Neutrino masses generated through new physics at the TeV scale

Renato Fonseca

fonseca@ipnp.mff.cuni.cz | renatofonseca.net

Institute of Particle and Nuclear Physics
Charles University, Prague, Czech Republic

Based on **Anamiati, Castillo-Felisola, R.F., Helo, Hirsch, JHEP 1812 (2018) 066**
and **Cepedello, R.F., Hirsch, JHEP 1810 (2018) 197**

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**

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

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SO(3,1)$
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\left(\frac{1}{2},0\right)$
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$\left(\frac{1}{2},0\right)$
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$\left(\frac{1}{2},0\right)$
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\left(\frac{1}{2},0\right)$
e^c	$\mathbf{1}$	$\mathbf{1}$	1	$\left(\frac{1}{2},0\right)$
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$(0,0)$
F_G	$\mathbf{8}$	$\mathbf{1}$	0	$(1,0)$
F_W	$\mathbf{1}$	$\mathbf{3}$	0	$(1,0)$
F_B	$\mathbf{1}$	$\mathbf{1}$	0	$(1,0)$

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

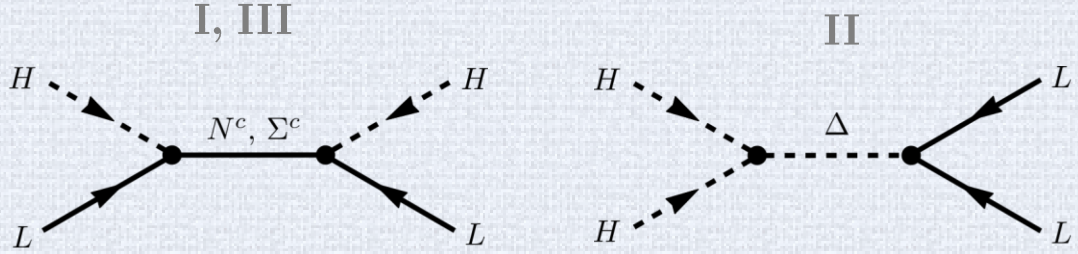
$$\frac{\kappa_{ij}}{\Lambda} L_i L_j H H$$

$$\downarrow$$

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

$\boxed{\text{Either } \kappa \text{ is very small or } \Lambda \text{ is very large}}$

Standard seesaw mechanism



Large masses and/or small couplings are needed

Adding very heavy (~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

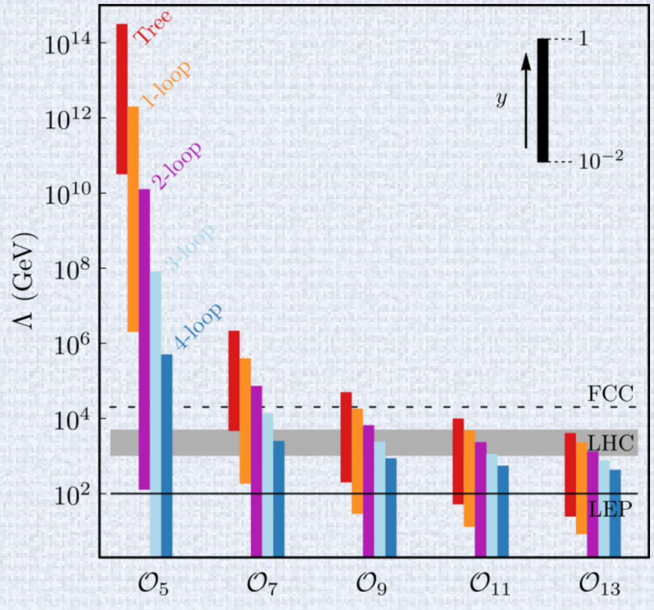
Generate the Weinberg operator *LLHH* via loops. Each loop yields a suppression factor of $1/16\pi^2$.

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

Higher dimensional operators

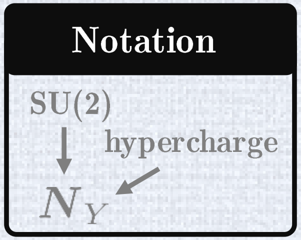
Neutrino masses can be generated by the operators
$$\mathcal{O}_d \equiv LLHH\left(H^*H\right)^{\frac{d-5}{2}}$$
with d=5,7,9,...
Increase d by 2 units: neutrino masses get a factor
$$\frac{y^2\left\langle H\right\rangle^2}{\Lambda^2}$$

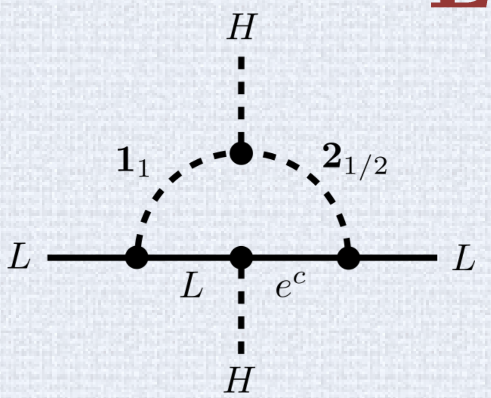
Λ = new physics scale



[Anamiati et al. 1806.07264]

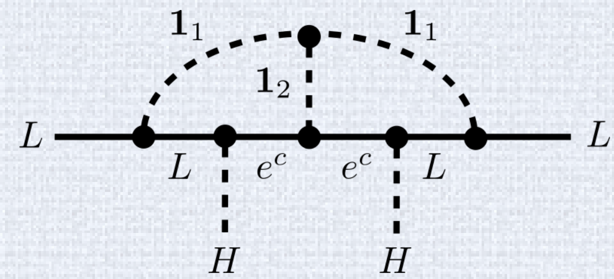
Examples





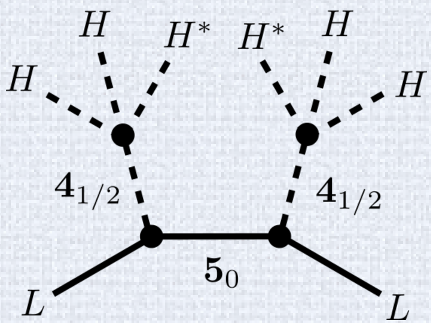
Zee model

[Zee 1980] [Wolfenstein 1980]

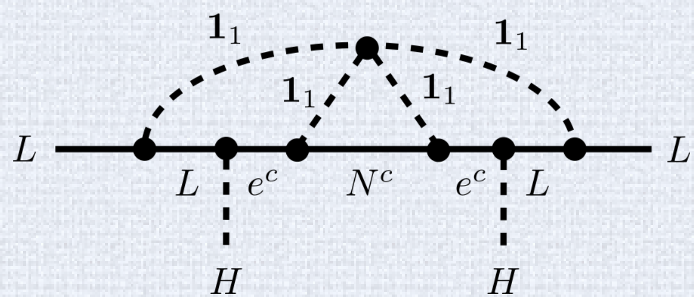


Babu-Zee model

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



[Picek, Radovčić 0911.1374]



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
$$\mathcal{O}_d \equiv LLHH\left(H^*H\right)^{\frac{d-5}{2}}$$
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

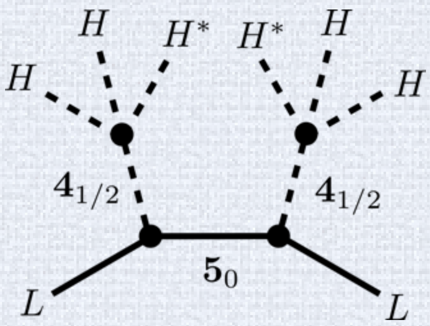
Leading neutrino mass contributions only

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,ℓ -dimensional neutrino mass model

Genuine models

Consider again this neutrino mass model:

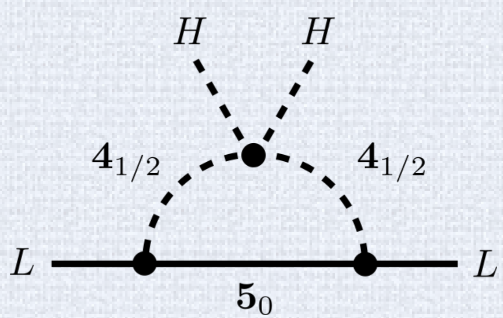
$\ell = 0\,, d = 9$



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?

$\ell = 1\,, d = 5$



In principle the loop diagram dominates so the top diagram is not considered genuine

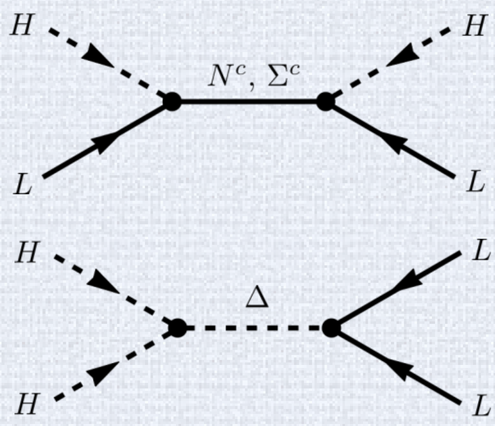
$$[\text{loop}] \sim \frac{1}{16\pi^2}\frac{1}{y}\left(\frac{\Lambda}{\langle H\rangle}\right)^4 [\text{tree}]$$

Tree-level neutrino mass models

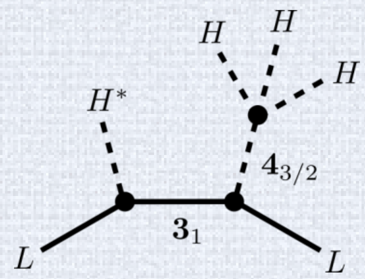
Genuine ones

Dimension 5

Seesaw type I, II, III



Dimension 7

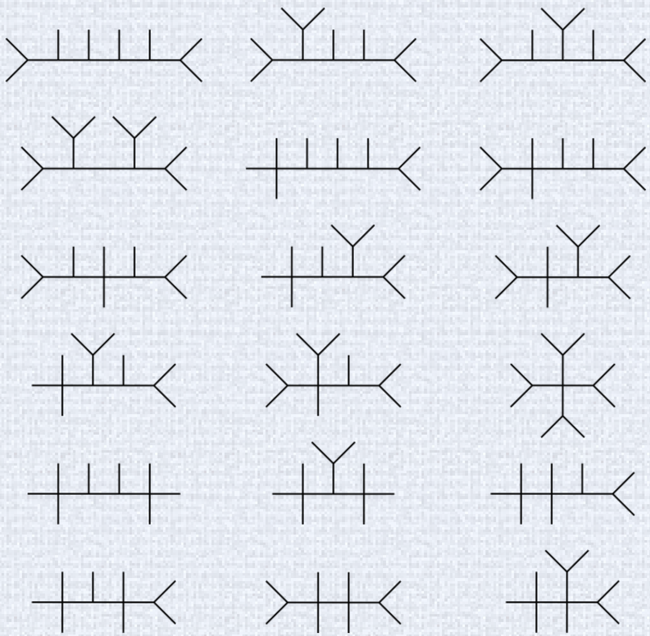


Tree-level neutrino mass models

Beyond dimension 7: our approach

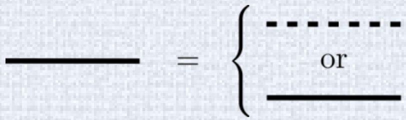
1. Find all topologies

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

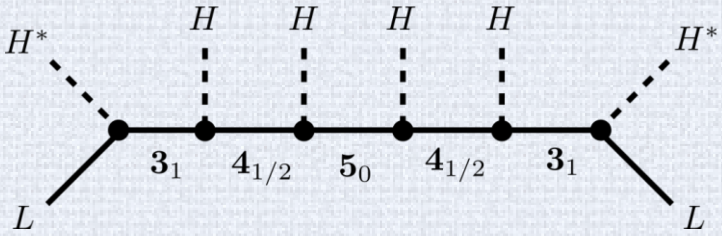
4. Keep only the valid <u>genuine</u> topologies/diagrams/models

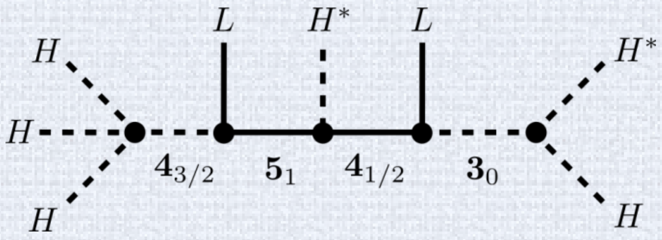
!

Tree-level neutrino mass models

Genuine ones

Dimension 9

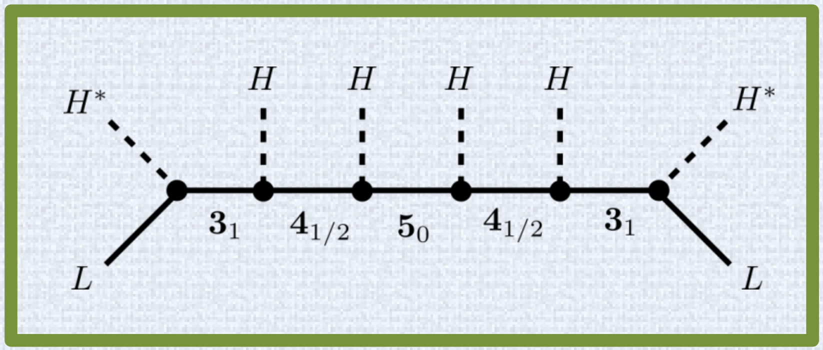


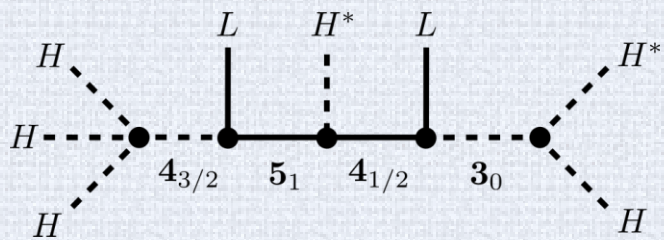


Tree-level neutrino mass models

Genuine ones

Dimension 9





Interesting model

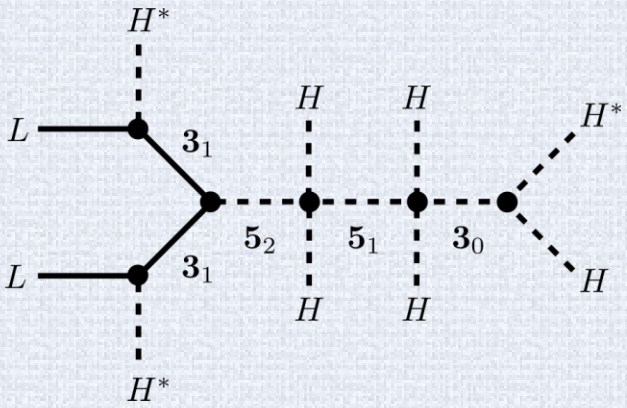
Assume that the Higgs is special: it is the only fundamental scalar. (Majorana) neutrino masses can be generated with the type I/III seesaw mechanism. But is there any other way? Yes, and this is the simplest possibility.

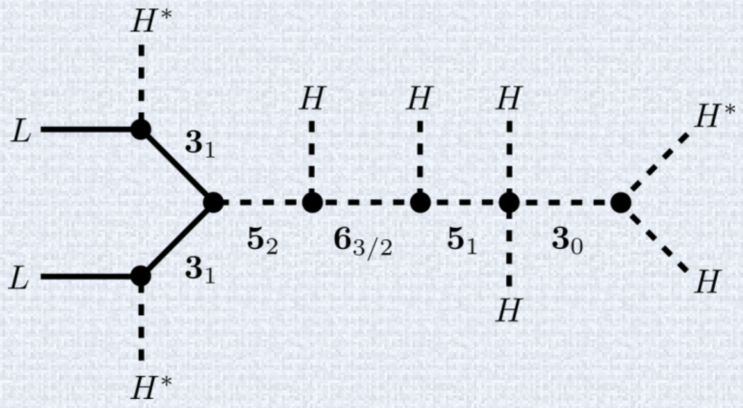
BSM fermions in the diagram can easily have TeV masses.

Tree-level neutrino mass models

Genuine ones

Dimension 11

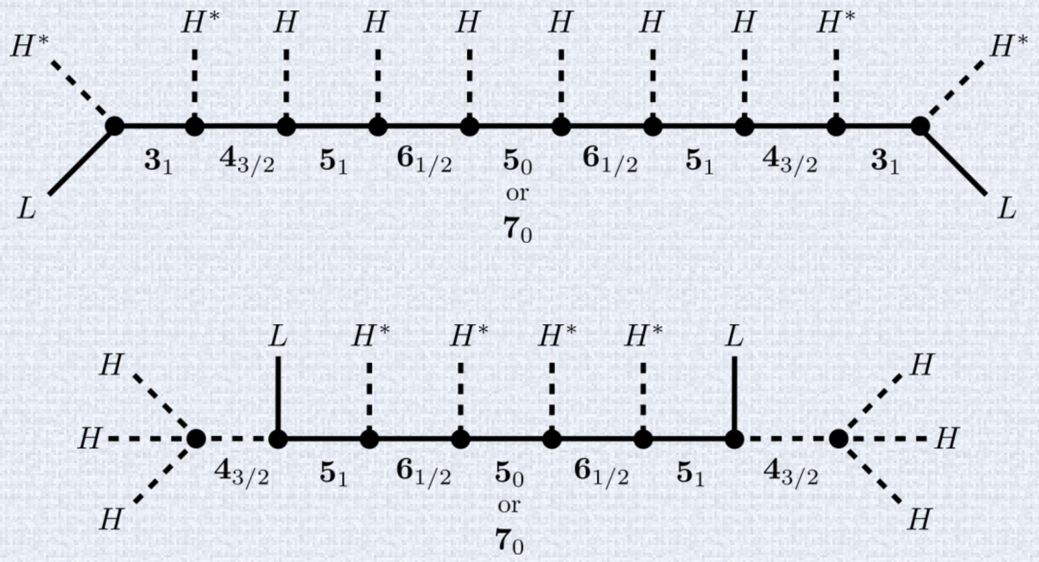




Tree-level neutrino mass models

Genuine ones

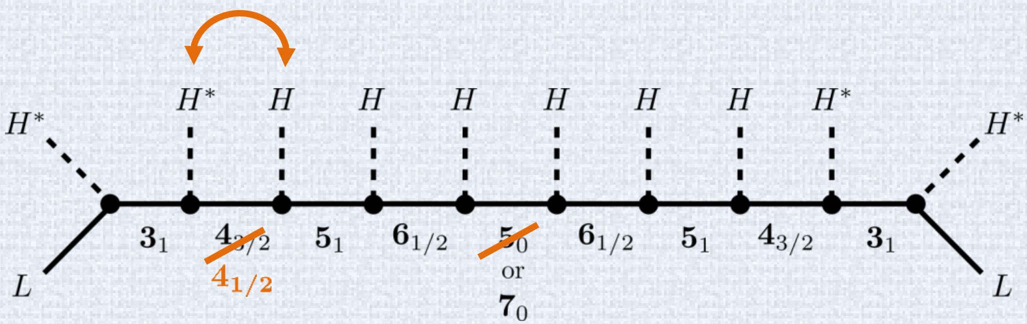
Dimension 13

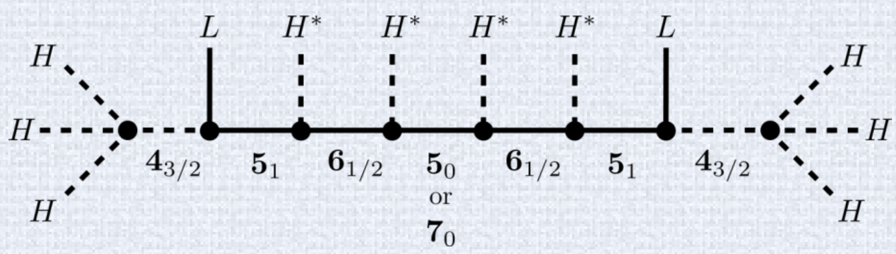


Tree-level neutrino mass models

Genuine ones

Dimension 13

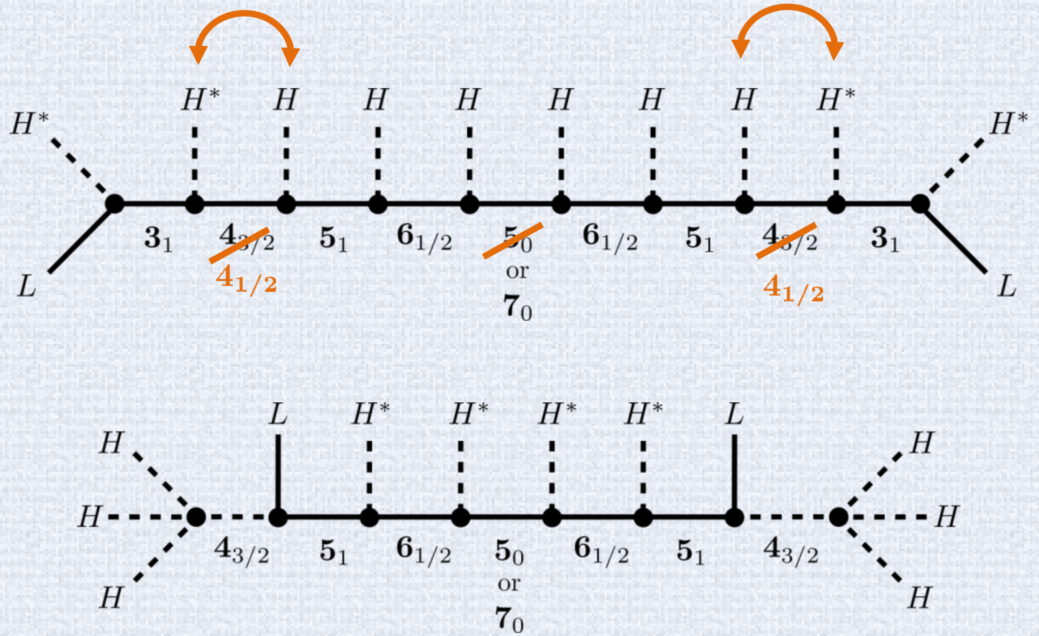




Tree-level neutrino mass models

Genuine ones

Dimension 13



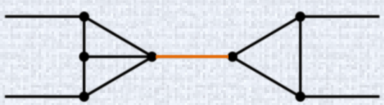
2 topologies
2 diagrams
6 models

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)

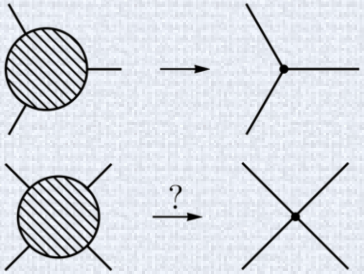
Removable loops

5. 1-particle irreducible (160)



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

6. No 3-point subgraphs (70)
7. No unavoidable 4-point scalar loop subgraphs (44)

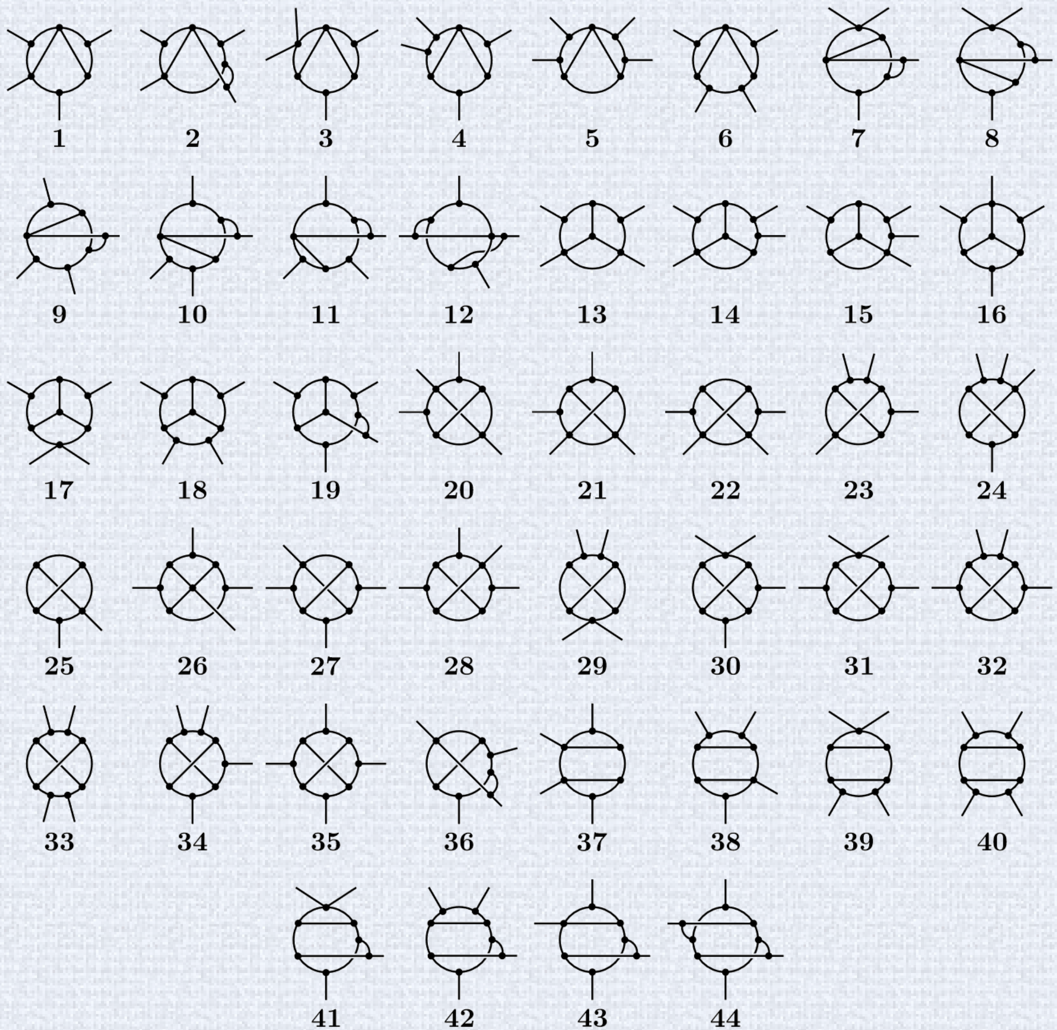


Removable loops

44 genuine* topologies

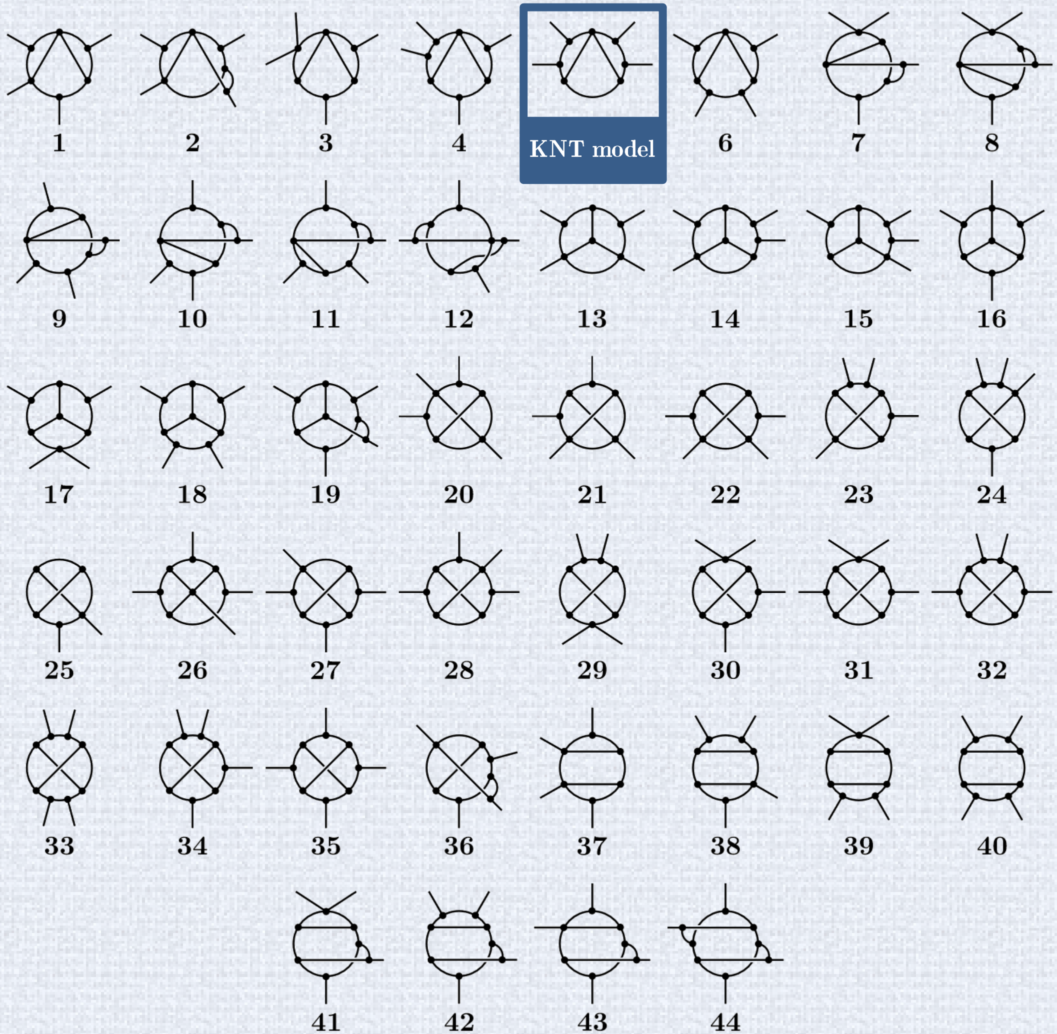
To be explained shortly

3-loop genuine* topologies



To be explained shortly

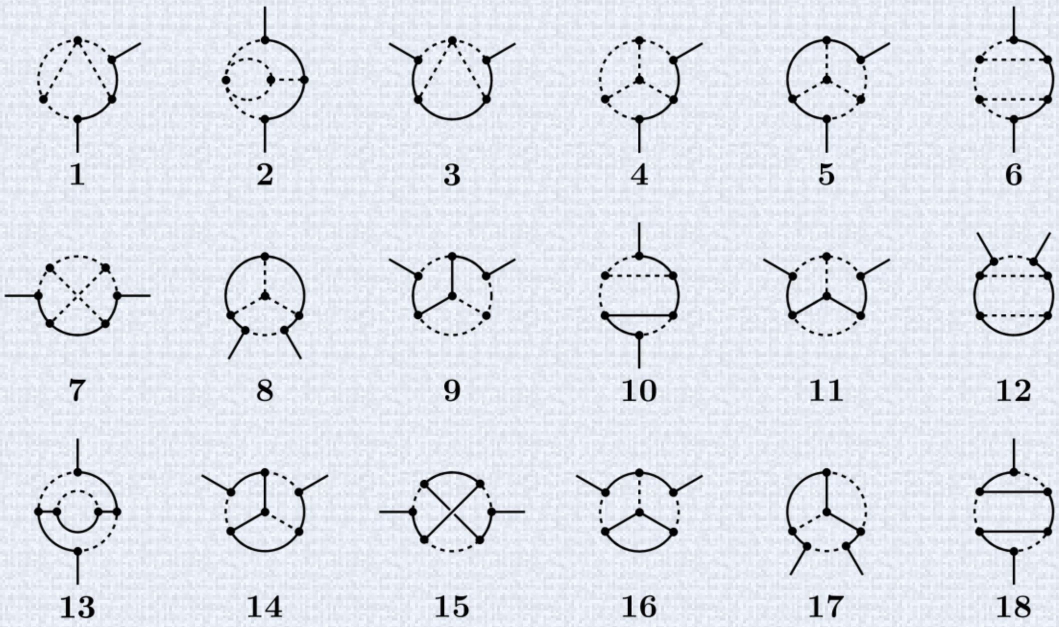
3-loop genuine* topologies



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)

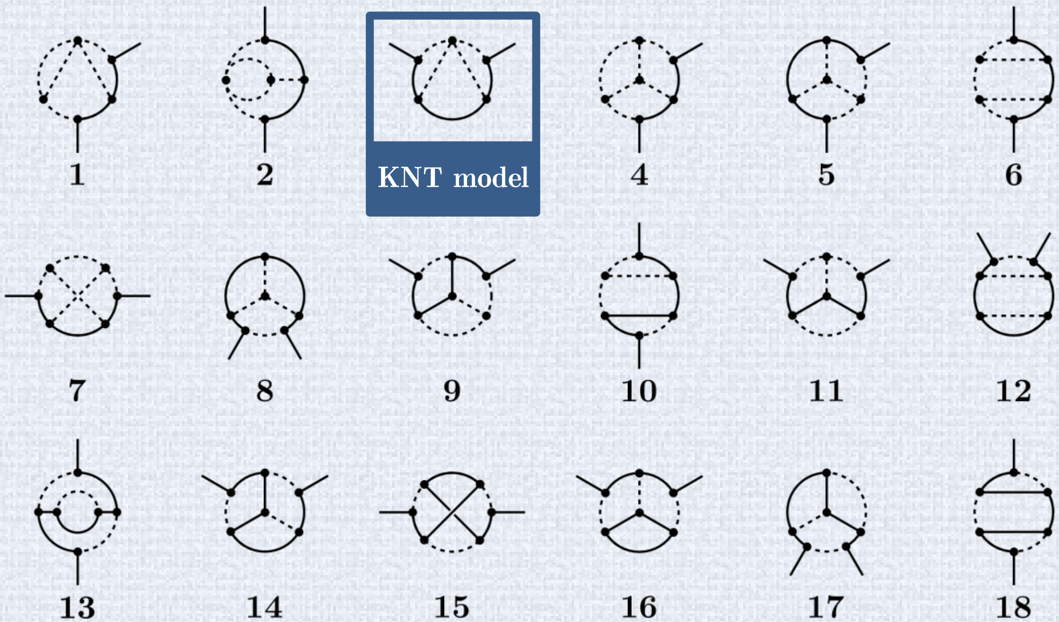


Only 18 genuine* diagrams in the mass basis

3-loop genuine* diagrams

In the mass basis

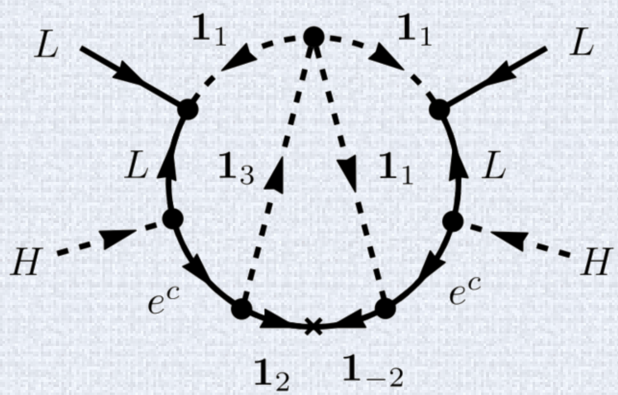
Label the topology lines as fermions or scalars in all possible ways. Then replace the 2 external H's by the VEVs (i.e. remove these lines)



Only 18 genuine* diagrams in the mass basis

One example

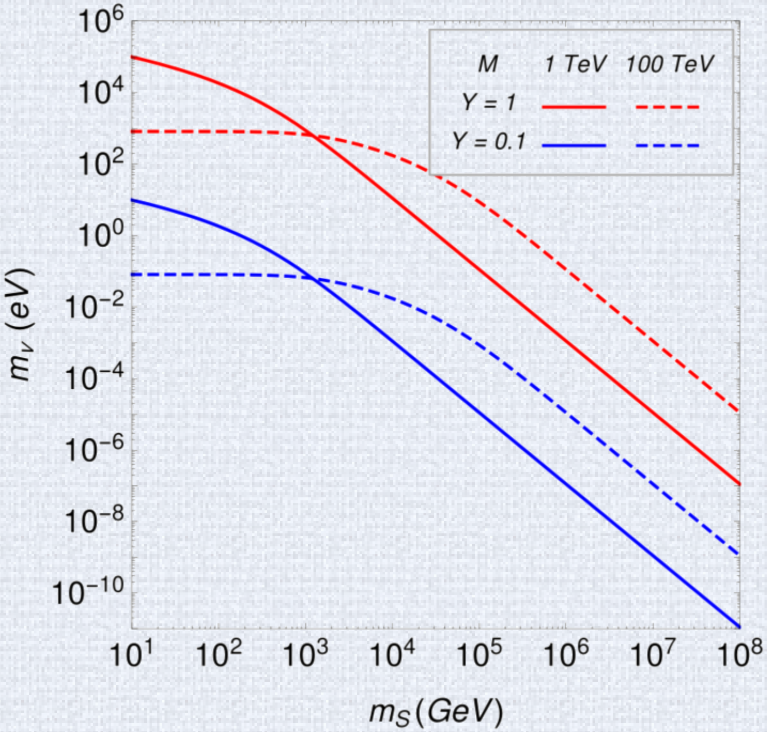
Diagram



New fields

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
S_1	1	1	1
S_2	1	1	3
F	1	1	2

Acceptable neutrino masses



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 <u>special cases</u>, models which fail to pass these cuts are also genuine

I have shown these already

Normal genuine

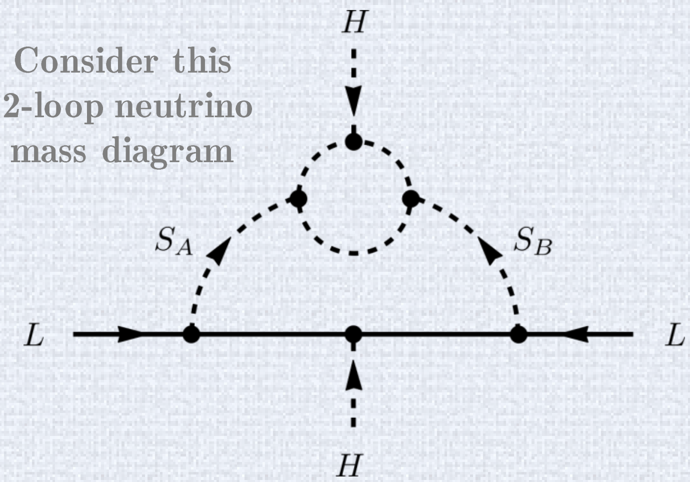
Special genuine

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

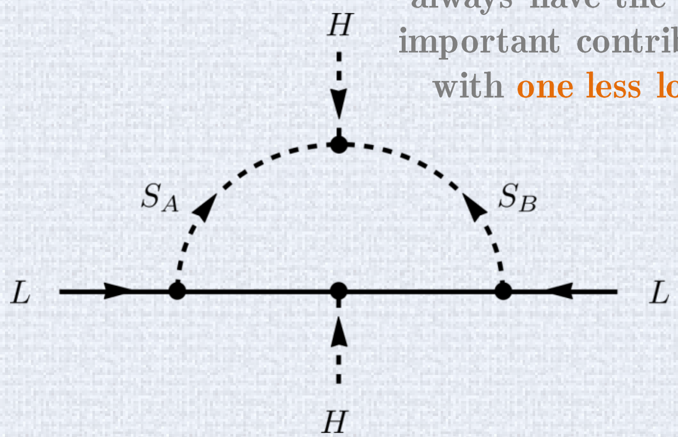
Special genuine topologies/diagrams

Simple example

Consider this 2-loop neutrino mass diagram



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



In most cases, the 1-loop diagram is unavoidable

but

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

(*HH 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