1-loop d=7 neutrino masses

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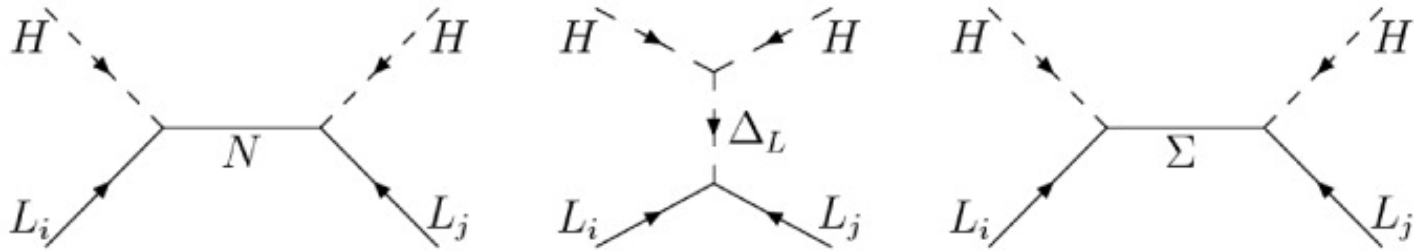
High Energy Physcis in the LHC era, Hep2018

Cepedello, Helo, Hirsch. JHEP 1707 (2017) 079, 1709.0339 (2017)

Outline

- Introduction:
  - Weinberg operator: Tree-level
  - Weinberg operator: Loop-level
  - Higher dimsional operators
- Classification of $d = 7$ 1-loop neutrino mass models
- Example models
  - Low energy constraints
  - LHC contraints
  - New LNV Searches at LHC.
  - Displaced vertex
- Conclusions

Weinberg operator: Tree-level



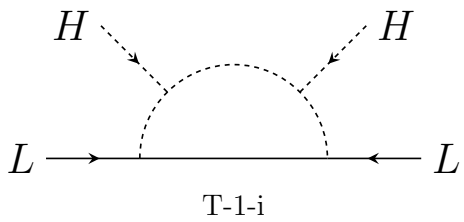
$O_W^{d=5} = \frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda} L_\alpha L_\beta H H + h.c$ (Tree Level)

Additional Suppresions ($c_{\alpha\beta} \sim 1 \rightarrow \Lambda \sim 10^{15} GeV$)

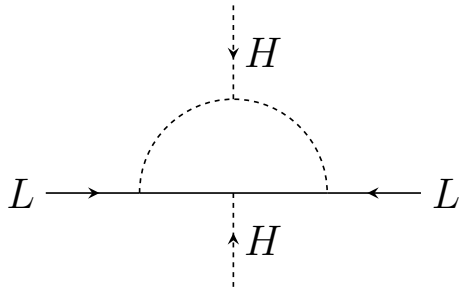
- Neutrino mass is generated radiatively.
- Neutrino mass is forbidden or supressed at $d = 5$, but appears from effective operators of higher dimension.

Weinberg operator: loop level.

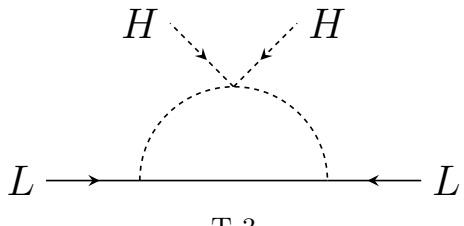
JHEP 1207 (2012) 153, Bonnet et. al.



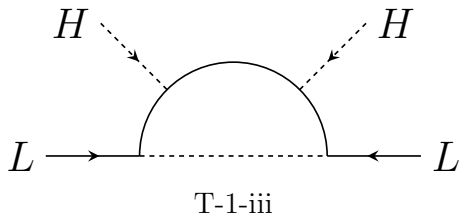
T-1-i



T-1-ii



T-3



T-1-iii

- 6 Topologies. 4 genuine diagrams (2 Topologies: T-1, T-3).
- Many possible models for each diagram
- Avoiding the tree-level: Discrete symmetry or particle content.
- Scotogenic T-3: $\nu_R = 1^F_0, S = 2^S_{1/2}$, . Not Genuine!
- Minimal "genuine" possibility T-3: $1^F_1, 2^S_{1/2}, 2^S_{3/2}$.
- Zee model: T-1-ii.

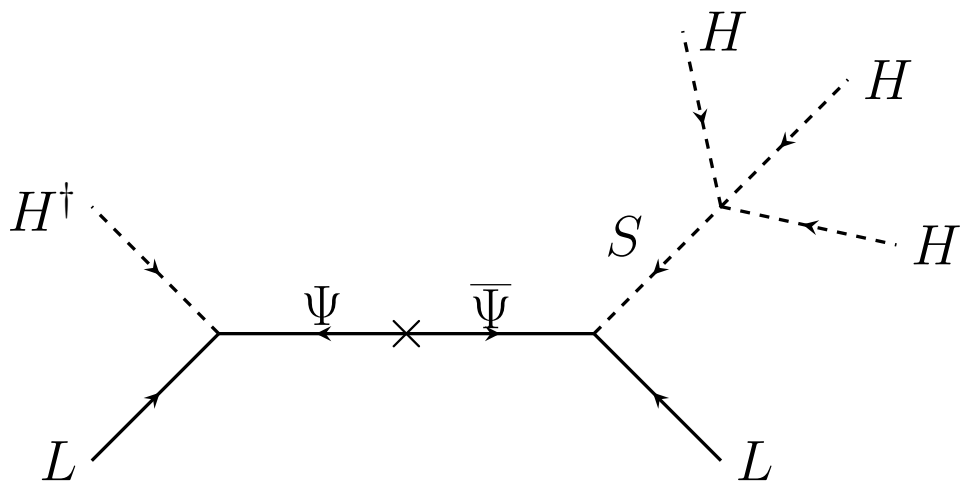
Higher dimensional operators

K. Babu and C. N. Leung, Nucl.Phys. B619, 667

- Majorana neutrinos: $O^{d=7} = LLHH \times HH^\dagger$.
- d=7 at tree level: 4 Topologies, 1 genuine: $\Psi = 3_1^F$, $S = 4_{3/2}^S$
- Suppresion of O^W: Discrete symmetry or particle content.
- $\frac{1}{\Lambda^3} LLHHH^\dagger \to \frac{1}{16\pi^2}\frac{1}{\Lambda} LLHH$. $\quad \Lambda \lesssim 2TeV (d = 7 \text{ dominate})$.
- LHC Phenomenolgy: LNV final state $l^\pm l^\pm W^\pm + W^\mp W^\mp W^\mp$

F. Bonnet, D. Hernandez, T. Ota, and W. Winter, JHEP 0910, 076 (2009)

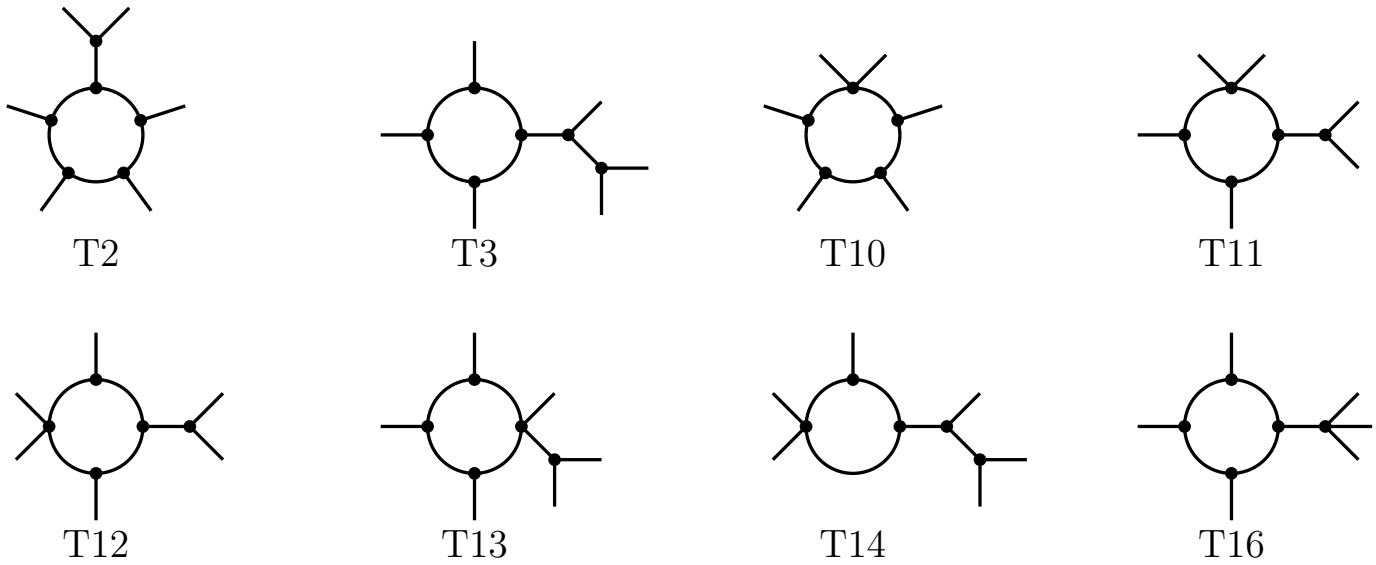
Babu et. al., Phys. Rev. D80, 071702 (2009)



Classification of $d = 7$ 1-loop neutrino mass models.

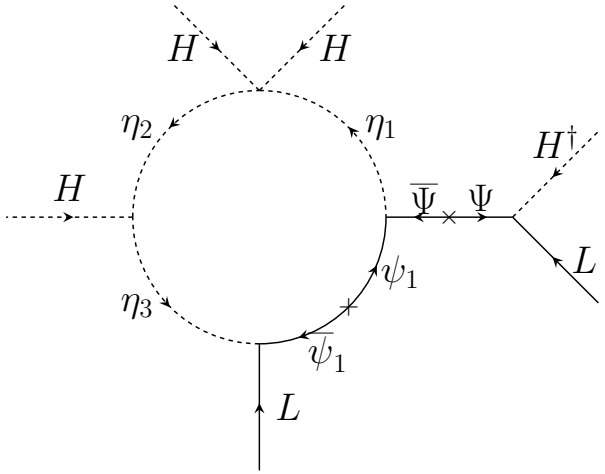
Cepedello, Helo, Hirsch. JHEP 1707 (2017) 079

- 48 topologies only 8 have least one genuine 1-loop $d = 7$ diagram
- From the 8 genuine topologies, one can generate 23 diagrams.
- 1 diagram for which a genuinne model with a triplet as the largest $SU(2)_L$ representation exists.



Triplet Model

$$
\begin{aligned}
\mathscr{L} &= Y_1 H^\dagger \Psi P_L L + Y_2 \overline{\psi}_1 P_L L \eta_3 \\
&+ Y_3 \eta_1^\dagger \overline{\Psi} \psi_1 + Y_4 \eta_1 \overline{\Psi} P_L L \\
&+ Y_5\, e_R \eta_1^\dagger \psi_1 + \mu_1\, H \eta_2 \eta_3^\dagger \\
&+ \lambda_2 \eta_2^\dagger H \eta_1 H
\end{aligned}
$$

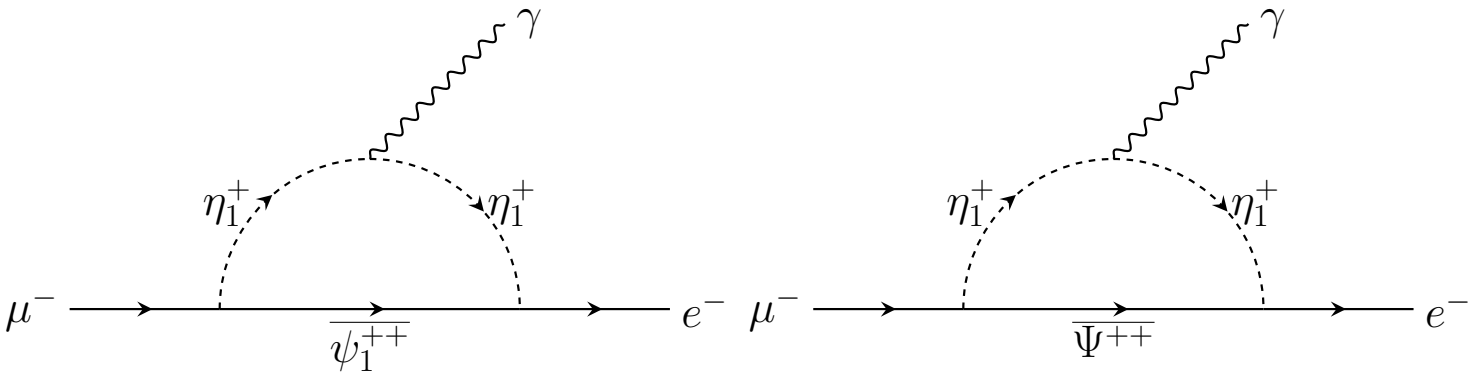


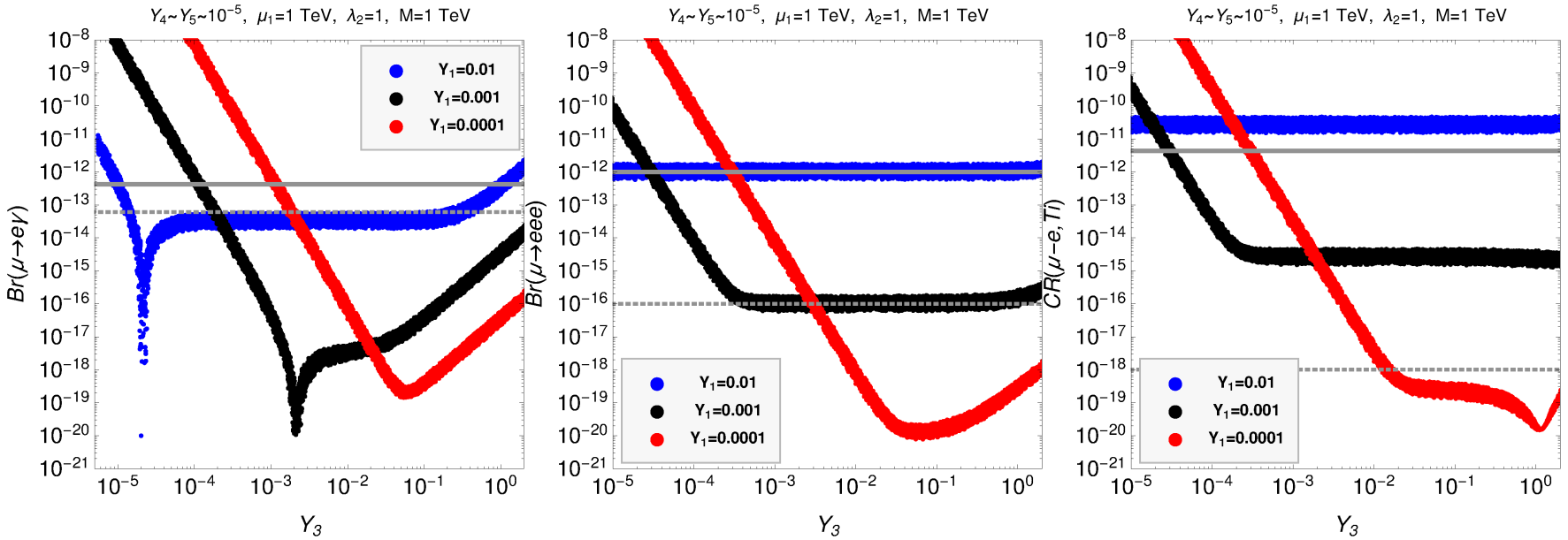
Particle content:

$$
\Psi = \begin{pmatrix} \Psi^{++} \\ \Psi^{+} \\ \Psi^{0} \end{pmatrix} \sim \mathbf{3}_1^F \quad \eta_1 = \begin{pmatrix} \eta_1^{++} \\ \eta_1^{+} \end{pmatrix} \sim \mathbf{2}_{3/2}^S \quad \eta_2 = \begin{pmatrix} \eta_2^{+++} \\ \eta_2^{++} \end{pmatrix} \sim \mathbf{2}_{5/2}^S
$$

$$
\eta_3 = \begin{pmatrix} \eta_3^{++++} \\ \eta_3^{+++} \\ \eta_3^{++} \end{pmatrix} \sim \mathbf{3}_3^S \qquad \psi_1 = \begin{pmatrix} \psi_1^{+++} \\ \psi_1^{++} \end{pmatrix} \sim \mathbf{2}_{5/2}^F .
$$

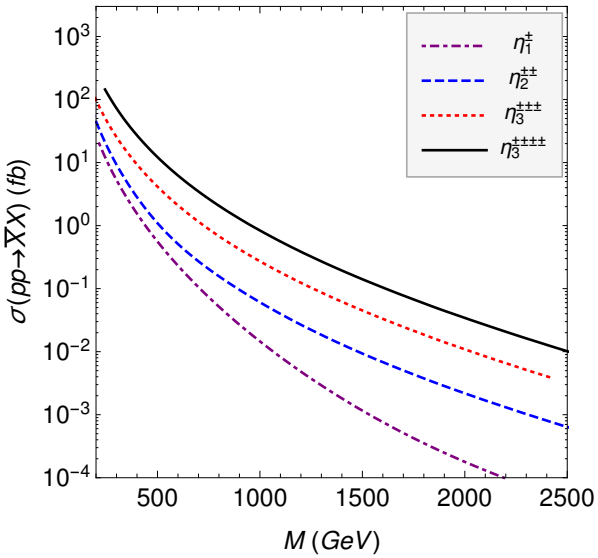
Low Energy contraints

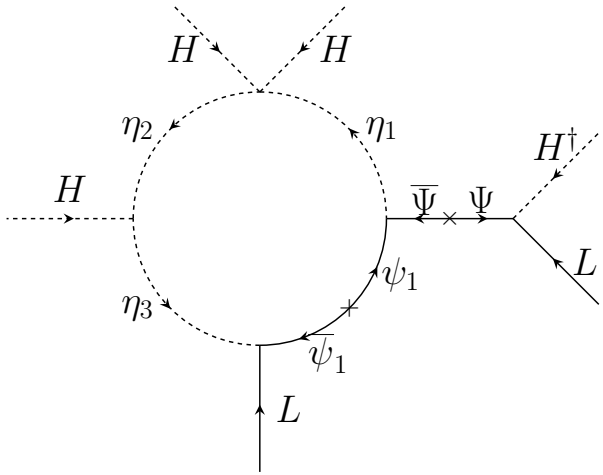




LHC contraints

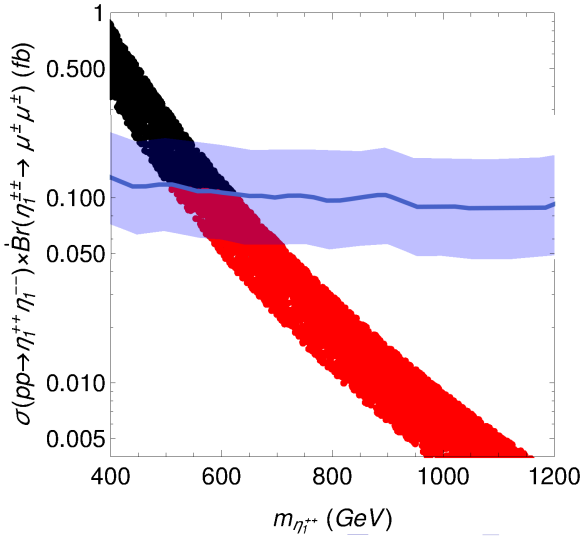
Doubly charged scalars and multi-lepton final states:





$$\Gamma(\eta_1^{++} \to l_\alpha^+ l_\beta^+) \simeq \frac{1}{8\pi}\left(\frac{v}{m_\Psi}\right)^2 m_{\eta_1^+}$$

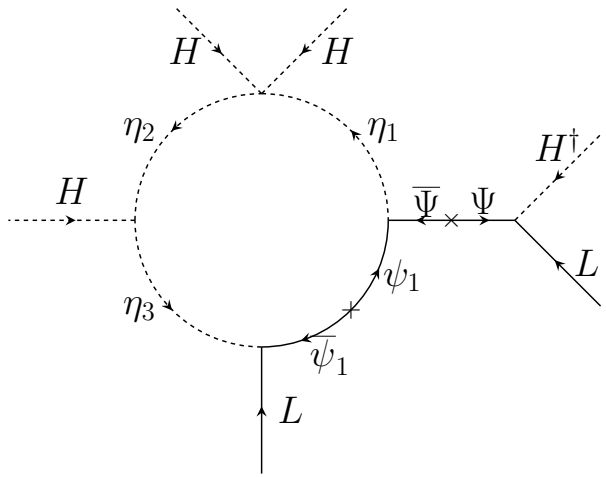
$$\left[(Y_4)_\alpha (Y_1)_\beta + (Y_4)_\beta (Y_1)_\alpha\right]^2$$



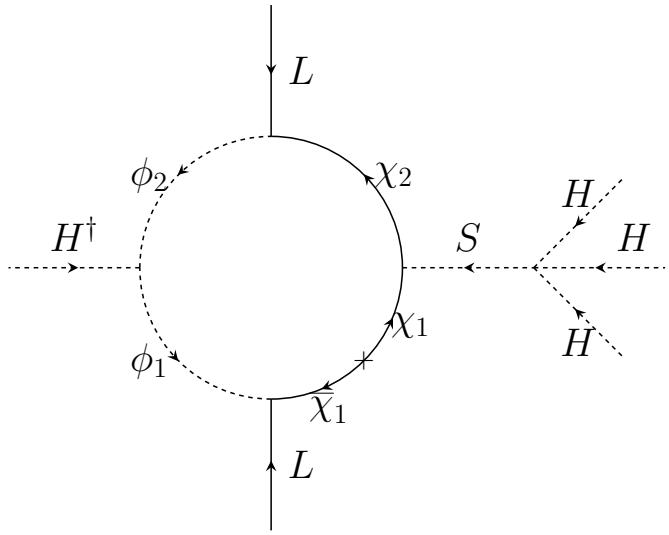
New LNV searches

M.	LNV Signal	Particles	Model	Mass range
4	$l^{\pm}l^{\pm} + W^{\mp}W^{\mp}$	$S^{\pm\pm}$, $\phi_1^{\pm\pm}$, $\phi_2^{\pm\pm}$	Q	$m < 1.4$TeV
6	$l^{\pm}l^{\pm}W^{\pm} + W^{\mp}W^{\mp}W^{\mp}$	S^{3+}, ϕ_2^{3+}	Q	$m < 2.0$TeV
6	$l^{\pm}l^{\pm}l^{\pm} + W^{\mp}W^{\mp}l^{\mp}$	χ_2^{3+}	Q	$m < 2.6$TeV
8	$l^{\pm}l^{\pm}W^{\pm}W^{\pm} + W^{\mp}W^{\mp}W^{\mp}W^{\mp}$	-	-	
8	$l^{\pm}W^{\pm}W^{\pm}W^{\pm} + l^{\mp}l^{\mp}l^{\mp}W^{\mp}$	χ_2^{4+}	Q	$m < 3.2$TeV
8	$l^{\pm}l^{\pm}l^{\pm}l^{\pm} + l^{\mp}l^{\mp}W^{\mp}W^{\mp}$	η_3^{4+}	T	$m < 2.5$TeV

Triplet:

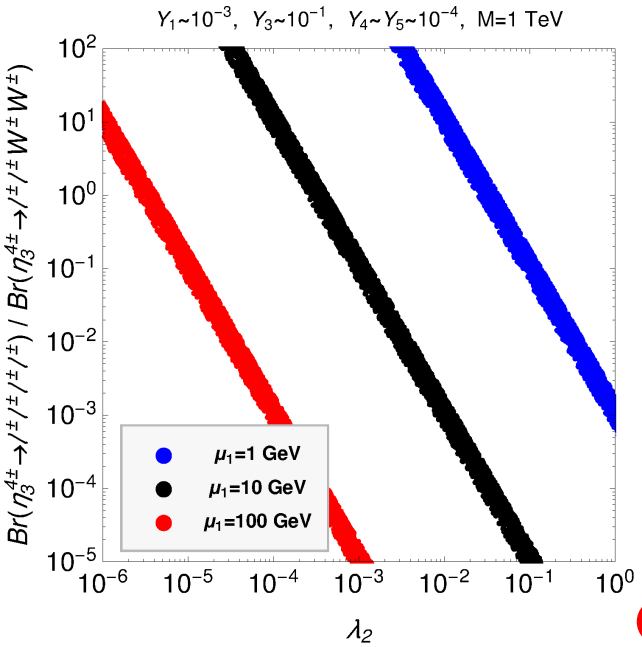


Quadruplet:

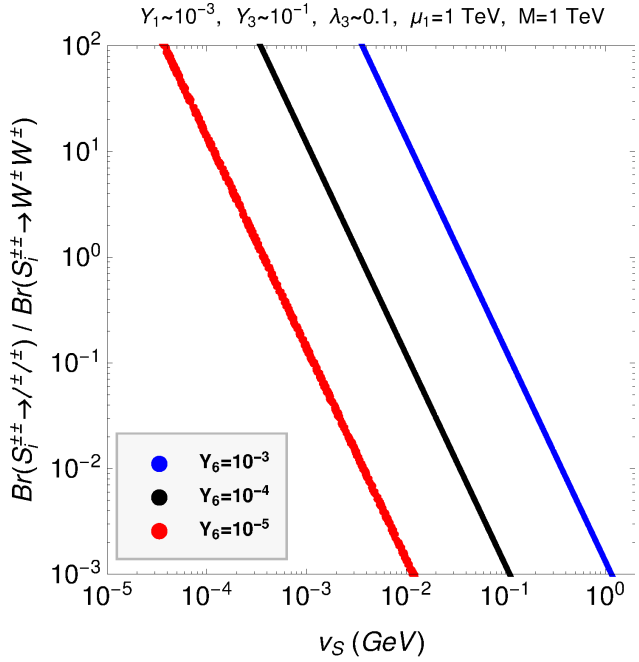


New LNV searches

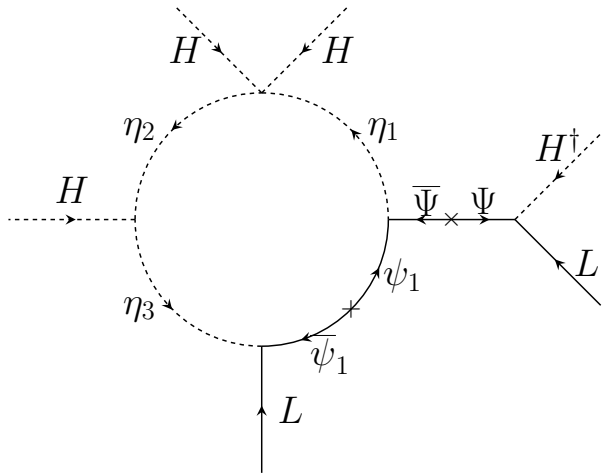
Triplet:



Quadruplet:



Displaced vertex



Triplet:

$$L_0(\eta_3^{3+} \to W^+ l^+ l^+) \sim 0.3 \left(\frac{10^{-1}}{\theta_{\eta_1 \eta_2}}\right)^2 \left(\frac{10^{-2}}{|Y_1|}\right)^2 \left(\frac{10^{-2}}{|Y_4|}\right)^2 \left(\frac{m_\psi}{\text{TeV}}\right)^2 \left(\frac{\text{TeV}}{M}\right) \text{mm}. \quad (1)$$

$$L_0(\eta_3^{4+} \to W^+ W^+ l^+ l^+) \sim 4 \left(\frac{1}{\lambda_2}\right)^2 \left(\frac{10^{-2}}{|Y_1|}\right)^2 \left(\frac{10^{-2}}{|Y_4|}\right)^2 \left(\frac{m_\psi}{\text{TeV}}\right)^2 \left(\frac{\text{TeV}}{M}\right) \text{cm}. \quad (2)$$

Conclusion

- We have discussed neutrino masses at 1-loop $d = 7$ order.
- We have identified all possible topologies that can lead to genuine models
- There is only one possible diagram for which the largest necessary representation is a triplet. The remaining 7 topologies yield 22 diagrams, with the largest representation being at least a quadruplet.
- We study two examples in detail: Triplet and quadruplet models.
- New LNV final states appears. In particular, final states with large multiplicites are predicted to occur (multiple W and multiple leptons) for which we expect standard model backgrounds to be negligible.