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

Talk by Gavela, Huber

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

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

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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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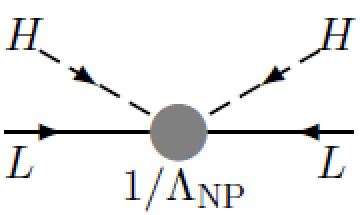

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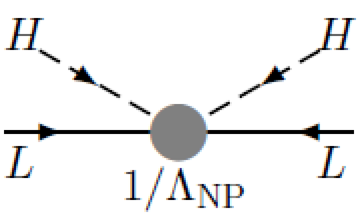

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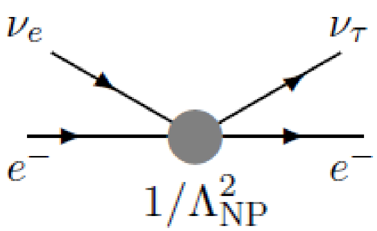
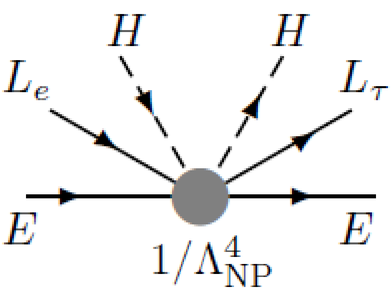


Four-Fermi

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



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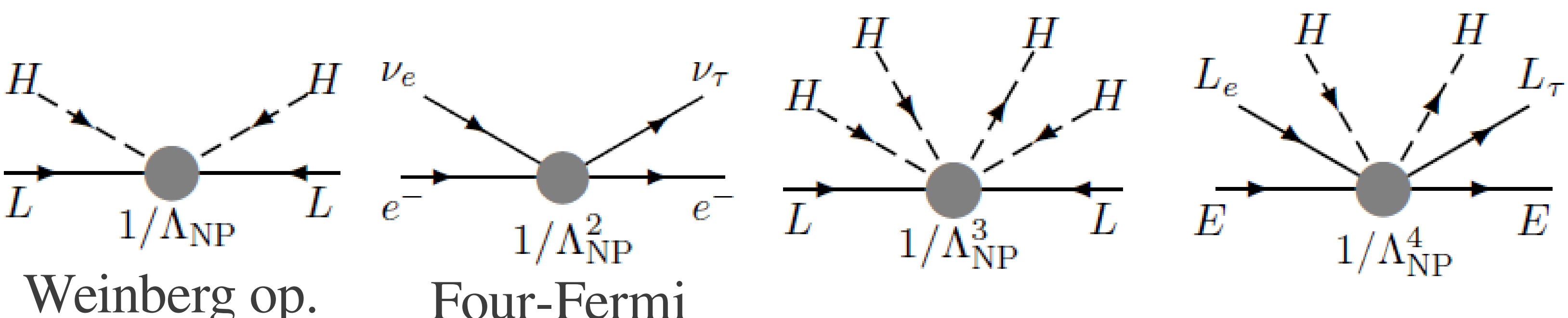

m_ν $\quad P_{\nu_\alpha\to\nu_\beta}$ $\quad m_\nu$ $\quad P_{\nu_\alpha\to\nu_\beta}$

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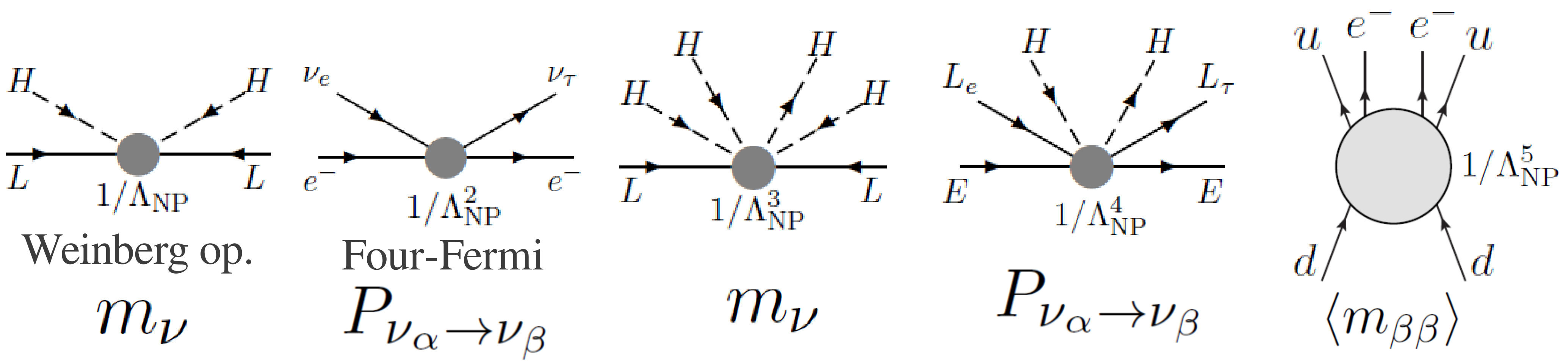

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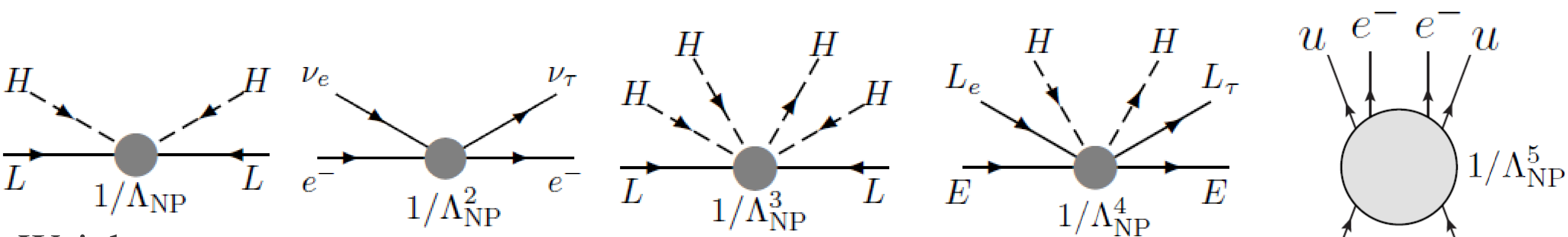

Weinberg op. m_ν | Four-Fermi $P_{\nu_\alpha \to \nu_\beta}$ | m_ν | $P_{\nu_\alpha \to \nu_\beta}$ | $\langle m_{\beta\beta} \rangle$

High E completion

Seesaw mech. (@tree)

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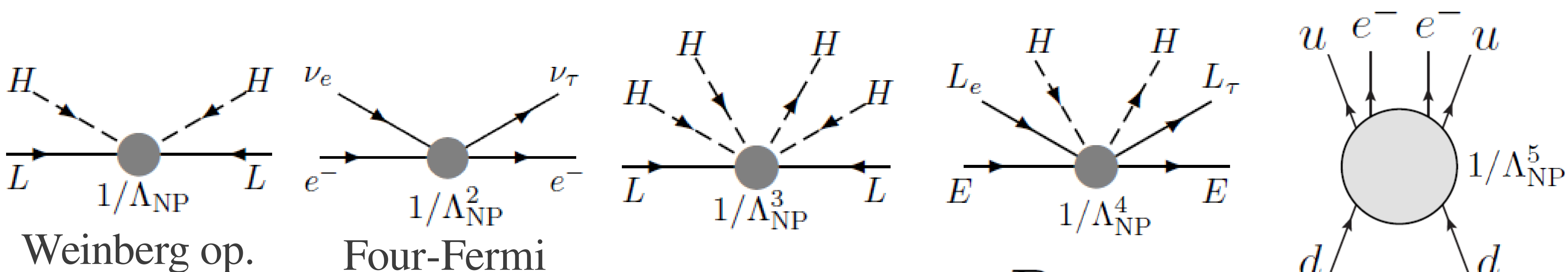

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What do these eff. ops. suggest to physics at high E scales?

Exhaustive bottom-up approach

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We focus on d=9 op in this talk

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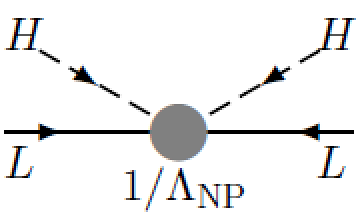
Effective operators are a typical low-E remnant … physics



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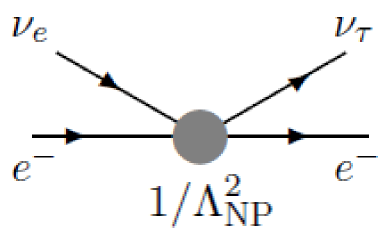

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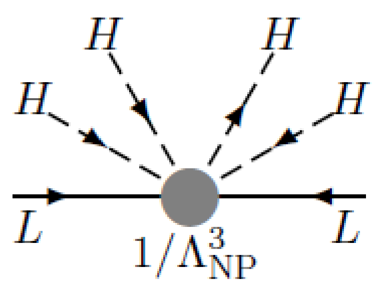

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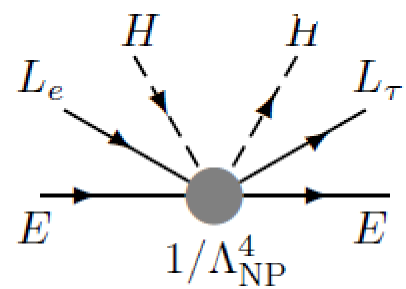

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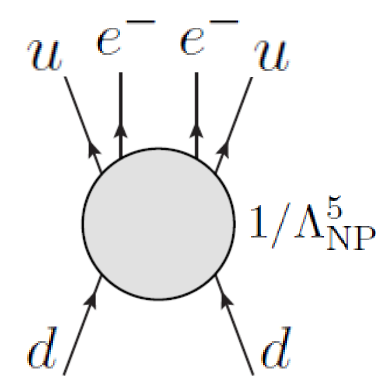

$\langle m_{\beta\beta} \rangle$

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Exhaustive bottom-up approach

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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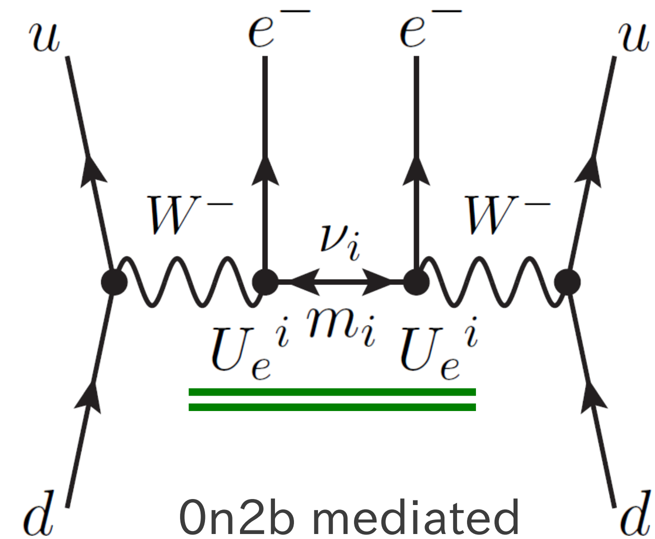

0n2b mediated by neutrinos

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

$$m_1 = \sqrt{|\Delta m_{31}^2| + m_0^2},\ m_2 = \sqrt{\Delta m_{21}^2 + |\Delta m_{31}^2| + m_0^2},$$
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m_0 represents the lightest neutrino mass

α and β are Majorana phases

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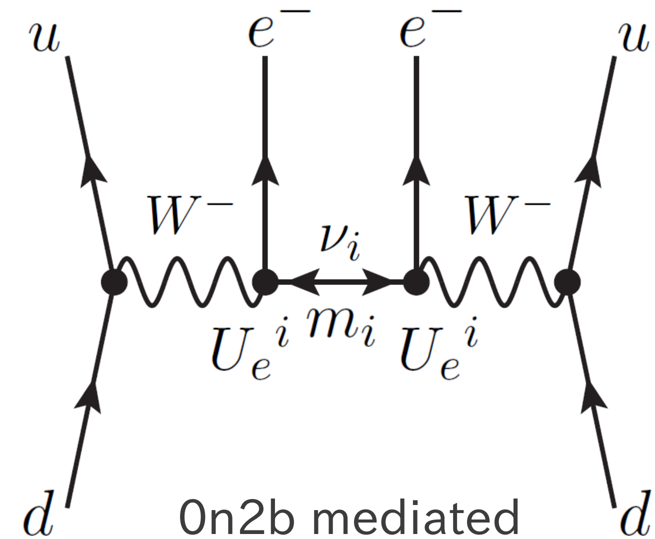

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$$s_{12}^2 = 0.3, \qquad s_{23}^2 = 0.41(0.59), \qquad s_{13}^2 = 0.023,$$
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So far, we know

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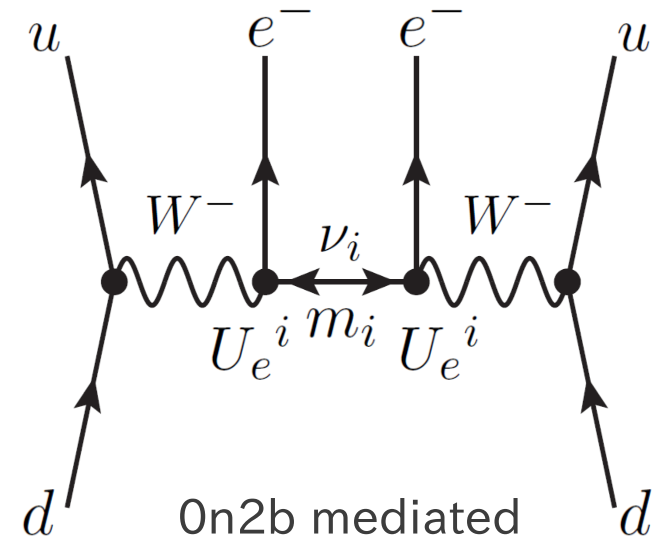

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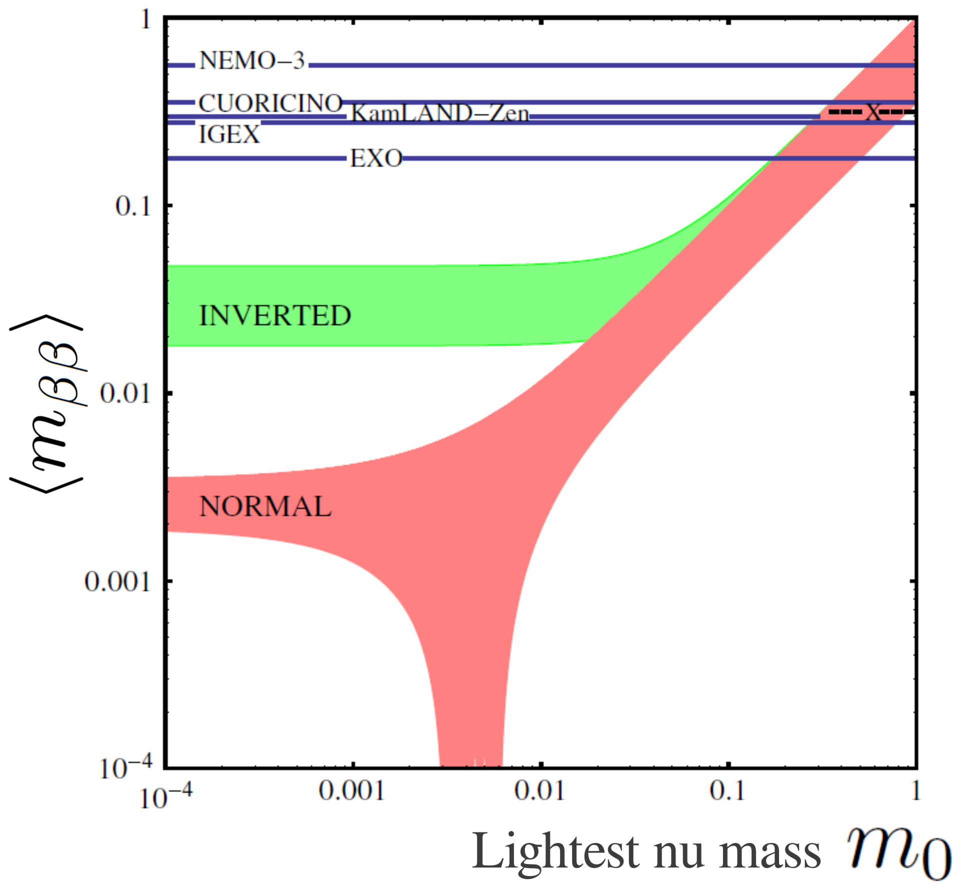

Standard 3nu parameter space

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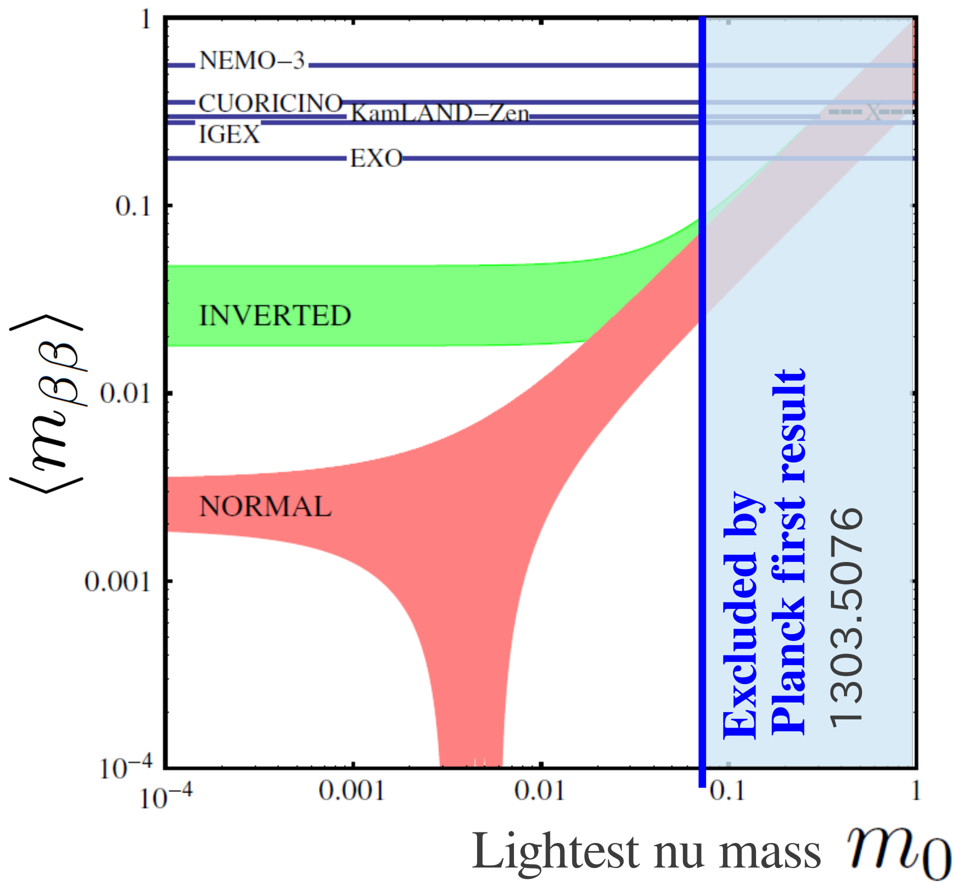

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SPT reports non-zero mNu?
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1307.4720
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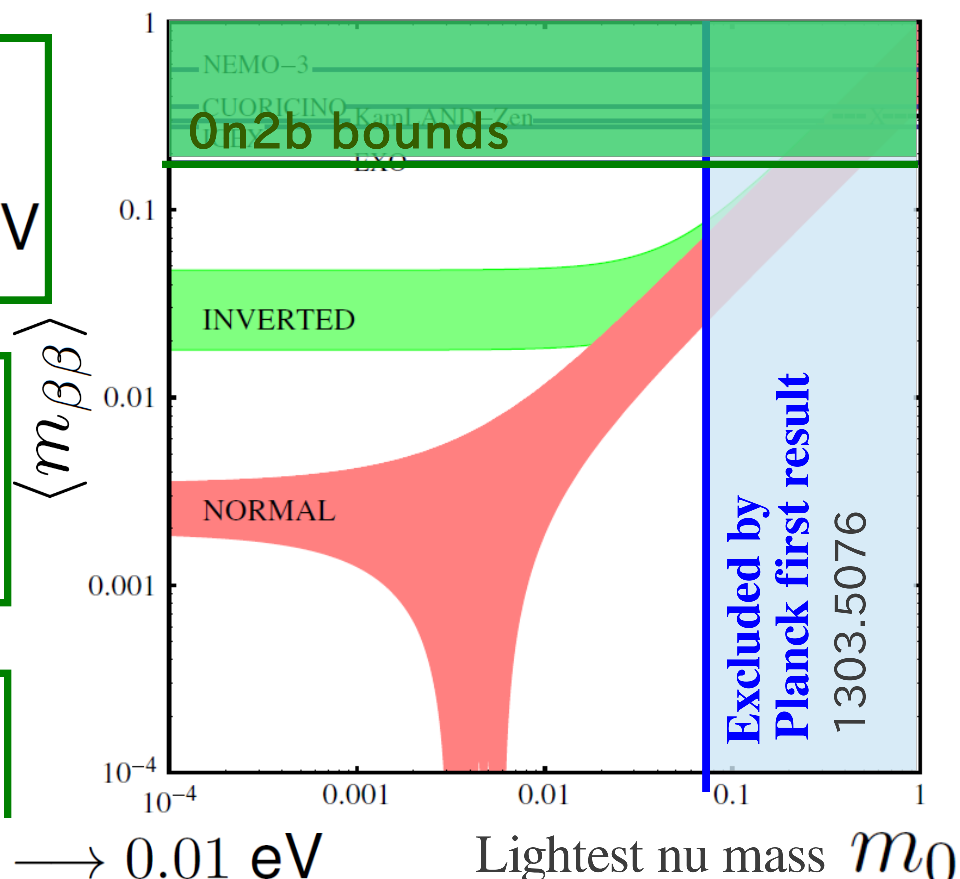
In future



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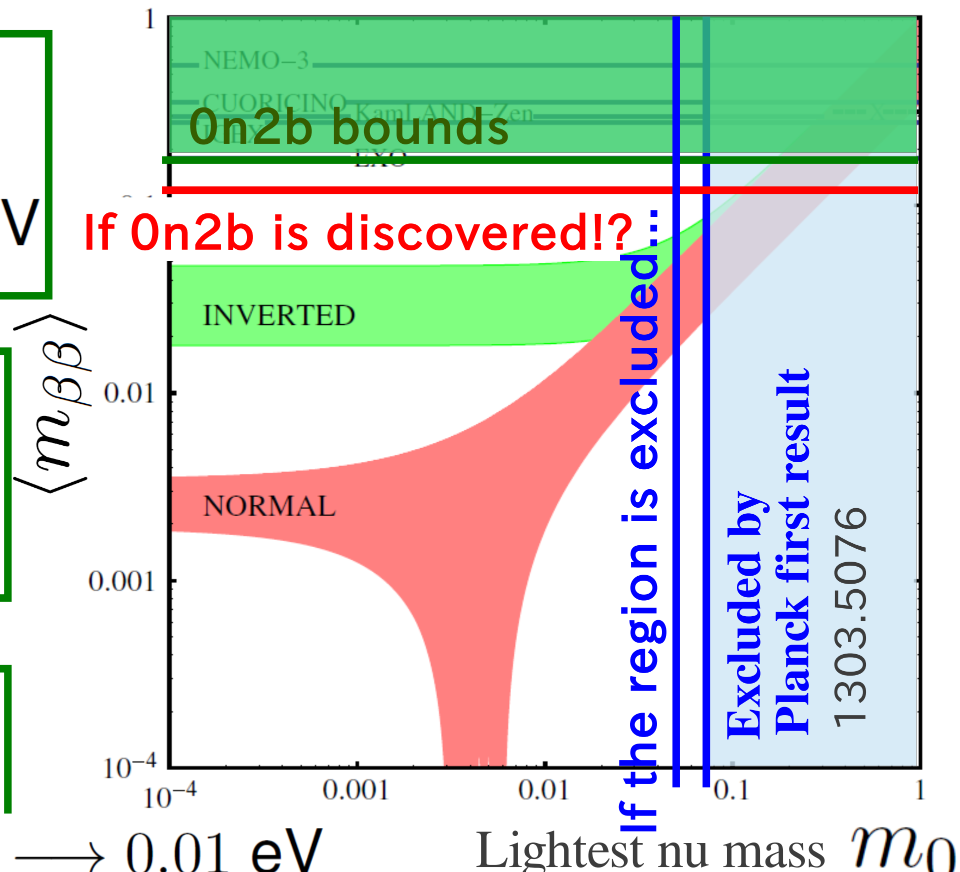

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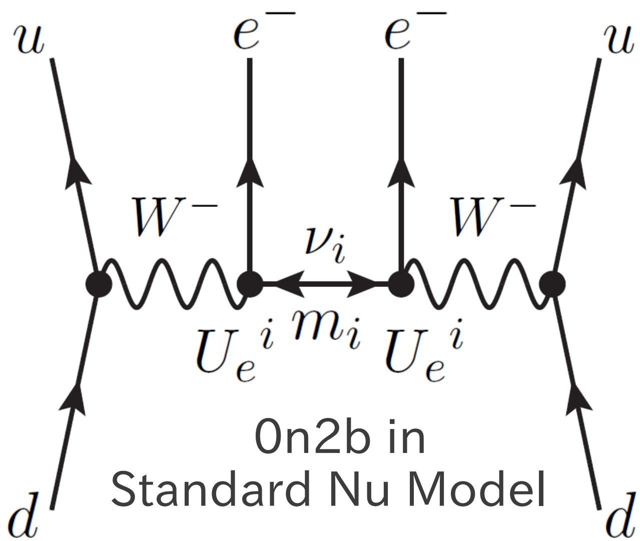
Q: If, in future, they will conflict with each other, what can we learn from them?

1 *d=9* op. in 0n2b

0n2b experiments measure...

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



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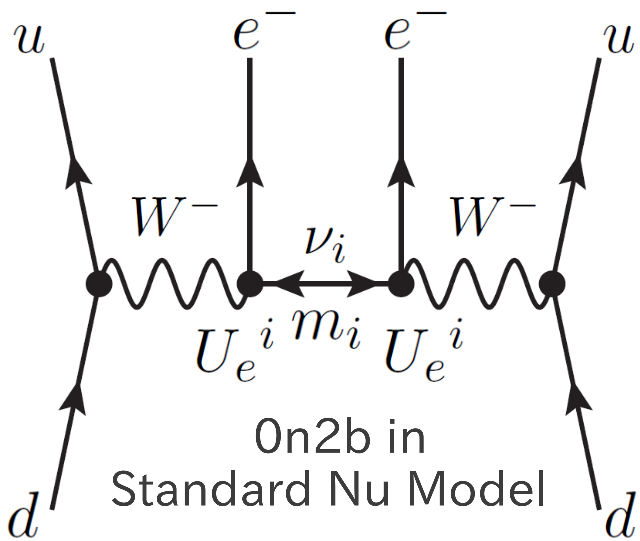

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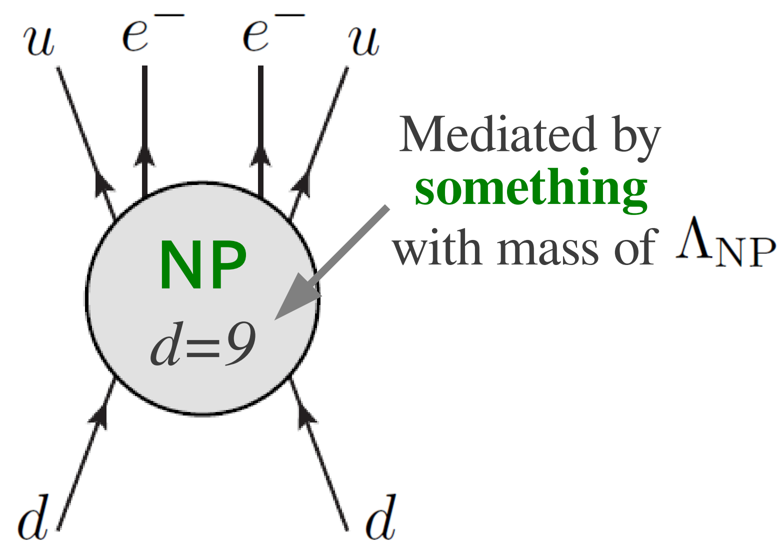

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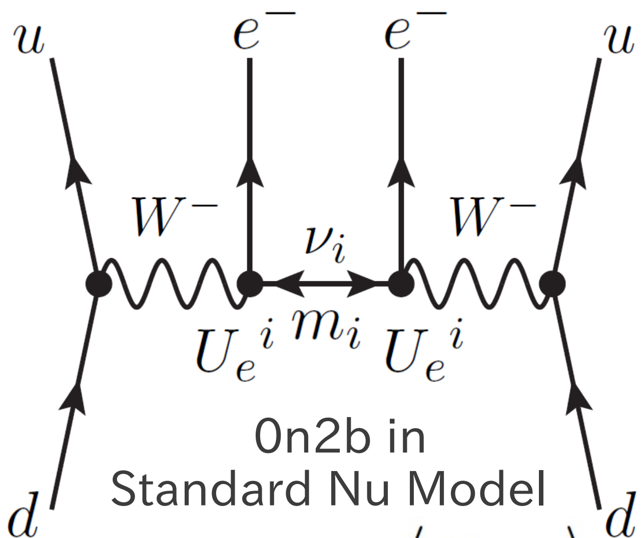
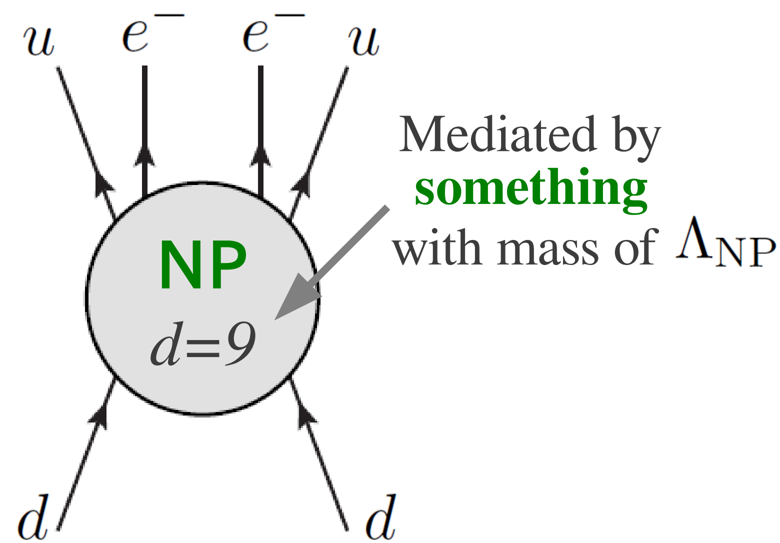


$$\mathcal{A}_{\mathrm{S}\nu\mathrm{M}} = G_F^2 \frac{\langle m_{\beta\beta} \rangle}{q^2}$$

+



~100 MeV
A typical momentum
of neutrino in atom

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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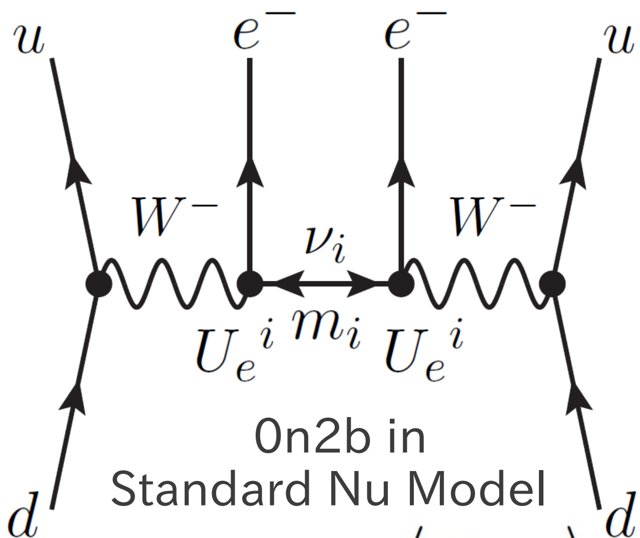

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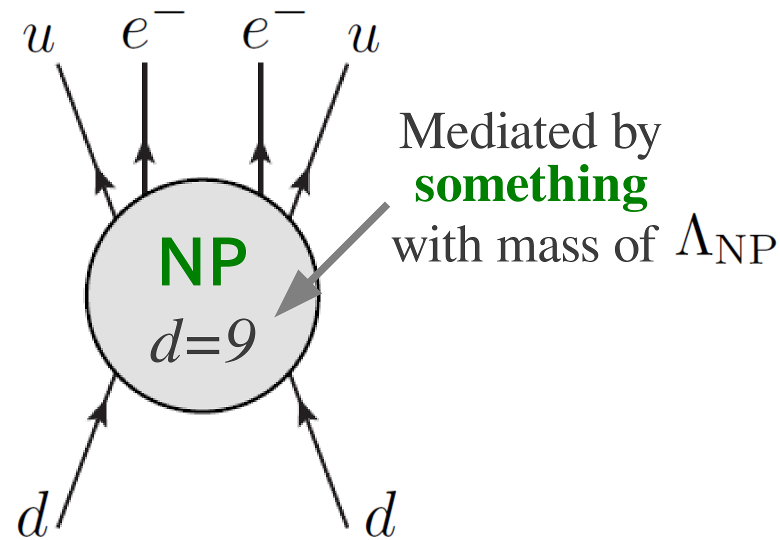

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Sensitive to

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$d=9$ op. in 0n2b

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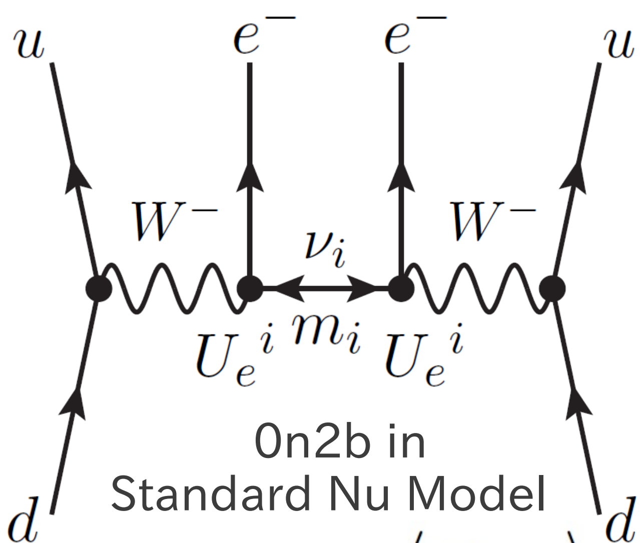

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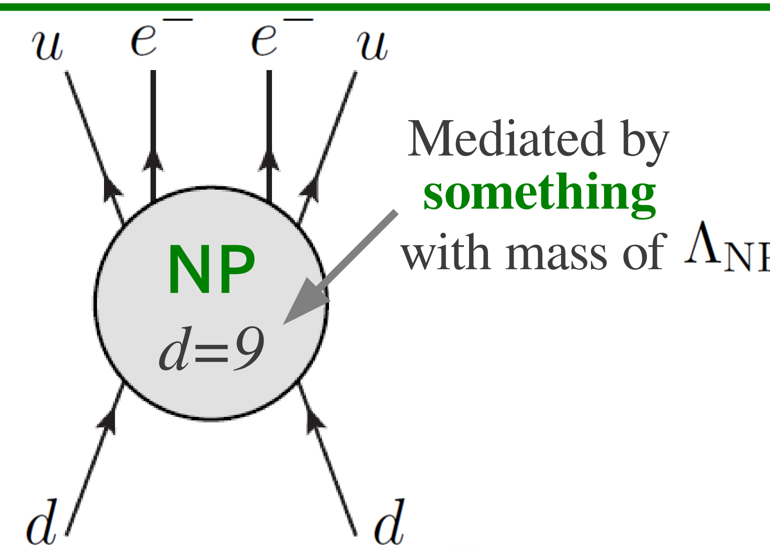
+



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

Current exp. limit

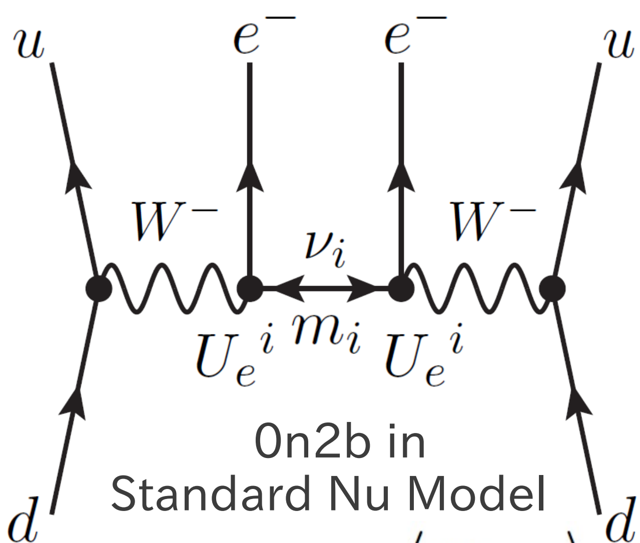
$$10^{25}\ [\mathrm{yr}] < T_{1/2}^{0\nu 2\beta} \propto 1/\left|\mathcal{A}_{\mathrm{S}\nu\mathrm{M}}\right|^2$$

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

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

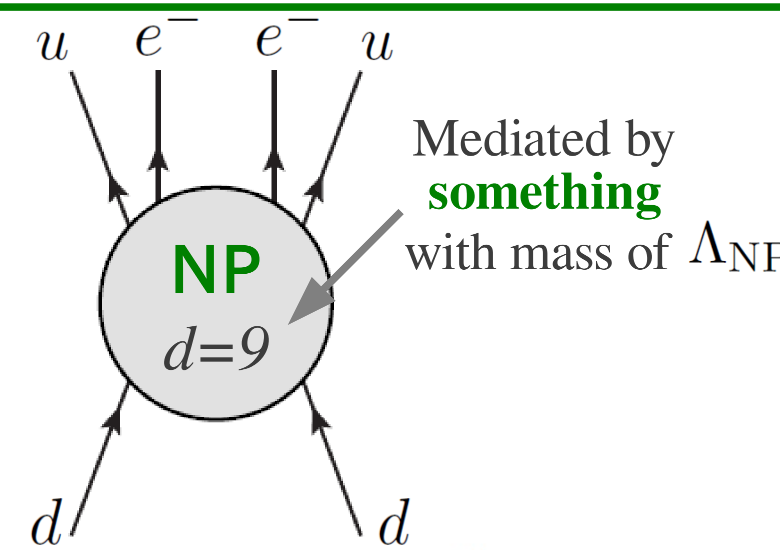
d=9 op. in 0n2b — 0n2b experiments measure...

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



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

+



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

Current exp. limit

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

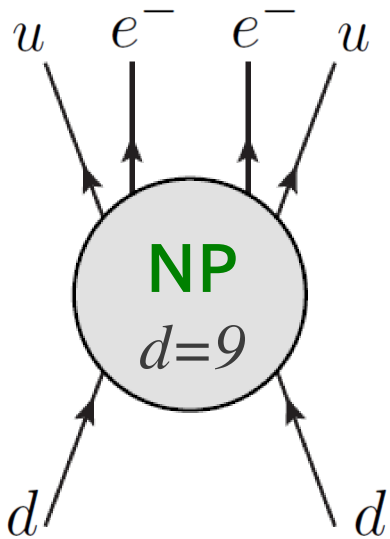
Sensitive to

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

LHC range!

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

d=9 op. in 0n2b



…falls into the following 5 types of effective ops.

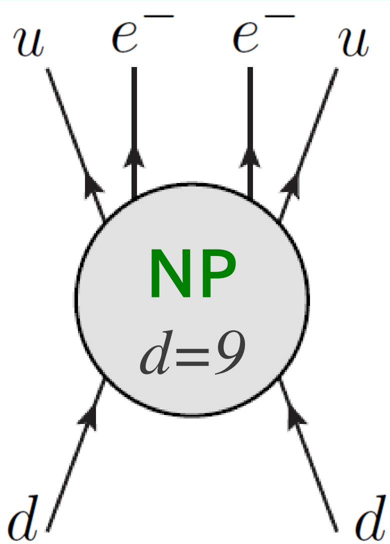
$$\mathscr{L}_{d=9} = \frac{G_F^2}{2m_P}\left[\sum_{i=1}^{3}\epsilon_i^{\{XY\}Z}(\mathcal{O}_i)_{\{XY\}Z} + \sum_{i=5}^{4}\epsilon_i^{XY}(\mathcal{O}_i)_{XY}\right],$$

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

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

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

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

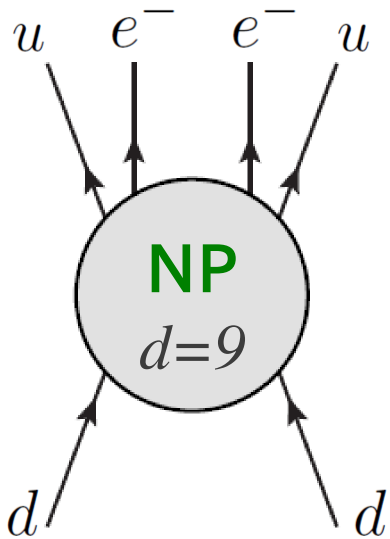
$$\left(T_{1/2}^{0\nu2\beta}\right)^{-1}_{\underline{\underline{d=9}}} = G_1\left|\sum_{i=1}^{3}\epsilon_i\mathcal{M}_i\right|^2 + G_2\left|\sum_{i=4}^{5}\epsilon_i\mathcal{M}_i\right|^2 + G_3\mathrm{Re}\left[\left(\sum_{i=1}^{3}\epsilon_i\mathcal{M}_i\right)\left(\sum_{i=4}^{5}\epsilon_i\mathcal{M}_i\right)^*\right]$$

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

$\mathcal{M}_i$ Nuclear matrix elements

G_i Phase space factors

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



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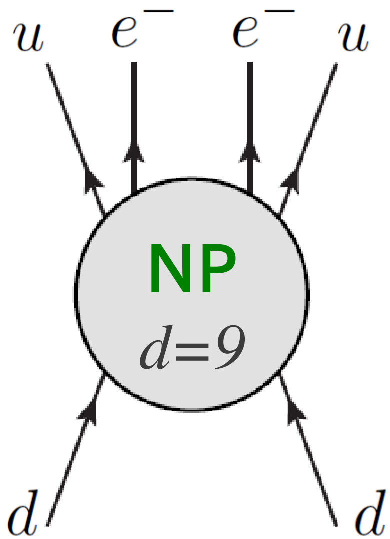
Q: What is the high *E* (TeV) origin of these *d=9* effective ops?

d=9 ops.



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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

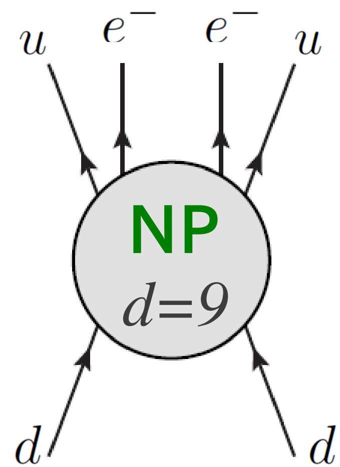
   "The list helps us to discriminate the models"

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

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

- High E completion: We focus on tree-level decompositions

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



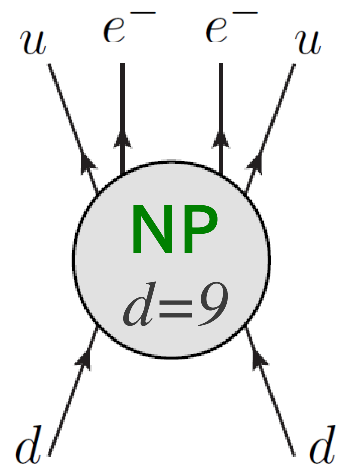
Signal @ 0n2b (low E)

$$T_{1/2}^{0\nu2\beta} > 10^{25}\ [\rm yr]$$

- High E completion: We focus on tree-level decompositions

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

Decompose



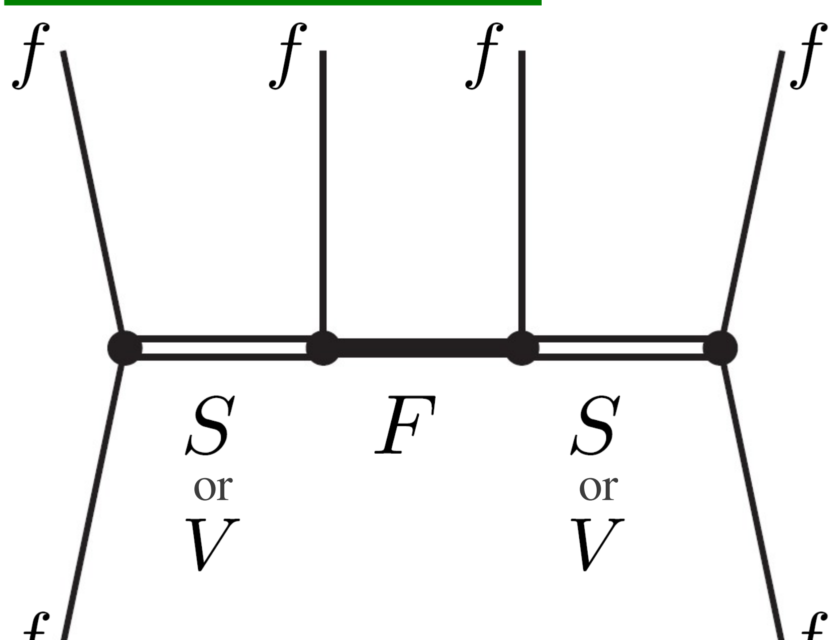
Signal @ 0n2b (low E)

$$T^{0\nu2\beta}_{1/2} > 10^{25}\ [\mathrm{yr}]$$

Correspond to

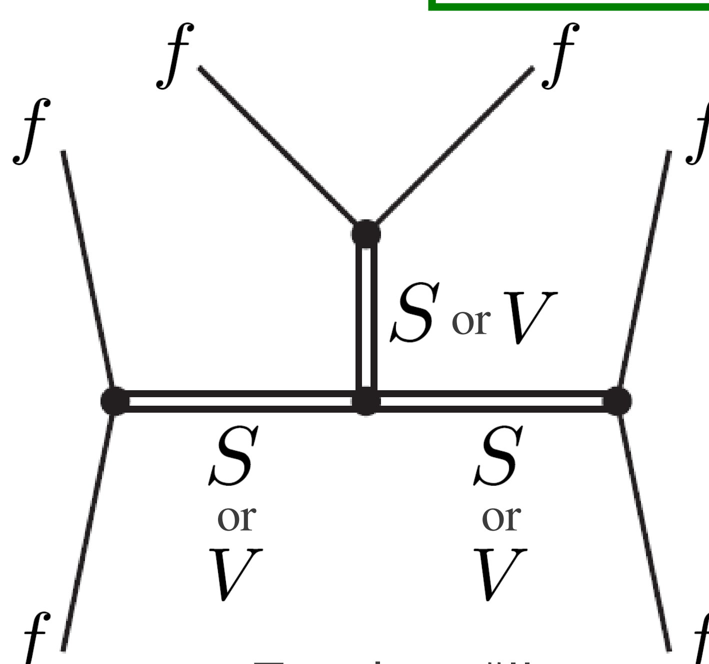
Testable @ LHC

Tree-level diagrams mediated by fields with masses of $\Lambda_{\rm NP} > \mathcal{O}(1)$ [TeV]



Topology #I

or

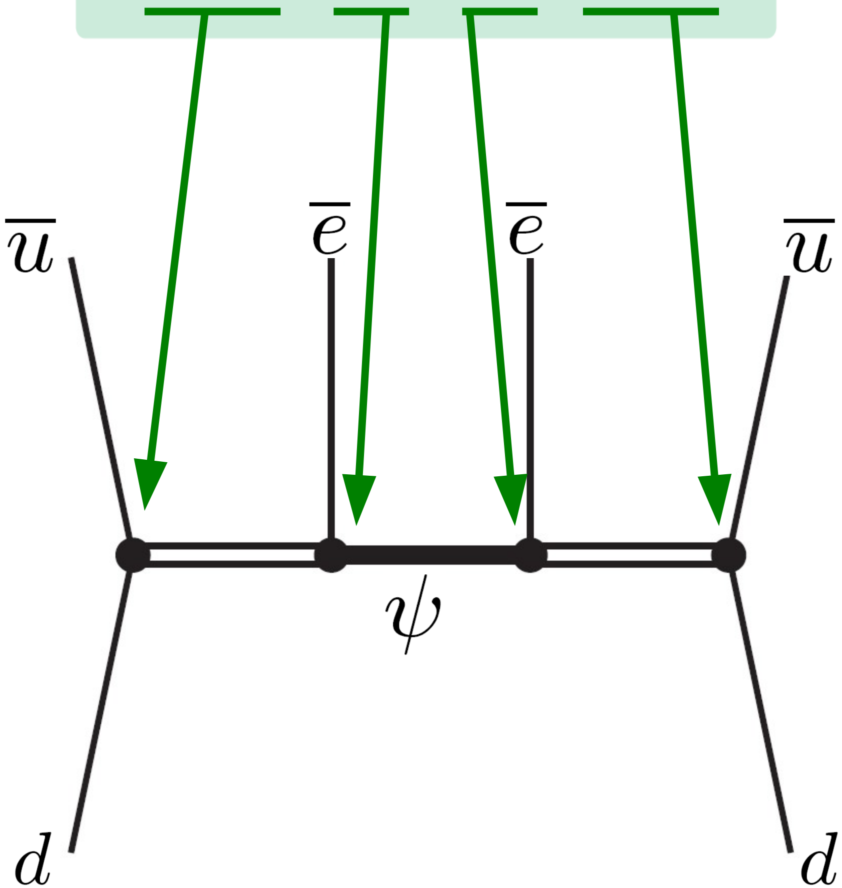


$f \in \{\overline{u}, d, \overline{e}\}$

Topology #II

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

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



- An example,
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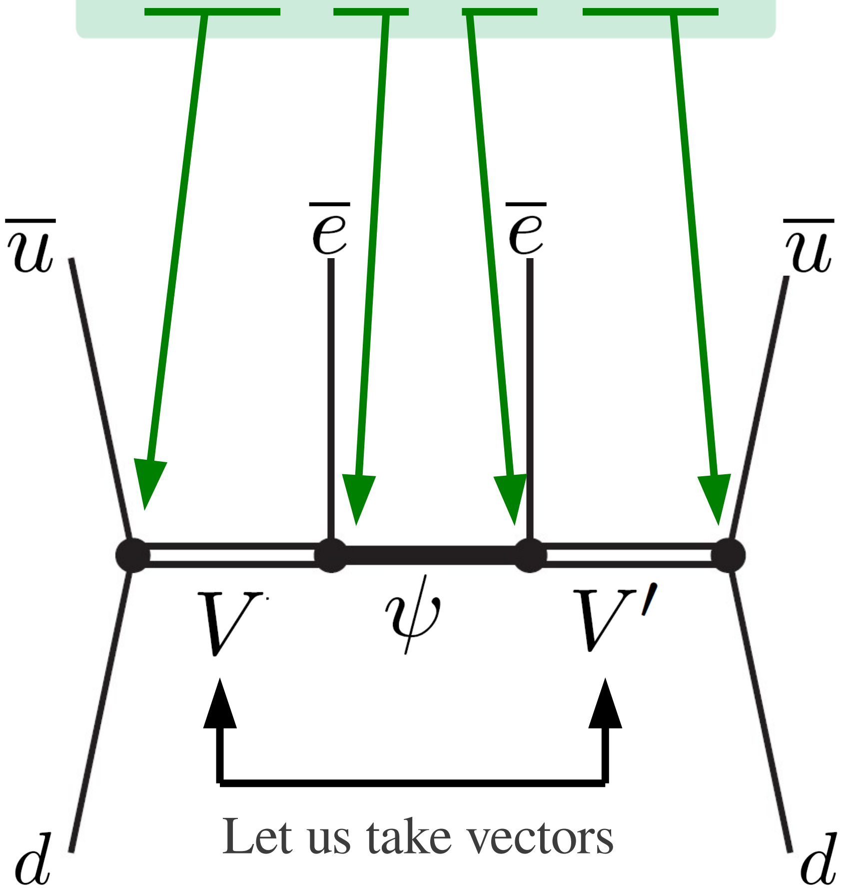

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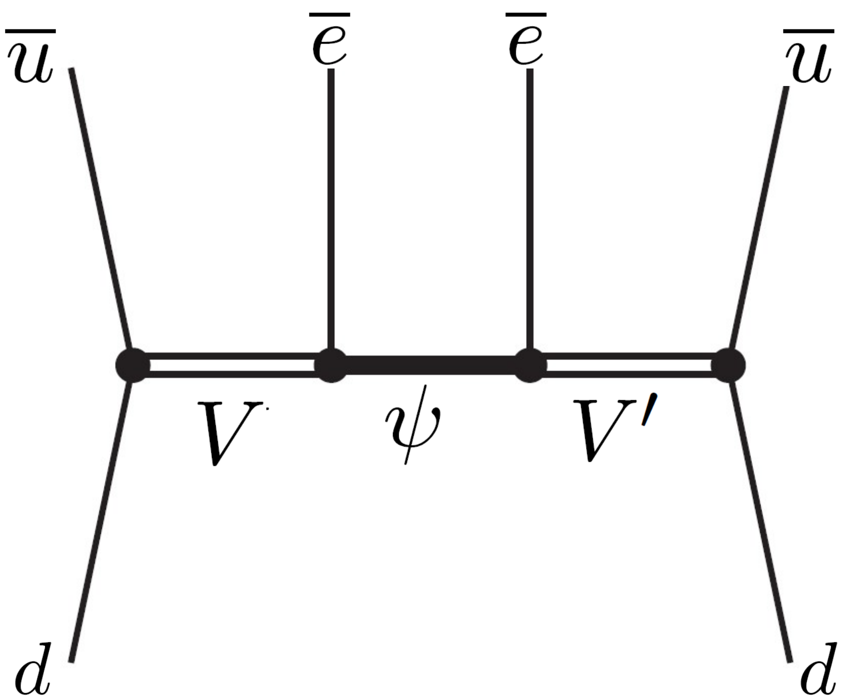


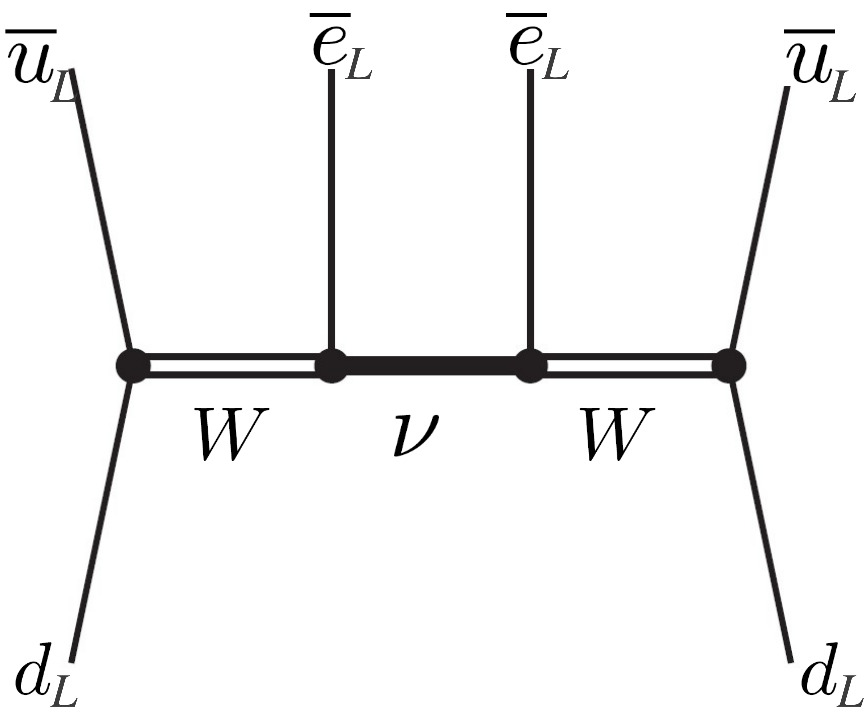
Necessary mediators

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

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

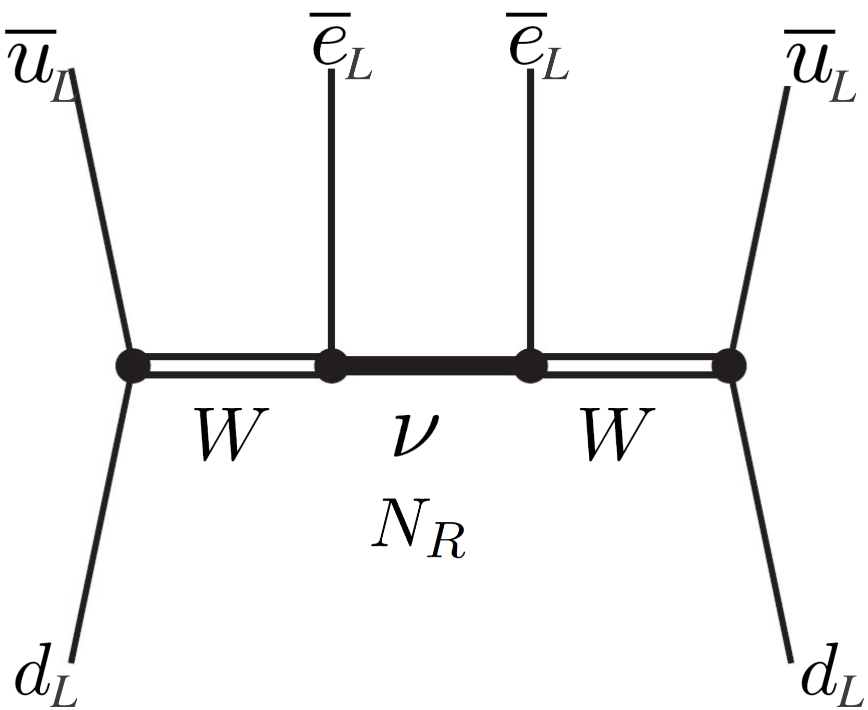
- An example,
  Taking Topology #I
  let us decompose $d=9$ op as

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

Necessary mediators

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

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



Rediscovery of the standard neutrino mass contribution

All the outer fermions must be left-handed

In Seesaw model,
right handed neutrinos can also mediate this diagram.

Talk by Lopez-Pavon

- Another example,

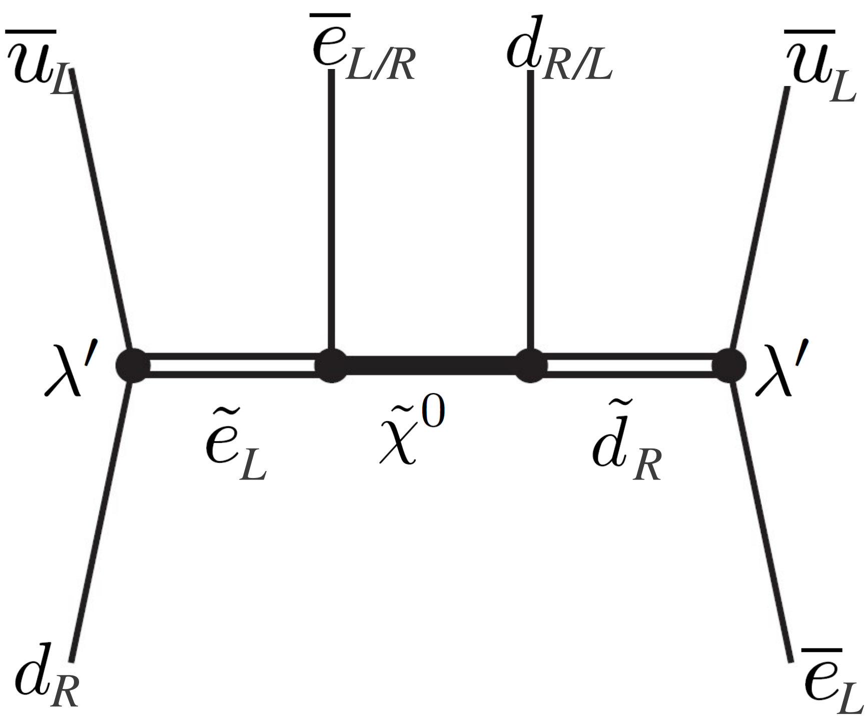
Decomposition

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

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

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

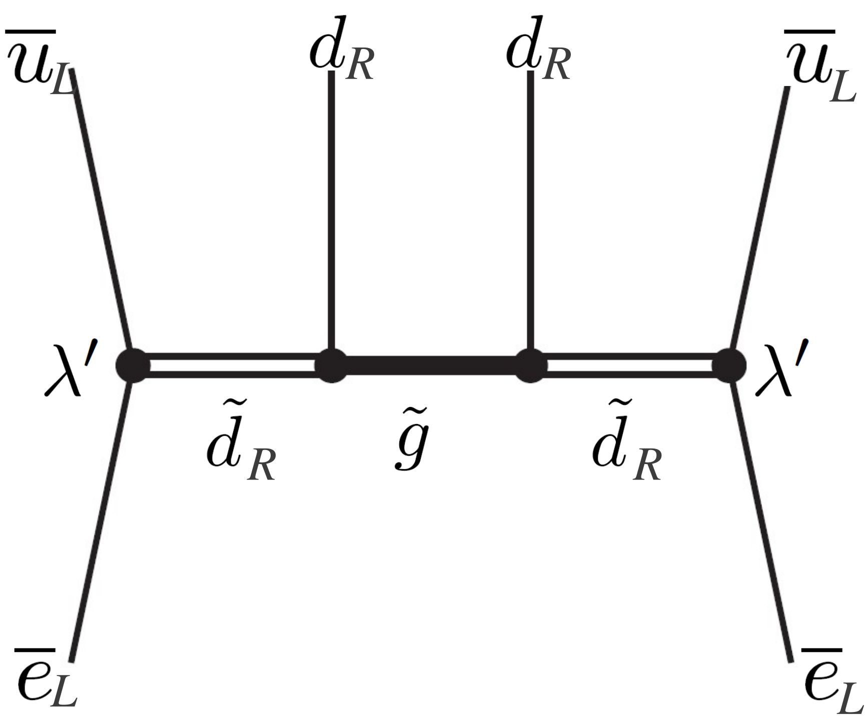
Hirsch Klapdor-Kleingrothaus Kovalenko, PLB**378** (1996) 17, PRD**54** (1996) 4207

SUSY (Rp-conserved) search at LHC
1[st] 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

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

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

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 1212.3045
- *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

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 1212.3045
- *Long Range?*
  Decomposition which can contain neutrino propagation

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2 *Decomposition*

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
  U(1) EM charge
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  → Decom of chirality-specified ops
  Bonnet Hirsch O Winter 1212.3045
- *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

Possible decompositions and Necessary mediators

(only Topology #I)

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  Bonnet Hirsch O Winter 1212.3045

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

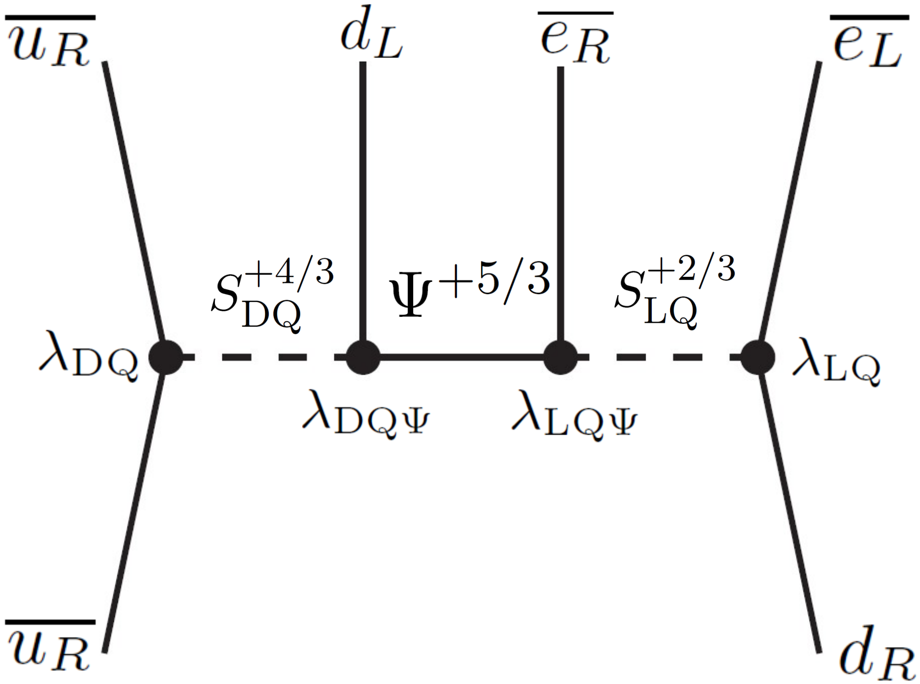
Let us have a look at this example.

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 1212.3045
- *Long Range?*
  Decomposition which can contain neutrino propagation



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

Take scalar mediators
Specify the chiralities

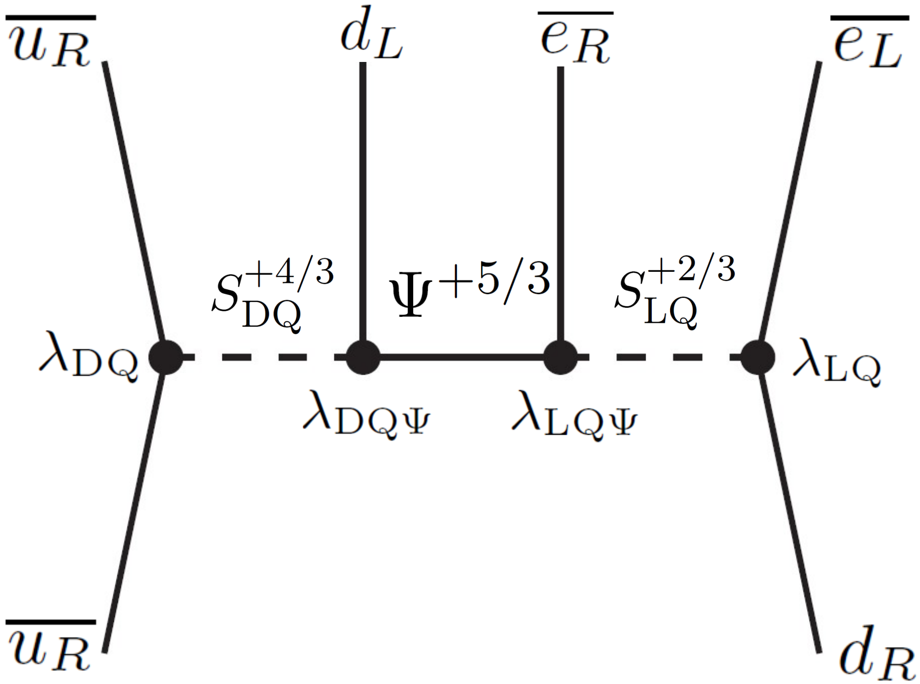
Necessary mediators

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

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

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

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



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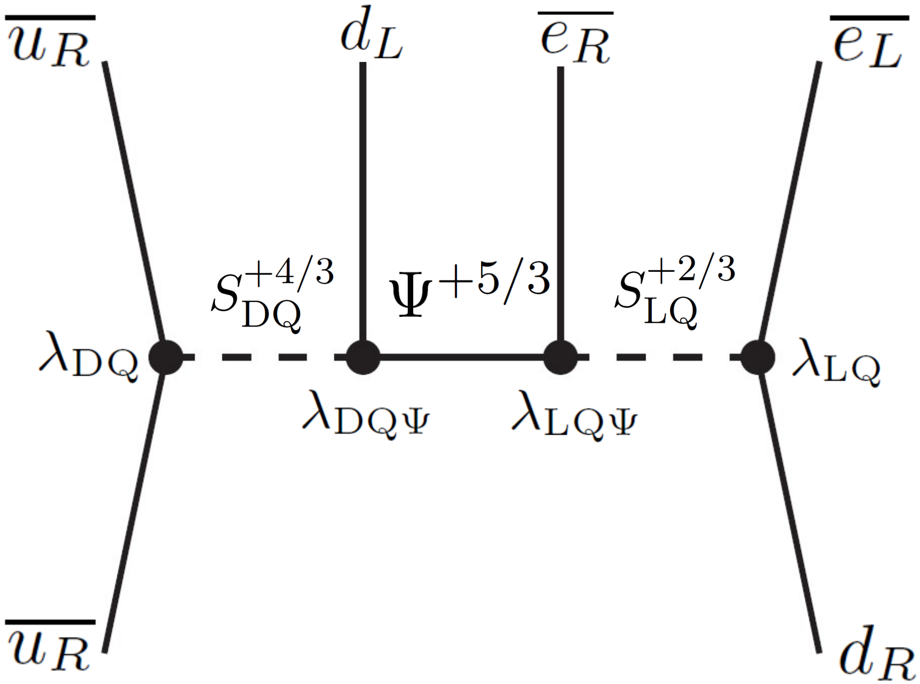
and $(\Psi_R)_{Ii}^{\dot a}$

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



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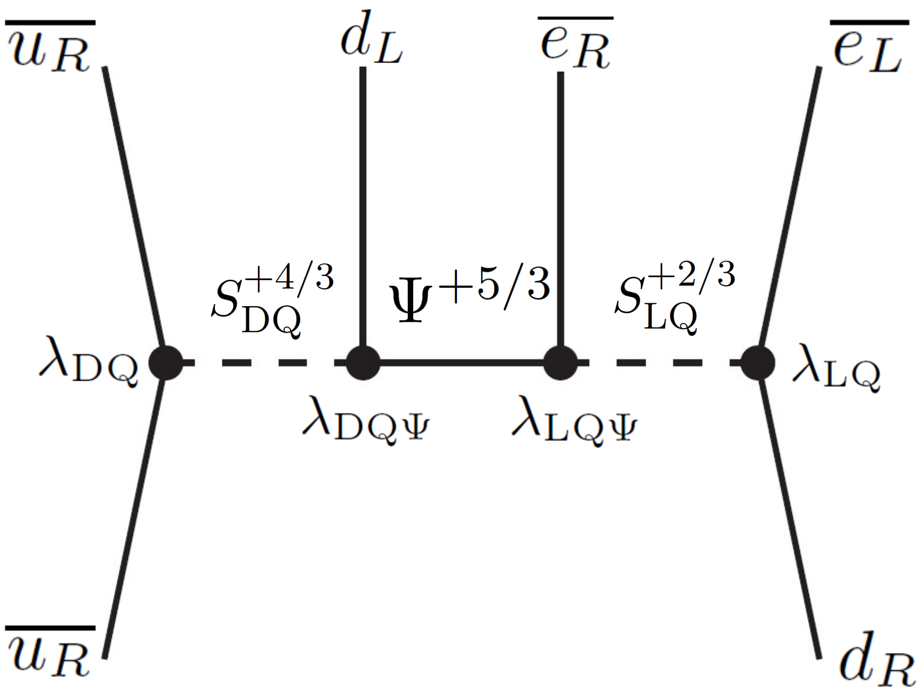
and $(\Psi_R)_{Ii}^{\dot{a}}$

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



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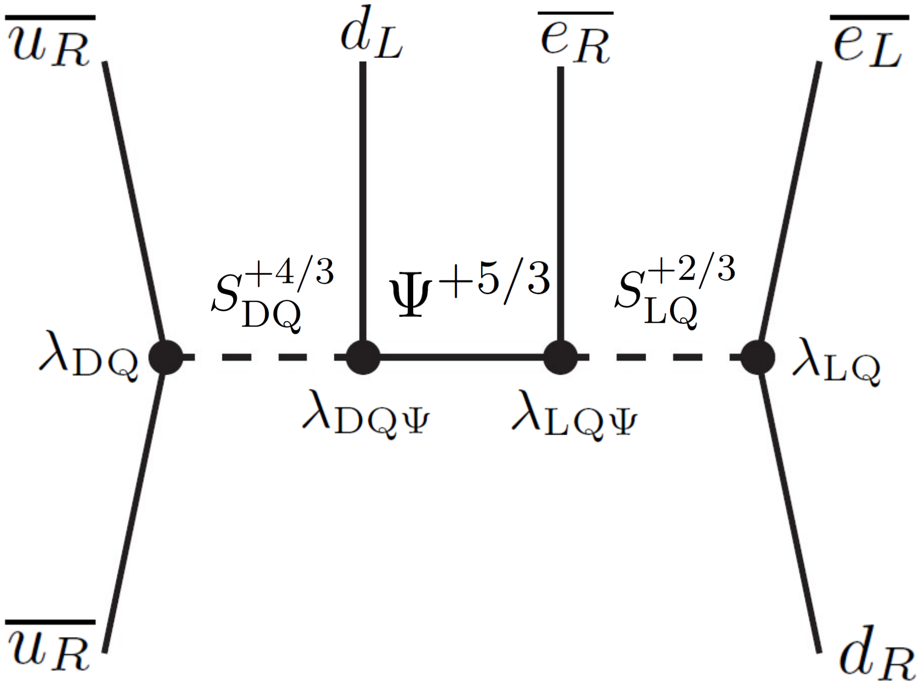
Take λ's =1, $m=\Lambda$

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

2 Decomposition

An example



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

Take scalar mediators
Specify the chiralities

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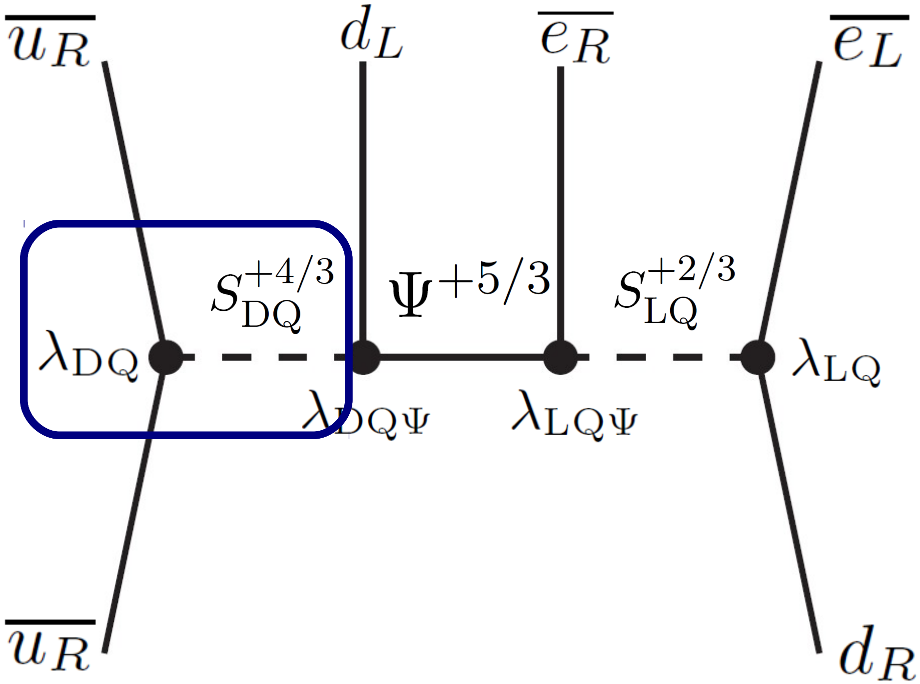
Take λ's $=1$, $m = \Lambda$

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

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?



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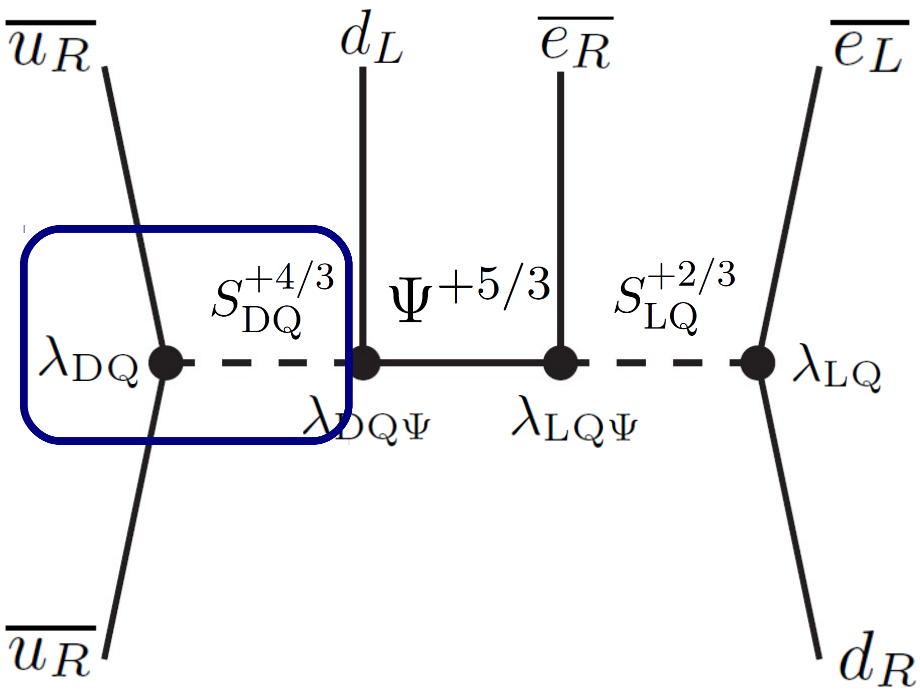
- Diquark (DQ):

Decomposition

An example



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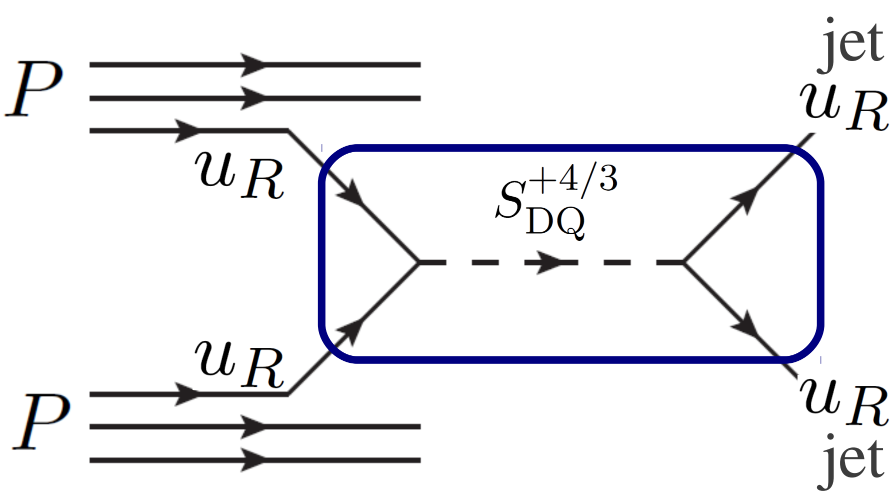
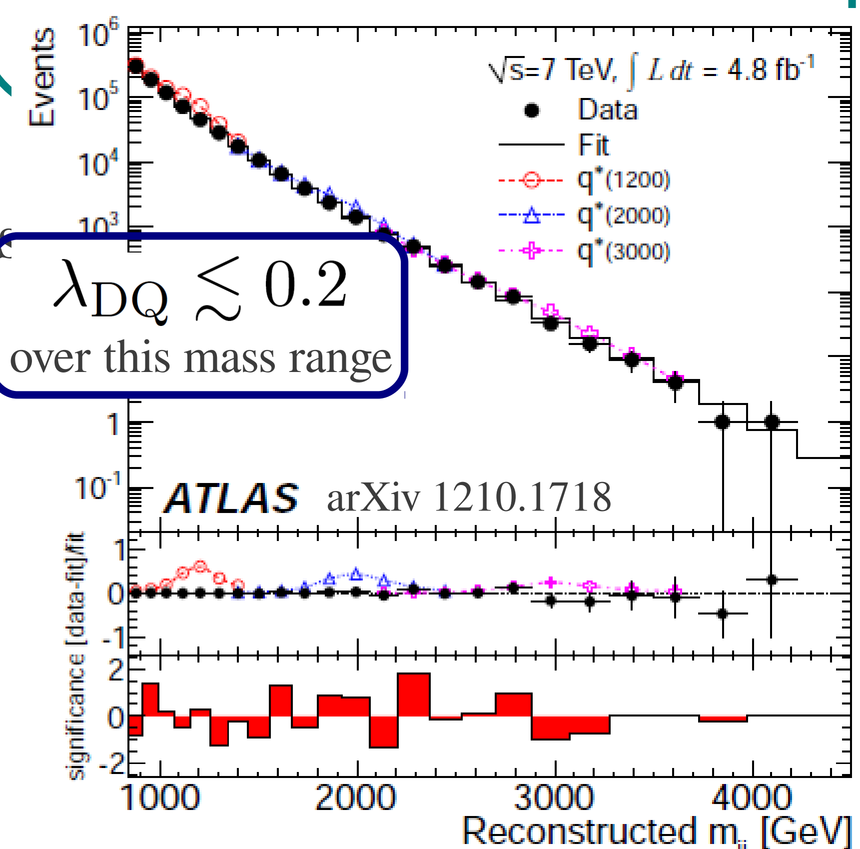
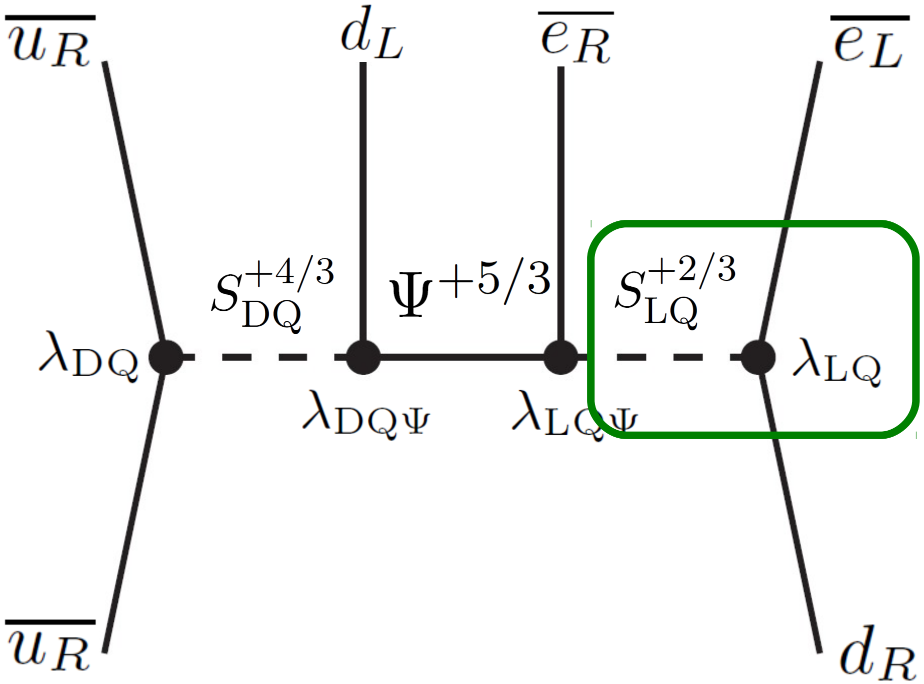
- Diquark (DQ): Search for a resonance in 2-jets





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



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

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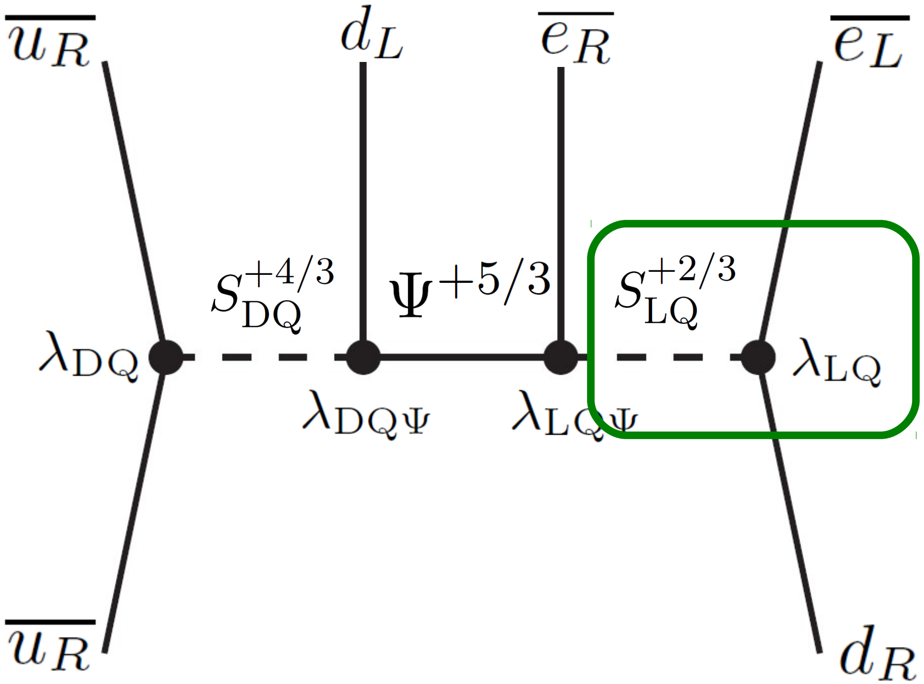
- Leptoquark (LQ):

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

Take scalar mediators
Specify the chiralities



Necessary mediators

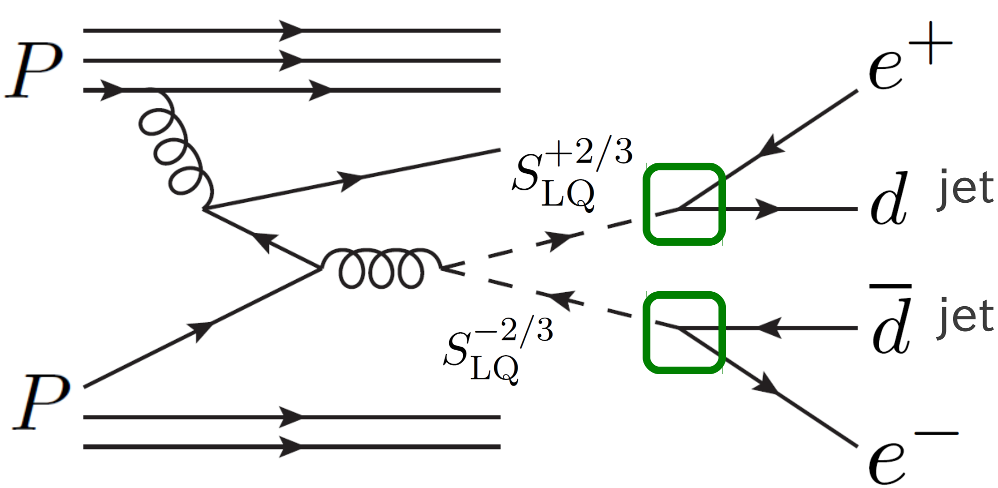
$(S_{\rm DQ}^{+4/3})_X$

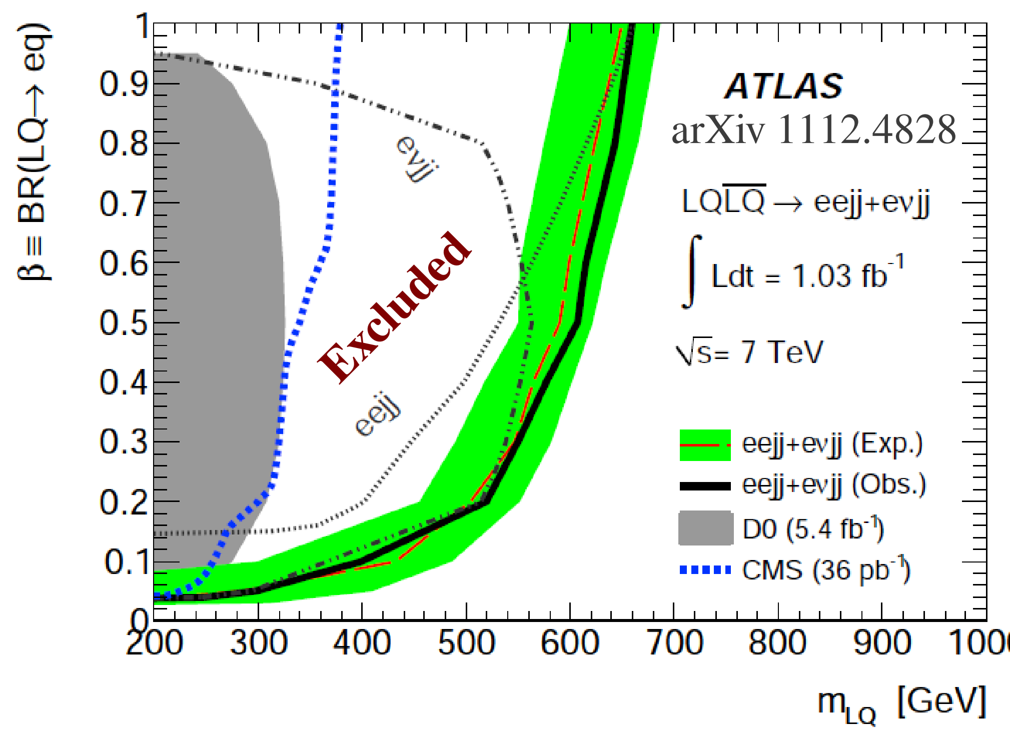
$(S_{\rm LQ})_{Ii} = \left((S_{\rm LQ}^{+2/3})_I, (S_{\rm LQ}^{-1/3})_I\right)^T$

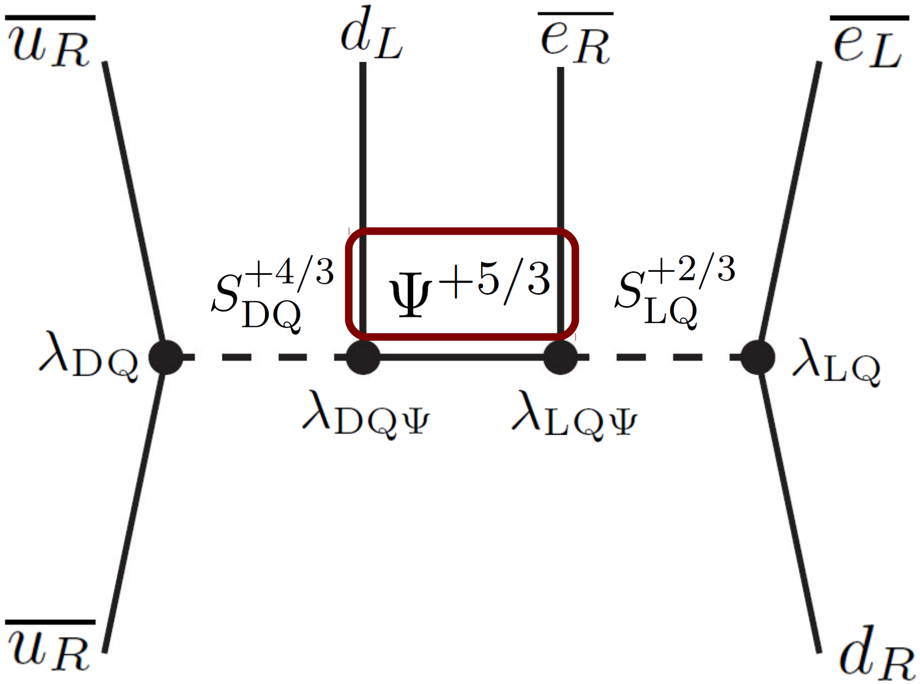
$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^T$

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

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







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

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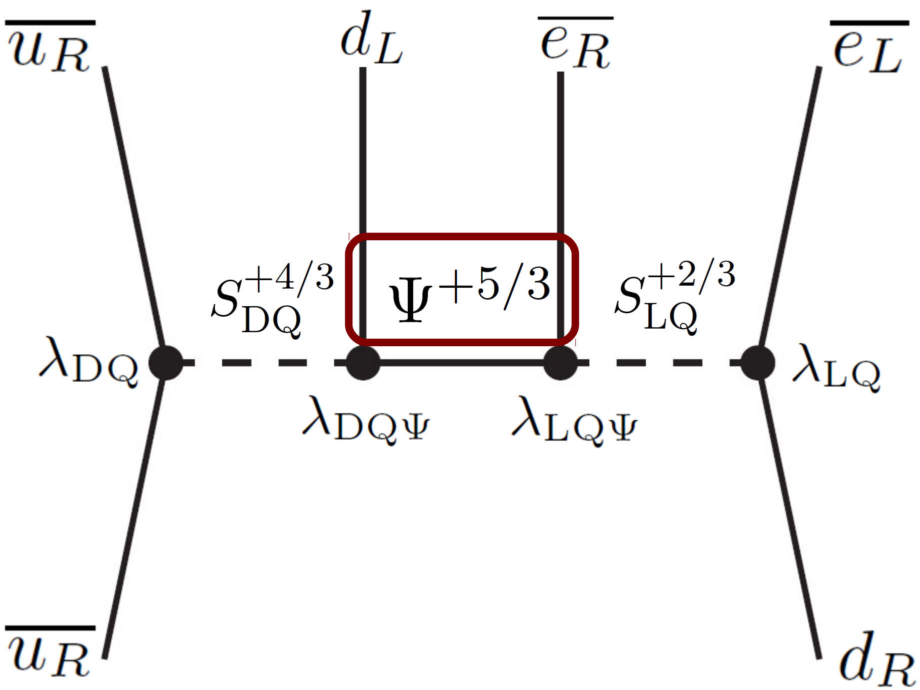
and $(\Psi_R)^{\dot a}_{Ii}$

- Vector-like Quark (VLQ):



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

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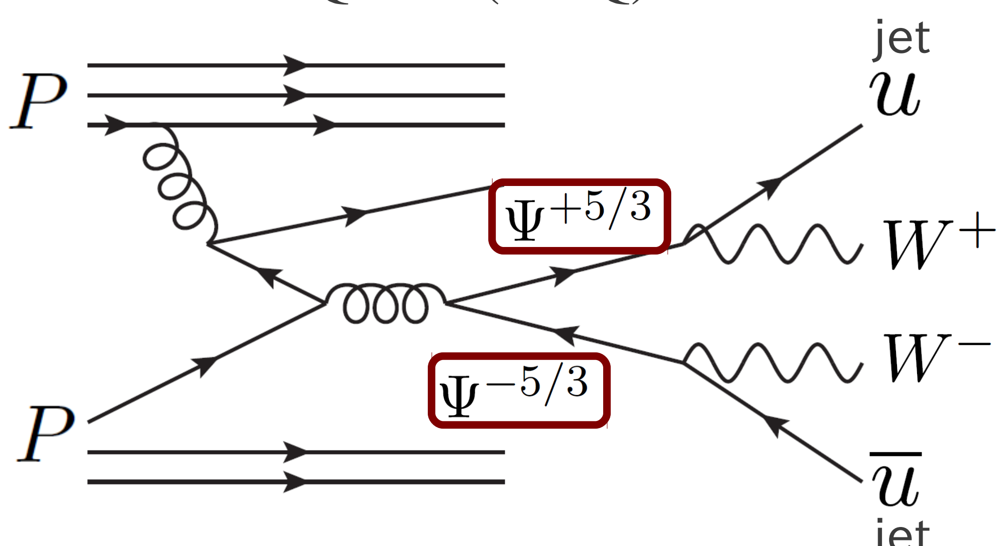
$(\Psi_L)_{Iia} = \left((\Psi_L^{+5/3})_{Ia}, (\Psi_L^{+2/3})_{Ia},\right)^{\rm T}$

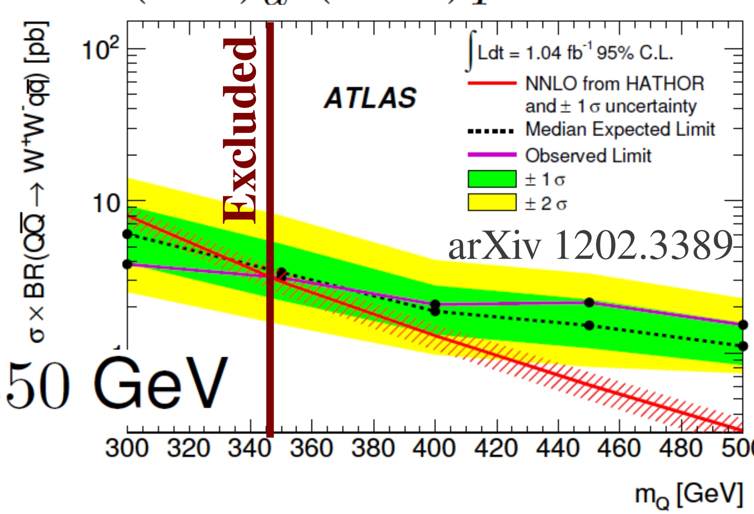
and $(\Psi_R)_{Ii}^{\dot{a}}$

- 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 ***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

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 $m_\nu \sim 0.1\mathrm{eV}$

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

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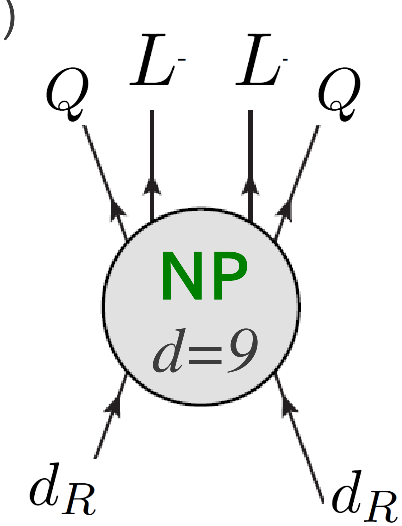
Examples introduced in recent papers, based on Decomposition of $LLQQd_Rd_R$

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

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

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



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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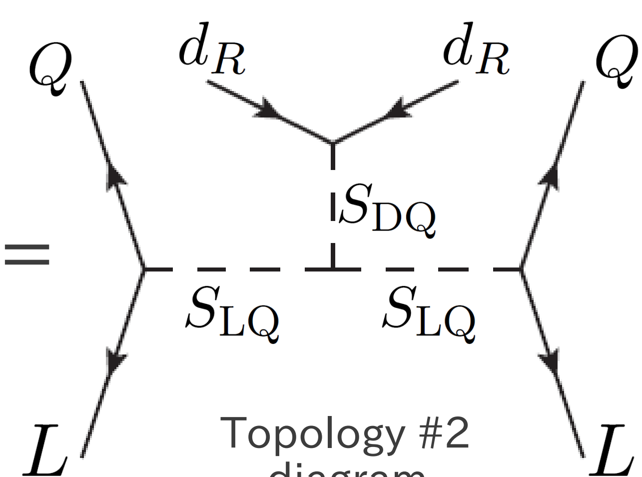

Topology #2 diagram

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

Saitama University 埼玉大学

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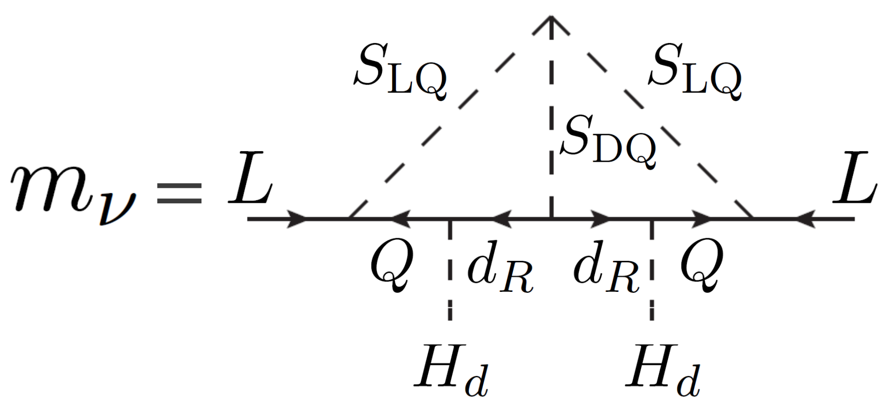

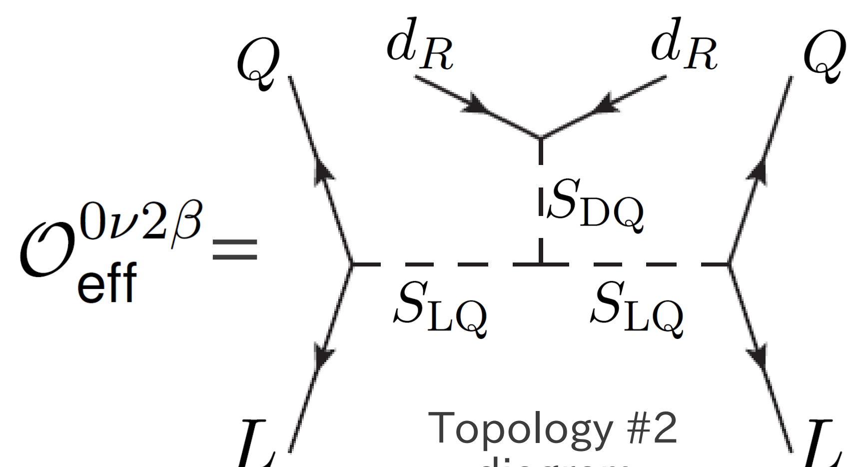

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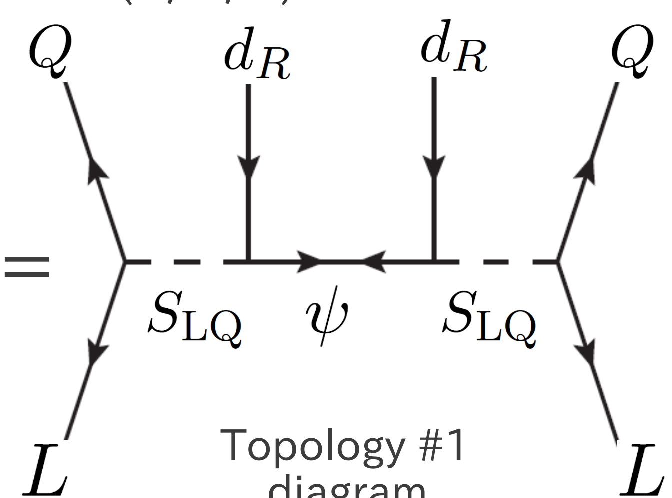
Two-loop mNu model with LQ(**3**, **1**, -1/3), Majorana fermion (**8**, **1**, 0)

Angel Cai Rodd Schmidt Volkas 1308.0463

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



Topology #1 diagram

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$m_\nu \sim 0.1\text{eV}$	$\Lambda_{\text{NP}} \sim 1$ TeV

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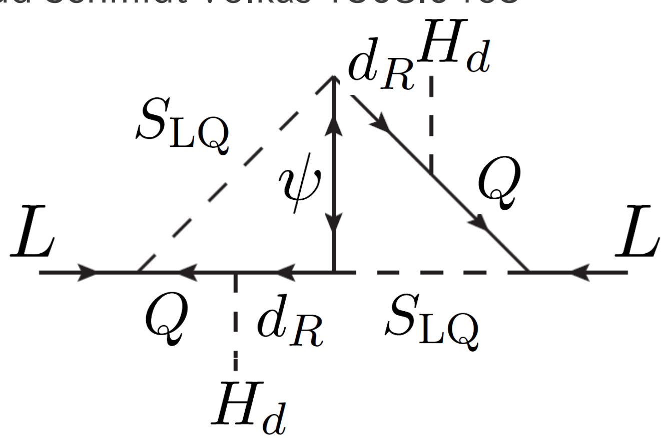
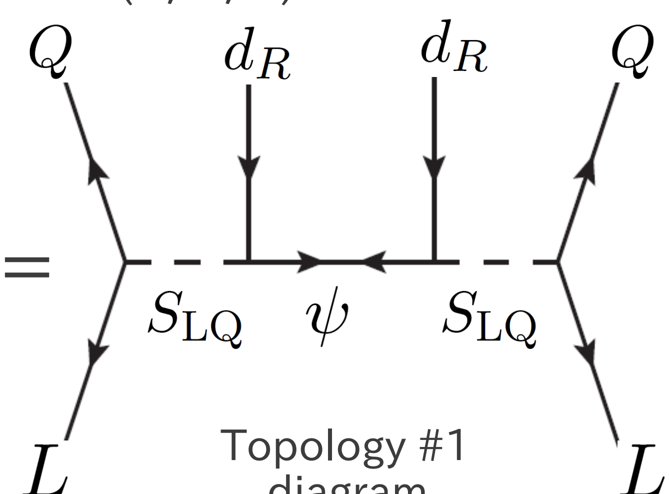
Angel Cai Rodd Schmidt Volkas 1308.0463

$m_\nu =$



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



Topology #1 diagram

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Seeking the relation to the models

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

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Radiative neutrino mass models with TeV ingredients

In such models

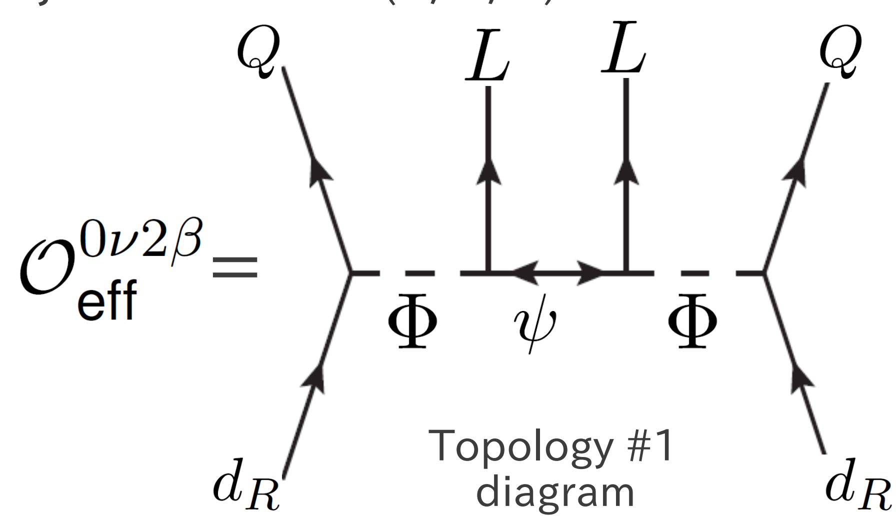
Size of **two contributions** to 0n2b can be comparable!

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

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

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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Radiative neutrino mass models with TeV ingredients

In such models

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

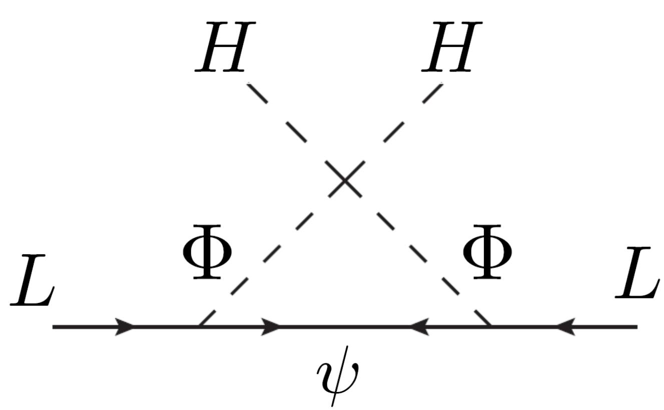
Standard one	dim=9
$m_\nu \sim 0.1\text{eV}$	$\Lambda_{NP} \sim 1$ TeV

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

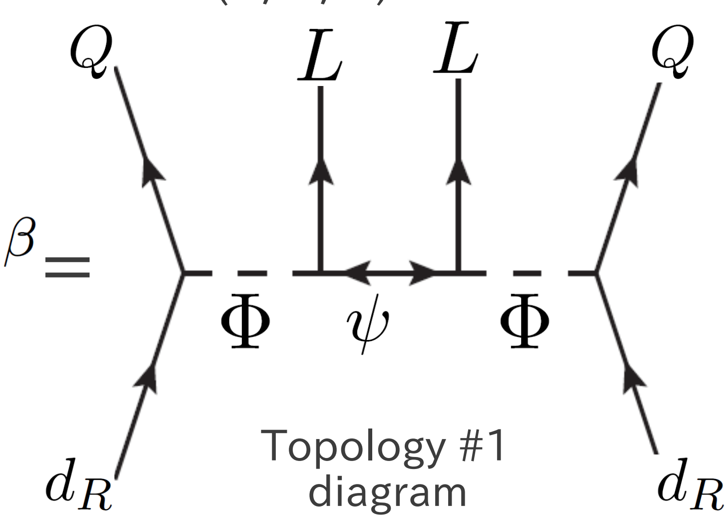
Colour-8 mNu model with Scalar (**8**, **2**, 1/2), Majorana fermion (**8**, **1**, 0)

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

$m_\nu =$



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



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

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 $\Lambda_{\text{NP}} \sim 1$ 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...

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

8 3 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

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Summary

		Long	Mediator ($U(1)_{em}$, $SU(3)_c$)			
#	Decomposition	Range?	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)	$(-2/3, \bar 3)$	$(0, 1)$	$(+2/3, 3)$	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]
			$(-1/3, 3)$	$(0, 8)$	$(+1/3, \bar 3)$	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!

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

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!

My last message:

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

Back up slides

1. Neutrino mass bound from cosmological observations

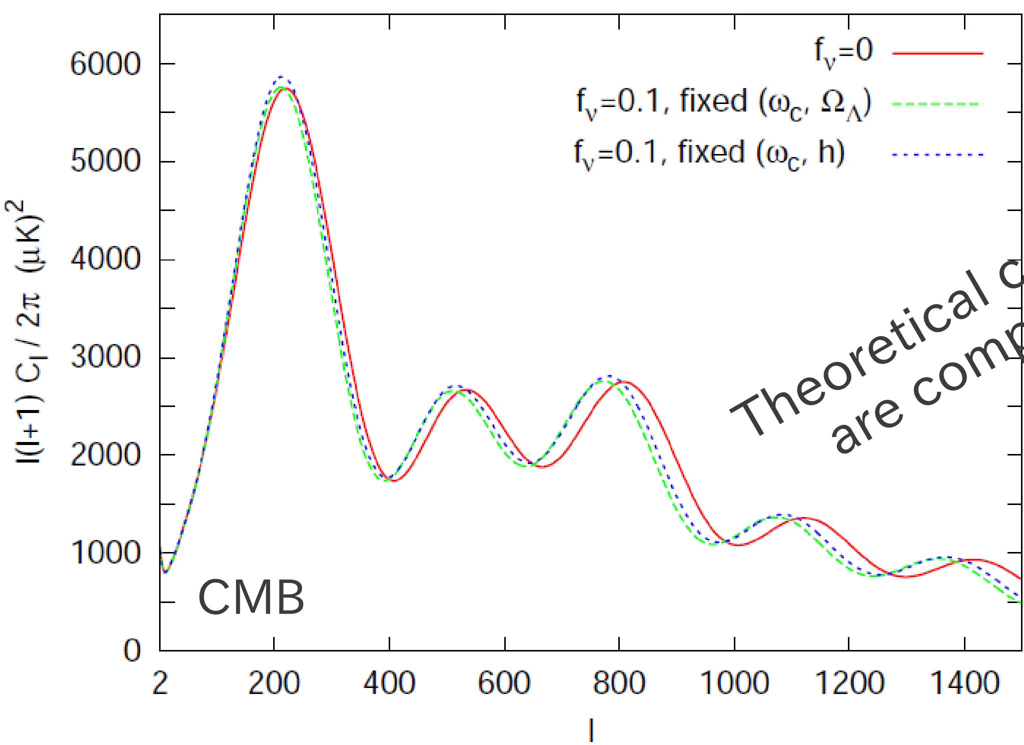
2. LR symmetric model as a Decomposition of dim=9 op

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

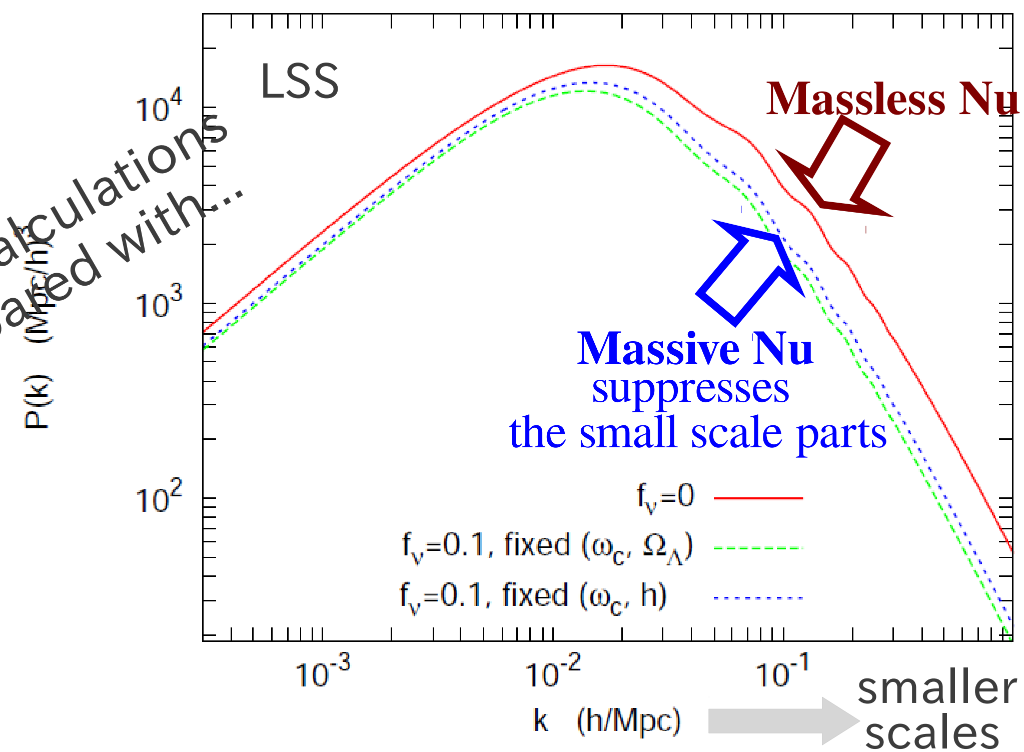
$$\langle m_{\beta\beta}\rangle \equiv \sum_{i=1}^{3} (U_e{}^i)^2 m_i$$

- **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

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

- **0n2b exp** are sensitive to

Effective nu mass

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

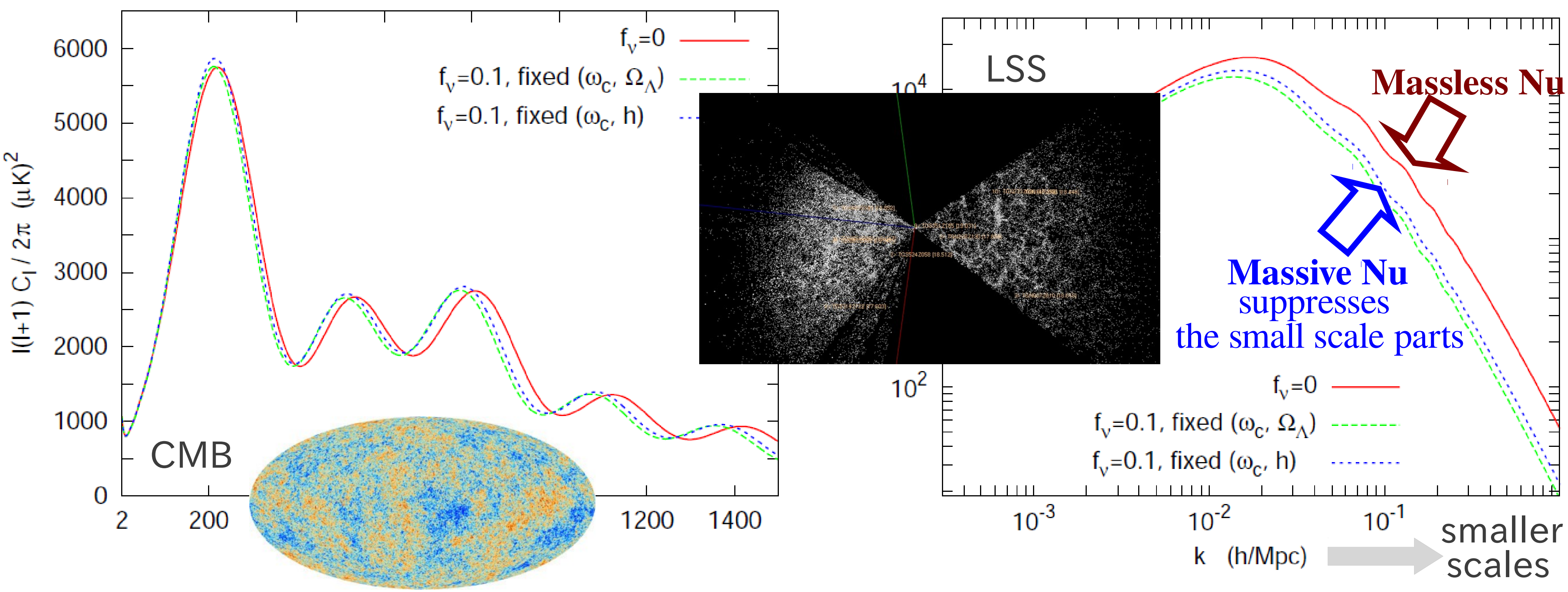
- **Cosmological obs** constrain

Sum of nu masses

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

Obs: Planck, WMAP-9year, and balloons

Obs: SDSS, 2dFGRS



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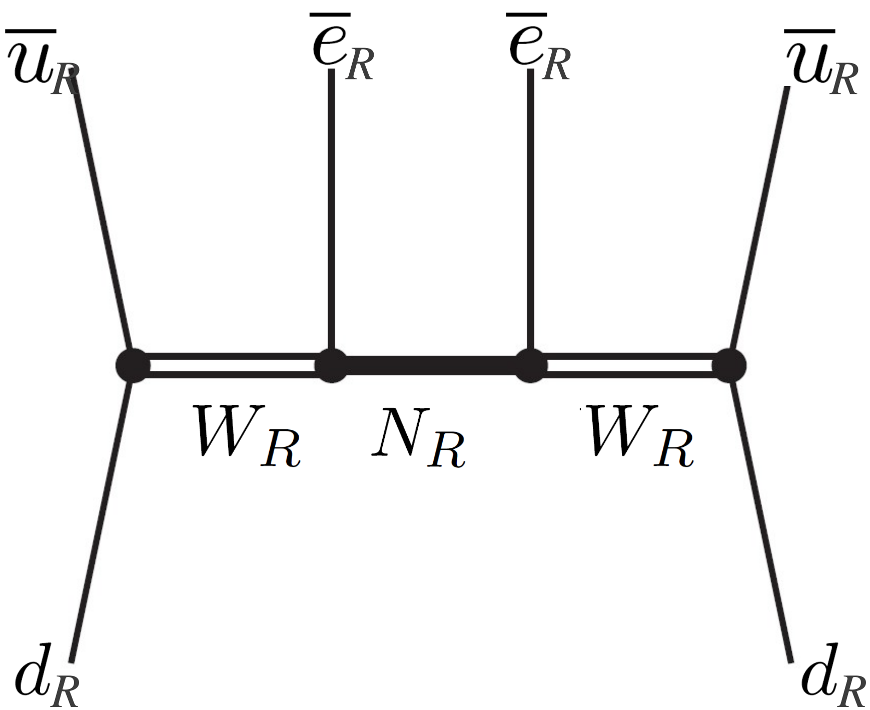
Talk by Wong

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

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



Necessary mediators

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

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

Left-right symmetric model

All the outer fermions are right-handed

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

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

- An example,

  Taking Topology #I

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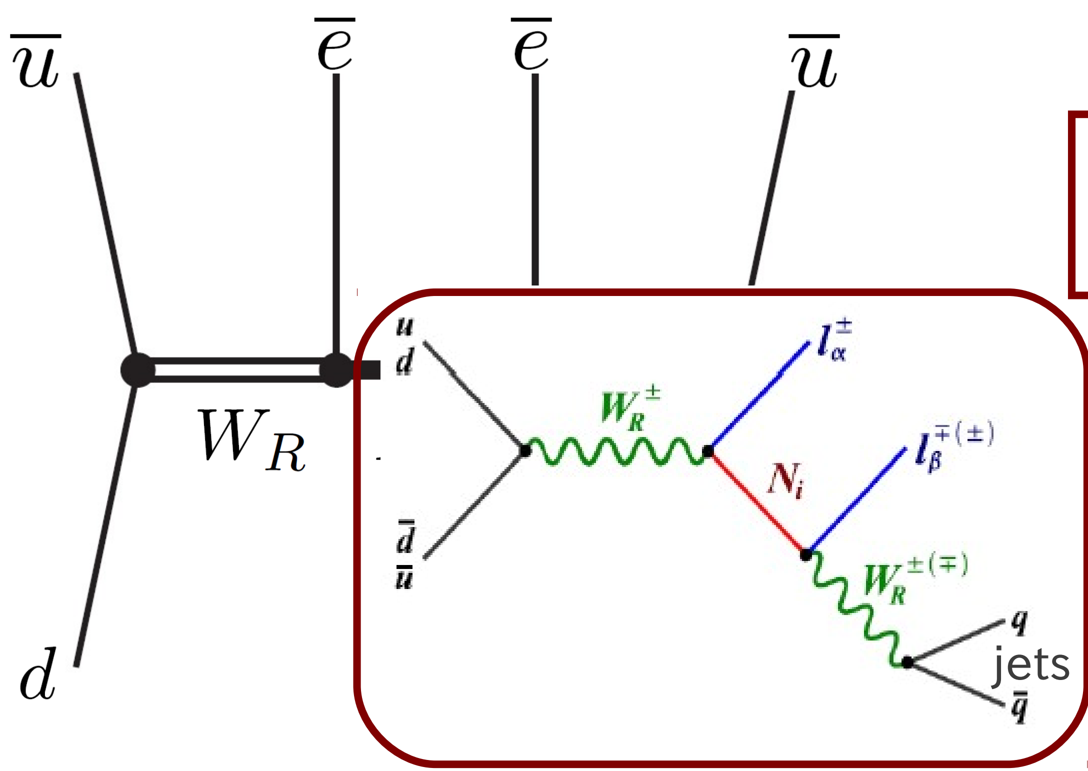

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N_R and W_R collider search

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

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

ATLAS search for 2 leptons+jets: arXiv.1203.5420