Radiative origin of Majorana neutrino masses

Diego Aristizabal

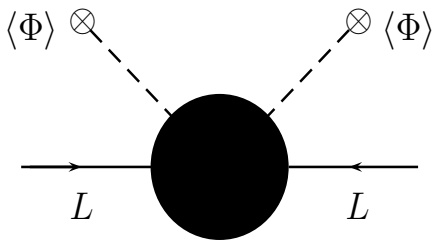
IFPA Group, Université de Liège , Belgium

Based on:

arXiv:1411.7038: DAS, A. Degee (IFPA), L. Dorame (VLC), M. Hirsch (VLC)

Different ways to neutrino masses

Majorana neutrino masses



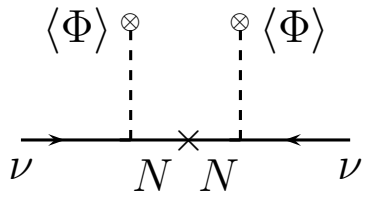
$$\left(M_\nu^{\text{eff}}\right)_{ij} \sim C_{ij}\,\frac{v^2}{\Lambda}$$

"Natural" couplings $\mathcal{O}(C_{ij}) \sim 1$ point towards a GUT

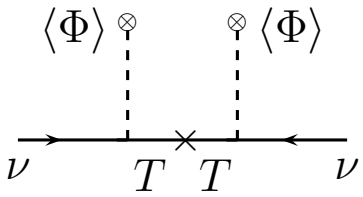
lepton number-breaking scale $\Lambda \sim 10^{15}$ GeV

The high-energy picture

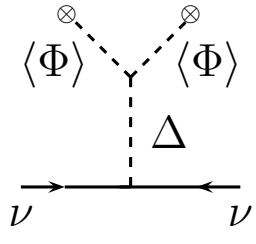
Tree level



Type-I



Type-III

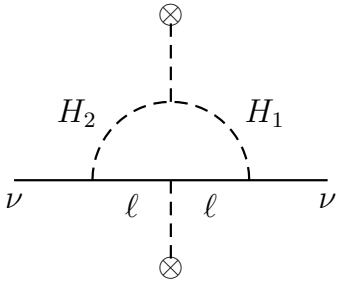


Type-II

Beyond tree-level

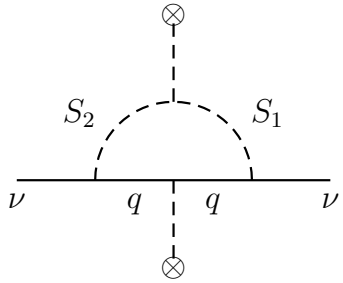
Besides the "natural" tree level realizations, others can be conceived (some examples with Yukawa lepton number-conserving interactions):

One-loop level



$\mathbf{2HDM + } h^{\pm}$

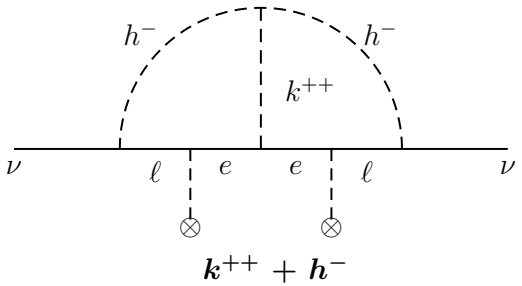
$\Delta L = 2 : \mu H_1 H_2 h$



LQ interactions

$\Delta L = 2 : S_1 S_2 H$

Two-loop level



$k^{++} + h^-$

$\Delta L = 2 : \mu k^{++} h^- h^-$

These realizations allow $\Lambda \sim \Lambda_{EW}$

lead to testable predictions!

Constructing potentially testable models

The neutrino mass matrix generated from an $n-loop$ and dimension d diagram:

(Bonnet, Hirsch et. al. 2012)

$$m_\nu \sim \varepsilon \times \frac{Y^2 v^2}{\Lambda} \times \left(\frac{Y^2}{16\pi^2}\right)^n \times \left(\frac{v^2}{\Lambda}\right)^{d-5}$$

Lower scale models

- The neutrino mass matrix arises from higher-order loop diagrams
- The neutrino mass matrix arises from higher-order effective operators
- The neutrino mass matrix involves small parameters
- Combinations...

Allowing for Y couplings in the range $[10^{-3}, 1]$, all possibilties enable $\Lambda \sim \Lambda_{\text{EW}}$

Potential testabilty at LHC!

What has been done?

Model-dependent results

(An almost "infinite" list)

Loop-induced

Ext. scalar sectors: Babu-Zee (1988), Zee (1980)

Ext. scalar + fermion sector: Scotogenic (2006)

Hybrid tree+loop: A. Pilaftsis 1992

Higher operators

$d = 7$ (Babu et. al. 2009)

$d \geq 7$+1-loop (Kanemura & Ota, 2010)

Slightly broken L

Inverse seesaw (Valle & Mohapatra, 1986)

Hambye et. al, 2009

Pilaftsis & Dev 2012,2013

Complete picture only possible in model-independent approaches

Loop-induced

Eff. Op. approach

Babu & Leung (2001)

de Gouvea & Jenkins (2007)

Volkas et. al. 2012

Diagrammatic approach

1-loop: Hirsch et. al. 2012

Mixed: Pascoli et. al. 2012

2-loop: DAS et. al. 2014

Higher order

Winter et. al. 2005 (Non-SUSY)

Winter et. al. 2011 (SUSY)

The two-loop case

The recipe

A systematic classification (at a given loop order) 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. Fix the $SU(2)_L \times U(1)_Y$ quantum numbers (color can be trivially done).
4. Calculate loop integrals

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

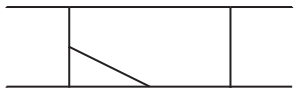
Item 3 can be addressed by using $SU(2)$ product representation decomposition

Item 4 can be addressed by using partial fraction decomposition and "master" integrals

Renormalizable topologies

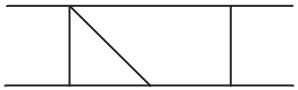
Box-based

$\boldsymbol{T2_1^B}$



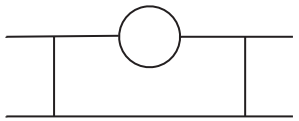
$\boldsymbol{T2_2^B}$

$\boldsymbol{T2_3^B}$

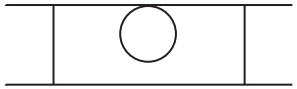


$\boldsymbol{T2_4^B}$

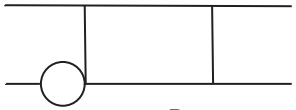
$\boldsymbol{T2_5^B}$



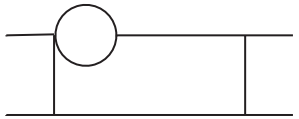
$T2_6^B$



$T2_7^B$

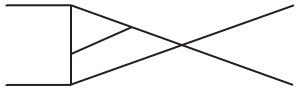


$T2_8^B$

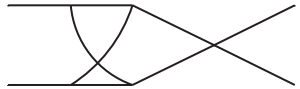


$T2_9^B$

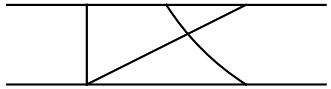
Triangular-based



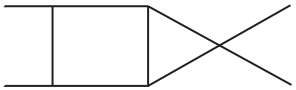
$\boldsymbol{T2_1^T}$



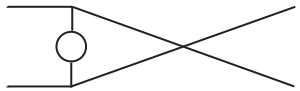
$\boldsymbol{T2_2^T}$



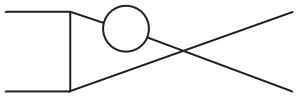
$\boldsymbol{T2_3^T}$



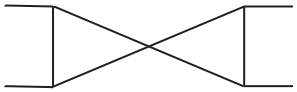
$T2_4^T$



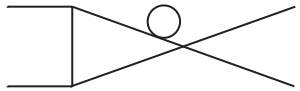
$T2_5^T$



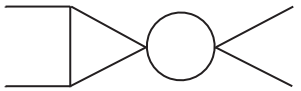
$T2_6^T$



$T2_7^T$



$T2_8^T$



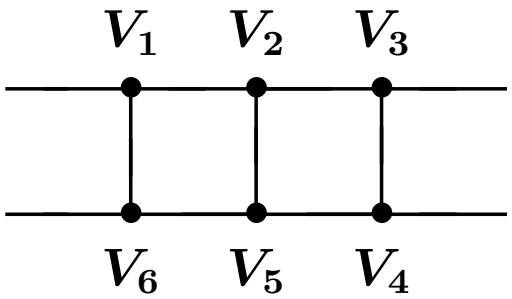
$T2_9^T$

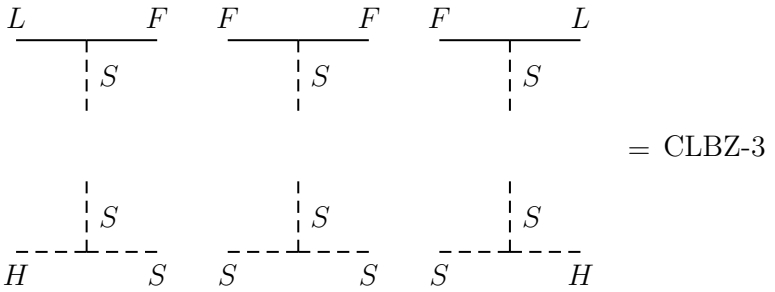
Field insertions

Focusing only on fermions and scalar bosons [Not considering gauge bosons]:

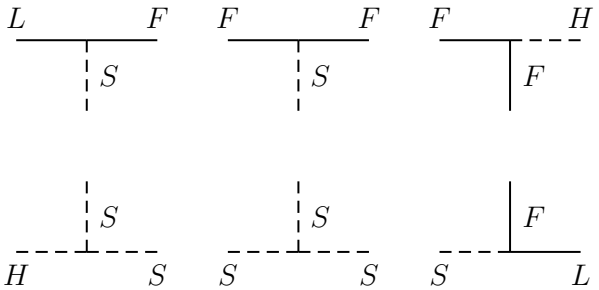
Ask `FeynArts` to insert fermions and bosons

Double check by hand using tree-like structures and sequential vertex insertions

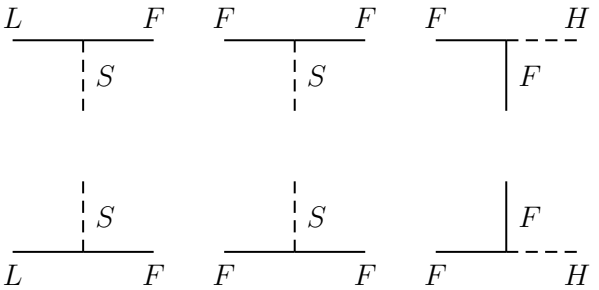




= CLBZ-3



= CLBZ-2



= RB-2

Second step: rèsumè

At this point the number of possible diagrams can be already determined.

However with certain caution!

Box-based topologies

TOPOLOGY	$T2_1^B$	$T2_2^B$	$T2_3^B$	$T2_4^B$	$T2_5^B$	$T2_6^B$	$T2_7^B$	$T2_8^B$	$T2_9^B$	TOTAL
# OF DIAG	10	14	9	3	1	12	4	2	3	58

Triangle-based topologies

TOPOLOGY	$T2_1^T$	$T2_2^T$	$T2_3^T$	$T2_4^T$	$T2_5^T$	$T2_6^T$	$T2_7^T$	$T2_8^T$	$T2_9^T$	TOTAL
# OF DIAG	2	1	2	2	1	2	1	1	1	13

Order-2-uniqueness applied to resulting diagrams

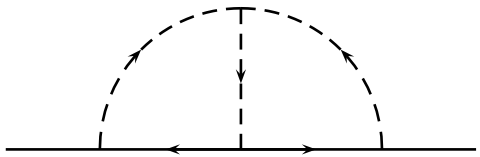
Type of diagrams

Genuine Diagrams for which absence of leading order diagrams is guaranteed.

Non-genuine finite Diagrams are 1-loop, but one of the couplings is generated radiatively. They are "effectively" 2-loop.

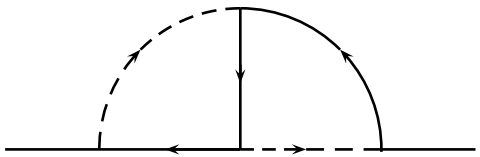
Non-genuine divergent Are just corrections to leading-order neutrino masses, generated at the 1-loop level.

Despite the large number of diagrams, genuine diagrams reduce to "just" variations of



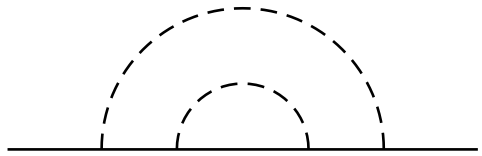
10 diagrams

CLBZ diagrams



6 diagrams

PTBM diagrams



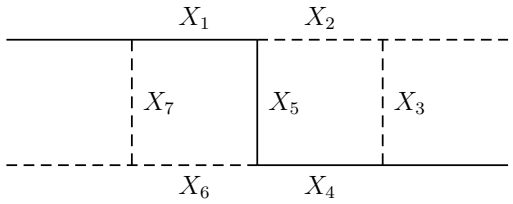
4 diagrams

RB diagrams

QNs: an exercise

Tables with QNs for all genuine diagrams as well as all results for all possible two-loop integrals in **DAS, Degee, Dorame and Hirsch, 2014**

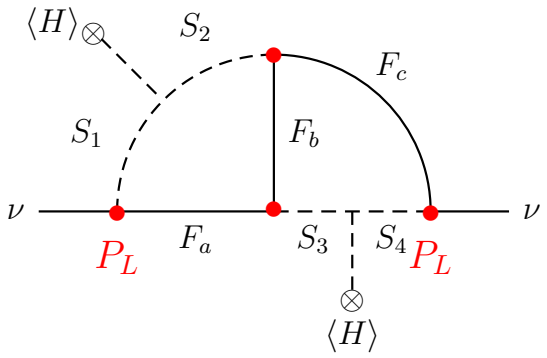
Using these results



$\alpha = 2$ and $\beta = -3$

X_2 \ X_1	1				
	X_5	X_7	X_6	X_3	X_4
1	1	2	1 3	2	1
2	**2**	**2**	**1** 3	**1** 3	**2**
3	3	2	1 3	2	1 3

Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
$-1+\alpha$	$-1+\beta$	β	$-1+\beta$	$\alpha-\beta$	$-1+\alpha$	α



PTBM-3 model							
FIELDS	F_a	F_b	F_c	S_1	S_2	S_3	S_4
$SU(2)_L$	1	2	2	2	1	2	1
$U(1)_Y$	1	5	-4	2	1	-4	-3

The chiral structure of internal vertices fixes the type of integrals

List of integrals tabulated in DAS et. al. (2014)

Summary

Rèsumè

- Neutrino masses, in addition to the BAU and DM, provide the most strong evidence for physics beyond the SM.
- If neutrinos indeed get their masses via certain “form” of a “standard” high-scale mechanism, no experimental prove is possible.
- Other forms, “low-energy” forms, do exist and can lead—in principle—to testable predictions.
- Understanding whether this is the case calls for a full program which requires a systematic understanding of all possibilities: For radiative generated scenarios task completed at the one- and two-loop order

Scenario I:

A positive collider signal...

First step towards the mechanism

Scenario II:

No signal at all...

Increase the likelihood for

$\Delta L \neq 0$ at $\Lambda \sim \Lambda_{\text{GUT}}$