

Radiative origin of neutrino masses

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Based on:

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

Different ways for neutrino masses

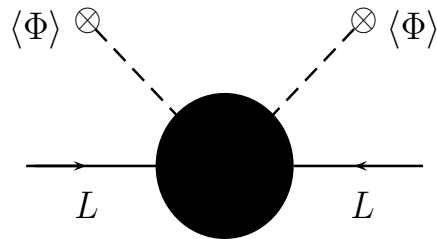
- Majorana neutrino masses
- Beyond tree-level
- Predictions: the (1-loop) LQ case
- Constructing potentially testable models
- What has been done?

The two-loop case

Summary

Different ways for neutrino masses

Majorana neutrino masses

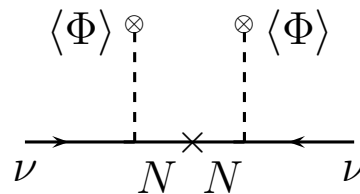


$$\left(M_\nu^{\text{eff}}\right)_{ij} \sim C_{ij} \frac{v^2}{\Lambda}$$

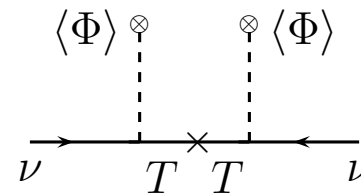
“Natural” couplings $\mathcal{O}(C_{ij}) \sim 1$ point towards a GUT lepton number-breaking scale $\Lambda \sim 10^{15}$ GeV

The high-energy picture

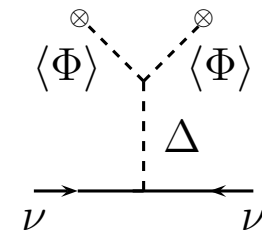
Tree level



Type-I



Type-III



Type-II

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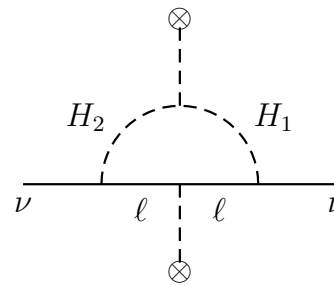
The two-loop case

Summary

Beyond tree-level

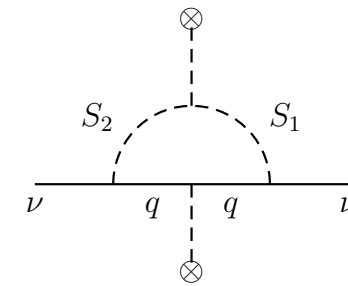
Besides the “natural” tree level realizations, others can be conceived (some examples with Yukawa lepton number-conserving interactions):

One-loop level



2HDM + h^\pm

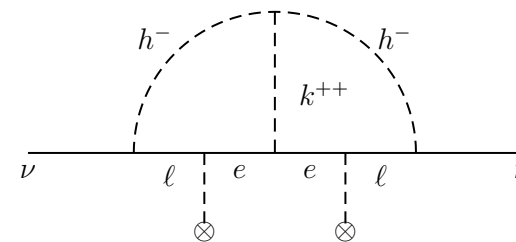
$$\Delta L = 2 : \mu H_1 H_2 h$$



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!

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Predictions: the (1-loop) LQ case

For a LQ model where neutrinos acquire masses via one-loop diagrams with the top quark flowing in the loop (DAS & Hirsch & Kovalenko, 2007):

Different ways for neutrino masses

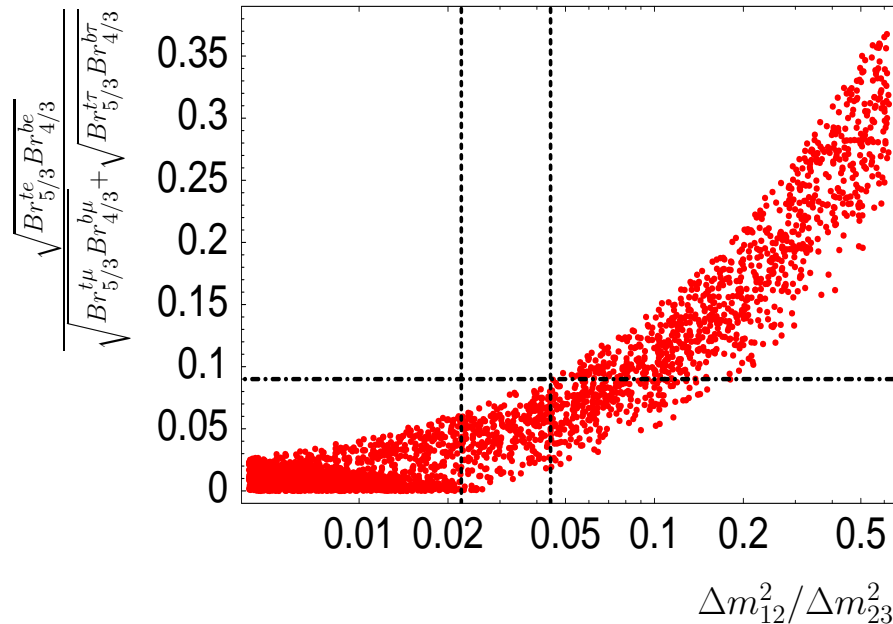
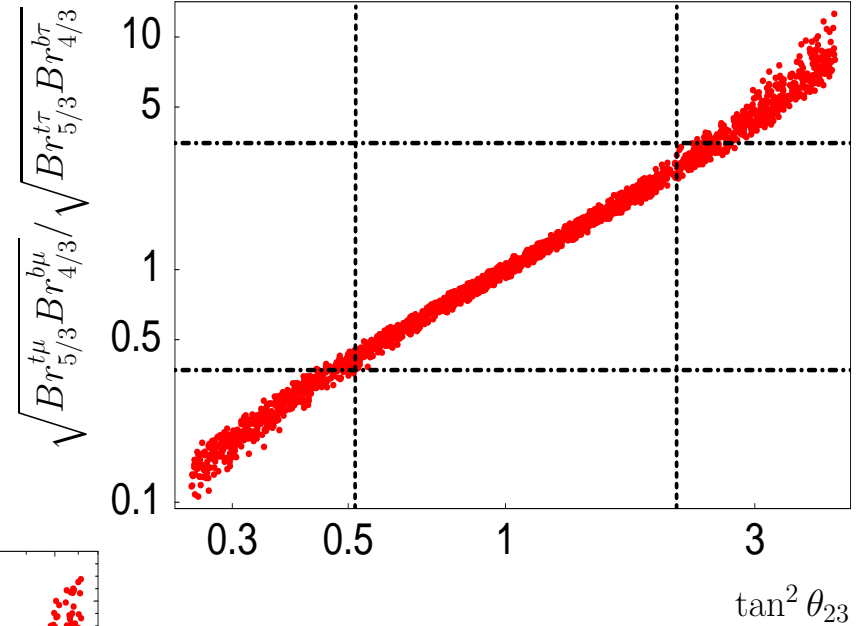
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Same parameters that control neutrino data also control other decay modes

$$Br(S_Q \rightarrow q\ell) \equiv Br_Q^{q\ell}$$



Other correlations with low-energy data can be established

Constructing potentially testable models

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

(Bonnet, Hirsch et. al. 2012)

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

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 possibilities enable $\Lambda \sim \Lambda_{EW}$

**Potential testability
at LHC!**

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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)

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The two-loop case

- The recipe
- Renormalizable topologies
- Field insertions
- Second step: r sum 
- Type of diagrams
- QNs: an exercise

Summary

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

Different ways for neutrino
masses

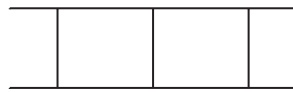
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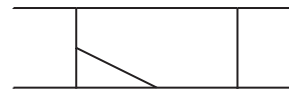
Summary

Renormalizable topologies

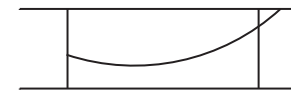
Box-based



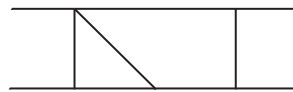
$T2_1^B$



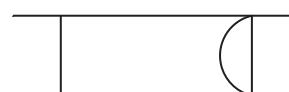
$T2_2^B$



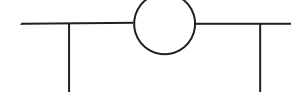
$T2_3^B$



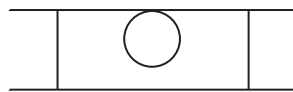
$T2_4^B$



$T2_5^B$



$T2_6^B$



$T2_7^B$

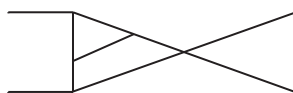


$T2_8^B$



$T2_9^B$

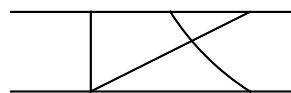
Triangular-based



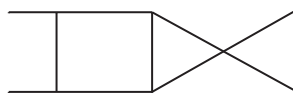
$T2_1^T$



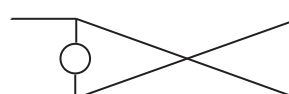
$T2_2^T$



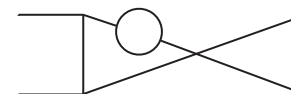
$T2_3^T$



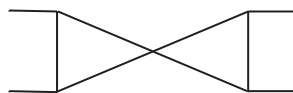
$T2_4^T$



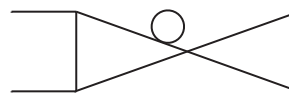
$T2_5^T$



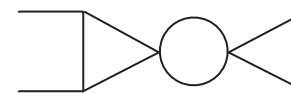
$T2_6^T$



$T2_7^T$



$T2_8^T$



$T2_9^T$

Different ways for neutrino masses

The two-loop case

- The recipe
- Renormalizable topologies

- Field insertions
- Second step: résumé
- Type of diagrams
- QNs: an exercise

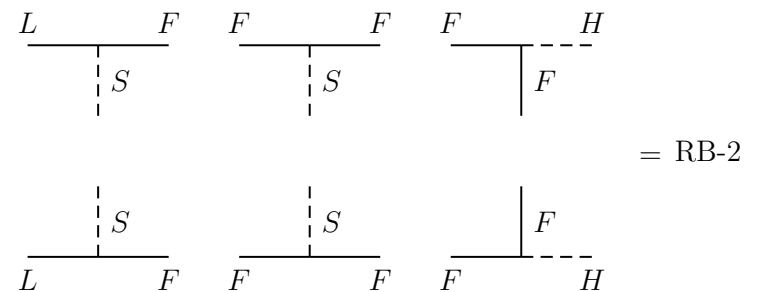
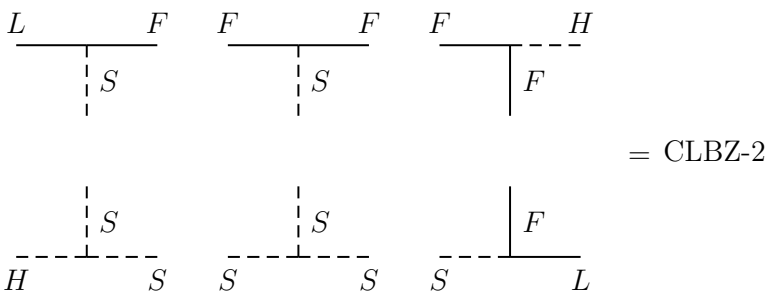
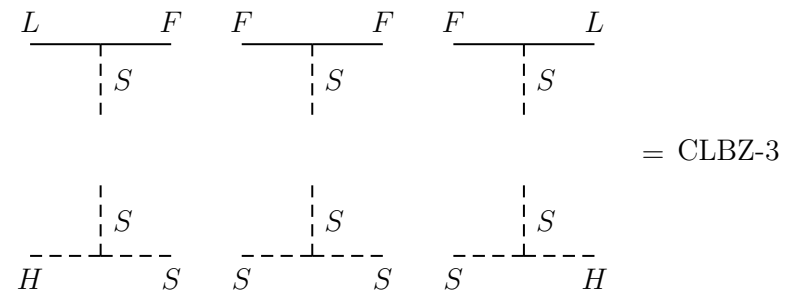
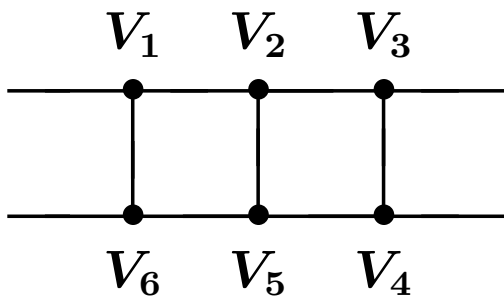
Summary

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



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Second step: r sum 

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**

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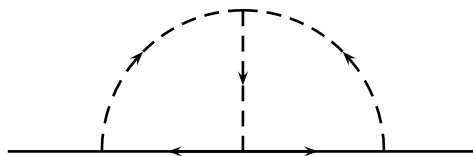
Type of diagrams

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

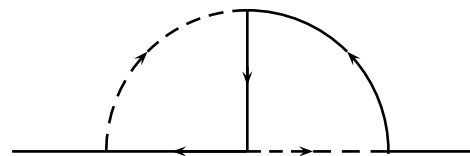
Non-genuine finite Diagrams are 1-loop, but one of the couplings is generated radiatively. They are “effectively” 2-loop.

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

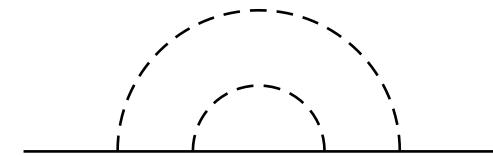
Despite the large number of diagrams, **genuine** diagrams reduce to “just” variations of



10 diagrams
CLBZ diagrams



6 diagrams
PTBM diagrams



4 diagrams
RB diagrams

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QNs: an exercise

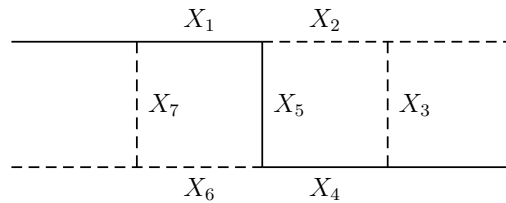
Tables with QNs for all genuine diagrams as well as all results for all possible two-loop integrals in **DAS, Degee, Dorame and Hirsch, 2014**

Different ways for neutrino masses

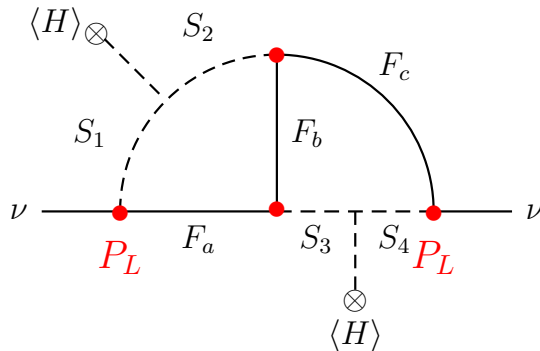
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$$\alpha = 2 \text{ and } \beta = -3$$



**The chiral structure of internal vertices
fixes the type of integrals**

Using these results

$X_2 \backslash X_1$	1				
	X_5	X_7	X_6	X_3	X_4
1	1	2	$\frac{1}{3}$	2	1
2	2	2	$\frac{1}{3}$	$\frac{1}{3}$	2
3	3	2	$\frac{1}{3}$	2	$\frac{1}{3}$

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

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

Different ways for neutrino masses

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Summary

● Résumé

Summary

- 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**
- **Next step:** systematic classification according to the different forms of lepton number violation. Allows “experimental” identification of different categories.

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 $\Lambda \sim \Lambda_{\text{GUT}}$