

An Effective Theory of Neutrino

Systematic decomposition of the neutrinoless double beta decay operator

Toshihiko Ota



based on

Florian Bonnet, Martin Hirsch, TO, Walter Winter JHEP 1303 (2013) 055 arXiv. 1212. 3045

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

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

If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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

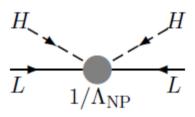


If the SM is a low-*E* effective model of a fundamental theory...

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

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

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



Weinberg op.

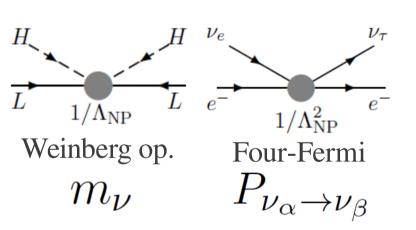
$$m_{\nu}$$



If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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



$$L_e$$
 H
 H
 L_τ
 E
 $1/\Lambda_{\rm NP}^4$
 E

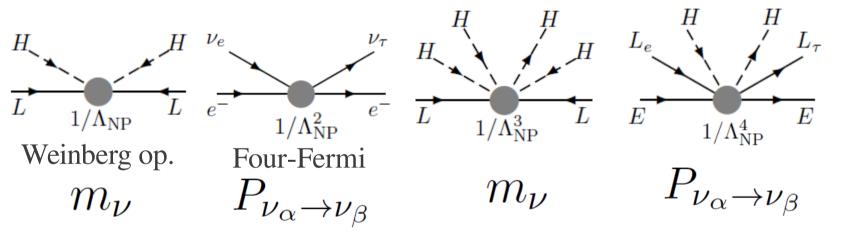
$$P_{\nu_{\alpha} \to \nu_{\beta}}$$



If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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

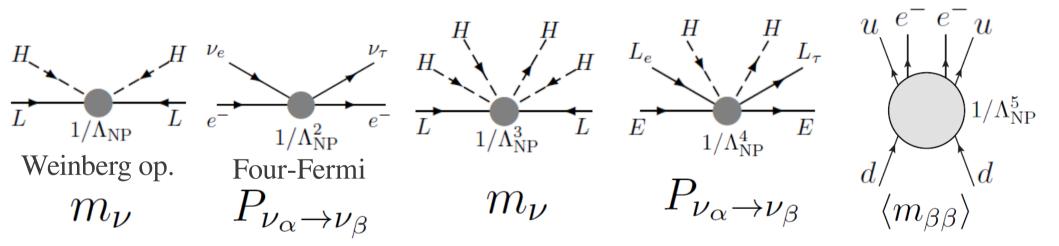




If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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



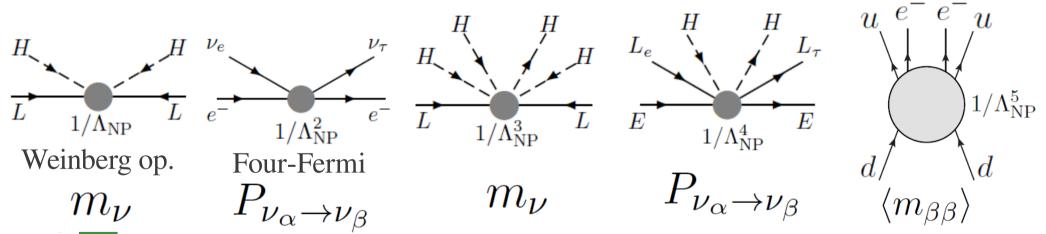


If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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

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



High *E* completion

Seesaw mech. (@tree)

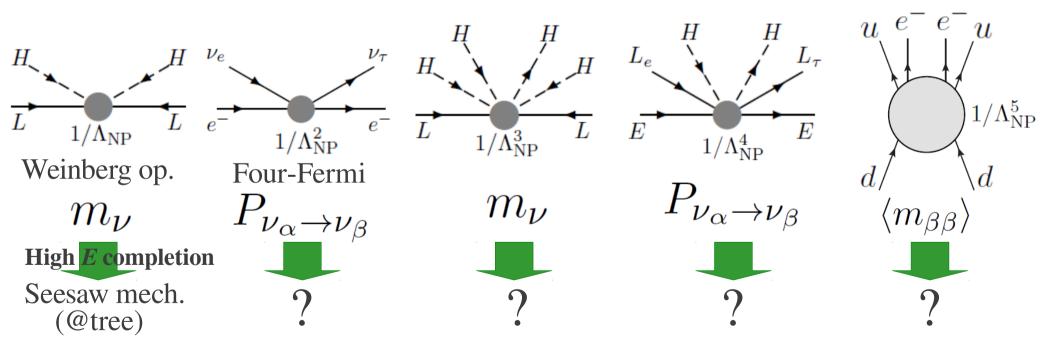


If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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

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

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



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

Exhaustive bottom-up approach



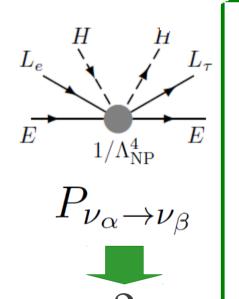
(@tree)

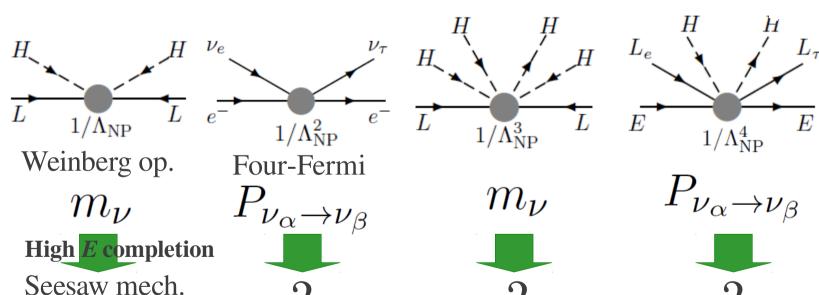
Preface

 $1/\Lambda_{\mathrm{NP}}^{5}$

If the SM is a low-*E* effective model of a fundamental theory... Talk by Gavela, Huber

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





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

Exhaustive bottom-up approach



Outline

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

- Motivation: Why On2b? Why dim=9 ops?
 - $d=9 \text{ ops} \rightarrow \text{half-life time of 0n2b processes}$ "How sensitive 0n2b experiments to the d=9 ops?"
- What do the d=9 ops suggest to TeV scale physics?

d=9 ops \rightarrow decompose them to the fundamental ints.

→ list the TeV signatures of each completion

"The list helps us to discriminate the models"

Seeking a relation to the models at the TeV scale

TeV scale models with LNV \rightarrow *Models for radiative neutrino masses*



Outline

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

Motivation: Why On2b? Why dim=9 ops?

d=9 ops \rightarrow half-life time of 0n2b processes "How sensitive 0n2b experiments to the d=9 ops?"

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

d=9 ops \rightarrow decompose them to the fundamental ints.

→ list the TeV signatures of each completion

"The list helps us to discriminate the models"

Seeking a relation to the models at the TeV scale

TeV scale models with LNV \rightarrow *Models for radiative neutrino masses*





Why 0n2b? Why d=9 op.?

Effective neutrino mass

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

Effective nu mass
$$\langle m_{\beta\beta}\rangle \equiv \sum_{i=1}^3 (U_e{}^i)^2 m_i \qquad U_e{}^1 = c_{12}c_{13} \\ U_e{}^2 = s_{12}c_{13}\mathrm{e}^{\mathrm{i}\alpha} \\ U_e{}^3 = s_{13}\mathrm{e}^{\mathrm{i}\beta}$$

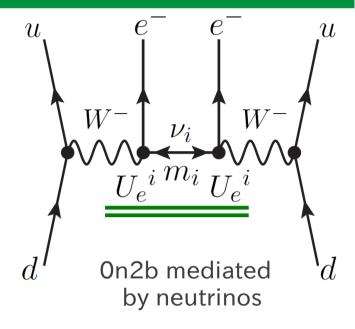
$$U_e^{\ 1} = c_{12}c_{13}$$
 $U_e^{\ 2} = s_{12}c_{13}e^{i\alpha}$
 $U_e^{\ 3} = s_{13}e^{i\beta}$

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 lpha and eta are Majorana phases



0n2b mediated

by neutrinos

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

Effective nu mass
$$U_e^{\ 1}=c_{12}c_{13}$$
 $V_e^{\ 2}=s_{12}c_{13}e^{\mathrm{i}\alpha}$ $U_e^{\ 3}=s_{12}e^{\mathrm{i}\beta}$

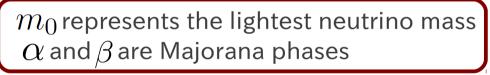
$$U_e{}^1=c_{12}c_{13}$$
 Unknow $U_e{}^2=s_{12}c_{13}\mathrm{e}^{\mathrm{i}lpha}$ $U_e{}^3=s_{13}\mathrm{e}^{\mathrm{i}eta}$

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

Inverted hierarchy

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

$$m_3 = m_0$$



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

$$s_{12}^2 = 0.3$$
,

$$s_{23}^2 = 0.41(0.59),$$

$$s_{13}^2 = 0.023$$

$$\Delta m_{21}^2 = 7.5 \cdot 10^{-5} \text{ eV}^2$$

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



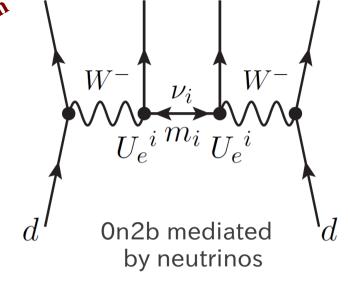


• In SM+3nu, **0n2b** exp are sensitive to

Effective nu mass
$$\langle m_{\beta\beta}\rangle \equiv \sum_{i=1}^3 (U_e{}^i)^2 m_i \qquad U_e{}^1 = c_{12}c_{13} \\ U_e{}^2 = s_{12}c_{13} e^{\mathrm{i}\alpha} \\ U_e{}^3 = s_{13} e^{\mathrm{i}\beta}$$

$$U_e{}^1=c_{12}c_{13}$$
 Unknown $U_e{}^2=s_{12}c_{13}\mathrm{e}^{\mathrm{i}lpha}$ $U_e{}^3=s_{13}\mathrm{e}^{\mathrm{i}eta}$

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



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

$$m_3 = m_0$$

 m_0 represents the lightest neutrino mass lpha and eta are Majorana phases

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

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



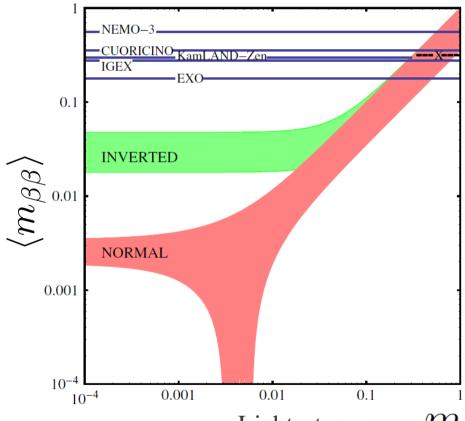
Cosmological obs are sensitive to the other combination of params....

• **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

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



Lightest nu mass m_0

Standard 3nu parameter space



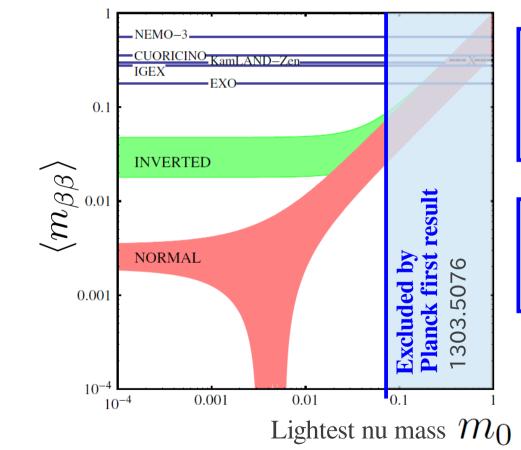


• **0n2b exp** are sensitive to Effective nu mass

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

Cosmological obs constrain Sum of nu masses

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



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

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

SPT reports non-zero mNu? 1212.6267

Standard 3nu parameter space





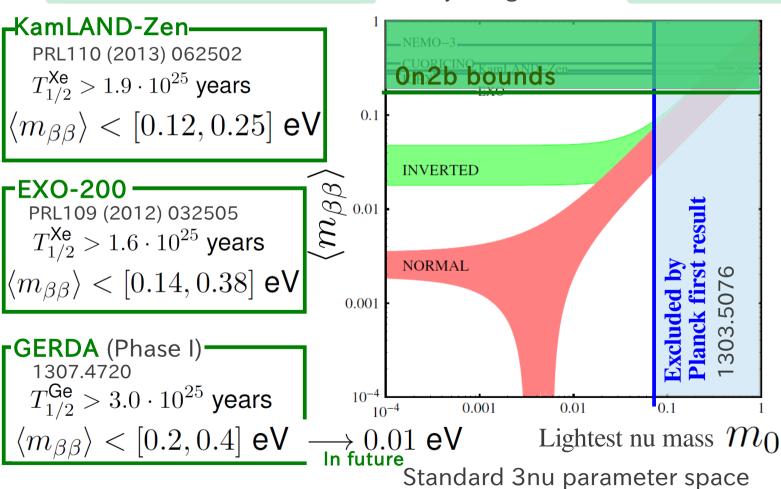
• **0n2b exp** are sensitive to Effective nu mass

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

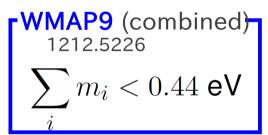
Talk by Yang

Cosmological obs constrain Sum of nu masses

$$\sum_{i=1}^{5} m_i (\simeq 3m_0 \text{ if } m_0 \gtrsim 0.1 \text{ eV})$$



Planck (combined) 1303.5076 $\sum m_i < 0.23 \; {\sf eV}$



SPT reports non-zero mNu? 1212.6267

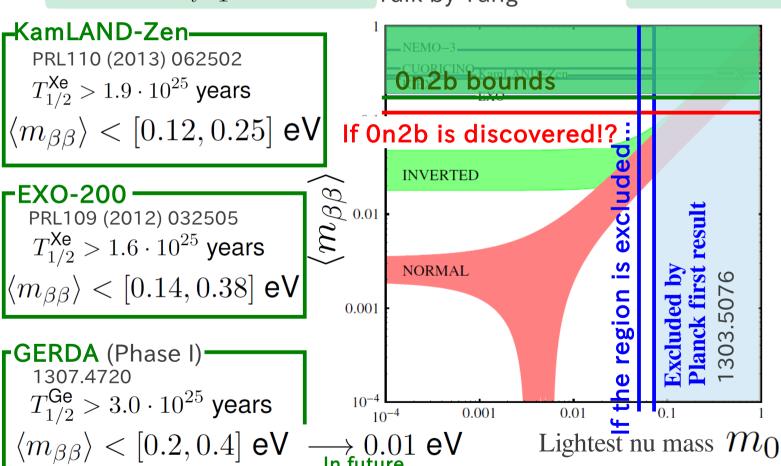
0n2b exp are sensitive to Effective nu mass

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

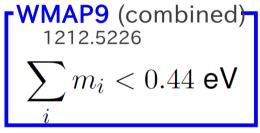
Talk by Yang

Cosmological obs constrain Sum of nu masses

$$\sum_{i=1}^{5} m_i (\simeq 3m_0 \text{ if } m_0 \gtrsim 0.1 \text{ eV})$$



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



SPT reports non-zero mNu? 1212.6267

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



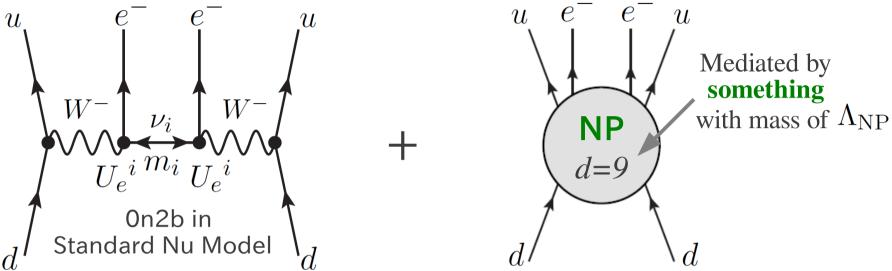


0n2b in

Standard Nu Model

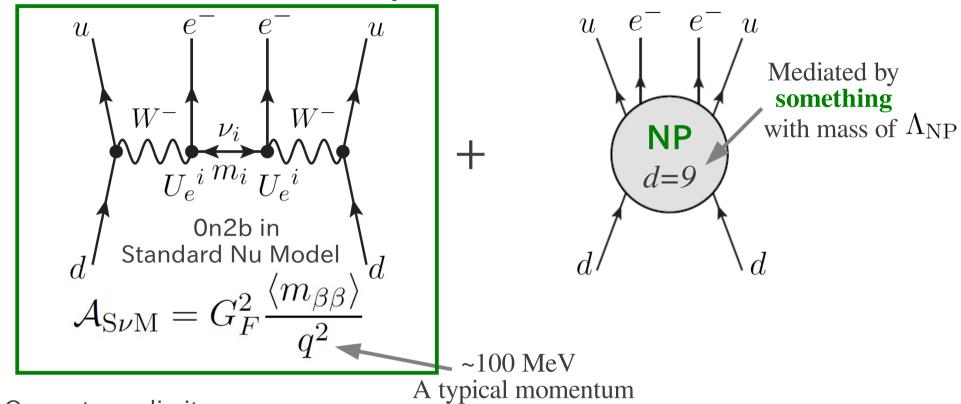










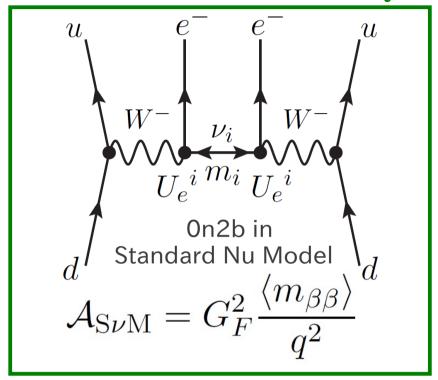


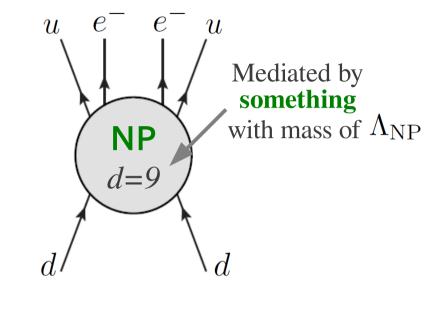
Current exp. limit

of neutrino in atom
$$10^{25}~{
m [yr]} < T_{1/2}^{0
u2eta} \propto 1/\left|{\cal A}_{
m S\nu M}\right|^2$$







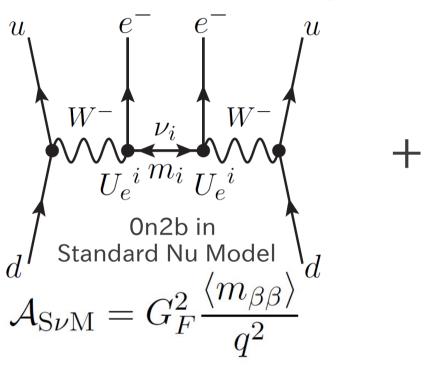


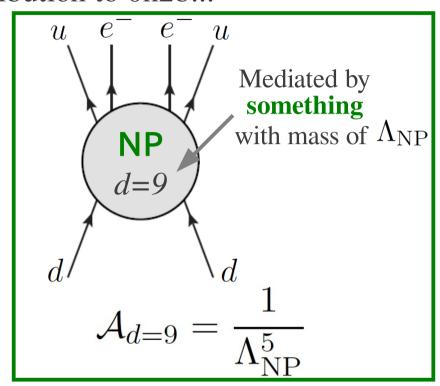
Current exp. limit

Sensitive to
$$10^{25}~{
m [yr]} < T_{1/2}^{0\nu2\beta} \propto 1/\left|{\cal A}_{
m S\nu M}\right|^2 ~~\langle m_{\beta\beta} \rangle < 0.3~{
m [eV]}$$







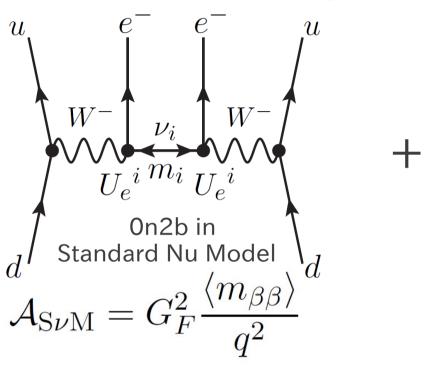


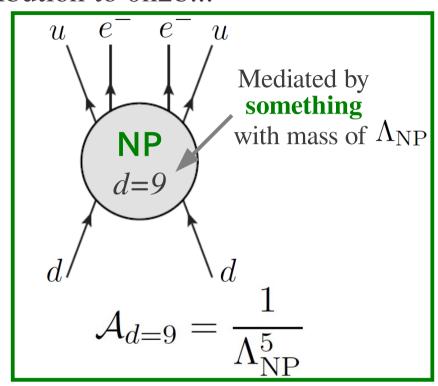
Current exp. limit

Sensitive to
$$10^{25}~{
m [yr]} < T_{1/2}^{0\nu2\beta} \propto 1/\left|{\cal A}_{
m S\nu M}\right|^2 ~~ \langle m_{\beta\beta}\rangle < 0.3~{
m [eV]}$$
 $\propto 1/\left|{\cal A}_{d=9}\right|^2$





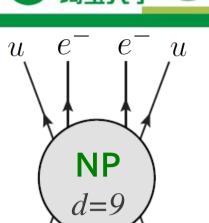




Current exp. limit Sensitive to
$$10^{25} \ [\mathrm{yr}] < T_{1/2}^{0\nu2\beta} \propto 1/\left|\mathcal{A}_{\mathrm{S}\nu\mathrm{M}}\right|^2 \qquad \langle m_{\beta\beta}\rangle < 0.3 \ [\mathrm{eV}]$$

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

On2b exps are sensitive to not only Majorana neutrino mass but also NP at TeV.

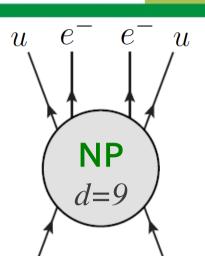


... Talls into the following 3 types of effective ops.
$$\mathcal{L}_{d=9} = \frac{G_F^2}{2m_P} \left[\sum_{i=1}^3 \epsilon_i^{\{XY\}Z} (\mathcal{O}_i)_{\{XY\}Z} + \sum_{i=5}^4 \epsilon_i^{XY} (\mathcal{O}_i)_{XY} \right],$$

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

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

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



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

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

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

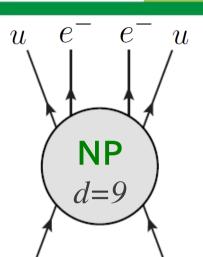
$$(\mathcal{O}_3) \equiv (J_X)^{\mu} (J_Y)_{\mu} j_Z,$$

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

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

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

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



$$\begin{cases}
\mathcal{L}_{d=9} = \frac{G_F^2}{2m_P} \left[\sum_{i=1}^3 \epsilon_i^{\{XY\}Z} (\mathcal{O}_i)_{\{XY\}Z} + \sum_{i=5}^4 \epsilon_i^{XY} (\mathcal{O}_i)_{XY} \right], \\
(\mathcal{O}_1) \equiv J_X J_Y j_Z, \quad (\mathcal{O}_4) \equiv (J_X)^{\mu\nu} (J_Y)_{\mu} (j)_{\nu}, \quad J_X = \overline{u} \Gamma P_X d \\
(\mathcal{O}_2) \equiv (J_X)^{\mu\nu} (J_Y)_{\mu\nu} j_Z, (\mathcal{O}_5) \equiv J_X (J_Y)_{\mu} (j)_{\mu} \quad j_X = \overline{e} \Gamma P_X e^c \\
d \quad (\mathcal{O}_3) \equiv (J_X)^{\mu} (J_Y)_{\mu} j_Z,
\end{cases}$$

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

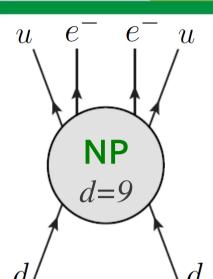
$$\left(T_{1/2}^{0\nu2\beta}\right)_{\underline{d=9}}^{-1} = G_1 \left| \sum_{i=1}^{3} \epsilon_i \mathcal{M}_i \right|^2 + G_2 \left| \sum_{i=4}^{5} \epsilon_i \mathcal{M}_i \right|^2 + G_3 \operatorname{Re} \left[\left(\sum_{i=1}^{3} \epsilon_i \mathcal{M}_i \right) \left(\sum_{i=4}^{5} \epsilon_i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

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

$$\mathcal{M}_i \text{ Nuclear matrix elements}$$

$$G_i \text{ Phase space factors}$$

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



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

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

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

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

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

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

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

$$\mathcal{M}_i \text{ Nuclear matrix elements}$$

$$G_i \text{ Phase space factors}$$

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

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



Outline

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

Motivation: Why On2b? Why dim=9 ops?

d=9 ops \rightarrow half-life time of 0n2b processes "How sensitive 0n2b experiments to the d=9 ops?"

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

d=9 ops \rightarrow decompose them to the fundamental ints.

→ list the TeV signatures of each completion

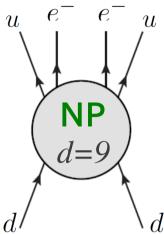
"The list helps us to discriminate the models"

3 Seeking a relation to the models at the TeV scale

TeV scale models with LNV \rightarrow *Models for radiative neutrino masses*

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

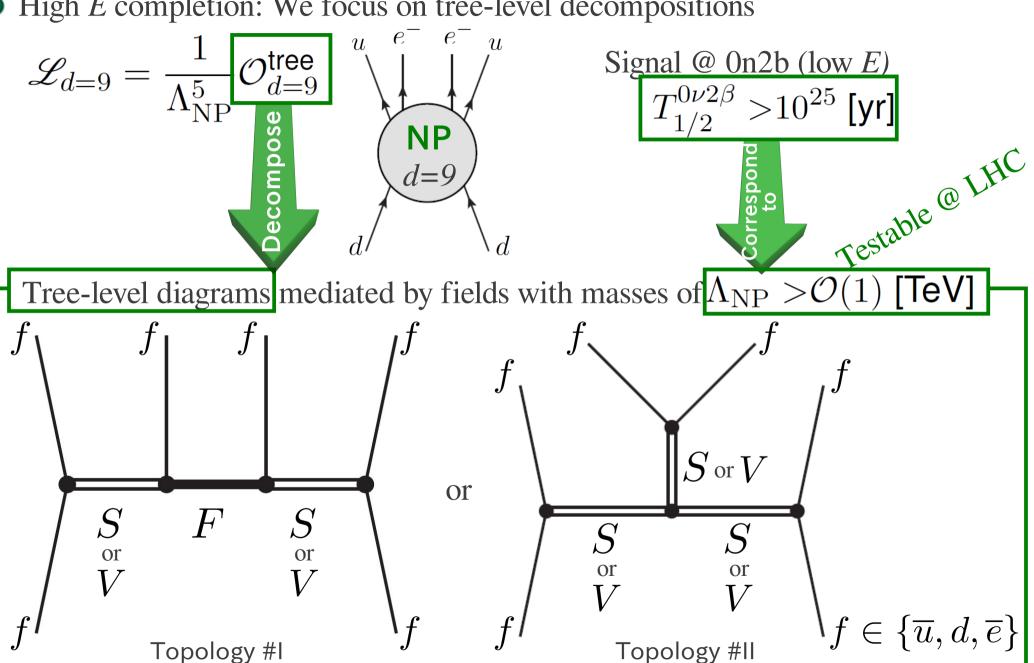
$$\mathscr{L}_{d=9} = rac{1}{\Lambda_{\mathrm{NP}}^{5}} \mathcal{O}_{d=9}^{\mathsf{tree}}$$



Signal @ 0n2b (low
$$E$$
) $T_{1/2}^{0\nu2\beta} > 10^{25} \text{ [yr]}$



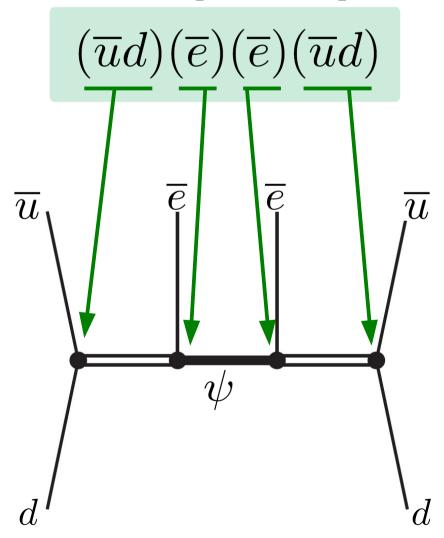
High E completion: We focus on tree-level decompositions





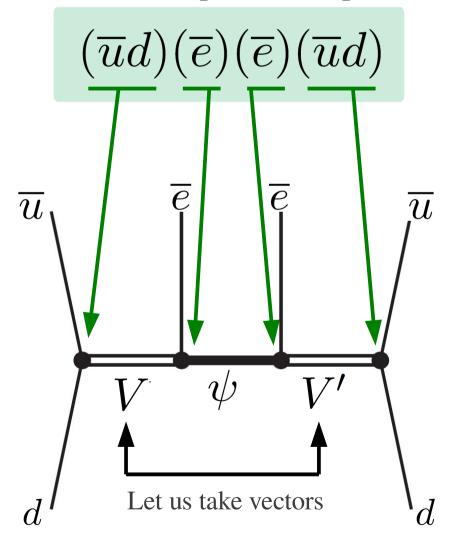


Taking Topology #I let us decompose d=9 op as





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

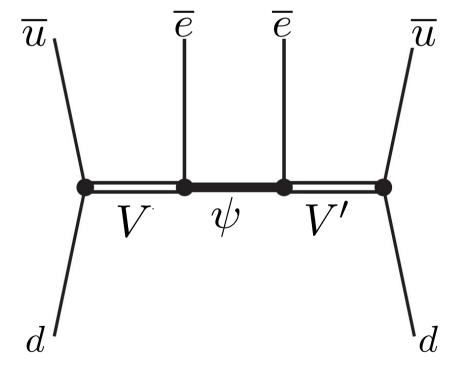






Taking Topology #I let us decompose d=9 op as

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



Necessary mediators

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

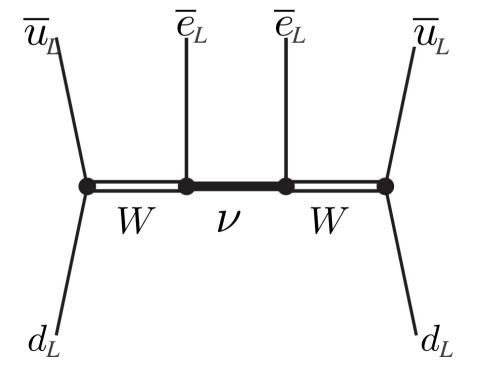
where $(U(1)_{em}, SU(3)_{c})$





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

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



Necessary mediators

$$V(+1,\mathbf{1}) \hspace{0.5cm} W^+ \ V'(-1,\mathbf{1}) \hspace{0.5cm} W^- \ \psi(0,\mathbf{1}) \hspace{0.5cm} \mathcal{V}$$

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

Rediscovery of the standard neutrino mass contribution

All the outer fermions must be left-handed

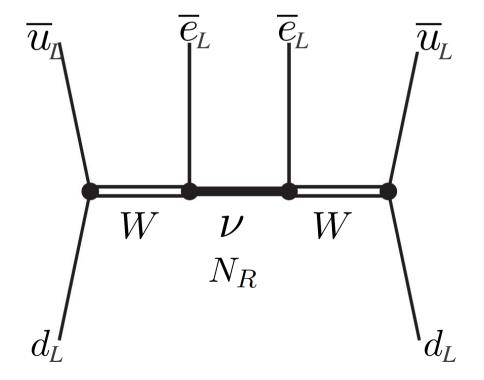




An example,

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

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



Necessary mediators

$$V(+1,{f 1}) \hspace{0.5cm} W^+ \ V'(-1,{f 1}) \hspace{0.5cm} W^- \ \psi(0,{f 1}) \hspace{0.5cm} {m
u} \hspace{0.5cm} N_R$$

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

Rediscovery of the standard neutrino mass contribution

All the outer fermions must be left-handed

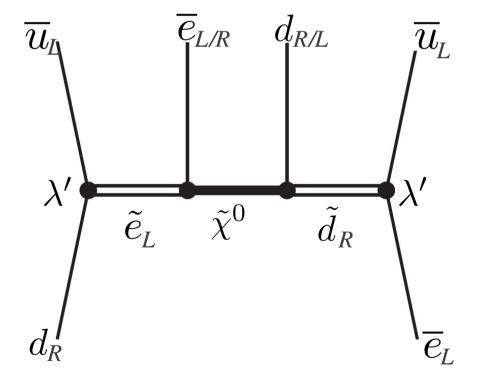
In Seesaw model, right handed neutrinos can also mediate this diagram. Talk by Lopez-Pavon



Another example,

Decomposition

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



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 $\mathscr{W}_{\cancel{R}}\ni \lambda'\hat{L}\hat{Q}\hat{D}^c$

Hirsch Klapdor-Kleingrothaus Kovalenko, PLB378 (1996) 17, PRD54 (1996) 4207

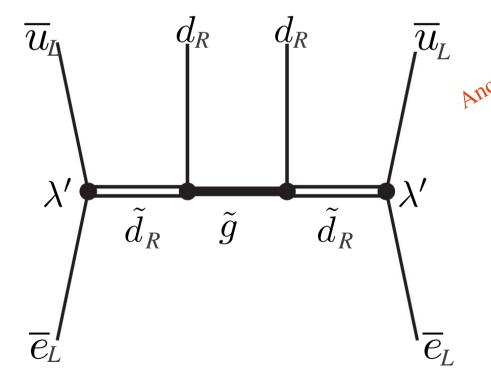
SUSY (Rp-conserved) search at LHC 1st generation squarks and gluino should be heavier than 1TeV



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

R-parity violating SUSY models $\mathscr{W}_{\cancel{R}}\ni \lambda'\hat{L}\hat{Q}\hat{D}^c$

Hirsch Klapdor-Kleingrothaus Kovalenko, PLB378 (1996) 17, PRD54 (1996) 4207

SUSY (Rp-conserved) search at LHC 1st generation squarks and gluino should be heavier than 1TeV





List of high *E* completions

_		$SU(3)_c$)	or $(U(1)_{em}, I$	Mediate	Long		
_	Models/Refs./Comments	S' or V'	1/2	S or V		Decomposition	#
Sn	Mass mechan., RPV [58-60],	(-1,1)	(0, 1)	(+1,1)	(a)	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	1-i
J	LR-symmetric models [39],						
Se	Mass mechanism with ν_S [61						
	TeV scale seesaw, e.g., [62, 63						
4	[04]	(-1,8)	(0, 8)	(+1,8)			
		(+2, 1)	(+5/3, 3)	(+1, 1)		$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	1-ii-a
		(+2, 1)	(+5/3, 3)	(+1, 8)			
		(+2, 1)	(+4/3, 3)	(+1, 1)		$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	1-ii-b
_		(+2,1)	(+4/3, 3)	(+1,8)		(- P/ P/-)/	
		(+1/3, 3)	(+4/3, 3)	(+1, 1)		$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	2-i-a
	DD11 (80, 00), 10, (08, 00)	(+1/3, 3)	(+4/3, 3)	(+1,8)	0.5	(= D (=) (D (==)	0.11
RP	RPV [58–60], LQ [65, 66]	$(+1/3, \overline{3})$	(0, 1)	(+1,1)	(b)	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	2-i-b
ILL		(+1/3, 3)	(0, 8)	(+1,8)		(=4)(=)(=)(4=)	0.00
		(+2/3, 3)	(+5/3, 3)	(+1,1)		$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	2-ii-a
	DDV [ES e0] LO [et ee]	(+2/3, 3)	(+5/3, 3)	(+1,8)	(1.)	(=J\(=\(-\)/J=\	9 :: 1-
	RPV [58–60], LQ [65, 66]	(+2/3, 3)	(0, 1)	(+1, 1)	(b)	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	2-ii-b
	RPV [58-60]	(+2/3, 3) (+1/3, 3)	(0, 8) (0, 1)	(+1, 8) $(-2/3, \overline{3})$	(c)	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	2-iii-a
	RPV [58–60]	(+1/3, 3) (+1/3, 3)	(0, 1)	(-2/3, 3) (-2/3, 3)	(c)	(ae)(u)(u)(ue)	2-111-a
	KI V [38-00]	(+1/3, 3) (+1/3, 3)	(0, 3) $(-1/3, 3)$	(-2/3, 3) (-2/3, 3)		$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	2-iii-b
		$(+1/3, \overline{3})$	$(-1/3, \overline{\bf 6})$	$(-2/3, \overline{3})$		(ac)(a)(a)(ac)	2-111-0
_	only with V_{ρ} and V'_{ρ}	(-2/3, 3)	$(+1/3, \overline{3})$	$(+4/3, \overline{3})$		$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	3-i
	only with v _p and v _p	(-2/3, 6)	(+1/3, 6)	(+4/3, 6)		(44)(0)(0)(44)	3-1
	only with V_{ρ}	(+2,1)	(+5/3, 3)	$(+4/3, \overline{3})$		$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	3-ii
	οιι, ποι τρ	(+2,1)	(+5/3, 3)	(+4/3, 6)		(44)(4)(4)	0 11
	only with V_{ρ}	(+2, 1)	(+4/3, 3)	(+2/3, 3)		$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	3-iii
	y	(+2, 1)	(+4/3, 3)	$(+2/3, \overline{6})$		(/(-/(-/	
_	RPV [58-60]	(+2/3, 3)	(0, 1)	(-2/3, 3)	(c)	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	4-i
	RPV [58–60]	(+2/3, 3)	(0, 8)	(-2/3, 3)	(-)	(/(-/(-/	
	only with V_{ρ}	(+2/3, 3)	(+5/3, 3)	(+4/3, 3)		$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	4-ii-a
	see Sec. 4 (this work)	(+2/3, 3)	(+5/3, 3)	(+4/3, 6)			
	only with V_{ρ}	(+2/3, 3)	$(+1/3, \overline{3})$	(+4/3, 3)		$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	4-ii-b
_		(+2/3, 3)	(+1/3, 6)	(+4/3, 6)		. ,,,,,,,	
L_{D}	RPV [58–60]	(+1/3, 3)	(0, 1)	(-1/3, 3)	(c)	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	5-i
JRP	RPV [58-60]	(+1/3, 3)	(0, 8)	(-1/3, 3)			
_	only with V'_{ρ}	(-2/3, 3)	$(+1/3, \overline{3})$	(-1/3, 3)		$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	5-ii-a
	-	(-2/3, 6)	(+1/3, 6)	(-1/3, 3)			
	only with V'_{ρ}	(-2/3, 3)	(-4/3, 3)	(-1/3, 3)		$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	5-ii-b
	•	(-2/3, 6)	(-4/3, 3)	(-1/3, 3)			

Possible decompositions and eesaw 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 $(SU(2)_I)$ 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

		Long	Mediat	or $(U(1)_{em})$	$SU(3)_c$	
#	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, 3)	(+2, 1)	
			(+1, 8)	(+4/3, 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, 3)	(+1/3, 3)	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	(+1/3, 3)	RPV [58–60], LQ [65,66]
0."	/= 1\/=\/-\/ !=\		(+1, 8)	(0,8)	$(+1/3, \overline{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 1)	(+5/3, 3)	(+2/3, 3)	
0 :: 1	/=J\/=\/=\/J=\	(1-)	(+1,8)	(+5/3, 3)	(+2/3, 3)	DDV (to eo) LO (et ee)
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]
2-iii-a	(da)(a)(d)(aa)	(a)	(+1, 8) $(-2/3, \overline{3})$	(0, 8) (0, 1)	(+2/3, 3) (+1/3, 3)	RPV [58-60]
2-111-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	(-2/3, 3) (-2/3, 3)	(0, 1)	(+1/3, 3) (+1/3, 3)	RPV [58–60] RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3, 3) (-2/3, 3)	(-1/3, 3)	(+1/3, 3) $(+1/3, 3)$	III V [56-00]
2-111-17	(ac)(a)(a)(ac)		$(-2/3, \overline{3})$	$(-1/3, \overline{6})$	$(+1/3, \overline{3})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	(-2/3, 3)	only with V_{ρ} and V'_{ρ}
	(44)(5)(5)(44)		(+4/3, 6)	(+1/3, 6)	(-2/3, 6)	οιι, · ρ αιια · ρ
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, 3)	(+2, 1)	only with V_{ρ}
			$(+2/3, \overline{6})$	$(+4/3, \overline{3})$	(+2, 1)	•
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3, 3)	(0, 1)	(+2/3, 3)	RPV [58–60]
			(-2/3, 3)	(0, 8)	(+2/3, 3)	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		(+4/3, 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)	$(+1/3, \overline{3})$	(+2/3, 3)	only with V_{ρ}
			(+4/3, 6)	(+1/3, 6)	(+2/3, 3)	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	(-1/3, 3)	(0, 1)	(+1/3, 3)	RPV [58–60]
	() (-) (-) (-)		(-1/3, 3)	(0,8)	(+1/3, 3)	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3, 3)	$(+1/3, \overline{3})$	(-2/3, 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)	

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 $(SU(2)_I)$ 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

	T.					
		Long	Mediat	or $(U(1)_{em})$	$SU(3)_c$	
#	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, 3)	(+2, 1)	
			(+1,8)	$(+4/3, \overline{3})$	(+2,1)	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		(+1,1)	(+4/3, 3)	(+1/3, 3)	
0:1	(=J\/=\/J\/==\	(1.)	(+1,8)	(+4/3, 3)	$(+1/3, \overline{3})$	DDV (to eo) LO (er ee)
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1,1)	(0, 1)	$(+1/3, \overline{3})$	RPV [58–60], LQ [65, 66]
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1,8)	(0,8)	$(+1/3, \overline{3})$ (+2/3, 3)	
2-11-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 1) (+1, 8)	(+5/3, 3) (+5/3, 3)	(+2/3, 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) $(+2/3, 3)$	RPV [58–60], LQ [65, 66]
2-11-13	(44)(c)(4)(4c)	(D)	(+1, 1)	(0, 1)	(+2/3, 3)	11 7 [55 55], 152 [55,55]
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \overline{3})$	(0, 0)	$(+1/3, \overline{3})$	RPV [58–60]
	(/(-/(-/	(-)	$(-2/3, \overline{3})$	(0, 8)	$(+1/3, \overline{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3, 3)	(-1/3, 3)	(+1/3, 3)	
			$(-2/3, \overline{3})$	$(-1/3, \overline{6})$	$(+1/3, \overline{3})$	
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, 3)	(+2, 1)	only with V_{ρ}
			$(+2/3, \overline{\bf 6})$	$(+4/3, \overline{3})$	(+2,1)	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3, 3)	(0, 1)	(+2/3, 3)	RPV [58–60]
4-ii-a	(==\/J\/=\/J=\		$(-2/3, \overline{3})$	(0,8)	(+2/3, 3)	RPV [58–60]
4-11-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \overline{3})$ (+4/3, 6)	(+5/3, 3) (+5/3, 3)	(+2/3, 3) (+2/3, 3)	only with V_{ρ} see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	(+2/3, 3) (+2/3, 3)	only with V_{ρ}
4-11-1)	(aa)(c)(a)(ac)		(+4/3, 6)	(+1/3, 6)	(+2/3, 3) $(+2/3, 3)$	only with Vp
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)	$(+1/3, \overline{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3, 3)	$(+1/3, \overline{3})$	(-2/3, 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)	- "

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 $(SU(2)_I)$ 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

		Long	Mediat	or $(U(1)_{em})$	$SU(3)_c$)	
#	Decomposition	Range?	S or V_{ρ}	7/2	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, 3)	(+2, 1)	
			(+1, 8)	$(+4/3, \overline{3})$	(+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)	$(\pm 4/3, 3)$	(+1/3, 3)	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	$(+1/3, \overline{3})$	RPV [58–60], LQ [65, 66]
			(+1, 8)	(0, 8)	(+1/3, 3)	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 1)	(+5/3, 3)	(+2/3, 3)	
	(- P.(-)(-)(-)	(1)	(+1, 8)	$(\pm 5/3, 3)$	(+2/3, 3)	DDITES OF TO SEE OF
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]
0	(T-) (-) (T) ()		(+1,8)	(0.8)	(+2/3, 3)	DD1 (80, 00)
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \overline{3})$	(0, 1)	$(+1/3, \overline{3})$	RPV [58–60]
0 ::: 1	(J=\/J\/=\/==\		$(-2/3, \overline{3})$	(0, 8)	$(+1/3, \overline{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \overline{3})$	(-1/3, 3)	$(+1/3, \overline{3})$ $(+1/3, \overline{3})$	
3-i	/::::\/::\/::\/.J.J\		$(-2/3, \overline{3})$	$(-1/3, \overline{6})$ $(+1/3, \overline{3})$	(-2/3, 3)	only with V_{ρ} and V'_{ρ}
9-1	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \overline{3})$ (+4/3, 6)	(+1/3, 6)	(-2/3, 6) (-2/3, 6)	only with v_{ρ} and v_{ρ}
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \frac{6}{3})$	(+5/3, 3)	(-2/3, 6) $(+2, 1)$	only with V_{ρ}
0-11	(uu)(u)(u)(ee)		(+4/3, 6)	(+5/3, 3) $(+5/3, 3)$	(+2, 1) (+2, 1)	only with Vp
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		(+2/3, 3)	$(+4/3, \overline{3})$	(+2, 1) $(+2, 1)$	only with V_{ρ}
o-m	(44)(4)(4)(44)		$(+2/3, \overline{6})$	$(+4/3, \overline{3})$	(+2, 1)	only with v _p
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3, 3)	(0, 1)	(+2/3, 3)	RPV [58-60]
	(30)(0)(0)	(0)	$(-2/3, \overline{3})$	(0, 1)	(+2/3, 3)	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \overline{3})$	(+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	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	(+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)	$(+1/3, \overline{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3, 3)	(+1/3, 3)	(-2/3, 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)	$(-2/3, \overline{3})$	only with V'_{ρ}
			(-1/3, 3)	(-4/3, 3)	(-2/3, 6)	

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 $(SU(2)_L \text{ and } U(1)_Y)$
 - → Decom of chirality-specified ops Bonnet Hirsch O Winter 1212.3045

• Long Range?

Decomposition which can contain neutrino propagation





List of high *E* completions

Long Mediator $(U(1)_{em}, SU(3)_c)$ # Decomposition Range? S or V_ρ ψ S' or V'_ρ Models/Refs./C 1-i $(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$ (a) $(+1, 1)$ $(0, 1)$ $(-1, 1)$ Mass mechan.,	Comments
	Commonto
1; (\(\bar{u}\)\(\bar{c}\)\(\bar{c}\)\(\bar{u}\)\(\dot\) (a) (b) (11) (01) (11) Mass mechan	Johnneins
	RPV [58–60],
LR-symmetric	
Mass mechanism	
TeV scale seesa	w, 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 $(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$ $(+1, 1)$ $(+4/3, 3)$ $(+2, 1)$	
$(+1,8)$ $(+4/3,\overline{3})$ $(+2,1)$	
2-i-a $(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$ $(+1,1)$ $(+4/3,3)$ $(+1/3,3)$	
$(+1,8)$ $(+4/3,\overline{3})$ $(+1/3,\overline{3})$	C. [0x 00]
2-i-b $(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$ (b) $(+1,1)$ $(0,1)$ $(+1/3,\overline{3})$ RPV [58–60], I.	Q [65, 66]
$(+1,8)$ $(0,8)$ $(+1/3,\overline{3})$	
2-ii-a $(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$ (+1,1) (+5/3,3) (+2/3,3)	
(+1, 8) $(+5/3, 3)$ $(+2/3, 3)2-ii-b (\bar{u}d)(\bar{e})(\bar{u})(d\bar{e}) (b) (+1, 1) (0, 1) (+2/3, 3) RPV [58–60], L$	O [0= 00]
	Q [00,00]
2-iii-a $(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$ (c) $(+1,8)$ $(0,8)$ $(+2/3,3)$ $(0,1)$ $(+1/3,3)$ RPV [58–60]	
2-III-a $(de)(u)(d)(ue)$ (c) $(-2/3, \overline{3})$ $(0, 1)$ $(+1/3, \overline{3})$ RPV [58-60] $(-2/3, \overline{3})$ $(0, 8)$ $(+1/3, \overline{3})$ RPV [58-60]	
2-iii-b $(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$ $(-2/3, \overline{3})$ $(0, 8)$ $(+1/3, \overline{3})$ $(1/3, \overline{3})$ $(-1/3, \overline{3})$ $(-1/3, \overline{3})$	
$(-2/3, \overline{3})$ $(-1/3, \overline{6})$ $(+1/3, \overline{3})$ $(-1/3, \overline{6})$	
	nd V'
$(+4/3, 6)$ $(+1/3, 6)$ $(-2/3, 6)$ saily with 7_{ρ} and $(+4/3, 6)$ $(-2/3, 6)$	ak a
3-ii $(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$ $(+4/3, \overline{3})$ $(+5/3, 3)$ $(+2, 1)$ only with V_{ρ}	100 my
(+4/3, 6) $(+5/3, 3)$ $(+2, 1)$	a Rexam
3-iii $(dd)(\bar{u})(\bar{e}\bar{e})$ $(+2/3,3)$ $(+4/3,3)$ $(+2,1)$ only with Ω	this
$(+2/3, \overline{6})$ $(+4/3, \overline{3})$ $(+2, 1)$	a look this examp
3-i $(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$ $(+4/3, \overline{3})$ $(+1/3, \overline{3})$ $(-2/3, \overline{3})$ only with V_{ρ} and $(+4/3, \overline{6})$ $(+1/3, \overline{6})$ $(-2/3, \overline{6})$ 3-ii $(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$ $(+4/3, \overline{3})$ $(+5/3, \overline{3})$ $(+2, 1)$ only with V_{ρ} $(+4/3, \overline{6})$ $(+5/3, \overline{3})$ $(+2, 1)$ 3-iii $(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$ $(+2/3, \overline{3})$ $(+4/3, \overline{3})$ $(+2, 1)$ only with V_{ρ} $(+2/3, \overline{6})$ $(+4/3, \overline{3})$ $(+2, 1)$ only with V_{ρ} $(+2/3, \overline{6})$ $(+4/3, \overline{3})$ $(+2, 1)$ only with V_{ρ} 4-i $(d\bar{e})(\bar{u})(d\bar{e})$ (c) $(-2/3, \overline{3})$ $(0, 1)$ $(+2/3, 3)$ $(-2/3, \overline{3})$ $(-2/3,$	
$(-2/3, \overline{3})$ $(0, 8)$ $(+2/3, 3)$ RPV [58–60]	
4-ii-a $(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$ $(+4/3, 3)$ $(+5/3, 3)$ $(+2/3, 3)$ only with V_{ρ}	
(+4/3, 6) $(+5/3, 3)$ $(+2/3, 3)$ see Sec. 4 (this	work)
4-II-D $(uu)(e)(a)(ae)$ $(+4/3, 3)$ $(+1/3, 3)$ $(+2/3, 3)$ 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]	
$(-1/3, 3)$ $(0, 8)$ $(+1/3, \overline{3})$ RPV [58–60]	
5-ii-a $(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$ $(-1/3, 3)$ $(+1/3, \overline{3})$ $(-2/3, \overline{3})$ only with V'_{ρ}	
(-1/3, 3) $(+1/3, 6)$ $(-2/3, 6)$	
5-ii-b $(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$ $(-1/3, 3)$ $(-4/3, 3)$ $(-2/3, \overline{3})$ only with V'_{ρ}	
(-1/3, 3) $(-4/3, 3)$ $(-2/3, 6)$	

Possible decompositions and Necessary mediators

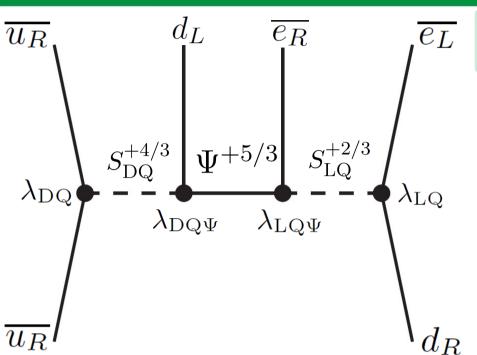
(only Topology #I)

- 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 $(SU(2)_L \text{ and } U(1)_Y)$
 - → Decom of chirality-specified ops Bonnet Hirsch O Winter 1212.3045

contain neutrino propagation

Long Range?Decomposition which can





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

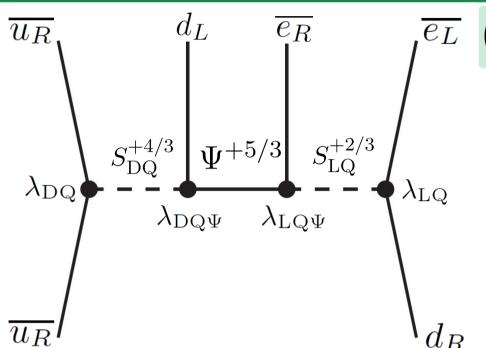
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

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

$$(\Psi_{L})_{Iia} = \left((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia}, \right)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$







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

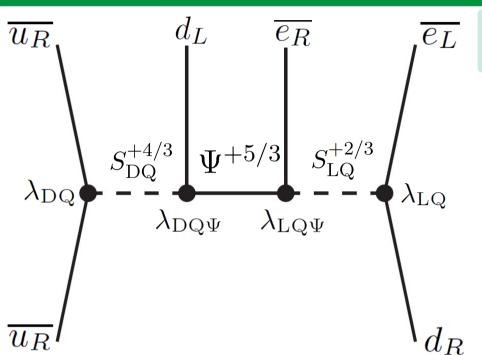
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

$$(S_{\mathrm{LQ}})_{Ii} = ((S_{\mathrm{LQ}}^{+2/3})_{I}, (S_{\mathrm{LQ}}^{-1/3})_{I})^{\mathsf{T}}$$

$$(\Psi_{L})_{Iia} = ((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia},)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

$$= \frac{\lambda_{\mathrm{DQ}}\lambda_{\mathrm{DQ}\Psi}\lambda_{\mathrm{LQ}\Psi}\lambda_{\mathrm{LQ}}}{m_{\mathrm{DQ}}^{2}m_{\mathrm{LQ}}^{2}m_{\Psi}} \left[(\overline{u_{R}})^{I'a} (T_{\overline{\mathbf{6}}})_{I'J'}^{X} (u_{R}^{c})_{a}^{J'} \right] \left[(\overline{d_{L}^{c}})_{I}^{b} (T_{\mathbf{6}})_{X}^{IJ} (e_{R}^{c})_{b} \right] \left[(\overline{e_{L}})_{\dot{c}} (d_{R})_{J}^{\dot{c}} \right]$$





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

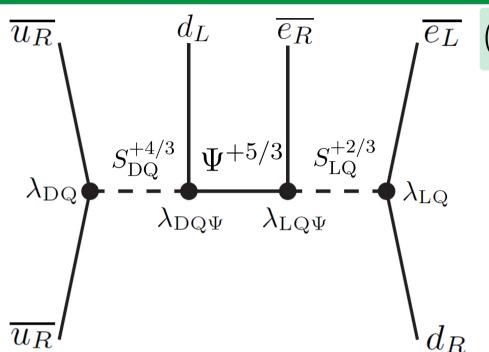
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

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

$$(\Psi_{L})_{Iia} = \left((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia}, \right)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

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





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

$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

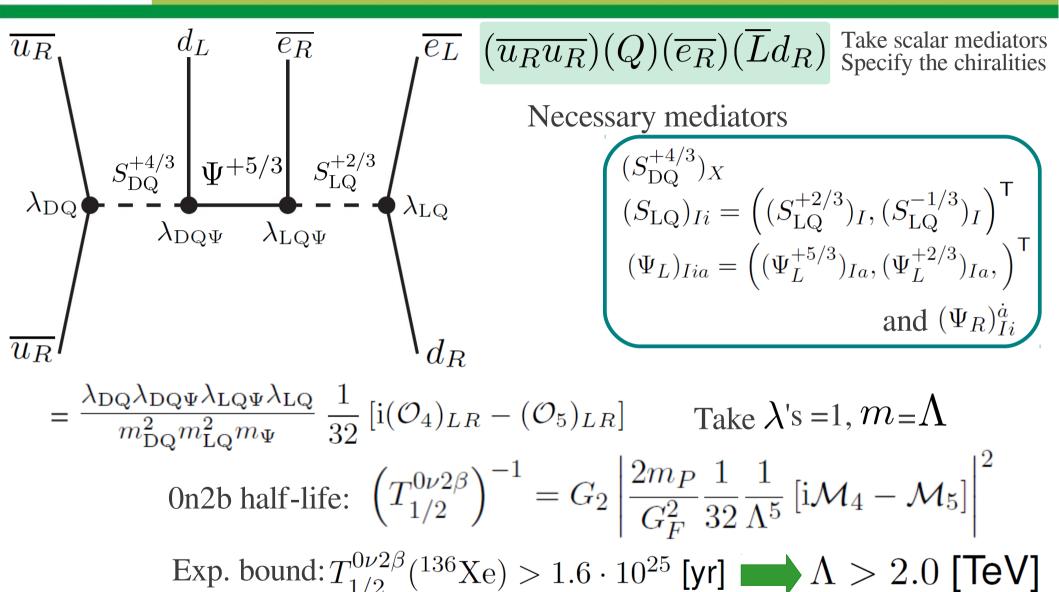
$$(S_{\mathrm{LQ}})_{Ii} = ((S_{\mathrm{LQ}}^{+2/3})_{I}, (S_{\mathrm{LQ}}^{-1/3})_{I})^{\mathsf{T}}$$

$$(\Psi_{L})_{Iia} = ((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia},)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

$$= \frac{\lambda_{\mathrm{DQ}}\lambda_{\mathrm{DQ}\Psi}\lambda_{\mathrm{LQ}\Psi}\lambda_{\mathrm{LQ}}}{m_{\mathrm{DQ}}^{2}m_{\mathrm{LQ}}^{2}m_{\Psi}} \frac{1}{32} \left[\mathrm{i}(\mathcal{O}_{4})_{LR} - (\mathcal{O}_{5})_{LR} \right] \qquad \text{Take } \lambda \text{'s = 1, } m = \Lambda$$

$$0 \text{n2b half-life: } \left(T_{1/2}^{0\nu2\beta} \right)^{-1} = G_{2} \left| \frac{2m_{P}}{G_{F}^{2}} \frac{1}{32} \frac{1}{\Lambda^{5}} \left[\mathrm{i}\mathcal{M}_{4} - \mathcal{M}_{5} \right] \right|^{2}$$



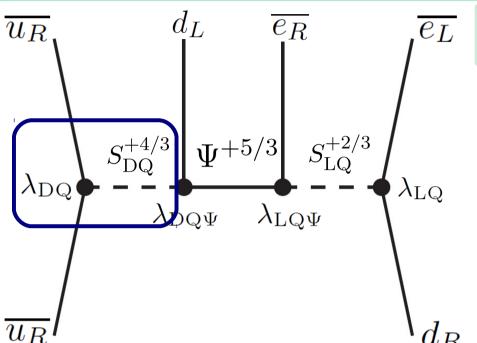


Q: What does this model suggest to LHC observables?









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

Necessary mediators

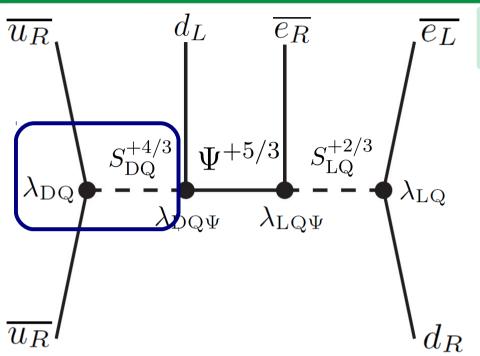
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

$$(S_{\mathrm{LQ}})_{Ii} = ((S_{\mathrm{LQ}}^{+2/3})_{I}, (S_{\mathrm{LQ}}^{-1/3})_{I})^{\mathsf{T}}$$

$$(\Psi_{L})_{Iia} = ((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia},)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

• Diquark (DQ):





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

Take scalar mediators Specify the chiralities

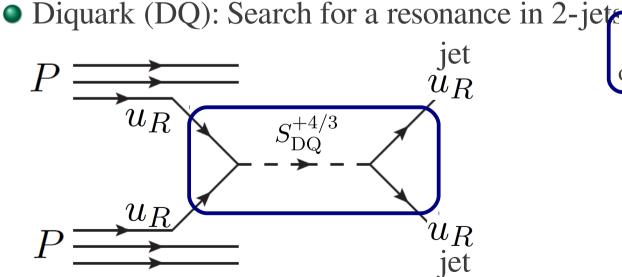
Data

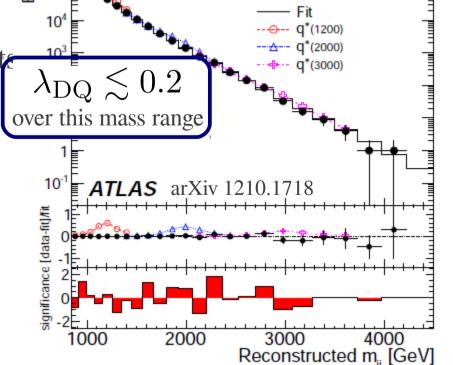
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

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

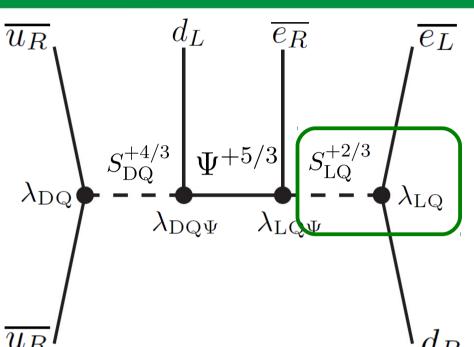
$$(\Psi_{L})_{Iia} = \left((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia}, \right)^{\mathsf{T}}$$

$$\sqrt{s} = 7 \text{ TeV, } \left[L \, dt = 4.8 \text{ fb}^{-1} \right]$$









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

Necessary mediators

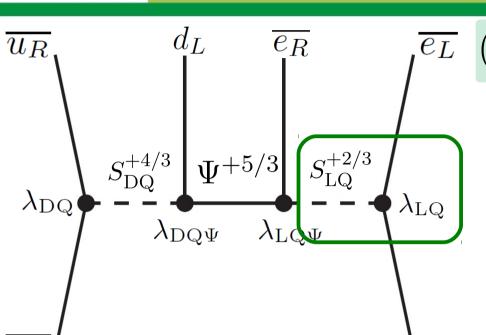
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

$$(S_{\mathrm{LQ}})_{Ii} = ((S_{\mathrm{LQ}}^{+2/3})_{I}, (S_{\mathrm{LQ}}^{-1/3})_{I})^{\mathsf{T}}$$

$$(\Psi_{L})_{Iia} = ((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia},)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

• Leptoquark (LQ):





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

Take scalar mediators Specify the chiralities

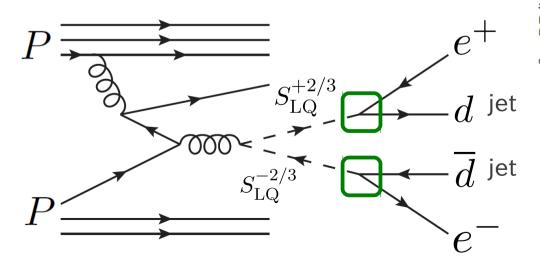
Necessary mediators

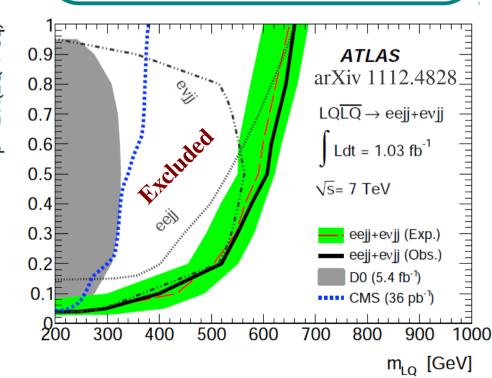
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

$$(S_{\mathrm{LQ}})_{Ii} = ((S_{\mathrm{LQ}}^{+2/3})_{I}, (S_{\mathrm{LQ}}^{-1/3})_{I})^{\mathsf{T}}$$

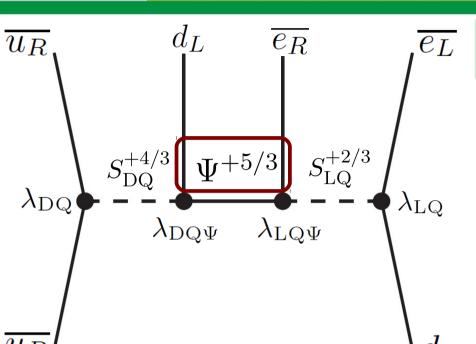
$$(\Psi_{L})_{Iia} = ((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia},)^{\mathsf{T}}$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

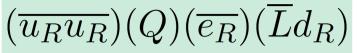
• Leptoquark (LQ): Search for a (eq)-pair











Necessary mediators

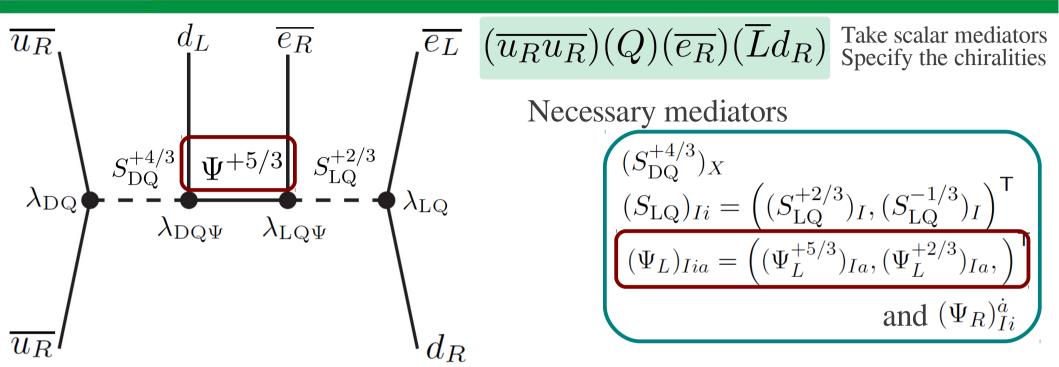
$$(S_{\mathrm{DQ}}^{+4/3})_{X}$$

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

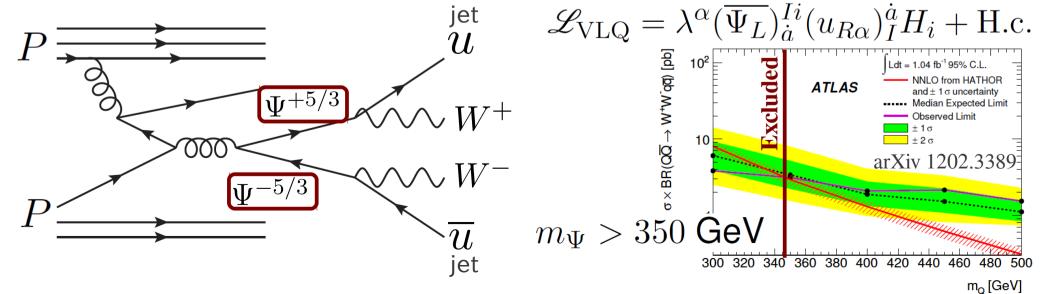
$$(\Psi_{L})_{Iia} = \left((\Psi_{L}^{+5/3})_{Ia}, (\Psi_{L}^{+2/3})_{Ia}, \right)$$
and $(\Psi_{R})_{Ii}^{\dot{a}}$

Vector-like Quark (VLQ):





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





Outline

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

Motivation: Why On2b? Why dim=9 ops?

d=9 ops \rightarrow half-life time of 0n2b processes "How sensitive 0n2b experiments to the d=9 ops?"

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

d=9 ops \rightarrow decompose them to the fundamental ints.

- → list the TeV signatures of each completion
- → The list helps us to discriminate the models

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...

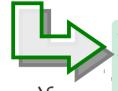
• They have masses of the TeV scale • #L must be violated in somewhere





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



Size of two contributions to 0n2b can be comparable!

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

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



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



Size of two contributions to 0n2b can be comparable!

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

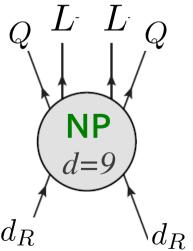
dim=9 $\Lambda_{\rm NP} \sim 1 \text{ TeV}$

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 PLB718 (2013) 1436

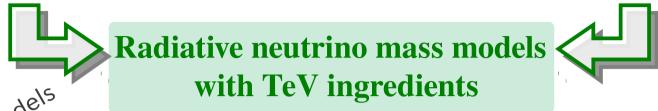
$$\mathcal{O}_{\mathsf{eff}}^{0
u2eta} =$$





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



In such most Size of two contributions to 0n2b can be comparable!

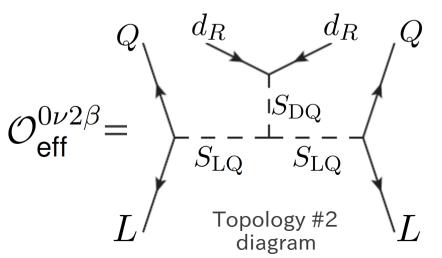
Standard one $m_{\nu} \sim 0.1 \mathrm{eV}$

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

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 PLB718 (2013) 1436





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



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

Standard one

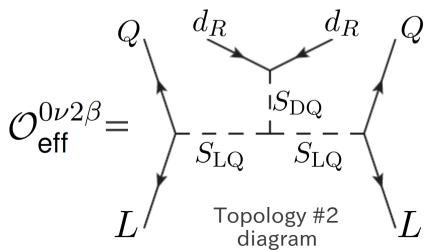
dim=9 m_{ν} ~ 0.1eV $\Lambda_{\rm NP}$ ~1 TeV

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 PLB718 (2013) 1436

$$m_{
u} = L$$
 $Q \mid d_R \mid d_R \mid Q$
 $H_d \mid H_d$



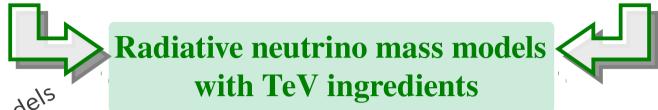


3

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



In such most Size of two contributions to 0n2b can be comparable!

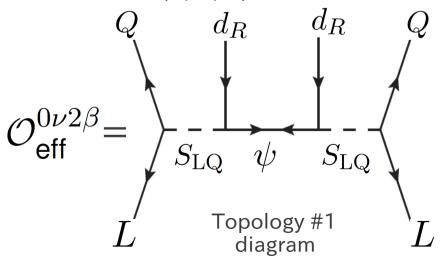
Standard one $m_{\nu} \sim 0.1 \mathrm{eV}$

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

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

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

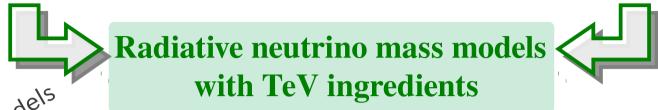
Angel Cai Rodd Schmidt Volkas 1308.0463





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

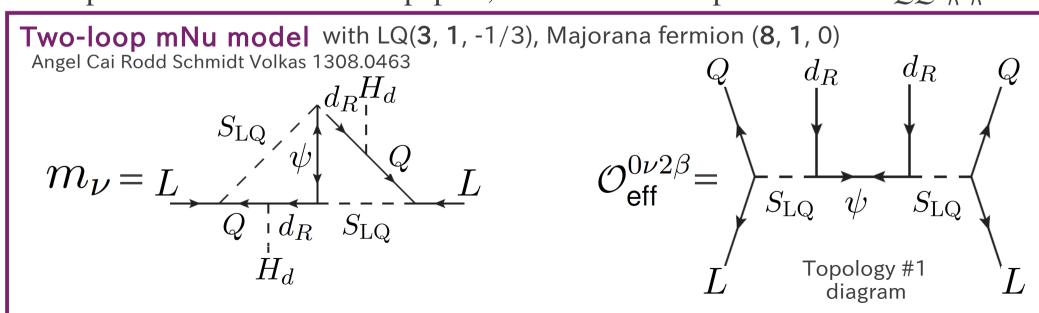


In such mo Size of two contributions to 0n2b can be comparable!

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

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

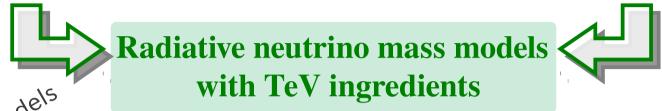
Examples introduced in recent papers, based on Decomposition of $LLQQd_Rd_R$





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



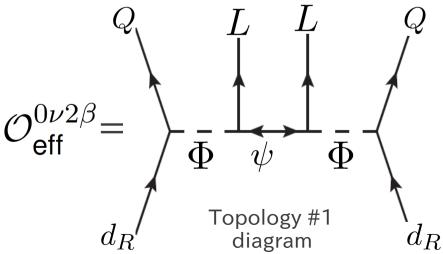
In such models Size of **two contributions** to 0n2b can be comparable!

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



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

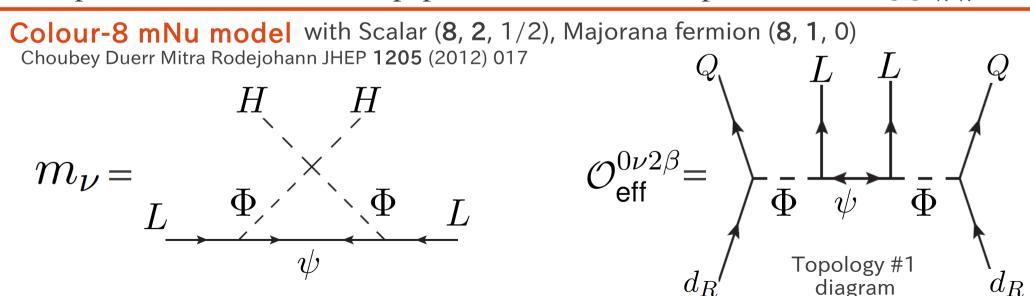


In such "Size of two contributions to 0n2b can be comparable!

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

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

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



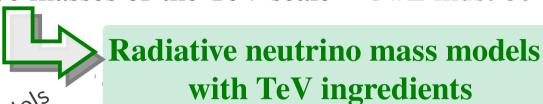
In this case, dim=9 op is not directly proportional to $m_
u$

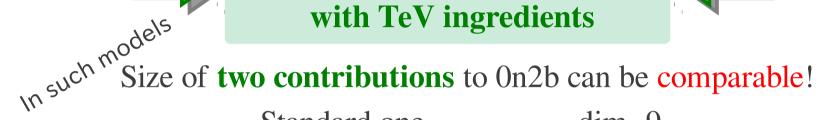




Maybe, we have already known the mediators appear in the big table...

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





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

$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	-60], 39], _S [61]
1-i $(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$ (a) $(+1,1)$ (0,1) $(-1,1)$ Mass mechan., RPV [58-LR-symmetric models [3] Mass mechanism with ν_{S} TeV scale seesaw, e.g., [6] 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) (+1,8) (+4/3,3) (+2,1) (+1,8) (+4/3,3) (+2,1) (+1,8) (+4/3,3) (+2,1) (+1,8) (+4/3,3) (+2,1) (+1,8) (+4/3,3) (+1/3,3)	-60], 39], _S [61]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	s [61]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	62,63
1-ii-a $(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$ $(+1,1)$ $(+5/3,3)$ $(+2,1)$ $(+1,8)$ $(+5/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+2,1)$ $(+1,8)$ $(+4/3,3)$ $(+1$]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	
2-i-a $(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$ $(+1,1)$ $(+4/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1,1)$ $(0,1)$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1,8)$ $(0,8)$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1/3,\overline{3})$ $(-1/3,\overline{3})$ $(-1/3,\overline{3})$ $(-1/3,\overline{3})$ RPV [58–60] $(-1/3,\overline{3})$ $(-1/3,\overline{3})$ RPV [58–60]	
2-i-b $(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$ (b) $(+1,8)$ $(+4/3,\overline{3})$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1,8)$ $(0,8)$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1,8)$ $(0,8)$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65, 66] $(+1,8)$ $(-1,8)$ RPV [58–60] $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ $(-1,8)$ RPV [58–60]	
2-i-b $(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$ (b) $(+1,1)$ $(0,1)$ $(+1/3,\overline{3})$ RPV [58–60], LQ [65,66] $(+1,8)$ $(0,8)$ $(+1/3,\overline{3})$ $(+1/3,\overline{3})$ 2-ii-a $(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$ $(+1,1)$ $(+5/3,3)$ $(+2/3,3)$ $(+1,8)$ $(+5/3,3)$ $(+2/3,3)$ $(+1,8)$ $(+1,1)$ $(-1/3,3)$ RPV [58–60], LQ [65,66] $(+1,1)$ $(-1/3,3)$ RPV [58–60], LQ [65,66] $(+1,8)$ $(-1/3,3)$ $(-1/3,3)$ RPV [58–60]	
2-ii-a $(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$ (+1,8) (0,8) (+1/3, $\overline{3}$) (+2/3,3) (+1,1) (+5/3,3) (+2/3,3) (+1,8) (+5/3,3) (+2/3,3) (+1,8) (0,1) (+2/3,3) RPV [58–60], LQ [65,66] (+1,8) (0,8) (+2/3,3) (+1/3) (0,8) (+2/3,3) (-2/3, $\overline{3}$) (0,1) (+1/3, $\overline{3}$) RPV [58–60]	9]
2-ii-a $(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$ $(+1,1)$ $(+5/3,3)$ $(+2/3,3)$ $(+1,8)$ $(+5/3,3)$ $(+2/3,3)$ $(+1,8)$ $(+5/3,3)$ $(+2/3,3)$ 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-ii-b $(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$ (b) $(+1,8)$ $(+5/3,3)$ $(+2/3,3)$ RPV [58–60], LQ [65, 66] $(+1,1)$ $(0,1)$ $(+2/3,3)$ RPV [58–60], LQ [65, 66] 2-iii-a $(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$ (c) $(-2/3,\overline{3})$ $(0,1)$ $(+1/3,\overline{3})$ RPV [58–60]	
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) $(-2/3,\overline{3})$ $(0,1)$ $(+1/3,\overline{3})$ RPV [58–60]	
2-iii-a $(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$ (c) $(-2/3, \overline{\bf 3})$ $(0, \bf 8)$ $(+2/3, \bf 3)$ $(0, \bf 1)$ $(+1/3, \overline{\bf 3})$ RPV [58–60]	3]
2-iii-a $(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$ (c) $(-2/3, \overline{3})$ $(0, 1)$ $(+1/3, \overline{3})$ RPV [58–60]	1
2-iii-b $(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$ $(-2/3, 3)$ $(-1/3, 3)$ $(+1/3, 3)$	
$(-2/3, \overline{\bf 3})$ $(-1/3, \overline{\bf 6})$ $(+1/3, \overline{\bf 3})$	
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 $(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$ $(+4/3, \overline{\bf 3})$ $(+5/3, \bf 3)$ $(+2, \bf 1)$ only with V_{ρ}	
(+4/3, 6) $(+5/3, 3)$ $(+2, 1)$	
3-iii $(dd)(\bar{u})(\bar{e}\bar{e})$ $(+2/3, 3)$ $(+4/3, 3)$ $(+2, 1)$ only with V_{ρ}	
$(+2/3, \overline{6})$ $(+4/3, \overline{3})$ $(+2, 1)$	
4-i $(d\bar{e})(\bar{u})(d\bar{e})$ (c) $(-2/3, \overline{3})$ $(0, 1)$ $(+2/3, 3)$ RPV [58–60]	
$(-2/3, \overline{3})$ $(0, 8)$ $(+2/3, 3)$ RPV [58–60]	
4-ii-a $(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$ $(+4/3, \overline{3})$ $(+5/3, 3)$ $(+2/3, 3)$ only with V_{ρ}	
(+4/3,6) $(+5/3,3)$ $(+2/3,3)$ see Sec. 4 (this work)	
4-ii-b $(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$ $(+4/3, \overline{3})$ $(+1/3, \overline{3})$ $(+2/3, 3)$ 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) $(0, 1)$ $(+1/3, 3)$ RPV [58–60] $(-1/3, 3)$ $(0, 8)$ $(+1/3, 3)$ RPV [58–60]	
5-ii-a $(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$ $(-1/3, 3)$ $(0, 8)$ $(+1/3, 3)$ RFV [38-60] $(-1/3, 3)$ $(-1/3, 3)$ $(-1/3, 3)$ only with V_o	
$(-1/3, 3)$ $(+1/3, 6)$ $(-2/3, 6)$ only with \mathbf{v}_{ρ} $(-1/3, 3)$ $(+1/3, 6)$ $(-2/3, 6)$	
5-ii-b $(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$ $(-1/3, 3)$ $(-4/3, 3)$ $(-2/3, \overline{3})$ only with V_o'	
$(-1/3, 3)$ $(-4/3, 3)$ $(-2/3, 6)$ only with \mathbf{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



Summary

		Long	Mediat	tor $(U(1)_{em},$	SU(3))		
#	Decomposition	Range?	S or V_{ρ}	ψ	S' or V'_{a}	Models/Refs./Comments	V
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]	
		7	<u> </u>			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)		
4 1	(= D (D (=) (==)		(+1.8)	(+5/3, 3)	(+2, 1)		_
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		(+1,1) (+1,8)	$(+4/3. \overline{3})$ $(+4/3. \overline{3})$	(+2, 1)	2	1
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		(+1, 1)	(+4/3, 3)	(+2, 1) (+1/3, 3)	<u> </u>	_
2-1-4	(uu)(u)(e)(ue)		(+1, 1)	(+4/3, 3)	(+1/3, 3)		
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	$(\pm 1/3.3)$	RPV [58–60], LQ [65, 66]	
	(/(-/(-/	(-)	(+1, 8)	(0, 8)	(±1/3 3)	[]	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	•	(+1, 1)	(+5/3, 3)	(±2/2, 2)		
			(+1.8)	$(\pm 5/3, 3)$	(+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)		
0 1	(I=\		(-2/3.3)	(0.8)	$(\pm 1/3.3)$	RPV [58–60]	
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3.3)	(-1/3,3)	$(\pm 1/3.3)$		
3-i	(āā)(ā)(ā)(dd)		(-2/3,3)	(-1/3, 6)	(+1/3, 3)	only with V_{ρ} and V'_{ρ}	_
9-1	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(\pm 4/3, 3)$	(+1/3, 3) (+1/3, 6)	(-2/3, 3) (-2/3, 6)	only with v_{ρ} and v_{ρ}	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		(+4/3, 6) (+4/3, 3)	(+5/3, 3)	(+2,1)	only with V_{ρ}	
0.11	(44)(4)(4)(66)		(+4/3, 6)	(+5/3, 3)	(+2,1)	υπή πτα τ _ρ	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(\pm 2/3.3)$	(+4/3, 3)	(+2, 1)	only with V_{ρ}	
			(±2/3 6	(±4/3 3)	(+2, 1)	,	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3, 3)	(0, 1)	$(\pm 2/3, 3)$	RPV [58–60]	_
			$(-2/3, \overline{3})$	(0.8)	(+2/3, 3)	RPV [58–60]	
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		(+4/3 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, 3)	(+2/3, 3)	only with V_{ρ}	
F :	/==\/J\/J\/==\	(-)	(+4/3.6)	(+1/3.6)	(+2/3.3)	DDV (50.00)	_
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	(-1/3,3)	(0, 1)	$(\pm 1/3, 3)$	RPV [58–60]	
5-ii-a	(\$\bar{a}\)(\$\bar{a}\)(\$\bar{a}\)(\$\bar{a}\)(\$\bar{a}\)(\$\bar{a}\)(\$\bar{a}\)		(-1/3,3) (-1/3,3)	(0, 8) (+1/3, 3)	(+1/3, 3) (-2/3, 3)	RPV [58–60] only with V'_{ρ}	
9-II-8	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3.3)	$(\pm 1/3.3)$	(-2/3, 3)	omy with v _p	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		(_1/9_9	(-4/3, 3)	(-2/3, 3)	only with V'_{ρ}	
0-11-17	(ac)(c)(a)(aa)		(-1/3, 3)	(-4/3, 3)	(-2/3, 6)	omy with v _p	
							_

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.						
		Long	Mediat	or $(U(1)_{em})$	$SU(3)_c$)		
#	Decomposition	Range?	S or V_{ρ}	ψ	S' or V'_{o}	Models/Refs./Comments	И
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)	$(\pm 5/3, 3)$	(+2, 1)		
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		(+1, 1)	$(\pm 4/3, 3)$	(+2, 1)		It
			(+1.8)	(+4/3, 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, 3)	(+1/3, 3)		
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	(+1/3.3)	RPV [58–60], LQ [65, 66]	
	(- D(-)(-)(-)		(+1, 8)	(0, 8)	(±1/3 3)		
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 1)	(+5/3, 3)	(+9/3, 9)		
0.11	(= I) (=) (=) (I=)	(1.)	(+1.8)	(+5/3,3)	$(\pm 2/3, 3)$	DD1 (50 00) 10 (05 00)	
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]	
0	(J=\/=\/J\/==\	(-)	(+1,8)	(0, 8)	(+2/3, 3)	DDV [50 60]	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	(-2/3,3) (-2/3,3)	(0, 1) (0, 8)	(+1/3, 3)	RPV [58–60] RPV [58–60]	
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3.3)	(-1/3, 3)	$(\pm 1/3.3)$ $(\pm 1/3.3)$	KP v [58-60]	
2-111-13	(ae)(a)(a)(ae)		(-2/3, 3)	(-1/3, 6)	+1/3, 3)		
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$					only with V_{ρ} and V'_{ρ}	_
0-1	(uu)(e)(e)(uu)		(+4/3, 3) (+4/3, 6)	(+1/3, 3) (+1/3, 6)	(-2/3, 3) (-2/3, 6)	only with v_{ρ} and v_{ρ}	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		(+4/3,3)	(+5/3, 3)	(+2,1)	only with V_{ρ}	
0-II	(44)(4)(4)(44)		(+4/3, 6)	(+5/3, 3)	(+2, 1)	only with vp	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		(+2/3.3)	$(\pm 4/3, 3)$	(+2, 1)	only with V_{ρ}	
	(44)(4)(4)(44)		(±2/3 6	(±4/3 3)	(+2, 1)	, , ρ	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3,3)	(0, 1)	(+2/3, 3)	RPV [58-60]	_
	()(-)(-)	(-)	(-2/3, 3)	(0, 8)	$(\pm 2/3, 3)$	RPV [58–60]	
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(\pm 4/3.9)$	$(\pm 5/3.3)$	$(\pm 2/3.3)$	only with V_{ρ}	
	(// // /		(±4/2 6	(45/2 9)	(±2/2 Q)	see Sec. 4 (this work)	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(\pm 4/3, 3)$	(+1/3, 3)	(+2/3, 3)	only with V_{ρ}	
			(+4/3.6)	$(\pm 1/3.6)$	$(\pm 2/3.3)$		
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	(-1/3, 3)	(0, 1)	(+1/3, 3)	RPV [58–60]	_
			(-1/3, 3)	(0, 8)	(+1/3, 3)	RPV [58-60]	
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3.3)	(+1/3, 3)	$(-2/3, \overline{3})$	only with V'_{ρ}	
			(_1/3_9	$(\pm 1/3, 6)$	(-2/3, 6)	•	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		(-1/2, 9)	(-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

It could be a large d=9 contribution

cosmological obs.,

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!





	The state of the s						
		Long	Mediat	or $(U(1)_{em})$	$SU(3)_c$)		
#	Decomposition	Range?	S or V_{ρ}	ψ	S' or V'_{ρ}	Models/Refs./Comments	W
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)		
	(- D(D(-) ()		(+1.8)	(+5/3, 3)	(+2, 1)		T .
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		(+1,1) (+1,8)	$(+4/3.\overline{3})$	(+2, 1)		It
9: -	/::J\/J\/:\/::\			(+4/3.3)	(+2,1)		
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		(+1, 1) (+1, 8)	(+4/3, 3) (+4/3, 3)	(+1/3,3) (+1/3,3)		
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	$(\pm 1/3, 3)$	RPV [58-60], LQ [65, 66]	
2-1-0	(44)(c)(4)(4c)	(1)	(+1, 1) $(+1, 8)$	(0, 1)	(±1/3 3)	11 1 [55-55], 110 [55,55]	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	'	(+1, 1)	(+5/3,3)	(19/9 9)		
	(/(-/(-/		(+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]	
			(-2/3.3)	(0.8)	$(\pm 1/3.3)$	RPV [58–60]	
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3.3)	(-1/3,3)	$(\pm 1/3.3)$		
			(-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}'	
0 "	()(n(n()		(+4/3, 6)	(+1/3, 6)	(-2/3, 6)	1141. 17	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		(+4/3, 3)	(+5/3, 3)	(+2,1)	only with V_{ρ}	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		(+4/3, 6) (+2/3, 3)	(+5/3, 3) (+4/3, 3)	(+2, 1) (+2, 1)	only with V_{ρ}	
3-III	(aa)(a)(a)(ee)		(±2/3 6	$(\pm 4/3, 3)$	(+2, 1) (+2, 1)	only with Vp	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3,3)	(0, 1)	(+2,1)	RPV [58-60]	_
	(ac)(a)(a)(ac)	(0)	(-2/3, 3)	(0, 8)	(+2/3, 3)		
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(\pm 4/3.9)$	$(\pm 5/3.3)$	(±2/3 3)	only with V_{ρ}	
			(+4/3, 6	(+5/2,2)	(±2/2, 2)	see Sec. 4 (this work)	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		(+4/3, 3)	$(+1/3, \overline{3})$	(+2/3, 3)		
			(+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)		_
			(-1/3,3)	(0, 8)	(+1/3, 3)	RPV [58–60]	
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3,3)	$(+1/3, \overline{3})$	$(-2/3, \overline{3})$	only with V'_{ρ}	
	/> /> /> /> />		(-1/3.9)	$(\pm 1/3, 6)$	(-2/3, 6)		
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		(-1/2, 9)	(-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!

My last message:

On2b exps, cosmological obs, LHC and ILC are complementary!



Back up slides

Neutrino mass bound from cosmological observations

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



Why 0n2b? Why d=9 op.?

Effective neutrino mass

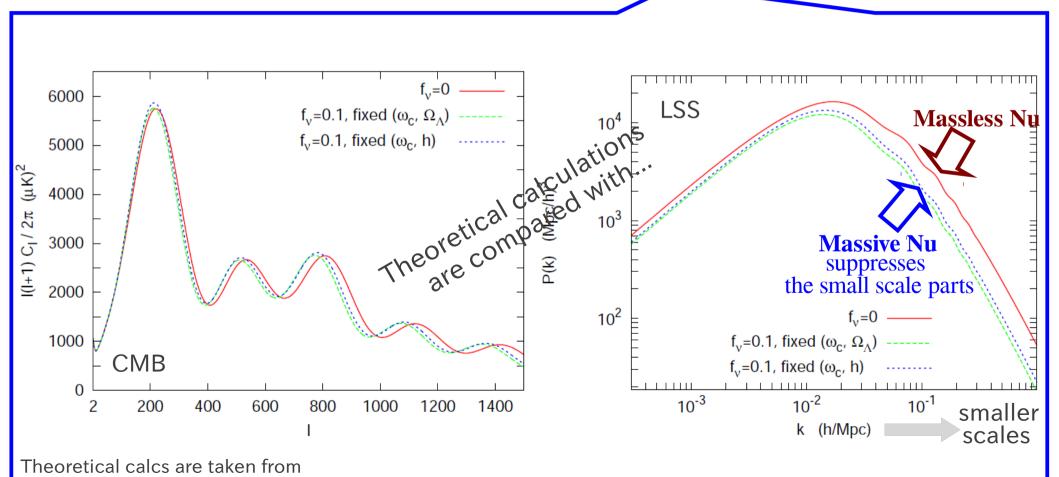
On2b exp are sensitive to
 Effective nu mass

Phys.Rep **429** (2006) 307 Lesgourgues and Pastor

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

Cosmological obs constrain Sum of nu masses

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







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

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

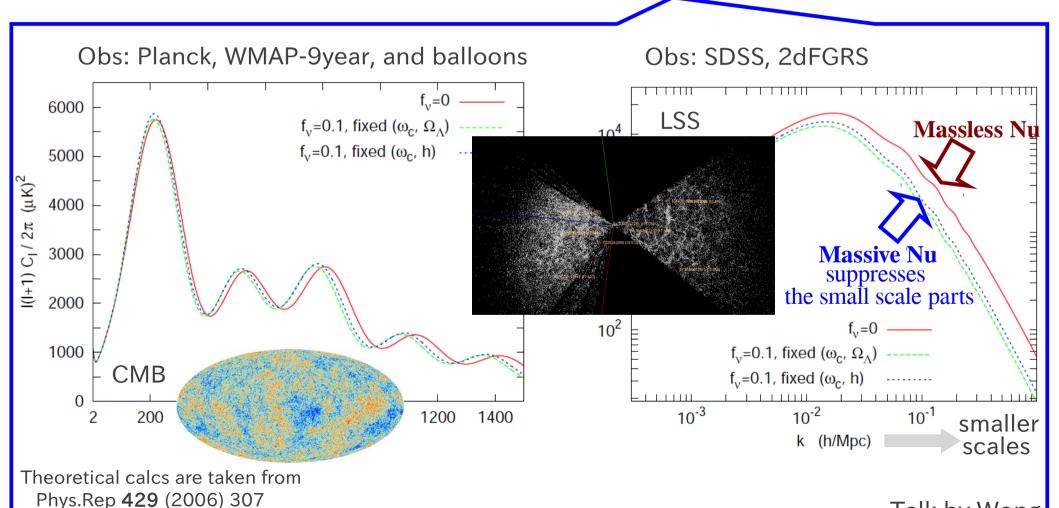
Lesgourgues and Pastor

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

Cosmological obs constrain Sum of nu masses

 $\sum m_i (\simeq 3m_0 \text{ if } m_0 \gtrsim 0.1 \text{ eV})$

Talk by Wong

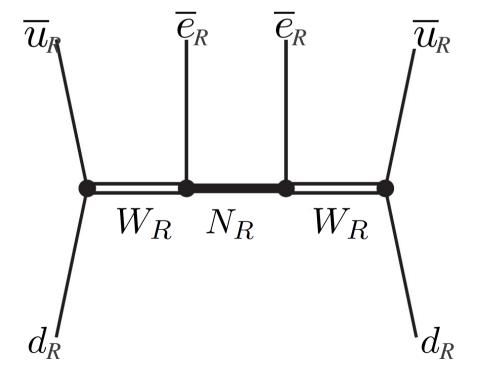




An example,

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

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



Necessary mediators

$$egin{array}{lll} V(+1,\mathbf{1}) & W_R \ V'(-1,\mathbf{1}) & W_R \ \psi(0,\mathbf{1}) & N_R \end{array}$$

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

Left-right symmetric model

All the outer fermions are right-handed

Bound from 0n2b

Riazuddin Marshak Mohapatra PRD24 (1981) 1310

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

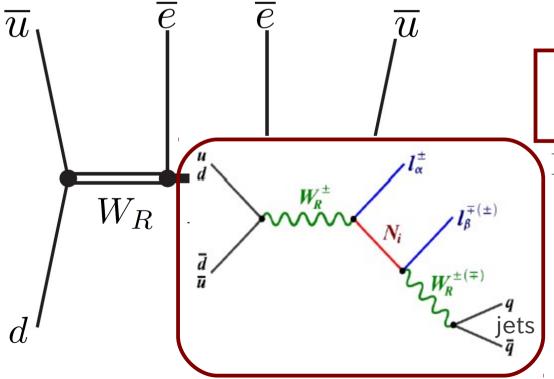




An example,

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

Left-right symmetric model

All the outer fermions are right-handed

Bound from 0n2b

Riazuddin Marshak Mohapatra PR**D24** (1981) 1310

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

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