Neutrino Mass from d>5 Effective Operators in a SUSY GUT framework

in collaboration with D. Meloni, W. Winter and W. Porod
PLANCK 2013

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May 22, 2013

Motivation and Outline

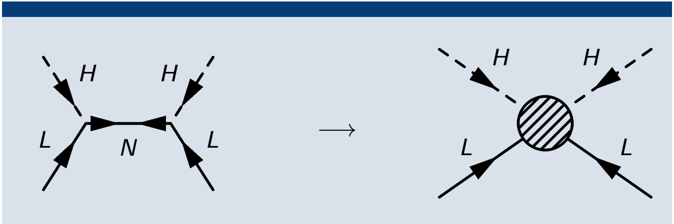
Which scales are relevant for neutrino physics?

- Light neutrino masses $\lesssim$ eV
- Default mechanism: (type I) seesaw $\rightarrow$ new physics at $\sim$ GUT scale
- Recently discussed: Neutrino mass generation at TeV scale
  (radiative mass generation, inverse seesaw, higher-dimensional operators)

- Systematic study of neutrino mass generation
  by higher-dimensional effective operators
- New physics at the TeV scale and
  phenomenological implications at the LHC
- Embedding in SUSY GUT model
  and consequences for phenomenology

From new physics close to the GUT scale. . .

- The usual type I seesaw introduces new physics close to the GUT scale.

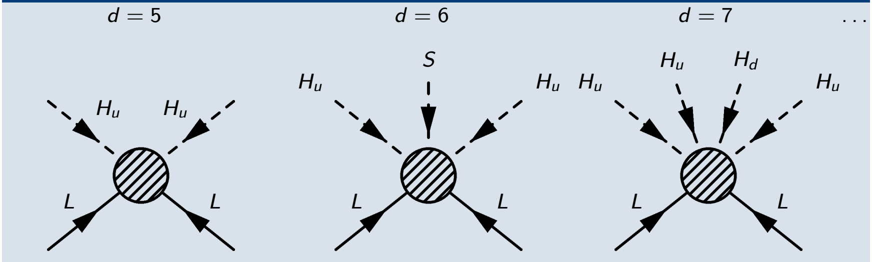


- At low energies the new physics effects can be described by the **Weinberg operator** $\mathcal{O}_W = (\overline{L^c} \mathrm{i}\tau^2 H)\,(H \mathrm{i}\tau^2 L)$ of $d = 5$.
- Generates neutrino mass $m_\nu^{\mathrm{eff}} \propto \frac{v^2}{\Lambda}$, with $\Lambda = m_N$

Not testable in experiments!

. . . down to the TeV scale

In theories with additional scalars (THDM, MSSM, NMSSM, . . .)
$\rightarrow$ *Operators with $d > 5$ can have significant contribution to neutrino mass*



$\frac{1}{\Lambda}\langle H_u\rangle^2$ $\quad$ $\frac{1}{\Lambda^2}\langle H_u\rangle^2\langle S\rangle$ $\quad$ $\frac{1}{\Lambda^3}\langle H_u\rangle^2\langle H_u\rangle\langle H_d\rangle$

- Theories with discrete symmetries $\rightarrow$ operator can be forbidden at $d = 5$
- Operator with $d > 5$ as leading contribution to neutrino mass
- New physics scale can be at **lower energy**

Possible Effective Operators in the NMSSM

$$W_{\text{NMSSM}} = y_u u^c Q H_u + y_d d^c Q H d + y_e e^c L H_d + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

	Op.#	Effective interaction	Charge	Same as
$d=5$	1	LLH_uH_u	$2q_L + 2q_{H_u}$	
$d=6$	2	LLH_uH_uS	$2q_L + q_{H_u} - q_{H_d}$	
$d=7$	3	$LLH_uH_uH_dH_u$	$2q_L + 3q_{H_u} + q_{H_d}$	
	4	LLH_uH_uSS	$2q_L - 2q_{H_d}$	
$d=8$	5	$LLH_uH_uH_dH_uS$	$2q_L + 2q_{H_u}$	#1
	6	LLH_uH_uSSS	$2q_L + 2q_{H_u}$	#1
$d=9$	7	$LLH_uH_uH_dH_uH_dH_u$	$2q_L + 4q_{H_u} + 2q_{H_d}$	
	8	$LLH_uH_uH_dH_uSS$	$2q_L + q_{H_u} - q_{H_d}$	#2
	9	LLH_uH_uSSSS	$2q_L + q_{H_u} - q_{H_d}$	#2

Characteristics

- Condition for discrete charges of fields from neutrality of superpotential
- Rules out some operators as leading contribution to neutrino mass
- Several possible fundamental theories can lead to the same effective operator

MBK, Ota, Porod, Winter (2011); *PRD 84, 115023*

(c.f. Bonnet, Hernandez, Ota, Winter (2009); *JHEP 0910, 076* for a study in the THDM)

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	4	LLH_uH_uSS	$2q_L - 2q_{H_d}$	
$d = 8$	5	$LLH_uH_uH_dH_uS$	$2q_L + 2q_{H_u}$	#1
	6	LLH_uH_uSSS	$2q_L + 2q_{H_u}$	#1
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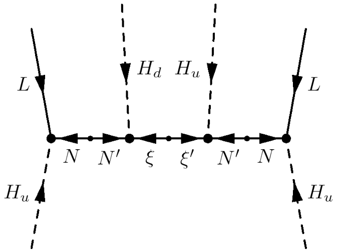
A $d = 7$ Example

Superpotential

$$W = W_{\mathrm{(N)MSSM}} + Y_N \hat{N}\hat{L}\cdot\hat{H}_u - \kappa_1 \hat{N}'\hat{\xi}\cdot\hat{H}_d + \kappa_2 \hat{N}'\hat{\xi}'\cdot\hat{H}_u + m_N \hat{N}\hat{N}' + m_\xi \hat{\xi}\cdot\hat{\xi}'$$



New fields:
SM singlets N, N', $\mathrm{SU}(2)_L$ doublets ξ, ξ'

Neutral fermion mass matrix:

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

$$M_n = \begin{pmatrix} 0 & Y_N v_u & 0 & 0 & 0 \\ Y_N v_u & 0 & m_N & 0 & 0 \\ 0 & m_N & 0 & \kappa_1 v_d & \kappa_2 v_u \\ 0 & 0 & \kappa_1 v_d & 0 & m_\xi \\ 0 & 0 & \kappa_2 v_u & m_\xi & 0 \end{pmatrix}.$$

Integrating out the heavy fields

$m_\xi > m_N$ ↙

$m_N > m_\xi$ ↘

Inverse see-saw

$n_0' = (\nu, N, N')$

$$M_n{}' = \begin{pmatrix} 0 & Y_N\, v_u & 0 \\ Y_N\, v_u & 0 & m_N \\ 0 & m_N & \hat{\mu} \end{pmatrix}$$

with $\hat{\mu} = v_u v_d\,(2\kappa_1\kappa_2)/m_\xi$.

Linear see-saw

$n_0'' = (\nu, \xi^0, \xi'^0)$

$$M_n{}'' = \begin{pmatrix} 0 & \tilde{\kappa}_1\, v_d & \tilde{\kappa}_2\, v_u \\ \tilde{\kappa}_1\, v_d & 0 & m_\xi \\ \tilde{\kappa}_2\, v_u & m_\xi & 0 \end{pmatrix} ,$$

where $\tilde{\kappa}_{1/2} = \kappa_{1/2}\, Y_N^2/m_N$.

↘ ↙

$$m_\nu = v_u^3 v_d Y_N^2 \frac{\kappa_1\kappa_2}{m_\xi m_N^2}$$

Masses at TeV scale for couplings $\mathcal{O}(10^{-3})$

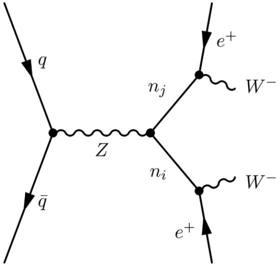
LHC Phenomenology

Production of the new particles

- Rare production of $\hat{N}$ and $\hat{N}'$ due to small Yukawa couplings
- $SU(2)_L$ doublets can be produced in Drell-Yan processes ($\sigma \sim 10^2$ fb)

Characteristic Signals

- Displaced vertices due to small mixing between heavy and light neutrinos
- Lepton number violating processes
  - LNC cross-section for $pp \to W\ell\ell$ of $\mathcal{O}(10^2)$ fb
    LNV processes suppressed due to pseudo-Dirac pairs ($< \mathcal{O}(10^{-9})$ fb)
  - For $pp \to W\ell W\ell$ LNV processes larger than naively expected ($\mathcal{O}(10^{-2})$ fb)



MBK, Ota, Porod, Winter (2011); *PRD 84, 115023*

GUT Completion

- Additional particles modify running of the gauge couplings
- Spoils unification
- Add complete SU(5) multiplets to avoid this
  - Singlets: N, N', (S)
  - 5-plets:

$$\bar{5}_M = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad \bar{5}_{\xi'} = \begin{pmatrix} d_1'^c \\ d_2'^c \\ d_3'^c \\ \xi'^- \\ -\xi'^0 \end{pmatrix}_L \qquad 5_\xi = \begin{pmatrix} d_1'' \\ d_2'' \\ d_3'' \\ \xi^+ \\ -\xi^0 \end{pmatrix}_R$$

$$H_5 = \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_{\bar{5}} = \begin{pmatrix} H_1' \\ H_2' \\ H_3' \\ H_d^- \\ H_d^0 \end{pmatrix}$$

  - matter 10-plet

MBK, Meloni, Porod, Winter (2013); *JHEP*; arXiv:1301.4221

Heavy d-Quarks

$$\begin{pmatrix} d_1'^c \\ d_2'^c \\ d_3'^c \\ \xi'^- \\ -\xi'^0 \end{pmatrix}_L$$

Interactions of d'

- Colored components of mediator 5-plets
- Behave like heavy d-quarks
- RGE running leads to mass shift between quarks and lepton doublet
- Decay of d' protected by symmetry that forbids $d = 5$ operator

Cosmological constraints:

- From Big Bang Nucleosynthesis: Heavy nuclei
  $\rightarrow$ altering BBN processes $\rightarrow$ affecting observed abundances of light elements
  e.g. Iocco *et. al.* (2009); *Phys.Rept. 472*
- Search for heavy hadrons in water excludes stable heavy d-like quarks
  Nardi, Roulet (1990); *Phys. Lett. B 245, 105*
- d' decay via the symmetry breaking operator $\overline{5}_\xi H_{\overline{5}} 10$

$$\overline{d}' \rightarrow H_u^+ \overline{u}$$

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MSSM scenario

If charged under a discrete symmetry,

Multiplet	$\bar{5}_M$	H_5	$H_{\bar{5}}$	N	N'	5_ξ	$\bar{5}_{\xi'}$	10
$\mathbb{Z}_3$ charge	1	1	1	1	2	0	0	1

the superpotential reduces to

$$\begin{aligned} W \quad = \quad & y_3\, N\, \bar{5}_M\, H_5 + y_1',\, N'\, 5_\xi\, H_{\bar{5}} + y_2'\, N'\, \bar{5}_{\xi'}\, H_5 + m_\xi\, \bar{5}_{\xi'}\, 5_\xi + m_N N' N \\ & y_d\, \bar{5}_M\, 10\, H_{\bar{5}} + y_u\, 10\, 10\, H_5 - \mu H_{\bar{5}} H_5\,. \end{aligned}$$

- The term $\mu H_u H_d$ explicitly breaks the discrete symmetry (Otherwise every operator of the type $LLH_uH_u(H_uH_d)^n$ has same charge as Weinberg operator)
- μ-problem of the MSSM (μ has to be set to 100 GeV to few TeV by hand)
- Same issue with TeV mediator masses

Possible Alternative:
Use the NMSSM where μ and the mediator masses are generated by VEV of an additional scalar field S.

NMSSM scenario

- Superpotential constrains charges in a way that we always will have a $d = 5$ contribution.
- We introduce an additional scalar S' and obtain the superpotential

$$W = \quad y_3\, N\, \overline{5}_M\, H_5 + y_1',\, N'\, 5_\xi\, H_{\overline{5}} + y_2'\, N'\, \overline{5}_{\xi'}\, H_5 + \lambda_\xi\, S'\, \overline{5}_{\xi'}\, 5_\xi + \lambda_N S'\, N' N$$
$$+\, y_d\, \overline{5}_M\, 10\, H_{\overline{5}} + y_u\, 10\, 10\, H_5 + \lambda_S S H_{\overline{5}} H_5 + \kappa S^3 + \lambda_S' S' H_{\overline{5}} H_5 + \kappa' S'^3\,.$$

- The term λ_S' breaks the discrete symmetry.
- Symmetry breaking term $y_3'\, N'\, \overline{5}_M\, H_5 \to d = 5$ contribution to m_ν
- $m_\nu^{d=5} < m_\nu^{d=7} \to$ symmetry breaking couplings $< 10^{-8}$

Symmetry breaking as source for non-zero θ_{13}?

- Experimental observation of $\theta_{13} \neq 0$
- Models with tri-bimaximal mixing in trouble
- In our model: Breaking of discrete symmetry $\rightarrow$ corrections to TBM mixing

$$
\begin{aligned}
m_\nu &= m_\nu^{d=7} + m_\nu^{d=5} \\
&= M_{\mathrm{TB}} + \frac{v_u^2}{\langle S \rangle}\left(y_3 (y_3')^T + y_3' (y_3)^T\right)
\end{aligned}
$$

Possible structure of the coupling:

$$
y_3' \propto \left[\begin{pmatrix} 0 & 0 & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{2\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & -\frac{1}{2\sqrt{3}} & 0 \end{pmatrix} \sqrt{\frac{m_3}{m_2}} - \begin{pmatrix} 0 & 0 & \frac{1}{3\sqrt{2}} \\ 0 & \frac{1}{2\sqrt{3}} & \frac{1}{3\sqrt{2}} \\ 0 & \frac{1}{2\sqrt{3}} & \frac{1}{3\sqrt{2}} \end{pmatrix} \right]
$$

Decompositions

#	Operator	Mediators	SU(5) multiplets
1	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 H_u)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{1}_0^s$	$\mathbf{1}, \mathbf{1}, \mathbf{1}$
2	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L\ \mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{3}_0^s$	$\mathbf{24}, \mathbf{24}, (\mathbf{1}), (\mathbf{1}), \mathbf{24}$
3	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(H_u \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{1}_0^s$	$\mathbf{24}, \mathbf{24}, \mathbf{1}$
4	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(H_u \mathrm{i}\tau^2 \tau^b L)(H_d \mathrm{i}\tau^2 \tau^c H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{3}_0^s$	$\mathbf{24}, \mathbf{24}, \mathbf{24}$
5	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_d \mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	$\mathbf{3}_{+1}^s,\ \mathbf{3}_{+1}^s,\ \mathbf{1}_0^s$	$\mathbf{15}, \mathbf{15}, \mathbf{1}$
6	$(-\mathrm{i}\epsilon_{abc})(\overline{L^c} \mathrm{i}\tau^2 \tau_a L)(H_d \mathrm{i}\tau^2 \tau_b H_u)(H_u \mathrm{i}\tau^2 \tau_c H_u)$	$\mathbf{3}_{+1}^s,\ \mathbf{3}_{+1}^s,\ \mathbf{3}_0^s$	$\mathbf{15}, \mathbf{15}, \mathbf{24}$
7	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L \mathrm{i}\tau^2 \vec{\tau} H_d)(H_u \mathrm{i}\tau^2 \vec{\tau} H_u)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{3}_{-1}^R,\ \mathbf{3}_{-1}^L,\ \mathbf{3}_{+1}^s$	$\mathbf{1}, \mathbf{1}, \mathbf{15}, \overline{\mathbf{15}}, \mathbf{15}$
8	$(-\mathrm{i}\epsilon^{abc})(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(L \mathrm{i}\tau^2 \tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^c H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{3}_{-1}^R,\ \mathbf{3}_{-1}^L,\ \mathbf{3}_{+1}^s$	$\mathbf{24}, \mathbf{24}, \mathbf{15}, \overline{\mathbf{15}}, \mathbf{15}$
9	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,\ \mathbf{1}_0^s$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{1}$
10	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\mathrm{i}\tau^2 \vec{\tau} H_u)(L)(H_d \mathrm{i}\tau^2 H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,\ \mathbf{1}_0^s$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{1}$
11	$(H_u \mathrm{i}\tau^2 \overline{L^c})(\mathrm{i}\tau^2 H_u)(\vec{\tau} L)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,\ \mathbf{3}_0^s$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{24}$
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14	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} L)(\mathrm{i}\tau^2 H_u)(H_d \mathrm{i}\tau^2 H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{2}_{+1/2}^s,\ \mathbf{1}_0^s$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \mathbf{1}$
15	$(H_u \mathrm{i}\tau^2 \overline{L^c})(L)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_d \mathrm{i}\tau^2 \vec{\tau} H_u)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{2}_{+1/2}^s,\ \mathbf{3}_0^s$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \mathbf{24}$
16	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a L)(\mathrm{i}\tau^2 \tau^b H_u)(H_d \mathrm{i}\tau^2 \tau^b H_u)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{2}_{+1/2}^s,\ \mathbf{3}_0^s$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \mathbf{24}$
17	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}$
18	$(H_u \mathrm{i}\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} H_d)(\mathrm{i}\tau^2 H_u)(H_u \mathrm{i}\tau^2 L)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,\ \mathbf{1}_0^R,\ \mathbf{1}_0^L$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}, (\mathbf{1}), (\mathbf{1})$
19	$(H_u \mathrm{i}\tau^2 \overline{L^c})(H_d)(\mathrm{i}\tau^2 \vec{\tau} H_u)(H_u \mathrm{i}\tau^2 \vec{\tau} L)$	$\mathbf{1}_0^R,\ \mathbf{1}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,\ \mathbf{3}_0^R,\ \mathbf{3}_0^L$	$(\mathbf{1}), (\mathbf{1}), \mathbf{5}, \overline{\mathbf{5}}, \mathbf{24}, \mathbf{24}$
20	$(H_u \mathrm{i}\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(\mathrm{i}\tau^2 \tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b L)$	$\mathbf{3}_0^R,\ \mathbf{3}_0^L,\ \mathbf{2}_{-1/2}^R,\ \mathbf{2}_{-1/2}^L,$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}$
21	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_u \mathrm{i}\tau^2 \tau^a)(\tau^b H_d)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	$\mathbf{3}_{+1}^s,\ \mathbf{2}_{+1/2}^s\ ,\ \mathbf{3}_{+1}^s$	$\mathbf{15}, \mathbf{5}, \mathbf{15}$
22	$(\overline{L^c} \mathrm{i}\tau^2 \tau^a L)(H_d \mathrm{i}\tau^2 \tau^a)(\tau^b H_u)(H_u \mathrm{i}\tau^2 \tau^b H_u)$	$\mathbf{3}_{+1}^s,\ \mathbf{2}_{+3/2}^s,\ \mathbf{3}_{+1}^s$	$\mathbf{15}, \mathbf{40}, \mathbf{15}$
23	$(\overline{L^c} \mathrm{i}\tau^2 \vec{\tau} L)(H_u \mathrm{i}\tau^2 \vec{\tau})(H_u)(H_u \mathrm{i}\tau^2 H_u)$	$\mathbf{3}^s,\ \mathbf{2}^s,\ \mathbf{1}^s$	$\mathbf{15}, \mathbf{5}, \mathbf{1}$

Decompositions

#	Operator	Mediators	SU(5) multiplets
1	$(H_u i\tau^2 \overline{L^c})(H_u i\tau^2 L)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{1}^s_0$	**1, 1, 1**
2	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(H_u i\tau^2 L)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$ $\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{3}^s_0$	**24, 24, (1), (1), 24**
3	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(H_u i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{1}^s_0$	**24, 24, 1**
4	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(H_u i\tau^2 \tau^b L)(H_d i\tau^2 \tau^c H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{3}^s_0$	**24, 24, 24**
5	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)(H_u i\tau^2 \vec{\tau} H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{3}^s_{+1}$, $\mathbf{1}^s_0$	**15, 15, 1**
6	$(-i\epsilon_{abc})(\overline{L^c} i\tau^2 \tau_a L)(H_d i\tau^2 \tau_b H_u)(H_u i\tau^2 \tau_c H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{3}^s_{+1}$, $\mathbf{3}^s_0$	**15, 15, 24**
7	$(H_u i\tau^2 \overline{L^c})(L i\tau^2 \vec{\tau} H_d)(H_u i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{3}^R_{-1}$, $\mathbf{3}^L_{-1}$, $\mathbf{3}^s_{+1}$	**1, 1, 15, $\overline{\mathbf{15}}$, 15**
8	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(L i\tau^2 \tau^b H_d)(H_u i\tau^2 \tau^c H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{3}^R_{-1}$, $\mathbf{3}^L_{-1}$, $\mathbf{3}^s_{+1}$	**24, 24, 15, $\overline{\mathbf{15}}$, 15**
9	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(L)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^s_0$	**1, 1, 5, $\overline{\mathbf{5}}$, 1**
10	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(i\tau^2 \vec{\tau} H_u)(L)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^s_0$	**24, 24, 5, $\overline{\mathbf{5}}$, 1**
11	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(\vec{\tau} L)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^s_0$	**1, 1, 5, $\overline{\mathbf{5}}$, 24**
12	$(H_u i\tau^2 \tau^a \overline{L^c})(i\tau^2 \tau^a H_u)(\tau^b L)(H_d i\tau^2 \tau^b H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^s_0$	**24, 24, 5, $\overline{\mathbf{5}}$, 24**
13	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{1}^s_0$	**1, 1, 5, 1**
14	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{1}^s_0$	**24, 24, 5, 1**
15	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 \vec{\tau} H_u)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_0$	**1, 1, 5, 24**
16	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a L)(i\tau^2 \tau^b H_u)(H_d i\tau^2 \tau^b H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_0$	**24, 24, 5, 24**
17	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$	**1, 1, 5, $\overline{\mathbf{5}}$**
18	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^R_0$, $\mathbf{1}^L_0$	**24, 24, 5, $\overline{\mathbf{5}}$, (1), (1)**
19	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 \vec{\tau} H_u)(H_u i\tau^2 \vec{\tau} L)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^R_0$, $\mathbf{3}^L_0$	**(1), (1), 5, $\overline{\mathbf{5}}$, 24, 24**
20	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(i\tau^2 \tau^b H_u)(H_u i\tau^2 \tau^b L)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$,	**24, 24, 5, $\overline{\mathbf{5}}$**
21	$(\overline{L^c} i\tau^2 \tau^a L)(H_u i\tau^2 \tau^a)(\tau^b H_d)(H_u i\tau^2 \tau^b H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_{+1}$	**15, 5, 15**
22	$(\overline{L^c} i\tau^2 \tau^a L)(H_d i\tau^2 \tau^a)(\tau^b H_u)(H_u i\tau^2 \tau^b H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{2}^s_{+3/2}$, $\mathbf{3}^s_{+1}$	**15, 40, 15**
23	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_u i\tau^2 \vec{\tau})(H_u)(H_u i\tau^2 H_u)$	$\mathbf{3}^s$, $\mathbf{2}^s$, $\mathbf{1}^s$	**15, 5, 1**

Decompositions

#	Operator	Mediators	SU(5) multiplets
1	$(H_u i\tau^2 \overline{L^c})(H_u i\tau^2 L)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{1}^s_0$	$\mathbf{1}, \mathbf{1}, \mathbf{1}$
2	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(H_u i\tau^2 L)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$ $\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{3}^s_0$	$\mathbf{24}, \mathbf{24}, (\mathbf{1}), (\mathbf{1}), \mathbf{24}$
3	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(H_u i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{1}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{1}$
4	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(H_u i\tau^2 \tau^b L)(H_d i\tau^2 \tau^c H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{3}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{24}$
5	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_d i\tau^2 H_u)(H_u i\tau^2 \vec{\tau} H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{3}^s_{+1}$, $\mathbf{1}^s_0$	$\mathbf{15}, \mathbf{15}, \mathbf{1}$
6	$(-i\epsilon_{abc})(\overline{L^c} i\tau^2 \tau_a L)(H_d i\tau^2 \tau_b H_u)(H_u i\tau^2 \tau_c H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{3}^s_{+1}$, $\mathbf{3}^s_0$	$\mathbf{15}, \mathbf{15}, \mathbf{24}$
7	$(H_u i\tau^2 \overline{L^c})(L i\tau^2 \vec{\tau} H_d)(H_u i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{3}^R_{-1}$, $\mathbf{3}^L_{-1}$, $\mathbf{3}^s_{+1}$	$\mathbf{1}, \mathbf{1}, \mathbf{15}, \overline{\mathbf{15}}, \mathbf{15}$
8	$(-i\epsilon^{abc})(H_u i\tau^2 \tau^a \overline{L^c})(L i\tau^2 \tau^b H_d)(H_u i\tau^2 \tau^c H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{3}^R_{-1}$, $\mathbf{3}^L_{-1}$, $\mathbf{3}^s_{+1}$	$\mathbf{24}, \mathbf{24}, \mathbf{15}, \overline{\mathbf{15}}, \mathbf{15}$
9	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(L)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^s_0$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{1}$
10	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(i\tau^2 \vec{\tau} H_u)(L)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{1}$
11	$(H_u i\tau^2 \overline{L^c})(i\tau^2 H_u)(\vec{\tau} L)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^s_0$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{24}$
12	$(H_u i\tau^2 \tau^a \overline{L^c})(i\tau^2 \tau^a H_u)(\tau^b L)(H_d i\tau^2 \tau^b H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}, \mathbf{24}$
13	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{1}^s_0$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \mathbf{1}$
14	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} L)(i\tau^2 H_u)(H_d i\tau^2 H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{1}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \mathbf{1}$
15	$(H_u i\tau^2 \overline{L^c})(L)(i\tau^2 \vec{\tau} H_u)(H_d i\tau^2 \vec{\tau} H_u)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_0$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \mathbf{24}$
16	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a L)(i\tau^2 \tau^b H_u)(H_d i\tau^2 \tau^b H_u)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_0$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \mathbf{24}$
17	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$	$\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{5}}$
18	$(H_u i\tau^2 \vec{\tau}\overline{L^c})(\vec{\tau} H_d)(i\tau^2 H_u)(H_u i\tau^2 L)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{1}^R_0$, $\mathbf{1}^L_0$	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}, (\mathbf{1}), (\mathbf{1})$
19	$(H_u i\tau^2 \overline{L^c})(H_d)(i\tau^2 \vec{\tau} H_u)(H_u i\tau^2 \vec{\tau} L)$	$\mathbf{1}^R_0$, $\mathbf{1}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$, $\mathbf{3}^R_0$, $\mathbf{3}^L_0$	$(\mathbf{1}), (\mathbf{1}), \mathbf{5}, \overline{\mathbf{5}}, \mathbf{24}, \mathbf{24}$
20	$(H_u i\tau^2 \tau^a \overline{L^c})(\tau^a H_d)(i\tau^2 \tau^b H_u)(H_u i\tau^2 \tau^b L)$	$\mathbf{3}^R_0$, $\mathbf{3}^L_0$, $\mathbf{2}^R_{-1/2}$, $\mathbf{2}^L_{-1/2}$,	$\mathbf{24}, \mathbf{24}, \mathbf{5}, \overline{\mathbf{5}}$
21	$(\overline{L^c} i\tau^2 \tau^a L)(H_u i\tau^2 \tau^a)(\tau^b H_d)(H_u i\tau^2 \tau^b H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{2}^s_{+1/2}$, $\mathbf{3}^s_{+1}$	$\mathbf{15}, \mathbf{5}, \mathbf{15}$
22	$(\overline{L^c} i\tau^2 \tau^a L)(H_d i\tau^2 \tau^a)(\tau^b H_u)(H_u i\tau^2 \tau^b H_u)$	$\mathbf{3}^s_{+1}$, $\mathbf{2}^s_{+3/2}$, $\mathbf{3}^s_{+1}$	$\mathbf{15}, \mathbf{40}, \mathbf{15}$
23	$(\overline{L^c} i\tau^2 \vec{\tau} L)(H_u i\tau^2 \vec{\tau})(H_u)(H_u i\tau^2 H_u)$	$\mathbf{3}^s$, $\mathbf{2}^s$, $\mathbf{1}^s$	$\mathbf{15}, \mathbf{5}, \mathbf{1}$
24	[illegible]	[illegible]	[illegible]

Summary

- Possible to use effective operators with $d > 5$ to generate neutrino masses
- New physics at TeV scale, phenomenological implications at LHC
- Full SU(5) multiplets necessary to not spoil unification
- Additional d-quarks $\rightarrow$ consider cosmological constraints, decay via symmetry breaking operator
- NMSSM realization with broken symmetry