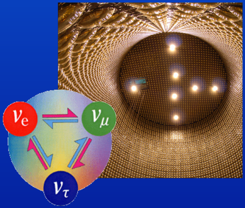
A novel horizon

The last 20 years have been very exciting in neutrino physics, with the confirmation that neutrinos have masses, and that mass and flavour eigenstates are mixed.

During these years, we have learnt about the structure of the lepton sector, and discovered that it is quite different from that of the quarks.



Yet there still remain some unanswered questions, such as which is the true character of neutrino masses –Dirac or Majorana–, or what are their absolute values.

What we know, what we don't

Thus stays our knowledge of the neutrino parameters as of today:

- Mass scale
  It is very light, well under the electroweak scale. Tritium decay experiments yield $m_\nu < 2\ \mathrm{eV}$, with $m_\nu^2 \simeq {}^2\!/_3\, m_1^2 + {}^1\!/_3\, m_2^2$.

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- Three angles
  Two are known to be big. The third could be zero, but recent results seem to point towards non-zero values. The situation is compatible with the so-called tribimaximal mixing (TBM) scheme.

$$\theta_{12} = 34.0 \pm 1.0\ ^\circ$$
$$\theta_{23} = 46 \pm 4\ ^\circ$$
$$\theta_{13} = 6.5 \pm 1.7\ ^\circ$$

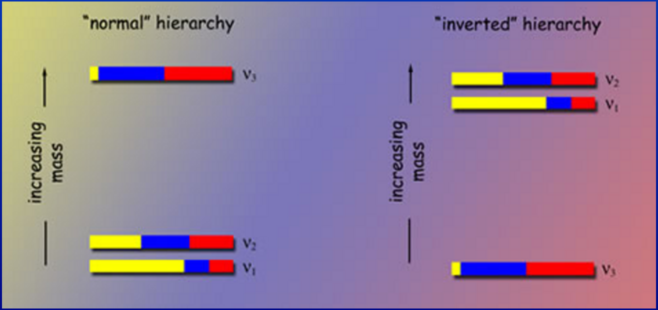
$$V_{\mathrm{PMNS}} \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

[Schwetz, Tórtola, Valle; **arXiv:1108.1376**]

What we know, what we don't

- Mass splittings

  With three masses, only two of them are independent. We know their values, but have no information on the sign of one of them. So, two mass orderings are possible: they are called normal and inverted hierarchy (NH, IH).



Looking for an explanation

Whatever their value, neutrino masses lie well below the mass scale of other fermions. This seems to suggest that they involve new physics apart from the Higgs mechanism.

Many proposals:

- Seesaw mechanism with heavy new particles.
- Supersymmetry with R-parity breaking.
- Plenty of models with enlarged scalar sector.
- ...

Can we generate small neutrino masses in less sophisticated scenarios? For instance, with new generations?

Neutrino masses with four generations

[Babu, Ma; **Phys.Rev.Lett 61** (1988) 674]

Adding one extra generation and one right-handed neutrino:

$$\nu_e \qquad \nu_\mu \quad \nu_\tau \qquad \nu_E \qquad\qquad \nu_R$$

we end up with a projective mass matrix

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & 0 & y_e\, v \\ 0 & 0 & 0 & 0 & y_\mu\, v \\ 0 & 0 & 0 & 0 & y_\tau\, v \\ 0 & 0 & 0 & 0 & y_E\, v \\ y_e\, v & y_\mu\, v & y_\tau\, v & y_E\, v & m_R \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_D \\ 0 & 0 & 0 & m_D & m_R \end{pmatrix}$$

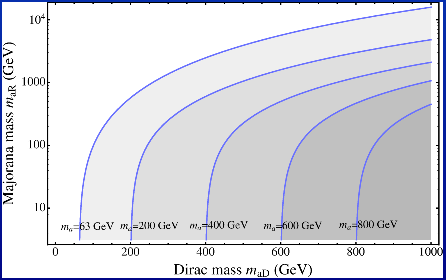
which upon diagonalisation yields two massive Majorana and three massless neutrinos at tree level.

Neutrino masses with four generations

The two tree-level massive neutrinos are a mixture of the sterile ν_R and a combination of the active ν_L's (mailny the 4-G ν_E) ; so, they can be produced in Z decays and are subject to the LEP bound for Majorana neutrinos, $m_N > 63$ GeV.

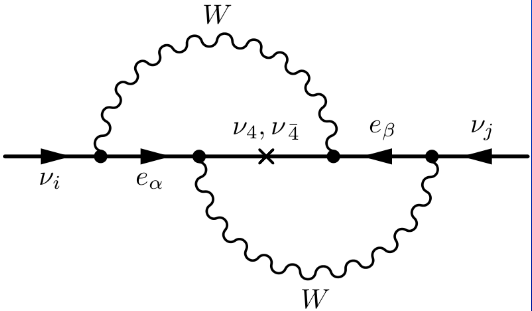
$$m_{4,\bar{4}} = \frac{1}{2}\left(\sqrt{m_R + 4m_D} \pm m_R\right)$$

This means that in this setup the Majorana mass m_R cannot be artbitrarily large, otherwise one of the two neutrinos would be too light.



Neutrino masses with four generations

The light neutrino masses are generated radiatively at two loops:



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

A not-so-perfect world

$$m_{ij} = -\frac{g^4}{m_W^4}\, m_{\mathrm{R}} m_{\mathrm{D}}^2 \sum_{\alpha} V_{\alpha i} V_{\alpha 4} m_{\alpha}^2 \sum_{\beta} V_{\beta j} V_{\beta 4} m_{\beta}^2 \; \mathrm{I}_{\alpha\beta}$$

The dependence on the charged lepton masses induces a huge hierarchy between the generated neutrino masses,

$$\frac{m_2}{m_3} \lesssim \left(\frac{m_\tau}{m_E}\right)^4 ,$$

which cannot fit the measured mass splittings. So, the model is already excluded.

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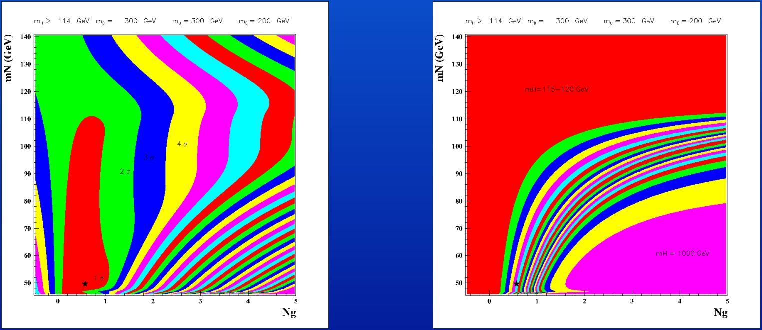
Still there!

Even though this mechanism does not do the job with 4 G alone, one must bear in mind that it's always there whenever a model has extra generations with Majorana masses, and it can spoil the light neutrino masses.

Five generations?

The possibility of two extra generations is definitely disfavoured, but not yet excluded:



[Novikov et al; **Phys.Atom.Nucl. 73** (2010) 636]

The LHC searches for the Higgs further constrain this possibity, but they still can be circumvented if new physics is invoked.

Reloading the game

We can try and reproduce the same mechanism with two additional generations and two ν_R's:

$$\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_E \quad \nu_F \qquad \nu_{4R} \quad \nu_{5R}$$

Then the tree-level mass matrix is also projective:

$$M_\nu = v \begin{pmatrix} & & & & & y_e & y'_e \\ & \ddots & \vdots & \iddots & & y_\mu & y'_\mu \\ & \cdots & 0 & \cdots & & y_\tau & y'_\tau \\ & \iddots & \vdots & \ddots & & y_E & y'_E \\ & & & & & y_F & y'_F \\ y_e & y_\mu & y_\tau & y_E & y_F & m_{4R}/v & 0 \\ y'_e & y'_\mu & y'_\tau & y'_E & y'_F & 0 & m_{5R}/v \end{pmatrix}$$

but quite more complicated.

Reloading the game

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$$\nu_e \qquad \nu_\mu \qquad \nu_\tau \qquad \nu_E \qquad \nu_F \qquad\qquad \nu_{4R} \qquad \nu_{5R}$$

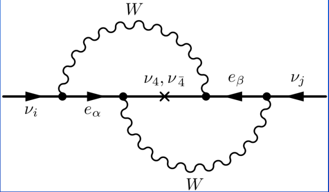
We choose a simplified setup for this scenario:

$$M_\nu = v \begin{pmatrix} & & & & & \epsilon_e & \epsilon'_e \\ & \ddots & \vdots & \cdot^{\cdot^{\cdot}} & & \epsilon_\mu & \epsilon'_\mu \\ & \cdots & 0 & \cdots & & \epsilon_\tau & \epsilon'_\tau \\ & \cdot^{\cdot^{\cdot}} & \vdots & \ddots & & y_E & 0 \\ & & & & & 0 & y'_F \\ \epsilon_e & \epsilon_\mu & \epsilon_\tau & y_E & 0 & m_{4R}/v & 0 \\ \epsilon'_e & \epsilon'_\mu & \epsilon'_\tau & 0 & y'_F & 0 & m_{5R}/v \end{pmatrix}$$

which is a sort of 'doubled' version of the 4-G mass matrix.

Generating the masses

The diagram that generates the light masses is the same as in the 4-G case. The main difference is that in our setup there's one mass generated essentially by E, ν_4 and $\nu_{\bar{4}}$, and a second one generated by F, ν_5 and $\nu_{\bar{5}}$.



In this basis, the masses correspond basically to the diagonal elements of the 2-loops mass matrix,

$$M_{22} \simeq \epsilon^2\, m_{4R} \frac{g^4\, m_{4D}^2\, m_E^2}{2(4\pi)^4 m_W^4} \ln \frac{m_E}{m_{\bar{4}}} \qquad M_{33} \simeq \epsilon'^2\, m_{5R} \frac{g^4\, m_{5D}^2\, m_F^2}{2(4\pi)^4 m_W^4} \ln \frac{m_F}{m_{\bar{5}}}$$

The third mass is suppressed by powers of m_τ and is way smaller. The conclusion is that this model generates a nearly-zero mass, and thus cannot reproduce the so-called 'degenerate hierarchy'.

Getting the mixings

If the model is to be realistic, we need to generate the correct mixing pattern. We choose to reproduce TBM, a popular approximation to the measured values.

$$\begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

The mixings happen to be directly related to the first three generation Yukawa couplings: symmetries in the mixings reflect flavour symmetries of the Yukawas.

Normal hierarchy

$$Y_\nu = \begin{pmatrix} \epsilon & 0 \\ \epsilon & \epsilon' \\ -\epsilon & \epsilon' \\ y_E & 0 \\ 0 & y'_F \end{pmatrix}$$

Inverted hierarchy

$$Y_\nu = \begin{pmatrix} -2\epsilon & \epsilon' \\ \epsilon & \epsilon' \\ -\epsilon & -\epsilon' \\ y_E & 0 \\ 0 & y'_F \end{pmatrix}$$

Constraining the parameter space

- Masses for new generation leptons
  Lower bounds given by direct detection of the new particles:
  $m_N > 63$ GeV, $m_E > 100$ GeV.

  Upper bound on the Dirac masses given by perturbative unitarity: $m_E, m_{a\mathrm{D}} < 1.2$ TeV.

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- Majorana masses
  Majorana masses are the LNV parameter of our model; therefore, will be best constrained by $0\nu2\beta$ experiments.

  Unfortunately, the contribution of the heavy neutrinos is too small in the relevant region, so we get no information from the current or near future experimental bounds.

Constraining the parameter space

- Mixing between heavy and light generations
  Mixing between families generate LFV effects; the most important for our purposes are the bounds on $\mu \to e\gamma$ and the tests of universality in the weak interactions.

$$\begin{array}{rll} \text{NH}: & \epsilon < 0.03 & \epsilon' < 0.04 \\ \text{IH}: & \epsilon < 0.02 & \epsilon' < 0.03 \end{array}$$

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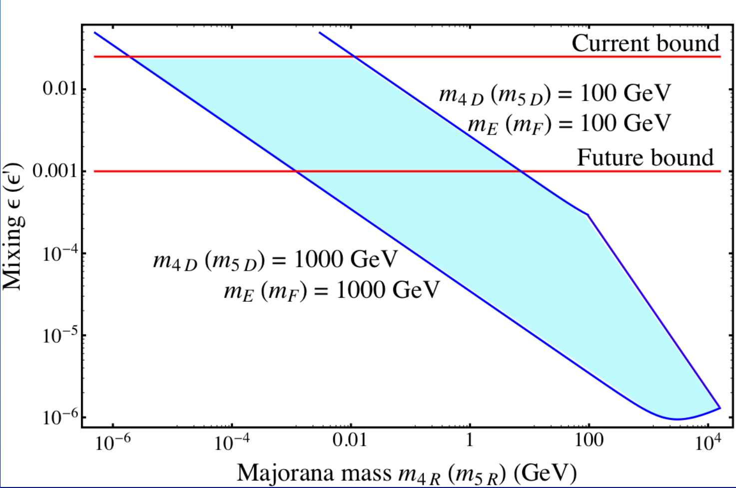
- Light neutrino masses
  Finally we need to ensure that we generate the right mass scale for the light neutrinos. Provided that the lightest must be nearly massless, the mass splittings yield for the 'heaviest' a mass of 0.05 eV.

Constraining the parameter space



Collider signals

The signatures of this model in collider experiments are not essentially different from those of extra generations, with the particularity of having Majorana neutrinos.

In the relevant parameter region, the heavy-light mixings are quite small, and probably the production of a heavy-light pair will be suppressed. It's better to look for heavy-heavy pair production, which is independent from the mixings.

- Small vs. big mixings
  Big mixings means generally good news for LFV experiments.
  Small mixings can be good news for colliders, because the lightest heavy neutrino can be long-lived and generate a displaced vertex.
  For instance, for $\epsilon \sim 10^{-7}$ the decay length is $\mathcal{O}(\text{cm})$.

Collider signals

- $q\,\bar{q}' \to W^{\pm} \to \nu_I\,\ell^{\pm}$
  This is a channel suppressed by mixing.
  The Majorana neutrino will decay via $\nu_I \to W^{\mp}\ell^{\pm}$, leading to same-sign dileptons in half the events.

- $q\,\bar{q} \to Z \to \nu_I\,\nu_J$
  This channel is not suppressed by mixing, but more constrained by kinematics.
  If the mixings are small, heavy neutrinos will decay mainly to one another via $\nu_I \to \nu_J\,Z$, generating a cascade of Z's.

- $q\,\bar{q}' \to W^{\pm} \to E^{\pm}\,\nu_I$
  This channel is not suppressed by mixing, but more constrained by kinematics.
  If the ν_I is heavier than the E, it will decay via $\nu_I \to E^{\pm}\,W^{\mp}$, producing same-sign heavy dileptons in half the events.

Conclusions

- There's a mechanism to generate small neutrino masses radiatively in the presence of extra generations, if these have Majorana masses.
- The mechanism doesn't work for 4G without any further addition.
- Even if it cannot explain the light neutrino masses, this mechanism is always present, and can have the opposite effect: spoiling the neutrino mass matrix by generating too large masses.
- We have presented a 5G model which can successfully accommodate the neutrino masses and mixings, even in a deliberately simplified realisation.

Conclusions

- The model can give rise to both normal and inverted hierarchy, but not the degenerate one, as it generates a very small mass for the lightest neutrino.
- The model does not produce a significant signal for $0\nu2\beta$ experiments, apart from the 'standard' contribution of light neutrino masses.
- If we are to see hints of this model in LFV experiments (i.e., if the mixings are large), then the heavy neutrinos have to live in the pseudo-Dirac regime in order to generate the right light neutrino masses.
- The model presents the same collider phenomenology as other extra generations models. Particularly, if the mixings are small we might see displaced decay vertices at the LHC.

Thank you for your attention!

To see the original work: **JHEP 1107** (2011) 122