Neutrino mass models at the TeV scale, *naturally*

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Contents

- Introduction
- Ingredients for “natural” neutrino mass at TeV scale?
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- Summary

Effective field theories

BSM physics described by effective operators in the low-E limit (gauge invariant, SM **external** fields):

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Λ: Scale of new physics

$$\mathcal{L}_5 = LLHH$$

$$\mathcal{L}_6 = \bar{L}L\bar{L}L$$

$$\mathcal{L}_7 = (LLHH)(H^\dagger H)$$

$$\mathcal{L}_8 = (\bar{L}L\bar{L}L)(H^\dagger H)$$

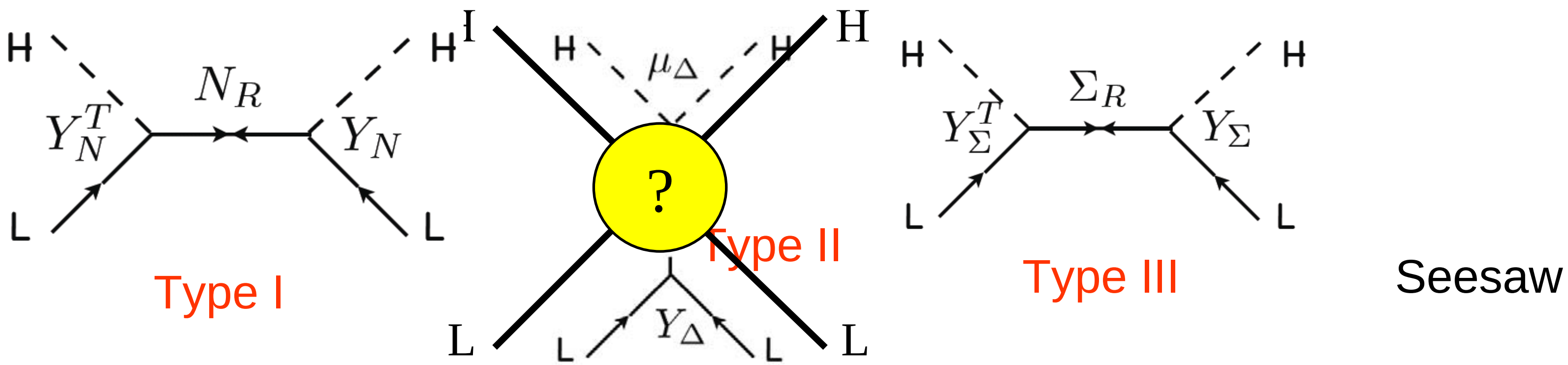
Neutrino mass (LNV) $0\nu\beta\beta$ decay!

Lepton flavor violation (LFV)

But these are no fundamental theories (non-renormalizable operators). Idea: Investigate fundamental theories (TeV completions) systematically! ⇨ **see also talk by R. Volkas**

See-saw mechanism

- Neutrino mass from d=5 (Weinberg) - Operator
- Fundamental theories at tree level:



- Neutrino mass ~ $Y^2\ v^2/\Lambda$ (type I, III see-saw)
- For Y = O(1), v ~ 100 GeV: Λ ~ GUT scale
- For Λ ~ TeV scale: Y << 10^{-5}
  - ➢ Interactions difficult to observe at LHC
  - ➢ Couplings “unnaturally“ small? Will not discuss these …

Neutrino masses at the TeV scale

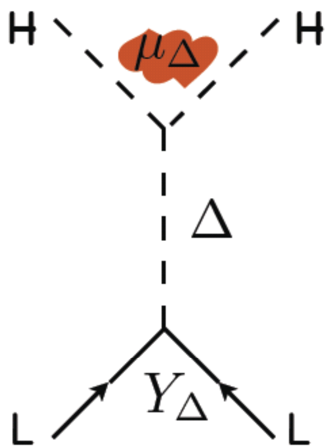
- **Goals:**
  - New physics scale “naturally“ at TeV scale (i.e., TeV scale not put in by hand)
    ⇨ Testable at the LHC?!
  - Yukawa couplings of order one
- Requires additional suppression mechanisms:
  1) Radiative generation of neutrino mass (**n** loops)
  2) Neutrino mass from higher than **d**=5 effective operator
  3) Small lepton number violating contribution ε (e.g. **inverse see-saw**, RPV SUSY models, …)

$$m_\nu \propto \frac{\langle H^0 \rangle^2}{\Lambda} \times \left(\frac{1}{16\pi^2}\right)^n \times \epsilon \times \left(\frac{\langle H^0 \rangle}{\Lambda}\right)^{d-5}$$

Example (suppression 3):

Type-II, inverse seesaw

Type II : natural

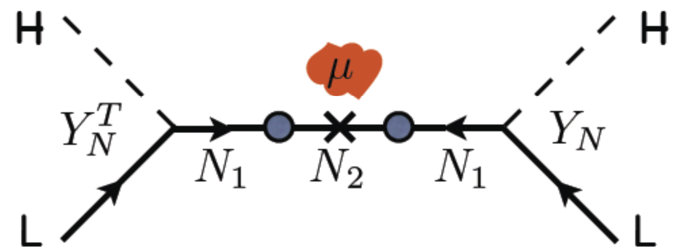


Inverse Seesaw

Type I/III : extra fermion

Mohapatra, Valle 1986

$$\begin{array}{c c} & \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{array}{c} \nu \\ N_1 \\ N_2 \end{array} & \begin{pmatrix} 0 & Y_N & 0 \\ Y_N^T & 0 & \Lambda \\ 0 & \Lambda & \mu \end{pmatrix} \end{array}$$



m_ν	$Y_\Delta \mu_\Delta \frac{v^2}{M_\Delta^2}$
LFV	$Y_\Delta^\dagger Y_\Delta$

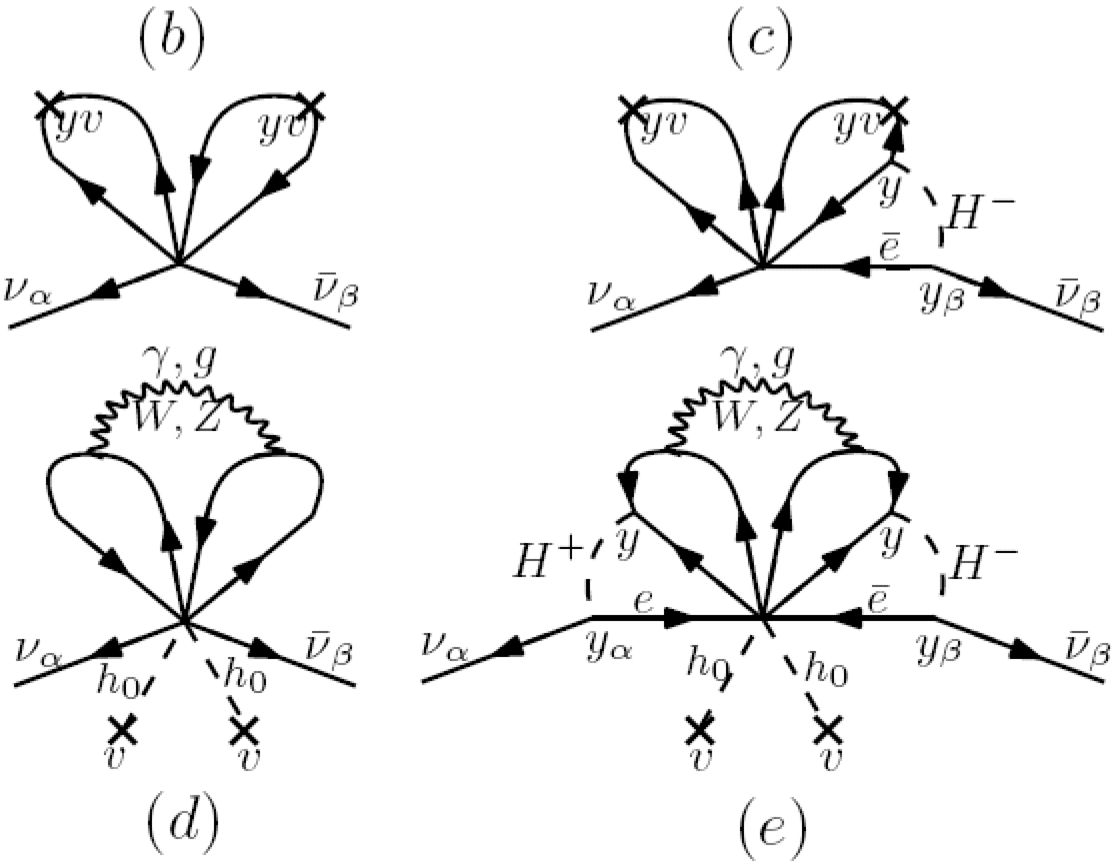
(Florian Bonnet @GGI Florence 2012)

m_ν	$-Y_N^T \frac{\mu}{\Lambda^2} Y_N v^2$
LFV	$Y_N^\dagger Y_N$

Radiative neutrino mass
(suppression 1)

- Reminder (yesterday):

  All of these generate neutrino mass by d=5 operator!



$$m_\nu \propto \frac{\langle H^0 \rangle^2}{\Lambda} \times \left(\frac{1}{16\pi^2} \right)^n$$

(at least, since the non-renormalizable vertex may be radiatively induced?)

from: de Gouvea, Jenkins, 2007

Loops versus dimension

Loop suppression, controlled by $1/(16\,\pi^2)$

Type I, II, II seesaw

Depends on mediators/int/sym.

2-loop

$$
\begin{aligned}
\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} &+ \frac{1}{\Lambda_{\mathrm{NP}}}\left[\mathscr{L}^{(0)}_{d=5} + \delta\mathscr{L}^{(1)}_{d=5} + \delta\mathscr{L}^{(2)}_{d=5} + \cdots\right] \\
&+ \frac{1}{\Lambda^3_{\mathrm{NP}}}\left[\mathscr{L}^{(0)}_{d=7} + \cdots\right] \\
&+ \frac{1}{\Lambda^5_{\mathrm{NP}}}\left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots\right] \\
&+ \frac{1}{\Lambda^7_{\mathrm{NP}}}\left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots\right] \\
&+ \cdots
\end{aligned}
$$

d=5

d=7

d=9

d=11

Discrete symmetry to forbid d=5?

Depends on scale: $\Lambda > 4\pi v \sim 3$ TeV?

Suppression by d, controlled by $1/\Lambda^2$

How can I make sure that no lower order operators are generated?

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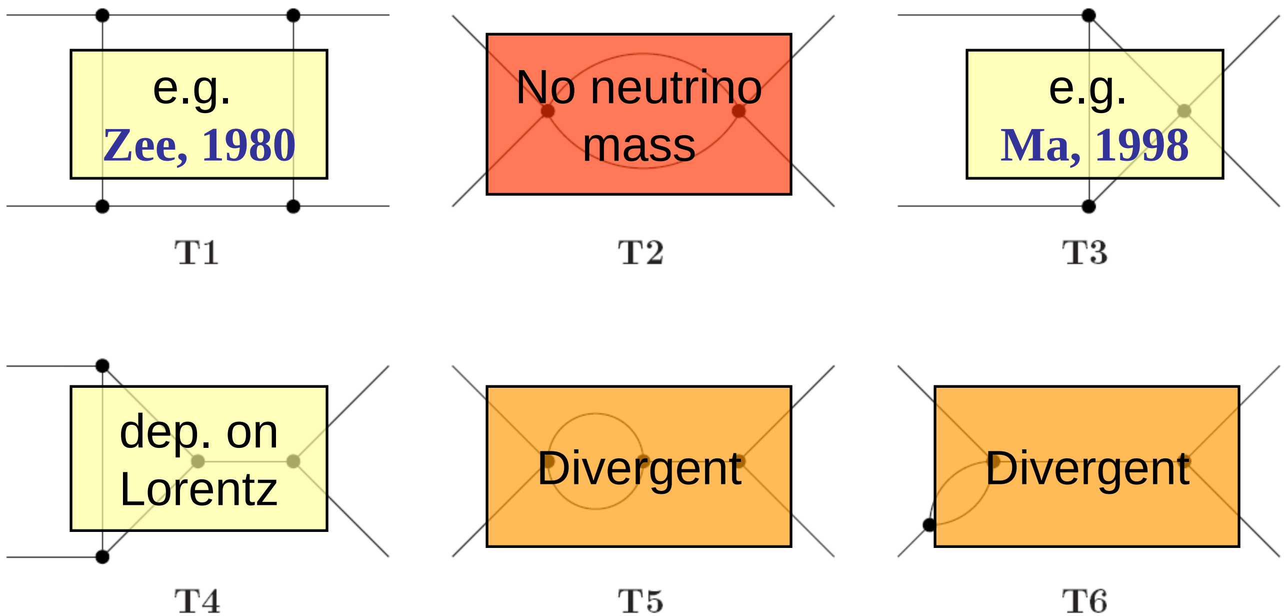
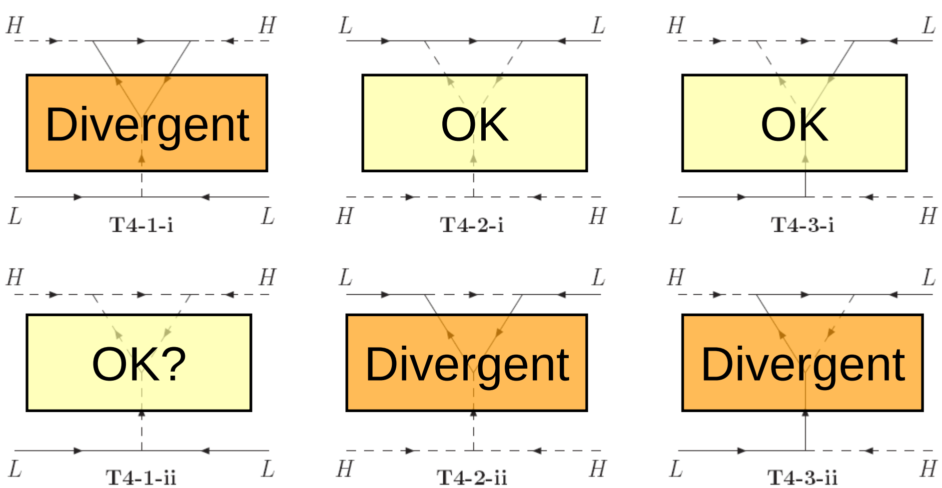
One-loop d=5,
systematic decomposition

$$\begin{aligned}\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} &+ \frac{1}{\Lambda_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=5} + \delta\mathscr{L}^{(1)}_{d=5} + \delta\mathscr{L}^{(2)}_{d=5} + \cdots\right]\\ &+ \frac{1}{\Lambda^3_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=7} + \delta\mathscr{L}^{(1)}_{d=7} + \delta\mathscr{L}^{(2)}_{d=7} + \cdots\right]\\ &+ \frac{1}{\Lambda^5_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots\right]\\ &+ \frac{1}{\Lambda^7_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots\right]\\ &+ \cdots\end{aligned}$$

Topologies from FeynArts:





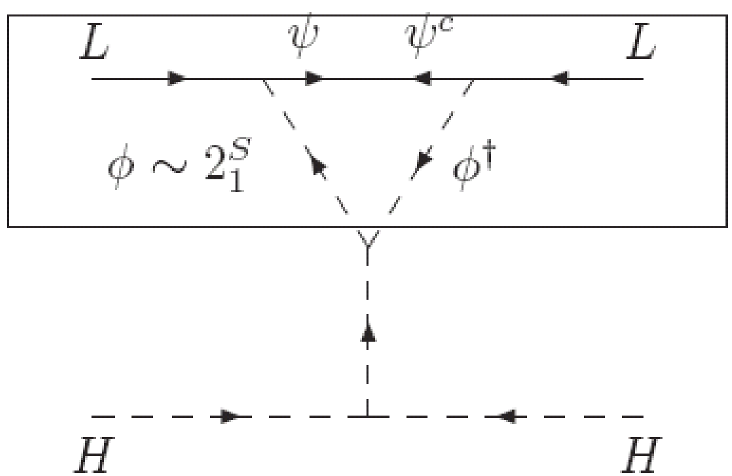
However: cannot avoid tree-level contribution by discrete symmetry

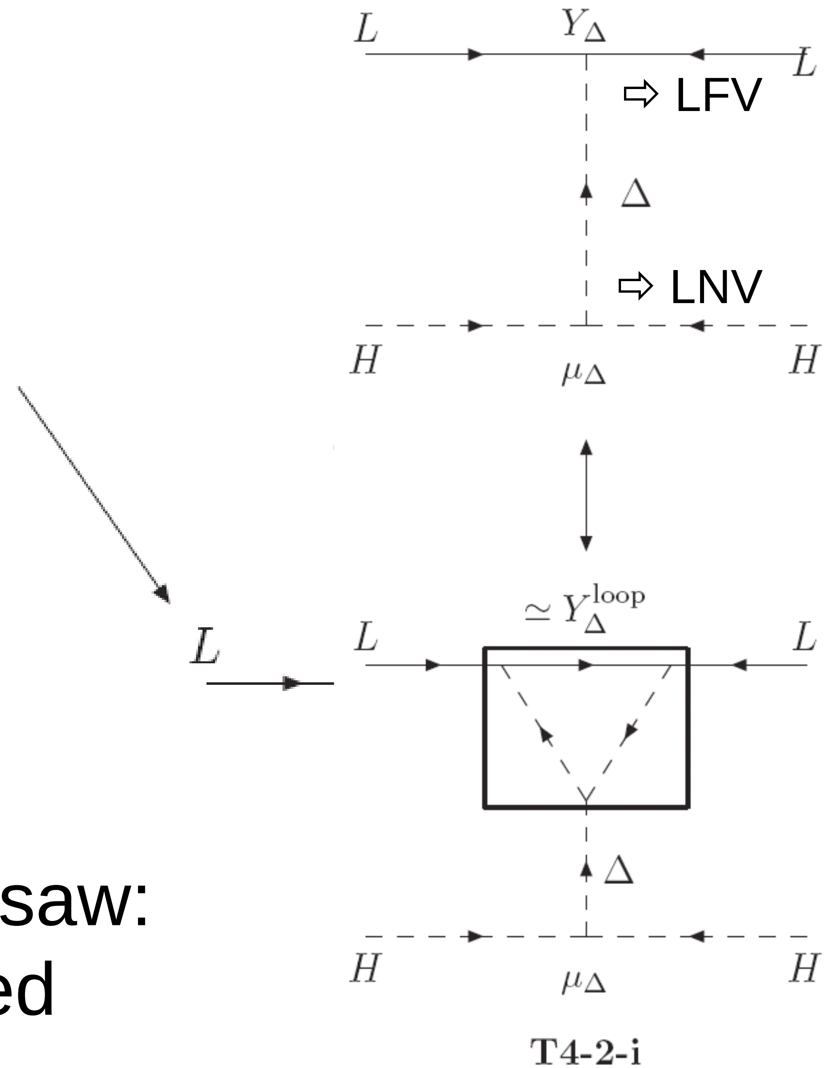
Solution: Majorana fermion in loop + lepton number conserving couplings

Bonnet, Hirsch, Ota, Winter, 2012

Example (1)

- Additional Z_2 to prevent scalar from taking VEV:

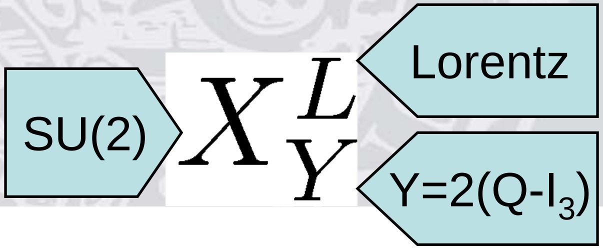




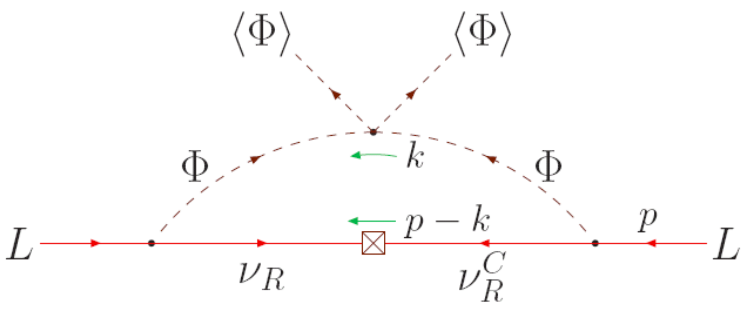
- Compare to type-II see-saw: LFV coupling suppressed by loop

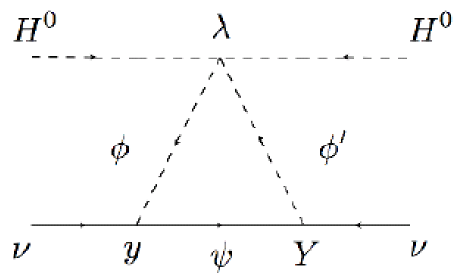
Bonnet, Hirsch, Ota, Winter, 2012

Example (2)



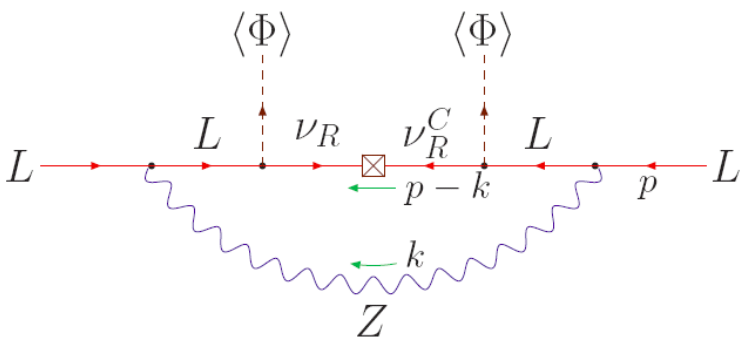
Dev, Pilaftsis, arXiv:1209.4051

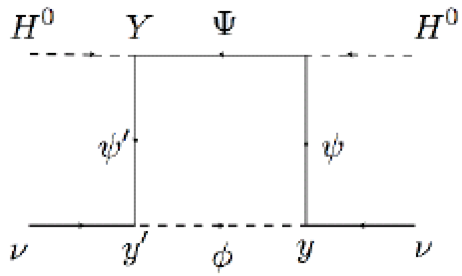




T3

ϕ'	ϕ	ψ
1^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$1^F_{1+\alpha}$
2^S_α	$2^S_{2+\alpha}$	$3^F_{1+\alpha}$
3^S_α	$1^S_{2+\alpha}$	$2^F_{1+\alpha}$
3^S_α	$3^S_{2+\alpha}$	$2^F_{1+\alpha}$





T1-3

(here: scalar;
we did not consider vectors
explicitely!)

Ψ	ψ'	ϕ	ψ
1^F_α	$2^F_{1+\alpha}$	1^S_α	$2^F_{\alpha-1}$
1^F_α	$2^F_{1+\alpha}$	3^S_α	$2^F_{\alpha-1}$
2^F_α	$1^F_{1+\alpha}$	2^S_α	$1^F_{\alpha-1}$
2^F_α	$1^F_{1+\alpha}$	2^S_α	$3^F_{\alpha-1}$
2^F_α	$3^F_{1+\alpha}$	2^S_α	$1^F_{\alpha-1}$
2^F_α	$3^F_{1+\alpha}$	2^S_α	$3^F_{\alpha-1}$
3^F_α	$2^F_{1+\alpha}$	1^S_α	$2^F_{\alpha-1}$
3^F_α	$2^F_{1+\alpha}$	3^S_α	$2^F_{\alpha-1}$

(α: integer)

Decompositions work (by construction)
for SM and new physics fields!

Bonnet, Hirsch, Ota, Winter, 2012

Neutrino mass from higher dimensional operators (suppression 2)

- Approach:
Use higher dimensional operators, e.g.

$$\begin{aligned} \mathcal{O}^5 &= \mathcal{O}_W = LLHH \\ \mathcal{O}^7 &= (LLHH)(H^\dagger H) \\ \mathcal{O}^9 &= (LLHH)(H^\dagger H)(H^\dagger H) \\ &\vdots \end{aligned}$$

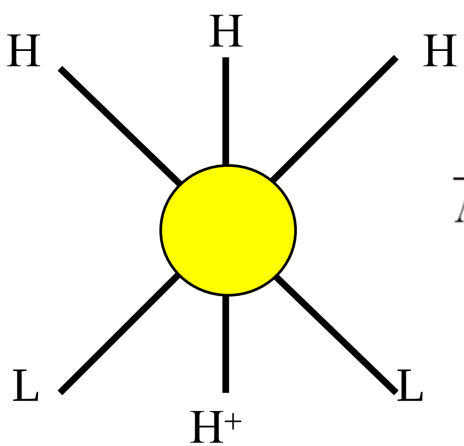
(Babu, Bonnet, Chen, Giudice, Godoladze, de Gouvea, Gu, Dobrescu, Hernandez, Kanemura, Langacker, Lebedev, Liao, Nandi, Ning, Okada, Ota, Picek, Radovcic, Ren, Sarkar, Shafi, Tavartkiladze, Winter, Zhang, …)

- Leads to

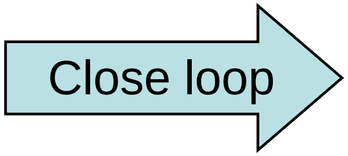
$$m_\nu \sim v \left(\frac{v}{\Lambda_{\mathrm{NP}}} \right)^{d-4}$$

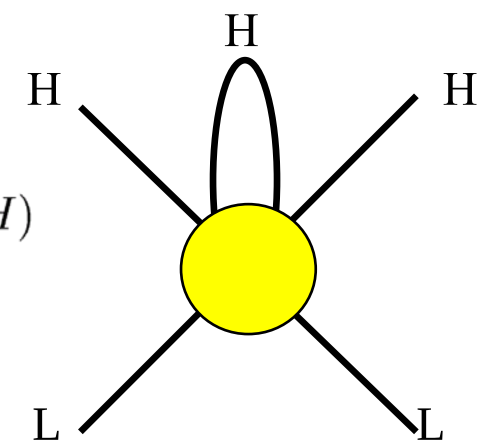
- Estimate: for Λ ~ 1 – 10 TeV and m_ν linear in Yukawas (worst case):
  - d = 9 sufficient if no other suppression mechanism
  - d = 7 sufficient if Yukawas ~ m_e/v ~ 10^{-6} allowed

The loop issue



$$\frac{1}{\Lambda_{\mathrm{NP}}^3}(LLHH)(H^\dagger H) \to \frac{1}{16\pi^2}\frac{1}{\Lambda_{\mathrm{NP}}}(LLHH)$$





d=7 operator

d=5 operator

- Loop d=5 contribution dominates for

  $$\frac{1}{\Lambda_{\mathrm{NP}}^3} < \frac{1}{16\pi^2}\frac{1}{\Lambda_{\mathrm{NP}}}$$ or Λ > 3 TeV

- Conclusion: If assumed that d=7 leading, one effectively has to assume Λ < 3 TeV by hand
  (see e.g. Babu, Nandi, Tavartkiladze, arXiv:0905.2710)

- How can one make this a feature of the theory?

Forbid lower dim. operators

- Define *genuine* d=D operator as leading contribution to neutrino mass with all operators d<D forbidden
- Use new U(1) or discrete symmetry ("matter parity")
- Problem: H^+H can never be charged under the new symmetry! ⇨ **Need new fields!**
- The simplest possibilities are probably

$$\mathscr{L}_{\mathrm{eff}}^{d=n+5} = \frac{1}{\Lambda_{\mathrm{NP}}^{d-4}} (LLHH)(S)^n \,, \quad n = 1, 2, 3, \ldots$$

(NMSSM: n=1,2 only)

(e.g. Chen, de Gouvea, Dobrescu, hep-ph/0612017; Godoladze, Okada, Shafi, arXiv:0809.0703; Krauss, Ota, Porod, Winter, arXiv:1109.4636)

$$\mathscr{L}_{\mathrm{eff}}^{d=2n+5} = \frac{1}{\Lambda_{\mathrm{NP}}^{d-4}} (LLH_uH_u)(H_dH_u)^n \,, \quad n = 1, 2, 3, \ldots$$

(e.g. Babu, Nandi, hep-ph/9907213; Giudice, Lebedev, arXiv:0804.1753; Bonnet, D. Hernandez, Bonnet, Winter, arXiv:0907.3143)

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Higher dim. operators in THDM

Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

	SUSY	Op.#	Effective interaction	Cond.#	Charge of effective int.
dim.5	✓	1	LLH_uH_u	1	$2q_L+2q_{H_u}$
		2	$LLH_d^*H_u$	2	$2q_L-q_{H_d}+q_{H_u}$
		3	$LLH_d^*H_d^*$	3	$2q_L-2q_{H_d}$
dim.7	✓	4	$LLH_uH_uH_dH_u$	4	$2q_L+q_{H_d}+3q_{H_u}$
		5	$LLH_uH_uH_d^*H_d$	1	$2q_L+2q_{H_u}$
		6	$LLH_uH_uH_u^*H_u$	1	$2q_L+2q_{H_u}$
		7	$LLH_d^*H_uH_d^*H_d$	2	$2q_L-q_{H_d}+q_{H_u}$
		8	$LLH_d^*H_uH_u^*H_u$	2	$2q_L-q_{H_d}+q_{H_u}$
		9	$LLH_d^*H_d^*H_d^*H_d$	3	$2q_L-2q_{H_d}$
		10	$LLH_d^*H_d^*H_u^*H_u$	3	$2q_L-2q_{H_d}$
		11	$LLH_d^*H_d^*H_u^*H_d^*$	5	$2q_L-3q_{H_d}-q_{H_u}$
dim.9	✓	12	$LLH_uH_uH_dH_uH_dH_u$	6	$2q_L+2q_{H_d}+4q_{H_u}$
		13	$LLH_uH_uH_dH_uH_d^*H_d$	4	$2q_L+q_{H_d}+3q_{H_u}$
		14	$LLH_uH_uH_dH_uH_u^*H_u$	4	$2q_L+q_{H_d}+3q_{H_u}$
		15	$LLH_uH_uH_d^*H_dH_d^*H_d$	1	$2q_L+2q_{H_u}$
		16	$LLH_uH_uH_d^*H_dH_u^*H_u$	1	$2q_L+2q_{H_u}$
		17	$LLH_uH_uH_u^*H_uH_u^*H_u$	1	$2q_L+2q_{H_u}$
		18	$LLH_d^*H_uH_d^*H_dH_d^*H_d$	2	$2q_L-q_{H_d}+q_{H_u}$
		19	$LLH_d^*H_uH_d^*H_dH_u^*H_u$	2	$2q_L-q_{H_d}+q_{H_u}$
		20	$LLH_d^*H_uH_u^*H_uH_u^*H_u$	2	$2q_L-q_{H_d}+q_{H_u}$
		21	$LLH_d^*H_d^*H_d^*H_dH_d^*H_d$	3	$2q_L-2q_{H_d}$
		22	$LLH_d^*H_d^*H_d^*H_dH_u^*H_u$	3	$2q_L-2q_{H_d}$
		23	$LLH_d^*H_d^*H_u^*H_uH_u^*H_u$	3	$2q_L-2q_{H_d}$
		24	$LLH_d^*H_d^*H_d^*H_u^*H_d^*H_d$	5	$2q_L-3q_{H_d}-q_{H_u}$
		25	$LLH_d^*H_d^*H_d^*H_u^*H_u^*H_u$	5	$2q_L-3q_{H_d}-q_{H_u}$
		26	$LLH_d^*H_d^*H_u^*H_d^*H_u^*H_d^*$	7	$2q_L-4q_{H_d}-2q_{H_u}$
dim.11			...		

SUSY:
only this one
(but: there can
be operators with
the scalar singlet
in the NMSSM)

Same for d=9

- Simplest possibility (d=7): Z_5 with e.g.

$$q_{H_u}=0\,,\ q_{H_d}=3\,,\ q_L=1\,,\ q_E=1$$

$$q_Q=0\,,\ q_U=0\,,\ q_D=2$$

(SUSY: Z_3)

Systematic study of d=7

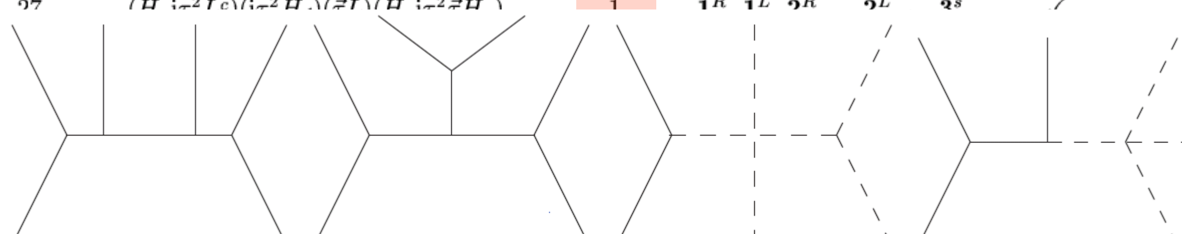
Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

- Systematically decompose d=7 operator in all possible ways (tree level)
- Notation for mediators:

SU(2) X^{L}_{Y} Lorentz

Y=Q-I_3

#	Operator	Top.	Mediators	Phenom. NU	Phenom. δg_L	Phenom. 4ℓ
1	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 H_u)$	2	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{1}_0^s$	✓		
2	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$ $\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{3}_0^s$	✓	✓	
3	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{1}_0^s$	✓	✓	
4	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(H_u \mathrm{i}\tau^2 \tau^b L)(H_d \mathrm{i}\tau^2 \tau^c H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_0^s$	✓	✓	
5	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	2/3	$\mathbf{3}_{-1}^s$, $\mathbf{3}_{-1}^s/\mathbf{1}_0^s$			✓
6	$(-\mathrm{i}\epsilon^{abc})(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_d \mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^c H_u)$	2/3	$\mathbf{3}_{-1}^s$, $\mathbf{3}_{-1}^s/\mathbf{3}_0^s$			✓
7	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L \mathrm{i}\tau^2 \vec{\tau} H_d)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	2	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_{-1}^s$	✓	✓	
8	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(L \mathrm{i}\tau^2 \tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^c H_u)$	2	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{3}_{-1}^s$	✓	✓	
9	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^s$	✓		
10	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\mathrm{i}\tau^2 \vec{\tau} H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^s$	✓	✓	
11	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(\vec{\tau} L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^s$	✓		
12	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\mathrm{i}\tau^2 \tau^a H_u)(\tau^b L)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^s$	✓	✓	
13	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{1}_0^s)$	✓		
14	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} L)(\mathrm{i}\tau^2 H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{1}_0^s)$	✓	✓	
15	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	1/4	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{3}_0^s)$	✓		
16	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a L)(\mathrm{i}\tau^2 \tau^b H_u)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^s$, $(\mathbf{3}_0^s)$	✓	✓	
17	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$	✓		
18	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{1}_0^R$, $\mathbf{1}_0^L$	✓	✓	
19	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} L)$	1	$\mathbf{1}_0^R$, $\mathbf{1}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$, $\mathbf{3}_0^R$, $\mathbf{3}_0^L$	✓	✓	
20	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(\mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b L)$	1	$\mathbf{3}_0^R$, $\mathbf{3}_0^L$, $\mathbf{2}_{-1/2}^R$, $\mathbf{2}_{-1/2}^L$,	✓	✓	
21	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_u \mathrm{i}\tau^2 \tau^a)(\tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_{-1}^s)$			✓
22	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_d \mathrm{i}\tau^2 \tau^a)(\tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+3/2}^s$, $(\mathbf{3}_{-1}^s)$			✓
23	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau})(H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{1}_0^s)$			✓
24	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_u \mathrm{i}\tau^2 \tau^a)(\tau^b H_u)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}_{-1}^s$, $\mathbf{2}_{+1/2}^s$, $(\mathbf{3}_0^s)$			✓
25	$(H_d \mathrm{i}\tau^2 H_u)(\overline{L^c} \mathrm{i}\tau^2)(\vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}_0^s$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_{-1}^s$			
26	$(H_d \mathrm{i}\tau^2 \tau^a H_u)(\overline{L^c} \mathrm{i}\tau^2 \tau^a)(\tau^b L)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}_0^s$, $\mathbf{2}_{+1/2}^L$, $\mathbf{2}_{+1/2}^R$, $\mathbf{3}_{-1}^s$			



Topology 1 Topology 2 Topology 3 Topology 4

Generalizations of see-saws

Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

- Generalizations of originial see-saws: Duplication of the original see-saws plus scalars
  - Type I (fermionic singlet)
  - Type II (scalar triplet)
  - Type III (fermionic triplet)

Characteristics: Similar phenomenology!

				Phenom.		
#	Operator	Top.	Mediators	NU	δg_L	4ℓ
1	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 H_u)$	2	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{1}^s_0$	✓		
2	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	2	$\mathbf{3}^R_0, \mathbf{3}^L_0\ \mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{3}^s_0$	✓	✓	
3	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)$	2	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{1}^s_0$	✓	✓	
4	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(H_u \mathrm{i}\tau^2 \tau^b L)(H_d \mathrm{i}\tau^2 \tau^c H_u)$	2	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{3}^s_0$	✓	✓	
5	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	2/3	$\mathbf{3}^s_{-1}, \mathbf{3}^s_{-1}/\mathbf{1}^s_0$			✓
6	$(-\mathrm{i}\epsilon^{abc})(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_d \mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^c H_u)$	2/3	$\mathbf{3}^s_{-1}, \mathbf{3}^s_{-1}/\mathbf{3}^s_0$			✓
7	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L \mathrm{i}\tau^2 \vec{\tau} H_d)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	2	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{3}^s_{-1}$	✓	✓	
8	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(L \mathrm{i}\tau^2 \tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^c H_u)$	2	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{3}^s_{-1}$	✓	✓	
9	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	1	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{1}^s_0$	✓		
10	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\mathrm{i}\tau^2 \vec{\tau} H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	1	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{1}^s_0$	✓	✓	
11	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(\vec{\tau} L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{3}^s_0$	✓		
12	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\mathrm{i}\tau^2 \tau^a H_u)(\tau^b L)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{3}^s_0$	✓	✓	
13	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^s_{-1/2}, (\mathbf{1}^s_0)$	✓		
14	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} L)(\mathrm{i}\tau^2 H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^s_{-1/2}, (\mathbf{1}^s_0)$	✓	✓	
15	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	1/4	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^s_{-1/2}, (\mathbf{3}^s_0)$	✓		
16	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a L)(\mathrm{i}\tau^2 \tau^b H_u)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^s_{-1/2}, (\mathbf{3}^s_0)$	✓	✓	
17	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	1	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}$	✓		
18	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	1	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{1}^R_0, \mathbf{1}^L_0$	✓	✓	
19	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} L)$	1	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2}, \mathbf{3}^R_0, \mathbf{3}^L_0$	✓	✓	
20	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(\mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b L)$	1	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^R_{-1/2}, \mathbf{2}^L_{-1/2},$	✓	✓	
21	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_u \mathrm{i}\tau^2 \tau^a)(\tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^s_{-1}, \mathbf{2}^s_{+1/2}, (\mathbf{3}^s_{-1})$			✓
22	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_d \mathrm{i}\tau^2 \tau^a)(\tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^s_{-1}, \mathbf{2}^s_{+3/2}, (\mathbf{3}^s_{-1})$			✓
23	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau})(H_u)(H_d \mathrm{i}\tau^2 H_u)$	1/4	$\mathbf{3}^s_{-1}, \mathbf{2}^s_{+1/2}, (\mathbf{1}^s_0)$			✓
24	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_u \mathrm{i}\tau^2 \tau^a)(\tau^b H_u)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^s_{-1}, \mathbf{2}^s_{+1/2}, (\mathbf{3}^s_0)$			✓
25	$(H_d \mathrm{i}\tau^2 H_u)(\overline{L^c} \mathrm{i}\tau^2)(\vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}^s_0, \mathbf{2}^L_{+1/2}, \mathbf{2}^R_{+1/2}, \mathbf{3}^s_{-1}$			
26	$(H_d \mathrm{i}\tau^2 \tau^a H_u)(\overline{L^c} \mathrm{i}\tau^2 \tau^a)(\tau^b L)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}^s_0, \mathbf{2}^L_{+1/2}, \mathbf{2}^R_{+1/2}, \mathbf{3}^s_{-1}$			
27	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_d)(\vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	1	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^R_{+1/2}, \mathbf{2}^L_{+1/2}, \mathbf{3}^s_{-1}$	✓		
28	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\mathrm{i}\tau^2 \tau^a H_d)(\tau^b L)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^R_{+1/2}, \mathbf{2}^L_{+1/2}, \mathbf{3}^s_{-1}$	✓	✓	
29	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 \vec{\tau} H_d)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	1/4	$\mathbf{1}^R_0, \mathbf{1}^L_0, \mathbf{2}^s_{+1/2}, (\mathbf{3}^s_{-1})$	✓		
30	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a L)(\mathrm{i}\tau^2 \tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^R_0, \mathbf{3}^L_0, \mathbf{2}^s_{+1/2}, (\mathbf{3}^s_{-1})$	✓	✓	
31	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a H_d)(\mathrm{i}\tau^2 \tau^a H_u)(\tau^b L)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1	$\mathbf{3}^L_{+1}, \mathbf{3}^R_{+1}, \mathbf{2}^L_{+1/2}, \mathbf{2}^R_{+1/2}, \mathbf{3}^s_{-1}$	✓	✓	
32	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a H_d)(\tau^a L)(\mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	1/4	$\mathbf{3}^L_{+1}, \mathbf{3}^R_{+1}, \mathbf{2}^s_{-3/2}, (\mathbf{3}^s_{-1})$	✓	✓	
33	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} H_d)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_u)(H_u \mathrm{i}\tau^2 L)$	1	$\mathbf{3}^L_{+1}, \mathbf{3}^R_{+1}, \mathbf{2}^L_{-3/2}, \mathbf{2}^R_{-3/2}, \mathbf{1}^L_0, \mathbf{1}^R_0$	✓	✓	
34	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a H_d)(\mathrm{i}\tau^2 \tau^a H_u)(\tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b L)$	1	$\mathbf{3}^L_{+1}, \mathbf{3}^R_{+1}, \mathbf{2}^L_{-3/2}, \mathbf{2}^R_{-3/2}, \mathbf{3}^L_0, \mathbf{3}^R_0$	✓	✓	

A SUSY example

Krauss, Ota, Porod, Winter, Phys. Rev. D84 (2011) 115023

- Neutral fermion mass matrix after EWSB in basis

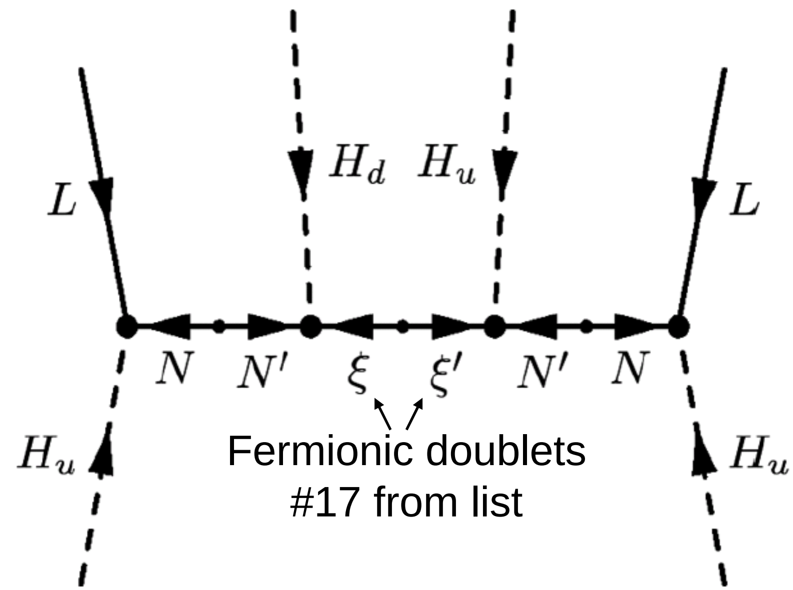
$$f^0 = (\nu, N, N', \xi^0, \xi'^0)$$

Flavor struct. by 3 2 2 1 1 Mass states: n_i

$$M_f^0 = \begin{pmatrix} 0 & Y_N v_u & 0 & 0 & 0 \\ Y_N^T v_u & 0 & m_N^T & 0 & 0 \\ 0 & m_N & 0 & \kappa_1 v_d & \kappa_2 v_u \\ 0 & 0 & \kappa_1^T v_d & 0 & -m_\xi \\ 0 & 0 & \kappa_2^T v_u & -m_\xi & 0 \end{pmatrix}$$

$$(\nu,\ N,\ N')$$

$$M_f^{0\prime} = \begin{pmatrix} 0 & Y_N v_u & 0 \\ Y_N v_u & 0 & m_N \\ 0 & m_N & \hat{\mu} \end{pmatrix}$$

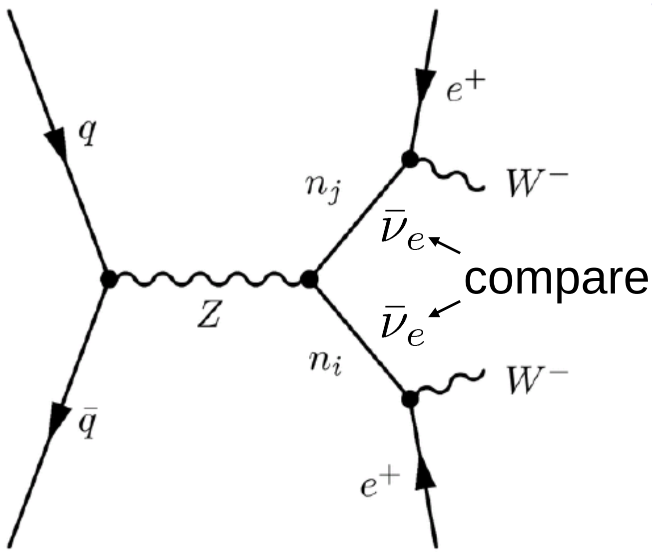


Compare to “inverse see-saw“ (suppression mechanism 3) if heavy doublets integrated out

$$\hat{\mu} \propto \frac{v_u v_d}{m_\xi} \sim \frac{1}{\Lambda_{\mathrm{NP}}}$$

Test at the LHC? (example)

Krauss, Ota, Porod, Winter, Phys. Rev. D84 (2011) 115023



Process	σ [fb] (7 TeV)	σ [fb] (14 TeV)
$pp \to W^+e^-W^-e^+$	$(3.447 \pm 0.87) \cdot 10^{-1}$	(1.277 ± 0.66)
$pp \to W^+e^-W^-\mu^+$	$(7.06 \pm 0.15) \cdot 10^{-3}$	$(3.141 \pm 0.027) \cdot 10^{-2}$
$pp \to W^+e^+W^-\mu^-$	$(6.99 \pm 0.16) \cdot 10^{-3}$	$(3.206 \pm 0.027) \cdot 10^{-2}$
$pp \to W^+e^-W^-\tau^+$	$(1.037 \pm 0.020) \cdot 10^{-2}$	$(4.293 \pm 0.036) \cdot 10^{-2}$
$pp \to W^+e^+W^-\tau^-$	$(1.015 \pm 0.021) \cdot 10^{-2}$	$(4.411 \pm 0.036) \cdot 10^{-2}$
$pp \to W^+\mu^-W^-\mu^+$	$(3.74 \pm 0.10) \cdot 10^{-1}$	(1.279 ± 0.017)
$pp \to W^+\mu^-W^-\tau^+$	$(2.913 \pm 0.048) \cdot 10^{-3}$	$(1.096 \pm 0.007) \cdot 10^{-1}$
$pp \to W^+\mu^+W^-\tau^-$	$(2.990 \pm 0.042) \cdot 10^{-2}$	$(1.139 \pm 0.007) \cdot 10^{-1}$
$pp \to W^+\tau^-W^-\tau^+$	$(4.27 \pm 0.10) \cdot 10^{-1}$	(1.606 ± 0.017)
$pp \to W^+e^-W^+e^-$	$(1.112 \pm 0.013) \cdot 10^{-4}$	$(4.261 \pm 0.028) \cdot 10^{-4}$
$pp \to W^+e^-W^+\mu^-$	$(1.537 \pm 0.023) \cdot 10^{-3}$	$(5.810 \pm 0.050) \cdot 10^{-3}$
$pp \to W^+e^-W^+\tau^-$	$(4.721 \pm 0.055) \cdot 10^{-3}$	$(1.761 \pm 0.016) \cdot 10^{-2}$
$pp \to W^+\mu^-W^+\mu^-$	$(4.099 \pm 0.052) \cdot 10^{-3}$	$(1.514 \pm 0.013) \cdot 10^{-2}$
$pp \to W^+\mu^-W^+\tau^-$	$(2.704 \pm 0.036) \cdot 10^{-2}$	$(1.062 \pm 0.093) \cdot 10^{-1}$
$pp \to W^+\tau^-W^+\tau^-$	$(4.614 \pm 0.065) \cdot 10^{-2}$	$(1.729 \pm 0.016) \cdot 10^{-1}$

- Test mediators
- Test LFV
- Test LNV

Works also in SU(5) GUT: **Krauss, Meloni, Porod, Winter, in prep.**

Even higher suppression?

Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

Loop suppression, controlled by $1/(16\,\pi^2)$

Tree | 1-loop | 2-loop

$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM}$ + Switched off by discrete symmetry — d=5

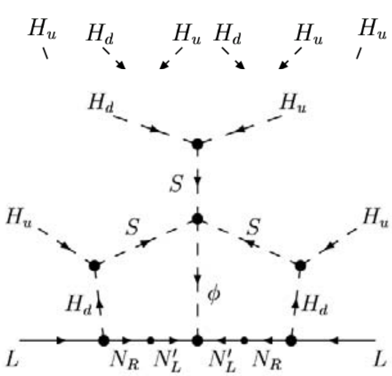
+ $\frac{1}{\Lambda^3_{\rm NP}}[\ldots]$ — d=7

+ $\frac{1}{\Lambda^5_{\rm NP}}[\ldots]$ — d=9

+ $\frac{1}{\Lambda^7_{\rm NP}}[\ldots + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots]$ — d=11

+ $\cdots$

Construction principles for higher loops:
Babu, Leung, 2001;
de Gouvea, Jenkins, 2008;
Angel, Volkas, 2012;
Farzan, Pascoli, Schmidt, 2012; …



Suppression by d, controlled by $1/\Lambda^2$

Example 1: d=9 at tree level

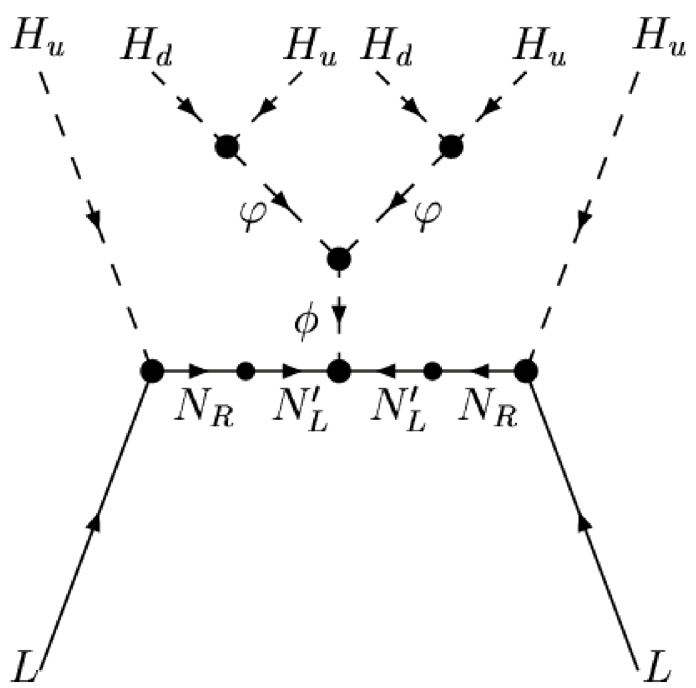
Physics at TeV scale with O(1) couplings

Example 2: d=7 at two loop ⇨ **Suppression mechanisms 1), 2), and 3)**

Example 1: d=9 tree level

$$\mathscr{L} = \frac{1}{2}\left(\overline{\nu^c_{L\alpha}} \quad \overline{N_{Ra}} \quad (\overline{N'^c_L})_c\right)\begin{pmatrix} 0 & (Y_\nu^\top)_{\alpha b}\langle H_u^0\rangle & 0 \\ (Y_\nu)_{a\beta}\langle H_u^0\rangle & 0 & M_{ad} \\ 0 & (M^\top)_{cb} & (\Lambda^{-3})_{cd}\langle H_d^0 H_u^0\rangle^2 \end{pmatrix}\begin{pmatrix} \nu_{L\beta} \\ (N_R^c)_b \\ N'_{Ld} \end{pmatrix} + \text{H.c.}$$

$$\boxed{(\Lambda^{-3})_{ab} = 2\kappa_{ab}\frac{\mu^2\omega}{M_\phi^2 M_\varphi^4} \sim \mathcal{O}\left(\frac{1}{\Lambda_{\text{NP}}^3}\right)}$$



- Inverse see-saw-like, with even higher suppression of LNV term
- Requires Z_7 symmetry

Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

Example 2: two-loop d=7

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \Big[(Y_N)_{a\alpha}(\overline{N_R})_a H_d^\dagger L_\alpha + (\alpha_1)_{ab}\phi(\overline{N_R^c})_a(N_R)_b + (\alpha_2)_{ab}\phi(\overline{N_L'^c})_a(N_L')_a$$
$$+ \mu S^* H_d \mathrm{i}\tau^2 H_u + (\overline{N_R})_a M_{ab}(N_L')_b + \mathrm{H.c.}\Big] - \mathscr{V}(H_u,\, H_d,\, \phi,\, S)\,.$$

Without scalar potential: Respects $U(1)_Y$, $U(1)_L$, and a new U(1); no ν mass

$$\mathscr{V}(H_u,\, H_d,\, \phi,\, S) = \left[\lambda_1 S\phi^3 + \mu_1 S^*\phi^2 + \lambda_2 S^3\phi^* + \mathrm{H.c.}\right] + M_S^2 S^* S + M_\phi^2 \phi^*\phi + \cdots$$

Violates all cont. symmetries except from $U(1)_Y$, while respecting Z_5
If S is integrated out: Term ~ ϕ^5 (respects Z_5, violates U(1))

- Neutrino masses emerge from “breaking of the new symmetry“
- Charges (Z_5)

$$q_{H_u} = 0\,, \quad q_{H_d} = 1\,, \quad q_L = 2, \quad q_{N_R} = q_{N_L'} = 1\,, \quad q_\phi = 3\,, \quad q_S = 1$$

Neutrino mass in example 2

- Neutral fermion fields (integrate out scalars):

$$\mathscr{L} = \frac{1}{2}\left(\overline{\nu^c_{L\alpha}} \quad \overline{N_{Ra}} \quad (\overline{N'^c_L})_c\right) \begin{pmatrix} m^{(\text{2-loop})}_{\nu\alpha\beta} & (Y_N^\mathsf{T})_{\alpha b}\langle H_d^{0*}\rangle & (\epsilon Y'_\nu)^{(\text{1-loop})\mathsf{T}}_{\alpha d} \\ (Y_N)_{a\beta}\langle H_d^{0*}\rangle & \mu'^{(\text{tree})}_{ab} & M_{ad} \\ (\epsilon Y'_\nu)^{(\text{1-loop})}_{c\beta} & (M^\mathsf{T})_{cb} & \mu^{(\text{tree})}_{cd} \end{pmatrix} \begin{pmatrix} \nu_{L\beta} \\ (N_R^c)_b \\ N'_{Ld} \end{pmatrix} + \text{H.c.}$$

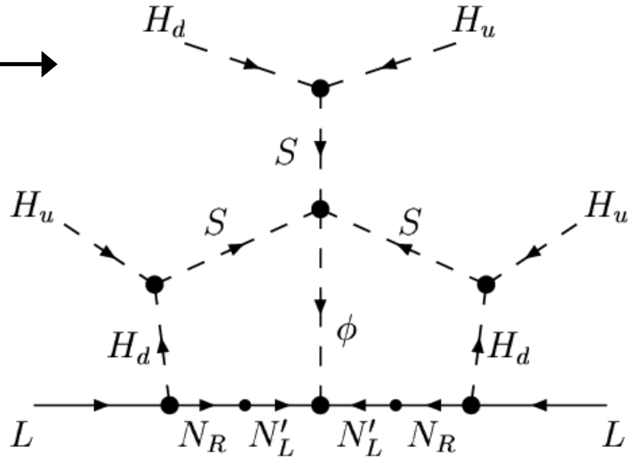
Contributions to neutrino mass:

$$m^{(\text{2-loop})}_{\nu\alpha\beta} \sim \frac{1}{(16\pi^2)^2}\frac{v_d v_u^3}{\Lambda_{\text{NP}}}\lambda_2[Y_N^\mathsf{T}(M^\mathsf{T})^{-1}\alpha_2 M^{-1}Y_N]_{\alpha\beta},$$

$$(\epsilon Y'_\nu)^{(\text{1-loop})}_{c\beta} \sim \frac{1}{16\pi^2}\frac{v_d^2 v_u^3}{\Lambda^3_{\text{NP}}}\lambda_2[\alpha_2 M^{-1}Y_N]_{c\beta},$$

$$\mu^{(\text{tree})}_{cd} \sim \frac{v_d^3 v_u^3}{\Lambda^5_{\text{NP}}}\lambda_2(\alpha_2)_{cd},$$

$$\mu'^{(\text{tree})}_{ab} \sim \frac{v_d^3 v_u^3}{\Lambda^5_{\text{NP}}}\lambda_2^*(\alpha_1^*)_{ab}.$$



Leading contribution for Λ > 3 TeV

Bonnet, D. Hernandez, Ota, Winter, JHEP 10 (2009) 076

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Features of example 2

- Incorporates all three suppression mechanisms:
  - Radiative generation of neutrino mass
  - Small lepton number violating contribution (optional: LNV couplings can be chosen small)
  - Neutrino mass from higher than d=5 effective operator (d=5 forbidden)
- Neutrino mass related to breaking of new U(1) to discrete symmetry
- TeV scale naturally coming out, with **large** Yukawa couplings possible

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Summary

- “Natural“ TeV see-saw requires additional suppression mechanisms :
  - Radiative generation of neutrino mass (n)
  - Higher dimensional operator (d)
  - Small LNV parameter (ε)

$$m_\nu \propto \frac{\langle H^0 \rangle^2}{\Lambda} \times \left(\frac{1}{16\pi^2} \right)^n \times \epsilon \times \left(\frac{\langle H^0 \rangle}{\Lambda} \right)^{d-5}$$

- Decompositions of higher dimensional operators often lead to inverse/linear seesaws
- Mediators typically testable at the LHC: “hierarchy“ LFC – LFV – LNV likely