Neutrino masses generated through new physics at the TeV scale

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Neutrino masses
... and the Weinberg operator $LLHH$

There is overwhelming evidence that neutrinos have mass from oscillation experiments at different energies and baselines

The mass of these (active) neutrinos is tiny

$$m_\nu \sim 10^{-1} \text{ eV} \Rightarrow \frac{m_\nu}{\langle H \rangle} \sim 10^{-12}$$

Without extra fields, the SM symmetries only* allow neutrino masses generated through the dimension 5 operator

$$\frac{\kappa_{ij}}{\Lambda} L_i L_j H H \downarrow$$

Either $\kappa$ is very small or $\Lambda$ is very large

$$m_\nu = \frac{\kappa \langle H \rangle^2}{\Lambda}$$
Standard seesaw mechanism

Adding very heavy ($\sim 10^{14}$ GeV) right-handed neutrinos to the SM is arguably the simplest and most elegant way to explain the observed neutrino masses (however, this is a very subjective assessment).

But ... Nature might be different from what we expect it to be. So perhaps it is worth considering other scenarios.

In this talk I will discuss the possibility that new physics at the TeV scale might be responsible for neutrino masses, without the need for couplings to be small.
Loops and high-dimensional operators

There are two simple ways of reducing neutrino masses without the need of small couplings nor heavy mediators:

**Loops**

Generate the Weinberg operator $LLHH$ via loops. Each loop yields a suppression factor of $1/16\pi^2$.

We also get a factor $y^2$ ($y$ is some average trilinear couplings)

**Higher dimensional operators**

Neutrino masses can be generated by the operators

$$O_d \equiv LLHH (H^* H)^{d-5 \over 2}$$

with $d=5,7,9,...$

Increase $d$ by 2 units: neutrino masses get a factor

$$\frac{y^2 \langle H \rangle^2}{\Lambda^2} \quad \Lambda = \text{new physics scale}$$
Examples

Zee model
[Zee 1980] [Wolfenstein 1980]

Babu-Zee model
[Cheng, Lee 1980] [Zee 1986] [Babu 1988]

KNT model
[Krauss, Nasri, Trodden 2003]

(For a recent review with more examples see [Cai et al. 1706.08524])
Classifying the possibilities

There have been many papers trying to list the different ways of generating neutrino masses.

[Babu, Leung 2001] [Gouvea, Jenkins 0708.1344]
[Farzan, Pascoli, Schmidt 1208.2732] [Angel, Rodd, Volkas 1212.6111]
[Bonnet, Hirsch, Ota, Winter 1204.5862] [Sierra, Degee, Dorame, Hirsch 1411.7038]
[Cepedello, Hirsch, Helo 1705.01489] [Klein, Lindner, Ohmer 1901.03225]
...

There are different ways of approaching this classification problem. In this talk, I will discuss the results of two papers:

[Anamiati et al. 1806.07264] – 0 loops, dimension >5 models
[Cepedello, Fonseca, Hirsch 1807.00629] – 3 loops, dimension 5 models
Assumptions

- **Majorana neutrinos**
- **The Higgs is the only scalar acquiring a VEV**
  
  (or at least, this is the only VEV relevant for neutrino masses). Consequence: the effective operators
  \[ O_d \equiv L L H H (H^* H)^{\frac{d-6}{2}} \]
  are the only important ones

- **The SM gauge group is the only symmetry**
  
  Consequence: the only way to forbid an interaction is if the SM quantum numbers of the fields do not allow it; otherwise it exists

- **Leading neutrino mass contributions only**
  
  For a particular model we are only after the leading contribution to neutrino masses. This leads to the concept of what we called a genuine $d$-loop,$\ell$-dimensional neutrino mass model
Genuine models

Consider again this neutrino mass model:

If we could build another neutrino mass diagram with \(d=5\) or 7, we would not consider this a genuine \(l=0\) \(d=9\) neutrino mass model because the \(d=5\) or 7 contribution would be dominant.

However, there are no \((l,d)=(0,5/7)\) diagrams. Is this diagram then the main neutrino mass contribution?

\[ \text{[loop]} \sim \frac{1}{16\pi^2} \frac{1}{y} \left( \frac{\Lambda}{\langle H \rangle} \right)^4 \text{[tree]} \]
Tree-level neutrino mass models

Genuine ones

Dimension 5

Seesaw type I, II, III

Dimension 7
Tree-level neutrino mass models
Beyond dimension 7: our approach

1. Find all topologies

Example: $d=9$

2. Find all diagrams

Topology lines are differentiated into scalar and fermion lines

3. Find all models

Assign SM quantum numbers to the scalars and fermions

4. Keep only the valid genuine topologies/diagrams/models
Tree-level neutrino mass models
Genuine ones

Dimension 9
Tree-level neutrino mass models

Genuine ones

Assume that the Higgs is special: it is the only fundamental scalar. (Majorana) neutrino masses can be generated with the type I/III seesaw mechanism. But is there any other way? Yes, and this is the simplest possibility.

BSM fermions in the diagram can easily have TeV masses.
Tree-level neutrino mass models

Genuine ones

Dimension 11
Tree-level neutrino mass models

Genuine ones

Dimension 13

\[
\begin{array}{cccccccccc}
H^* & H & H & H & H & H & H & H & H^* \\
3_1 & 4_{3/2} & 5_1 & 6_{1/2} & 5_0 & 6_{1/2} & 5_1 & 4_{3/2} & 3_1 \\
L & & & & & & & & L \\
\end{array}
\]

\[
\begin{array}{cccccccccc}
H & L & H^* & H^* & H^* & L & H & & \\
H & 4_{3/2} & 5_1 & 6_{1/2} & 5_0 & 6_{1/2} & 5_1 & 4_{3/2} & H \\
H & & & & & & & & H \\
\end{array}
\]
Tree-level neutrino mass models

Genuine ones

Dimension 13

Neutrino masses generated through new physics at the TeV scale
Tree-level neutrino mass models

Genuine ones

Dimension 13

2 topologies
2 diagrams
6 models
3-loop neutrino mass models

1. Generate all topologies with 3 loops and 4 legs (4367)
2. Must allow 2 external fermions (3269)
3. No tadpoles (1056)
4. No self-energies (370)
5. 1-particle irreducible (160)
6. No 3-point subgraphs (70)
7. No unavoidable 4-point scalar loop subgraphs (44)

Removable loops

Must be a seesaw type I/II/III particle (so topology is not genuine)

Removable loops

44 genuine* topologies
3-loop genuine* topologies

To be explained shortly
3-loop genuine* topologies

To be explained shortly
3-loop genuine* diagrams
In the mass basis

Label the topology lines as fermions or scalars in all possible ways. Then replace the 2 external $H$'s by the VEVs (i.e. remove these lines)

1  2  3  4  5  6
7  8  9 10 11 12
13 14 15 16 17 18

Only 18 genuine* diagrams in the mass basis
3-loop genuine* diagrams

In the mass basis

Label the topology lines as fermions or scalars in all possible ways. Then replace the 2 external $H$'s by the VEVs (i.e. remove these lines)

Only 18 genuine* diagrams in the mass basis
One example

Diagram

Acceptable neutrino masses

New fields

<table>
<thead>
<tr>
<th>Fields</th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$S_2$</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$F$</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

$m_\nu$ (eV) vs. $m_S$ (GeV)

$M$ 1 TeV 100 TeV
$Y = 1$ red dashed blue
$Y = 0.1$ green dashed
The *

The lists of genuine 3-loop neutrino mass topologies (44) and diagrams (18) which I showed previously are not complete

Why?

We used a series of cuts to weed out those cases which always generate neutrino masses with less loops

But in some special cases, models which fail to pass these cuts are also genuine

I have shown these already

Normal genuine

Special genuine

Not shown (see paper) These topologies/diagrams are genuine only if the internal particles have very special quantum numbers
Special genuine topologies/diagrams

Consider this 2-loop neutrino mass diagram

 Won’t it be possible to always have the more important contribution with one less loop?

If \( S_A = H \) and \( S_B = 1_{-1} \) then the 2-loop diagram exists but the 1-loop does not

\((HH \text{ Singlet interaction does not exist})\)

(Beyond this example: see [Cepedello, Fonseca, Hirsch 1807.00629] for the 3-loop special genuine topologies and diagrams)
Summary

1. The standard seesaw mechanism is not the only way to generate small neutrino masses

2. We may generate $LLHH$ through loops or generate higher dimensional operators. BSM physics might be as low as the TeV scale

3. We classified the tree-level neutrino mass models up to dimension 13, as well as the 3-loop dimension 5 models

4. The concept of a ‘genuine’ model is important to avoid misrepresenting the origin of the dominant contribution to the neutrino mass matrix

Thank you