Majorana neutrino masses

beyond the tree level

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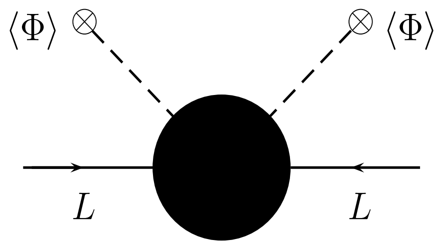
Mathematical relation

$$\mathbf{JWFV} \Leftrightarrow \nu$$

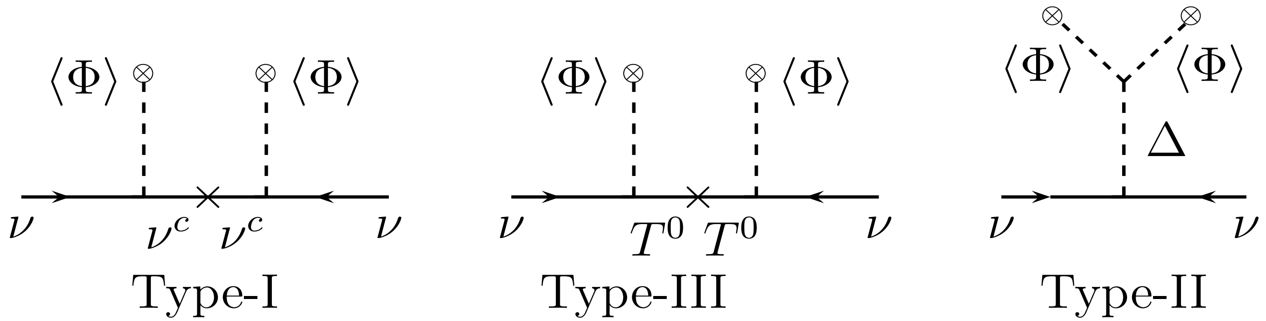
Some remarks on neutrino masses...

Model independent approach: induced by $\mathcal{O}_5 \sim LL\Phi\Phi \Rightarrow \Delta L = 2$

S. Weinberg, Phys. Rev. D **22**, 1694 (1980)



Tree-level UV completions



Minkowski, 1977

Mohapatra & Senjanovic, 1980

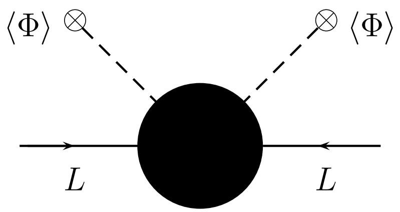
Schechter & JWFV, 1980 ...

Foot, Lew, He & Joshi, 1989

Schechter & JWFV, 1980 ...

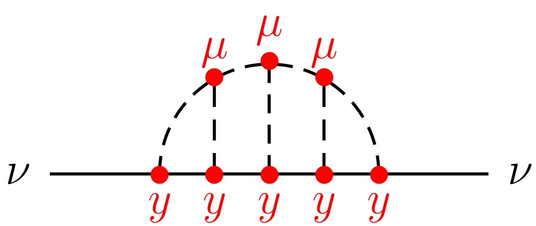
Higher order

Insisting on only $d=5$ and not slightly broken $U(1)_L$:



$$= \sum_i D^{(i)}$$

Phenomenological constraints however rule out $D^{(i)} > D^{(4)} \ldots$ and perhaps even $D^{(i)} > D^{(3)} \ldots$



$$m_\nu \sim \left(\frac{1}{16\pi^2}\right)^4 m_F^4 y^5 \mu^3 \int d^{16}k \left(\frac{1}{k^2-m_S^2}\right)^7 \left(\frac{1}{k^2-m_F^2}\right)^4$$

$$\sim \left(\frac{1}{16\pi^2}\right)^4 \frac{m_F^4}{m_S^6} y^5 \mu^3 \sim 10^3 y^5\,\text{eV} \;\Rightarrow \boldsymbol{\mathcal{O}(y) \sim 0.1}$$

$$\boxed{\text{BR}_{\text{LFV}} > \text{BR}_{\text{LFV}}^{\text{Exp}}}$$

For $D^{(3)}$ one can calculate $\mathcal{O}(y) \sim \mathbf{0.05}$. Some three-loop models analyzed at about ~ 2000-2003:

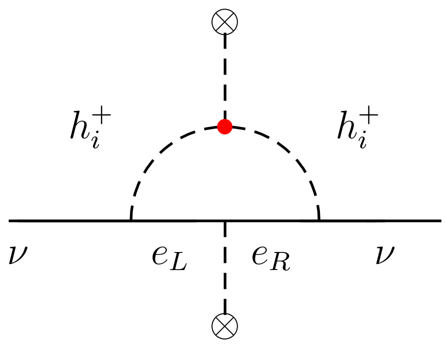
Until 2011 MEGA bound: $\text{BR}^\mu_{e\gamma} \lesssim 2.1 \times 10^{-11}$
MEG bound as 2013: $\text{BR}^\mu_{e\gamma} \lesssim 5.7 \times 10^{-13}$

3−loop models might be already ruled out (!?)

Warming up: some examples

Basically, viable realizations are reduced to one and two loops:

Zee model



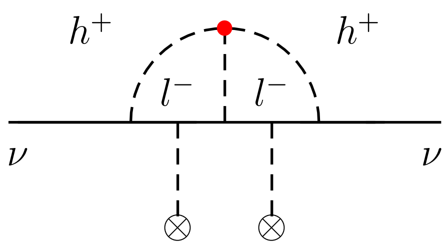
Scalar sector: $h^\pm$, $H_{1,2}$: $\mathcal{L} = f\bar{L}^cLh^+ + \underbrace{\mu H_1 H_2 h^+}_{\Delta L=2}$

<u>Restricted version</u>: Type-I 2HDM $\Rightarrow$ Maximal $\theta_\odot$ **Ruled out**

<u>General version</u>: Type-III 2HDM **Viable!!**

At the light of LHC data **worth exploring!!**

Cheng-Li-Babu-Zee model



Scalar sector: h^+, k^{++} : $\mathcal{L} = f\bar{L}^cLh^+ + h\bar{e}^cek^{++} + \underbrace{\mu h^+h^+k^{--}}_{\Delta L=2}$

Already constraints from LFV $\mu \to e\gamma$:

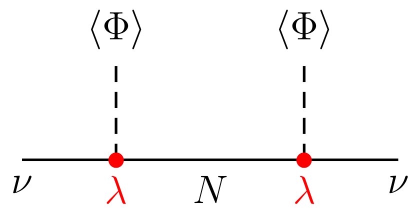
<u>Normal mass spectrum</u>: $m_h \gtrsim 590$ GeV

<u>Inverted mass spectrum</u>: $m_h \gtrsim 5.04$ TeV

The motivation starts being WEAK!

High scale approaches

"Conventional wisdom": Neutrino acquire their masses via the type-I seesaw (standard seesaw):



- $M_N \gg \Lambda_{\rm EW} \quad \Rightarrow \quad \mathcal{O}(\lambda) \sim 1$ $\boxed{m_\nu \sim 0.1 \text{ eV}}$
- $N \to LH$ addresses $n_{\Delta B} \sim 10^{-10}$

Lacking experimental prove

- No direct prove possible given the large scale involved $M_N \sim \Lambda_{\rm GUT}$
- No indirect test possible:

$$\{9|\lambda_{ij}|, 6 \text{ CP phases}, 3 M_N\} \quad \textbf{VS} \quad \{3|\theta_{ij}|, 3 \text{ CP phases}, 3 m_{\nu_i}, n_{\Delta B}\}$$

The Lagrangian parameters can not be reconstructed

A "novel" path can be followed to "test" these approaches

Underpinning the mechanism?

Models involving LHC physics are based in the following possibilities:

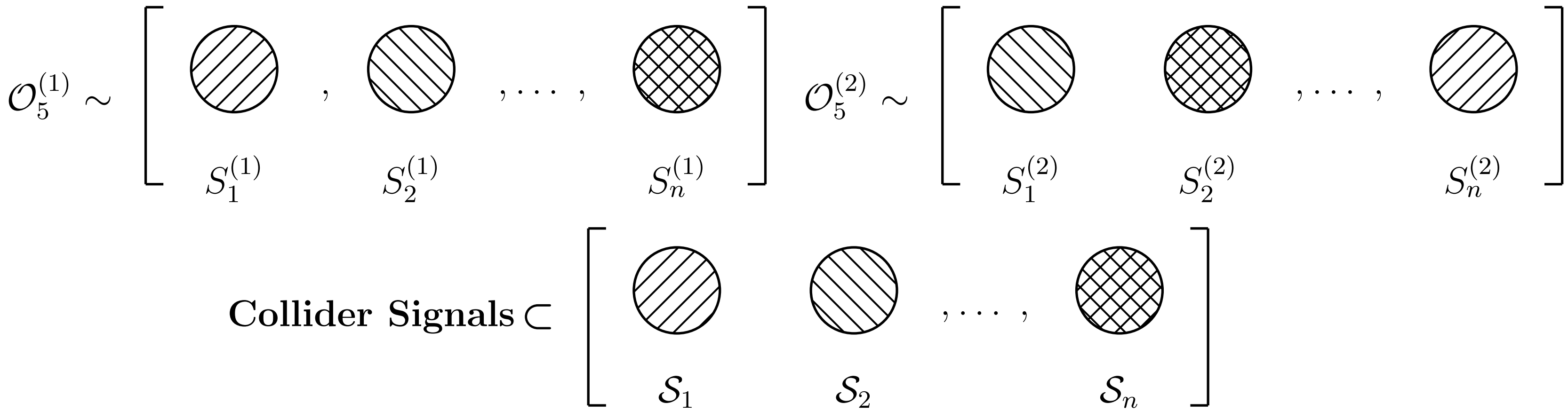
Bonnet, Hernandez, Ota and Winter [arXiv:0907.3143]

1. $\mathscr{O}_5$ arising at the one or two loop order.
2. $\mathscr{O}_5 = 0$ and so Majorana neutrino masses generated from $d = 7$ effective operators.
3. $\mathscr{O}_5$ involving small parameters related with slightly broken L.

IDEAL/NAIVE PROGRAM

I. Systematically classify the viable $\mathscr{O}_5$ one and two loop realizations.

II. Classify the different possibilities in sets, according to their collider signals.



Addressing item I.

A systematic classification of the possible realizations is feasible through the following **"recipe"**

Bonnet, Hirsch, Ota and Winter [arXiv:arXiv:1204.5862]

Algorithm

1. Identify possible topologies.
2. For all possible external legs configurations $(2\Phi + 2L)$ insert internal lines (fermion or boson) subject to renormalizability conditions.
3. Assuming the internal fermion/bosons are $SU(3)_C$ singlets fix the $SU(2)_L \times U(1)_Y$ quantum numbers.
4. Calculate loop integrals

Items 1 & 2 can be done by using `FeynArts` cleverly

Following different approach, partially done at the 1-loop level by E. Ma [hep-ph/9805219]

Following "algorithm", task completed by AHEP and Würzburg groups for 1-loop.

Two-loop case: topologies

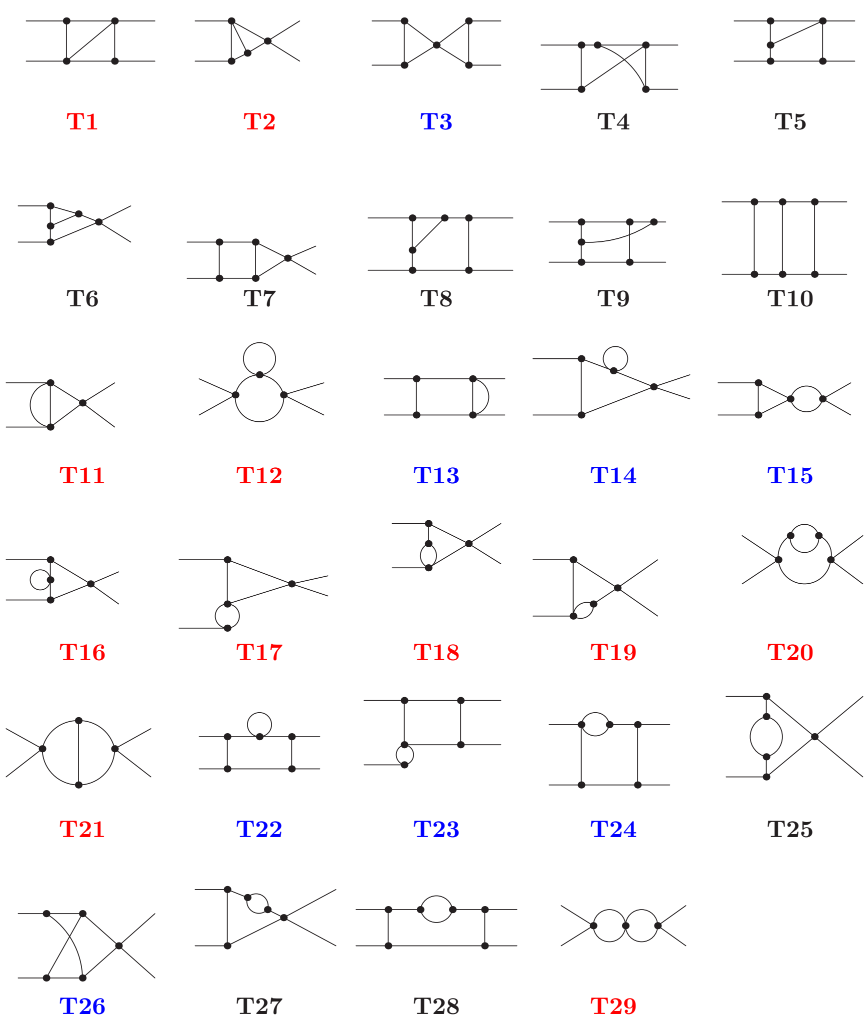
Ask FeynArts to calculate $2 \leftrightarrow 2$ "scattering"

for **only** ID and without self-energies and tadpoles

$\mathcal{O} \sim$ **200** diagrams

HOPELESS?

Topological equivalence $\Leftrightarrow$ 29



Renormalizable vertices

exclude 11 topologies

Make sure for a given diagram

a one-loop does not exist

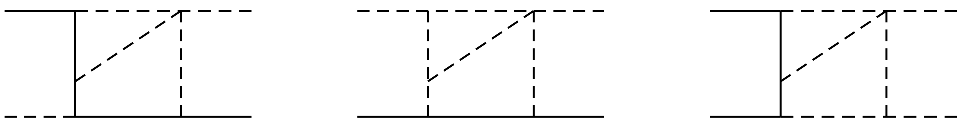
exclude 8 topologies

The problem "reduces" to

11 relevant topologies

Field insertions enlarge the number of possible diagrams:

T5



T7

Topology	Number of diagrams
T4	3
T5	3
T6	1
T7	2
T8	17
T9	11
T10	10
T25	1
T27	2
T28	13

Including the field representations defines the specific 2-loop realizations

A lot of work ahead!!

...The picture already defined!!

Going hybrid

Neutrino mass matrix involving mechanisms **(Data might be suggesting this!)**

DAS, I. de Medeiros, E. Houet [arXiv:1302.6499]

$U = \{v_1, v_2, v_3\}$

In the flavor basis:

$m_\nu = \sum_i m_{\nu_i} v_i \otimes v_i$

Current ν data

$\sin\theta_{ij} = \sin\theta_{ij}^{\mathrm{TBM}} + \epsilon_{ij}$, $\quad \epsilon_{ij} \ll 1$

$v_i = v_i^{\mathrm{TBM}} + \varepsilon_i$, $\quad \varepsilon_i = \varepsilon_i(\epsilon_{ij})$

$m_\nu = \sum_i m_{\nu_i} \left[v_i^{\mathrm{TBM}} \otimes v_i^{\mathrm{TBM}} + \mathcal{V}_i\right]$

$m_\nu = m_\nu^{(A)} + m_\nu^{(B)}$

10 years before these data:

The neutrino mass matrix such that:

Atmospheric scale due to tree-level BRpV

Solar scale due to triplet contributions

DAS, Martin, Albert, JWFV [hep-ph/0304141]

Jose and Latin-American physics

Spreading physics

JWFV ⇔ AHEP

CHILE	COLOMBIA
Marco Aurelio Diaz [**PUC**]	Diego Restrepo [**UdeA**]
Roberto Lineros [**AHEP**]	Jesus Mira [**UdeA**]
BRAZIL	Diego Aristizabal [**ULg**]
Fernando de Campos [**UEP**]	Oscar Zapata [**UdeA**]
Pedro de Holanda [**UNICAMP**]	Carolina Arbelaez [**AHEP**]
Orlando Peres [**UNICAMP**]	David Forero [**AHEP**]
Maurizio Magro [**USP**]	**MEXICO**
Celio Muora [**UFdABC**]	Omar Miranda [**Cinvestav**]
Urbano Franca [**NECSI**]	Juan Barranco [**UdeG**]
	Eduardo Peinado [**LNF**]
	Luis Dorame [**AHEP**]

More than ~20 LA students, postdocs in the last ~15 years

AHEP is **probably** one of the European HEP groups hosting the largest number of LA researchers