An Effective Theory of Neutrino

Systematic decomposition of the neutrinoless double beta decay operator

Toshihiko Ota

Saitama University

based on

Florian Bonnet, Martin Hirsch, TO, Walter Winter

JHEP **1303** (2013) 055

arXiv.1212.3045

Preface

If the SM is a low-*E* effective model of a fundamental theory...

$$\mathscr{L}_{\textsf{eff}} = \mathscr{L}_{\rm SM}$$

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Λ_{NP} : A typical scale of New physics

Effective operators are a typical low-*E* remnant of New physics

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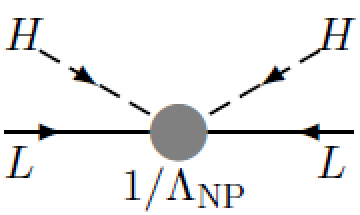

Weinberg op.

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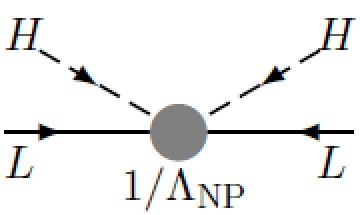

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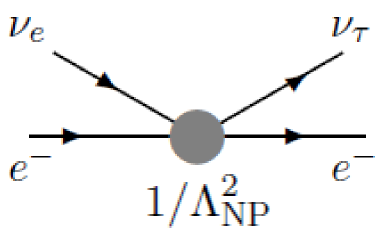
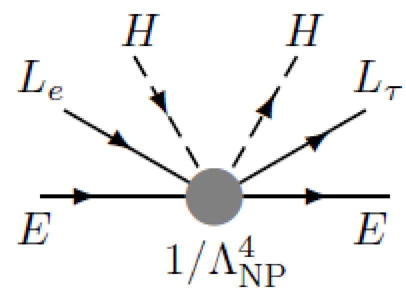


Four-Fermi

$P_{\nu_\alpha \to \nu_\beta}$



$P_{\nu_\alpha \to \nu_\beta}$

Non-standard (**LFV**) neutrino ints
→ Talk by O.Yasuda (Apr), J. Sato (Aug)

Related through SU(2)

Charged **LFV** (in SUSY)
→ Talk by M. Nagai

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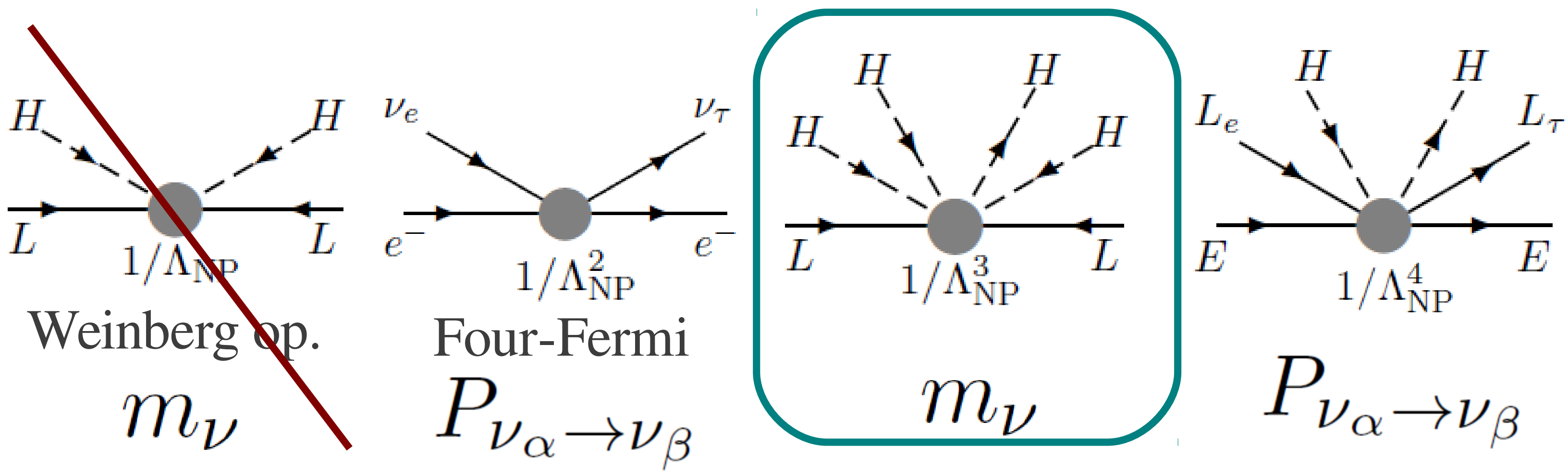

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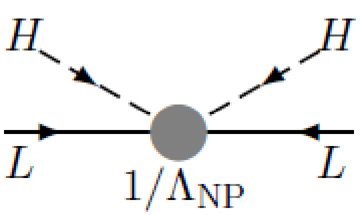

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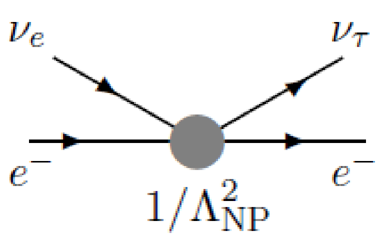

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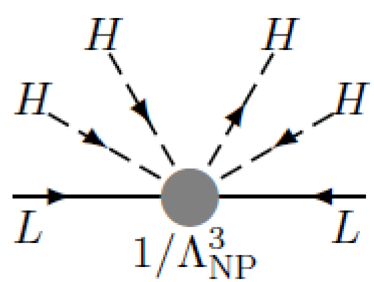

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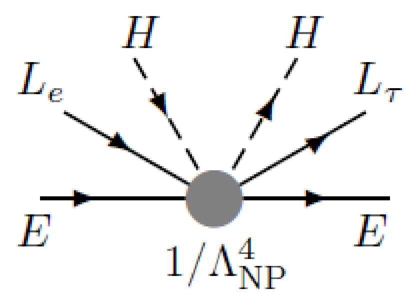

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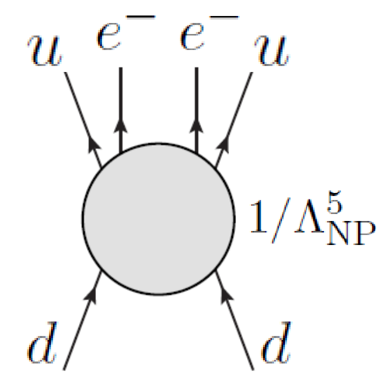

0n2b process

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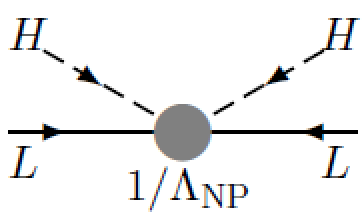

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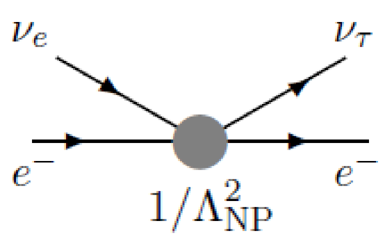

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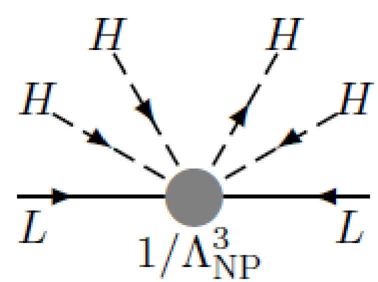

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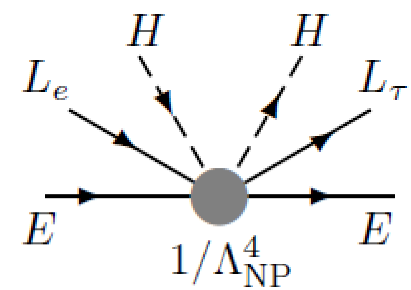

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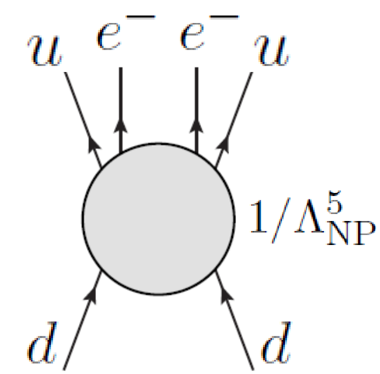

0n2b process

High E completion@Λ_{NP}

Seesaw mech.
(tree)

Seesaw shaved with Occam's razor
→ Talk by M. Ibe (Aug)

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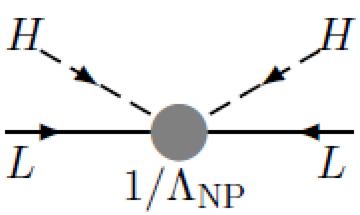

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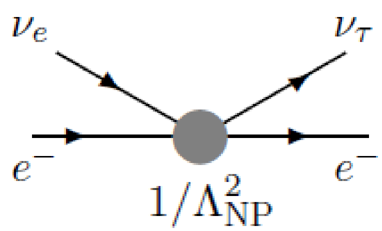

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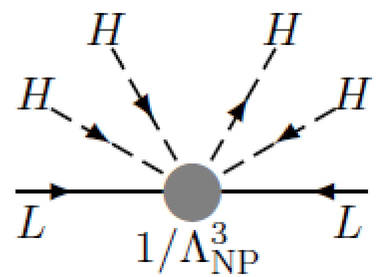

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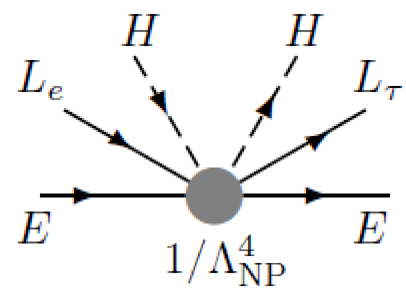

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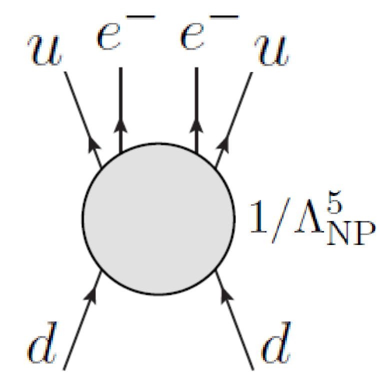

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What do these eff. ops. suggest to new physics at high E scales?

Exhaustive bottom-up approach

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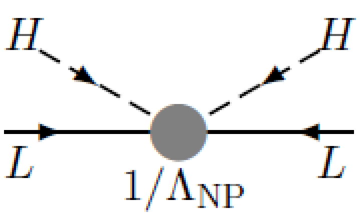
We focus on *d*=9 op in this talk

$\Lambda_{\rm NP}$: A typical scale of New physics

Effective operators are a typical low-*E* remnant ... hysics



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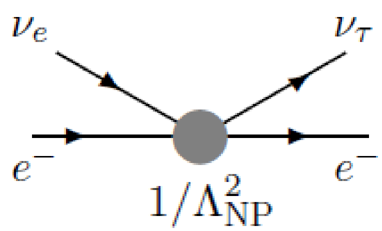

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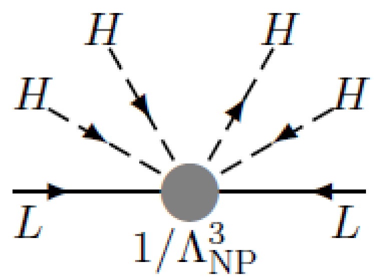

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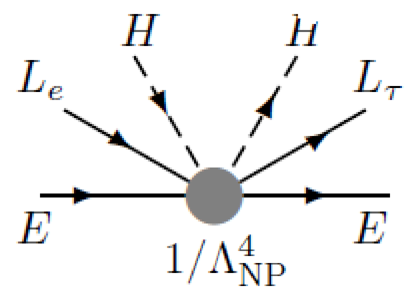

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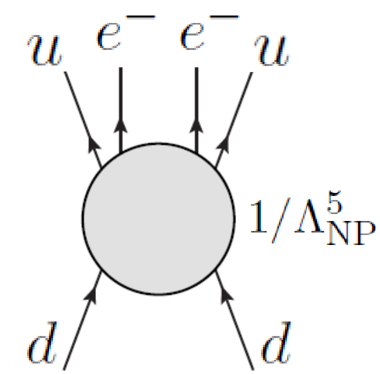

$\langle m_{\beta\beta} \rangle$

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Outline

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

1. ***Motivation: Why 0n2b? Why 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. ***Seeking a relation to the models at the TeV scale***

   TeV scale models with LNV → *Models for radiative neutrino masses*

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

Effective nu mass

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

$$U_e{}^1 = c_{12}c_{13}$$
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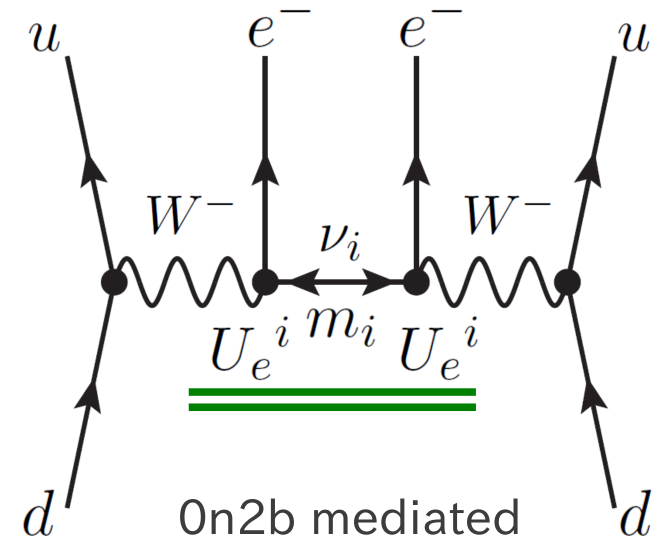

0n2b mediated by neutrinos

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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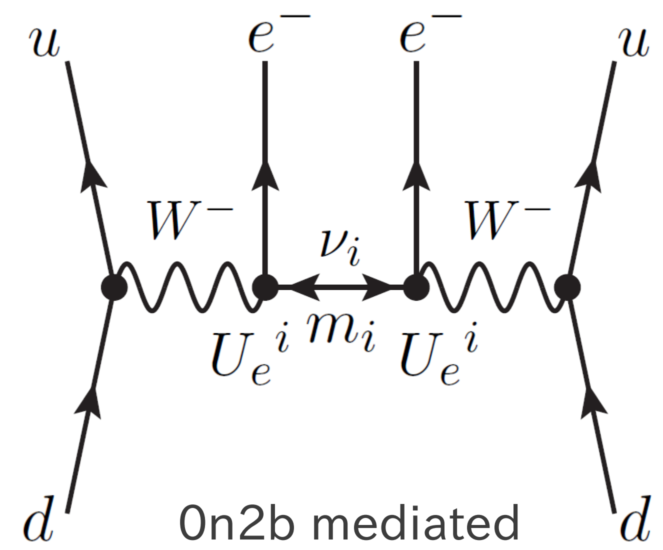

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- **Oscillation exp** told us... e.g., Gonzalez-Garcia Maltoni Salvado Schwetz, JHEP 1212 (2012) 123

$$s_{12}^2 = 0.3, \qquad s_{23}^2 = 0.41(0.59), \qquad s_{13}^2 = 0.023,$$
$$\Delta m_{21}^2 = 7.5 \cdot 10^{-5}\ \text{eV}^2, \quad |\Delta m_{31}^2| = 2.5 \cdot 10^{-3}\ \text{eV}^2$$

So far, we know

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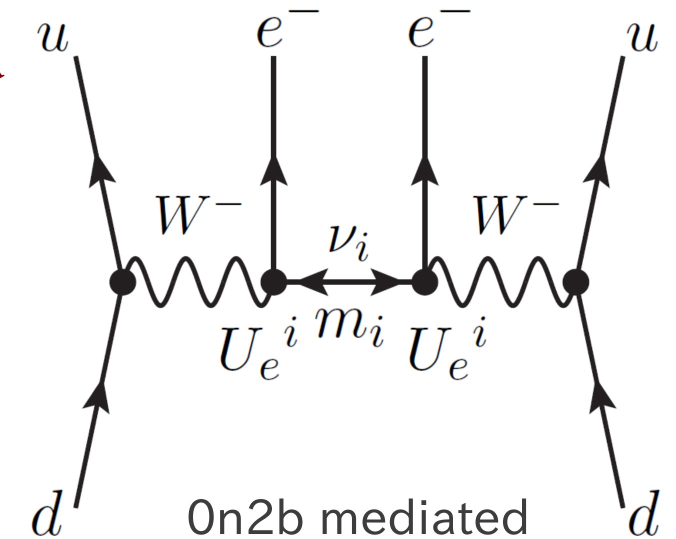

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- **Cosmological obs** are sensitive to the other combination of params....

→Talk by M. Hasegawa (Aug)

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

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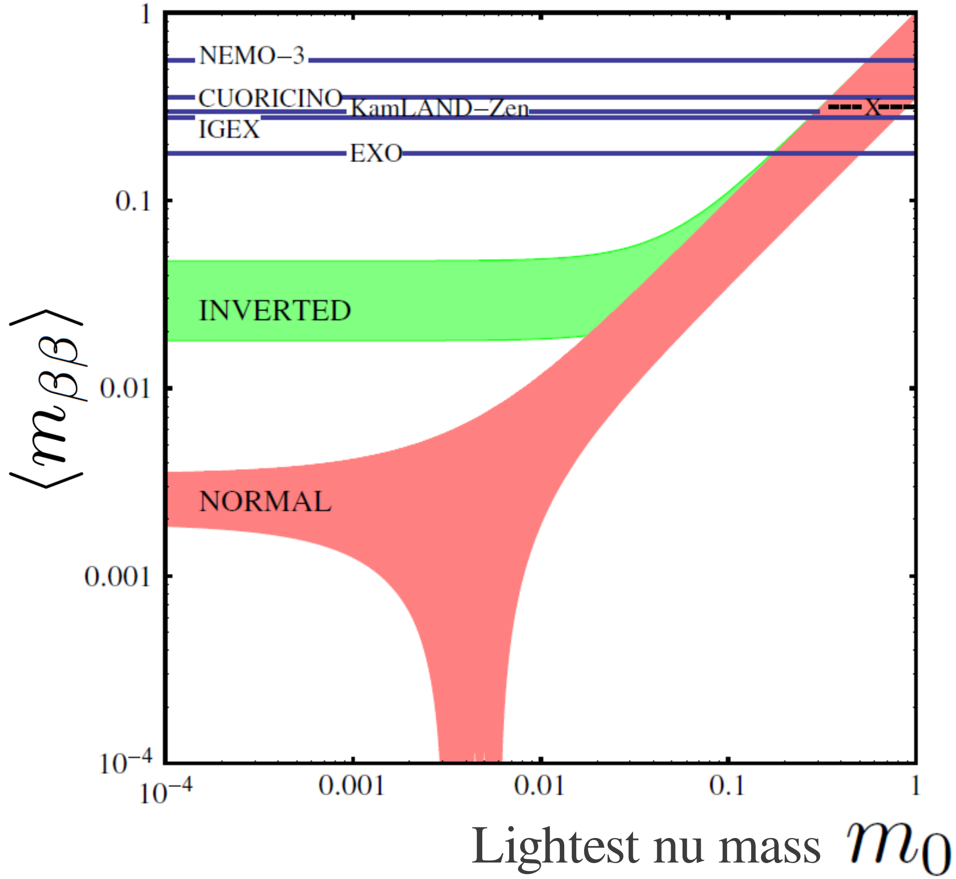
Sum of nu masses

$$\sum_{i=1}^{3} m_i (\simeq 3\boxed{m_0} \text{ if } m_0 \gtrsim 0.1 \text{ eV})$$



Standard 3nu parameter space

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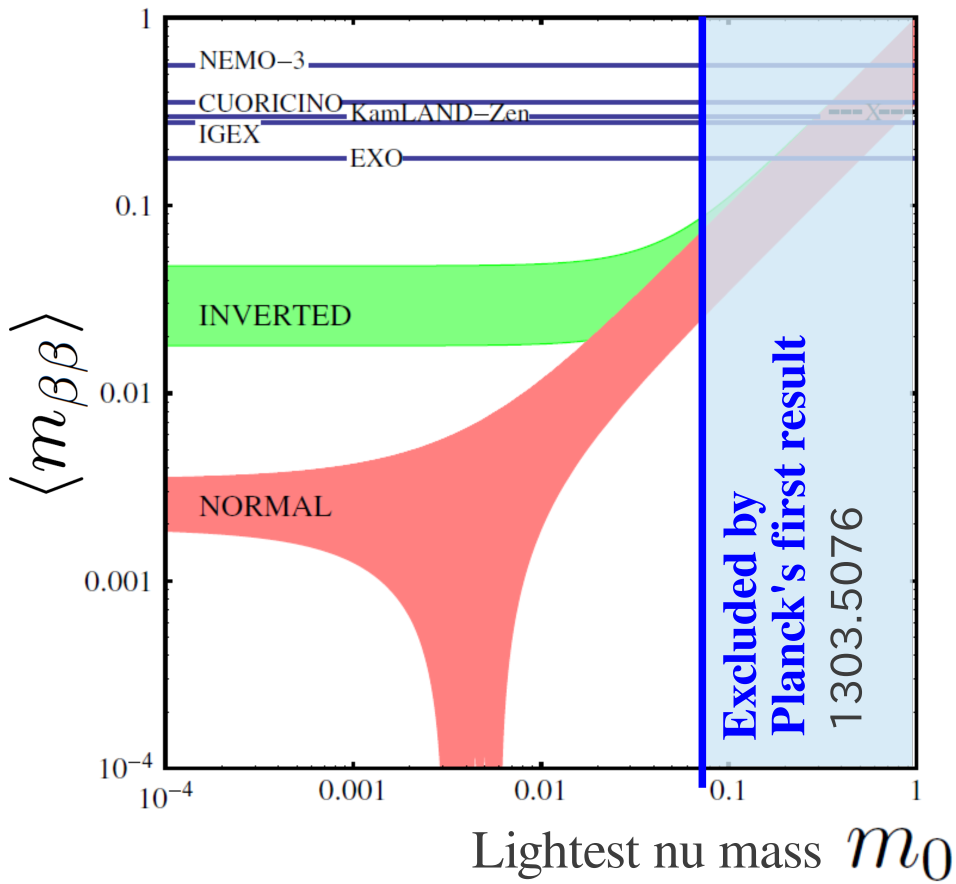

Standard 3nu parameter space

Planck (combined)
1303.5076

$$\sum_i m_i < 0.23 \text{ eV}$$

WMAP9 (combined)
1212.5226

$$\sum_i m_i < 0.44 \text{ eV}$$

SPT reports non-zero mNu?
1212.6267

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Talk by I. Shimizu (Apr)

KamLAND-Zen
PRL110 (2013) 062502
$T_{1/2}^{\text{Xe}} > 1.9 \cdot 10^{25}$ years
$\langle m_{\beta\beta} \rangle < [0.12, 0.25]$ eV

EXO-200
PRL109 (2012) 032505
$T_{1/2}^{\text{Xe}} > 1.6 \cdot 10^{25}$ years
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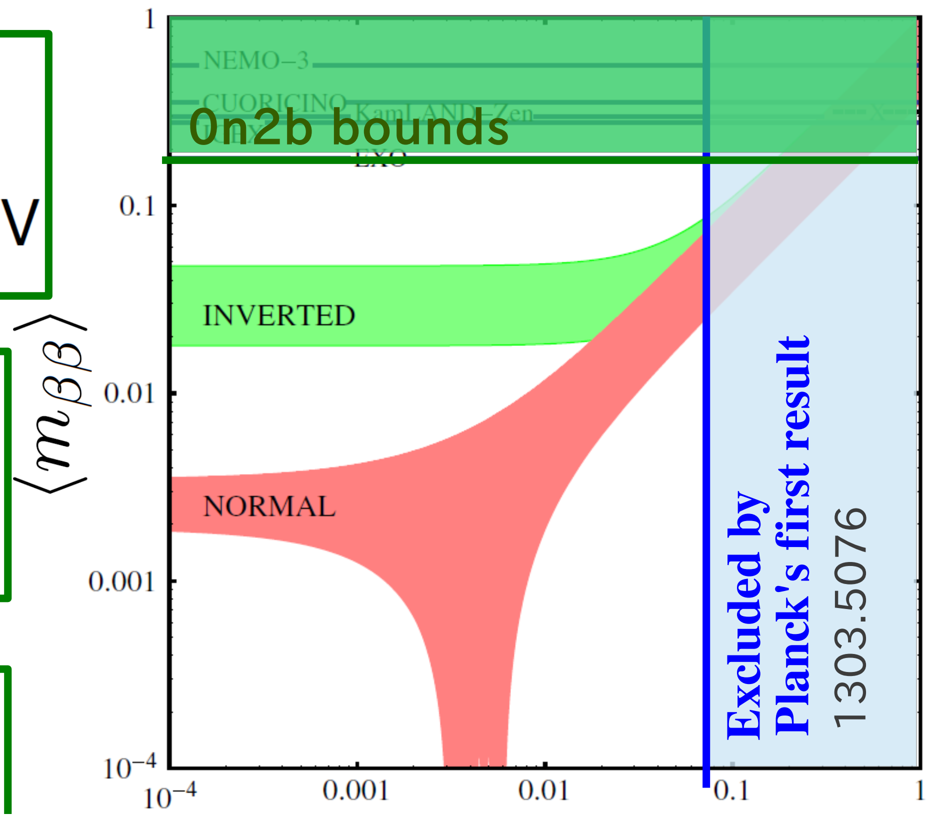
GERDA (Phase I)
1307.4720
$T_{1/2}^{\text{Ge}} > 3.0 \cdot 10^{25}$ years
$\langle m_{\beta\beta} \rangle < [0.2, 0.4]$ eV $\longrightarrow$ 0.01 eV
In future



Lightest nu mass m_0

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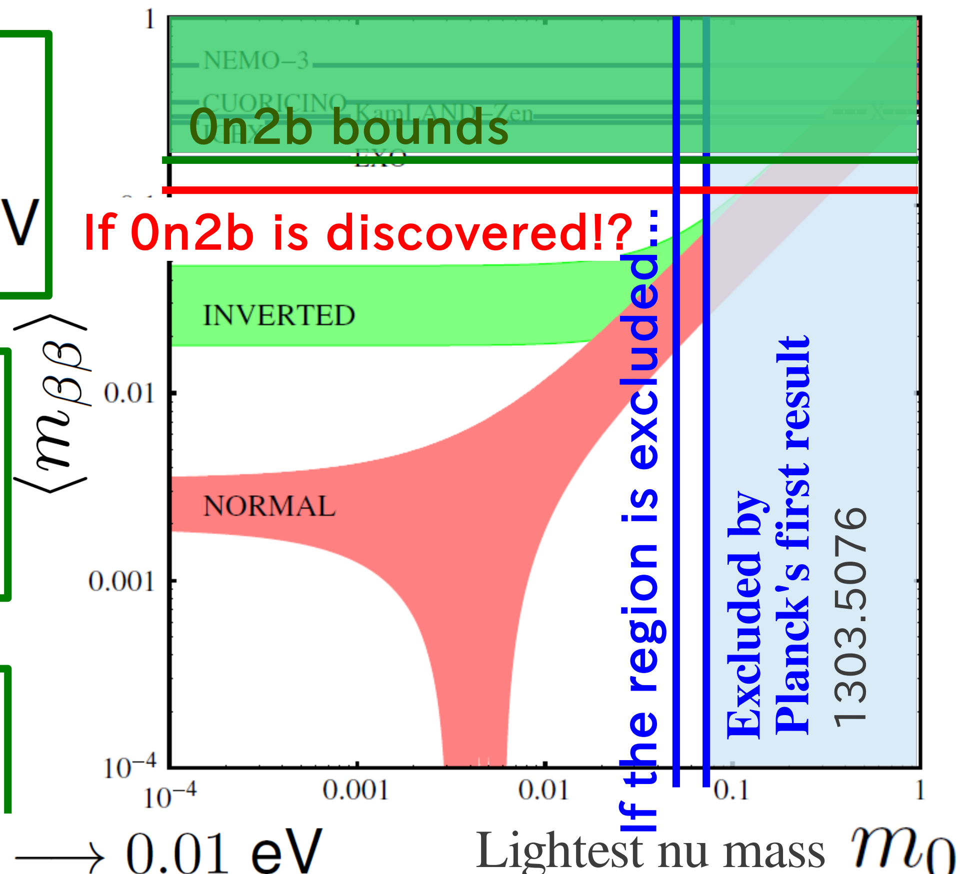
1307.4720
$T_{1/2}^{\text{Ge}} > 3.0 \cdot 10^{25}$ years
$\langle m_{\beta\beta}\rangle < [0.2, 0.4]$ eV $\longrightarrow$ 0.01 eV
In future



Planck (combined)
1303.5076
$$\sum_i m_i < 0.23 \text{ eV}$$

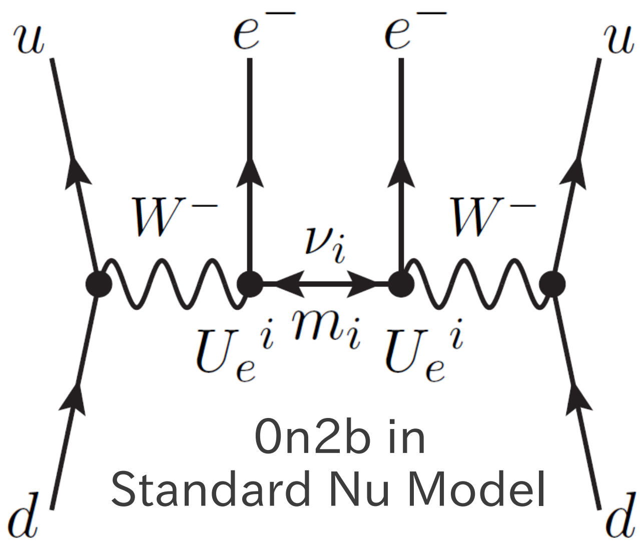
WMAP9 (combined)
1212.5226
$$\sum_i m_i < 0.44 \text{ eV}$$

SPT reports non-zero mNu?
1212.6267

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

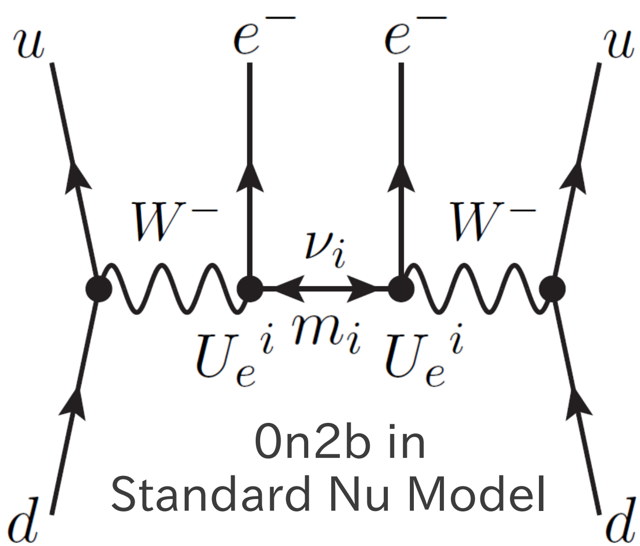
0n2b experiments measure...

- If we have an additional **New Physics** contribution to 0n2b...

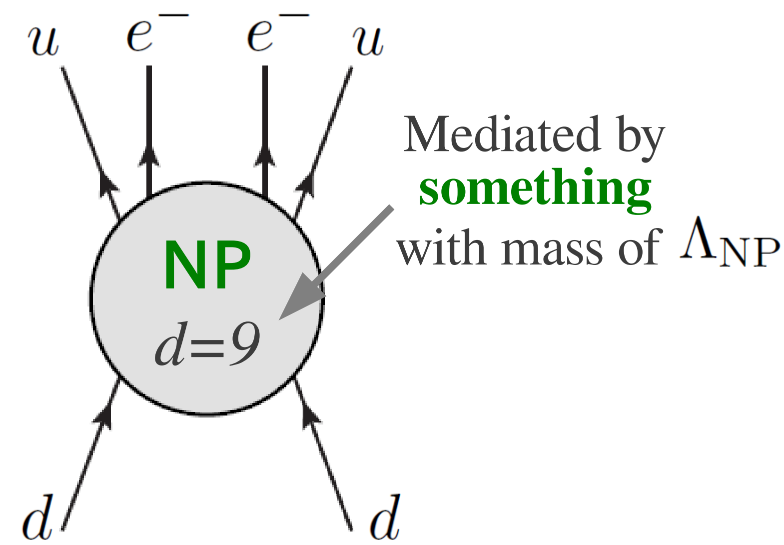


d=9 op. in 0n2b

- If we have an additional **New Physics** contribution to 0n2b...

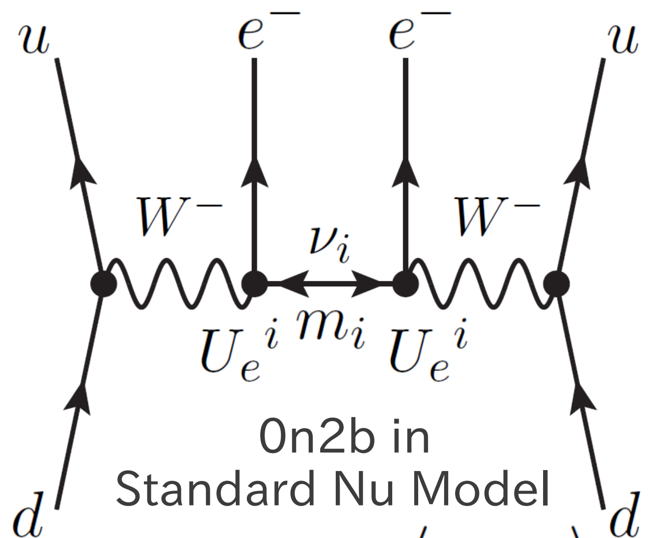


+



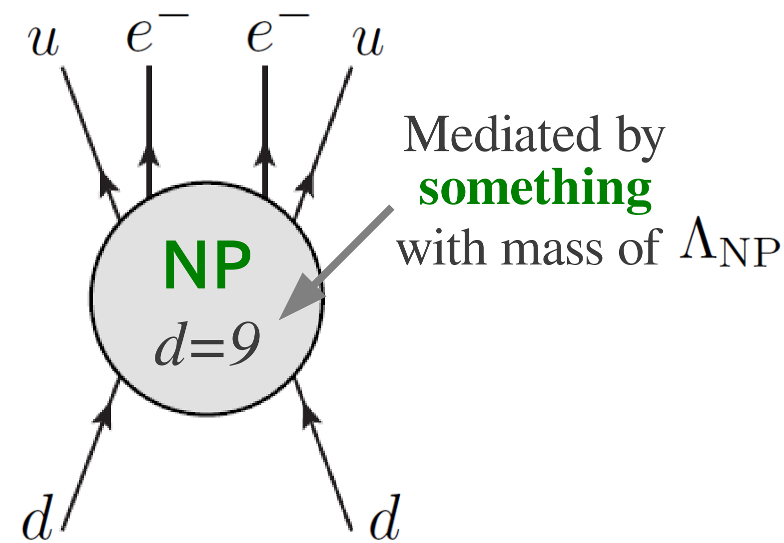
0n2b experiments measure...

- If we have an additional **New Physics** contribution to 0n2b...



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

+



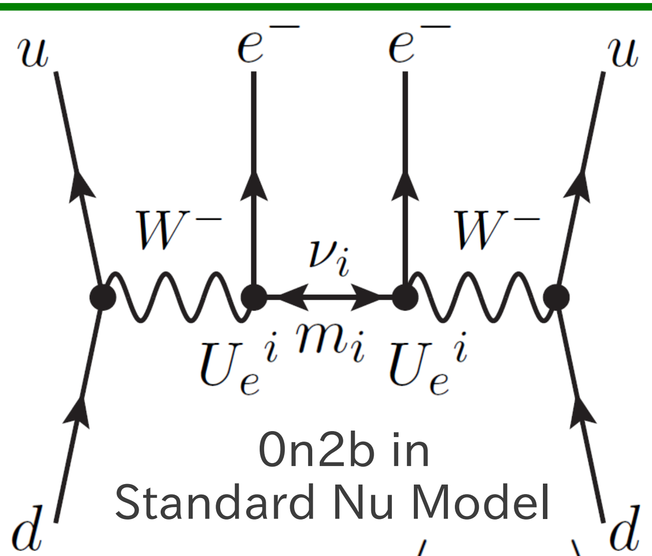
~100 MeV
A typical size of momentum that neutrino propagating in nucleus has

Current exp. limit

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

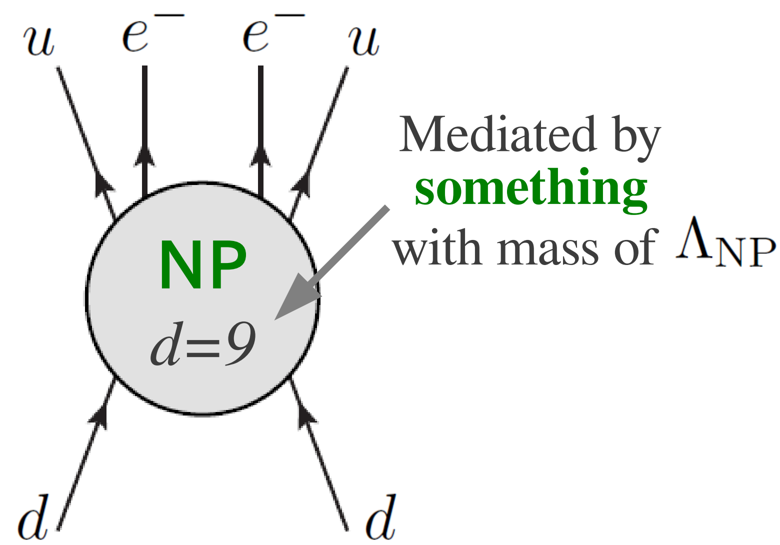
① d=9 op. in 0n2b — 0n2b experiments measure...

- If we have an additional **New Physics** contribution to 0n2b...



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

+



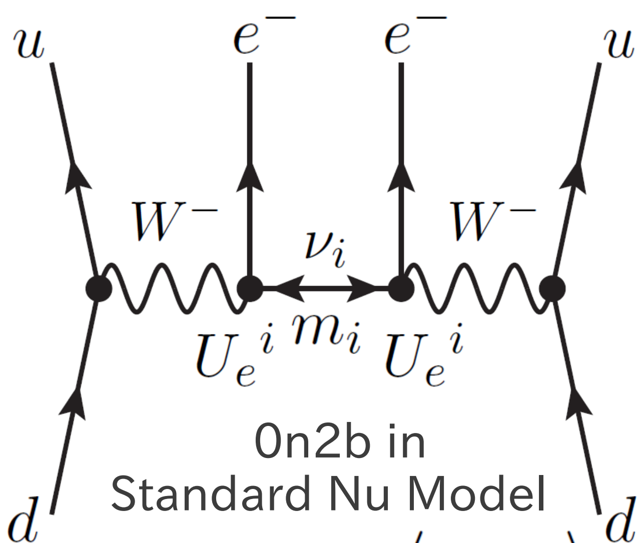
Current exp. limit

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

Sensitive to

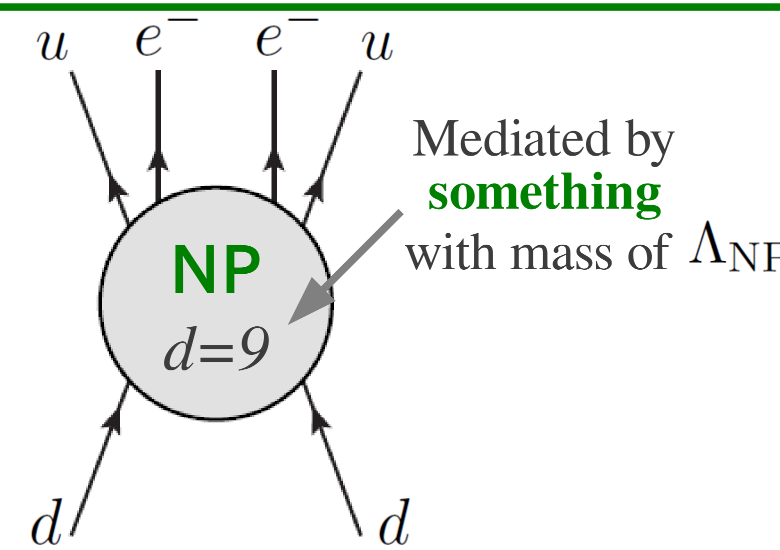
0n2b experiments measure...

- If we have an additional **New Physics** contribution to 0n2b...



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

+



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

Current exp. limit

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

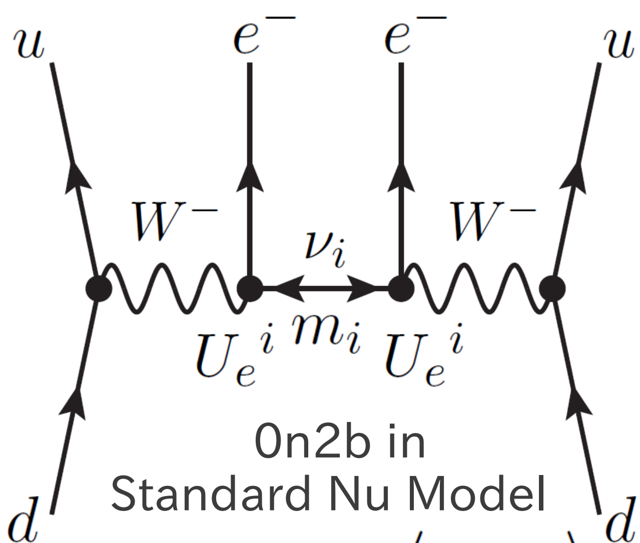
$$\propto 1/\left|\mathcal{A}_{d=9}\right|^2$$

Sensitive to

Saitama University 埼玉大学

1 *d=9* op. in 0n2b — 0n2b experiments measure…

- If we have an additional **New Physics** contribution to 0n2b…



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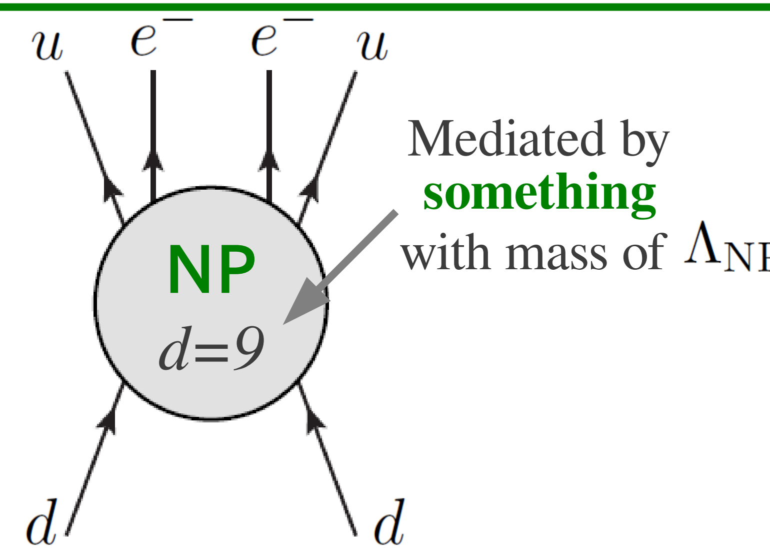
$+$



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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

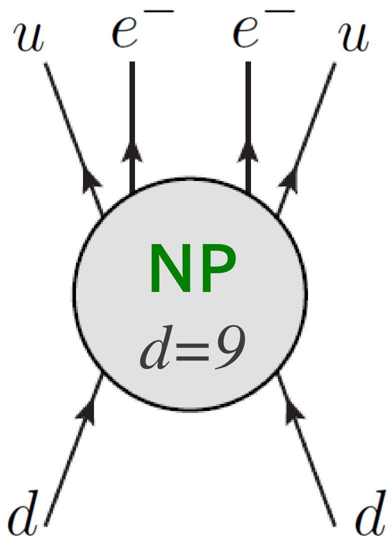
$$\propto 1/\left|\mathcal{A}_{d=9}\right|^2 \Rightarrow \Lambda_{\mathrm{NP}} > \mathcal{O}(1)\ [\mathrm{TeV}]$$

LHC range!

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

1 *d=9* op. in 0n2b

Effective ops → half-life time



…falls into the following 5 types of effective ops.

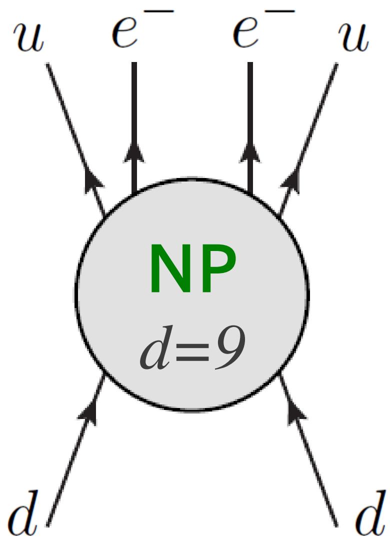
$$\mathscr{L}_{d=9} = \frac{G_F^2}{2m_P}\left[\sum_{i=1}^{3}\epsilon_i^{\{XY\}Z}(\mathcal{O}_i)_{\{XY\}Z} + \sum_{i=5}^{4}\epsilon_i^{XY}(\mathcal{O}_i)_{XY}\right],$$

$$(\mathcal{O}_1) \equiv J_X J_Y j_Z, \qquad (\mathcal{O}_4) \equiv (J_X)^{\mu\nu}(J_Y)_\mu (j)_\nu, \quad J_X = \overline{u}\Gamma \mathrm{P}_X d$$

$$(\mathcal{O}_2) \equiv (J_X)^{\mu\nu}(J_Y)_{\mu\nu} j_Z, (\mathcal{O}_5) \equiv J_X (J_Y)_\mu (j)_\mu \quad j_X = \overline{e}\Gamma \mathrm{P}_X e^c$$

$$(\mathcal{O}_3) \equiv (J_X)^\mu (J_Y)_\mu j_Z,$$

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



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$$(\mathcal{O}_3) \equiv (J_X)^\mu (J_Y)_\mu j_Z,$$

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

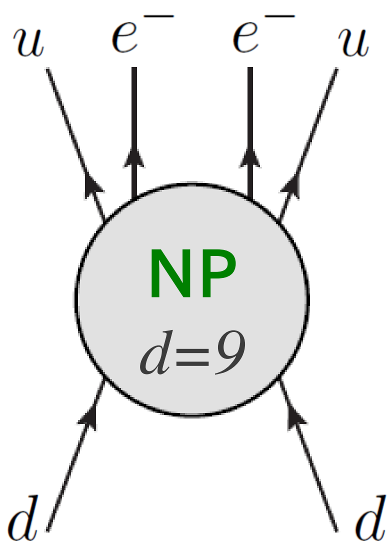
$$\left(T_{1/2}^{0\nu2\beta}\right)^{-1}_{\underline{\underline{d=9}}} = G_1 \left|\sum_{i=1}^{3} \epsilon_i \mathcal{M}_i\right|^2 + G_2 \left|\sum_{i=4}^{5} \epsilon_i \mathcal{M}_i\right|^2 + G_3 \mathrm{Re}\left[\left(\sum_{i=1}^{3} \epsilon_i \mathcal{M}_i\right)\left(\sum_{i=4}^{5} \epsilon_i \mathcal{M}_i\right)^*\right]$$

$$\left(T_{1/2}^{0\nu2\beta}\right)^{-1}_{\mathrm{S}\nu\mathrm{M}} = G_1 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\left[\mathcal{M}_{\mathrm{GT}} - \frac{g_V^2}{g_A^2}\mathcal{M}_{\mathrm{F}}\right]\right|^2$$

$\mathcal{M}_i$ Nuclear matrix elements

G_i Phase space factors

Effective ops → half-life time



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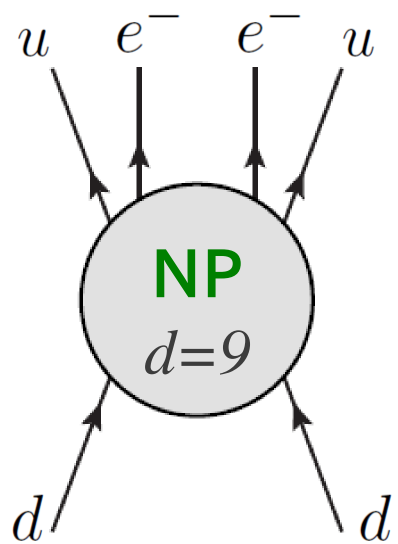
$\mathcal{M}_i$ Nuclear matrix elements
G_i Phase space factors

Q: What is the high *E* (TeV) origin of these *d=9* effective ops?

d=9 ops.

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



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

Q: What is the high *E* (TeV) origin of these *d=9* effective ops?

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

Outline

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

1. ***Motivation: Why 0n2b? Why 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

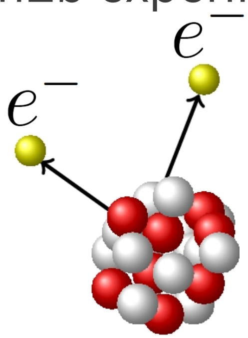
   "The list helps us to discriminate the models"

3. ***Seeking a relation to the models at the TeV scale***

   TeV scale models with LNV → *Models for radiative neutrino masses*

Exhaustive bottom-up approach

0n2b experiments

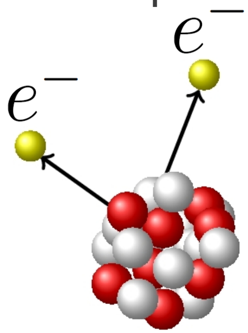


Discover!
(or constrain)
$T_{1/2}^{0\nu2\beta} > 10^{25}$ [yr]

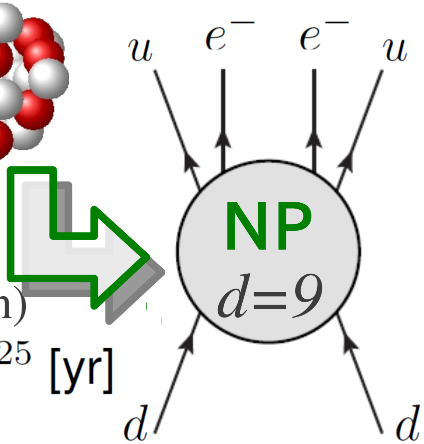
2 *Effective ops → High E completions*

Exhaustive bottom-up approach

0n2b experiments



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



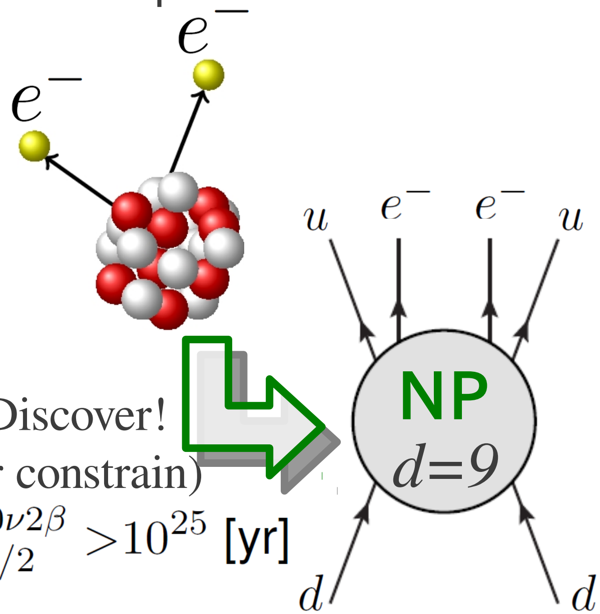
$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}^{\rm tree}_{d=9} \; @\Lambda_{\rm EW}$$

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

2 *Effective ops → High E completions*

Exhaustive bottom-up approach

0n2b experiments

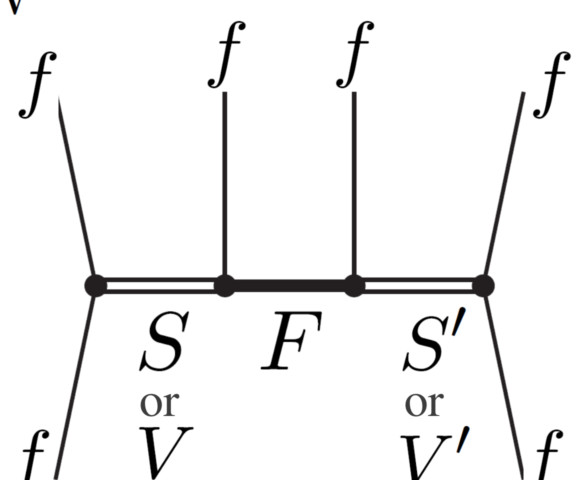


Discover!
(or constrain)
$T_{1/2}^{0\nu 2\beta} > 10^{25}$ [yr]

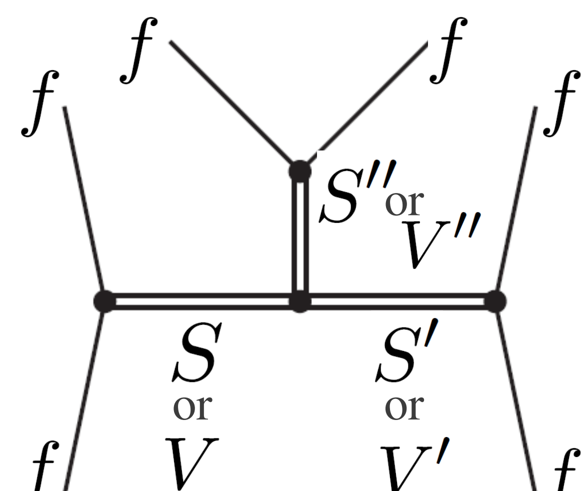
$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\rm NP}^5} \mathcal{O}_{d=9}^{\rm tree} \ @\Lambda_{\rm EW}$$

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

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



Topology #I

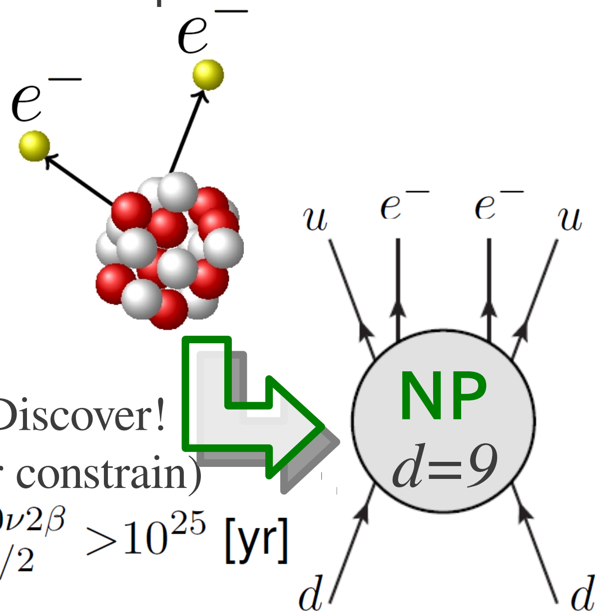


Topology #II

2 Effective ops → High E completions

Exhaustive bottom-up approach

0n2b experiments



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

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

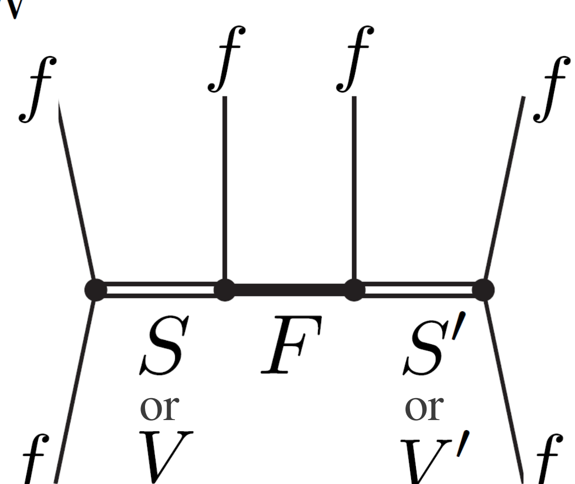
→ $\Lambda_{\rm NP} > \mathcal{O}(1)$ [TeV]

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

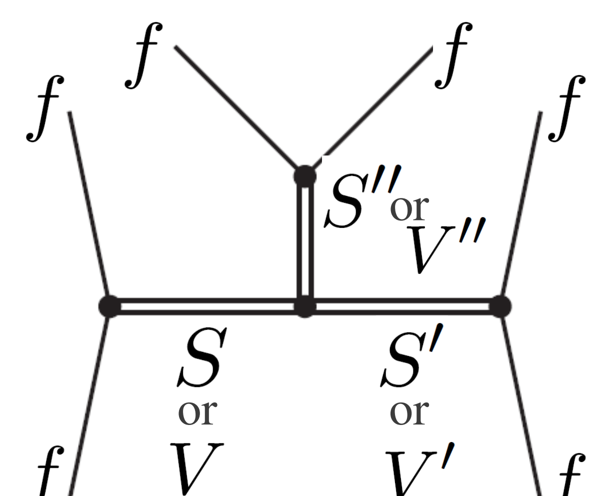
How to decompose — Necessary Mediators

		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@$\Lambda_{\rm NP}$



Topology #I



Topology #II

2 *Effective ops → High E completions*

- **Exhaustive bottom-up approach**

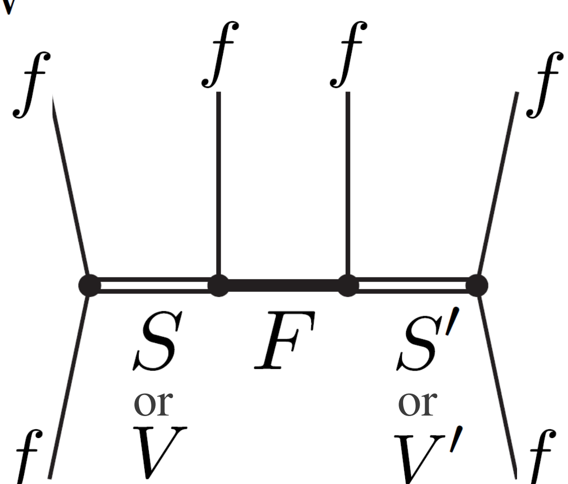
How to decompose — **Necessary Mediators**

		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	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

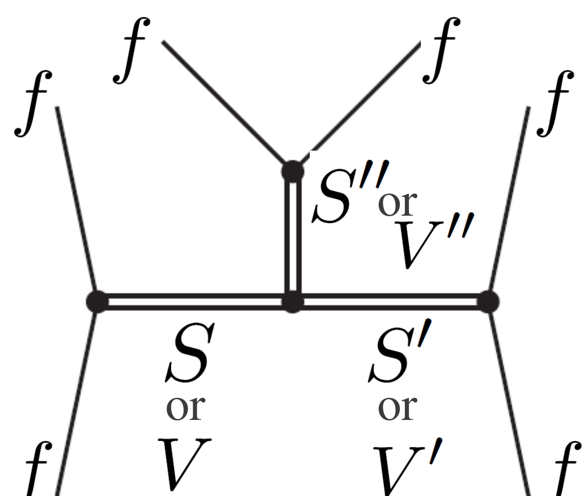
List of high *E* completions@$\Lambda_{\rm NP}$

@$\Lambda_{\rm EW}$

ms



Topology #I



Topology #II

- **Exhaustive bottom-up approach**

Re-integrate out the Mediators

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

How to decompose

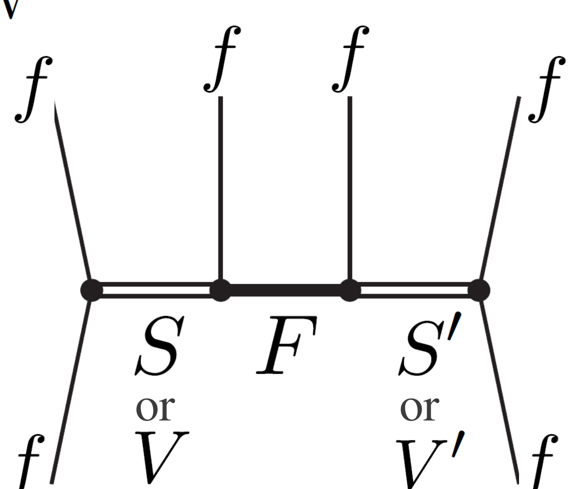
Necessary Mediators

		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	$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{1})_{+1/3}$	$-\frac{1}{2}J_R J_R j_R$
	⋮		$(\mathbf{1},\mathbf{2})_{+1/2}$	$(\mathbf{1},\mathbf{3})_0$	$(\overline{\mathbf{3}},\mathbf{3})_{+1/3}$	

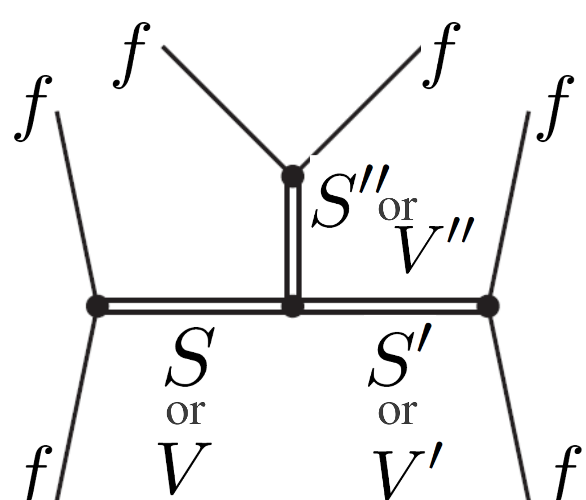
List of high *E* completions@$\Lambda_{\rm NP}$

@$\Lambda_{\rm EW}$

ns



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@$\Lambda_{\rm EW}$

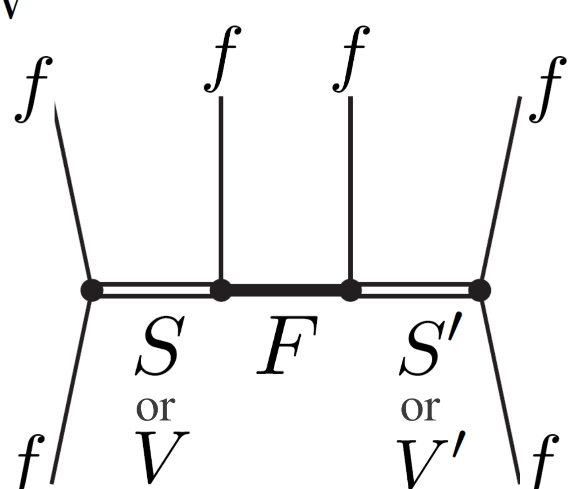
$$\mathscr{L}_{d=9} = \frac{1}{\Lambda_{\rm NP}^5}\mathcal{O}^{\rm tree}_{d=9} + $$

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

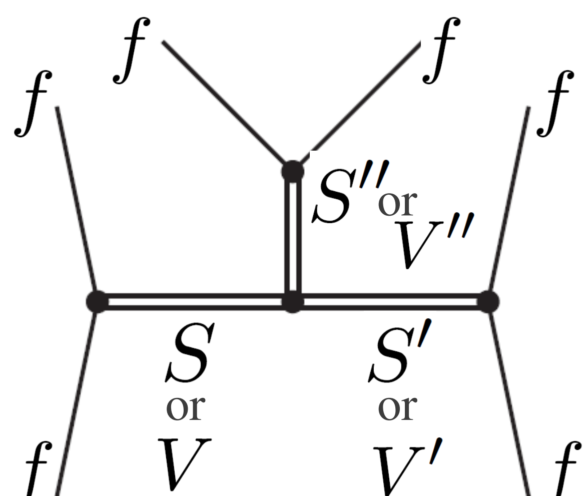
List of high *E* completions@$\Lambda_{\rm NP}$

@$\Lambda_{\rm EW}$

ms



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@$\Lambda_{\rm EW}$

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

+

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

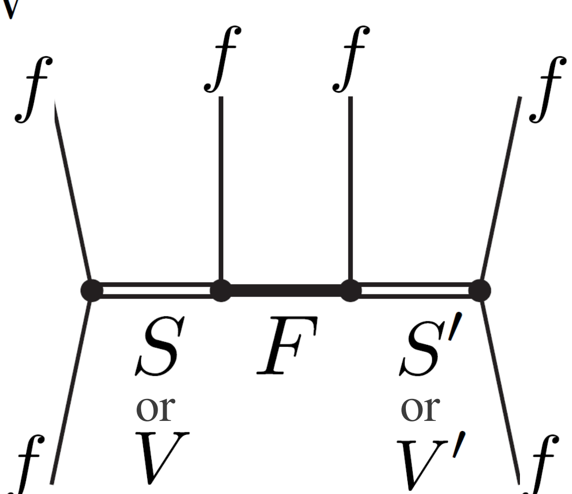
⋮

Testing phenos, we can identify the models@$\Lambda_{\rm NP}$

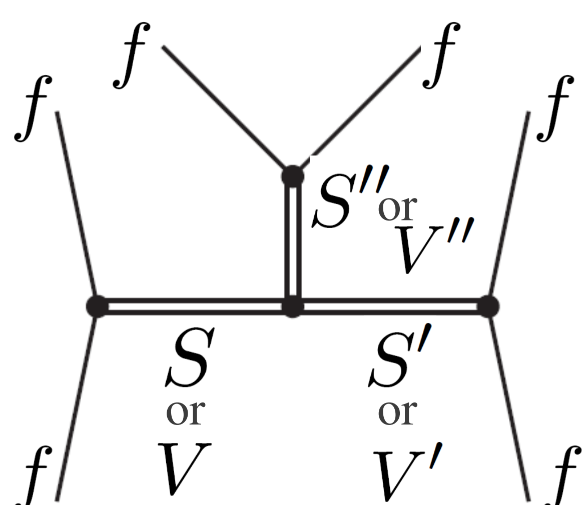
List of high E completions@$\Lambda_{\rm NP}$

@$\Lambda_{\rm EW}$

ns



Topology #I

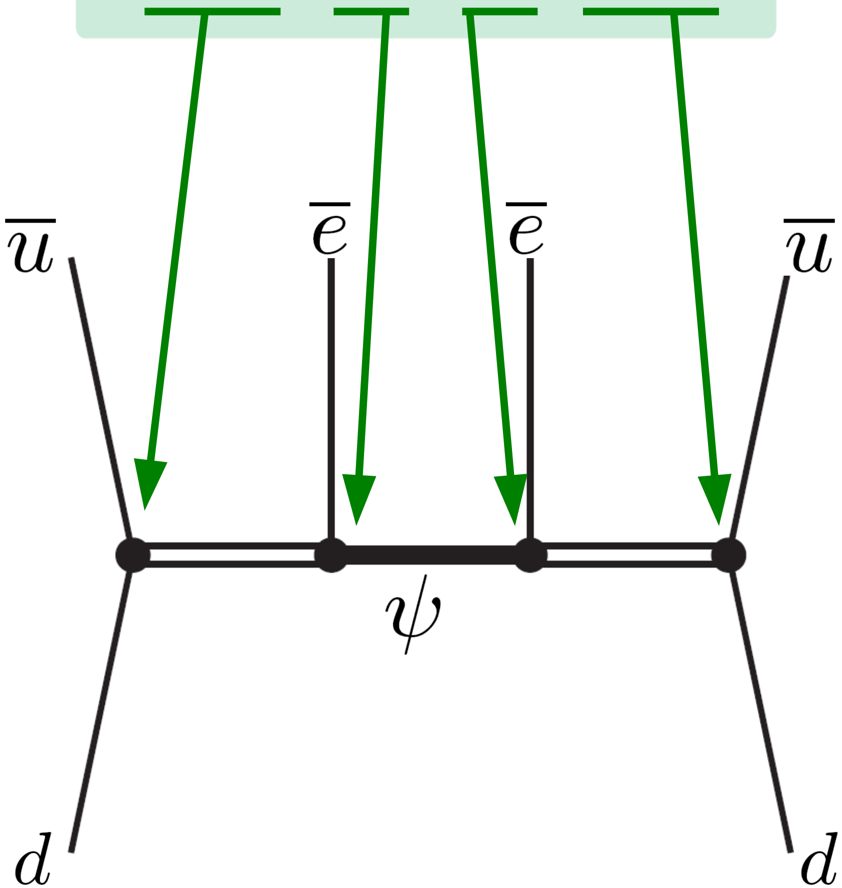


Topology #II

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

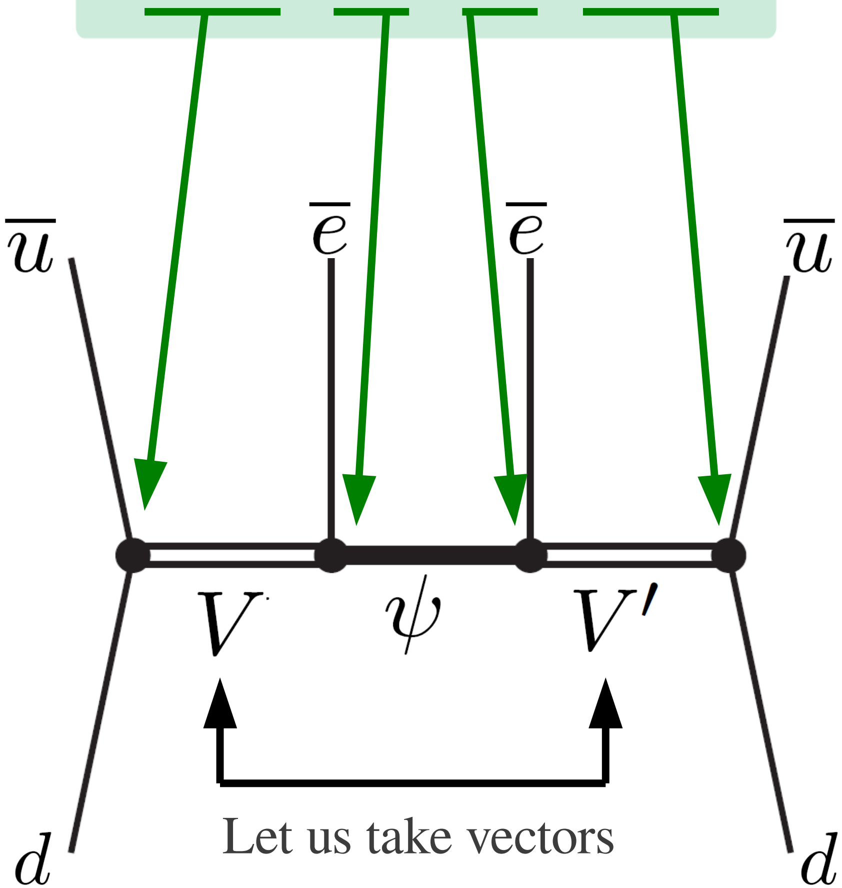
- An example,
  Taking Topology #I
  let us decompose *d=9* op as

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



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

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



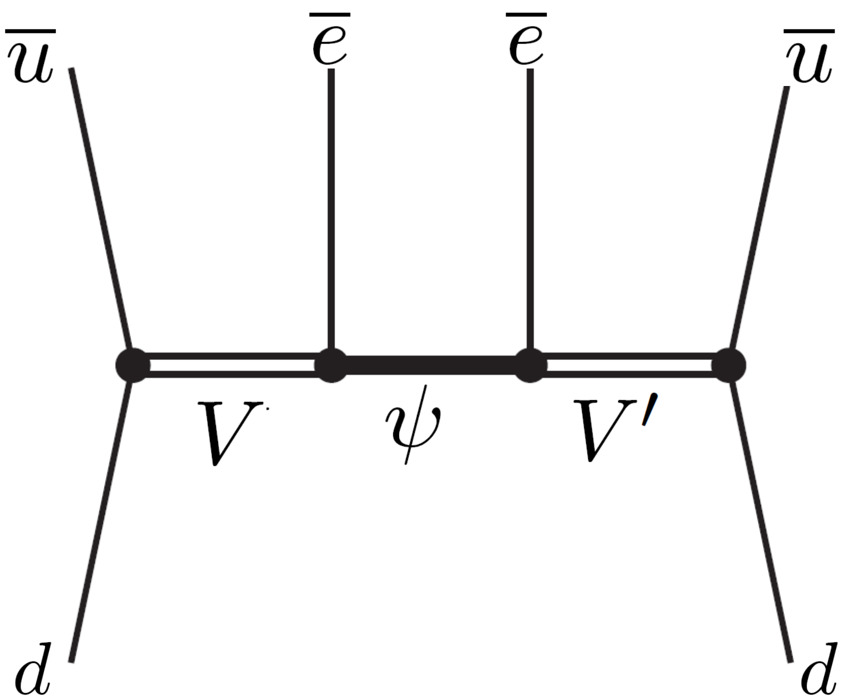
- An example,
  Taking Topology #I
  let us decompose *d=9* op as

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

Necessary mediators

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

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



- An example,

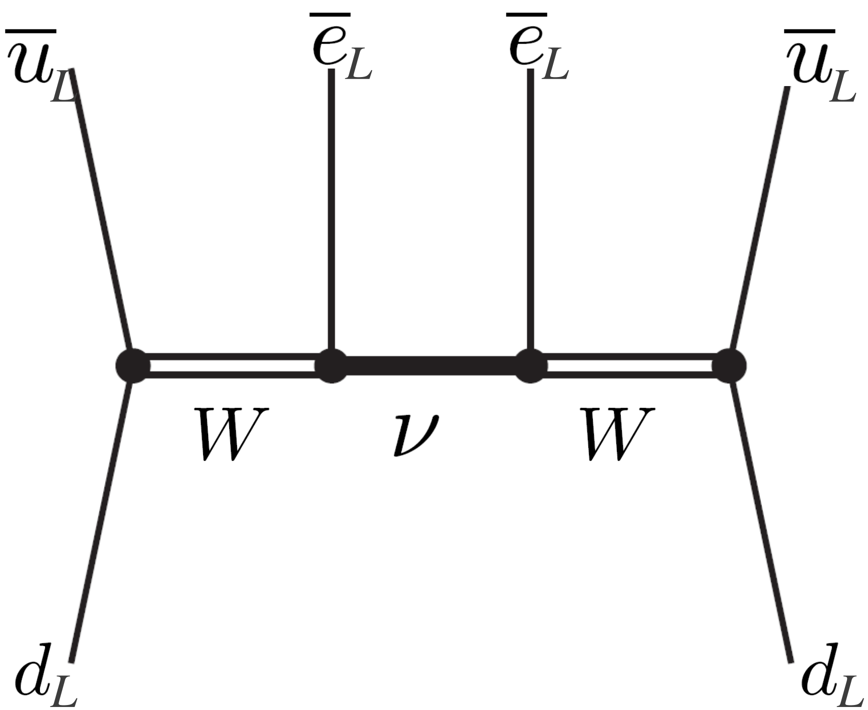
Taking Topology #I
let us decompose *d=9* op as

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

Necessary mediators

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

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



Rediscovery of the standard neutrino mass contribution

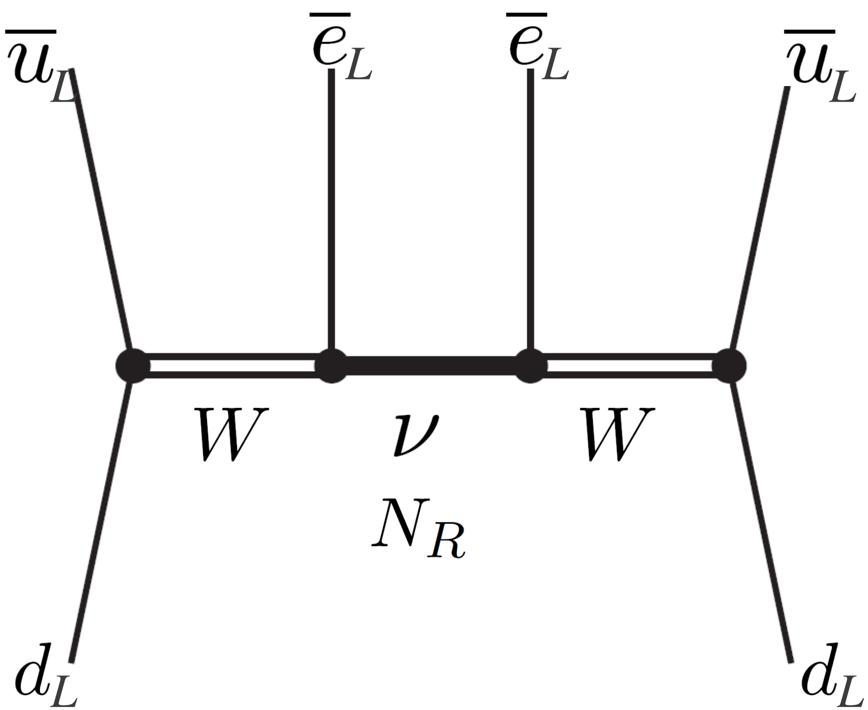
All the outer fermions must be left-handed

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

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,

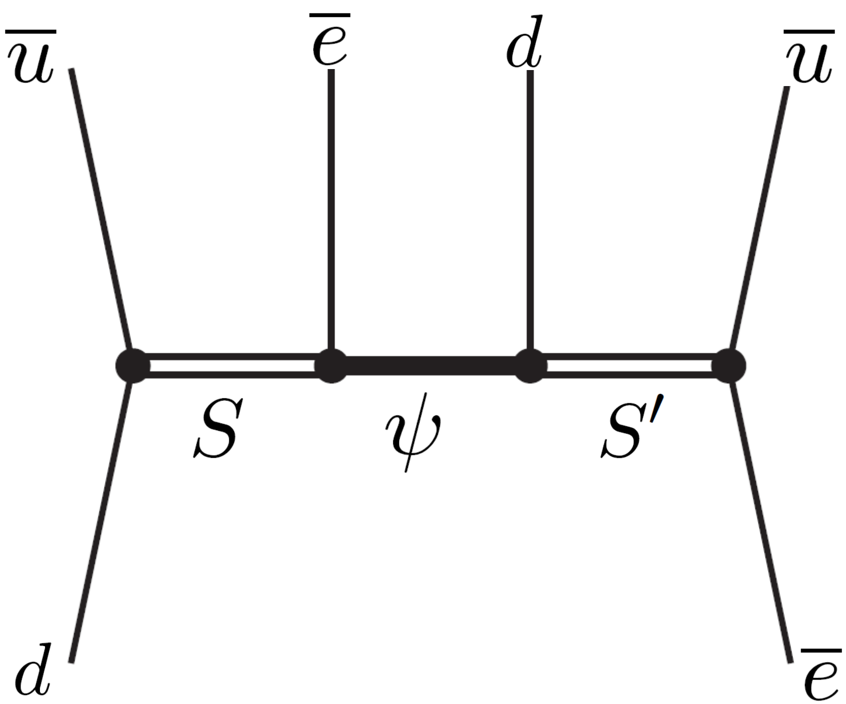
Decomposition

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

Necessary mediators

$$S(1, \mathbf{1})$$
$$S'(+1/3, \overline{\mathbf{3}})$$
$$\psi(0, \mathbf{1})$$

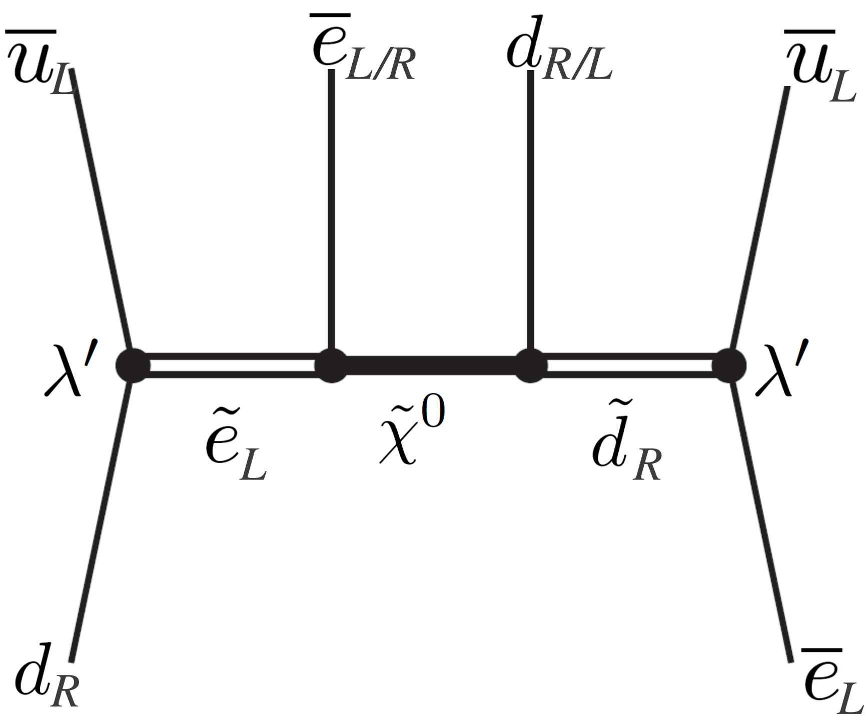
where $(U(1)_{\mathrm{em}}, SU(3)_{\mathrm{c}})$



- 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 ($U(1)_{em}$, $SU(3)_c$)

R-parity violating SUSY models

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

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,

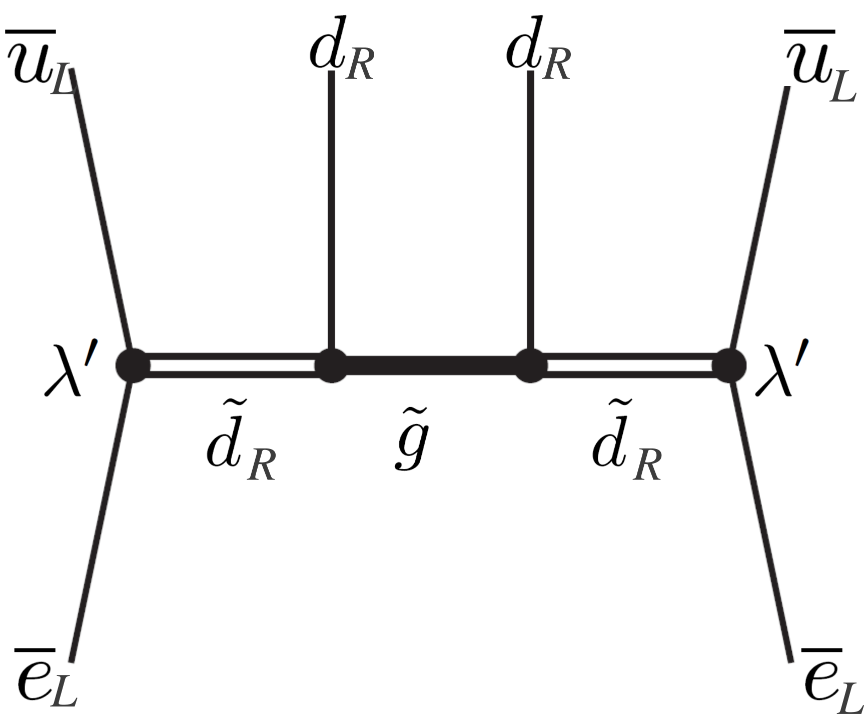
Decomposition

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

Necessary mediators

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

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



Another diagram in

R-parity violating SUSY models

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

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

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
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

SnuM Seesaw

RPV

RPV

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
  JHEP**1303** (2013) 055
- *Long Range?*
  Decomposition which can contain neutrino propagation

2 Decompositions — 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

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
  JHEP**1303** (2013) 055
- *Long Range?*
  Decomposition which can contain neutrino propagation

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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  Decomposition which can contain neutrino propagation

List of high E completions

#	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)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	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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#	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	$(\bar u d)(d)(\bar u)(\bar e\bar e)$		$(+1,\mathbf{1})$	$(+4/3,\bar{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\bar{\mathbf{3}})$	$(+2,\mathbf{1})$	
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'
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
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
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar u)(\bar u)(\bar e\bar e)$		$(+2/3,\mathbf{3})$	$(+4/3,\bar{\mathbf{3}})$	$(+2,\mathbf{1})$	[illegible]
			$(+2/3,\bar{\mathbf{6}})$	$(+4/3,\bar{\mathbf{3}})$	$(+2,\mathbf{1}$	
4-i	$(d\bar e)(\bar u)(\bar u)(d\bar e)$	(c)	$(-2/3,\bar{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3}$	[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

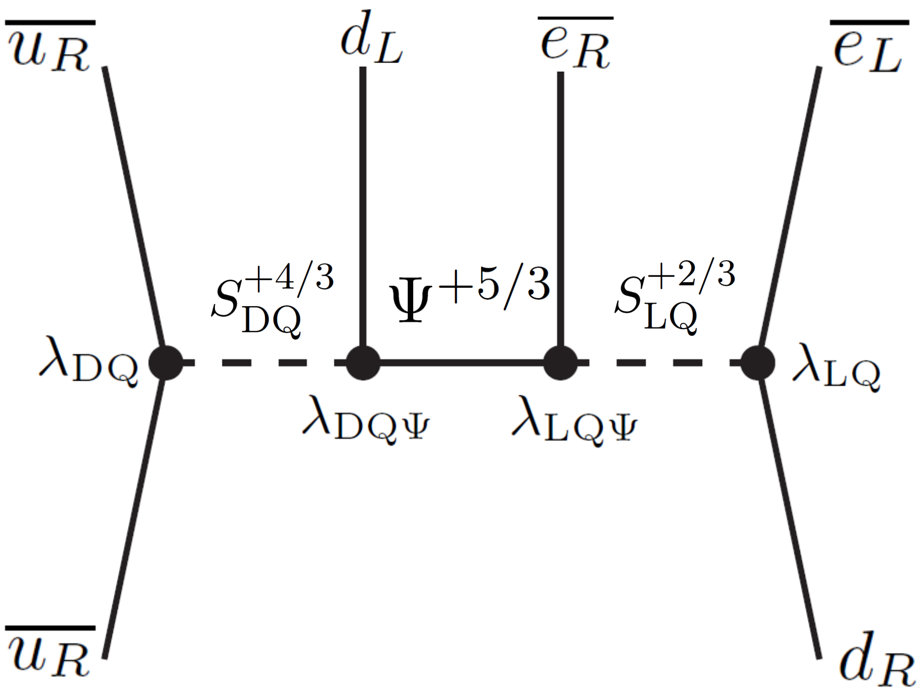
Let us have a closer look at this example.

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
  JHEP**1303** (2013) 055
- *Long Range?*
  Decomposition which can contain neutrino propagation

An example



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

Take scalar mediators
Specify the chiralities

Necessary mediators

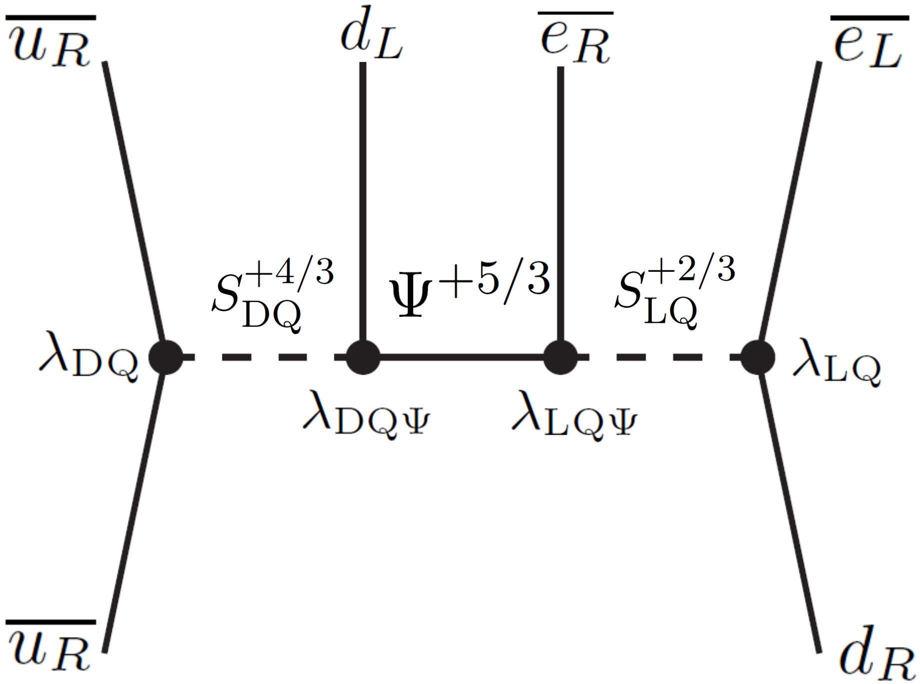
$$(S_{\rm DQ}^{+4/3})_X$$

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

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

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

An example



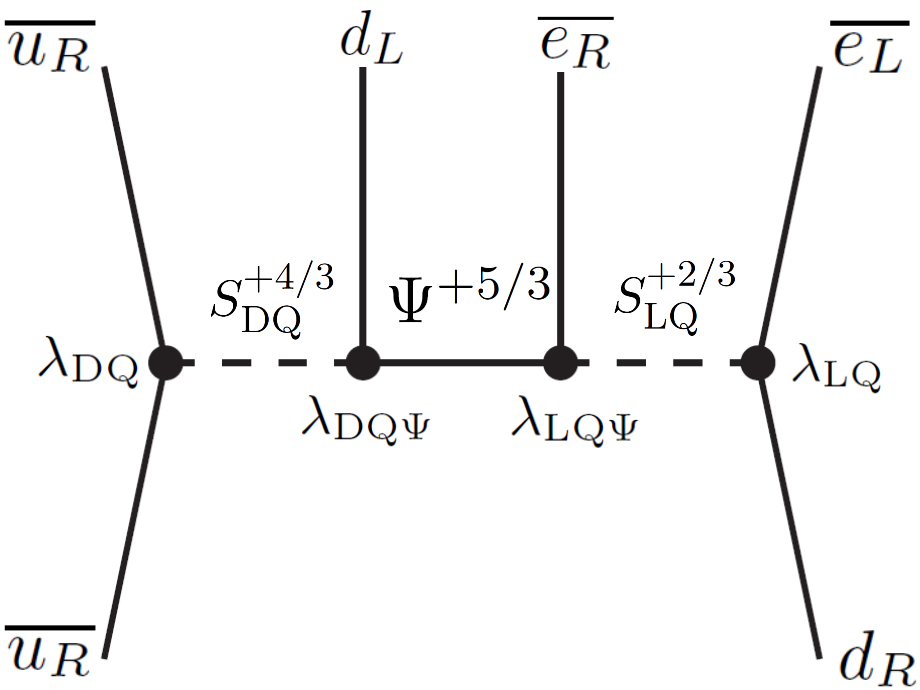
$$(\overline{u_R u_R})(Q)(\overline{e_R})(\overline{L} d_R)$$

Take scalar mediators
Specify the chiralities

Necessary mediators

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

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



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

Take scalar mediators
Specify the chiralities

Necessary mediators

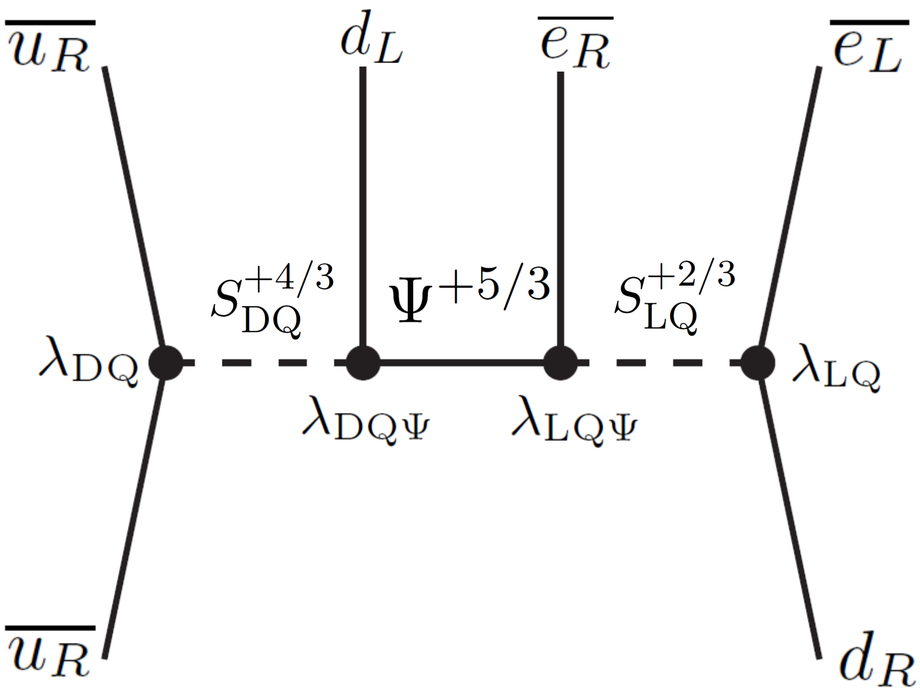
$(S^{+4/3}_{\rm DQ})_X$

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

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

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

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



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

Take scalar mediators
Specify the chiralities

Necessary mediators

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

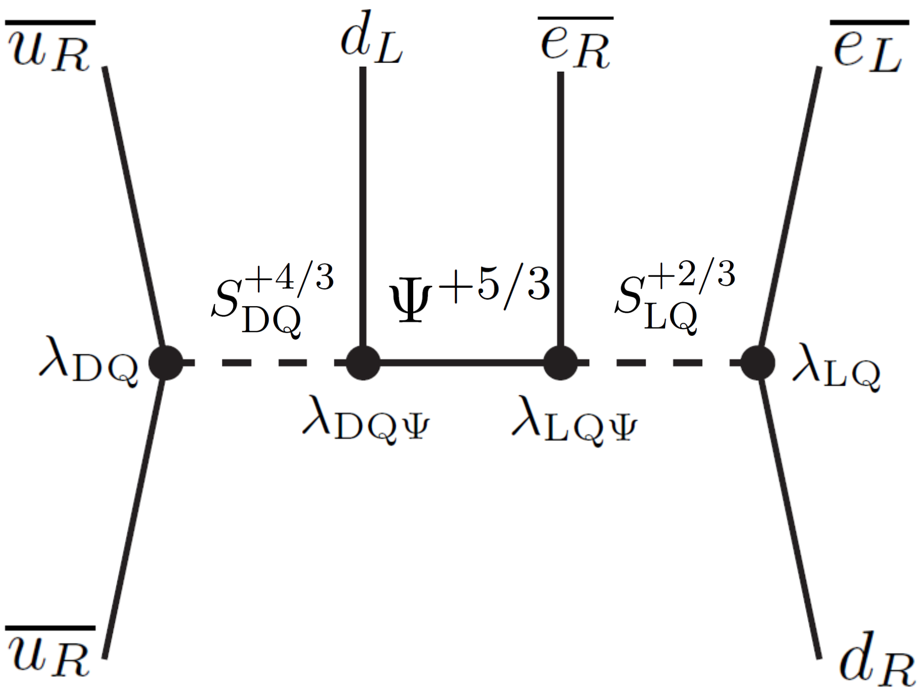
$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m^2_{\rm DQ} m^2_{\rm LQ} m_\Psi} \frac{1}{32} \left[i(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{LR} \right]$$

Take λ's =1, m=Λ

0n2b half-life: $\left(T^{0\nu2\beta}_{1/2}\right)^{-1} = G_2 \left| \frac{2m_P}{G_F^2} \frac{1}{32} \frac{1}{\Lambda^5} \left[i\mathcal{M}_4 - \mathcal{M}_5 \right] \right|^2$

Saitama University 埼玉大学

2 High E models — An example



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

Take scalar mediators
Specify the chiralities

Necessary mediators

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

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

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

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

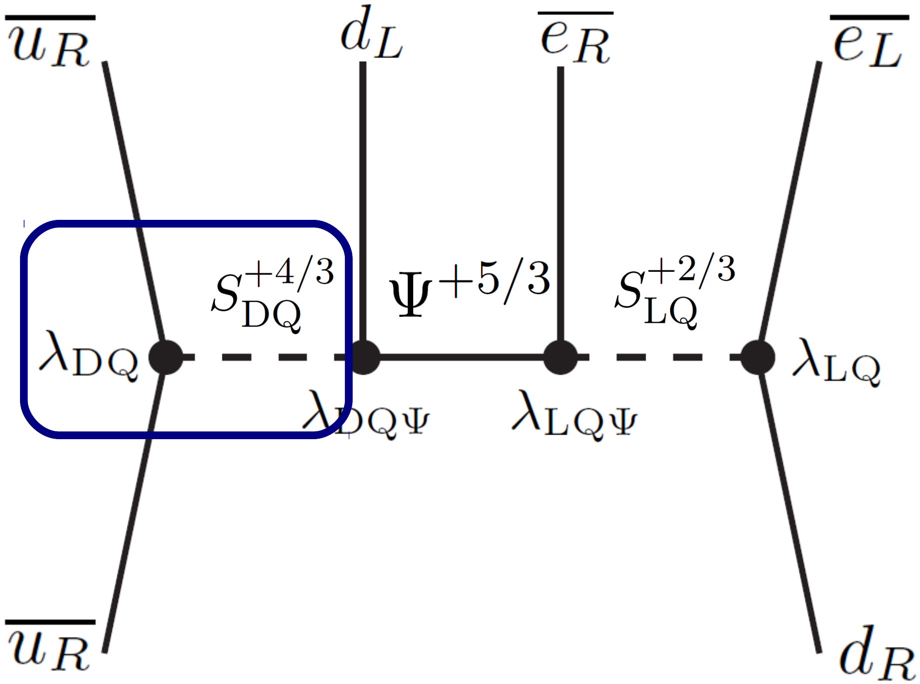
$$= \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\Psi}\lambda_{\rm LQ\Psi}\lambda_{\rm LQ}}{m_{\rm DQ}^2 m_{\rm LQ}^2 m_\Psi} \frac{1}{32} [{\rm i}(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{LR}]$$

Take λ's =1, m=Λ

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

Exp. bound: $T_{1/2}^{0\nu 2\beta}(^{136}{\rm Xe}) > 1.6 \cdot 10^{25}$ [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

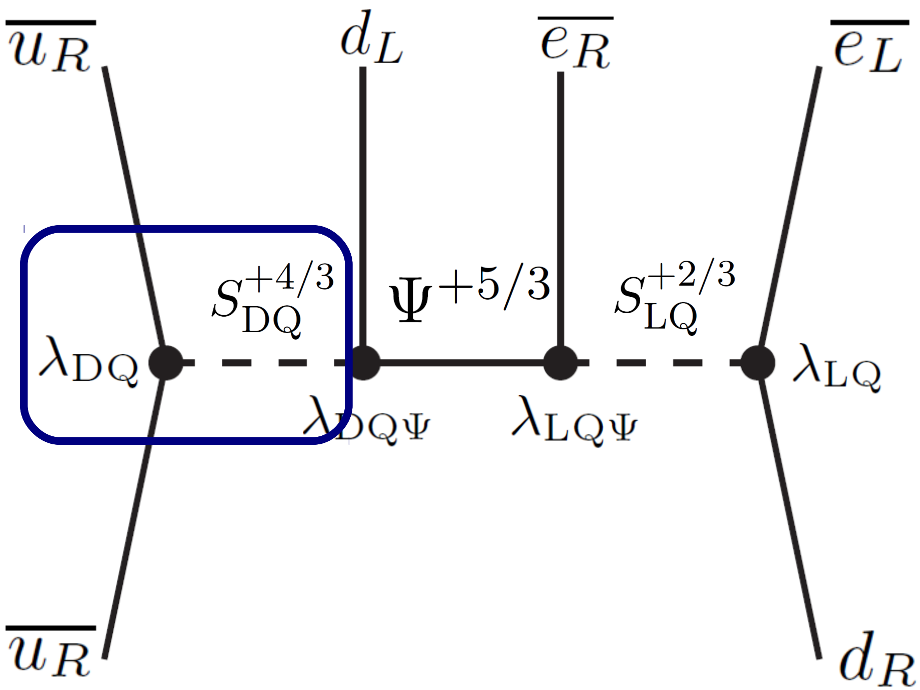
$(S_{\rm DQ}^{+4/3})_X$

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

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

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

- **Diquark (DQ):**



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

Take scalar mediators
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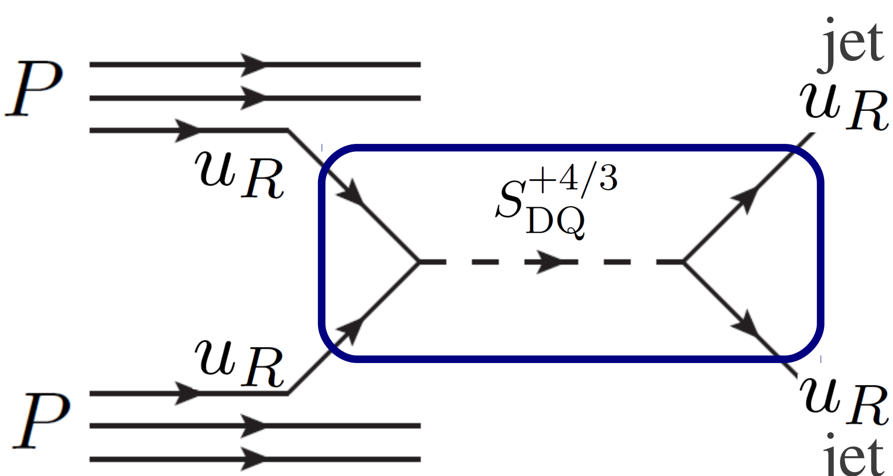
Necessary mediators

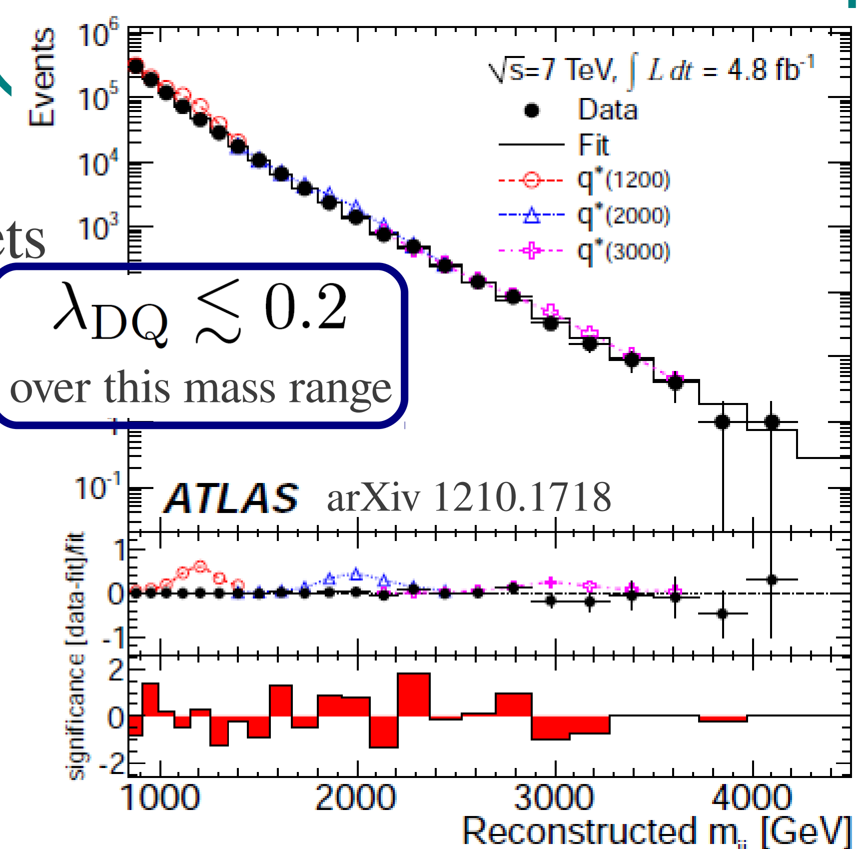
$$(S_{\rm DQ}^{+4/3})_X$$

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

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

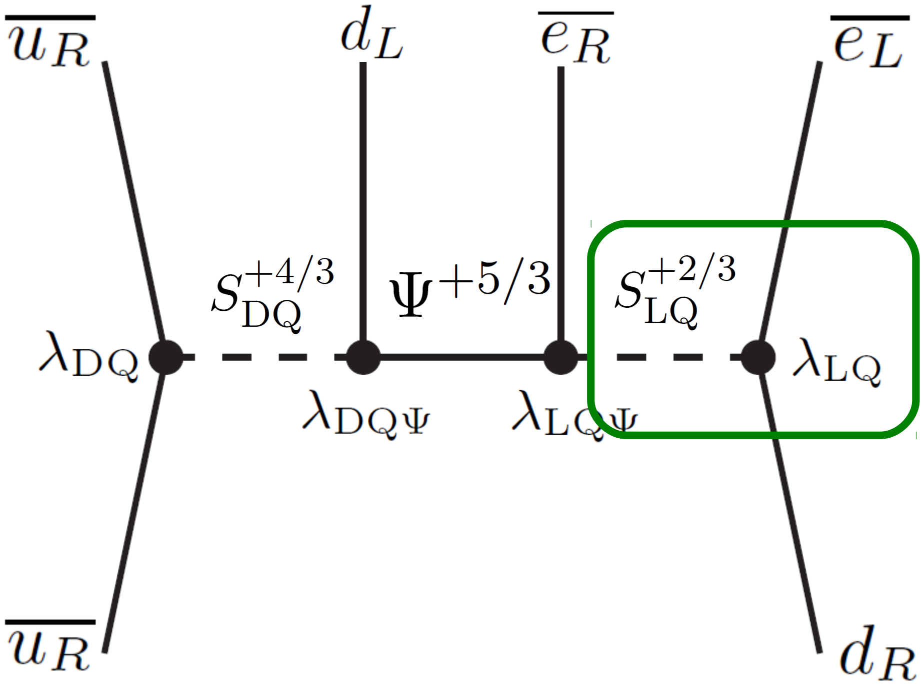
- **Diquark (DQ)**: Search for a resonance in 2-jets





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

An example



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

Take scalar mediators
Specify the chiralities

Necessary mediators

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

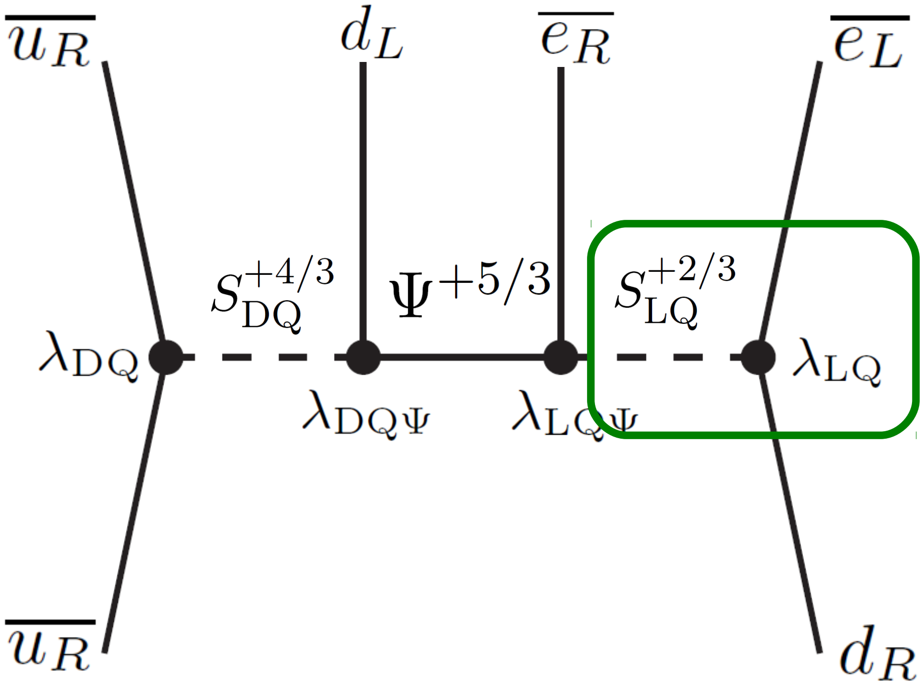
$$(S_{\rm LQ})_{Ii} = \left((S^{+2/3}_{\rm LQ})_I, (S^{-1/3}_{\rm LQ})_I \right)^{\rm T}$$

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

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

- **Leptoquark (LQ)**:

An example



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

Take scalar mediators
Specify the chiralities

Necessary mediators

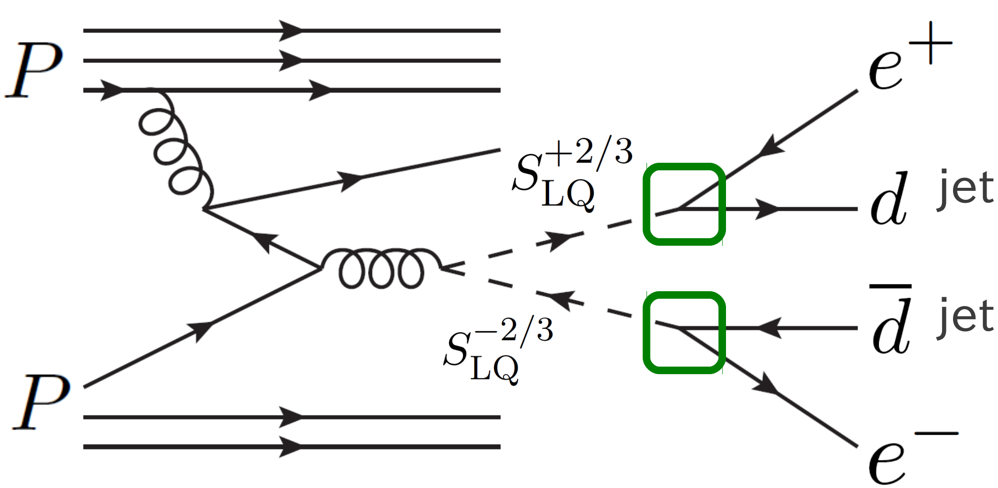
$(S^{+4/3}_{\rm DQ})_X$

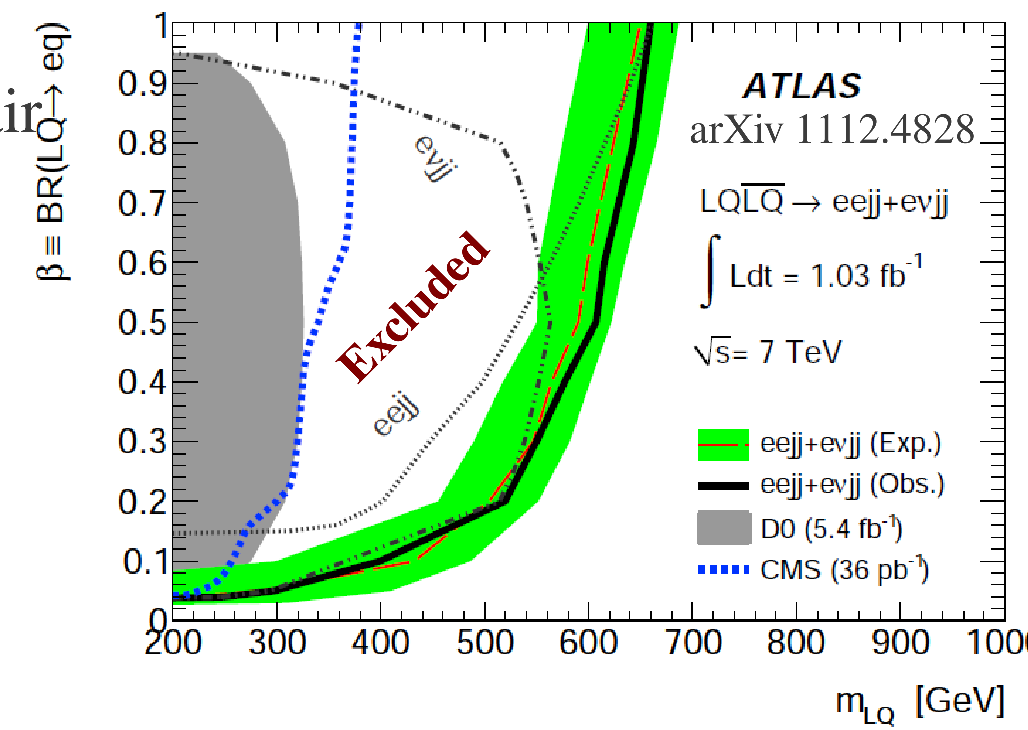
$(S_{\rm LQ})_{Ii} = \left((S^{+2/3}_{\rm LQ})_I, (S^{-1/3}_{\rm LQ})_I\right)^{\rm T}$

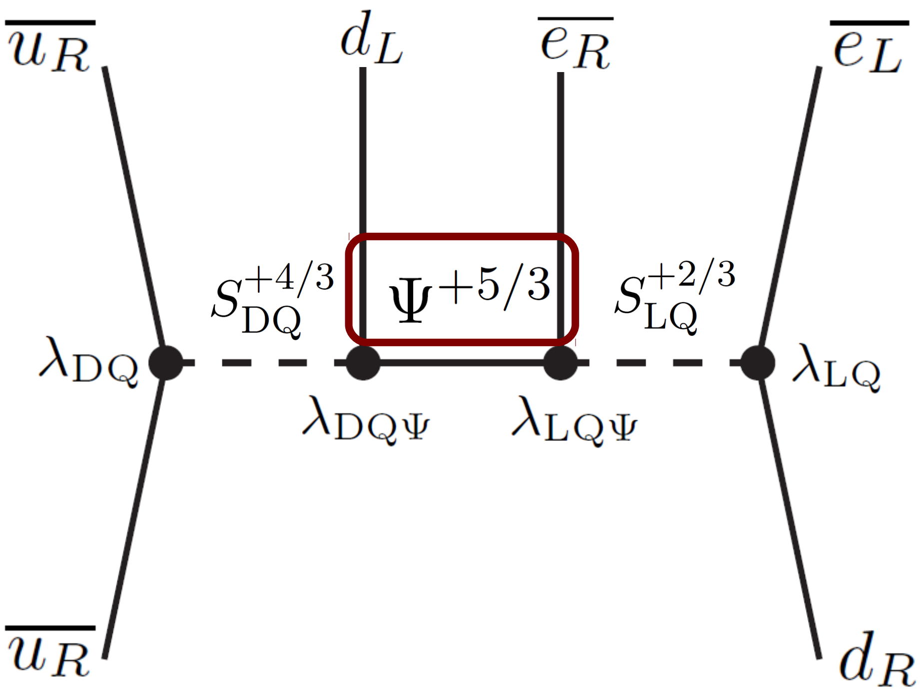
$(\Psi_L)_{Iia} = \left((\Psi^{+5/3}_L)_{Ia}, (\Psi^{+2/3}_L)_{Ia},\right)^{\rm T}$

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

- **Leptoquark (LQ)**: 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

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

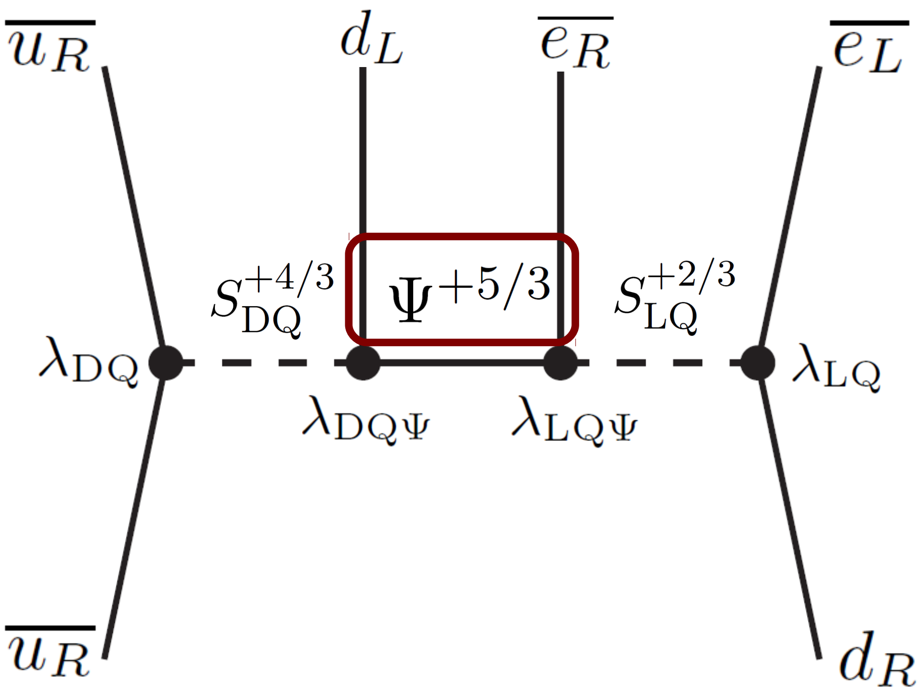
$$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^{\rm T}$$

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

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

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

An example



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

Take scalar mediators
Specify the chiralities

Necessary mediators

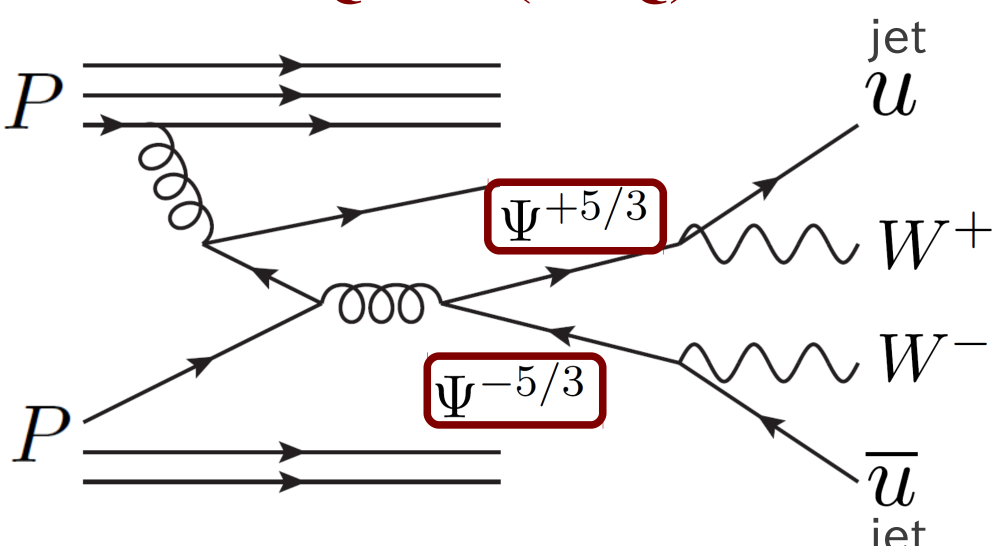
$(S_{\rm DQ}^{+4/3})_X$

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

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

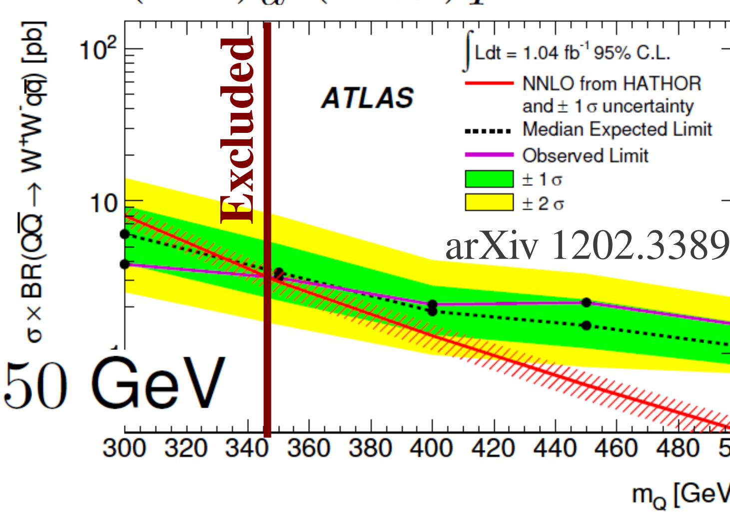
and $(\Psi_R)^{\dot a}_{Ii}$

- **Vector-like Quark (VLQ)**: 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 ***Motivation: Why 0n2b? Why 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.

Summary

→ list the TeV signatures of each completion

→ The list helps us to discriminate the models

3 ***Seeking a relation to the models at the TeV scale***

TeV scale models with LNV → Models for radiative neutrino masses

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

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
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[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)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	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
			$(+2/3, \bar{\mathbf{6}})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
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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
			$(+4/3, \mathbf{6})$	$(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$	
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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
			$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \mathbf{6})$	

Colour 8

Colour 3

Colour 6

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

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			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[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	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\mathbf{3})$	$(+1/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+4/3,\bar{\mathbf{3}})$	$(+1/3,\bar{\mathbf{3}})$	
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]
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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
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
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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
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

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1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$	
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2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \mathbf{3})$	$(+1/3, \mathbf{3})$	
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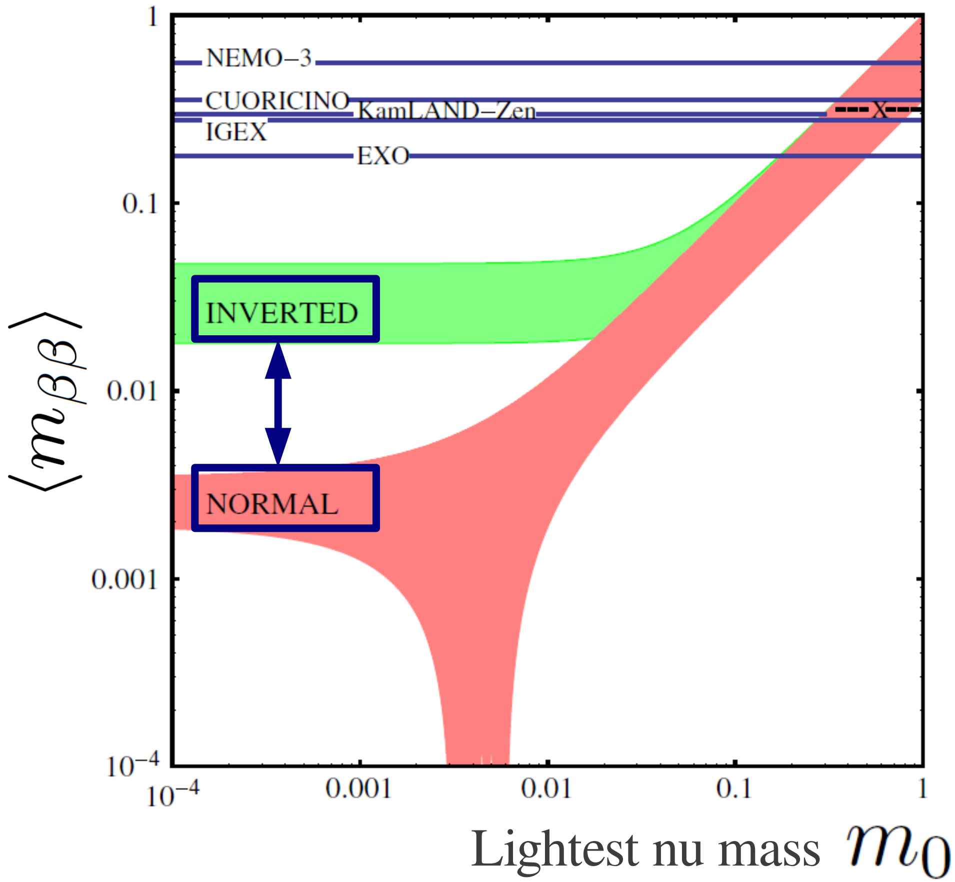
T-I-1-i can be examined at ILC! exotic interactions with electron!

My 2nd last message:

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

Summary



Standard 3nu parameter space

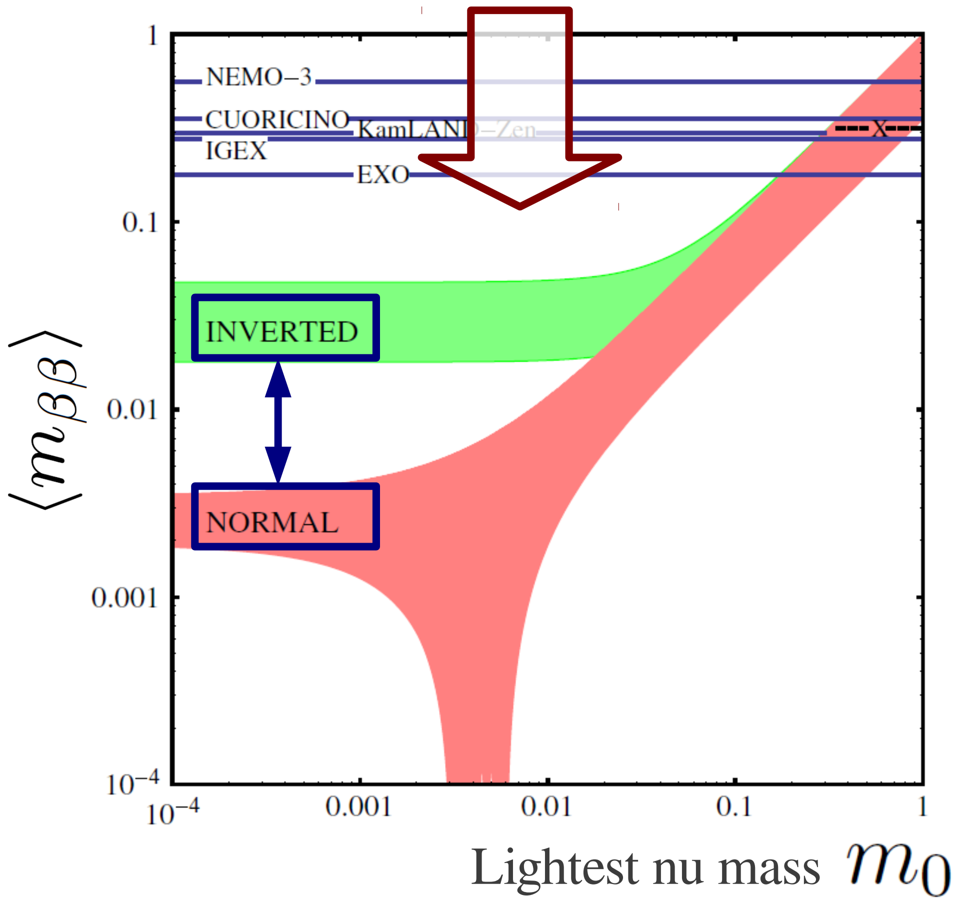
Neutrino mass search is

the foremost front where

- **Oscillation experiments**,

face to the *Neutrino effective theory in the Universe*

Summary



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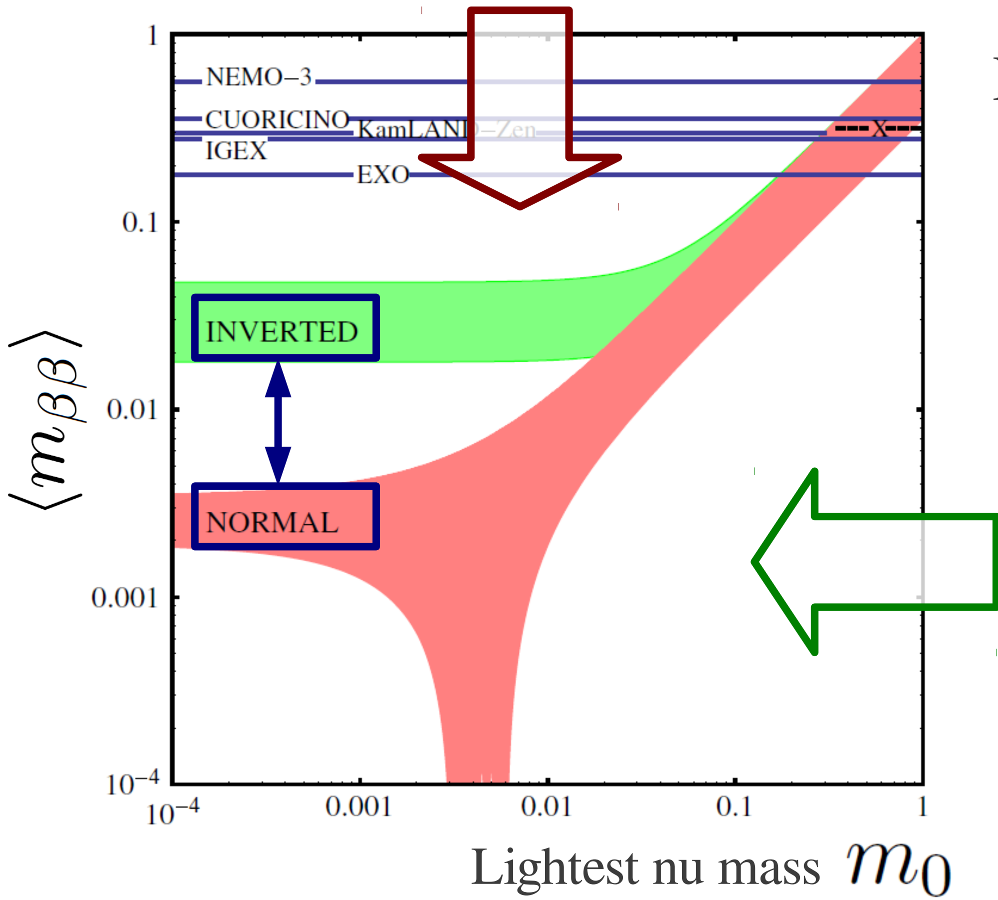

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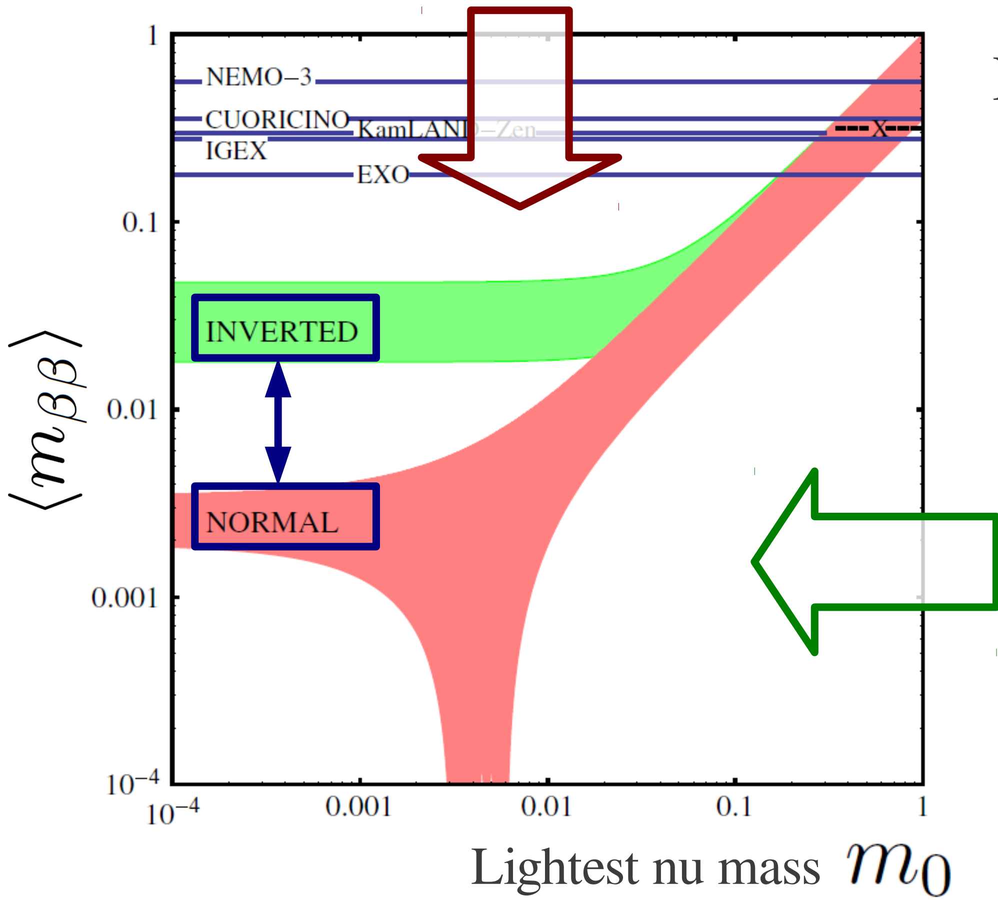

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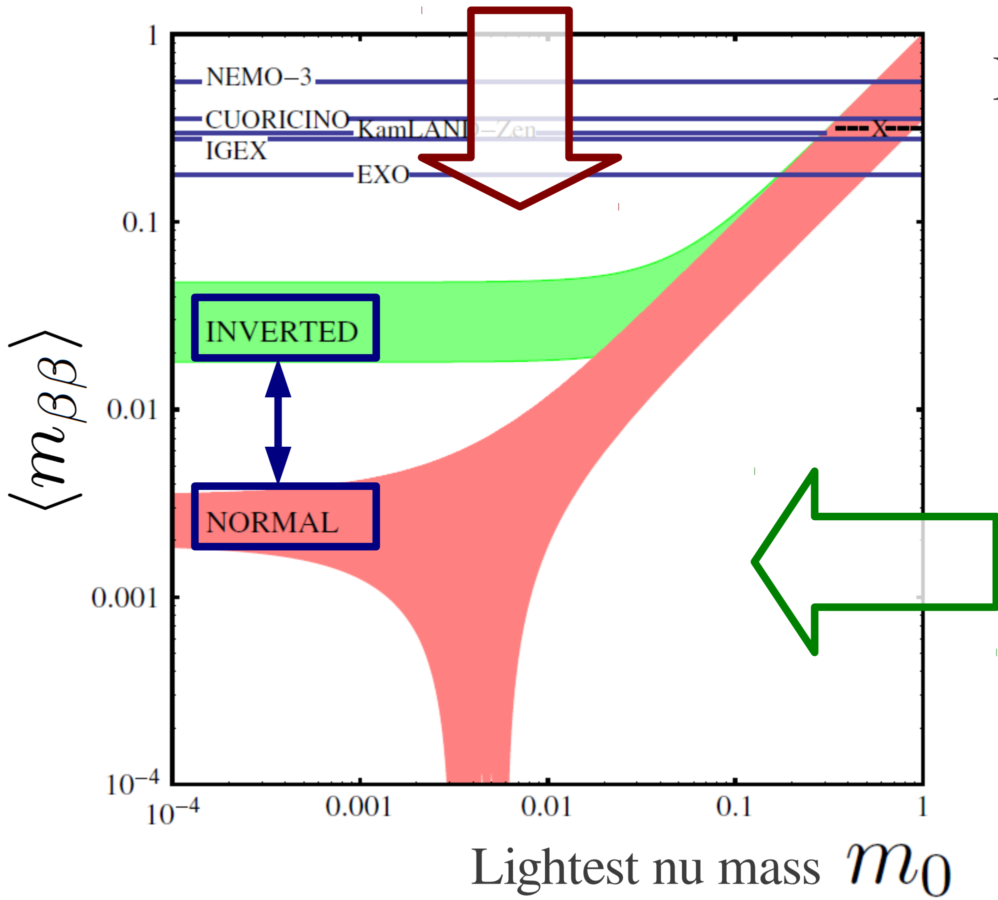
If something unexpected will happen on this plane...

In this talk we focus on the particle physics side. How about cosmological side?

Summary



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Cosmological side: Possible disturbance of neutrino mass bound?

Dark matter effective theory? and its high *E* completions?

Outline

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

1. ***Motivation: Why 0n2b? Why 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

In progress
Under discussion

3. ***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 $m_\nu \sim 0.1\text{eV}$

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

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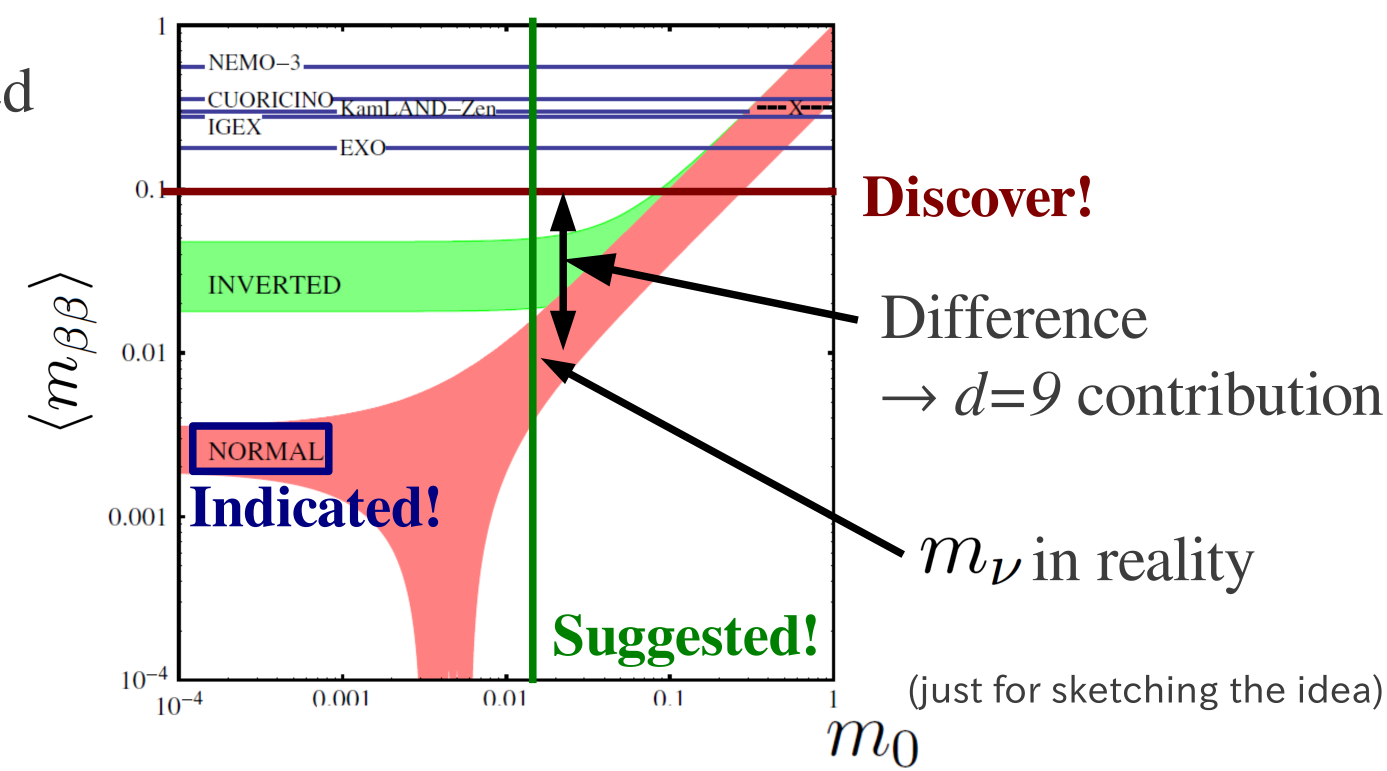

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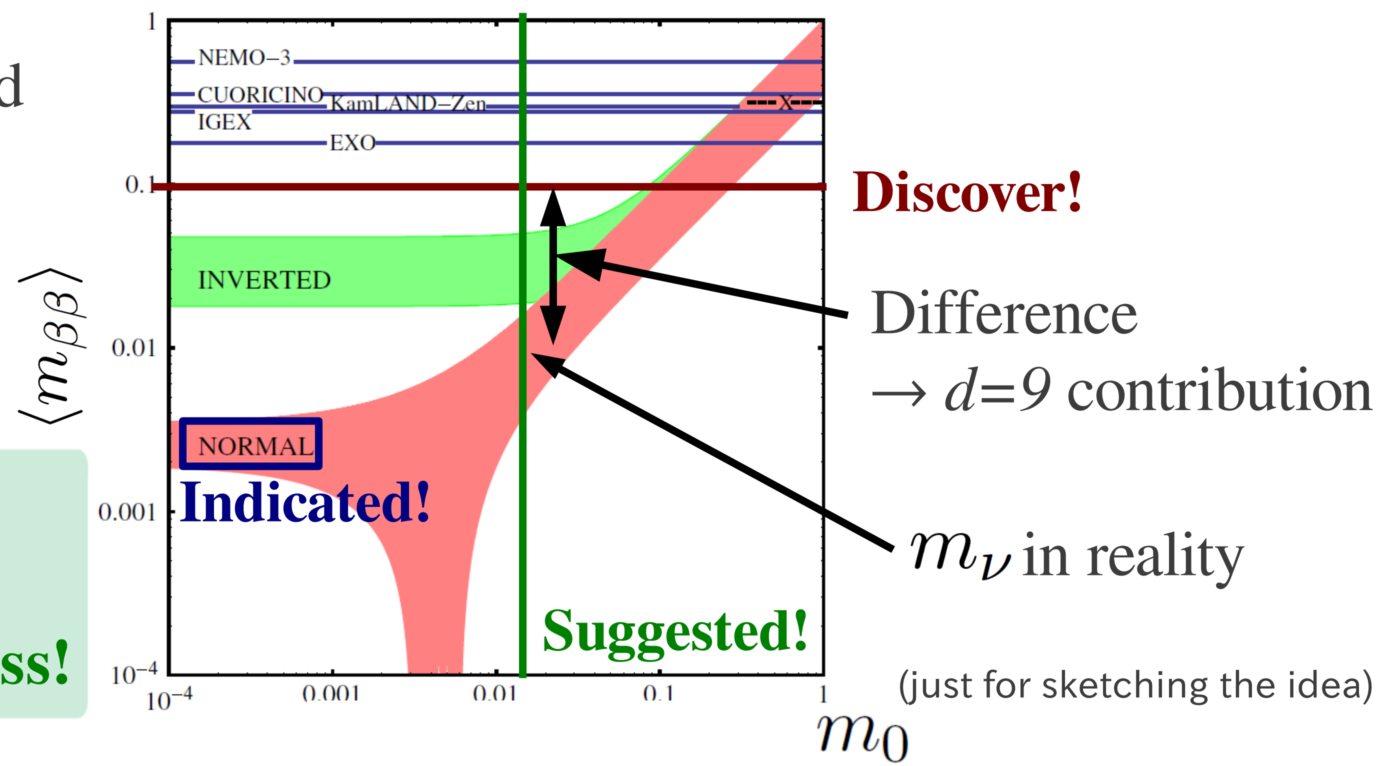

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With the info on this plane, we have a chance to know the origin of neutrino mass!

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

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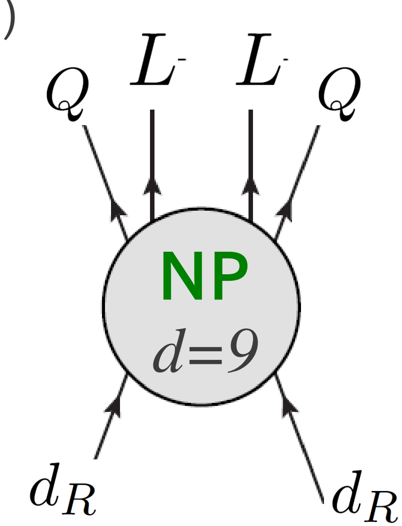
Examples introduced in recent papers, based on Decomposition of $LLQQd_Rd_R$

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.

3 Seeking the relation to the models

Examples

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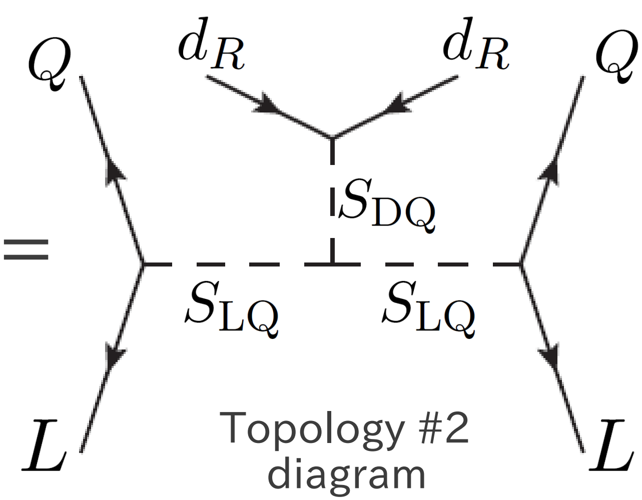


Dim=9 op is directly proportional to m_ν, and its contribution to 0n2b seems to be large.

3 Seeking the relation to the models

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

Radiative neutrino mass models with TeV ingredients

In such models

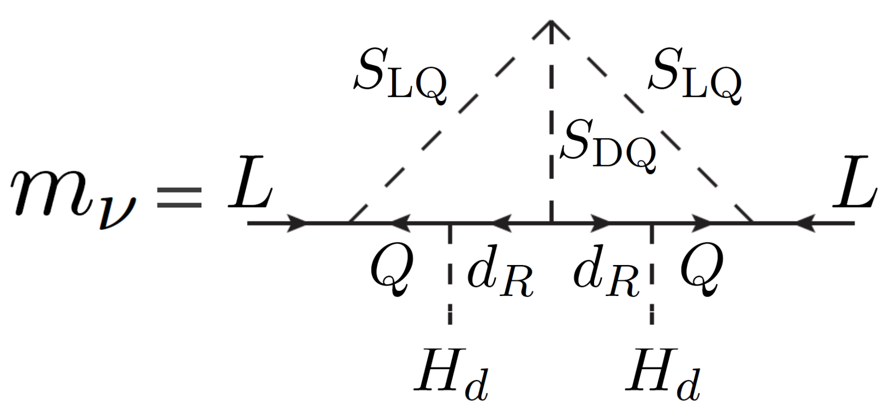
Size of **two contributions** to 0n2b can be comparable!

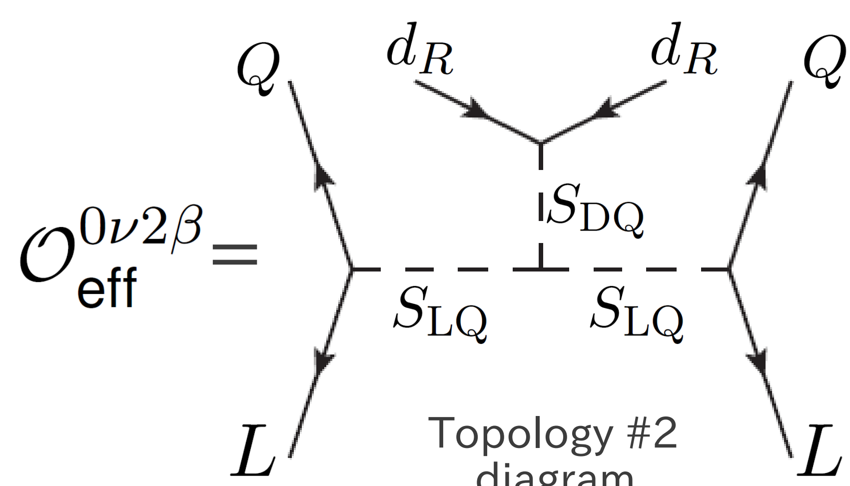
Standard one $m_\nu \sim 0.1\text{eV}$ dim=9 $\Lambda_{NP} \sim 1$ TeV

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

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

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





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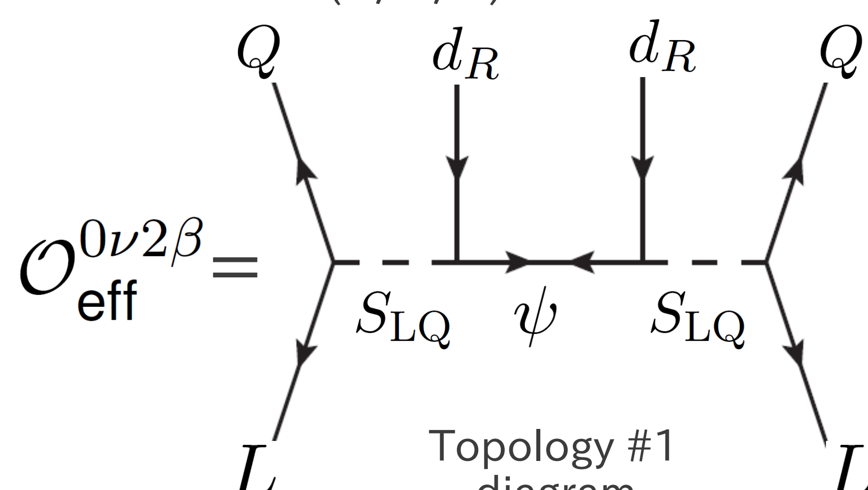
Two-loop mNu model with LQ(**3**, **1**, -1/3), Majorana fermion (**8**, **1**, 0)

Angel Cai Rodd Schmidt Volkas 1308.0463



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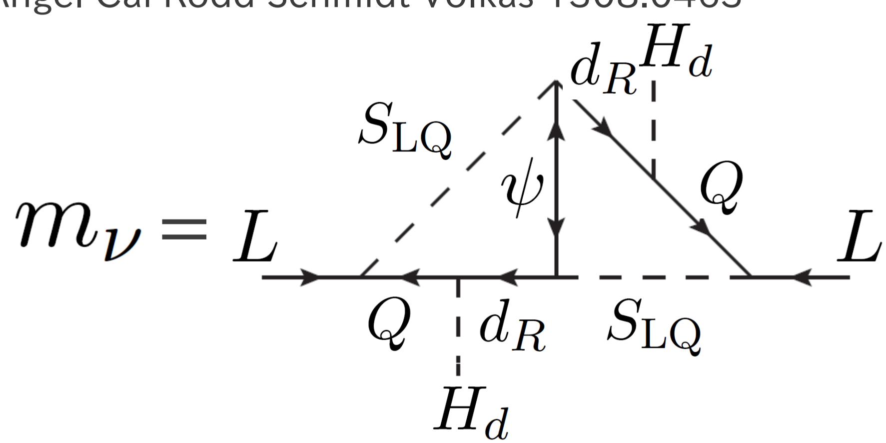

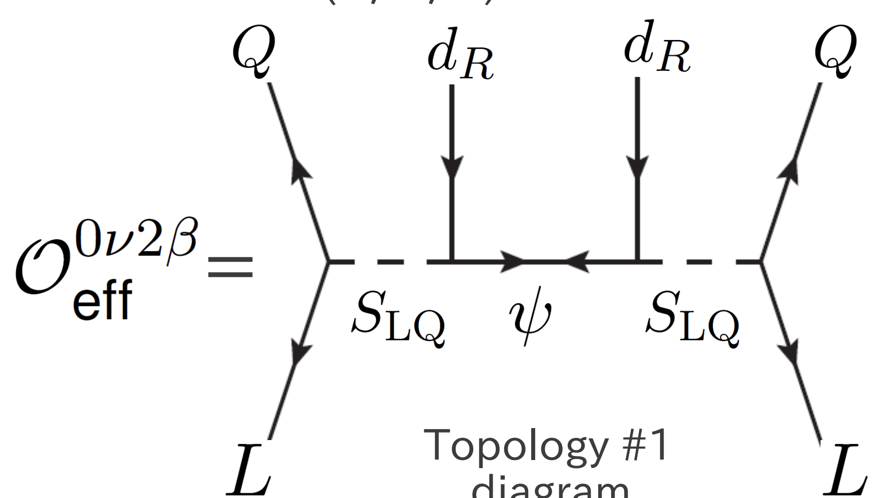

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Choubey Duerr Mitra Rodejohann JHEP **1205** (2012) 017

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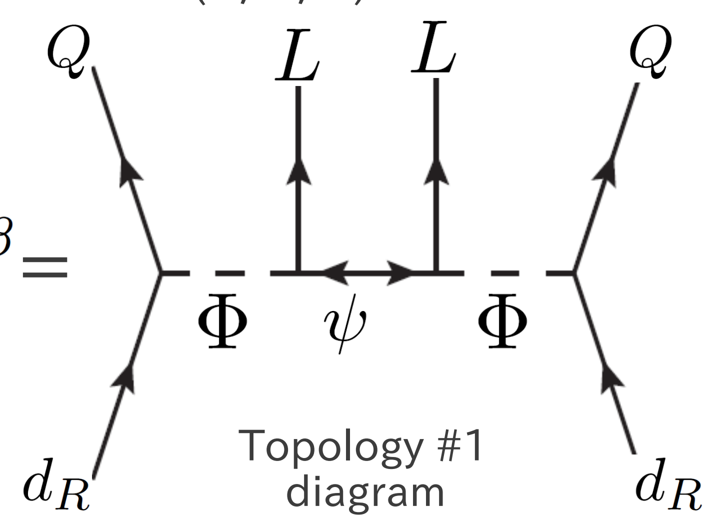

In this case, dim=9 op is not directly proportional to m_ν

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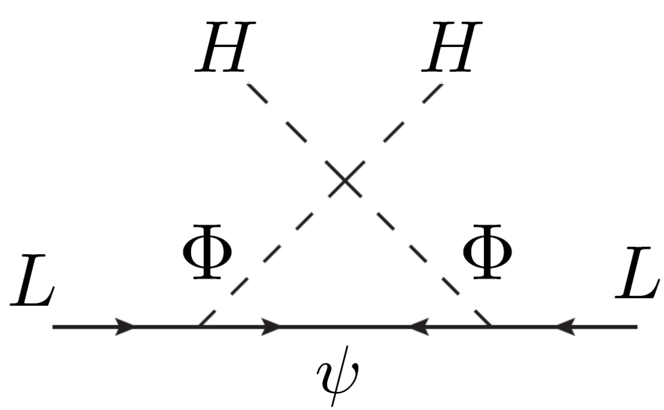
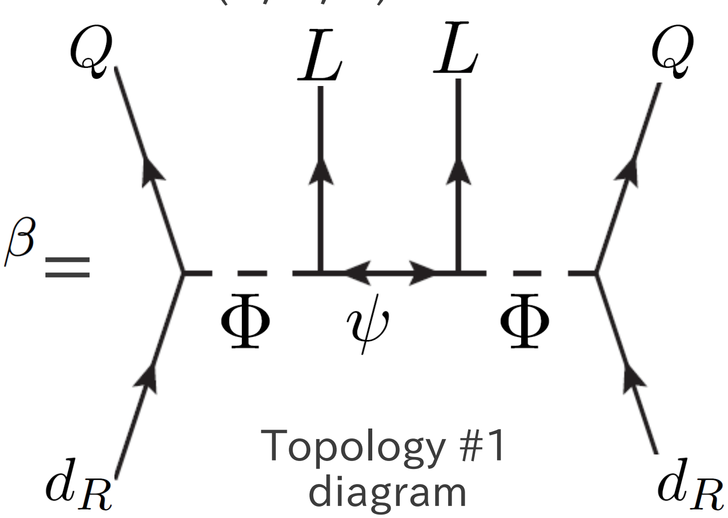
$m_\nu =$ 

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

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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...

Back up slides

1. Neutrino mass bound from cosmological observations
2. LR symmetric model as a Decomposition of dim=9 op

1 Why 0n2b? Why *d=9* op.? Effective neutrino mass

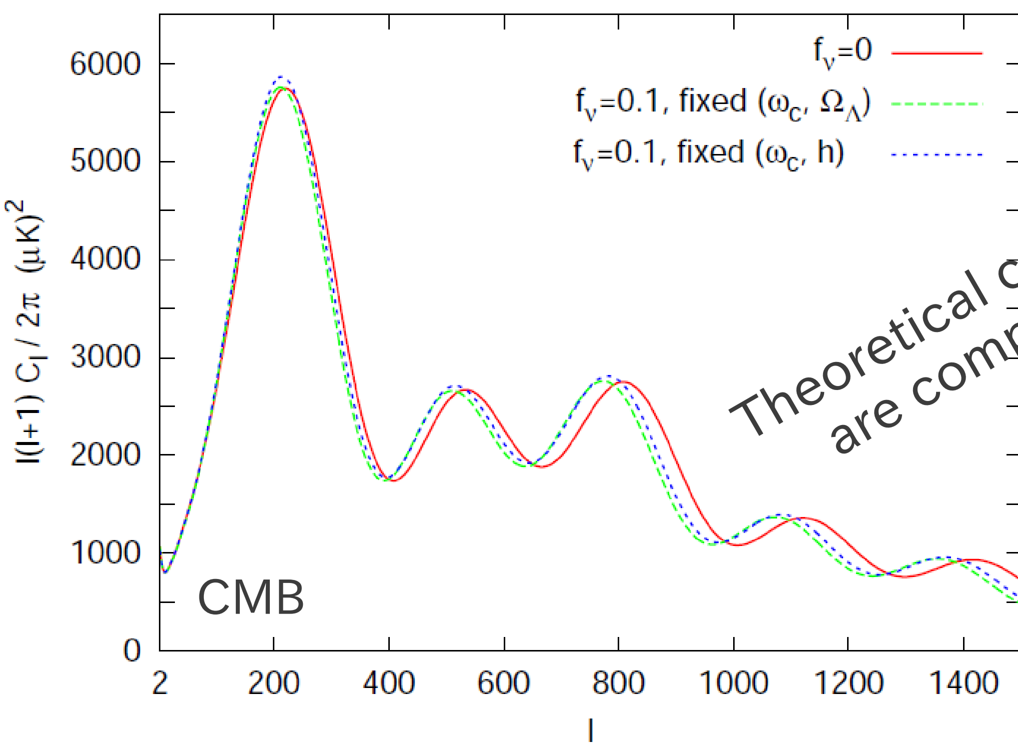
- **0n2b exp** are sensitive to
  Effective nu mass

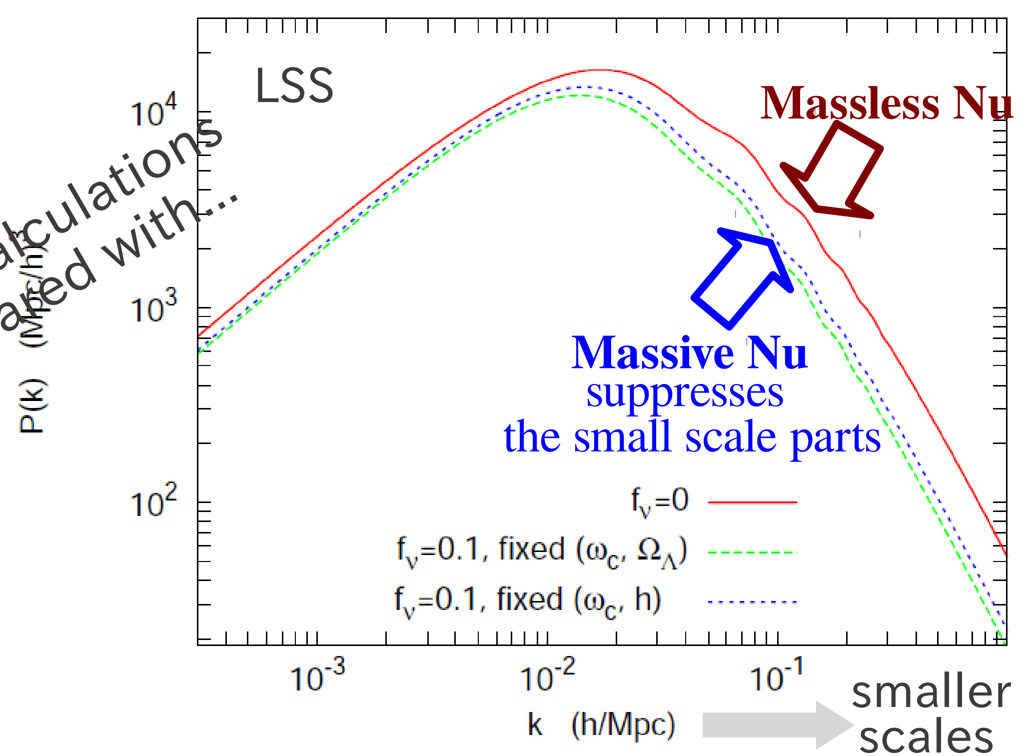
$$\langle m_{\beta\beta}\rangle \equiv \sum_{i=1}^{3} (U_e{}^i)^2 m_i$$

- **Cosmological obs** constrain
  Sum of nu masses

$$\sum_{i=1}^{3} m_i (\simeq 3m_0 \text{ if } m_0 \gtrsim 0.1 \text{ eV})$$

Theoretical calculations are compared with...





Theoretical calcs are taken from
Phys.Rep **429** (2006) 307
Lesgourgues and Pastor

→ Talk by Hasegawa (Aug)

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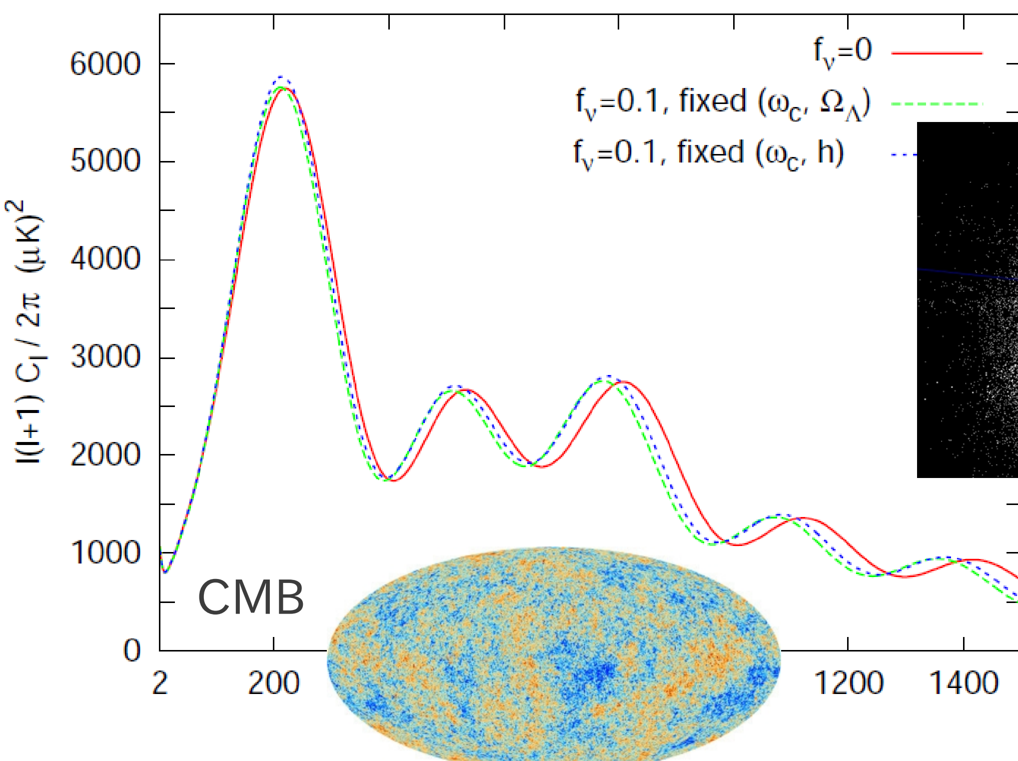
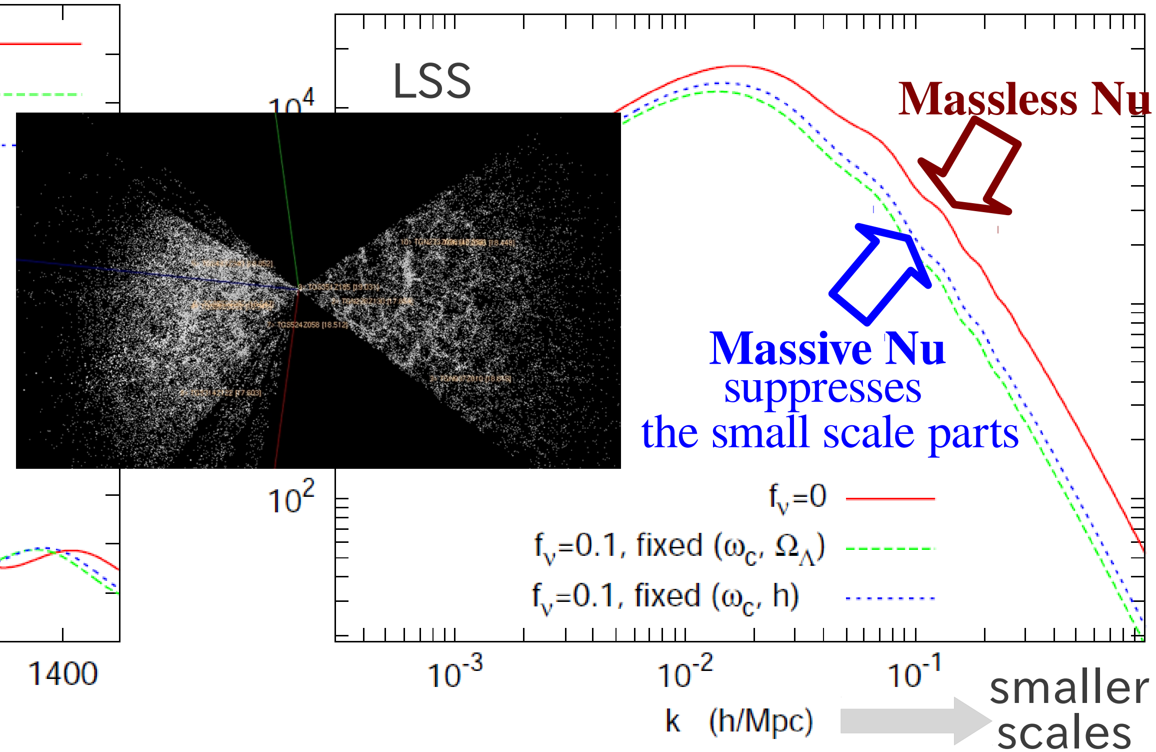
Obs: Planck, WMAP-9year, and balloons



Obs: SDSS, 2dFGRS



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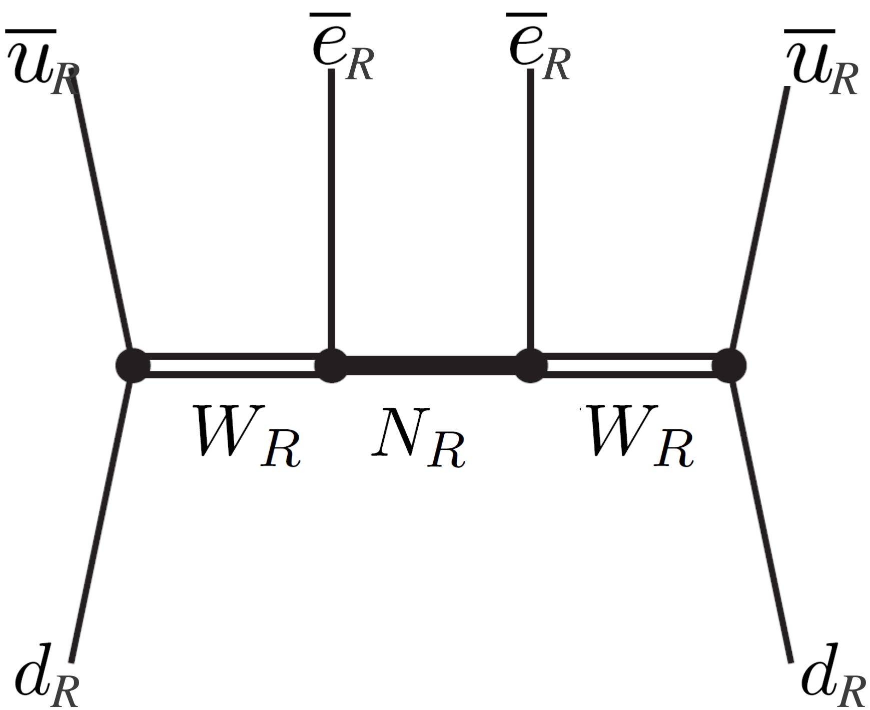
- An example,
  Taking Topology #I
  let us decompose d=9 op as

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



Necessary mediators

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

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

Left-right symmetric model
All the outer fermions are right-handed

Bound from 0n2b
Riazuddin Marshak Mohapatra PR**D24** (1981) 1310

$$M_{N_R} = M_{W_R} > 1.3\ \text{TeV}\ (g_L = g_R)$$

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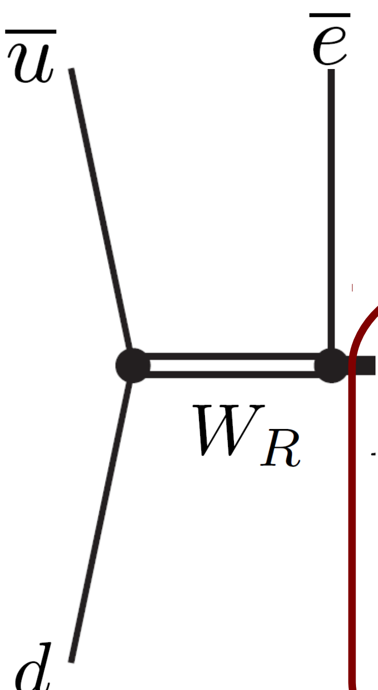

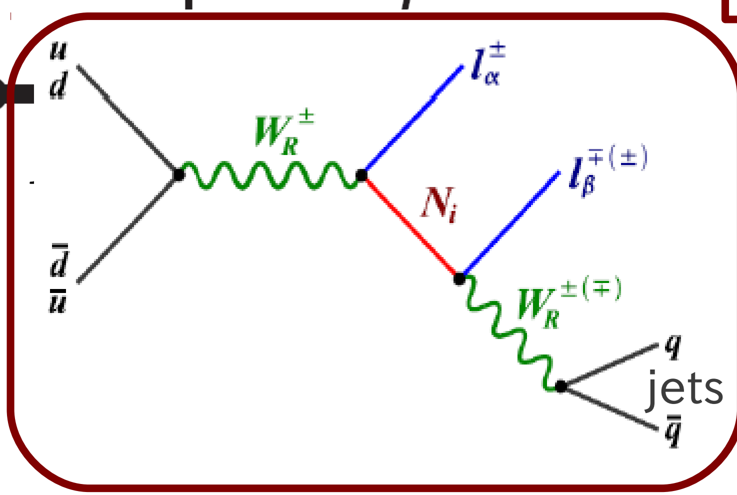

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N_R and W_R collider search

Rizzo, Phys. Lett. **B116** (1982) 23

Keung Senjanovic, Phys. Rev. Lett **50** (1983) 1427

ATLAS search for 2 leptons+jets: arXiv.1203.5420