Saitama University
埼玉大学

An Effective Theory of Neutrino

Systematic decomposition of the neutrinoless double beta decay operator

Toshihiko Ota

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based on

Florian Bonnet, Martin Hirsch, TO, Walter Winter

JHEP **1303** (2013) 055
arXiv.1212.3045

Motivation: Why 0n2b?

- In SM+3nu, **0n2b exp** are sensitive to

Effective nu mass

$$\langle m_{\beta\beta}\rangle \equiv \sum_{i=1}^{3} ({U_e}^i)^2 m_i$$

$${U_e}^1 = c_{12}c_{13}$$
$${U_e}^2 = s_{12}c_{13}\mathrm{e}^{\mathrm{i}\alpha}$$
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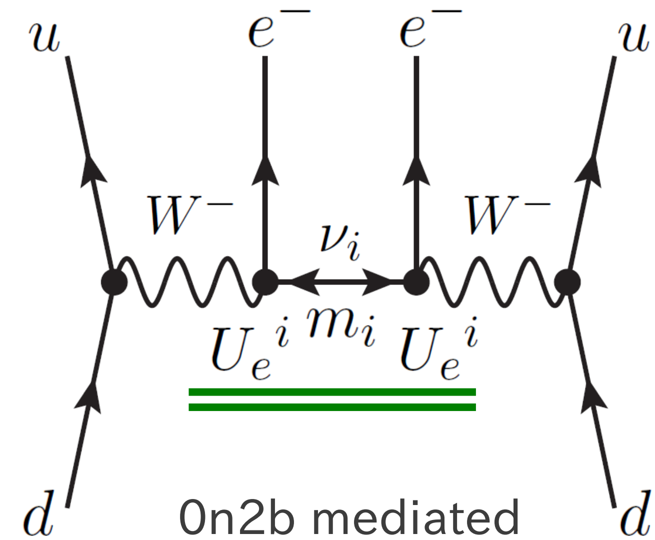

0n2b mediated by neutrinos

Normal hierarchy

$$m_1 = m_0, m_2 = \sqrt{\Delta m_{21}^2 + m_0^2}, m_3 = \sqrt{\Delta m_{31}^2 + m_0^2}$$

Inverted hierarchy

$$m_1 = \sqrt{|\Delta m_{31}^2| + m_0^2},\ m_2 = \sqrt{\Delta m_{21}^2 + |\Delta m_{31}^2| + m_0^2},$$
$$m_3 = m_0$$

m_0 represents the lightest neutrino mass

α and β are Majorana phases

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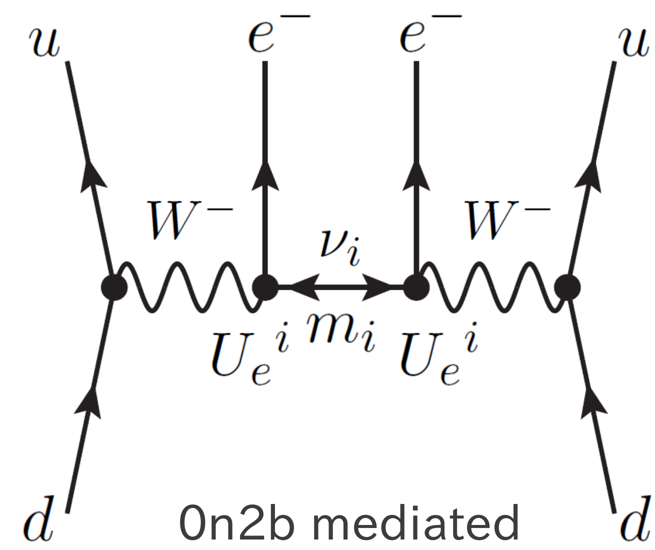

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- **Oscillation exp** told us... e.g., Gonzalez-Garcia Maltoni Salvado Schwetz, JHEP 1212 (2012) 123

$$s_{12}^2 = 0.3, \qquad s_{23}^2 = 0.41(0.59), \qquad s_{13}^2 = 0.023,$$
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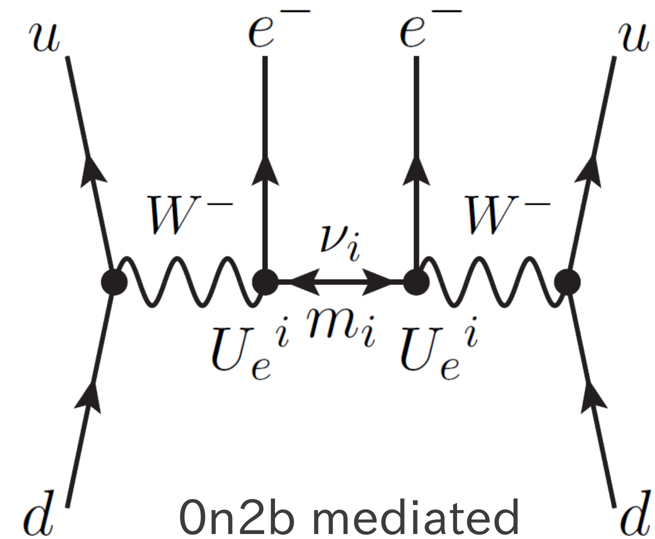

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→Talk by Saito-san

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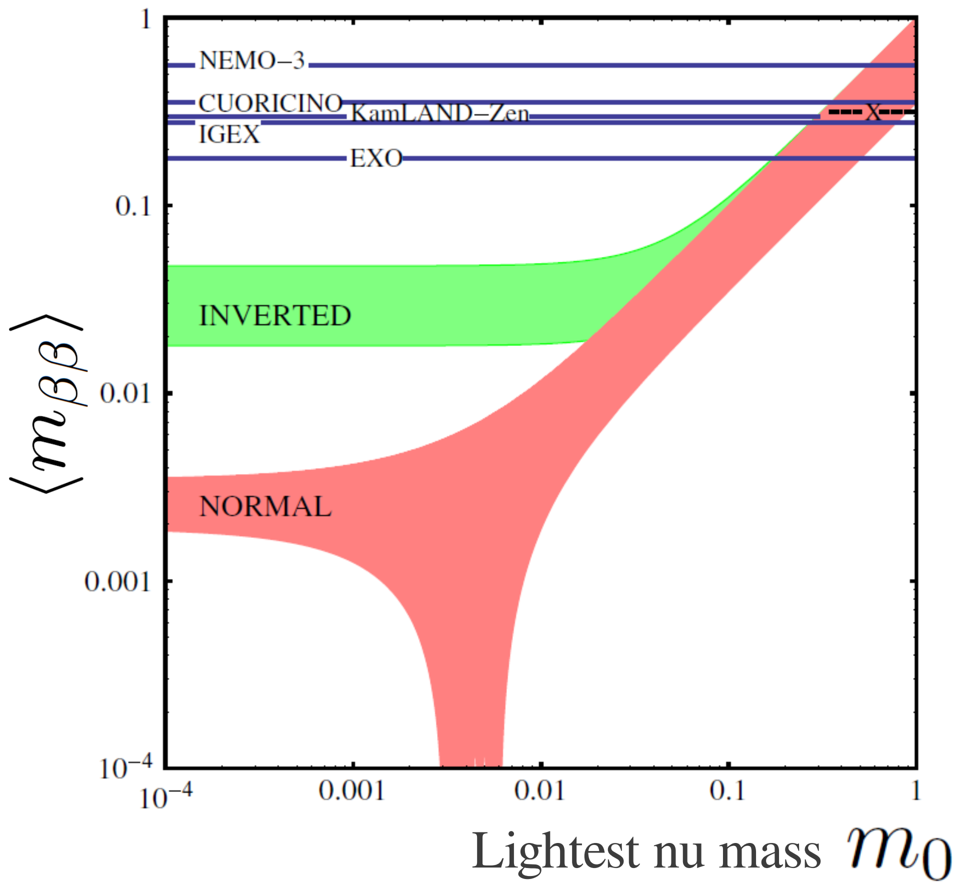

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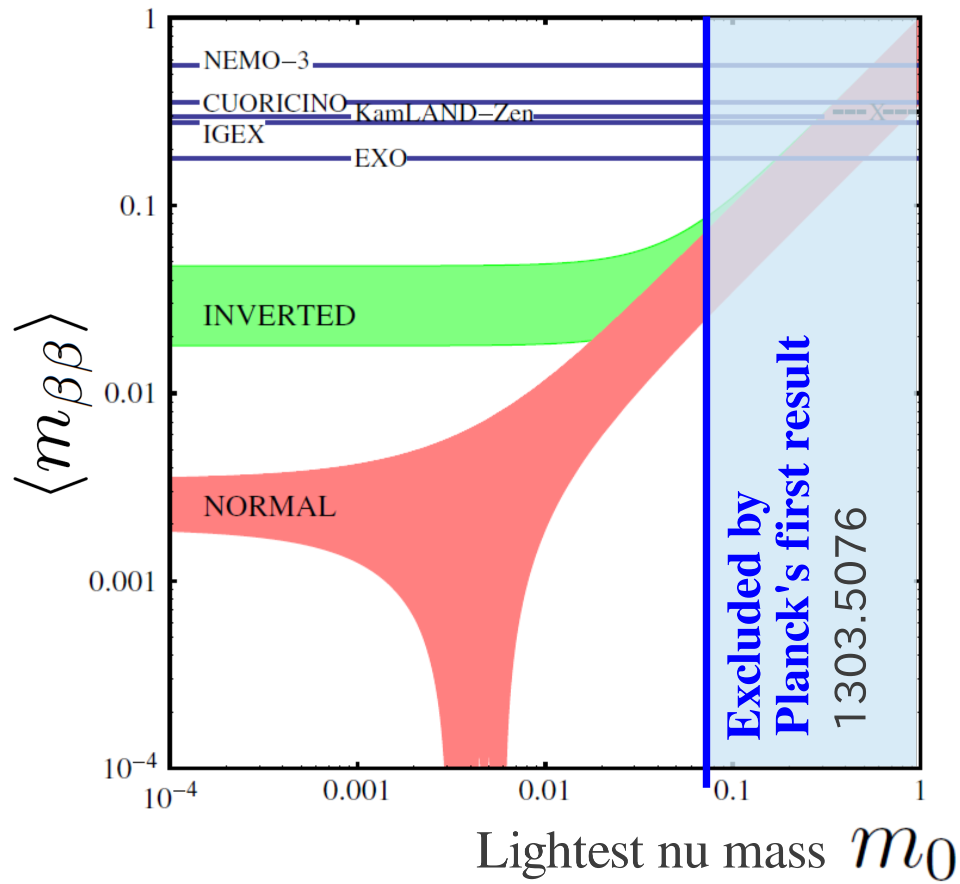

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KamLAND-Zen

PRL110 (2013) 062502

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EXO-200

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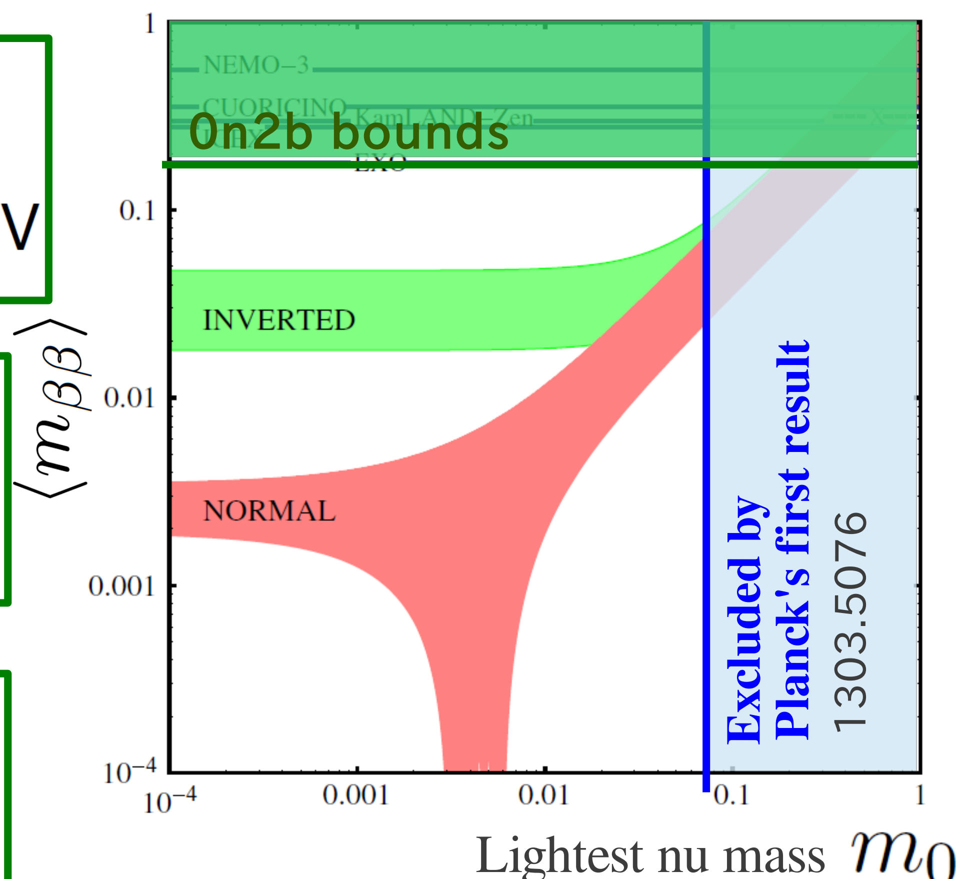

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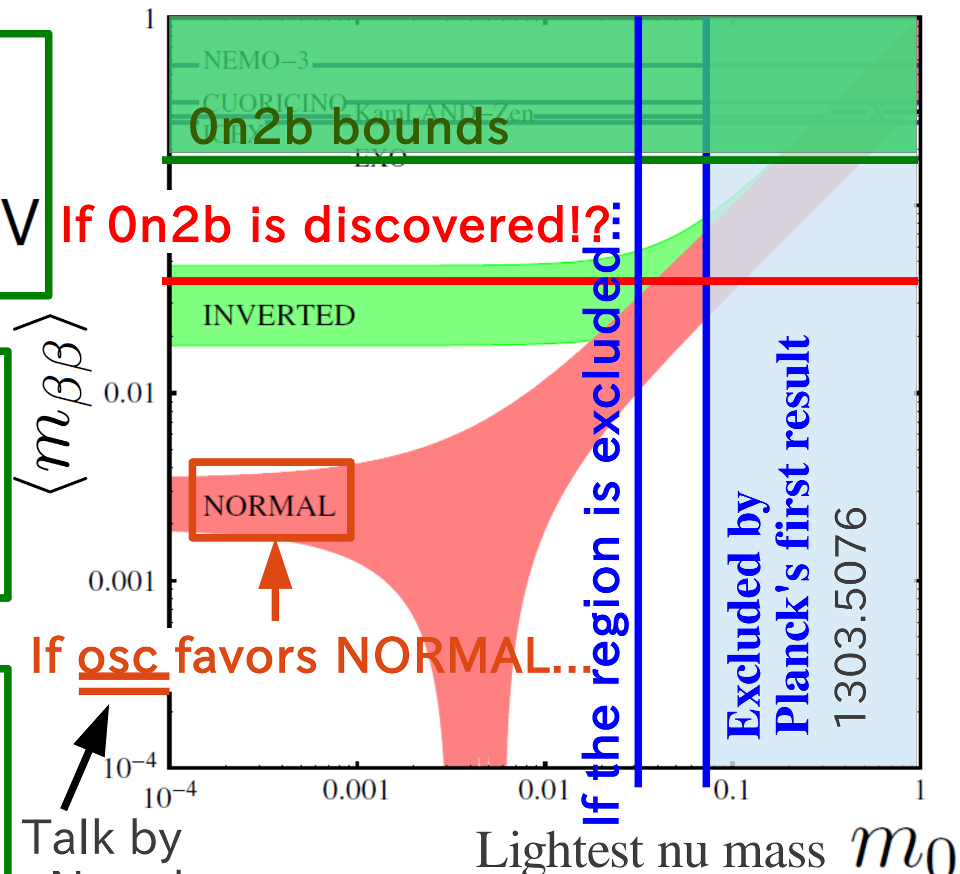

Talk by Nunokawa-san

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Q: If, in future, they will conflict with each other, what can we learn from them?

Outline

New Physics (***d=9***) contributions in neutrinoless double beta decay (0n2b)

1. ***Neutrino mass searches as a frontier to new physics: dim=9 ops***

   d=9 ops → half-life time of 0n2b processes

   "How sensitive 0n2b experiments to the d=9 ops?"

2. ***What do the d=9 ops suggest to TeV scale physics?***

   d=9 ops → decompose them to the fundamental ints.

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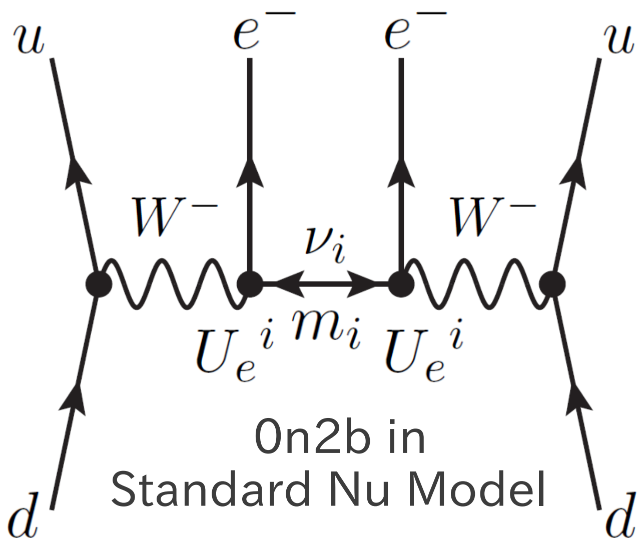

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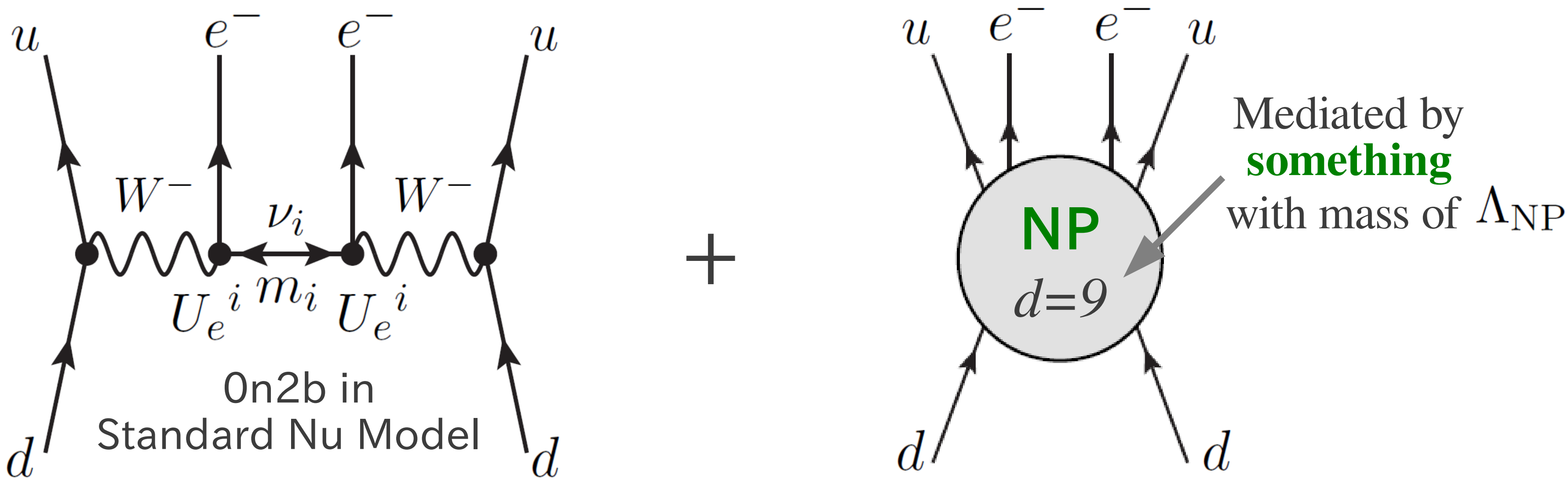

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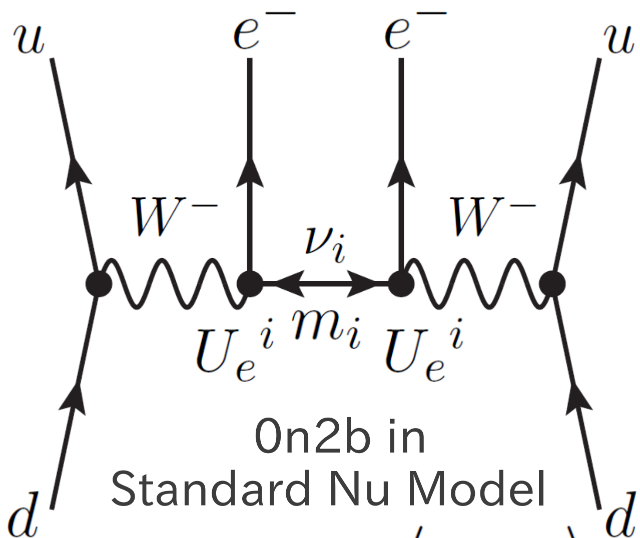

$$\mathcal{A}_{\mathrm{S}\nu\mathrm{M}} = G_F^2 \frac{\langle m_{\beta\beta} \rangle}{q^2}$$

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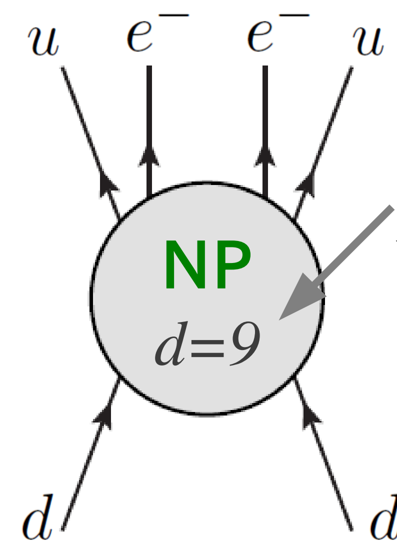

Mediated by **something** with mass of Λ_{NP}

~100 MeV
A typical size of momentum of neutrino propagating in nucleus

Current exp. limit

$$10^{25}\ [\mathrm{yr}] < T_{1/2}^{0\nu 2\beta} \propto 1/\left|\mathcal{A}_{\mathrm{S}\nu\mathrm{M}}\right|^2$$

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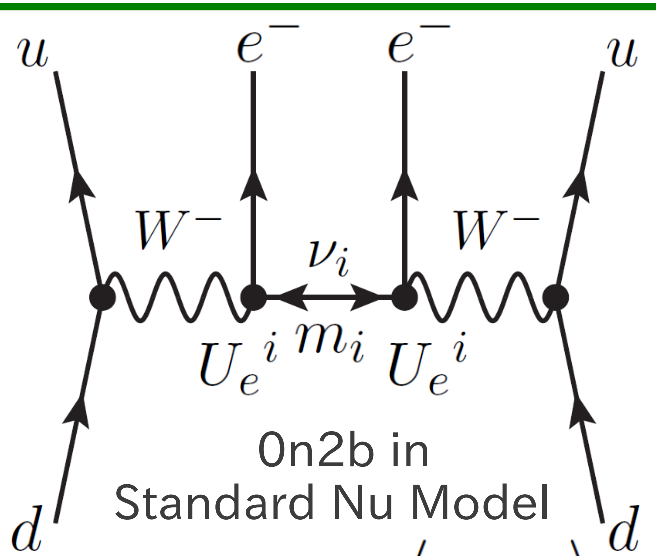

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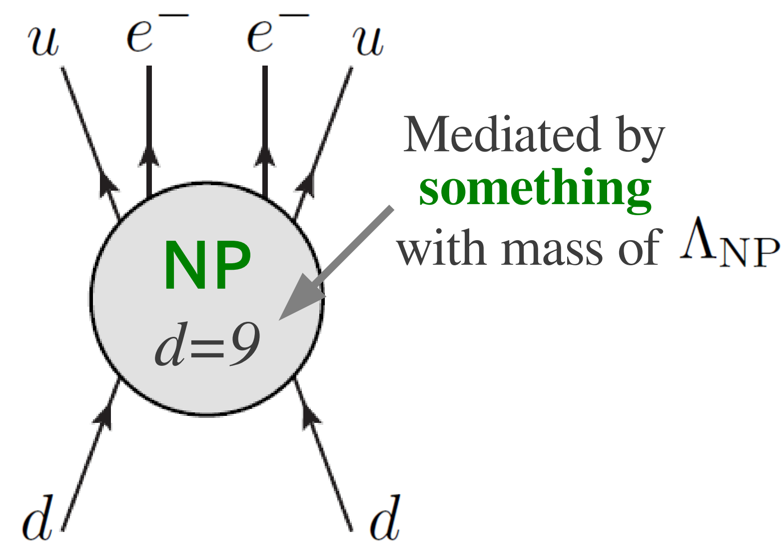

Current exp. limit

$$10^{25}\ [\mathrm{yr}] < T_{1/2}^{0\nu 2\beta} \propto 1/\left|\mathcal{A}_{\mathrm{S}\nu\mathrm{M}}\right|^2 \Rightarrow \langle m_{\beta\beta} \rangle < 0.3\ [\mathrm{eV}]$$

Sensitive to

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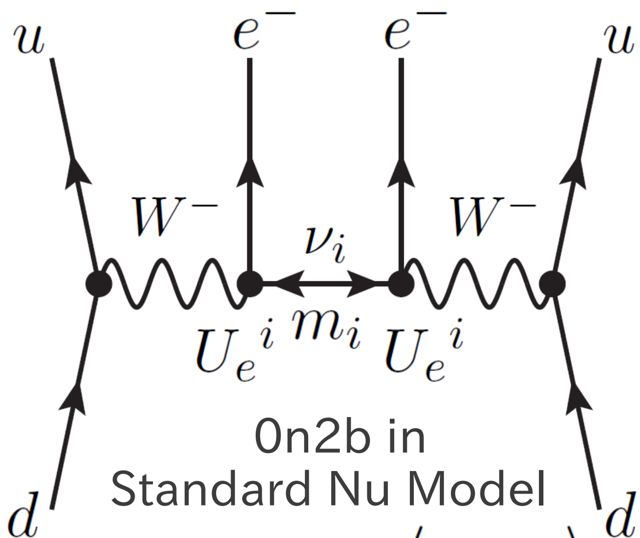

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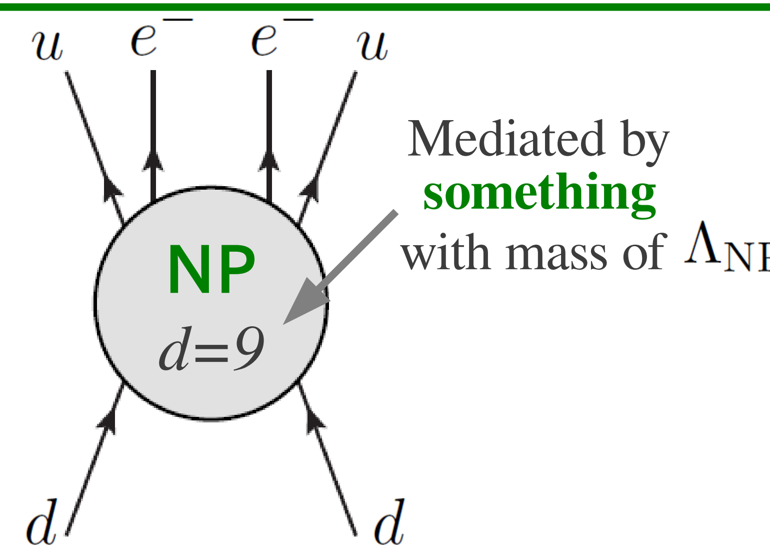

$$\mathcal{A}_{d=9} = \frac{1}{\Lambda_{\mathrm{NP}}^5}$$

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➡ Sensitive to $\langle m_{\beta\beta} \rangle < 0.3$ [eV]

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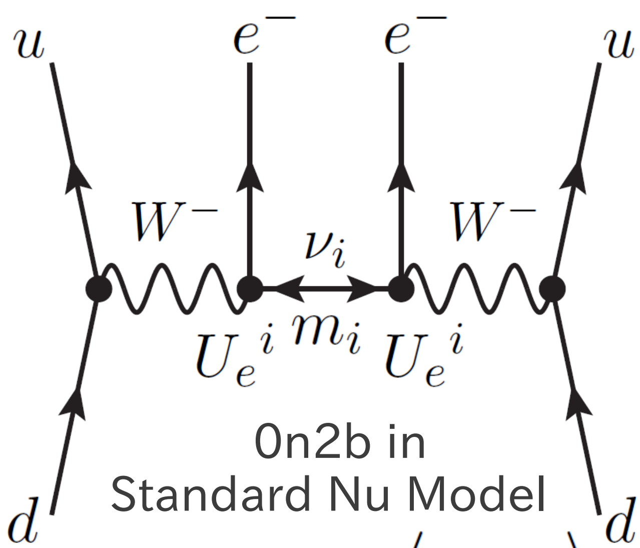

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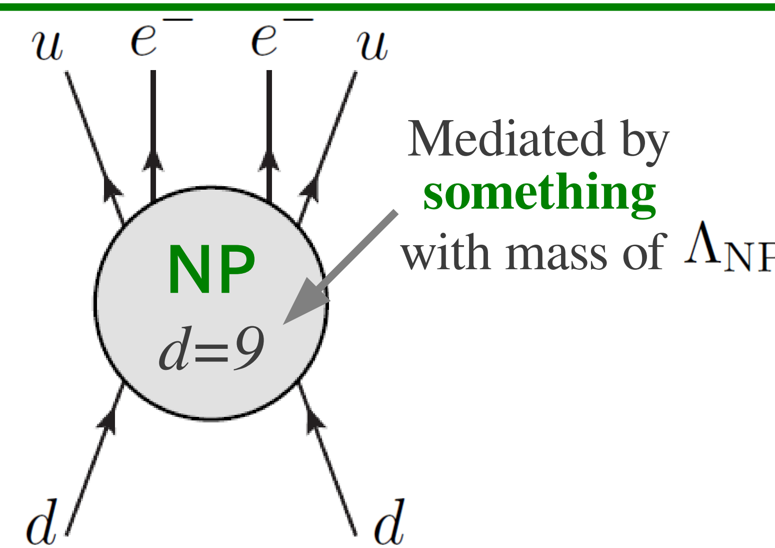

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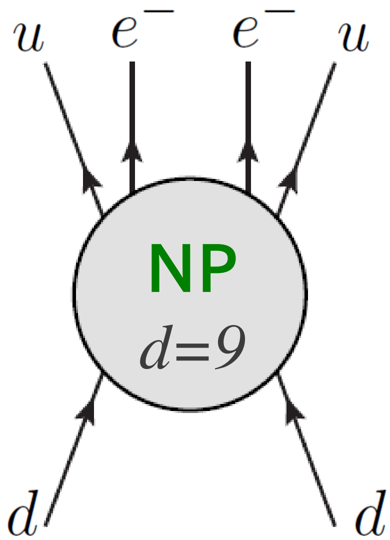
$$\propto 1/\left|\mathcal{A}_{d=9}\right|^2 \Rightarrow \Lambda_{\mathrm{NP}} > \mathcal{O}(1)\ [\mathrm{TeV}]$$

LHC range!

0n2b exps are sensitive to not only Majorana neutrino mass but also NP at TeV.



…falls into the following 5 types of effective ops.

$$\mathscr{L}_{d=9} = \frac{G_F^2}{2m_P}\left[\sum_{i=1}^{3}\epsilon_i^{\{XY\}Z}(\mathcal{O}_i)_{\{XY\}Z} + \sum_{i=5}^{4}\epsilon_i^{XY}(\mathcal{O}_i)_{XY}\right],$$

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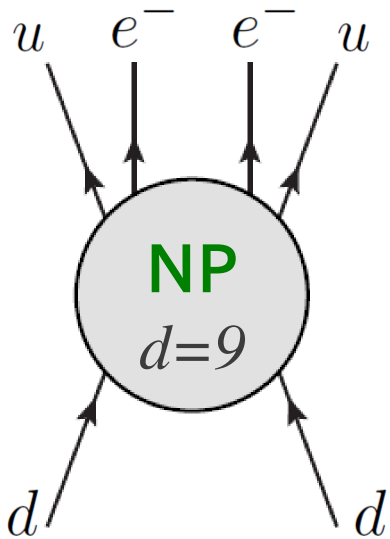
1 *d=9* op. in 0n2b — Effective ops → half-life time



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- Nice (&compact) formula to calculate the half-life time: Paes et al. PLB498 (2001) 35

$$\left(T_{1/2}^{0\nu 2\beta}\right)^{-1}_{\underline{\underline{d=9}}} = G_1 \left|\sum_{i=1}^{3} \boxed{\epsilon_i} \mathcal{M}_i\right|^2 + G_2 \left|\sum_{i=4}^{5} \boxed{\epsilon_i} \mathcal{M}_i\right|^2 + G_3 \mathrm{Re}\left[\left(\sum_{i=1}^{3} \boxed{\epsilon_i} \mathcal{M}_i\right)\left(\sum_{i=4}^{5} \boxed{\epsilon_i} \mathcal{M}_i\right)^*\right]$$

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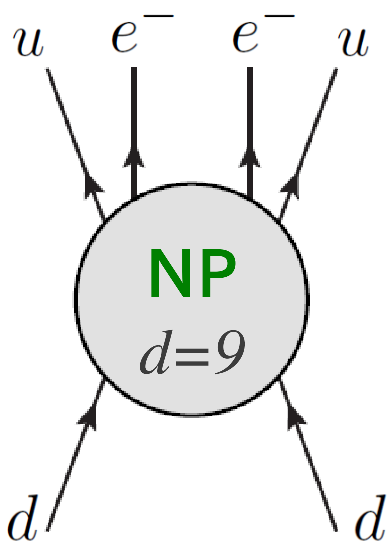
$\mathcal{M}_i$ Nuclear matrix elements
G_i Phase space factors



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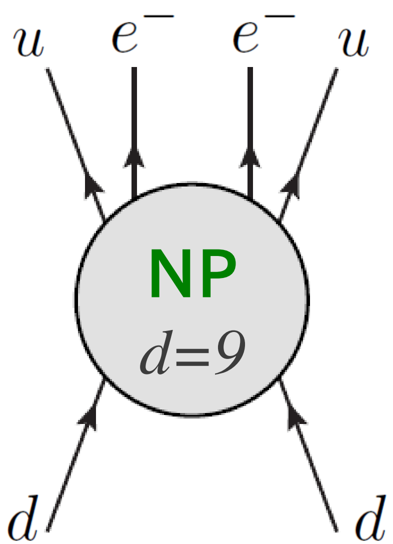

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d=9 ops. **bottom-up** → List high *E* (TeV) completions → complementarity with LHC

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Exhaustive bottom-up approach

A well-known example: 3 types of Seesaw mechanism

Theory at Λ_{EW}

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}}$$

Exhaustive bottom-up approach

A well-known example: 3 types of Seesaw mechanism

Theory at $\Lambda_{\rm EW}$

$$\mathscr{L}_{\sf eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\rm NP}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9} + \cdots$$

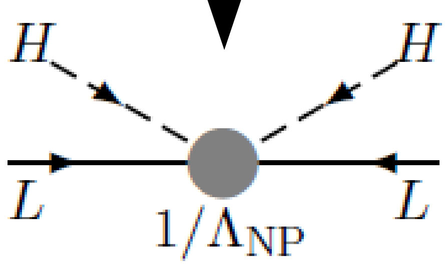
2 Effective ops → High E completions

- **Exhaustive bottom-up approach**

A well-known example: 3 types of Seesaw mechanism

Theory at Λ_{EW}

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\mathrm{NP}}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\mathrm{NP}}^5}\mathcal{O}_{d=9} + \cdots$$



d=5 Weinberg operator
(would-be **neutrino mass**)

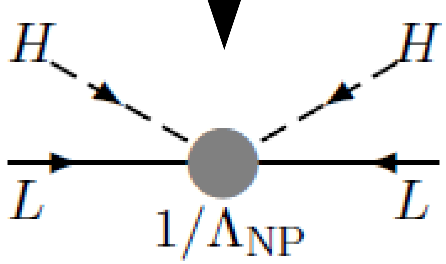
2 Effective ops → High E completions

Exhaustive bottom-up approach

A well-known example: 3 types of Seesaw mechanism

Theory at $\Lambda_{\rm EW}$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\rm NP}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9} + \cdots$$



d=5 Weinberg operator
(would-be **neutrino mass**)

bottom-up

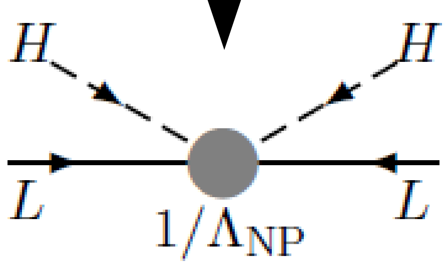
$\Lambda_{\rm EW}$ to $\Lambda_{\rm NP}$

Exhaustive bottom-up approach

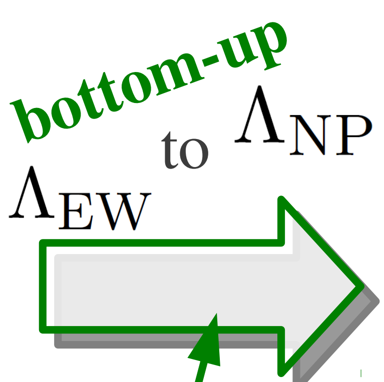
A well-known example: 3 types of Seesaw mechanism

Theory at $\Lambda_{\rm EW}$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\rm NP}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9} + \cdots$$



d=5 Weinberg operator
(would-be **neutrino mass**)



Ansatz

The op comes from a tree diagram

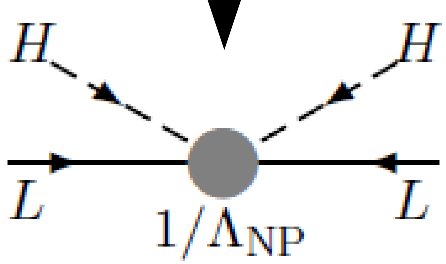
Effective ops → High E completions

Exhaustive bottom-up approach

A well-known example: 3 types of Seesaw mechanism

Theory at Λ_{EW}

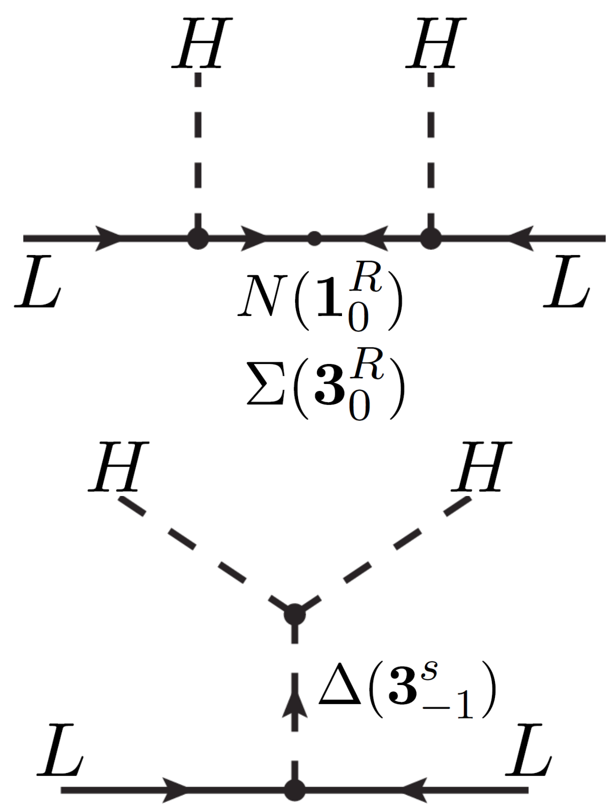
$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\mathrm{NP}}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\mathrm{NP}}^5}\mathcal{O}_{d=9} + \cdots$$



d=5 Weinberg operator
(would-be **neutrino mass**)

bottom-up
Λ_{EW} to Λ_{NP}

Ansatz
The op comes from a tree diagram



Theory at Λ_{NP}

Seesaw mech.

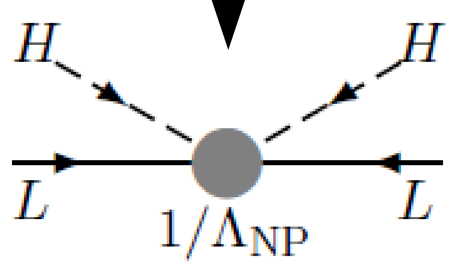
2 *Effective ops → High E completions*

- **Exhaustive bottom-up approach**

A well-known example: 3 types of Seesaw mechanism

Theory at $\Lambda_{\rm EW}$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\rm NP}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9} + \cdots$$

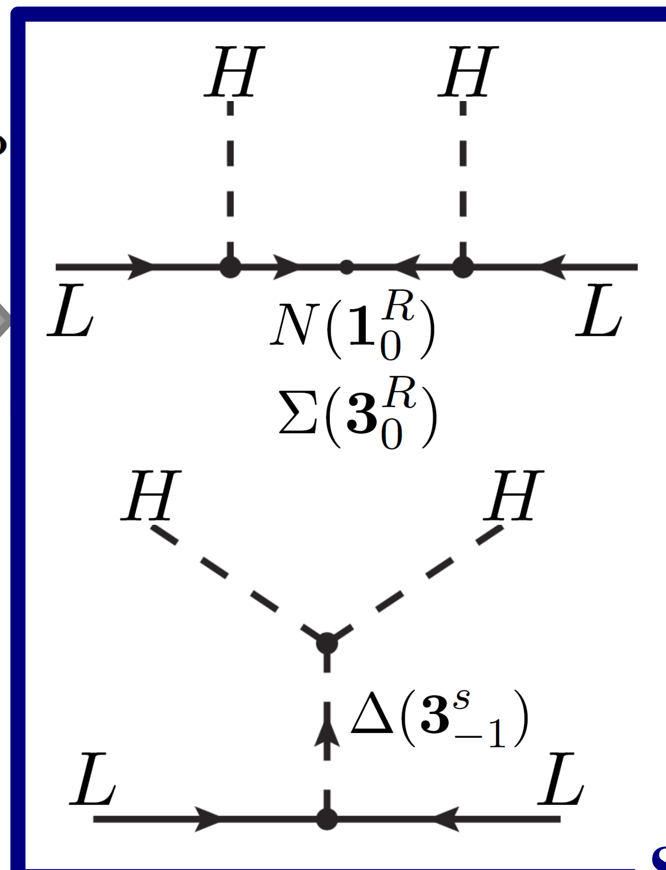


d=5 Weinberg operator
(would-be **neutrino mass**)

Ansatz

The op comes from a tree diagram

bottom-up
$\Lambda_{\rm EW}$ to $\Lambda_{\rm NP}$



Seesaw mech.

Different types,
Diffrent Phenos

LFV
Leptogenesis
⋮

Discrimination
of types

Theory at $\Lambda_{\rm NP}$

2 Effective ops → High E completions

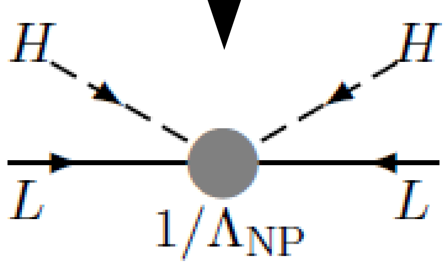
- **Exhaustive bottom-up approach**

A well-known example: 3 types of Seesaw mechanism

NP contribution to 0n2b

Theory at $\Lambda_{\rm EW}$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda_{\rm NP}}\mathcal{O}_{d=5} + \frac{1}{\Lambda_{\rm NP}^2}\mathcal{O}_{d=6} + \frac{1}{\Lambda_{\rm NP}^3}\mathcal{O}_{d=7} + \frac{1}{\Lambda_{\rm NP}^4}\mathcal{O}_{d=8} + \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9} + \cdots$$



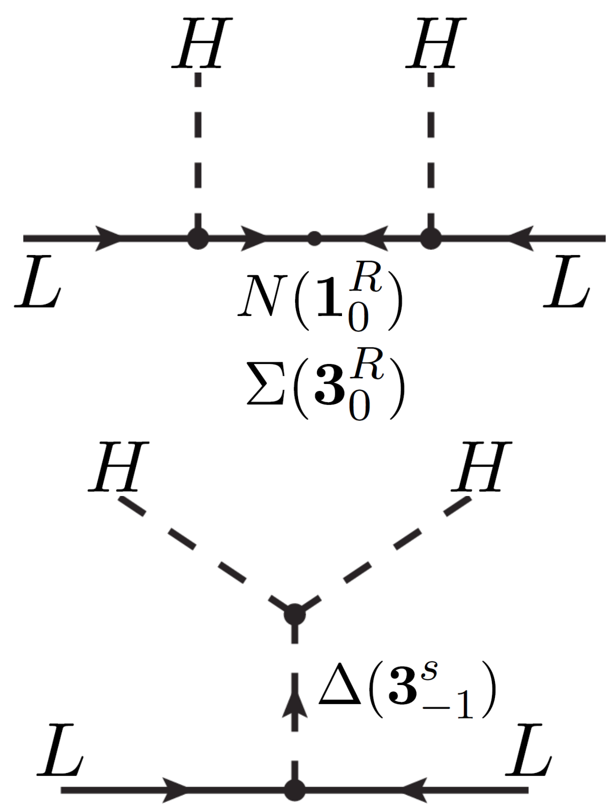
d=5 Weinberg operator (would-be **neutrino mass**)

bottom-up

$\Lambda_{\rm EW}$ to $\Lambda_{\rm NP}$

Ansatz

The op comes from a tree diagram



Seesaw mech.

Different types, Diffrent Phenos

LFV

Leptogenesis

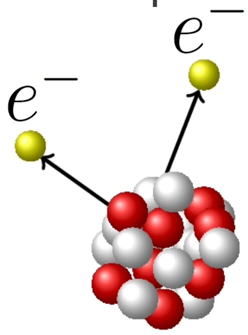
⋮

Discrimination of types

Theory at $\Lambda_{\rm NP}$

Exhaustive bottom-up approach

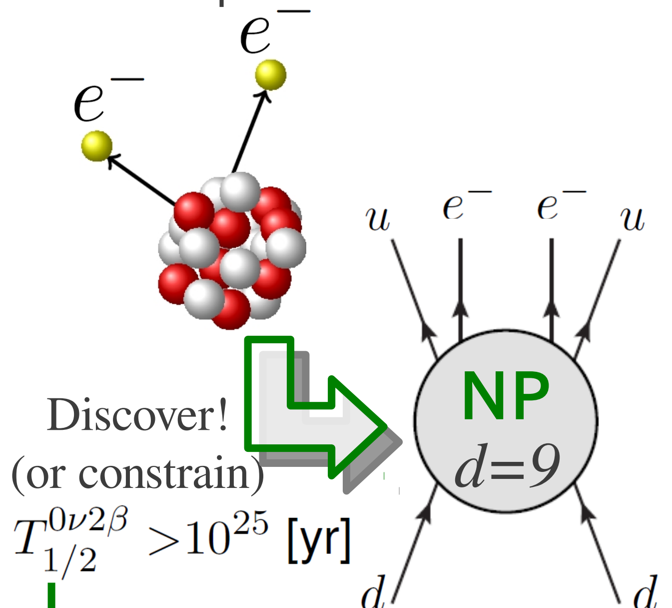
0n2b experiments



Discover!
(or constrain)
$T_{1/2}^{0\nu 2\beta} > 10^{25}$ [yr]

Exhaustive bottom-up approach

0n2b experiments



$T_{1/2}^{0\nu 2\beta} > 10^{25}$ [yr]

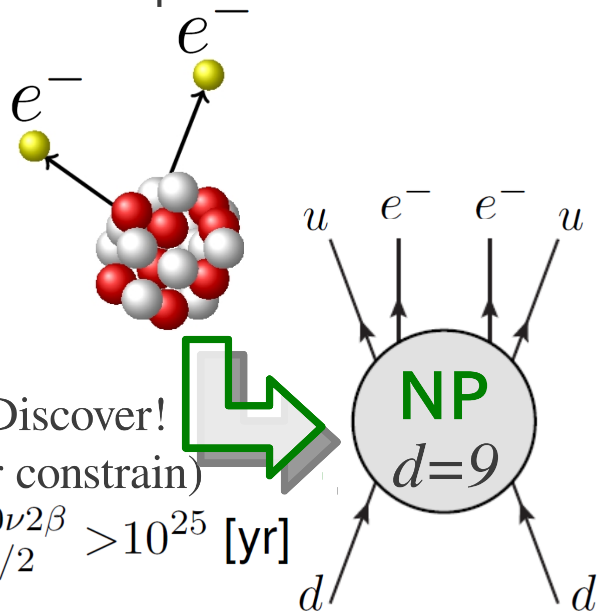
$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}_{d=9}^{\rm tree} \; @\Lambda_{\rm EW}$$

→ $\Lambda_{\rm NP} > \mathcal{O}(1)$ [TeV]

2 Effective ops → High E completions

- **Exhaustive bottom-up approach**

0n2b experiments



Discover!
(or constrain)
$T_{1/2}^{0\nu 2\beta} > 10^{25}$ [yr]

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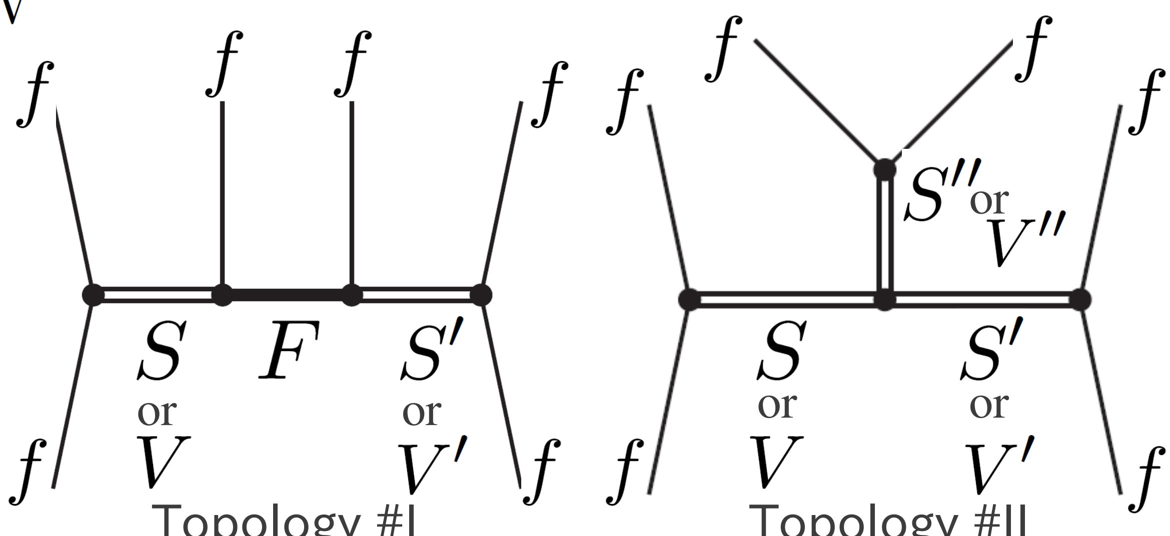
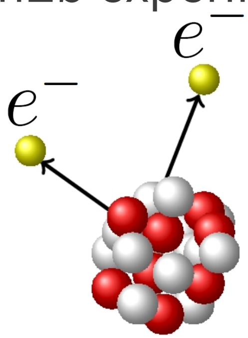
Decompose
Eff. *d=9* ops
to tree diagrams

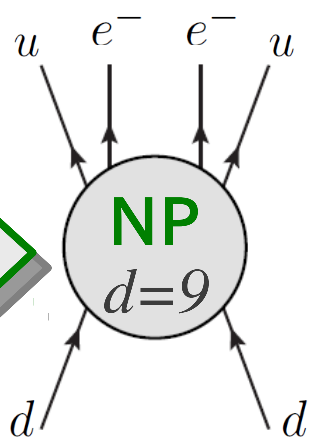
$@\Lambda_{\rm NP}$



Exhaustive bottom-up approach

0n2b experiments





Discover!
(or constrain)
$T^{0\nu2\beta}_{1/2} > 10^{25}$ [yr]

How to decompose / Necessary Mediators

		BL op.	S	F	S'	Basis operators
2-i-a	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#19	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_R(J_R)^\rho(j)_\rho$
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#14	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_L J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#20	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_L(J_R)^\rho(j)_\rho$
2-i-b	$(\overline{u_L}d_R)(\overline{e_L})(d_R)(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

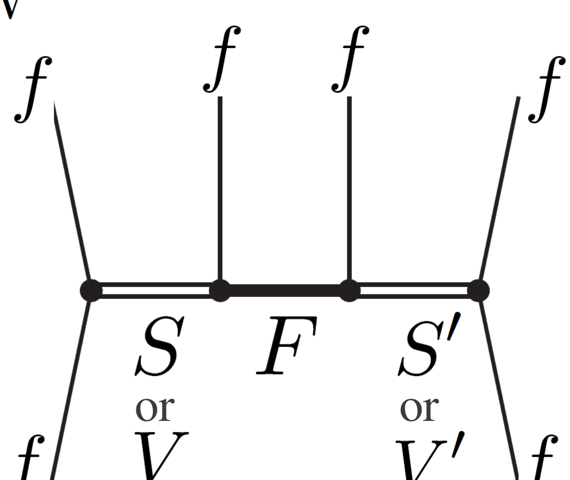
List of high E completions@$\Lambda_{\rm NP}$

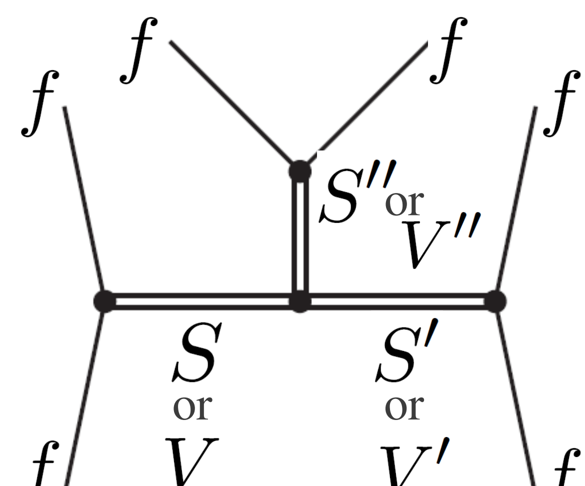
$$\mathcal{L}_{d=9} = \frac{1}{\Lambda^5_{\rm NP}}\mathcal{O}^{\rm tree}_{d=9} \ @\Lambda_{\rm EW}$$

→ $\Lambda_{\rm NP} > \mathcal{O}(1)$ [TeV]

Decompose
Eff. *d=9* ops
to tree diagrams

@$\Lambda_{\rm NP}$





2 Effective ops → High E completions

Exhaustive bottom-up approach

How to decompose / **Necessary Mediators**

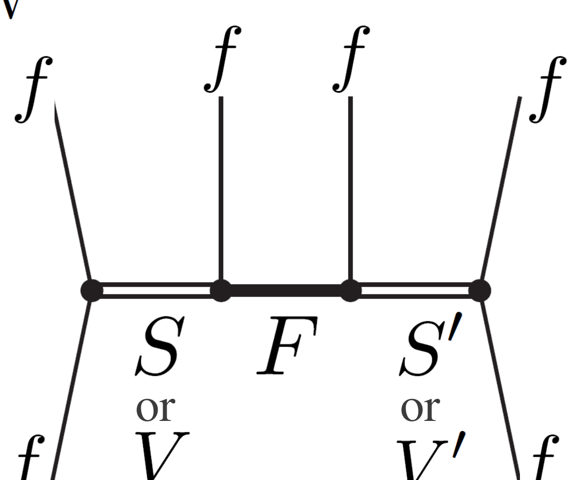
		BL op.	S	F	S'	Basis operators
2-i-a	$(\overline{u_L} d_R)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_L} d_R)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#19	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_R(J_R)^\rho(j)_\rho$
	$(\overline{u_R} d_L)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#14	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_L J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_R} d_L)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#20	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_L(J_R)^\rho(j)_\rho$
2-i-b	$(\overline{u_L} d_R)(\overline{e_L})(d_R)(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

List of high *E* completions@ $\Lambda_{\rm NP}$

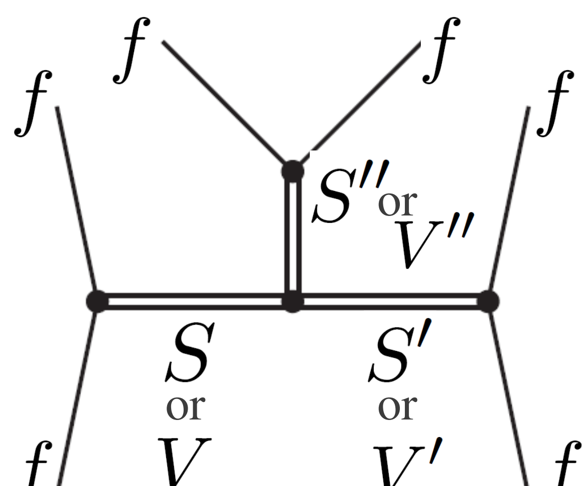
@ $\Lambda_{\rm EW}$

ms

@ $\Lambda_{\rm NP}$



Topology #I



Topology #II

2 Effective ops → High E completions

- **Exhaustive bottom-up approach**

Re-integrate out the Mediators → Effective theories@Λ_{EW}

How to decompose — **Necessary Mediators**

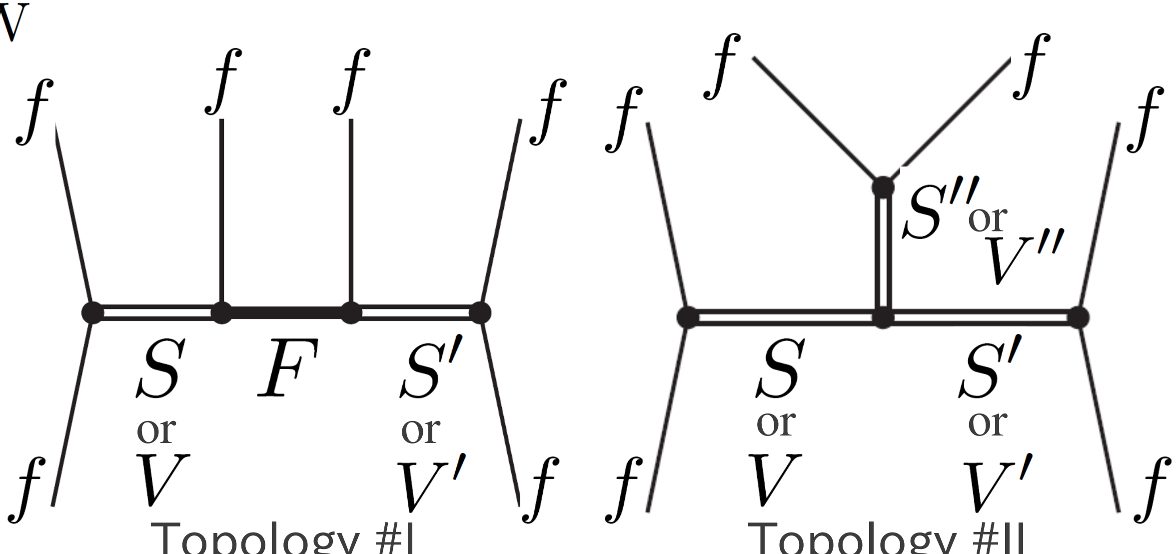
		BL op.	S	F	S'	Basis operators
2-i-a	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#19	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_R(J_R)^\rho(j)_\rho$
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#14	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_L J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#20	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_L(J_R)^\rho(j)_\rho$
2-i-b	$(\overline{u_L}d_R)(\overline{e_L})(d_R)(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

List of high *E* completions@Λ_{NP}

@Λ_{EW}

ms

@Λ_{NP}



2 Effective ops → High E completions

- **Exhaustive bottom-up approach**

Re-integrate out the Mediators

How to decompose

Necessary Mediators

		BL op.	S	F	S'	Basis operators
2-i-a	$(\overline{u_L} d_R)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2} J_R J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_L} d_R)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#19	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2} J_R (J_R)^\rho (j)_\rho$
	$(\overline{u_R} d_L)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#14	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2} J_L J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_R} d_L)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#20	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2} J_L (J_R)^\rho (j)_\rho$
2-i-b	$(\overline{u_L} d_R)(\overline{e_L})(d_R)(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2} J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

Effective theories@$\Lambda_{\rm EW}$

$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\rm NP}^5} \mathcal{O}^{\rm tree}_{d=9} +$$

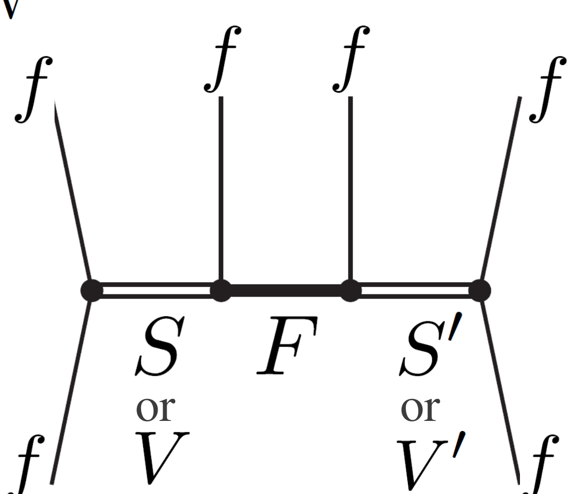
- Low E pheno #1
- Low E pheno #2
- Low E pheno #3
- Low E pheno #4
- ⋮

List of high E completions@$\Lambda_{\rm NP}$

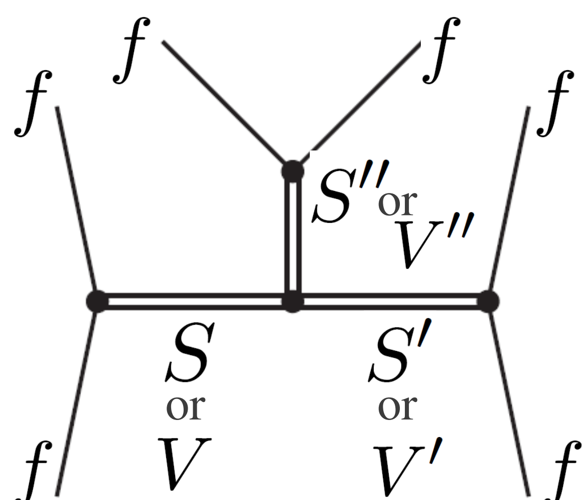
@$\Lambda_{\rm EW}$

ms

@$\Lambda_{\rm NP}$



Topology #I



Topology #II

2 *Effective ops → High E completions*

- **Exhaustive bottom-up approach**

Re-integrate out the Mediators

How to decompose

Necessary Mediators

	BL op.		S	F	S'	Basis operators
2-i-a	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_L}d_R)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#19	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_R(J_R)^\rho(j)_\rho$
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_L e_L})$	#14	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_L J_R j_R$
			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	
	$(\overline{u_R}d_L)(d_R)(\overline{e_L})(\overline{u_R e_R})$	#20	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\overline{\mathbf{3}},\mathbf{2})_{+5/6}$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$\frac{1}{2}J_L(J_R)^\rho(j)_\rho$
2-i-b	$(\overline{u_L}d_R)(\overline{e_L})(d_R)(\overline{u_L e_L})$	#11	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
⋮			$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

Effective theories@Λ_{EW}

$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\mathrm{NP}}^5}\mathcal{O}_{d=9}^{\mathrm{tree}}$$

\+

- Low E pheno #1
- Low E pheno #2
- Low E pheno #3
- Low E pheno #4

⋮

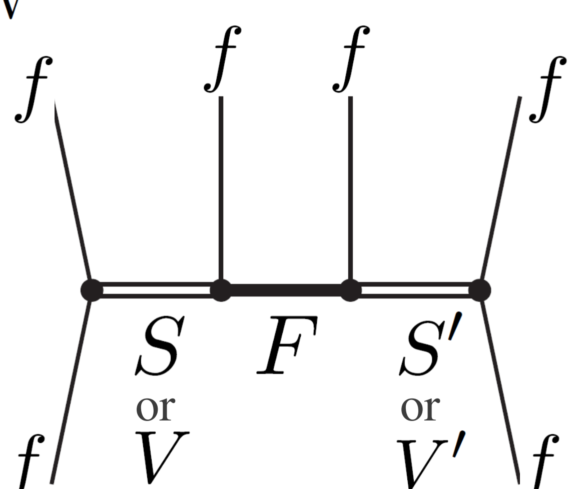
Testing phenos, we can identify the models@Λ_{NP}

List of high E completions@Λ_{NP}

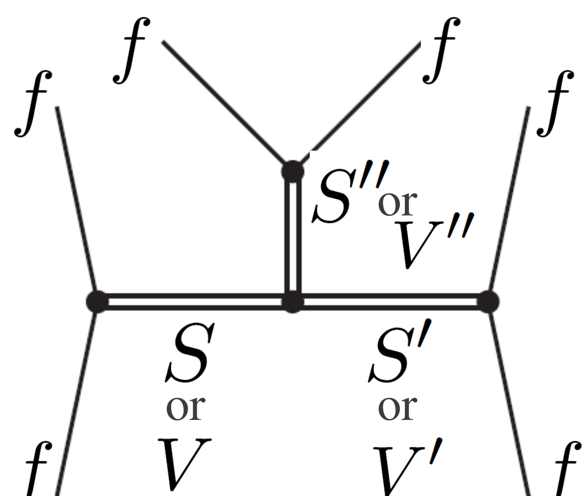
@Λ_{EW}

ms

@Λ_{NP}



Topology #I



Topology #II

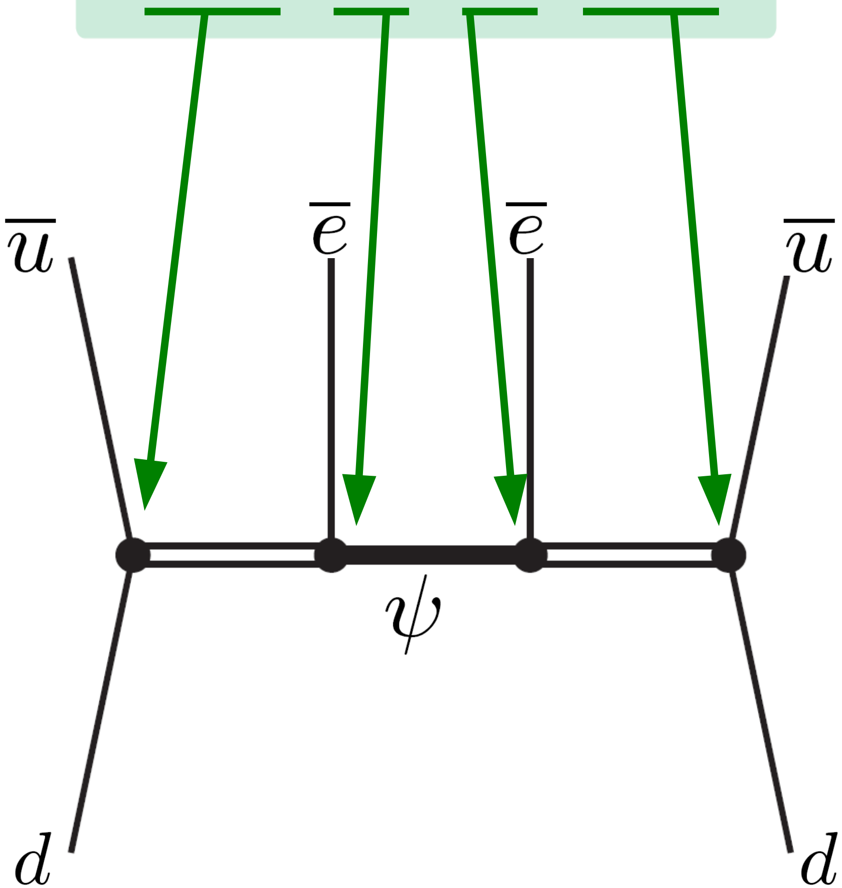
We can explore high E models relating to $\mathcal{O}_{d=9}$, systematically.

- An example,

  Taking Topology #I

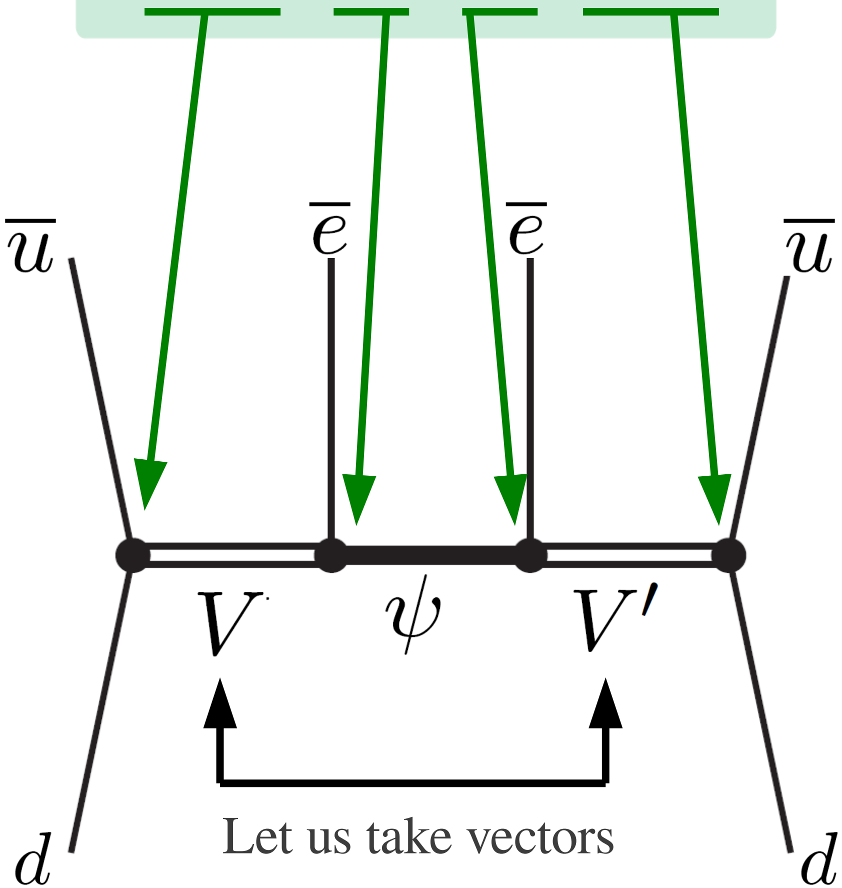
  let us decompose d=9 op as

$$(\overline{u}d)(\overline{e})(\overline{e})(\overline{u}d)$$



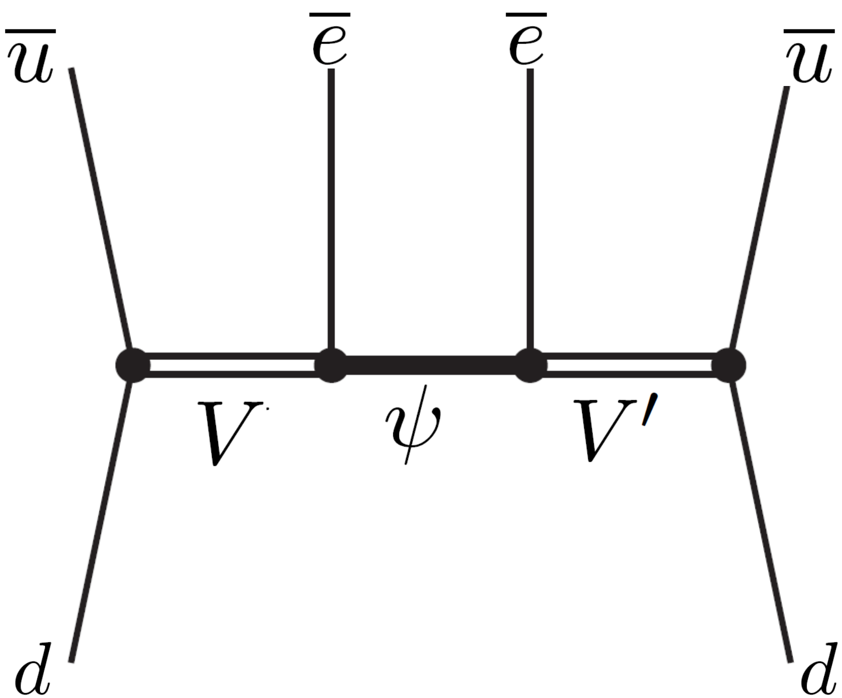
- An example,
  Taking Topology #I
  let us decompose *d=9* op as

$$(\overline{u}d)(\overline{e})(\overline{e})(\overline{u}d)$$



- An example,
  Taking Topology #I
  let us decompose *d=9* op as

$$(\overline{u}d)(\overline{e})(\overline{e})(\overline{u}d)$$



Necessary mediators

$$V(+1,\mathbf{1})$$
$$V'(-1,\mathbf{1})$$
$$\psi(0,\mathbf{1})$$

where $(U(1)_{\mathrm{em}}, SU(3)_{\mathrm{c}})$

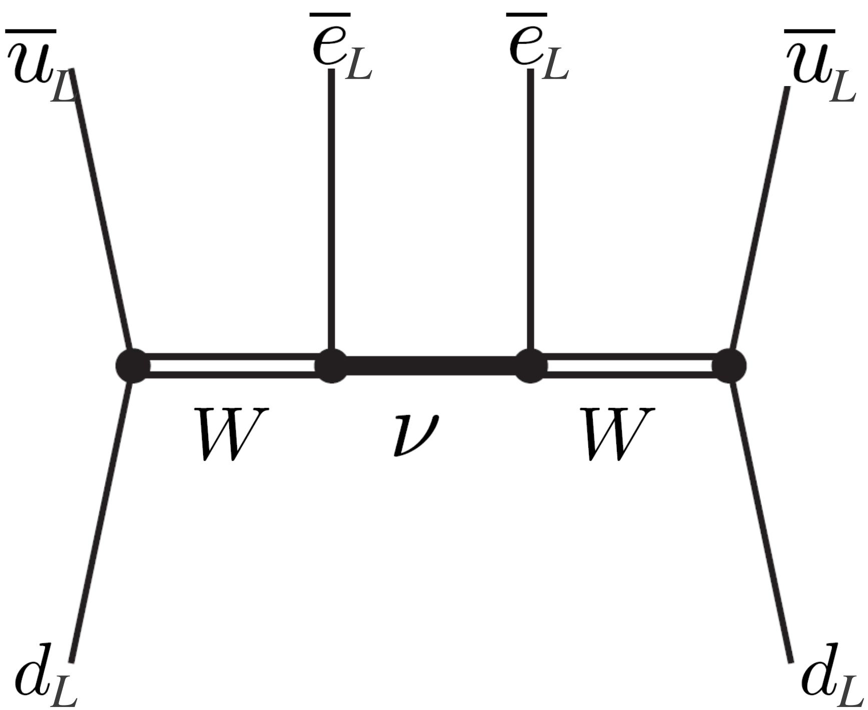
- An example,
  Taking Topology #I
  let us decompose *d=9* op as

$$(\overline{u}d)(\overline{e})(\overline{e})(\overline{u}d)$$

Necessary mediators

$V(+1,\mathbf{1})$	W^+
$V'(-1,\mathbf{1})$	W^-
$\psi(0,\mathbf{1})$	ν

where $(U(1)_{\text{em}}, SU(3)_{\text{c}})$



Rediscovery of the standard neutrino mass contribution

All the outer fermions must be left-handed

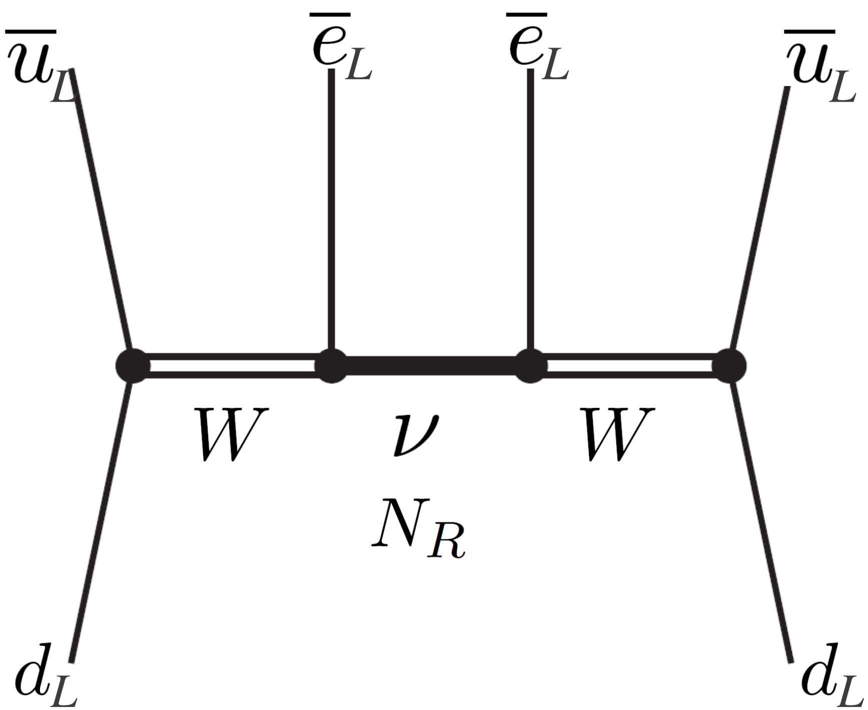
- An example,
  Taking Topology #I
  let us decompose *d=9* op as

$$(\overline{u}d)(\overline{e})(\overline{e})(\overline{u}d)$$

Necessary mediators

$V(+1,\mathbf{1})$	W^+	
$V'(-1,\mathbf{1})$	W^-	
$\psi(0,\mathbf{1})$	ν	N_R

where ($U(1)_{\text{em}}$, $SU(3)_{\text{c}}$)



Rediscovery of the standard neutrino mass contribution

All the outer fermions must be left-handed

In Seesaw model,
right-handed neutrinos (sterile neutrinos) can also mediate this diagram.

- Another example,

Decomposition

$$(\overline{u}d)(\overline{e})(d)(\overline{ue})$$

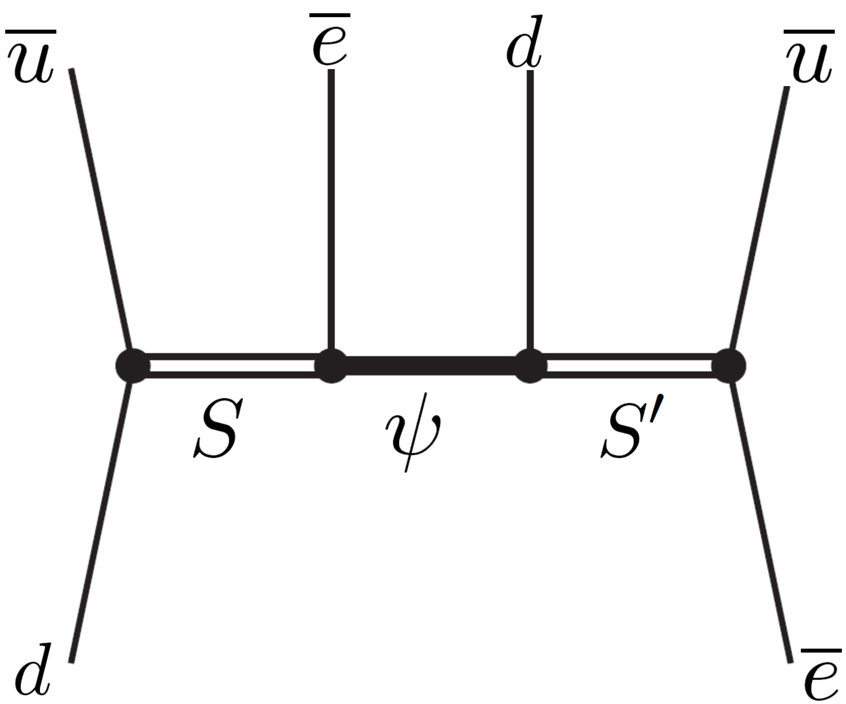
Necessary mediators

$S(1, \mathbf{1})$

$S'(+1/3, \overline{\mathbf{3}})$

$\psi(0, \mathbf{1})$

where $(U(1)_{\text{em}}, SU(3)_{\text{c}})$



- Another example,

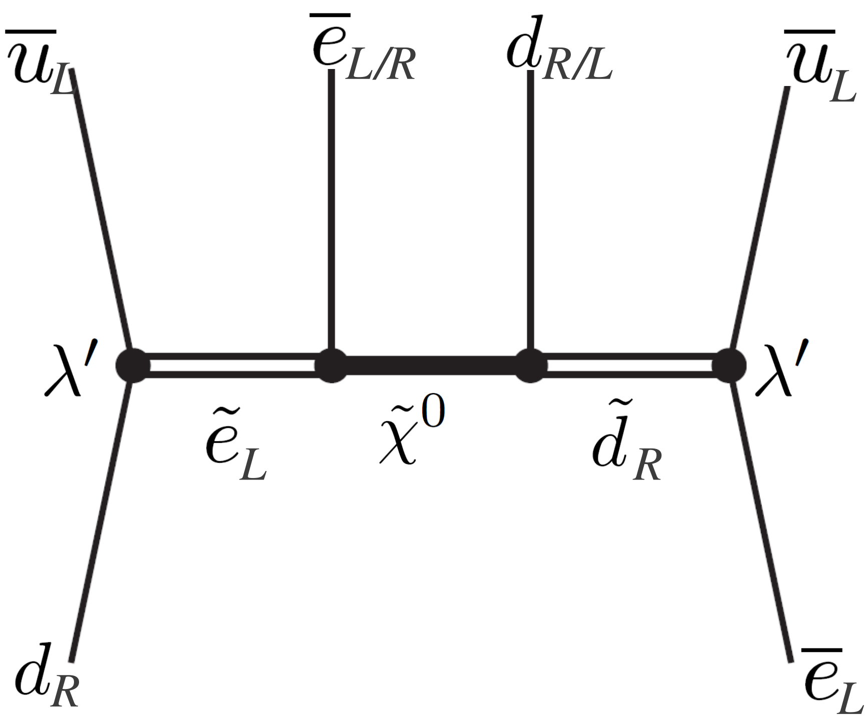
Decomposition

$$(\overline{u}d)(\overline{e})(d)(\overline{ue})$$

Necessary mediators

$S(1,\mathbf{1})$	$\tilde{e}^*$
$S'(+1/3,\overline{\mathbf{3}})$	$\tilde{d}^*$
$\psi(0,\mathbf{1})$	$\tilde{\chi}^0$

where $(U(1)_{\rm em}, SU(3)_{\rm c})$



R-parity violating SUSY models

$$\mathcal{W}_{\not R} \ni \lambda' \hat{L}\hat{Q}\hat{D}^c$$

Hirsch Klapdor-Kleingrothaus Kovalenko, PL**B378** (1996) 17, PR**D54** (1996) 4207

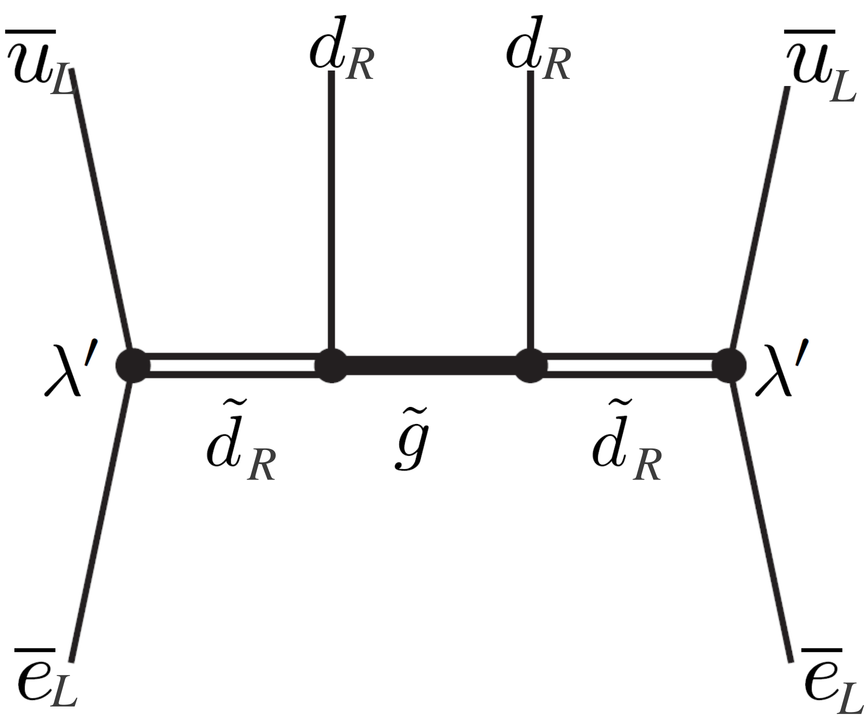
SUSY (Rp-conserved) search at LHC

1st generation squarks and gluino should be heavier than 1TeV

- Another example,

Decomposition

$$(\overline{ue})(d)(d)(\overline{ue})$$



Necessary mediators

$S(-1/3, \mathbf{3})$	$\tilde{d}$
$S'(+1/3, \overline{\mathbf{3}})$	$\tilde{d}^*$
$\psi(0, \mathbf{8})$	$\tilde{g}$

where $(U(1)_{\rm em}, SU(3)_{\rm c})$

Another diagram in

R-parity violating SUSY models

$$\mathcal{W}_{\not R} \ni \lambda' \hat{L}\hat{Q}\hat{D}^c$$

Hirsch Klapdor-Kleingrothaus Kovalenko, PL**B378** (1996) 17, PR**D54** (1996) 4207

SUSY (Rp-conserved) search at LHC

$1^{\rm st}$ generation squarks and gluino should be heavier than 1TeV

List of high E completions

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]	SnuM Seesaw
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]	
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$		
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$		
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$		
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$		
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$		
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$		
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]	RPV
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$		
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$		
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$		
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65, 66]	
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$		
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]	
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]	
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$		
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$		
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ	
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$		
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ	
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$		
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ	
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$		
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60]	
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58–60]	
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ	
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ	
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$		
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]	RPV
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]	
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ	
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$		
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ	
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$		

For Top #II → Bonnet Hirsch O Winter

Possible decompositions and Necessary mediators

(only Topology #I)

- 4 possibilities for each decom.
  S-F-S, *V-F-V*, *S-F-V*, and *V-F-S*
- *Mediators* are specified with
  U(1) EM charge
  SU(3) colour charge
- Here, we do not specify the chiralities of outer fermions ($SU(2)_L$ and $U(1)_Y$)
  → Decom of chirality-specified ops
  Bonnet Hirsch O Winter
- *Long Range?*
  Decomposition which can contain neutrino propagation

List of high E completions

#	Decomposition	Long Range?	Mediator ($U(1)_{em}, SU(3)_c$) S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

For Top #II → Bonnet Hirsch O Winter

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  → Decom of chirality-specified ops
  Bonnet Hirsch O Winter
  JHEP**1303** (2013) 055
- *Long Range?*
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List of high E completions

#	Decomposition	Long Range?	Mediator $(U(1)_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar u d)(\bar e)(\bar e)(\bar u d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$	[64]
1-ii-a	$(\bar u d)(\bar u)(d)(\bar e\bar e)$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar u d)(d)(\bar u)(\bar e\bar e)$		$(+1, \mathbf{1})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar u d)(d)(\bar e)(\bar u\bar e)$		$(+1, \mathbf{1})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
			$(+1, \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
2-i-b	$(\bar u d)(\bar e)(d)(\bar u\bar e)$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	
2-ii-a	$(\bar u d)(\bar u)(\bar e)(d\bar e)$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar u d)(\bar e)(\bar u)(d\bar e)$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	
2-iii-a	$(d\bar e)(\bar u)(d)(\bar u\bar e)$	(c)	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar e)(d)(\bar u)(\bar u\bar e)$		$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}})$	
			$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \overline{\mathbf{6}})$	$(+1/3, \overline{\mathbf{3}})$	
3-i	$(\bar u\bar u)(\bar e)(\bar e)(dd)$		$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
3-ii	$(\bar u\bar u)(d)(d)(\bar e\bar e)$		$(+4/3, \overline{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar u)(\bar u)(\bar e\bar e)$		$(+2/3, \mathbf{3})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+2/3, \overline{\mathbf{6}})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar e)(\bar u)(\bar u)(d\bar e)$	(c)	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60]
			$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar u\bar u)(d)(\bar e)(d\bar e)$		$(+4/3, \overline{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar u\bar u)(\bar e)(d)(d\bar e)$		$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$	
5-i	$(\bar u\bar e)(d)(d)(\bar u\bar e)$	(c)	$(-1/3, \mathbf{3})$	$(0, \mathbf{1})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]
			$(-1/3, \mathbf{3})$	$(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar u\bar e)(\bar u)(\bar e)(dd)$		$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
5-ii-b	$(\bar u\bar e)(\bar e)(\bar u)(dd)$		$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{6})$	

For Top #II → Bonnet Hirsch O Winter

Possible decompositions and Necessary mediators

(only Topology #I)

- 4 possibilities for each decom.
  S-F-S, *V-F-V*, *S-F-V*, and *V-F-S*
- *Mediators* are specified with
  U(1) EM charge
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- Here, we do not specify the chiralities of outer fermions ($SU(2)_L$ and $U(1)_Y$)
  → Decom of chirality-specified ops
  Bonnet Hirsch O Winter
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- *Long Range?*
  Decomposition which can contain neutrino propagation

List of high E completions

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	
			$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \bar{\mathbf{6}})$	$(+1/3, \bar{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	$(-2/3, \bar{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, \mathbf{3})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+2/3, \bar{\mathbf{6}})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, \mathbf{3})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
			$(-1/3, \mathbf{3})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	$(-2/3, \bar{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \bar{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{6})$	

For Top #II → Bonnet Hirsch O Winter

Possible decompositions and Necessary mediators

(only Topology #I)

- 4 possibilities for each decom.
  S-F-S, *V-F-V*, *S-F-V*, *and V-F-S*
- *Mediators* are specified with
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List of high E completions

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	
			$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \bar{\mathbf{6}})$	$(+1/3, \bar{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	$(-2/3, \bar{\mathbf{3}})$	only with V_ρ and V'[illegible]
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	only with [illegible]
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, \mathbf{3})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	[illegible]
			$(+2/3, \bar{\mathbf{6}})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1}$[illegible]	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3}$[illegible]	[illegible] [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, \mathbf{3})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
			$(-1/3, \mathbf{3})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	$(-2/3, \bar{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \bar{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{6})$	

Let us have a closer look at this example.

For Top #II → Bonnet Hirsch O Winter

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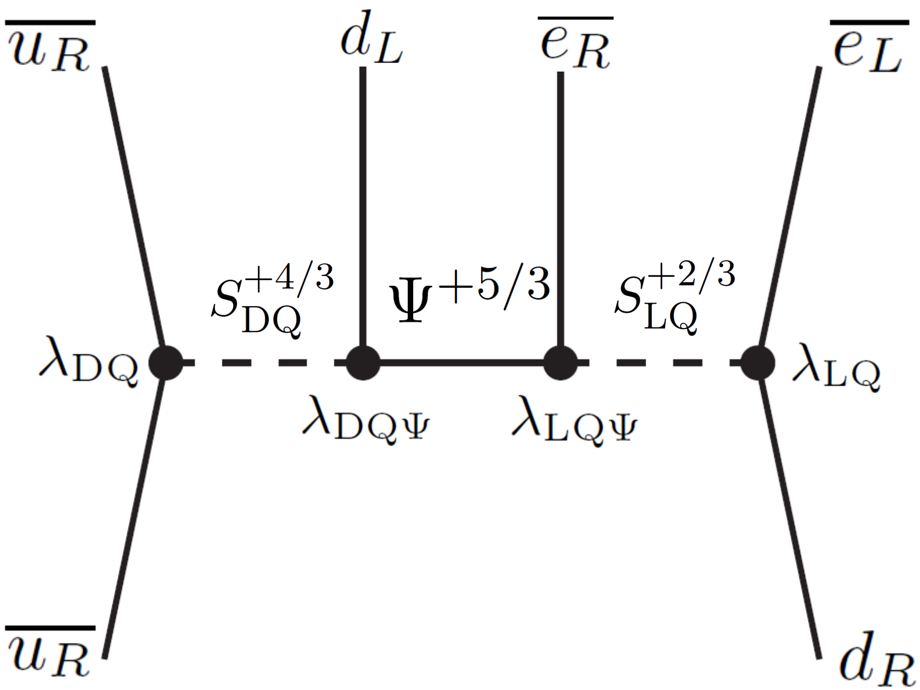


$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$

Take scalar mediators
Specify the chiralities

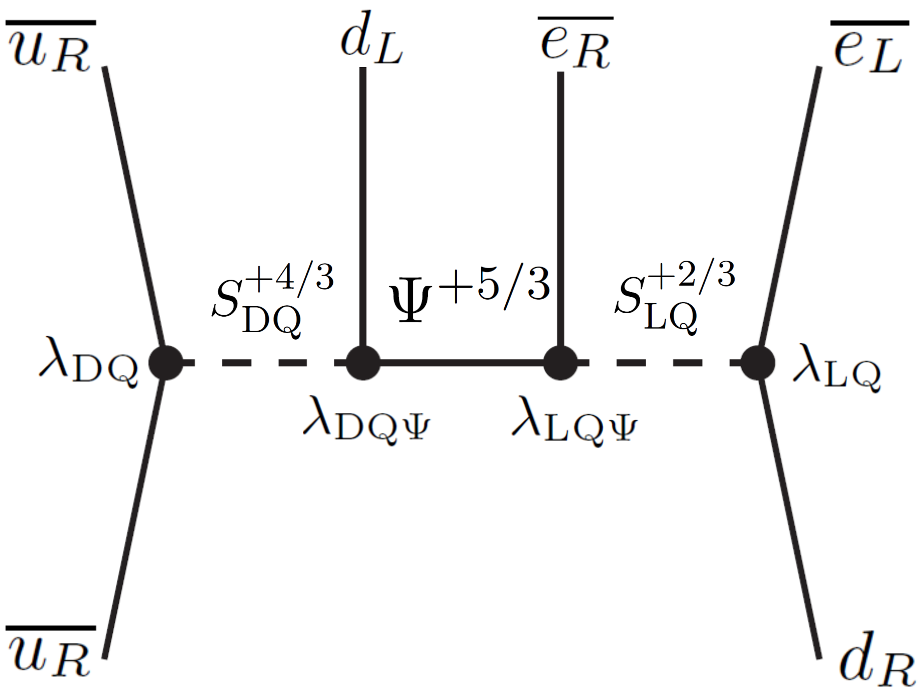
Necessary mediators

$(S_{\rm DQ}^{+4/3})_X$

$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$

$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$

and $(\Psi_R)_{Ii}^{\dot{a}}$



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

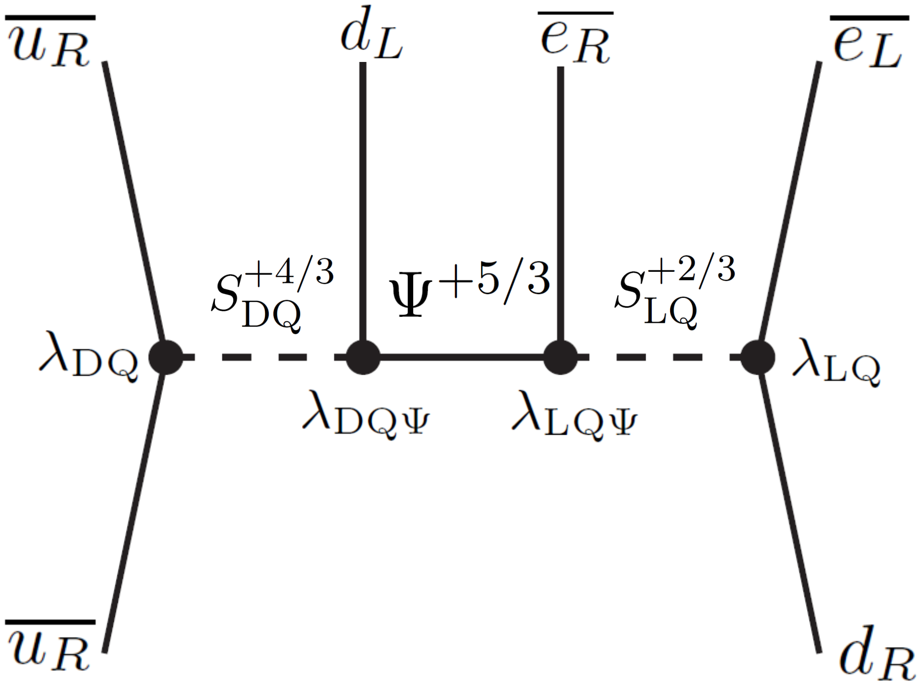
$$(S_{\rm DQ}^{+4/3})_X$$

$$(S_{\rm LQ})_{Ii} = \Big((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\Big)^{\sf T}$$

$$(\Psi_L)_{Iia} = \Big((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\Big)^{\sf T}$$

and $(\Psi_R)^{\dot{a}}_{Ii}$

$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m_{\rm DQ}^2 m_{\rm LQ}^2 m_\Psi}\left[(\overline{u_R})^{I'a}(T_{\overline{\mathbf{6}}})^X_{I'J'}(u_R{}^c)^{J'}_a\right]\left[(\overline{d_L{}^c})^b_I(T_{\mathbf{6}})^{IJ}_X(e_R{}^c)_b\right]\left[(\overline{e_L})_{\dot{c}}(d_R)^{\dot{c}}_J\right]$$



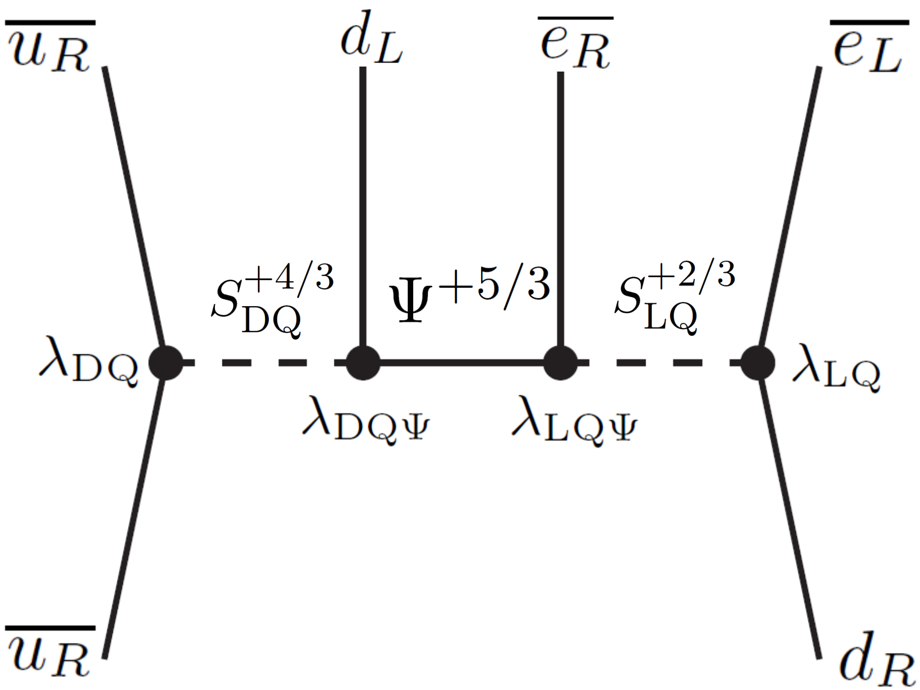
$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

$$(S_{\rm DQ}^{+4/3})_X$$
$$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\mathsf{T}}$$
$$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\mathsf{T}}$$
and $(\Psi_R)_{Ii}^{\dot{a}}$

$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m_{\rm DQ}^2 m_{\rm LQ}^2 m_\Psi} \frac{1}{32}\left[\mathrm{i}(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{LR}\right]$$



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
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Necessary mediators

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$$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$$

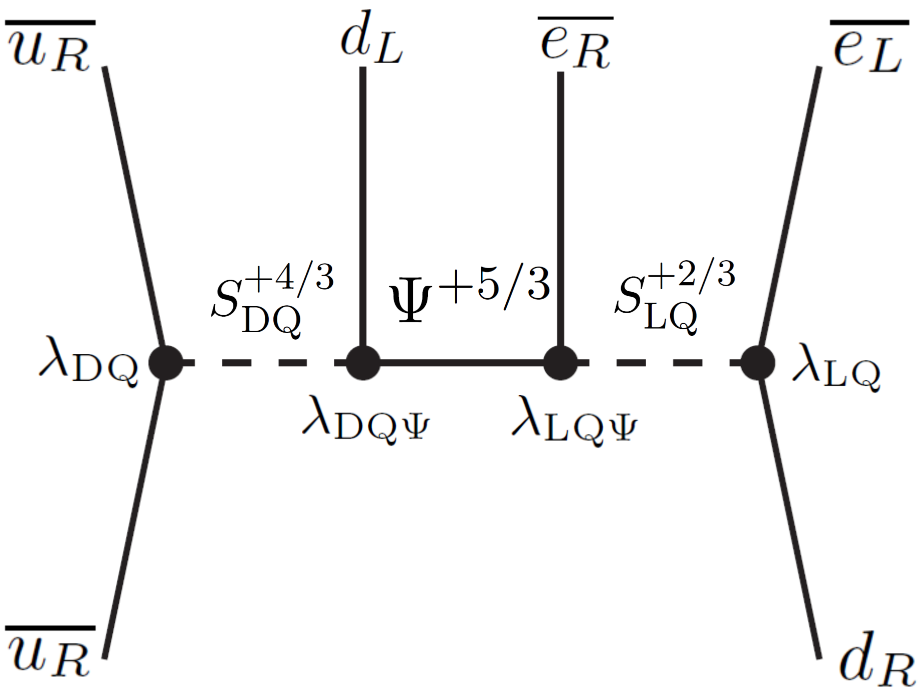
$$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$$

and $(\Psi_R)^{\dot a}_{Ii}$

$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m_{\rm DQ}^2 m_{\rm LQ}^2 m_\Psi} \frac{1}{32} \left[i(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{LR} \right]$$

Take λ's =1, $m=\Lambda$

0n2b half-life: $$\left(T_{1/2}^{0\nu 2\beta}\right)^{-1} = G_2 \left| \frac{2m_P}{G_F^2} \frac{1}{32} \frac{1}{\Lambda^5} \left[i\mathcal{M}_4 - \mathcal{M}_5 \right] \right|^2$$



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and $(\Psi_R)^{\dot a}_{Ii}$

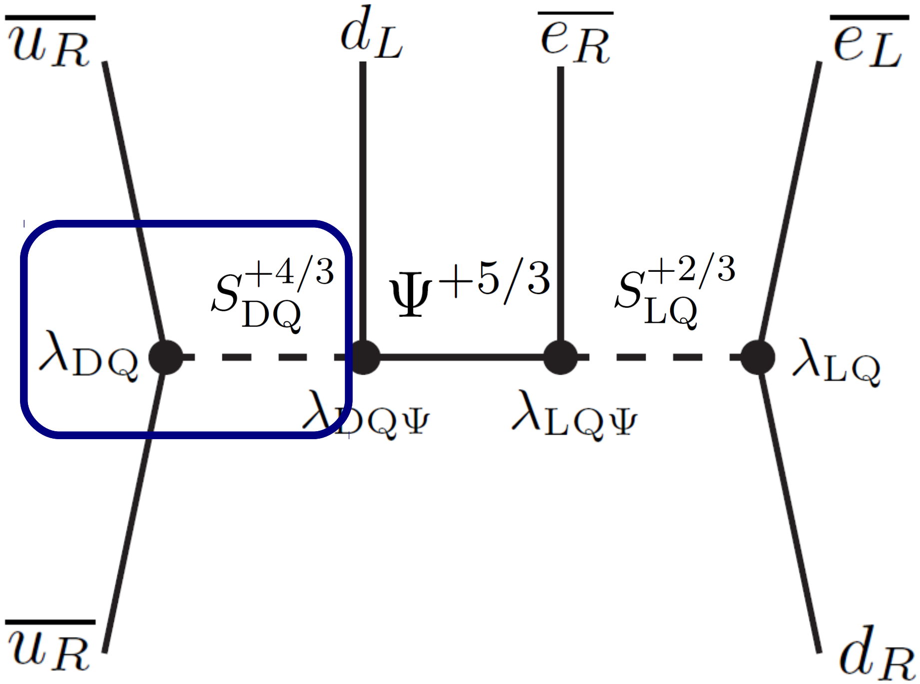
$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m_{\rm DQ}^2 m_{\rm LQ}^2 m_\Psi} \frac{1}{32} \left[i(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{LR}\right]$$

Take λ's =1, m=Λ

0n2b half-life: $$\left(T_{1/2}^{0\nu 2\beta}\right)^{-1} = G_2 \left| \frac{2m_P}{G_F^2} \frac{1}{32} \frac{1}{\Lambda^5} \left[i\mathcal{M}_4 - \mathcal{M}_5\right] \right|^2$$

Exp. bound: $T_{1/2}^{0\nu 2\beta}(^{136}\mathrm{Xe}) > 1.6 \cdot 10^{25}$ [yr] → $\Lambda > 2.0$ [TeV]

Q: What does this model suggest to LHC observables?



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L}d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

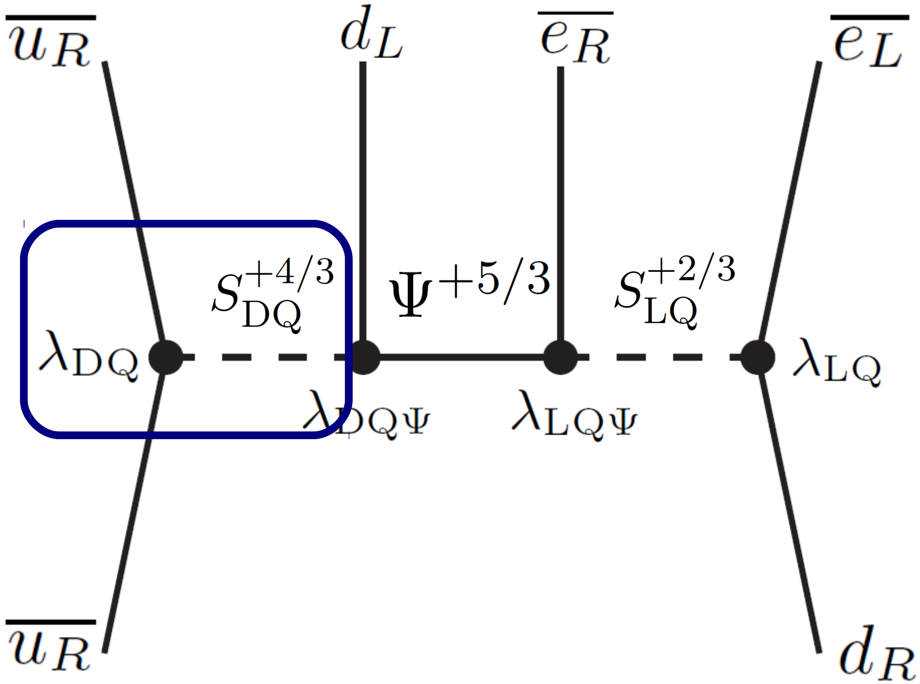
$$(S_{\rm DQ}^{+4/3})_X$$

$$(S_{\rm LQ})_{Ii} = \Big((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\Big)^{\rm T}$$

$$(\Psi_L)_{Iia} = \Big((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\Big)^{\rm T}$$

and $(\Psi_R)^{\dot{a}}_{Ii}$

- **Diquark (DQ):**



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

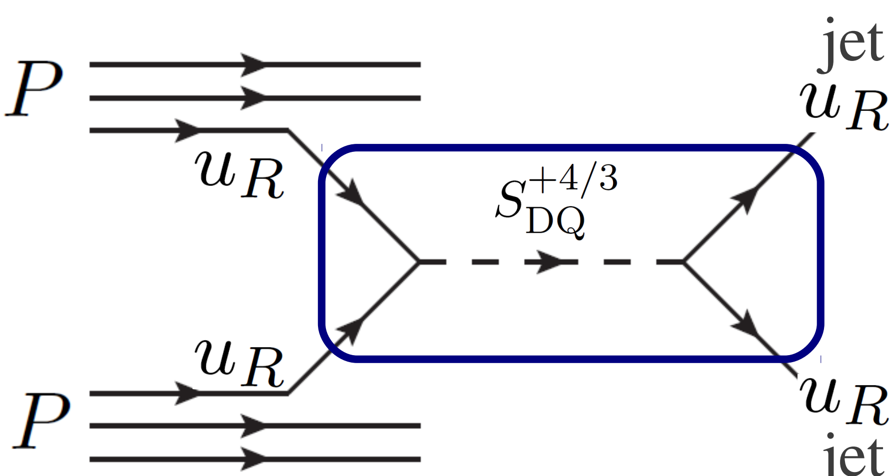
Necessary mediators

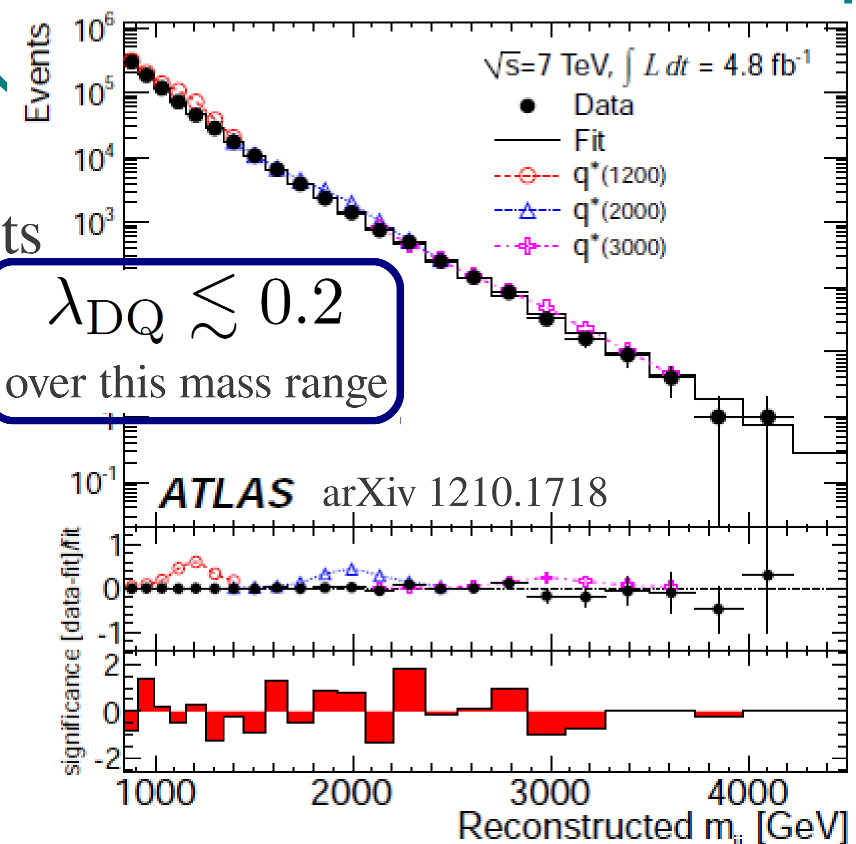
$$(S_{\rm DQ}^{+4/3})_X$$

$$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$$

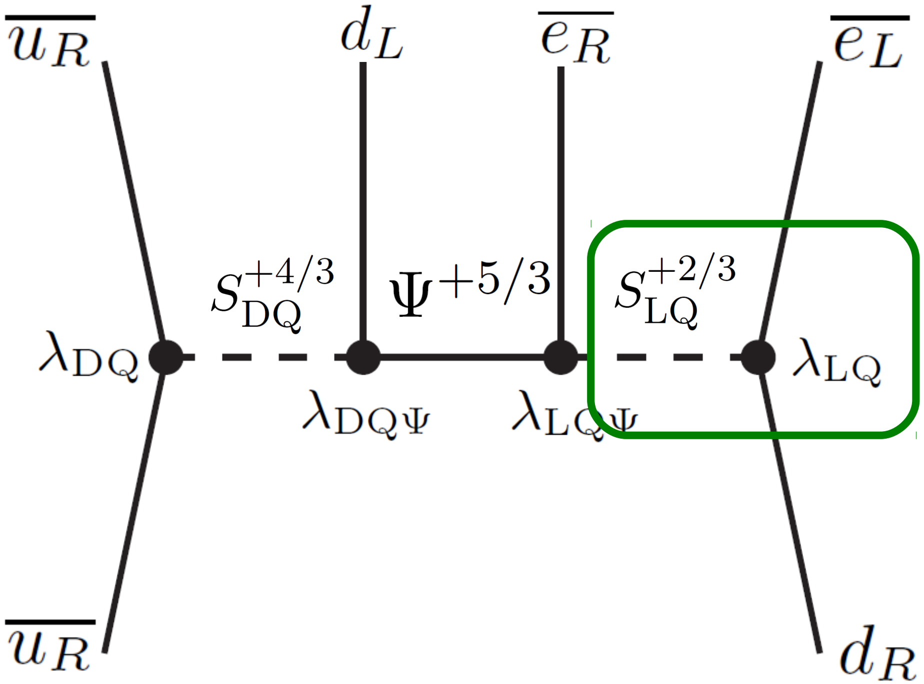
$$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$$

- **Diquark (DQ)**: Search for a resonance in 2-jets





$\lambda_{\rm DQ} \lesssim 0.2$
over this mass range



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

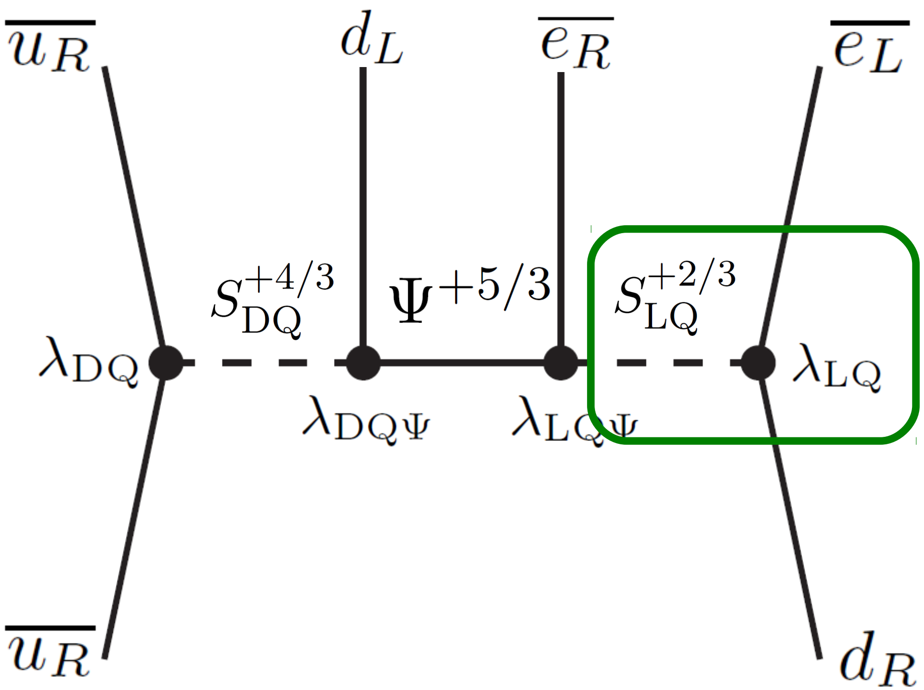
$(S^{+4/3}_{\rm DQ})_X$

$(S_{\rm LQ})_{Ii} = \left((S^{+2/3}_{\rm LQ})_I, (S^{-1/3}_{\rm LQ})_I\right)^{\rm T}$

$(\Psi_L)_{Iia} = \left((\Psi^{+5/3}_L)_{Ia}, (\Psi^{+2/3}_L)_{Ia},\right)^{\rm T}$

and $(\Psi_R)^{\dot a}_{Ii}$

- **Leptoquark (LQ)**:



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

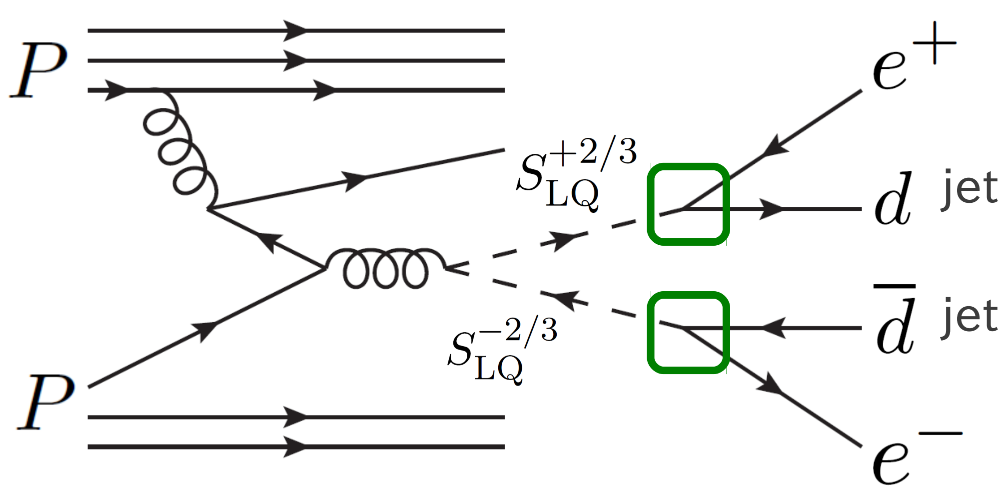
$$(S_{\rm DQ}^{+4/3})_X$$

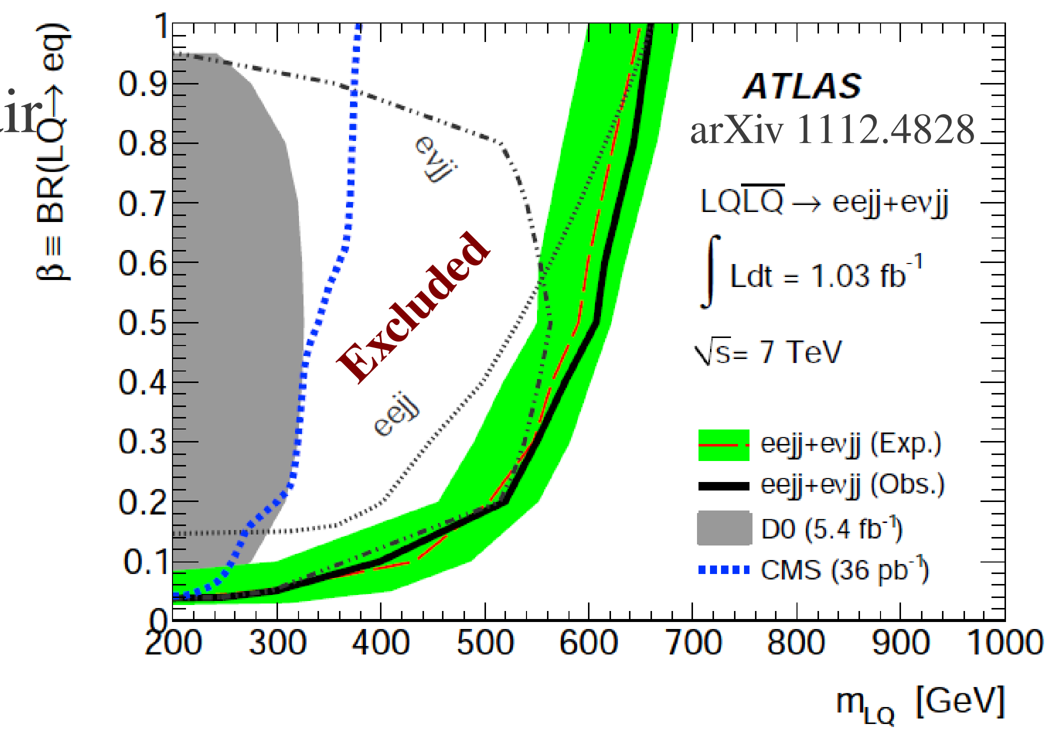
$$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$$

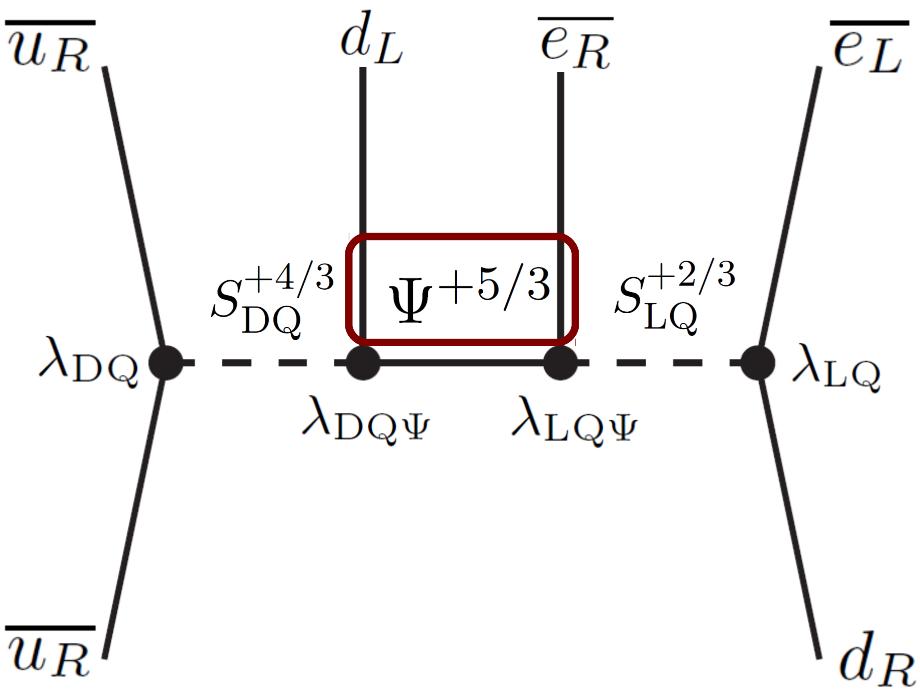
$$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$$

and $(\Psi_R)^{\dot{a}}_{Ii}$

- **Leptoquark (LQ)**: Search for a (eq)-pair







$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

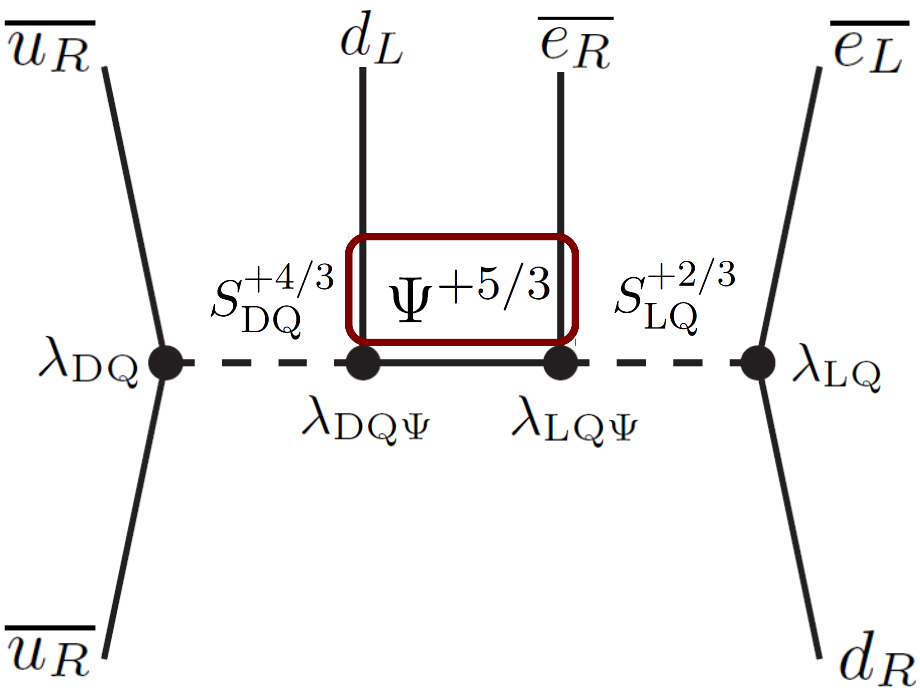
$(S_{\rm DQ}^{+4/3})_X$

$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$

$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$

and $(\Psi_R)^{\dot a}_{Ii}$

- **Vector-like Quark (VLQ)**:



$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

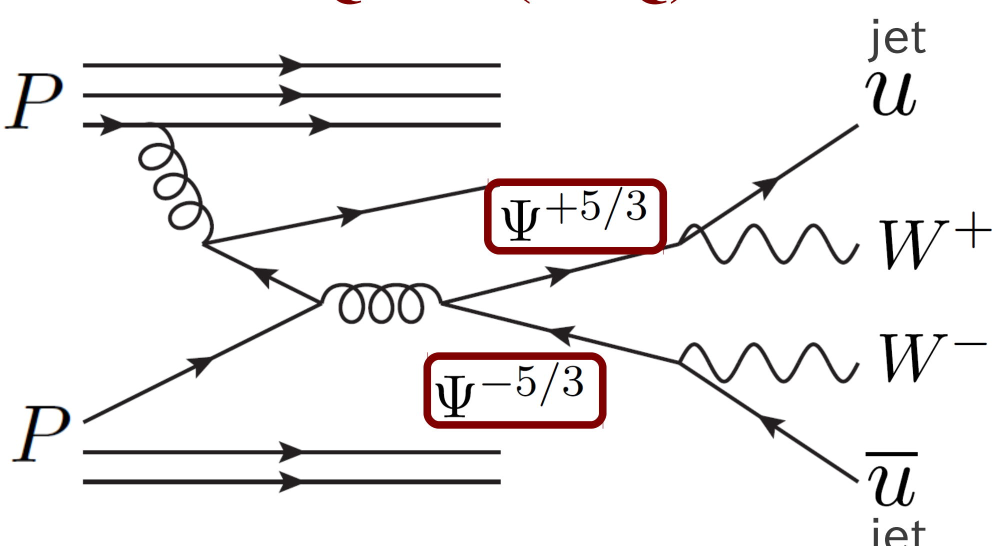
$(S_{\rm DQ}^{+4/3})_X$

$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I \right)^{\rm T}$

$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia}, \right)^{\rm T}$

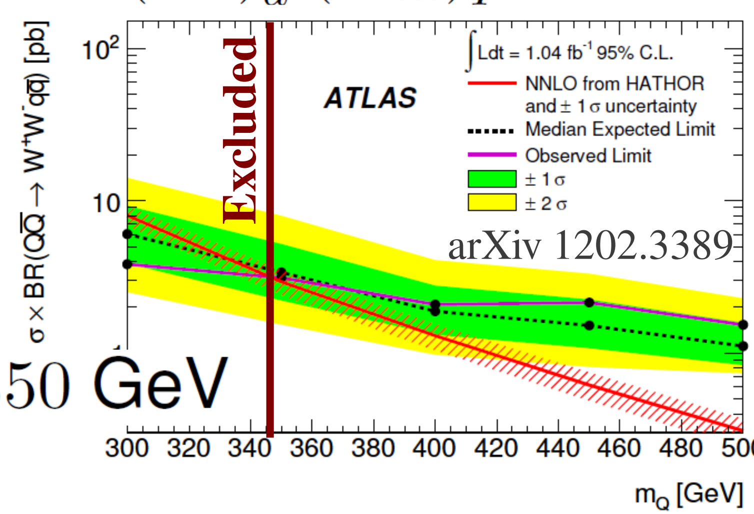
and $(\Psi_R)_{Ii}^{\dot a}$

- **Vector-like Quark (VLQ)**: Search for a (qW)-pair



$$\mathscr{L}_{\rm VLQ} = \lambda^{\alpha} (\overline{\Psi_L})^{Ii}_{\dot a} (u_{R\alpha})^{\dot a}_I H_i + {\rm H.c.}$$

$m_\Psi > 350$ GeV



Outline

New Physics (***d=9***) contributions in neutrinoless double beta decay (0n2b)

1 ***Neutrino mass searches as a frontier to new physics: dim=9 ops***

d=9 ops → half-life time of 0n2b processes

"How sensitive 0n2b experiments to the d=9 ops?"

2 ***What do the d=9 ops suggest to TeV scale physics?***

d=9 ops → decompose them to the fundamental ints.

→ list the TeV signatures of each completion

"The list helps us to discriminate the models"

3 ***Summary***

"Complementarity between 0n2b and LHC (and ILC)"

d=9 op. : Bridge between neutrino and TeV scale

Summary

#	Decomposition	Long Range?	Mediator $(U(1)_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar u d)(\bar e)(\bar e)(\bar u d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61] TeV scale seesaw, e.g., [62, 63
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar u d)(\bar u)(d)(\bar e\bar e)$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar u d)(d)(\bar u)(\bar e\bar e)$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar u d)(d)(\bar e)(\bar u\bar e)$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar u d)(\bar e)(d)(\bar u\bar e)$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar u d)(\bar u)(\bar e)(d\bar e)$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar u d)(\bar e)(\bar u)(d\bar e)$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar e)(\bar u)(d)(\bar u\bar e)$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar e)(d)(\bar u)(\bar u\bar e)$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar u\bar u)(\bar e)(\bar e)(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar u\bar u)(d)(d)(\bar e\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar u)(\bar u)(\bar e\bar e)$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar e)(\bar u)(\bar u)(d\bar e)$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar u\bar u)(d)(\bar e)(d\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar u\bar u)(\bar e)(d)(d\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar u\bar e)(d)(d)(\bar u\bar e)$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar u\bar e)(\bar u)(\bar e)(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar u\bar e)(\bar e)(\bar u)(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

What can we learn from this table?

If 0n2b conflicts with cosmological obs.,

It could be a large d=9 contribution

Summary

#	Decomposition	Long Range?	Mediator ($U(1)_{em}, SU(3)_c$) S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, 1)$	$(0, 1)$	$(-1, 1)$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61] TeV scale seesaw, e.g., [62, 63
			$(+1, 8)$	$(0, 8)$	$(-1, 8)$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2, 1)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2, 1)$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, 1)$	$(+4/3, \bar{3})$	$(+2, 1)$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+2, 1)$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, 1)$	$(+4/3, 3)$	$(+1/3, 3)$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+1/3, \bar{3})$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+1/3, \bar{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2/3, 3)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2/3, 3)$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+2/3, 3)$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, 3)$	$(0, 1)$	$(+1/3, 3)$	RPV [58–60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+1/3, \bar{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{3})$	$(-1/3, 3)$	$(+1/3, \bar{3})$	
			$(-2/3, 3)$	$(-1/3, 6)$	$(+1/3, 3)$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, 3)$	$(+1/3, 3)$	$(-2/3, 3)$	only with V_ρ and V'_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(-2/3, 6)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, 3)$	$(+5/3, 3)$	$(+2, 1)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2, 1)$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, 3)$	$(+4/3, \bar{3})$	$(+2, 1)$	only with V_ρ
			$(+2/3, \bar{6})$	$(+4/3, \bar{3})$	$(+2, 1)$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, 3)$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+2/3, 3)$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{3})$	$(+5/3, 3)$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2/3, 3)$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, 3)$	$(+1/3, \bar{3})$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(+2/3, 3)$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, 3)$	$(0, 1)$	$(+1/3, 3)$	RPV [58–60]
			$(-1/3, 3)$	$(0, 8)$	$(+1/3, 3)$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, 3)$	$(+1/3, \bar{3})$	$(-2/3, \bar{3})$	only with V'_ρ
			$(-1/3, 3)$	$(+1/3, 6)$	$(-2/3, 6)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 3)$	only with V'_ρ
			$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 6)$	

Colour 8

Colour 3

Colour 6

What can we learn from this table?

If 0n2b conflicts with cosmological obs.,

It could be a large *d=9* contribution

Such a large *d=9* contribution should leave the trace in LHC except for T-I-1-i (and T-II-1) that does not contain a coloured mediator

Summary

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$			Models/Refs./Comments
			S or V_ρ	ψ	S' or V'_ρ	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, 1)$	$(0, 1)$	$(-1, 1)$	Mass mechan., RPV [58–60],
						LR-symmetric models [39],
						Mass mechanism with ν_S [61]
						TeV scale seesaw, e.g., [62, 63
			$(+1, 8)$	$(0, 8)$	$(-1, 8)$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2, 1)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2, 1)$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, 1)$	$(+4/3, \bar{3})$	$(+2, 1)$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+2, 1)$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, 1)$	$(+4/3, 3)$	$(+1/3, 3)$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+1/3, \bar{3})$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+1/3, \bar{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2/3, 3)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2/3, 3)$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+2/3, 3)$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, 3)$	$(0, 1)$	$(+1/3, 3)$	RPV [58–60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+1/3, \bar{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{3})$	$(-1/3, 3)$	$(+1/3, \bar{3})$	
			$(-2/3, 3)$	$(-1/3, 6)$	$(+1/3, 3)$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, 3)$	$(+1/3, 3)$	$(-2/3, 3)$	only with V_ρ and V'_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(-2/3, 6)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, 3)$	$(+5/3, 3)$	$(+2, 1)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2, 1)$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, 3)$	$(+4/3, \bar{3})$	$(+2, 1)$	only with V_ρ
			$(+2/3, \bar{6})$	$(+4/3, \bar{3})$	$(+2, 1)$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, 3)$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+2/3, 3)$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{3})$	$(+5/3, 3)$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2/3, 3)$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(+2/3, 3)$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, 3)$	$(0, 1)$	$(+1/3, 3)$	RPV [58–60]
			$(-1/3, 3)$	$(0, 8)$	$(+1/3, \bar{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, 3)$	$(+1/3, \bar{3})$	$(-2/3, \bar{3})$	only with V'_ρ
			$(-1/3, 3)$	$(+1/3, 6)$	$(-2/3, 6)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 3)$	only with V'_ρ
			$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 6)$	

What can we learn from this table?

If 0n2b conflicts with cosmological obs.,

It could be a large *d=9* contribution

Such a large *d=9* contribution should leave the trace in LHC except for T-I-1-i (and T-II-1) that does not contain a coloured mediator

T-I-1-i can be examined at ILC! exotic interactions with electron!

Summary

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61] TeV scale seesaw, e.g., [62, 63 [64]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$	
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \mathbf{3})$	$(+1/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \mathbf{3})$	$(0, \mathbf{1})$	$(+1/3, \mathbf{3})$	RPV [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{\mathbf{3}})$	$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	
			$(-2/3, \mathbf{3})$	$(-1/3, \mathbf{6})$	$(+1/3, \mathbf{3})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \mathbf{3})$	$(+1/3, \mathbf{3})$	$(-2/3, \mathbf{3})$	only with V_ρ and V'_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \mathbf{3})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, \mathbf{3})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	only with V_ρ
			$(+2/3, \bar{\mathbf{6}})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60]
			$(-2/3, \bar{\mathbf{3}})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{\mathbf{3}})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	$(+2/3, \mathbf{3})$	only with V_ρ
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, \mathbf{3})$	$(0, \mathbf{1})$	$(+1/3, \mathbf{3})$	RPV [58–60]
			$(-1/3, \mathbf{3})$	$(0, \mathbf{8})$	$(+1/3, \mathbf{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, \mathbf{3})$	$(+1/3, \bar{\mathbf{3}})$	$(-2/3, \bar{\mathbf{3}})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(+1/3, \mathbf{6})$	$(-2/3, \mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{3})$	only with V'_ρ
			$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{6})$	

What can we learn from this table?

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It could be a large *d=9* contribution

Such a large *d=9* contribution should leave the trace in LHC except for T-I-1-i (and T-II-1) that does not contain a coloured mediator

T-I-1-i can be examined at ILC! exotic interactions with electron!

My last message:

0n2b exps, cosmological obs, LHC and ILC are complementary!

Saitama University 埼玉大学

Back-up

New Physics (***d=9***) contributions in neutrinoless double beta decay (0n2b)

In progress
Under discussion

Seeking a relation to the models at the TeV scale

TeV scale models with LNV → Models for radiative neutrino masses

Maybe, we have already known the mediators appear in the big table...

- They have masses of the TeV scale
- *#L* must be violated in somewhere

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Radiative neutrino mass models with TeV ingredients

In such models

Size of **two contributions** to 0n2b can be comparable!

Standard one m_ν ~ 0.1eV

dim=9 Λ_{NP} ~1 TeV

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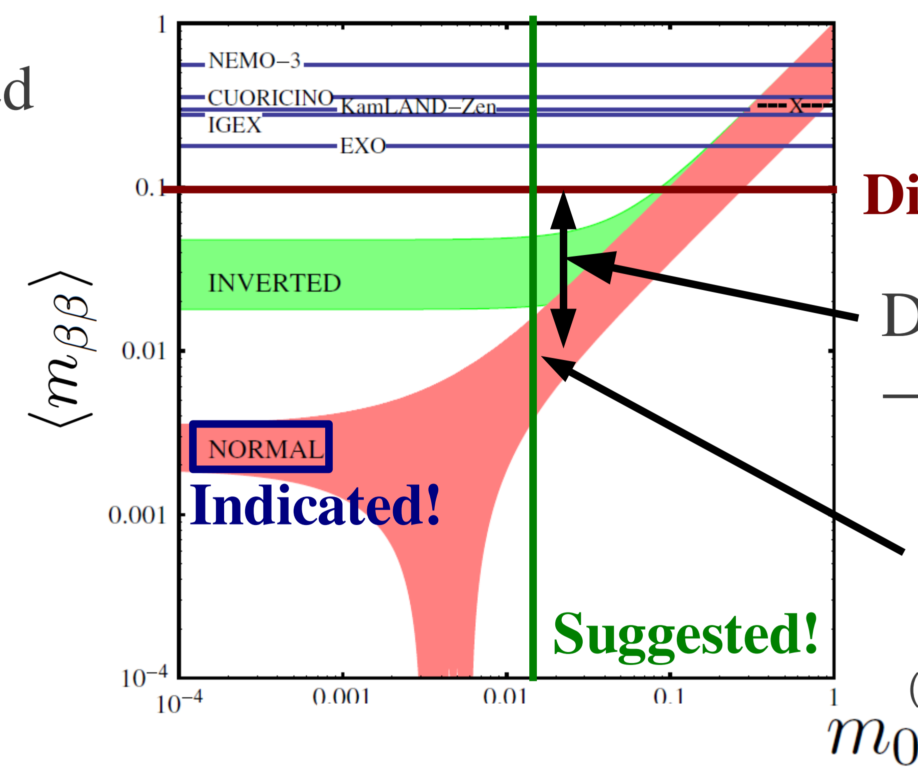
dim=9 $\Lambda_{NP} \sim 1$ TeV

If d=9 and m_ν are related in a model...



Discover!

Difference → d=9 contribution

m_ν in reality

(just for sketching the idea)

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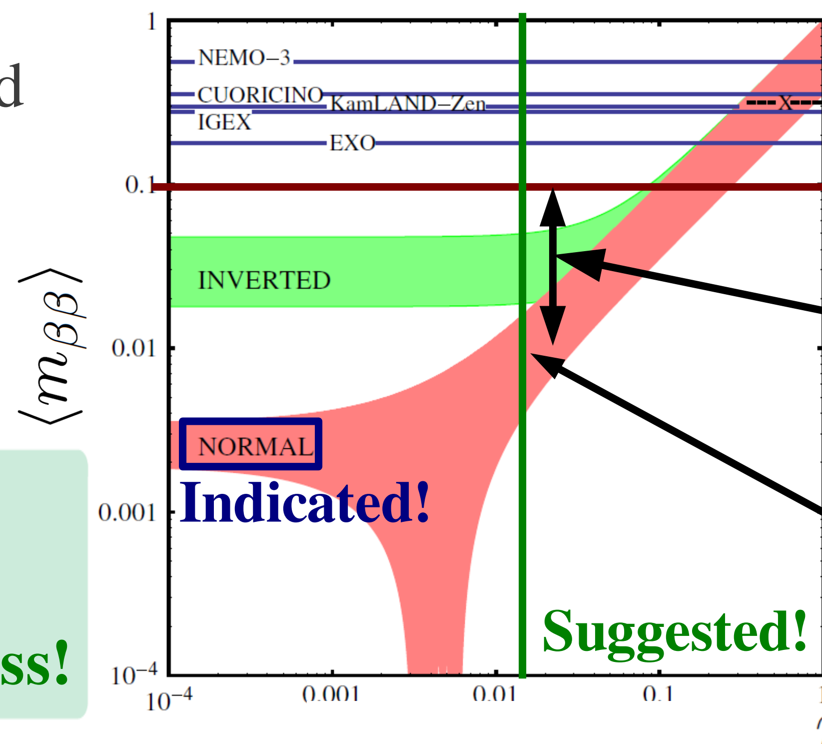

Discover!

Difference → *d=9* contribution

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With the info on this plane, we have a chance to know **the origin of neutrino mass!**

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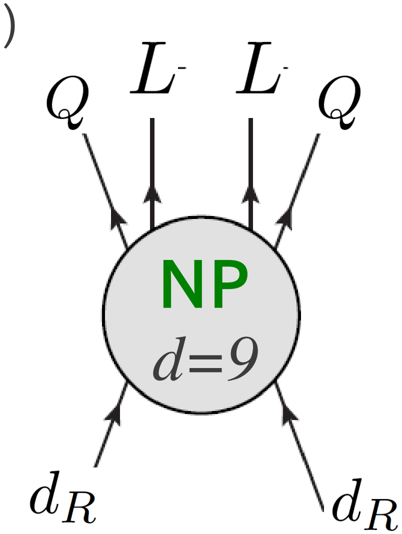
Examples introduced in recent papers, based on Decomposition of $LLQQd_Rd_R$

Coloured Babu-Zee model with LQ(**3**, **1**, -1/3), DQ(**6**, **1**, -2/3)

Kohda Sugiyama Tsumura PL**B718** (2013) 1436

$$\mathcal{O}^{0\nu2\beta}_{\text{eff}} =$$



Dim=9 op is directly proportional to m_ν, and its contribution to 0n2b seems to be large.

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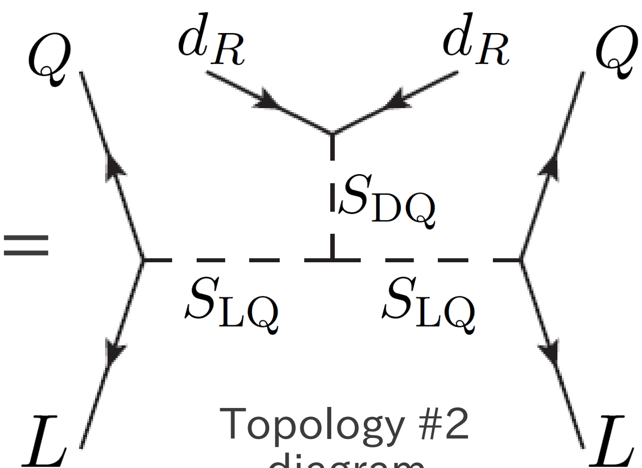

Topology #2 diagram

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3 Seeking the relation to the models

Examples

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Radiative neutrino mass models with TeV ingredients

In such models

Size of **two contributions** to 0n2b can be comparable!

Standard one	dim=9
$m_\nu \sim 0.1$eV	$\Lambda_{NP} \sim 1$ TeV

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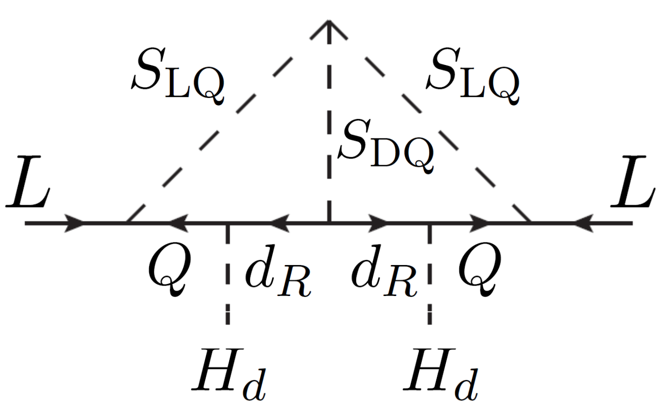
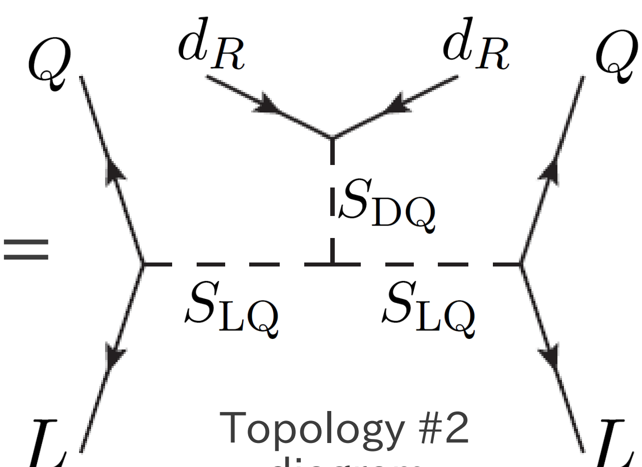
$m_\nu =$ 

$\mathcal{O}_{\text{eff}}^{0\nu 2\beta} =$ 

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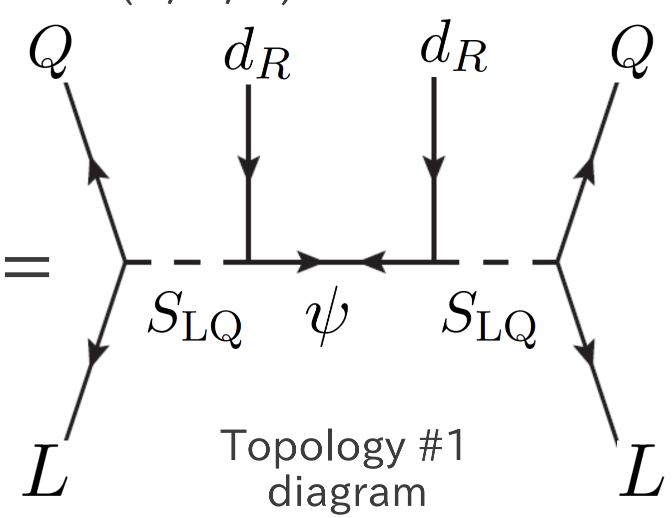
Two-loop mNu model with LQ(**3**, **1**, -1/3), Majorana fermion (**8**, **1**, 0)

Angel Cai Rodd Schmidt Volkas 1308.0463

$\mathcal{O}^{0\nu2\beta}_{\text{eff}} =$ 

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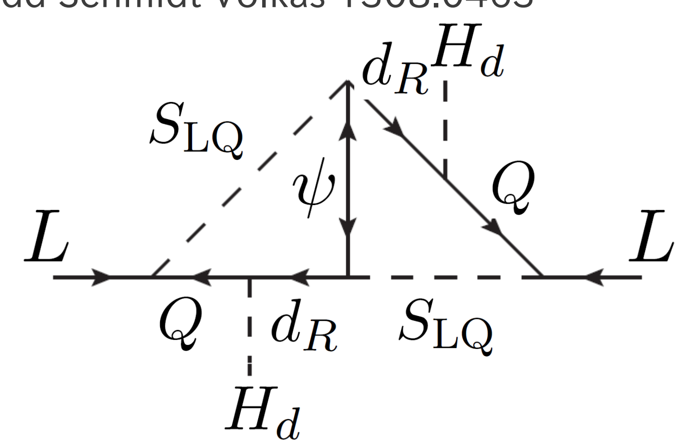
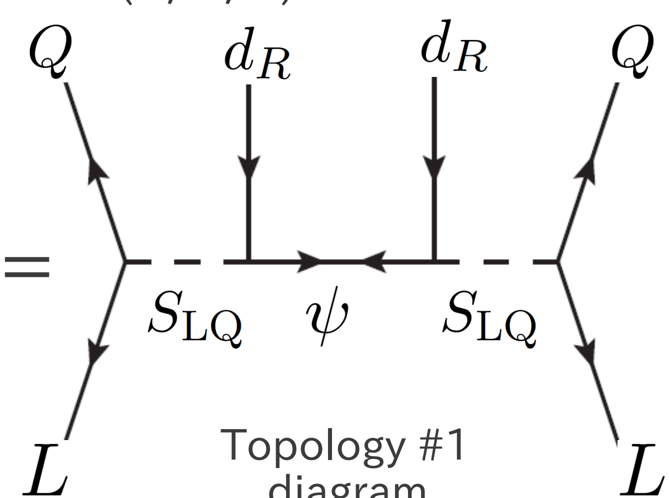
$m_\nu =$ 

$\mathcal{O}^{0\nu2\beta}_{\rm eff} =$ 

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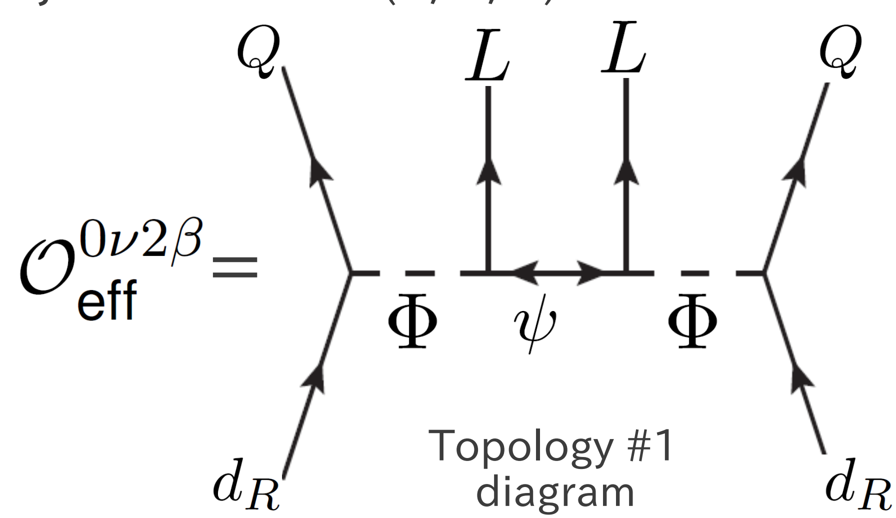
Standard one $m_\nu \sim 0.1\text{eV}$ | dim=9 $\Lambda_{NP} \sim 1$ TeV

Examples introduced in recent papers, based on Decomposition of $LLQQd_R d_R$

Colour-8 mNu model with Scalar (**8**, **2**, 1/2), Majorana fermion (**8**, **1**, 0)

Choubey Duerr Mitra Rodejohann JHEP **1205** (2012) 017



In this case, dim=9 op is not directly proportional to m_ν

Seeking the relation to the models

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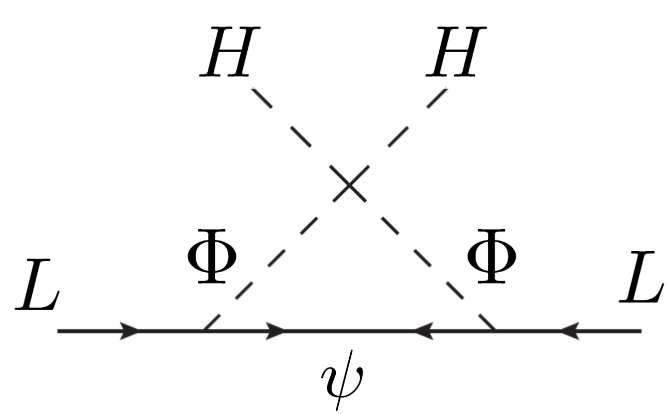
$m_\nu =$



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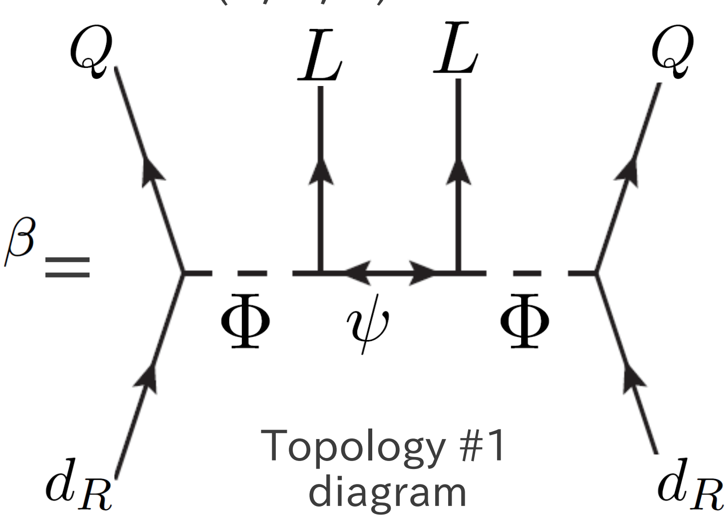

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Radiative neutrino mass models with TeV ingredients

In such models

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Standard one $m_\nu \sim 0.1\text{eV}$

dim=9 $\Lambda_{\text{NP}} \sim 1\ \text{TeV}$

Neutrino mass models based on the effective operator approach

Schechter Valle Phys. Rev. **D25** (1982) 2951

Babu Leung Nucl Phys **B619** (2001) 667

de Gouvea Jenkins Phys. Rev. **D77** (2008) 013008

del Aguila Aparici Bhattacharya Santamaria Wudka JHEP **1206** (2012) 146, JHEP **1205** (2012) 133

Angel Rodd Volkas Phys. Rev. **D87** (2013) 073007

Farzan Pascoli Schmidt JHEP **1303** (2013) 107

and more...