BLV Workshop
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Lepton number violation and neutrino masses in N_RSMEFT

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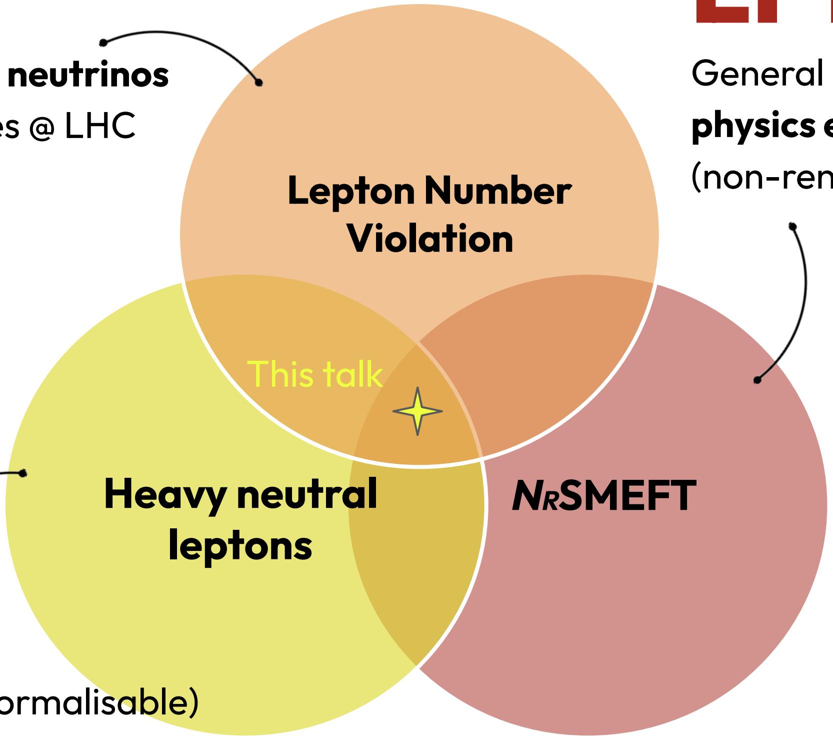
LNV

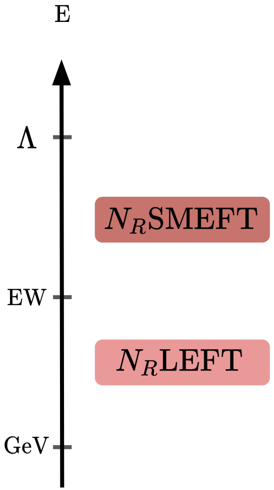
Linked to Majorana neutrinos

Distinctive signatures @ LHC

EFTs

General approach to describe **new physics effects** at **low energies** (non-renormalisable interactions)





HNLs

Neutrino Portal (renormalisable)

Minimal model: $(m_N\ ,\ U_{\ell N})$

mass, neutrino mixing

- ➔ What type of UV models give rise to **LNV interactions** in ***N_R*SMEFT**?
- ➔ What is the **connection** between LNV operators and Majorana masses for active neutrinos?
- ➔ Can we derive any **constraints** on the operators from neutrino masses?

- ➔ What type of UV models give rise to **LNV interactions** in ***N$_R$*SMEFT**?

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- ➔ Can we derive any **constraints** on the operators from neutrino masses?

Opening up N_RSMEFT

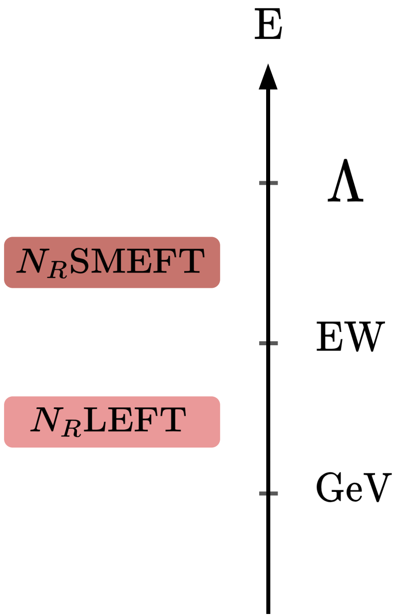
N_RSMEFT

SMEFT extended with invariant operators containing RH neutrinos:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}+N_R} + \sum_{d>4} C_i^{(d)} \mathcal{O}_i^{(d)} \qquad\qquad C_i^{(d)} \propto \Lambda^{4-d}$$

Motivation: provide a “dictionary” of particle extensions of the SM generating N_RSMEFT operators in the UV.

- Focus on d=6 and d=7 operators (LNV and BLV*)
- Generated at tree-level (vs. loop-level $\propto 1/(16\pi^2)$)
- Following a diagrammatic procedure



*Not in this talk

N_RSMEFT operators

d=6

$\psi^2 H^3$ (+h.c.)	
$\mathcal{O}_{LNH^3}$	$(\bar{L} N_R)\tilde{H}(H^\dagger H)$

$\psi^2 H^2 D$ (+h.c.)	
$\mathcal{O}_{NH^2D}$	$(\overline{N_R}\gamma^\mu N_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{NeH^2D}$	$(\overline{N_R}\gamma^\mu e_R)(\tilde{H}^\dagger i D_\mu H)$

$(\bar{L}R)(\bar{R}L)$ (+h.c.)	
$\mathcal{O}_{QuNL}$	$(\bar{Q} u_R)(\overline{N_R} L)$

$(\bar{R}R)(\bar{R}R)$	
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma^\mu N_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{eN}$	$(\overline{e}_R\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{uN}$	$(\overline{u}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{dN}$	$(\bar{d}_R\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{duNe}$	$(\bar{d}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$
$\mathcal{O}_{NNNN}$	$(\overline{N_R^c} N_R)(\overline{N_R^c} N_R)$

$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{LN}$	$(\bar{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{QN}$	$(\bar{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$

$(\bar{L}R)(\bar{L}R)$ (+h.c.)	
$\mathcal{O}_{LNLe}$	$(\bar{L} N_R)\epsilon(\bar{L} e_R)$
$\mathcal{O}_{LNQd}$	$(\bar{L} N_R)\epsilon(\bar{Q} d_R)$
$\mathcal{O}_{LdQN}$	$(\bar{L} d_R)\epsilon(\bar{Q} N_R)$

Generated @ loop level:

neutrino magnetic moment operators

[2405.08877] RB, Bolton, Deppisch, Hati, Hirsch

$\psi^2 H X$ (+h.c.)	
$\mathcal{O}_{NB}$	$g_1(\bar{L}\sigma_{\mu\nu} N)\tilde{H} B^{\mu\nu}$
$\mathcal{O}_{NW}$	$g_2(\bar{L}\sigma_{\mu\nu} N)\tau^I \tilde{H} W^{I\mu\nu}$

N_RSMEFT operators

d=7, ΔL = 2

$L(N_R) = 1$

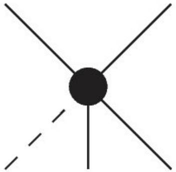
$\psi^2 H^3 D$	
$\mathcal{O}_{NLH^3D}$	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$ $\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\psi^2 H^2 D^2$	
$\mathcal{O}_{NeH^2D^2}$	$\epsilon_{ij}(\overline{N_R^c}\overleftrightarrow{D}_\mu e_R)(H^i D^\mu H^j)$
$\mathcal{O}_{NH^2D^2}$	$(\overline{N_R^c}\overleftrightarrow{\partial}_\mu N_R)(H^\dagger \overleftrightarrow{D}^\mu H)$ $(\overline{N_R^c}N_R)(D_\mu H)^\dagger D^\mu H$
$\psi^2 H^2 X$	
$\mathcal{O}_{NeH^2W}$	$(\epsilon\tau^I)_{ij}(\overline{N_R^c}\sigma^{\mu\nu}e_R)(H^i H^j)W^I_{\mu\nu}$
$\mathcal{O}_{NH^2B}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger H)B_{\mu\nu}$
$\mathcal{O}_{NH^2W}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger\tau^I H)W^I_{\mu\nu}$

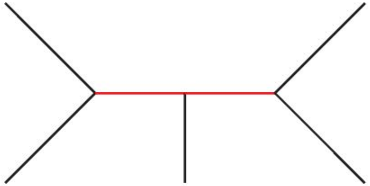
$\psi^4 H$	
$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\bar{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH}$	$\epsilon_{ij}(\bar{Q}\gamma_\mu Q)(\overline{N_R^c}\gamma^\mu L^i)H^j$ $\epsilon_{ij}(\bar{Q}\gamma_\mu Q^i)(\overline{N_R^c}\gamma^\mu L^j)H$
$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\overline{e_R}\gamma_\mu e_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu d_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\overline{u_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)\tilde{H}^j$
$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\overline{d_R}Q^i)(\overline{N_R^c}e_R)H^j$
$\mathcal{O}_{QuNeH}$	$(\bar{Q}u_R)(\overline{N_R^c}e_R)H$ $(\bar{Q}\sigma_{\mu\nu}u_R)(\overline{N_R^c}\sigma^{\mu\nu}e_R)H$

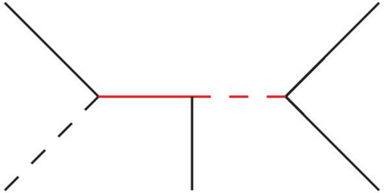
$\psi^4 H$	
$\mathcal{O}_{LNeH}$	$(\bar{L}N_R)(\overline{N_R^c}e_R)H$
$\mathcal{O}_{eLNH}$	$H^\dagger(\overline{e_R}L)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNdH}$	$(\bar{Q}N_R)(\overline{N_R^c}d_R)H$
$\mathcal{O}_{dQNH}$	$H^\dagger(\overline{d_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNuH}$	$(\bar{Q}N_R)(\overline{N_R^c}u_R)\tilde{H}$
$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\overline{u_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{LNNH}$	$(\bar{L}N_R)(\overline{N_R^c}N_R)\tilde{H}$
$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\overline{N_R}L)(\overline{N_R^c}N_R)$
$\psi^2 H^4$	
$\mathcal{O}_{NH^4}$	$(\overline{N_R^c}N_R)(H^\dagger H)^2$

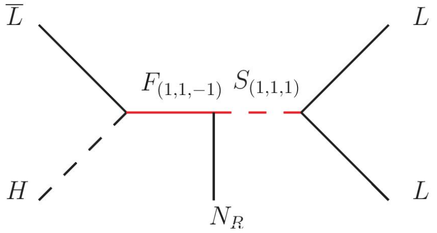
Missing those generated @ loop level

Diagrammatic method









EFT Operators — **Topologies** — **Diagrams** — **Model diagrams**

EFT Operators

- n light fields as external lines

Topologies

- only renormalisable vertices
- internal lines: BSM heavy fields

Diagrams

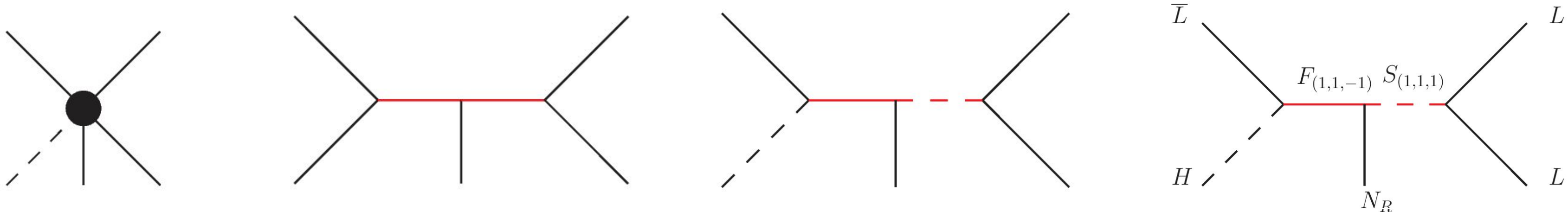
- assign Lorentz nature
- perform all possible permutations of the external fields

Model diagrams

- impose gauge invariance in each vertex

[1204.5862] Bonnet, Hirsch, Ota, Winter **[2009.13537]** Gargalionis, Volkas **[2207.13714]** Cepedello, Esser, Hirsch, Sanz

Diagrammatic method



EFT Operators — **Topologies** — **Diagrams** — **Model diagrams**

Operator

Lists of models

$$\mathcal{O}_{LNLH}\ (d=7) \quad \longrightarrow \quad (F_{(1,1,-1)}, S_{(1,1,1)}) \equiv (E, \mathcal{S}_1)$$

...

Powerful tool to systematically decompose N_RSMEFT operators at any loop order!

[1204.5862] Bonnet, Hirsch, Ota, Winter **[2009.13537]** Gargalionis, Volkas **[2207.13714]** Cepedello, Esser, Hirsch, Sanz

Particle dictionary

Scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	φ	Ξ	Ξ_1	ω_1	ω_2	Π_1	Π_7	ζ
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,2,\frac{1}{2})$	$(1,3,0)$	$(1,3,1)$	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$

Fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1,0)$	$(1,1,-1)$	$(1,2,-\frac{1}{2})$	$(1,2,-\frac{3}{2})$	$(1,3,0)$	$(1,3,-1)$	

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1,\frac{2}{3})$	$(3,1,-\frac{1}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$	$(3,3,\frac{2}{3})$

Vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{L}_1$	$\mathcal{L}_3$	$\mathcal{U}_1$	$\mathcal{U}_2$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,3,0)$	$(1,3,1)$	$(1,2,\frac{1}{2})$	$(1,2,-\frac{3}{2})$	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,3,\frac{2}{3})$

New!

[1711.10391] de Blas, Criado, Pérez-Victoria, Santiago
"Granada Dictionary"

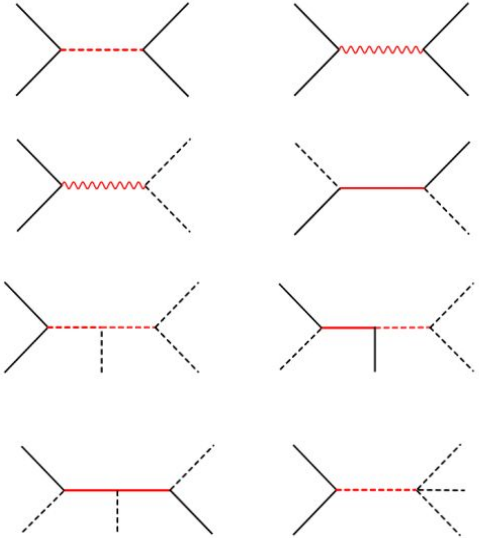
Dictionary for d=6

Operator classes → **Diagrams** → **Models**

ψ^4 :

$\psi^2 H^2 D$:

$\psi^2 H^3$:



$\psi^2 H^3$	Two-particle models
$\mathcal{O}_{LNH^3}$	SS: $(\mathcal{S},\varphi)$, (Ξ_1,φ), (Ξ,φ)
	FF: $(\Delta_1,\mathcal{N})$, (Δ_1,Σ_1), (Δ_1,Σ)
	FS: $(\mathcal{N},\mathcal{S})$, $(\Delta_1,\mathcal{S})$, (Δ_1,Ξ_1), (Σ_1,Ξ_1), (Δ_1,Ξ), (Σ,Ξ)

Models	Operators
$\mathcal{S}$	$\mathcal{O}_{NN}$, $\mathcal{O}_{NNNN}$
$\mathcal{S}_1$	$\mathcal{O}_{LNLe}$, $\mathcal{O}_{eN}$
φ	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNLe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{LNH^3}$
ω_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{duNe}$
ω_2	$\mathcal{O}_{uN}$
Π_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{QN}$
Δ_1	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NeH^2D}$
$\mathcal{B}$	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NN}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{QN}$
$\mathcal{B}_1$	$\mathcal{O}_{NeH^2D}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{duNe}$
$\mathcal{L}_1$	$\mathcal{O}_{LN}$
$\mathcal{U}_1$	$\mathcal{O}_{dN}$
$\mathcal{U}_2$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{duNe}$
$\mathcal{Q}_1$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{QN}$

Dictionary for d=7

Operator classes | **Diagrams** | **Models**

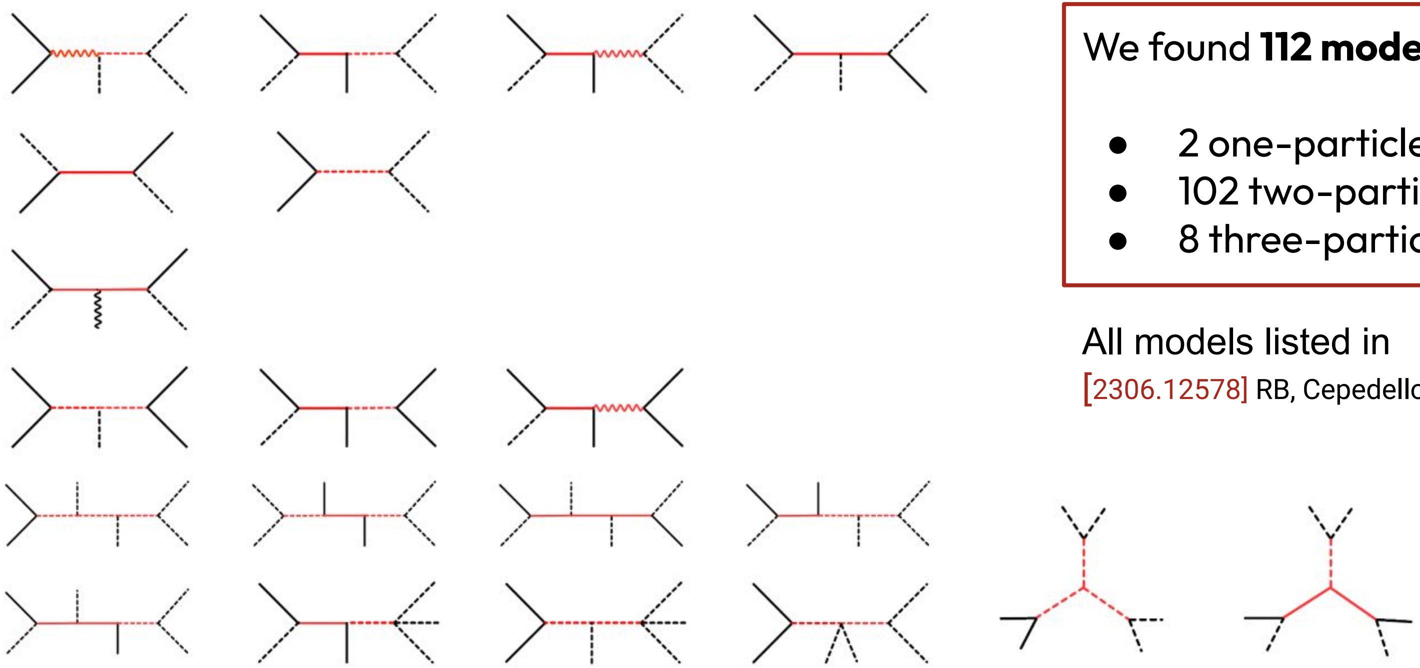
$\psi^2 H^3 D$:

$\psi^2 H^2 D^2$:

$\psi^2 H^2 X$:

$\psi^4 H$:

$\psi^2 H^4$:



We found **112 models**

- 2 one-particle
- 102 two-particle
- 8 three-particle

All models listed in

[2306.12578] RB, Cepedello, Hirsch

Explicit example: $\mathcal{O}_{LNLH}$

$\mathcal{O}_{LNLH}$ $\quad \epsilon_{ij}(\overline{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$

16 models (*SS, FS, FV*)

$\psi^4 H$	Models
$\mathcal{O}_{LNLH}$	SS : $(\mathcal{S}_1, \varphi)$ (φ, Ξ_1)
	FS : $(E, \mathcal{S}_1)$ (Σ_1, Ξ_1) $(\Delta_1, \mathcal{S}_1)$ (Δ_1, Ξ_1) $(\mathcal{N}, \varphi)$ (Σ, φ)
	FV : $(\mathcal{N}, \mathcal{B})$ $(\Sigma, \mathcal{W})$ $(\mathcal{N}, \mathcal{L}_1)$ $(\Sigma, \mathcal{L}_1)$ $(\Delta_1, \mathcal{B})$ $(\Delta_1, \mathcal{W})$ $(E, \mathcal{L}_1)$ $(\Sigma_1, \mathcal{L}_1)$

$\psi^4 H$:

Models for the rest of the operators
+ Lagrangian terms listed in [2306.12578] RB, Cepedello, Hirsch

- ➔ What type of UV models give rise to **LNV interactions** in ***N_R*SMEFT**?
- ➔ What is the **connection** between LNV operators and Majorana masses for active neutrinos?
- ➔ Can we derive any **constraints** on the operators from neutrino masses?

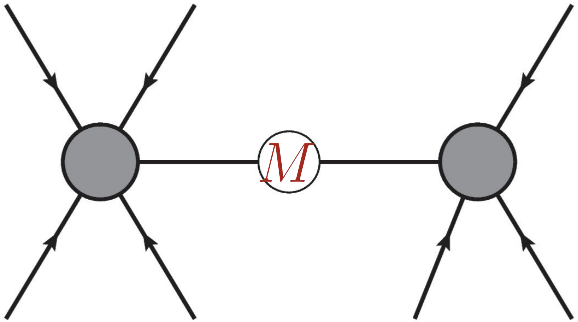
A black box for N_RSMEFT

LNV in *NR*SMEFT

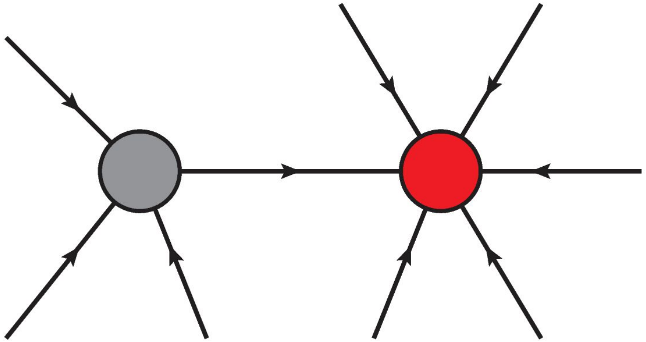
Extended black box:* Observation of LNV @ LHC guarantees the existence of Majorana masses for the active neutrinos.

We want to prove it in ***NR*SMEFT**, where $\Delta(L) = 2$ processes are generated by either:

A) two LNC operators and a **Majorana propagator**



B) one LNC and one **LNV operator**, along with a LNC propagator (no mass flip).

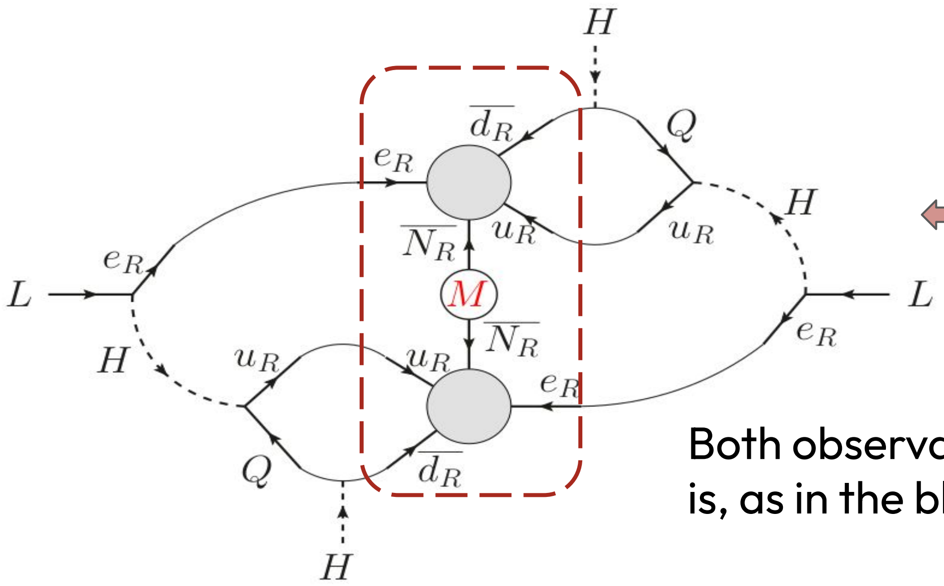


Black box theorem: Schechter & Valle, 1982 *[hep-ph/0608207] Hirsch, Kovalenko, Schimdt

LNV from Majorana propagator

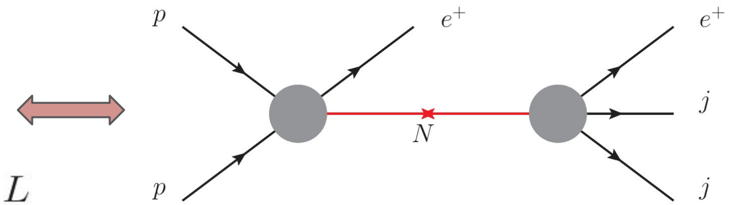
A) $\mathcal{O}_{duNe}$ $(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$ (d=6 LNC) + **Majorana mass** M_N

Majorana neutrino mass:
4-loop realisation of Weinberg operator



LNV process @LHC:

$pp \to e^+e^+jj$

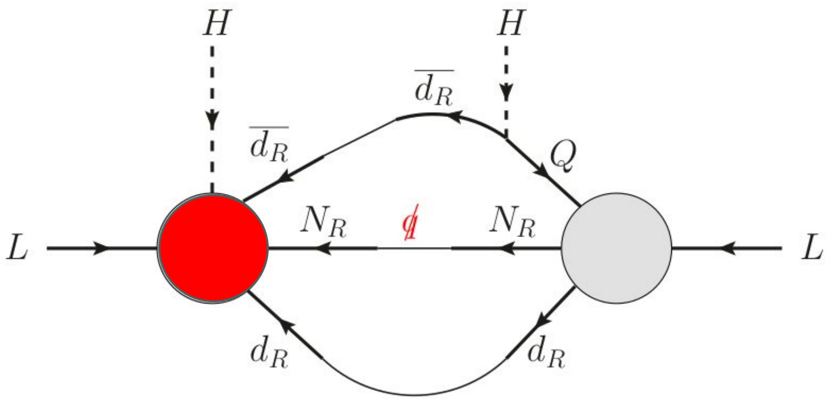


Both observables are present or none of them is, as in the black box theorem for **$0\nu\beta\beta$ decay**

LNV from d=7 operator

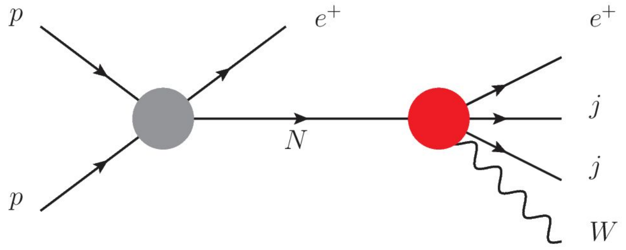
B) $\mathcal{O}_{LdQN}$ $(\overline{L^i}d_R)\epsilon_{ij}(\overline{Q^j}N_R)$ (d=6 LNC) + $\mathcal{O}_{dNLH}$ $\epsilon_{ij}(\overline{d_R}\gamma^\mu d_R)(\overline{N_R^c}\gamma_\mu L^i)H^j$ **(d=7 LNV)**

2-loop realisation of Weinberg operator:



LNV processes @LHC:

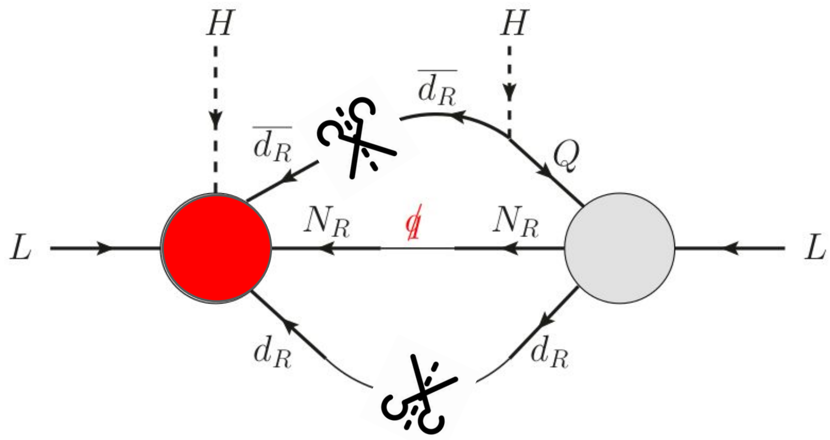
$$pp \to e^+e^+jjW$$



LNV from d=7 operator

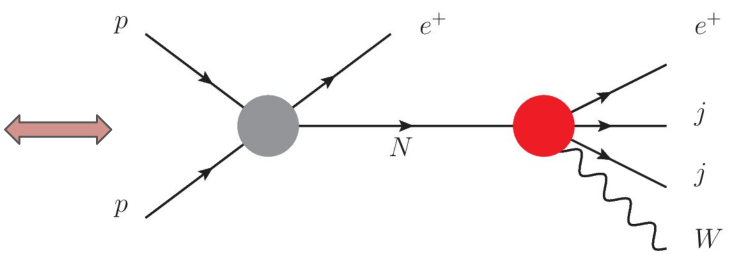
B) $\mathcal{O}_{LdQN}$ $(\overline{L^i}d_R)\epsilon_{ij}(\overline{Q^j}N_R)$ (d=6 LNC) + $\mathcal{O}_{dNLH}$ $\epsilon_{ij}(\overline{d_R}\gamma^\mu d_R)(\overline{N_R^c}\gamma_\mu L^i)H^j$ **(d=7 LNV)**

2-loop realisation of Weinberg operator:



LNV processes @LHC:

$$pp \to e^+e^+jjW$$



Note. Divergent loop integral, it should be cancelled with a lower order diagram. For the leading contribution **one needs to know the underlying UV model.**

- ➔ What type of UV models give rise to **LNV interactions** in ***N_R*SMEFT**?

- ➔ What is the **connection** between LNV operators and Majorana masses for active neutrinos?

- ➔ Can we derive any **constraints** on the operators from neutrino masses?

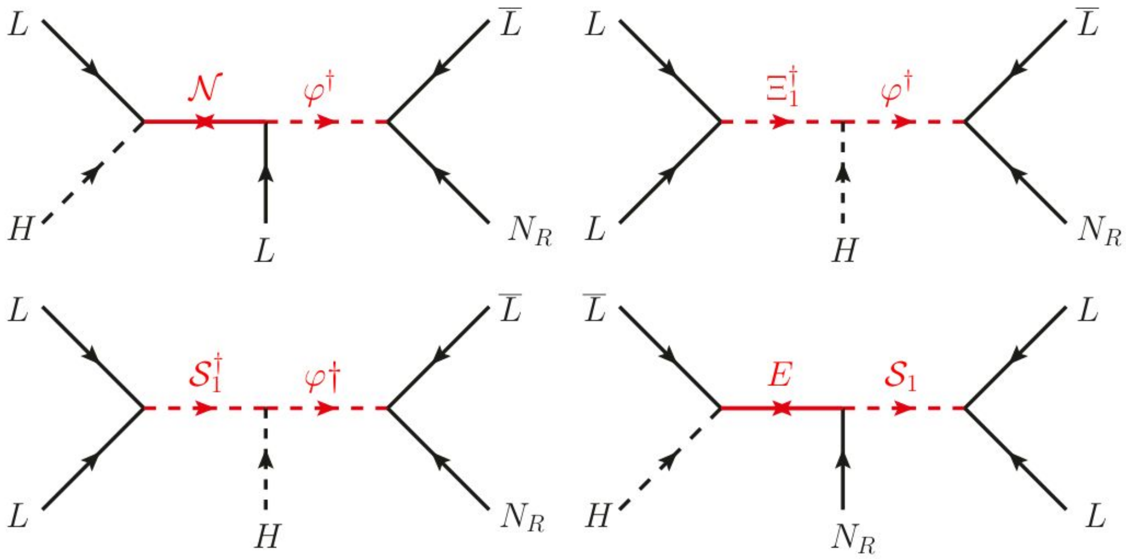
Neutrino masses in d=7 models

Example: $\mathcal{O}_{LNLH}$ decompositions

Neutrino masses:

- **tree level**

- **loop level**



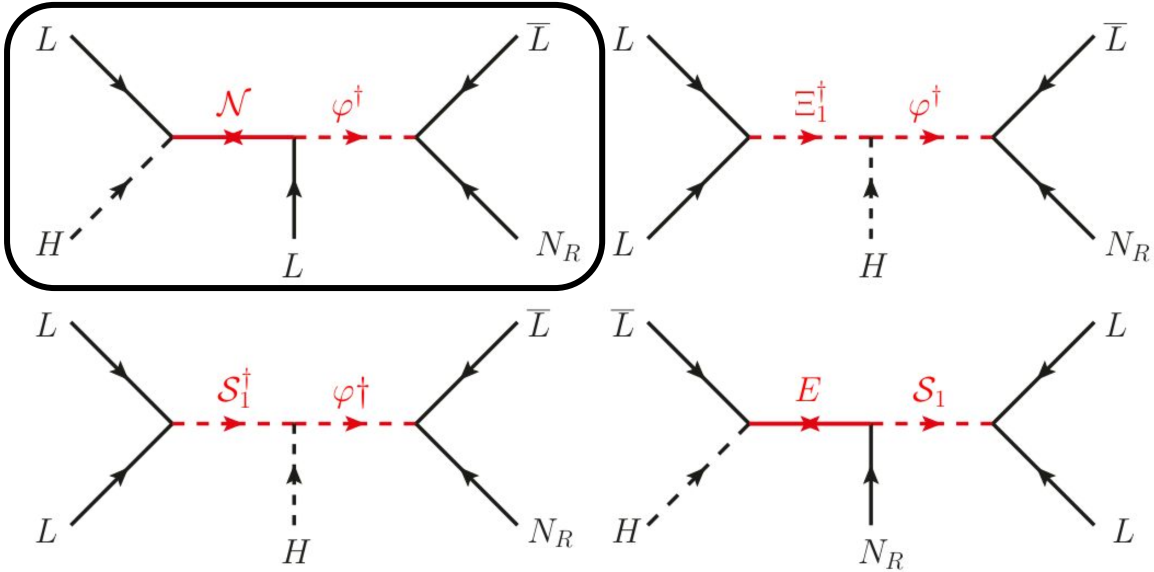
Example: $\mathcal{O}_{LNLH}$ decompositions

Neutrino masses:

- **tree level**
  type I seesaw

- **loop level**

$\#1(\mathcal{N}, \varphi)$

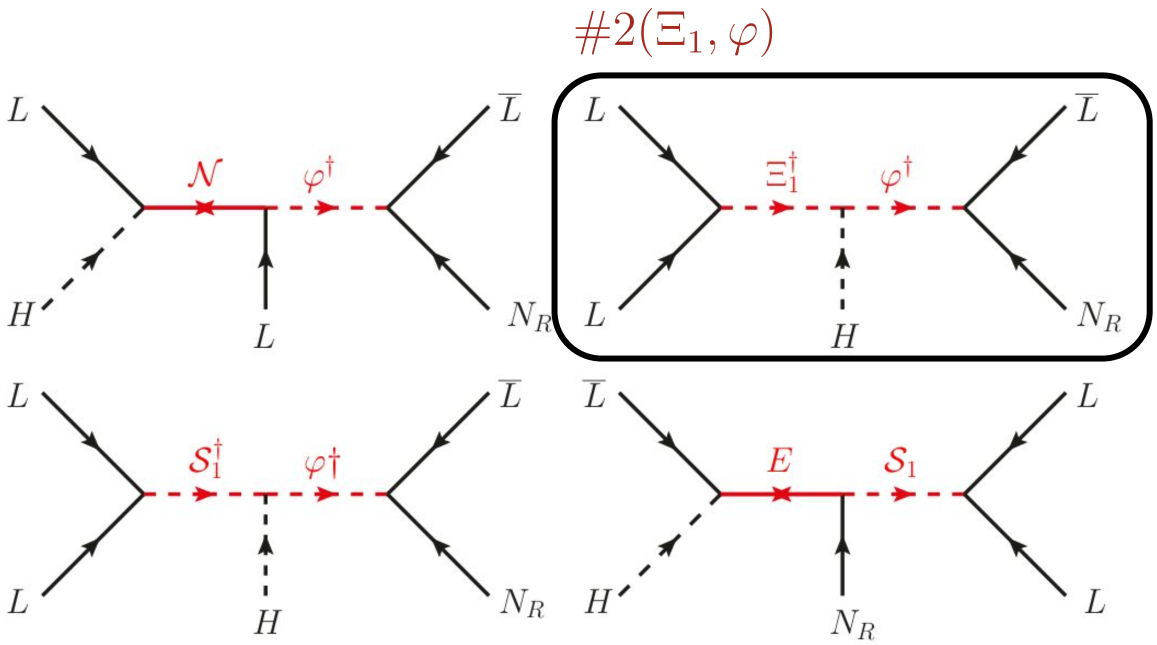


Example: $\mathcal{O}_{LNLH}$ decompositions

Neutrino masses:

- **tree level**
  type I seesaw
  type II seesaw

- **loop level**

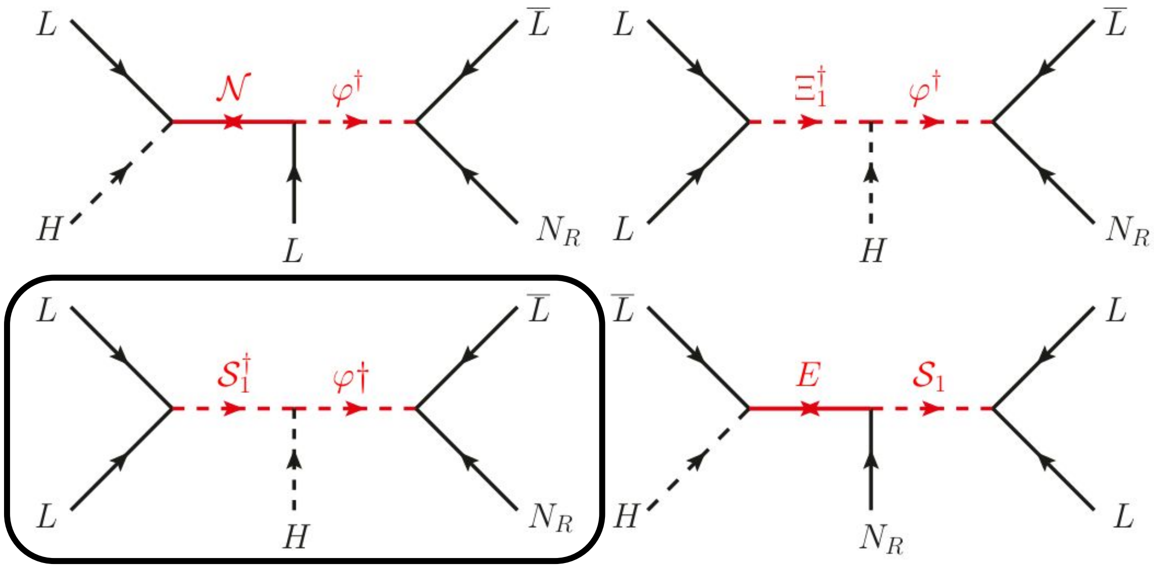


Example: $\mathcal{O}_{LNLH}$ decompositions

Neutrino masses:

- **tree level**
  type I seesaw
  type II seesaw

- **loop level**
  Zee model



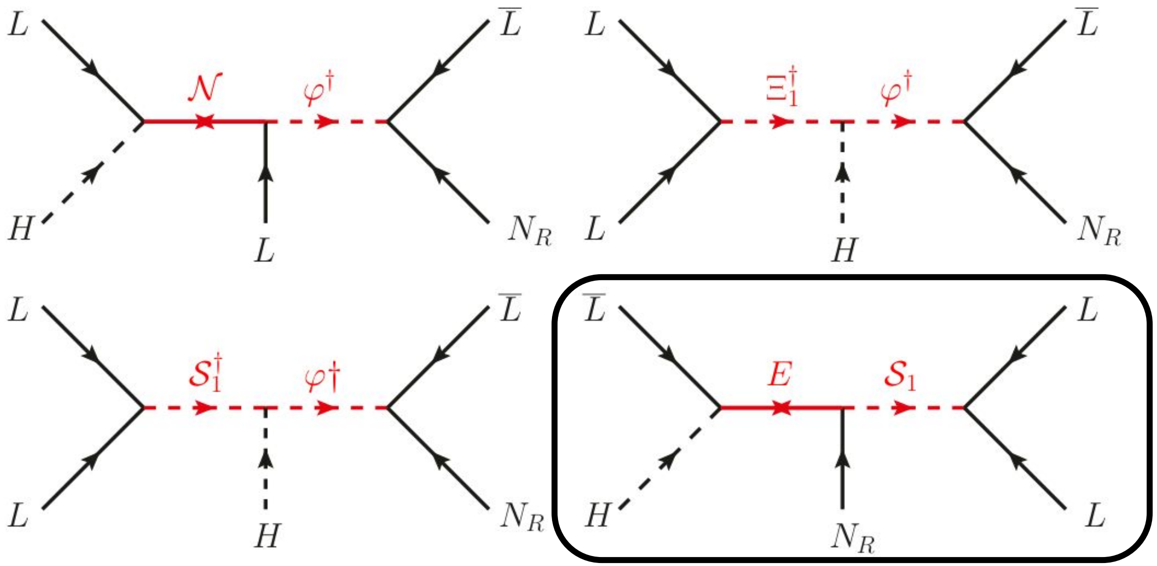
$\#3(\mathcal{S}_1, \varphi)$

Example: $\mathcal{O}_{LNLH}$ decompositions

Neutrino masses:

- **tree level**
  type I seesaw
  type II seesaw

- **loop level**
  Zee model
  2-loop



$\#4(E, \mathcal{S}_1)$

Setting constraints

$\#1(\mathcal{N},\varphi)$ Lagrangian of the model

$$\mathcal{L} \propto y^{\varphi}_{NL}\left(\overline{N_R}L\right)\varphi + y^{\varphi}_{\mathcal{N}L}\left(\overline{\mathcal{N}}L\right)\varphi + y_{\mathcal{N}L}\left(\overline{\mathcal{N}}L\right)H + \frac{1}{2}M_{\mathcal{N}}\overline{\mathcal{N}^c}\mathcal{N} + \text{h.c.}$$

Leading neutrino mass contribution

$$m_\nu \propto y^2_{\mathcal{N}L}\frac{v^2}{M_{\mathcal{N}}}$$

Matching to the operator WC

$$c_{LNLH} = -\frac{1}{4}\frac{y^{\varphi}_{NL}y^{\varphi}_{\mathcal{N}L}y_{\mathcal{N}L}}{M_{\mathcal{N}}m^2_{\varphi}}$$

$M_{\mathcal{N}} \simeq m_\varphi \simeq \Lambda$

Setting constraints

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Matching to the operator WC

$$c_{LNLH} = -\frac{1}{4}\frac{y^{\varphi}_{NL}y^{\varphi}_{\mathcal{N}L}y_{\mathcal{N}L}}{M_{\mathcal{N}}m^2_{\varphi}}$$

We can derive an upper limit on the WC:

$$c_{LNLH} \lesssim 10^{-6}\frac{y^{\varphi}_{NL}y^{\varphi}_{\mathcal{N}L}}{\Lambda^3}\left(\frac{\Lambda}{v}\right)^{1/2}\left(\frac{m_\nu}{0.1\,\text{eV}}\right)$$

Negligible observable processes

$$M_{\mathcal{N}} \simeq m_\varphi \simeq \Lambda$$

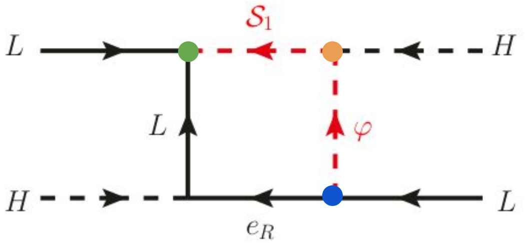
Setting constraints

$\#3(\mathcal{S}_1, \varphi)$ Lagrangian of the model

$$\mathcal{L} \propto y_L^{\mathcal{S}_1} \left(\overline{L^c} L\right) \mathcal{S}_1 + y_{Ne}^{\mathcal{S}_1} \left(\overline{N_R^c} e_R\right) \mathcal{S}_1 + y_{eL}^{\varphi} \left(\overline{e_R} L\right) \varphi^\dagger + \kappa_{\mathcal{S}_1 \varphi} \mathcal{S}_1^\dagger H \varphi + \text{h.c.} + \ldots$$

Leading neutrino mass contribution

$$m_\nu^{\text{Zee}} \simeq -\frac{1}{16\pi^2} y_L^{\mathcal{S}_1} m_\tau y_{eL}^{\varphi} \frac{\sqrt{2} v \kappa_{\mathcal{S}_1 \varphi}}{m_{h_2^+}^2 - m_{h_1^+}^2} \log\left(\frac{m_{h_2^+}^2}{m_{h_1^+}^2}\right)$$



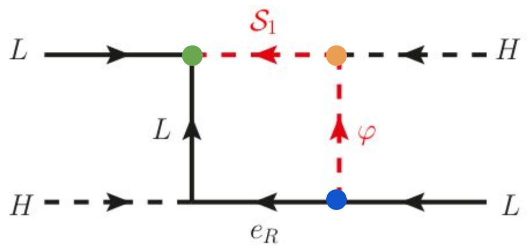
Setting constraints

$\#3(\mathcal{S}_1,\varphi)$ Lagrangian of the model

$$\mathcal{L} \propto y_L^{\mathcal{S}_1}\left(\overline{L^c}L\right)\mathcal{S}_1 + y_{Ne}^{\mathcal{S}_1}\left(\overline{N_R^c}e_R\right)\mathcal{S}_1 + y_{eL}^{\varphi}\left(\overline{e_R}L\right)\varphi^\dagger + \kappa_{\mathcal{S}_1\varphi}\mathcal{S}_1^\dagger H\varphi + \text{h.c.} + \dots$$

Leading neutrino mass contribution

$$m_\nu^{\text{Zee}} \simeq -\frac{1}{16\pi^2} y_L^{\mathcal{S}_1} m_\tau y_{eL}^{\varphi} \frac{\sqrt{2}v\kappa_{\mathcal{S}_1\varphi}}{m_{h_2^+}^2 - m_{h_1^+}^2} \log\left(\frac{m_{h_2^+}^2}{m_{h_1^+}^2}\right)$$



Matching to several operators

$$\begin{cases} c_{LNLH} \propto y_L^{\mathcal{S}_1} y_{NL}^{\varphi} \dfrac{\kappa_{\mathcal{S}_1\varphi}}{\Lambda} \\ c_{eNLH} \propto y_{Ne}^{\mathcal{S}_1} y_{eL}^{\varphi} \dfrac{\kappa_{\mathcal{S}_1\varphi}}{\Lambda} \\ c_{LNeH} \propto y_{Ne}^{\mathcal{S}_1} y_{NL}^{\varphi} \dfrac{\kappa_{\mathcal{S}_1\varphi}}{\Lambda} \end{cases}$$

$\Lambda \simeq m_{\mathcal{S}_1} \simeq m_\varphi$

Observability depends on which are the suppressed couplings:

$y_L^{\mathcal{S}_1} \sim y_{eL}^{\varphi} \sim (\kappa_{\mathcal{S}_1\varphi}/\Lambda) \sim \epsilon$ or

$y_L^{\mathcal{S}_1} \sim \epsilon^3$ or $y_{eL}^{\varphi} \sim \epsilon^3$

Summary

★ We provide the first **systematic decomposition** of d=6 and d=7 operators in N_RSMEFT at tree level.

★ Models for LNV d=7 operators will **always lead to Majorana active neutrino masse**s at tree-, 1- or 2-loop level.

★ Neutrino masses put **tight constraints** on the Wilson coefficients*

*Except for decompositions leading to radiative neutrino masses, where some operators might lead to observable effects.

BLV Workshop
KIT, Karlsruhe
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Lepton number violation and neutrino masses in N_RSMEFT

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Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

Backup: BNV models

$\psi^4 \quad (d=6)$		Models
$\mathcal{O}_{QQdN}$	$\varepsilon_{ij}\left(\overline{Q_i^c}Q_j\right)\left(\overline{d_R^c}N_R\right)$	S : ω_1 V : $\mathcal{Q}_1$
$\mathcal{O}_{uddN}$	$\left(\overline{u_R^c}d_R\right)\left(\overline{d_R^c}N_R\right)$	S : $\omega_1,\ \omega_2$
$\psi^4 H \quad (d=7)$		Models
$\mathcal{O}_{QNddH}$	$\varepsilon_{ij}\left(\overline{Q_i}N_R\right)\left(\overline{d_R}d_R^c\right)\tilde{H}_j$	SS : (ω_2,Π_1) FS : (U,ω_2) (Δ_1,ω_2) (Q_1,Π_1) FV : $(Q_1,\mathcal{Q}_1)$ $(Q_1,\mathcal{U}_1)$ $(\Delta_1,\mathcal{Q}_1)$ $(U,\mathcal{U}_1)$
$\mathcal{O}_{QNQH}$	$\varepsilon_{ij}\left(\overline{Q_i}N_R\right)\left(\overline{Q_j}Q^c\right)H$	SS : (ω_1,Π_1) (Π_1,ζ) FS : (D,ω_1) (Δ_1,ω_1) (T_1,ζ) (Δ_1,ζ) (D,Π_1) (T_1,Π_1)
$\mathcal{O}_{QNudH}$	$\left(\overline{Q}N_R\right)\left(\overline{u_R}d_R^c\right)H$	SS : (ω_1,Π_1) FS : (D,ω_1) (Δ_1,ω_1) (Q_5,Π_1) (Q_1,Π_1) FV : $(Q_1,\mathcal{Q}_1)$ $(Q_1,\mathcal{U}_1)$ $(Q_5,\mathcal{Q}_5)$ $(Q_5,\mathcal{U}_2)$ $(\Delta_1,\mathcal{Q}_1)$ $(D,\mathcal{U}_1)$ $(\Delta_1,\mathcal{Q}_5)$ $(D,\mathcal{U}_2)$

Table 10. Baryon number violating operators of $d=6$ and $d=7$ in N_RSMEFT and their tree-level decompositions. Models are classified in terms of the Lorentz nature of the fields.

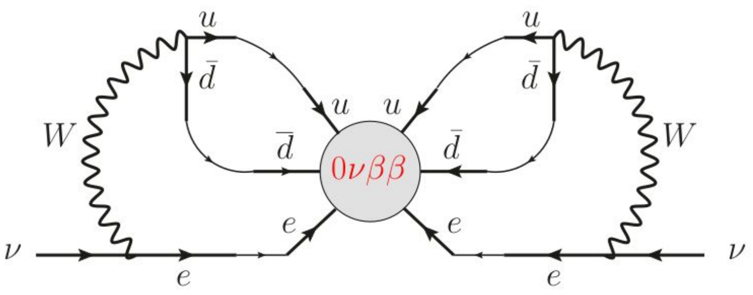
Backup: All d=7 operators

Class	Operator	Definition
$N\psi H^3 D$	$\mathcal{O}_{NL1}$	$\epsilon_{ij}(\overline{N^C}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
	$\mathcal{O}_{NL2}$	$\epsilon_{ij}(\overline{N^C}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$N\psi H^2 D^2$	$\mathcal{O}_{NeD}$	$\epsilon_{ij}(\overline{N^C}\overleftrightarrow{D}^\mu e)(H^i D^\mu H^j)$
$N\psi H^2 X$	$\mathcal{O}_{NeW}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\sigma^{\mu\nu}e)(H^i H^j)W^I_{\mu\nu}$
$N\psi HDX$	$\mathcal{O}_{NLB1}$	$g_1\epsilon_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)B_{\mu\nu}$
	$\mathcal{O}_{NLB2}$	$g_1\epsilon_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)\tilde{B}_{\mu\nu}$
	$\mathcal{O}_{NLW1}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)W^I_{\mu\nu}$
	$\mathcal{O}_{NLW2}$	$g_2(\epsilon\tau^I)_{ij}(\overline{N^C}\gamma^\mu L^i)(D^\nu H^j)\tilde{W}^I_{\mu\nu}$
$N^2 H^4$	$\mathcal{O}_{NH}$	$(\overline{N^C}N)(H^\dagger H)^2$
$N^2 H^2 D^2$	$\mathcal{O}_{NHD1}$	$(\overline{N^C}\overleftrightarrow{\partial}_\mu N)(H^\dagger\overleftrightarrow{D^\mu}H)$
	$\mathcal{O}_{NHD2}$	$(\overline{N^C}N)(D_\mu H)^\dagger D^\mu H$
$N^2 H^2 X$	$\mathcal{O}_{NHB}$	$g_1(\overline{N^C}\sigma_{\mu\nu}N)(H^\dagger H)B^{\mu\nu}$
	$\mathcal{O}_{NHW}$	$g_2(\overline{N^C}\sigma_{\mu\nu}N)(H^\dagger\tau^I H)W^{I\mu\nu}$
$N\psi^3 D$	$\mathcal{O}_{eNLLD}$	$\epsilon_{ij}(\bar{e}\gamma_\mu N)(\overline{L^{i,C}}i\overleftrightarrow{D}^\mu L^j)$
	$\mathcal{O}_{duNeD}$	$(\bar{d}\gamma_\mu u)(\overline{N^C}i\overleftrightarrow{D}^\mu e)$
	$\mathcal{O}_{QuNLD}$	$(\bar{Q}i\overleftrightarrow{D}_\mu u)(\overline{N^C}\gamma^\mu L)$
	$\mathcal{O}_{dQNLD}$	$\epsilon_{ij}(\bar{d}i\overleftrightarrow{D}_\mu Q^i)(\overline{N^C}\gamma^\mu L^j)$
$N^2\psi^2 D$	$\mathcal{O}_{LND}$	$(\bar{L}\gamma_\mu L)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
	$\mathcal{O}_{QND}$	$(\bar{Q}\gamma_\mu Q)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
	$\mathcal{O}_{eND}$	$(\bar{e}\gamma_\mu e)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
	$\mathcal{O}_{uND}$	$(\bar{u}\gamma_\mu u)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
	$\mathcal{O}_{dND}$	$(\bar{d}\gamma_\mu d)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$N^4 D$	$\mathcal{O}_{NND}$	$(\bar{N}\gamma_\mu N)(\overline{N^C}i\overleftrightarrow{\partial}^\mu N)$
$N\psi^3 H$	$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\bar{L}\gamma_\mu L)(\overline{N^C}\gamma^\mu L^i)H^j$
	$\mathcal{O}_{QNLH1}$	$\epsilon_{ij}(\bar{Q}\gamma_\mu Q)(\overline{N^C}\gamma^\mu L^i)H^j$
	$\mathcal{O}_{QNLH2}$	$\epsilon_{ij}(\bar{Q}\gamma_\mu Q^i)(\overline{N^C}\gamma^\mu L^j)H$
	$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\bar{e}\gamma_\mu e)(\overline{N^C}\gamma^\mu L^i)H^j$
	$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\bar{d}\gamma_\mu d)(\overline{N^C}\gamma^\mu L^i)H^j$
	$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\bar{u}\gamma_\mu u)(\overline{N^C}\gamma^\mu L^i)H^j$
	$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(\overline{N^C}\gamma^\mu L^i)\tilde{H}^j$
	$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\bar{d}Q^i)(\overline{N^C}e)H^j$
	$\mathcal{O}_{QuNeH1}$	$(\bar{Q}u)(\overline{N^C}e)H$
	$\mathcal{O}_{QuNeH2}$	$(\bar{Q}\sigma_{\mu\nu}u)(\overline{N^C}\sigma^{\mu\nu}e)H$
$N^2\psi^2 H$	$\mathcal{O}_{LNeH}$	$(\bar{L}N)(\overline{N^C}e)H$
	$\mathcal{O}_{eLNH}$	$H^\dagger(\bar{e}L)(\overline{N^C}N)$
	$\mathcal{O}_{QNdH}$	$(\bar{Q}N)(\overline{N^C}d)H$
	$\mathcal{O}_{dQNH}$	$H^\dagger(\bar{d}Q)(\overline{N^C}N)$
	$\mathcal{O}_{QNuH}$	$(\bar{Q}N)(\overline{N^C}u)\tilde{H}$
	$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\bar{u}Q)(\overline{N^C}N)$
$N^3\psi H$	$\mathcal{O}_{LNNH}$	$(\bar{L}N)(\overline{N^C}N)\tilde{H}$
	$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\bar{N}L)(\overline{N^C}N)$
$\not{B}$: $N\psi^3 D$ & $N\psi^3 H$	$\mathcal{O}_{uNdD}$	$\epsilon_{\alpha\beta\sigma}(\bar{u}_\alpha\gamma_\mu N)(\bar{d}_\beta i\overleftrightarrow{D}^\mu d^C_\sigma)$
	$\mathcal{O}_{dNQD}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\bar{d}_\alpha\gamma_\mu N)(\bar{Q}_{i\beta}i\overleftrightarrow{D}^\mu Q^C_{j\sigma})$
	$\mathcal{O}_{QNdH}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\bar{Q}_{i\alpha}N)(\bar{d}_\beta d^C_\sigma)\tilde{H}^j$
	$\mathcal{O}_{QNQH}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(\bar{Q}_{i\alpha}N)(\bar{Q}_{j\beta}Q^C_\sigma)H$
	$\mathcal{O}_{QNudH}$	$\epsilon_{\alpha\beta\sigma}(\bar{Q}_\alpha N)(\bar{u}_\beta d^C_\sigma)H$
$N^2 X^2$	$\mathcal{O}_{NB1}$	$\alpha_1(\overline{N^C}N)B_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{NB2}$	$\alpha_1(\overline{N^C}N)B_{\mu\nu}\tilde{B}^{\mu\nu}$
	$\mathcal{O}_{NW1}$	$\alpha_2(\overline{N^C}N)W^I_{\mu\nu}W^{I\mu\nu}$
	$\mathcal{O}_{NW2}$	$\alpha_2(\overline{N^C}N)W^I_{\mu\nu}\tilde{W}^{I\mu\nu}$
	$\mathcal{O}_{NG1}$	$\alpha_3(\overline{N^C}N)G^A_{\mu\nu}G^{A\mu\nu}$
	$\mathcal{O}_{NG2}$	$\alpha_3(\overline{N^C}N)G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$

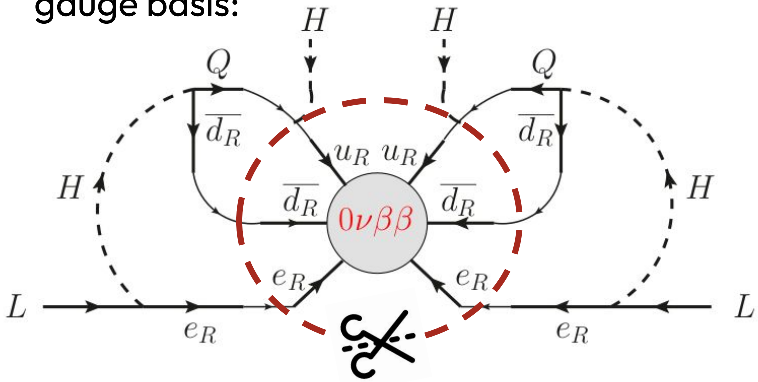
Backup: Black box theorem of $0\nu\beta\beta$

$0\nu\beta\beta$ decay guarantees a radiative contribution to the Majorana neutrino mass of a SM neutrino

mass eigenstate basis:



gauge basis:



Cutting at the thinner lines gives a contribution to $\mathcal{O}^9_{u\bar{d}e} \propto u_R^2 \overline{d_R}^2 e_R^2$

Schechter & Valle, 1982