Neutrino 2014
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Poster-ID 61, OTA

Systematic decomposition of the neutrinoless double beta decay operator

Abstract

If there were a tension between different measurements of neutrino mass (such as coming from neutrinoless double beta decay, cosmology, oscillation, and single beta decay), the contribution from a $d = 9$ (six-fermion) effective operator to the neutrinoless double beta decay process would gain particular importance. We first provide a complete list of tree-level diagrams for the $d = 9$ operators. It is interesting to point out that a typical energy scale of new physics, which is explored by the next generation neutrinoless double beta decay experiments, is $\mathcal{O}(1)$ TeV, which is now intensively investigated by the LHC. With the help of our complete list, one can systematically scan the possible high-energy theories associated with new physics beyond the standard neutrino model.

Based on
JHEP **1303** (2013) 055, e-Print: arXiv:1212.3045 [hep-ph],
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科研費 KAKENHI
Grant-in-Aid for Scientific Research

Effective operators

If the standard model is an effective model of a fundamental theory that is realised at a high-energy scale, the full Lagrangian $\mathscr{L}_{\rm eff}$ at the low-energy scales should be described by the standard-model Lagrangian $\mathscr{L}_{\rm SM}$ plus a series of effective interactions $\mathcal{O}_d$ that are suppressed by some new-physics scale $\Lambda_{\rm NP}$, where d is the mass dimension of the operators ($d > 4$):

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

The effective operators $\mathcal{O}_d$ consist of the standard-model fields and are expected to be invariant under the transformation of the standard-model gauge symmetries.

Effective operators are a typical low-energy remnant of new physics at high-energy scales.

$d = 9$ op. $\to$ $0\nu2\beta$ process

The $d = 9$ operators $\mathcal{O}_{d=9} \in \{\mathcal{O}_i\}$, which are relevant to neutrinoless double beta decay ($0\nu2\beta$) process, can be parameterised as

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

where ϵ_i is the dimensionless coefficients of the operator $\mathcal{O}_i$. Each $\mathcal{O}_i$ consists of three fermion currents JJj:

$$\mathcal{O}_1 = J_X J_Y j_Z, \quad \mathcal{O}_2 = (J_X)^{\mu\nu}(J_Y)_{\mu\nu}j_Z, \quad \mathcal{O}_3 = (J_X)^{\mu}(J_Y)_{\mu}j_Z,$$
$$\mathcal{O}_4 = (J_X)^{\mu\nu}(J_Y)_{\mu}(j)_{\nu}, \quad \mathcal{O}_5 = J_X(J_Y)^{\mu}(j)_{\mu}.$$

The currents are defined as $J_{L/R} \equiv \overline{u}\Gamma(1 \mp \gamma^5)d$, and $j_{L/R} \equiv \overline{e}\Gamma(1 \mp \gamma^5)e^c$ (Note $j^\mu = (j_R)_\mu = -(j_L)_\mu$). The index i specifies the Lorenz structures $\Gamma \in \{1, \gamma^\mu\sigma^{\mu\nu}\}$, and X, Y, Z represents the chirality of the current. There is a compact formula to calculate the half-life of $0\nu2\beta$ process triggered by $\mathcal{O}_i$'s [3]:

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

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

where G_i's are the kinematical factors (calculable), and $\mathcal{M}_i$'s are the nuclear matrix elements (given).

$0\nu2\beta$ vs Cosmology

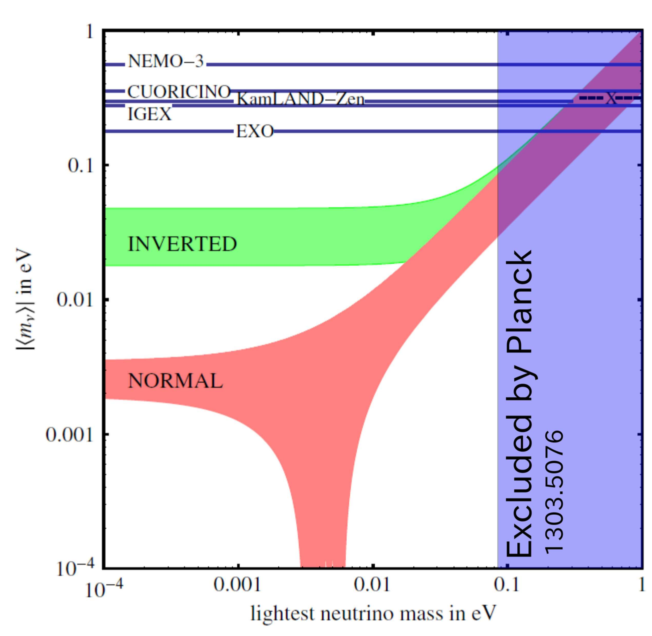


Fig. 1 Allowed parameter regions in the standard three-generation neutrino scenario; (Red) Normal mass hierarchy and (Green) Inverted mass hierarchy [1] ([2] for updates of the $0\nu2\beta$ experiments). Neutrinoless double beta decay experiments are sensitive to the effective neutrino mass $\langle m_\nu\rangle$. On the other hand, the cosmological observations constrain the sum of neutrino masses. Long baseline oscillation experiments are expected to determine the type of mass hierarchy.

If, in future, the combination of these experimental results will make a conflict with the standard scenario of neutrino, how can we interpret the results? what kind of beyond the standard neutrino model is required? and what can we learn from the conflict on new physics at high-energy scales?

Exhaustive Bottom-up approach

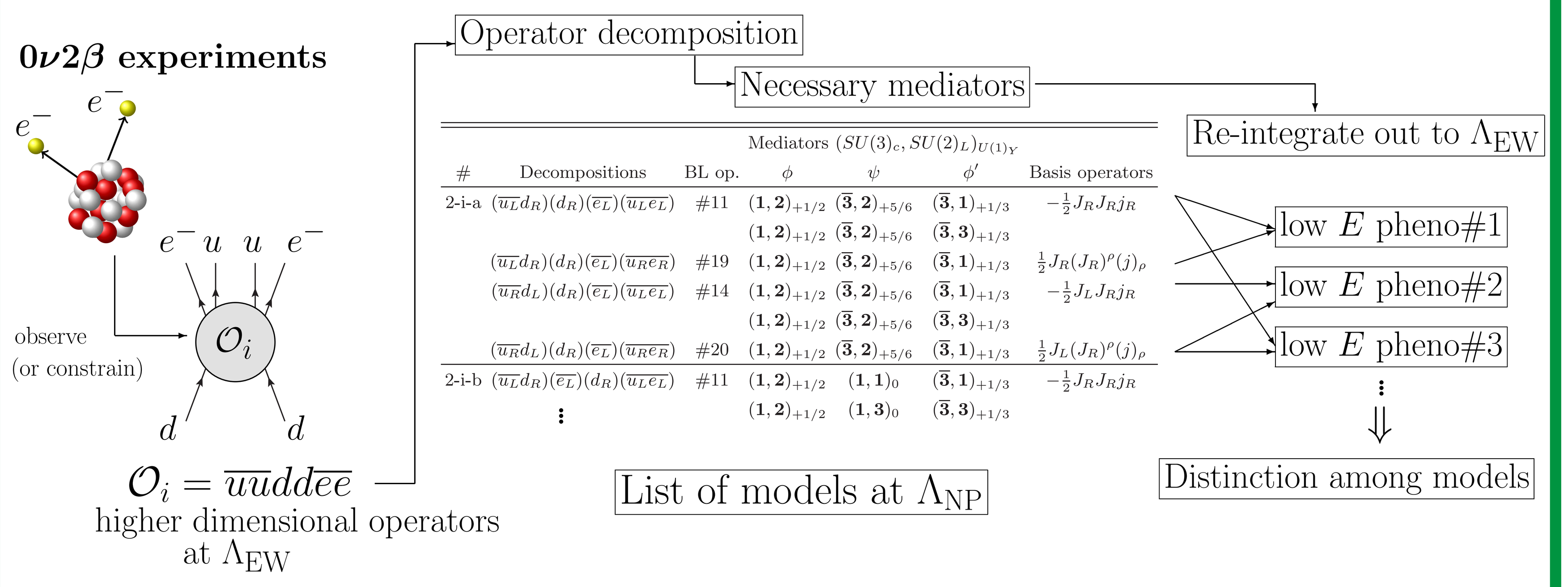


Fig. 2 Schematic explanation of the exhaustive bottom-up approach.

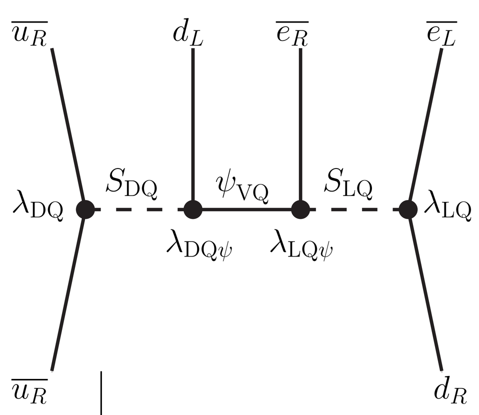
The $d = 9$ operators $\mathcal{O}_i$ are **decomposed** to all the possible tree-level diagrams. Each row in the table corresponds to a high-energy model. After the **mediators** are **integrated out again**, each model results in the different low-energy effective theories, which bring different phenomenological consequences.

Complementarity between $0\nu2\beta$ and LHC

#	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 [4,5] LR-symmetric models [6] Mass mechanism with ν_S [7] TeV scale seesaw, e.g. [8,9],
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	Colour-$\mathbf{8}$ m_ν model [10]
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 [4,5], LQ [11]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
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 [4,5], LQ [11]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
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 [4,5]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [4,5]
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 [4,5]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [4,5]
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 the right side of this section**
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 [4,5]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [4,5]
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
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

Tab. 1 Decompositions of the $d = 9$ operators and the necessary mediators for the boson-fermion-boson type tree-level diagrams.

An example of decomposition (4-ii-a with scalars)

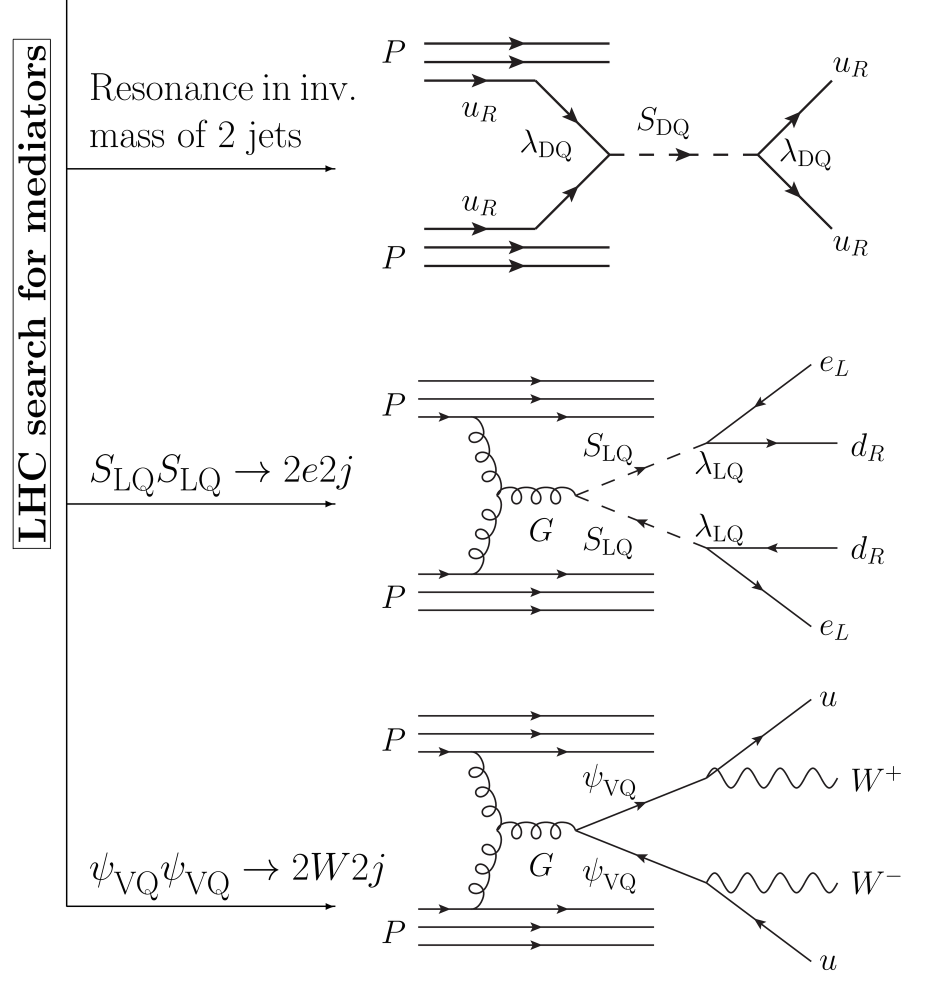


$0\nu2\beta$ **contribution** The left diagram is evaluated as

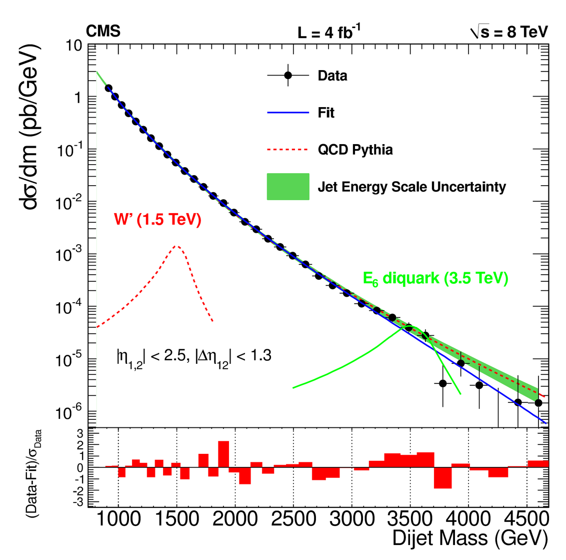
$$\mathcal{M} = \frac{\lambda_{\rm DQ}\lambda_{\rm DQ\psi}\lambda_{\rm LQ\psi}\lambda_{\rm LQ}}{M^2_{\rm DQ}M_{\rm VQ}M^2_{\rm LQ}}\frac{1}{32}\left[{\rm i}(\mathcal{O}_4)_{LR} - (\mathcal{O}_5)_{\rm LR}\right].$$

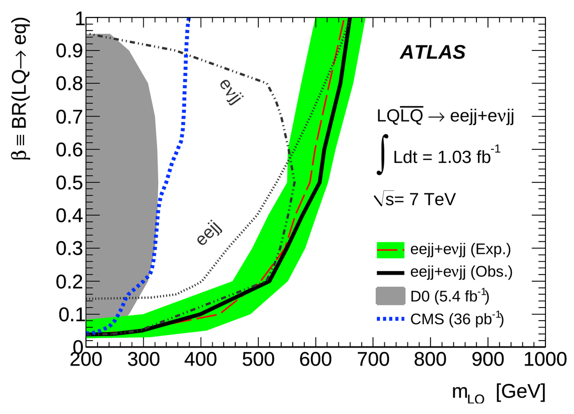
The half-life $T_{1/2}^{0\nu2\beta}$ of $0\nu2\beta$ process induced by this diagram can be calculated with the formula shown above. In the simplified limit (all the masses of the mediators take an identical value Λ, and all the couplings are set to be unity) the current experimental bound to the half-life places the limit on Λ at $\Lambda \gtrsim 2.0$ TeV.

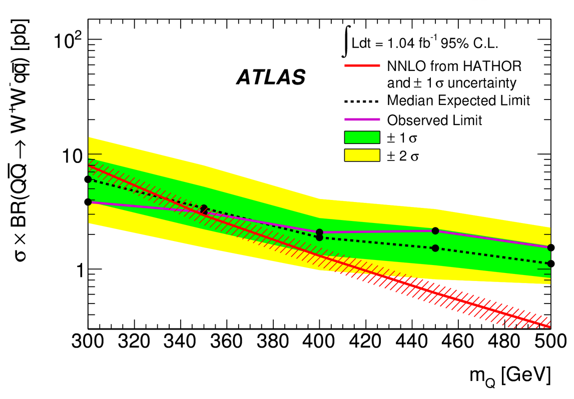
Mediators: $(SU(3)_c, SU(2)_L)_{U(1)_Y}$
Diquark: $S_{\rm DQ}(\mathbf{6},\mathbf{1})_{+4/3}$
Leptoquark: $S_{\rm LQ}(\mathbf{3},\mathbf{2})_{+1/6}$
Vector-like Quark: $\psi_{\rm VQ}(\mathbf{3},\mathbf{2})_{+7/6}$



$$\mathscr{L}_{\rm VQ} = y_{\rm VQ}(\overline{\psi_{\rm VQ}})^{Ii}_{\dot{a}}(u_R)^{\dot{a}}_I H_i + \text{H.c.}$$







Diquark coupling:
$\lambda_{\rm DQ} \lesssim \mathcal{O}(0.1)$
over the whole mass range explored.
1302.4794

This strong bound to colour **6** mediators reduces a number of possibilities.

1st gen. leptoquark:
$M_{\rm LQ} > 660$ GeV
ATLAS $\sqrt{s} = 7$ TeV, $\mathcal{L} = 1$ fb^{-1}
1112.4828

$M_{\rm LQ} > 830$ GeV
CMS $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb^{-1}
1207.5406

Vector-like quarks:
$M_{\rm VQ} > 350$ GeV
(Pair-production) 1202.3389
$M_{\rm VQ} > 900$ GeV
($q\psi_{\rm VQ}$-production) 1112.5755
ATLAS $\sqrt{s} = 7$ TeV, $\mathcal{L} = 1$ fb^{-1}

Work in progress

LNV interactions that appear in the decomposition of $d = 9$ operators may be the origin of neutrino Majorana mass. We are studying the relation between **Decompositions** and **Radiative neutrino mass models**. If neutrino mass measurements would require new physics beyond the standard neutrino physics, the relation should be an important clue to understand the fundamental theory of neutrinos. See e.g., [10,12-16].

References [1] Barea et al., PRL **109** (2012) 042501, [2] EXO-200 PRL **109** (2012) 032505, KamLAND-ZEN PRL **110** (2013) 062502, GERDA PRL **111** (2013) 122503, [3] Päs et al., PL **B498** (2001) 35, [4] Mohapatra, PR **D34** (1986) 3457, [5] Hirsch et al., PRL **75** (1995) 17, PR **D53** (1996) 1329, [6] Riazuddin et al., PR **D24** (1981) 1310, [7] Goswami Rodejohann, PR **D73** (2006) 113003, [8] Blannow et al., JHEP **1007** (2010) 096, [9] Ibarra et al., JHEP **1009** (2010) 108, [10] Choubey et al., JHEP **1205** (2012) 017, [11] Hirsch et al., PL **B378** (1996) 17, PR **D54** (1996) 4207, [12] Babu Leung, NP **B619** (2001) 667, [13] de Gouvea Jenkins, PR **D77** (2008) 013008, [14] Angel et al., PR **D87** (2013) 073007, [15] Angel et al., JHEP **1310** (2013) 118, [16] Kohda et al., PL **B718** (2013) 1436.

Acknowledgements: This work is partly supported by Japan Society for the Promotion of Science KAKENHI (Grant-in-Aid for Scientific Research) on Innovative Areas *"Neutrino Frontier"* (Number 2610 5503).