Neutrino masses from higher than $d = 5$ effective operators

Toshihiko Ota

F. Bonnet D. Hernandez T.O. W. Winter
JHEP **0910** (2009) 076

S. Kanemura T.O.
arXiv:1009.3845 [accepted by Phys. Letter B]

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
München

Overview

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH$$

Seesaw

Minkowski PL**B67** (1977) 421,
Yanagida (1979),
Gell-Mann Ramond Slansky (1979),
Mohapatra Senjanovic PRL **44** (1980) 912,
Schechter Valle PR**D22** (1980) 2227.

Overview

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{(16\pi^2)^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \cdots$$

Seesaw

Minkowski PL**B67** (1977) 421,
Yanagida (1979),
Gell-Mann Ramond Slansky (1979),
Mohapatra Senjanovic PRL **44** (1980) 912,
Schechter Valle PR**D22** (1980) 2227.

Zee, Dark-doublet

Zee PL**B93** (1980) 389,
Ma PRL **81** (1999) 1171, etc.

Babu-Zee

Babu PL**B203** (1988) 132, etc.

Overview

If forbidden

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \cancel{\mathscr{L}_{d=5}} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{(16\pi^2)^2}\frac{1}{\Lambda} LLHH + \cdots$$

Next leading contribution to m_ν with the SM particle contents

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \cdots$$

Overview

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \mathscr{L}_{d=6} + \mathscr{L}_{d=7} + \cdots$$

$$\mathscr{L}_{d=5} = \frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}} LLHH + \frac{1}{(16\pi^2)^2}\frac{1}{\Lambda} LLHH + \cdots$$

Next leading contribution to m_ν with the SM particle contents

$$\mathscr{L}_{d=7} = \frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \frac{1}{16\pi^2}\frac{1}{\Lambda_{\rm NP}^3} LLHHH^\dagger H + \cdots$$

Neutrino masses from a n-loop-induced dim-d operator

$$m_\nu = v \times \left(\frac{1}{16\pi^2}\right)^n \times \left(\frac{v}{\Lambda_{\rm NP}}\right)^{d-4}$$

- More suppression $\rightarrow$ lower $\Lambda_{\rm NP}$ $\rightarrow$ Collider testable

Outline

1. Introduction: Weinberg operator and higher
   - Weinberg op. $d = 5$ and Seesaw mechanism
   - Departure from $d = 5$
2. Effective operators at Λ_{EW}
   - Two Higgs doublet model with matter parity Z_n
3. Decompositions — Models at Λ_{NP}
   - Example
   - List of realizations
   - Loop-inducced $d > 5$ operator
4. Summary

Outline

1. Introduction: Weinberg operator and higher
   - Weinberg op. $d = 5$ and Seesaw mechanism
   - Departure from $d = 5$
2. Effective operators at Λ_{EW}
   - Two Higgs doublet model with matter parity Z_n
3. Decompositions — Models at Λ_{NP}
   - Example
   - List of realizations
   - Loop-inducced $d > 5$ operator
4. Summary

In an effective theory, the Lagrangian should be described as

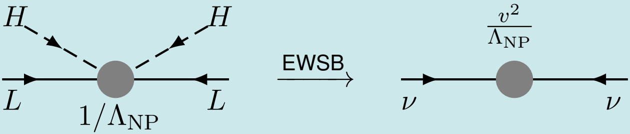
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}} \mathcal{O}^{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}^{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3} \mathcal{O}^{d=7} + \cdots$$

In an effective theory, the Lagrangian should be described as

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}^{d=7} + \cdots$$

Lowest higher dim. op. $\mathcal{O}^{d=5}$: Weinberg op Weinberg PRL**43** (1979) 1566

$$\frac{1}{\Lambda_{\rm NP}}\mathcal{O}^{d=5} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c}{\rm i}\tau^2 H)(H^{\mathsf{T}}{\rm i}\tau^2 L) \xrightarrow{\text{EWSB}} \frac{v^2}{2\Lambda_{\rm NP}}\overline{\nu^c}\nu$$



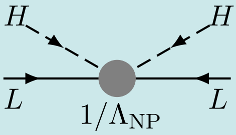
The SM is an effective theory at $\Lambda_{\rm EW}$ and there is New physics at higher scale $\Lambda_{\rm NP}$...

The effective op. is realized by the fundamental theory at Λ_{NP} — e.g., a model with right-handed SM singlet fermions N.

Realization of Weinberg op. — Seesaw mechanism

Minkowski, Yanagida, Gell-Mann Ramond Slansky, Mohapatra Senjanović, Schechter Valle

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}} (\overline{L^c} \mathrm{i}\tau^2 H)(H^{\mathsf{T}} \mathrm{i}\tau^2 L) + \text{H.c.},$$



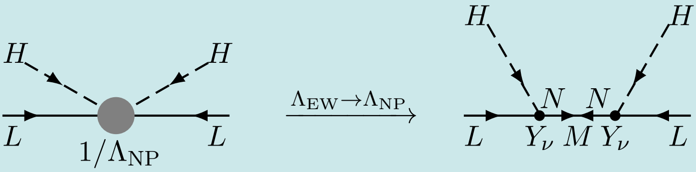
The effective op. is realized by the fundamental theory at $\Lambda_{\rm NP}$ — e.g., a model with right-handed SM singlet fermions N.

Realization of Weinberg op. — Seesaw mechanism

Minkowski, Yanagida, Gell-Mann Ramond Slansky, Mohapatra Senjanović, Schechter Valle

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) + {\rm H.c.},$$

$$\xrightarrow{\Lambda_{\rm EW} \to \Lambda_{\rm NP}} \mathscr{L}_{\rm SM} + Y_\nu \bar{N} H {\rm i}\tau^2 L + \frac{1}{2} M \overline{N^c} N + {\rm H.c.}.$$

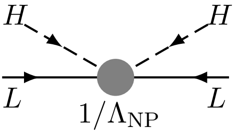


This suggests $\Lambda_{\rm NP} = M \gtrsim \mathcal{O}(10^{13})$ GeV (with $Y_\nu \sim \mathcal{O}(1)$)...

Motivation to depart from $d = 5$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \delta\mathscr{L}^{d=5} + \delta\mathscr{L}^{d=6} + \delta\mathscr{L}^{d=7} + \cdots$$

$$\delta\mathscr{L}^{d=5} = \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \to v \frac{v}{\Lambda_{\rm NP}} \overline{\nu^c}\nu,$$

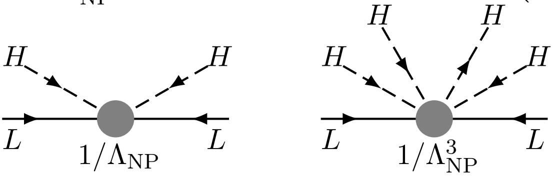


Motivation to depart from $d = 5$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \delta\mathscr{L}^{d=5} + \delta\mathscr{L}^{d=6} + \delta\mathscr{L}^{d=7} + \cdots$$

$$\delta\mathscr{L}^{d=5} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L) \to v\frac{v}{\Lambda_{\rm NP}}\overline{\nu^c}\nu,$$

$$\delta\mathscr{L}^{d=7} \ni \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3\overline{\nu^c}\nu,$$



“Higher d” = “Lower $\Lambda_{\rm NP}$”

If Weinberg op. ($d = 5$) is forbidden and m_ν is induced from $d = 7$ op., $\Lambda_{\rm NP}$ is lowered $\to$ Collider testability is recovered

One complication is...

When we have

$$\delta \mathscr{L}^{d=7} \ni \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L)(H^\dagger H) \to v \left(\frac{v}{\Lambda_{\rm NP}} \right)^3 \overline{\nu^c}\nu,$$

we also have to have

$$\delta \mathscr{L}^{d=5}_{\sf tree} = \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \to v \left(\frac{v}{\Lambda_{\rm NP}} \right) \overline{\nu^c}\nu,$$

One complication is...

When we have

$$\delta\mathscr{L}^{d=7} \ni \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}\mathrm{i}\tau^2 H)(H^{\mathsf{T}}\mathrm{i}\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3 \overline{\nu^c}\nu,$$

we also have to have

$$\delta\mathscr{L}^{d=5}_{\text{tree}} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c}\mathrm{i}\tau^2 H)(H^{\mathsf{T}}\mathrm{i}\tau^2 L) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)\overline{\nu^c}\nu,$$

$$\delta\mathscr{L}^{d=5}_{\text{1-loop}} = \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c}\mathrm{i}\tau^2 H)(H^{\mathsf{T}}\mathrm{i}\tau^2 L)\,(\overbrace{H^\dagger H}) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)\frac{1}{16\pi^2}\overline{\nu^c}\nu.$$

One complication is...

When we have

$$\delta \mathscr{L}^{d=7} \ni \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L)(H^\dagger H) \to v \left(\frac{v}{\Lambda_{\rm NP}} \right)^3 \overline{\nu^c} \nu,$$

we also have to have

$$\delta \mathscr{L}^{d=5}_{\text{tree}} = \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \to v \left(\frac{v}{\Lambda_{\rm NP}} \right) \overline{\nu^c} \nu,$$

$$\delta \mathscr{L}^{d=5}_{\text{1-loop}} = \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) \, (\overbracket{H^\dagger H}) \to v \left(\frac{v}{\Lambda_{\rm NP}} \right) \frac{1}{16\pi^2} \overline{\nu^c} \nu.$$

Solution We introduce

- two Higgs doublets, $H_u = (H_u^+, H_u^0)^{\sf T}$ and $H_d = (H_d^0, H_d^-)^{\sf T}$,
- Symmetry Z_n (matter parity), Ibáñez Ross NP**B368** (1992) 3,

to forbid the dimension five op and to control loop contributions.

Outline

1 Introduction: Weinberg operator and higher
- Weinberg op. $d = 5$ and Seesaw mechanism
- Departure from $d = 5$

2 Effective operators at Λ_{EW}
- Two Higgs doublet model with matter parity Z_n

3 Decompositions — Models at Λ_{NP}
- Example
- List of realizations
- Loop-inducced $d > 5$ operator

4 Summary

Set up

To realize $d = 7$ neutrino mass generation, we introduce

- two Higgs doublets H_u and H_d,
- Discrete symmetry Z_5 (matter parity)

Set up

To realize $d = 7$ neutrino mass generation, we introduce

- two Higgs doublets H_u and H_d,
- Discrete symmetry Z_5 (matter parity) whose charges are assigned to the SM fields as, e.g.,

$$q_{H_u} = 0, \quad q_{H_d} = 3, \quad q_L = 1, \quad q_{e_R^c} = 1.$$

Then, we have

$$\delta \mathscr{L}^{d=5} = \frac{1}{\Lambda_{\text{NP}}} (\overline{L^c} \mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}} \mathrm{i}\tau^2 L) \leftarrow \text{Forbidden},$$

$$\delta \mathscr{L}^{d=7} = \frac{1}{\Lambda_{\text{NP}}^3} (\overline{L^c} \mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}} \mathrm{i}\tau^2 L)(H_d^{\mathsf{T}} \mathrm{i}\tau^2 H_u) \to v_u \frac{v_u^2 v_d}{\Lambda_{\text{NP}}^3} \overline{\nu^c} \nu.$$

We do not have the quadratically divergent loop $\delta \mathscr{L}^{d=5}_{\text{1-loop}}$.

Charge assignments — in general

For $d = 7$ mass generation, we introduce $Z_{n=5}$ and require

Forbid $d = 5$

$$LLH_uH_u : (2q_L + 2q_{H_u}) \mod n \neq 0$$
$$LLH_d^*H_u : (2q_L + q_{H_u} - q_{H_d}) \mod n \neq 0$$
$$LLH_d^*H_d^* : (2q_L - 2q_{H_d}) \mod n \neq 0$$

Allow $d = 7$

$$LLH_uH_uH_dH_u : (2q_L + 3q_{H_u} + q_{H_d}) \mod n = 0$$

and the SM interactions $\mathscr{L}_{\rm SM}$

Extension: This can be generalized for $d = 9$... with $Z_{n=7...}$.

Outline

1. Introduction: Weinberg operator and higher
   - Weinberg op. $d = 5$ and Seesaw mechanism
   - Departure from $d = 5$
2. Effective operators at $\Lambda_{\rm EW}$
   - Two Higgs doublet model with matter parity Z_n
3. Decompositions — Models at $\Lambda_{\rm NP}$
   - Example
   - List of realizations
   - Loop-inducced $d > 5$ operator
4. Summary

Realization

$d = 5$

Weinberg op. $(d = 5)$ is realized by the seesaw model, i.e.,

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) + {\rm H.c.},$$

$$\xrightarrow{\text{high scale}} \mathscr{L}_{\rm SM} + Y_\nu \bar{N} H {\rm i}\tau^2 L + \frac{1}{2} M \overline{N^c} N + {\rm H.c.}.$$

Realization

$d = 5$

Weinberg op. $(d = 5)$ is realized by the seesaw model, i.e.,

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}} (\overline{L^c} {\rm i}\tau^2 H)(H^{\sf T} {\rm i}\tau^2 L) + {\rm H.c.},$$

$$\xrightarrow{\text{high scale}} \mathscr{L}_{\rm SM} + Y_\nu \bar{N} H {\rm i}\tau^2 L + \frac{1}{2} M \overline{N^c} N + {\rm H.c.}.$$

$d = 7$

Now, we have the effective Lagrangian,

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}^3} (\overline{L^c} {\rm i}\tau^2 H_u)(H_u^{\sf T} {\rm i}\tau^2 L)(H_d^{\sf T} {\rm i}\tau^2 H_u)$$

$$\xrightarrow{\text{high scale}} \mathscr{L}_{\rm SM} + ???$$

What high energy models make this $d = 7$ effective Lagrangian feasible? — an example...

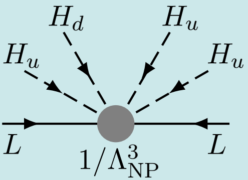
Example: Inverse seesaw type

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a SM singlet scalar ϕ, $q_\phi = 3$.

The relevant part of Lagrangian looks

$$\mathscr{L} = \mathscr{L}_{\rm SM} + Y_\nu \overline{N_R} H_u {\rm i}\tau^2 L + M \overline{N_R} N'_L + \kappa \overline{N'^c_L} N'_L \phi$$
$$+ \mu \phi^* H_d {\rm i}\tau^2 H_u + M_\phi^2 \phi^* \phi.$$



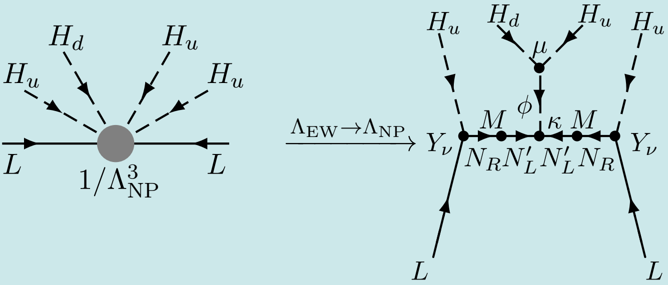
Example: Inverse seesaw type

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a SM singlet scalar ϕ, $q_\phi = 3$.

The relevant part of Lagrangian looks

$$\mathscr{L} = \mathscr{L}_{\rm SM} + Y_\nu \overline{N_R} H_u {\rm i}\tau^2 L + M \overline{N_R} N'_L + \kappa \overline{N'^c_L} N'_L \phi + \mu \phi^* H_d {\rm i}\tau^2 H_u + M_\phi^2 \phi^* \phi.$$



Example: Inverse seesaw type

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a SM singlet scalar ϕ, $q_\phi = 3$.

The Lagrangian can be expressed also as ...

$$\mathscr{L} = \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{N_R} & \overline{N_L'^c} \end{pmatrix} \begin{pmatrix} 0 & Y_\nu^{\sf T} H_u^0 & 0 \\ Y_\nu H_u^0 & 0 & M \\ 0 & M^{\sf T} & \Lambda^{-1} H_d^0 H_u^0 \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \\ N_L' \end{pmatrix} + {\rm H.c.},$$

where $\Lambda^{-1} = 2\kappa\mu/M_\phi^2$. For inverse seesaw, e.g. Gonzalez-Garcia Valle PL**B216** (1989) 360.

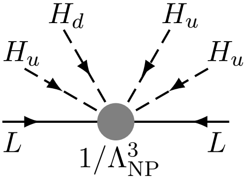
Neutrino masses are estimated as

$$m_\nu = \frac{v_u^3 v_d}{4} Y_\nu^{\sf T} (M^{-1})^{\sf T} \Lambda^{-1} M^{-1} Y_\nu \sim \mathcal{O}\left(v \frac{v^3}{\Lambda_{\rm NP}^3} \right)$$

If $m_\nu \sim 1$ eV and $Y_\nu \sim Y_\mu$, $\Lambda_{\rm NP} \sim \mathcal{O}(1)$ TeV $\rightarrow$ Collider testable!

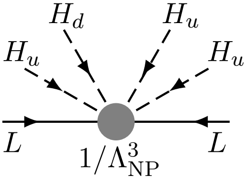
Systematic search for models

The effective operator



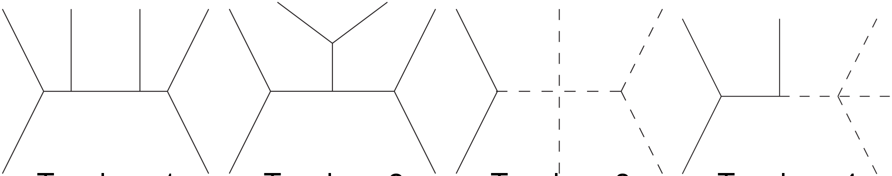
Systematic search for models

The effective operator



can be decomposed

with tree diagrams of the following possible topologies,



Topology 1 Topology 2 Topology 3 Topology 4

Assigning the fields to each leg, we can list the models...

Decompositions — Models at Λ_{NP}

Bonnet Hernandez O Winter JHEP **0910** (2009) 076

List of realizations

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

Decompositions

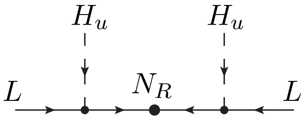
(with $\mathbf{X} \leq \mathbf{3}$)

For $\mathbf{X} = \mathbf{4}$, Babu Nandi Tavartkiladze PR**D80** (2009) 071702.

- Top.: Topology
- Mediators: Necessary new fields $\mathbf{X}^{\mathcal{L}}_{Y}$
  $\mathbf{X}$: $SU(2)$, Y: $U(1)_Y$
  $\mathcal{L}$: Lorentz property
- NU: Non-Unitary PMNS matrix
- δg_L: shift of the gauge coupling of charged leptons
- 4ℓ: four-charged lepton processes

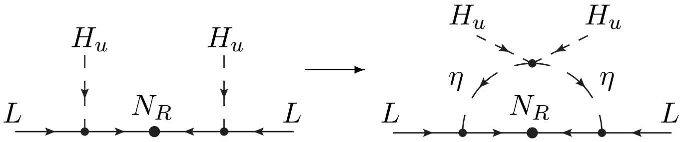
Extension: 1-loop induced $d = 7$ op.

- tree-induced $d = 5$ (Seesaw)



Extension: 1-loop induced $d = 7$ op.

- tree-induced $d = 5$ (Seesaw) $\to$ 1-loop



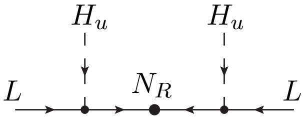
Dark doublet model Ma PR**D73** (2006) 077301

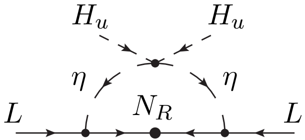
- Introduce additional Z_2 parity
- Assign Z_2 odd charge to N_R and a new scalar doublet η
- Introduce the quatic intaraction

$$\mathscr{L} = \frac{\lambda}{2}(\eta^\dagger H_u)(\eta^\dagger H_u) + \text{H.c.},$$

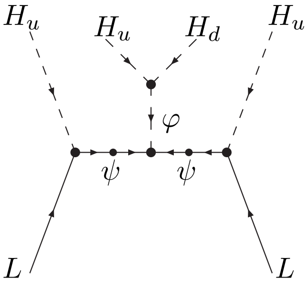
Extension: 1-loop induced $d = 7$ op.

- tree-induced $d = 5$ (Seesaw) $\rightarrow$ 1-loop



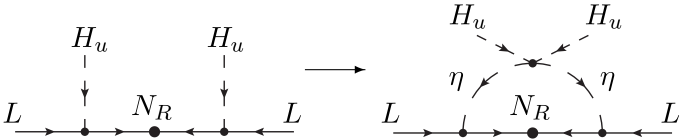


- tree-induced $d = 7$

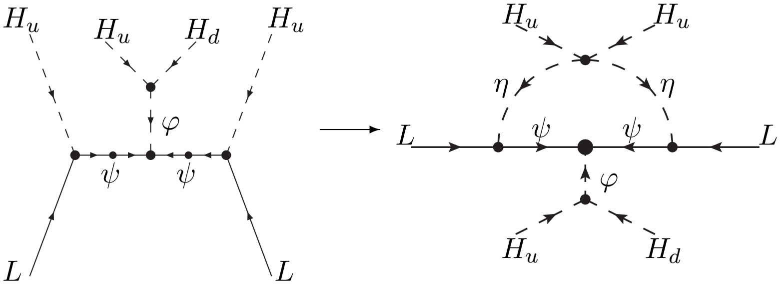


Extension: 1-loop induced $d = 7$ op.

- tree-induced $d = 5$ (Seesaw) $\rightarrow$ 1-loop



- tree-induced $d = 7$ $\rightarrow$1-loop Kanemura O PL**B** (2010)



Outline

1. Introduction: Weinberg operator and higher
   - Weinberg op. $d = 5$ and Seesaw mechanism
   - Departure from $d = 5$
2. Effective operators at $\Lambda_{\rm EW}$
   - Two Higgs doublet model with matter parity Z_n
3. Decompositions — Models at $\Lambda_{\rm NP}$
   - Example
   - List of realizations
   - Loop-inducced $d > 5$ operator
4. Summary

Higher dim. m_ν generation

- $d = 5$ Weinberg op. $\xrightarrow{\text{high scale } \Lambda_{\rm NP}}$ Seesaw Lagrangian
- We consider the possibility with $d > 5$:
  $\rightarrow$ More suppression by $v/\Lambda_{\rm NP}$
  $\rightarrow$ Lower $\Lambda_{\rm NP}$ $\rightarrow$ Recovery of collider testability
- $d = 7 : (\overline{L^c} {\rm i}\tau^2 H_u)(H_u^{\sf T} {\rm i}\tau^2 L)(H_d^{\sf T} {\rm i}\tau^2 H_u)$
  - THDM with matter parity Z_5
  - An example for realization — Inverse seesaw type
  - List of high energy models for tree-indeucd $d = 7$
- Extension
  - 1-loop-indeucd $d = 7$ with $Z_5 \times Z_2$
  - tree-indeucd $d = 9$ with Z_7
- Future study: higher d neutrino mass generation in SUSY
  Krauß O Porod Winter work in progress

Further Refs. Gogoladze Okada Shafi PL**B672** (2009) 235, Giudice Lebedev PL**B665** (2008) 79.

Back up

Problem?

Goldstone boson

We introduce $Z_{n=5}$

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\to$ But $\mathscr{L}$ respects $U(1)$
$\to$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$
$\rightarrow$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\rightarrow$ $U(1)$ is spontaneously broken

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$
$\rightarrow$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\rightarrow$ $U(1)$ is spontaneously broken
$\rightarrow$ Goldstone boson of new $U(1)$.

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\to$ But $\mathscr{L}$ respects $U(1)$
$\to$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\to$ $U(1)$ is spontaneously broken
$\to$ Goldstone boson of new $U(1)$.

Way out

We allow a soft $U(1)$ violation term

$$\mathscr{L} = m_3^2 H_d \mathrm{i}\tau^2 H_u + \mathrm{H.c.}.$$

$\to$ Goldstone boson gets mass $\sim m_3$.

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\to$ But $\mathscr{L}$ respects $U(1)$
$\to$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\to$ $U(1)$ is spontaneously broken
$\to$ Goldstone boson of new $U(1)$.

Way out

We allow a soft $U(1)$ violation term

$$\mathscr{L} = m_3^2 H_d \mathrm{i}\tau^2 H_u + \mathrm{H.c.}.$$

$\to$ Goldstone boson gets mass $\sim m_3$.
$\to$ Another problem: Loop $d = 5$ comes back

$$\delta\mathscr{L}^{d=7}_{\text{tree}} = \frac{1}{\Lambda^3_{\text{NP}}} (\overline{L^c} \mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}} \mathrm{i}\tau^2 L)\, \overbrace{(H_d \mathrm{i}\tau^2 H_u)}$$

But the loop contribution does not dominate — controllable.

Problem?

Goldstone boson

We introduce $Z_{n=5}$ $\rightarrow$ But $\mathscr{L}$ respects $U(1)$
$\rightarrow$ H_d which is charged under $Z_{n=5} \subset U(1)$ takes vev
$\rightarrow$ $U(1)$ is spontaneously broken
$\rightarrow$ Goldstone boson of new $U(1)$.

Way out

We allow a soft $U(1)$ violation term

$$\mathscr{L} = m_3^2 H_d \mathrm{i}\tau^2 H_u + \mathrm{H.c.}.$$

$\rightarrow$ Goldstone boson gets mass $\sim m_3$.
$\rightarrow$ Another problem: Loop $d = 5$ comes back

$$\delta\mathscr{L}^{d=5}_{\text{1-loop}} = \frac{m_3^2}{16\pi^2\Lambda_{\mathrm{NP}}^3}(\overline{L^c}\mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}}\mathrm{i}\tau^2 L)$$

But the loop contribution does not dominate — controllable.

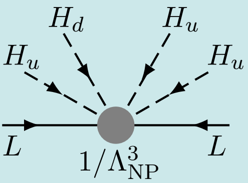
Example II

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a $SU(2)$ doublet scalar $\Phi(\mathbf{2}^s_{-1/2})$, $q_\Phi = 2$.

The relevant part of Lagrangian looks

$$\mathscr{L} = \mathscr{L}_{\rm SM} + Y_\nu \overline{N_R} H_u {\rm i}\tau^2 L + Y'_\nu \overline{N'^c_L} \Phi^\dagger L + M \overline{N_R} N'_L + \zeta \left\{ (H_d {\rm i}\tau^2 H_u)(\Phi {\rm i}\tau^2 H_u) \right\} + M_\Phi^2 \Phi^\dagger \Phi.$$



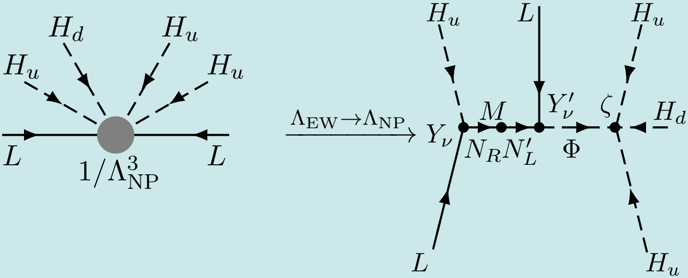
Example II

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a $SU(2)$ doublet scalar $\Phi(\mathbf{2}^s_{-1/2})$, $q_\Phi = 2$.

The relevant part of Lagrangian looks

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + Y_\nu \overline{N_R} H_u \mathrm{i}\tau^2 L + Y'_\nu \overline{N'^c_L} \Phi^\dagger L + M \overline{N_R} N'_L$$
$$+ \zeta \left\{ (H_d \mathrm{i}\tau^2 H_u)(\Phi \mathrm{i}\tau^2 H_u) \right\} + M^2_\Phi \Phi^\dagger \Phi.$$



Example II

We introduce new particles in the model, which are

- two SM singlet fermions, N_R and N'_L, $q_{N_R} = q_{N'_L} = 1$
- a $SU(2)$ doublet scalar $\Phi(\mathbf{2}^s_{-1/2})$, $q_\Phi = 2$.

The Lagrangian can be expressed also as ...
e.g., Abada Biggio Bonnet Gavela Hambye JHEP **12** (2007) 061.

$$\mathscr{L} = \frac{1}{2} \begin{pmatrix} \overline{\nu^c_L} & \overline{N_R} & \overline{N'^c_L} \end{pmatrix} \begin{pmatrix} 0 & Y_\nu^{\mathsf{T}} H_u^0 & Y_\nu'^{\mathsf{T}} \zeta \frac{H_d^0 H_u^{02}}{M_\Phi^2} \\ Y_\nu H_u^0 & 0 & M \\ Y_\nu' \zeta \frac{H_d^0 H_u^{02}}{M_\Phi^2} & M^{\mathsf{T}} & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ N^c_R \\ N'_L \end{pmatrix} + \text{H.c.}.$$

Neutrino masses are estimated as

$$m_\nu = \frac{\zeta v_u^3 v_d}{4 M_\Phi^2} \left[Y_\nu^{\mathsf{T}} (M^{-1}) Y_\nu' + Y_\nu'^{\mathsf{T}} (M^{-1})^{\mathsf{T}} Y_\nu \right] \sim \mathcal{O}\left(v \frac{v^3}{\Lambda_{\text{NP}}^3} \right)$$

If $m_\nu \sim 1$ eV, $Y_\nu \sim Y'_\nu \sim Y_\ell$, and $\zeta \sim \mathcal{O}(1)$, $\Lambda_{\text{NP}} \sim 1$ TeV.