Neutrino Mass from Higher-Dimensional Effective Operators in GUTs

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June 30, 2012

New Physics at the TeV Scale

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

$\rightarrow$ **not observable in experiments**

Generating neutrino mass @TeV

- Radiative generation of neutrino mass.
  (Suppression via loop integrals)
- Small lepton number violating contribution.
  (Inverse seesaw, SUSY with RpV, ...)
- No contribution from $d = 5$ operator, neutrino mass generated by higher dimensional operator

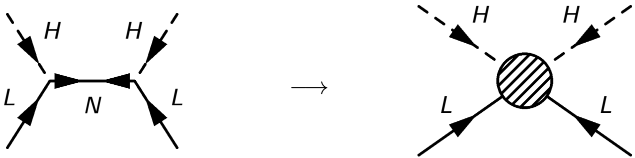
Effective Operators

BSM physics can be parameterized as **tower of effective operators**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}}^{d=5} + \mathcal{L}_{\mathrm{eff}}^{d=6} + \cdots , \quad \text{with} \quad \mathcal{L}_{\mathrm{eff}}^{d} \propto \frac{1}{\Lambda_{\mathrm{NP}}^{d-4}} \mathcal{O}^{d}$$

suppressed by powers of the new physics scale $\Lambda_{\mathrm{NP}}^{d-4}$

Seesaw mechanism: **Weinberg operator** $\mathcal{O}_W = (\overline{L^c} \mathrm{i}\tau^2 H)(H \mathrm{i}\tau^2 L)$ at $d = 5$.

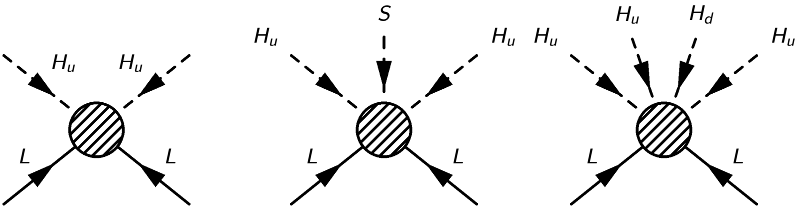


After EWSB $\frac{{Y_N}^2}{m_N} \langle H \rangle^2 \bar{\nu}^c \nu \rightarrow$ generates neutrino mass $m_\nu^{\mathrm{eff}} \propto \frac{v^2}{\Lambda}$, with $\Lambda = m_N$

Higher-Dimensional Effective Operators

Possible in theories with additional scalars (THDM, MSSM, NMSSM, . . .)

$d = 5$ $d = 6$ $d = 7$ . . .



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

- Neutrino mass is generated by **higher dimensional operators**
- New physics scale can be at **lower energy**
- Lower dimensional operators must be forbidden

Possible Effective Operators in the NMSSM

	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

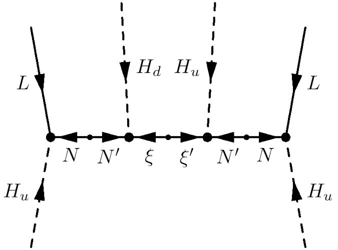
- Condition for discrete charges of fields from neutrality of superpotential
- Rules out some operators as leading contribution to neutrino mass
- Several possible fundamental theories can lead to the same effective operator at low energies

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

A $d = 7$ Example

Superpotential

$$W = W_{\text{NMSSM}} + Y_N \hat{N}\hat{L}\cdot\hat{H}_u - \kappa_1 \hat{N}'\hat{\xi}\cdot\hat{H}_d + \kappa_2 \hat{N}'\hat{\xi}'\cdot\hat{H}_u + m_N \hat{N}\hat{N}' + m_\xi \hat{\xi}\cdot\hat{\xi}'$$



New fields:

- SM singlets N, N'
- $SU(2)_L$ doublets ξ, ξ'

Mass Matrix

- In the basis $f^0 = (\nu, N, N', \xi^0, \xi'^0)$ we obtain the mass matrix

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

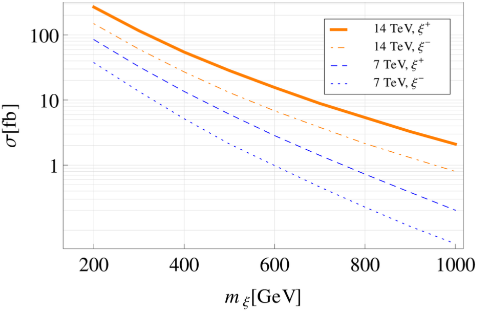
- By **integrating out** the heavy fields we obtain an **effective mass matrix** for the three SM neutrinos at **low energies**

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

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

Phenomenology

- Can the new particles be produced?
  - 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) (similarly to charginos and neutralinos)

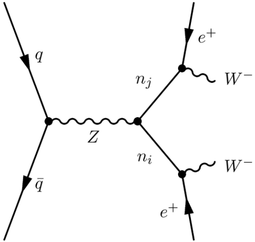


Phenomenology II

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)

(Numerical analysis with WHIZARD)



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

GUT Completion (work in progress...)

- Additional particles modify running of the gauge couplings
- Spoils unification
- Add complete SU(5) multiplets to avoid this

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

$$H_5 = \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} H_{\text{col}} \\ H_u \end{pmatrix} \qquad H_{\bar{5}} = \begin{pmatrix} H_1' \\ H_2' \\ H_3' \\ H_d^- \\ H_d^0 \end{pmatrix} = \begin{pmatrix} H_{\text{col}}' \\ H_d \end{pmatrix} \qquad N, N'(S) \ \text{fermionic singlets}$$

MSSM vs. NMSSM

Extension of MSSM

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

Extension of NMSSM

$$
\begin{aligned}
W \quad = \quad & y_1\, N\, 5_\xi\, H_{\bar{5}} + y_2\, N\, \bar{5}_{\xi'}\, H_5 + y_3\, N\, \bar{5}_M\, H_5 + \\
& y_1', N'\, 5_\xi\, H_{\bar{5}} + y_2'\, N'\, \bar{5}_{\xi'}\, H_5 + y_3'\, N'\, \bar{5}_M\, H_5 + \\
& \lambda_{\xi'}\, S\, \bar{5}_M\, 5_\xi + \lambda_\xi\, S\, \bar{5}_{\xi'}\, 5_\xi + \lambda_N S\, N' N + \lambda_{NN} S\, NN + \lambda_{N'N'} S\, N' N' + \\
& y_d\, \bar{5}_M\, 10\, H_{\bar{5}} + y_d'\, \bar{5}_{\xi'}\, 10\, H_{\bar{5}} + y_u\, 10\, 10\, H_5\, .
\end{aligned}
$$

GUT Extensions of the NMSSM

LLH_uH_u must have different charge than $(LLH_uH_u)(H_uH_d)$

MSSM

- The term μH_uH_d in the superpotential breaks the symmetry explicitly
- Mass terms set to TeV scale by hand

NMSSM

- μ-term replaced by λSH_uH_d
- Masses generated by the VEV of S

BUT if all masses generated by $\langle S\rangle$ the effective operators become

$$\frac{1}{\langle S\rangle}LLH_uH_u \qquad \frac{1}{\langle S\rangle^3}(LLH_uH_d)(H_uH_d)$$

$\Rightarrow \langle S\rangle$ breaks discrete symmetry

Heavy d-Quarks

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

Interactions of d'

- **From F-terms:**
  The only scalar term for the superpartners of the additional d-like quarks is their mass term $\mathbf{m}_\xi^2 \widetilde{\mathbf{d}}'^\dagger \widetilde{\mathbf{d}}''$.
- **From D-terms:**
  Kinetic terms for the 5-plets in SU(5) GUT is

$$\mathcal{L}_{\text{kin}}^{[5]} = \overline{\Psi}^{[5]} \not{D} \Psi^{[5]}$$

We obtain:

$$\begin{aligned} \bar{5}_\xi \not{D} 5_\xi = {} & \bar{d}' \not{\partial} d' + \bar{\xi}' \not{\partial} \xi \\ & - i g_5 \left(\bar{d}' \sum_{a=1}^{9} G_\mu^a \tilde{\lambda}_a d' + \bar{d}' B_\mu \tilde{\lambda}_{24} d' + \bar{\xi}' \sum_{a=21}^{23} A^a \tilde{\lambda}_a \xi' + \bar{\xi}' B_\mu \tilde{\lambda}_{24} \xi' + \text{lq. int.} \right) \end{aligned}$$

Heavy d-Quarks

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

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We obtain:

$$\bar{5}_\xi \not{D} 5_\xi = \bar{d}' \not{\partial} d' + \bar{\xi}' \not{\partial} \xi$$
$$- i g_5 \left(\bar{d}' \sum_{a=1}^{9} G_\mu^a \tilde{\lambda}_a d' + \bar{d}' B_\mu \tilde{\lambda}_{24} d' + \bar{\xi}' \sum_{a=21}^{23} A^a \tilde{\lambda}_a \xi' + \bar{\xi}' B_\mu \tilde{\lambda}_{24} \xi' + \text{lq. int.} \right)$$

Cosmological constraints

Stable d' bound in heavy nuclei $\rightarrow$ **Conflicts with Cosmological constraints!**

From Big Bang Nucleosynthesis

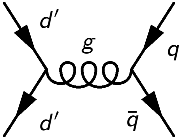
- Neutral hadrons
  - Pion production alters p-n equilibrium
  - heavy nucleon-nucleon scattering produces cascades of light nuclei altering abundances (^2H,^3H,^3He)
- Charged hadrons
  - Catalyzed nucleosynthesis
  - Changes properties of nuclear processes $\rightarrow$ alters abundances of light elements

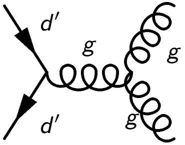
e.g. Iocco *et. al.* (2009); *Phys.Rept. 472*

From other heavy element searches

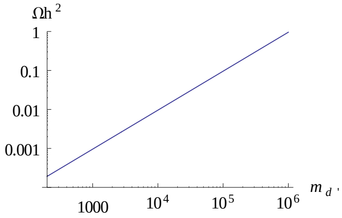
- Search for heavy hadrons in water
- Stability of neutron stars

Annihilation of d'





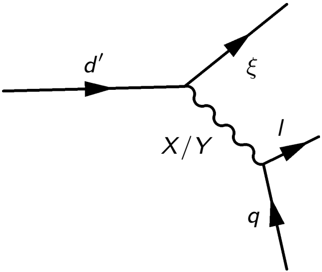
- d' in thermal equilibrium until freeze-out
- Freeze out point depends on $\langle \sigma v \rangle$
- Expected relic density far above experimental bounds
- Additional effects due to confinement, but still not in accordance with bounds



Nardi, Roulet (1990); *Phys. Lett. B 245, 105*

Leptoquarks

- d' can decay via leptoquarks into ξ components, which are unstable
- Decay width $\propto (100\,\text{GeV})^5/M_{\text{GUT}}^4$ larger than for proton decay ($\propto (1\,\text{GeV})^5/M_{\text{GUT}}^4$)
- Lifetime must be small enough to fit cosmological constraints
- Further contributions from decays via colored Higgses



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 in conflict with cosmological constraints
- NMSSM realization not possible with discrete symmetry

Open Issues

- d' decay via leptpoquarks
- Systematic study of GUT decompositions of the $d = 7$ operator

Backup-Slides

Decompositions

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

Possible Terms

- Terms from $\overline{\mathbf{5}} \otimes \mathbf{5} (\otimes \mathbf{1})$

$$N \left(5_\xi \, H_{\bar{5}} + \bar{5}_{\xi'} \, H_5 + \bar{5}_M \, H_5\right) + (N \leftrightarrow N')$$
$$m_{\xi'} \, \bar{5}_M \, 5_\xi$$
$$m_\xi \, \bar{5}_{\xi'} \, 5_\xi$$

- Terms from $\overline{\mathbf{5}} \otimes \mathbf{10} \otimes \overline{\mathbf{5}}$

$$\bar{5}_M \, 10 \, H_{\bar{5}}$$
$$\bar{5}_{\xi'} \, 10 \, H_{\bar{5}}$$

- Terms from $\mathbf{10} \otimes \mathbf{10} \otimes \mathbf{5}$
  The usual one which generates up-quark masses $(5 = H_5)$.