Complementary LHC searches for UV resonances of $0\nu\beta\beta$ decay operators

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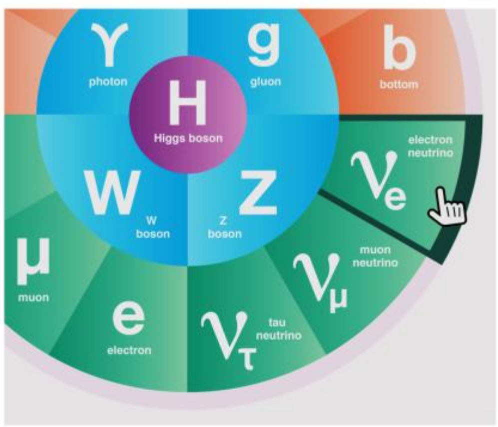
Neutrinos & neutrino physics

- Neutrinos are the most mysterious particles in the SM
- Open questions in neutrino physics

- **Normal or Inverted (sign of Δm^2_{31}?)**
- **Leptonic CP Violation (δ = ?)**
- **Octant of θ_{23} (> or < 45°?)**
- **Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)**
- **Majorana or Dirac Nature ($\nu=\nu^C$?)**
- **Majorana CP-Violating Phases (how?)**



- **Extra Neutrino Species**
- **Exotic Neutrino Interactions**
- **Various LNV & LFV Processes**
- **Leptonic Unitarity Violation**

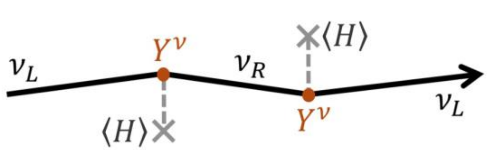
- **Origin of Neutrino Masses**
- **Flavor Structure (Symmetry?)**
- **Quark-Lepton Connection**
- **Relations to DM and/or BAU**

credit: Shun Zhou

Majorana neutrinos

- Mass origin and Majorana nature
  - **How do neutrinos get their masses?**
  - Are they Dirac or Majorana fermions?

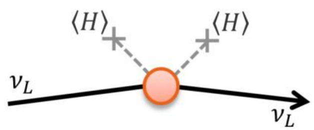
Dirac mass:



$$\mathcal{L}_D = -(Y^\nu \bar{L} H \nu_R + \text{h.c.})$$

very small coupling

Majorana mass:



$$\boxed{\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}}$$

Weinberg operator

(very) large scale

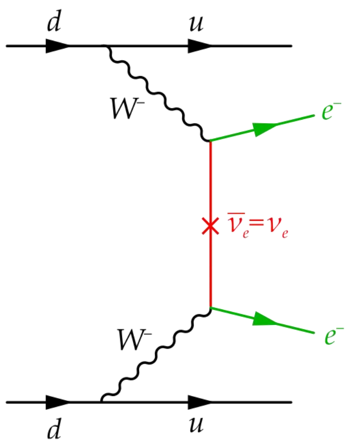
a la eg. type-I, II, III seesaw

$\Delta L = 2$ lepton numer violation (LNV)

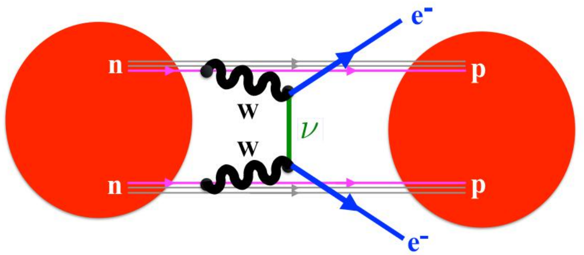
Majorana neutrinos

- Mass origin and Majorana nature
    - How do neutrinos get their masses?
    - **Are they Dirac or Majorana fermions?**

Majorana mass:



$0\nu\beta\beta$ decay:

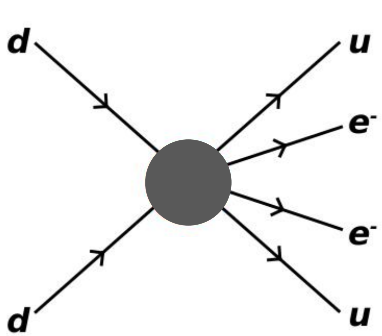


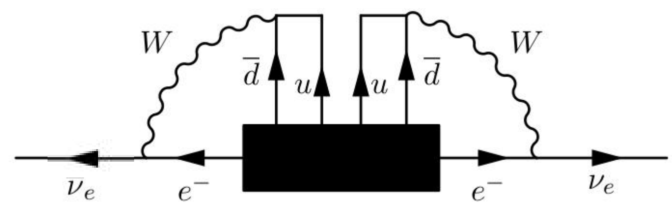
Furry, Phys. Rev. 56 (1939) 1184

Neutrinoless double beta decay

- $0\nu\beta\beta$ decay in nuclei

  An observation of $0\nu\beta\beta$ decay undoubtedly implies the Majorana nature of neutrinos

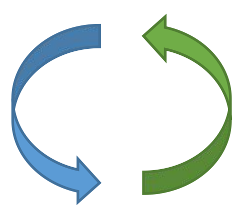




Schechter, Valle, Phys.Rev. D25 (1982) 774

various $\Delta L = 2$
LNV interactions

$\nu = \nu^c$

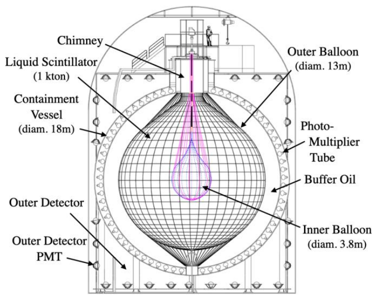


$0\nu\beta\beta$ decay

Neutrinoless double beta decay

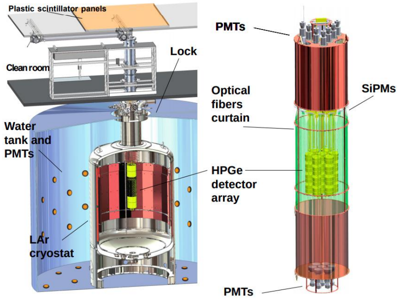
- Experimental searches

KamLAND-Zen: ^{136}Xe $\to$ ^{136}Ba $+ e^- + e^-$



$$T_{1/2}^{0\nu}(\mathrm{Xe}) > 1.07 \times 10^{26} \text{ year}$$

GERDA: ^{76}Ge $\to$ ^{76}Se $+ e^- + e^-$



$$T_{1/2}^{0\nu}(\mathrm{Ge}) > 1.8 \times 10^{26} \text{ year}$$

- Theoretical interpretation

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} {M_{0\nu}}^2 \langle m_{\beta\beta} \rangle^2$$

$G_{0\nu}$: phase space factor (atomic physics)

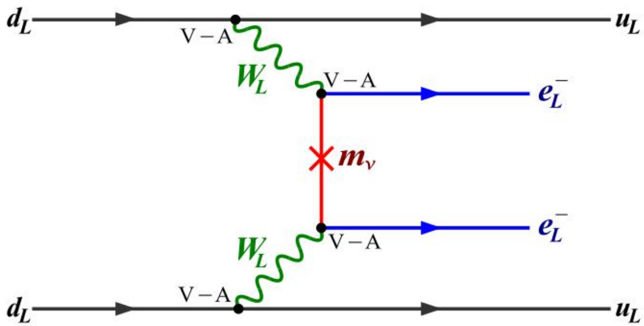
$M_{0\nu}$: nuclear matrix element (nuclear physics)

$\langle m_{\beta\beta} \rangle$: effective Majorana mass (particle physics)

What is $\langle m_{\beta\beta} \rangle$?

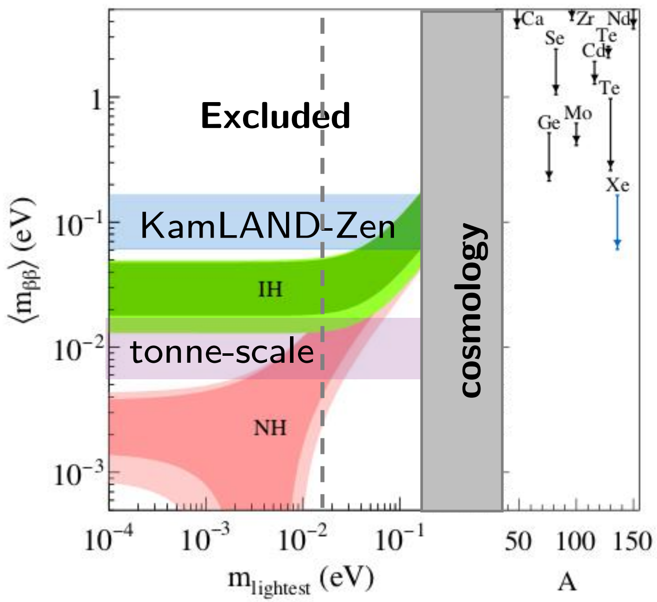
Mechanisms of $0\nu\beta\beta$ decay

- Standard mechanism



$$\langle m_{\beta\beta} \rangle = |\sum_i m_i U_{ei}^2|$$

From neutrino oscillation
$\Delta m_{21}^2, |\Delta m_{31}^2|, \theta_{ij}, \delta$

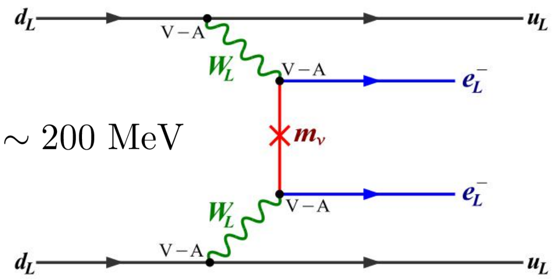


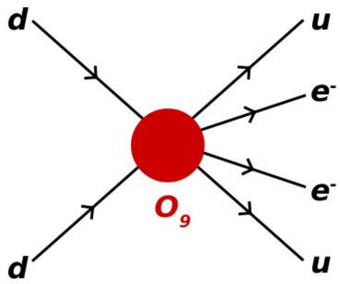
Phys.Rev.Lett. 117 (2016) 082503;
Phys.Rev.Lett. 125 (2023) 130, 051801

Mechanisms of $0\nu\beta\beta$ decay

- Non-standard mechanisms

$p \sim 200\ \mathrm{MeV}$





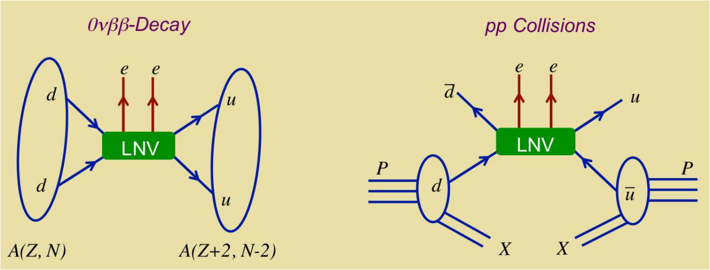
W. Rodejohann, 1106.1334

$\sim G_F^2 m_{\beta\beta}/p^2$ $\sim c/\Lambda^5$

TeV scale LNV:

$$\frac{c/\Lambda^5}{G_F^2 m_{\beta\beta}/p^2} = c\left(\frac{3.3\ \mathrm{TeV}}{\Lambda}\right)^5 \frac{0.1\ \mathrm{eV}}{m_{\beta\beta}}$$

c: new coupling
Λ: new particle mass

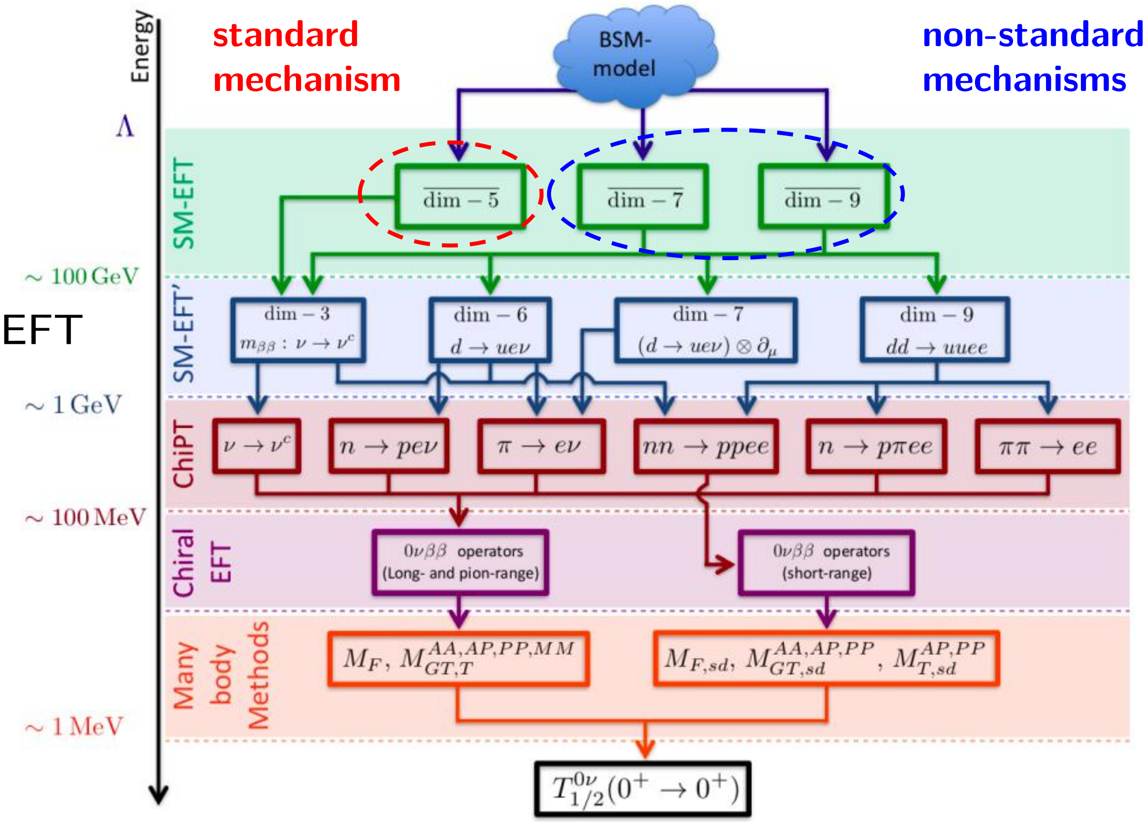


Heavy resonances could be produced on shell at the LHC

Effective field theory approach

- A systematic and end-to-end description of $\Delta L = 2$ LNV sources

or LEFT



$\mathcal{L}(u, d, \nu, e)$

$\mathcal{L}(N, \pi, \nu, e)$

From TeV to MeV
$\sim$ 6 orders

V. Cirigliano et al., 2203.12169, Snowmass 2021

Effective field theory approach

Inverse half-life for $0\nu\beta\beta$ decay in the EFT approach

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \Big\{ G_{01}\ \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2$$
$$+2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu + \mathcal{A}_R)\right)\right]$$
$$-2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right]$$
$$+G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\}.$$

G. Prézeau, M. Ramsey-Musolf, P. Vogel, Phys. Rev. D 68, 034016 (2003)
V. Cirigliano et al, 1708.09390 (JHEP), 1806.02780 (JHEP)

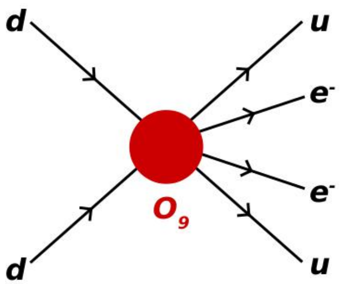
Effective Majorana mass

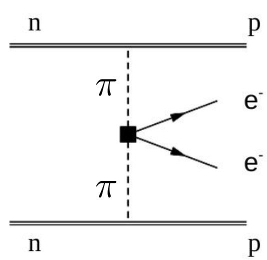
$\langle m_{\beta\beta}\rangle \sim \sum$ LEC x Wilson Coeff

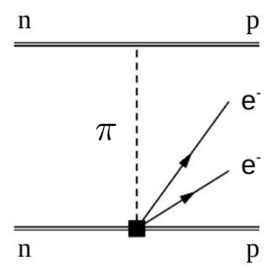
- non-perturbative QCD
- low-energy constant (LEC) as the weight

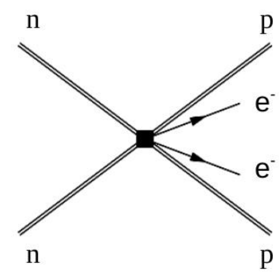
Effective field theory approach

LECs are ordered in powers of p/Λ_χ using chiral effective field theory









	p^{-2}, p^0	p^0	p^0
$\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$	$\pi^-\pi^-\bar{e}_R e^c_R$	$\left(\bar{p}S\cdot\partial\pi^- n\right)\bar{e}_R e^c_R$	$(\bar{p}n)(\bar{p}n)\bar{e}_R e^c_R$
	$\partial_\mu\pi^-\partial^\mu\pi^-\bar{e}_R e^c_R$	$\bar{p}\left(S\cdot\partial\pi^- n\right)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c$	$(\bar{p}n)(\bar{p}n)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c$

Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016 $\quad R\to L$

$p^{-2}:\ \dfrac{\Lambda_\chi}{p^2}\simeq 25$ chiral enhancement at the amplitude level

Effective field theory approach

Dim-9 LEFT operators: $\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$

- lepton bilinear

$$\bar{e}\Gamma_3 e^c = \bar{e}_L e^c_L\ , \bar{e}_R e^c_R\ , \bar{e}\gamma_\mu\gamma_5 e^c$$

- quark biliners

M. L. Graesser, 1606.04549 (JHEP)

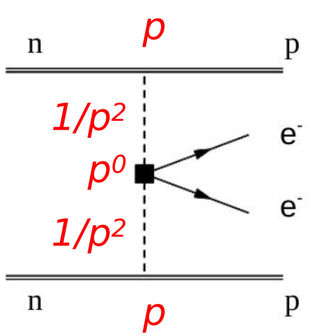
$$O_1 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_L \gamma^\mu \tau^+ q^\beta_L\,, \qquad O'_1 = \bar{q}^\alpha_R \gamma_\mu \tau^+ q^\alpha_R\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_2 = \bar{q}^\alpha_R \tau^+ q^\alpha_L\ \bar{q}^\beta_R \tau^+ q^\beta_L\,, \qquad O'_2 = \bar{q}^\alpha_L \tau^+ q^\alpha_R\ \bar{q}^\beta_L \tau^+ q^\beta_R\,,$$

$$O_3 = \bar{q}^\alpha_R \tau^+ q^\beta_L\ \bar{q}^\beta_R \tau^+ q^\alpha_L\,, \qquad O'_3 = \bar{q}^\alpha_L \tau^+ q^\beta_R\ \bar{q}^\beta_L \tau^+ q^\alpha_R\,,$$

$$O_4 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_5 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\beta_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\alpha_R\,,$$



$\sim p^{-2}$

$$O^\mu_6 = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L \tau^+ q_R\right)\ , \qquad O^{\mu\,\prime}_6 = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R \tau^+ q_L\right)\ ,$$

$$O^\mu_7 = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ , \qquad O^{\mu\,\prime}_7 = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ ,$$

$$O^\mu_8 = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R \tau^+ q_L\right)\ , \qquad O^{\mu\,\prime}_8 = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L \tau^+ q_R\right)\ ,$$

$$O^\mu_9 = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ , \qquad O^{\mu\,\prime}_9 = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ ,$$

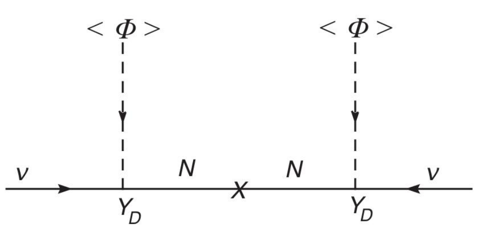
UV completions

- TeV scale LNV correlated with observed neutrino masses

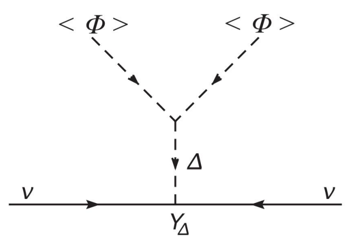
$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \qquad \bar{e}_L e_L^c, \bar{e}_R e_R^c$$

Both left- and right-handed charged currents, thus the most manifest UV realization is the **left-right symmetric model**

Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165



type-I seesaw



type-II seesaw

$$\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta e^{-i\alpha} \\ \sin\zeta e^{i\alpha} & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix}$$

$$\tan\zeta = \frac{M_W^2}{M_{W_R}^2}\sin(2\beta)$$

UV completions

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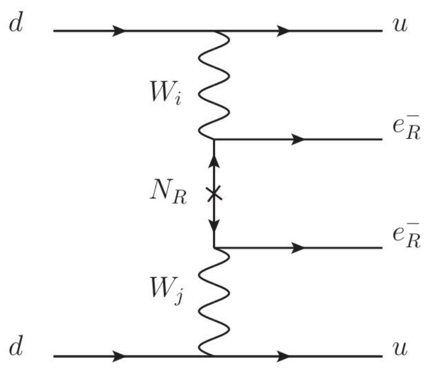


$$(i,j) = (R,R) \qquad \bar{u}_R \gamma_\mu d_R \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_1' \bar{e}_R e_R^c$$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \left(\frac{M_W}{M_{W_R}}\right)^4 p^0$$

$$(i,j) = (1,2) \qquad \bar{u}_L \gamma_\mu d_L \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_4 \bar{e}_R e_R^c$$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \sin 2\beta \left(\frac{M_W}{M_{W_R}}\right)^4 \Lambda_\chi^2 p^{-2}$$

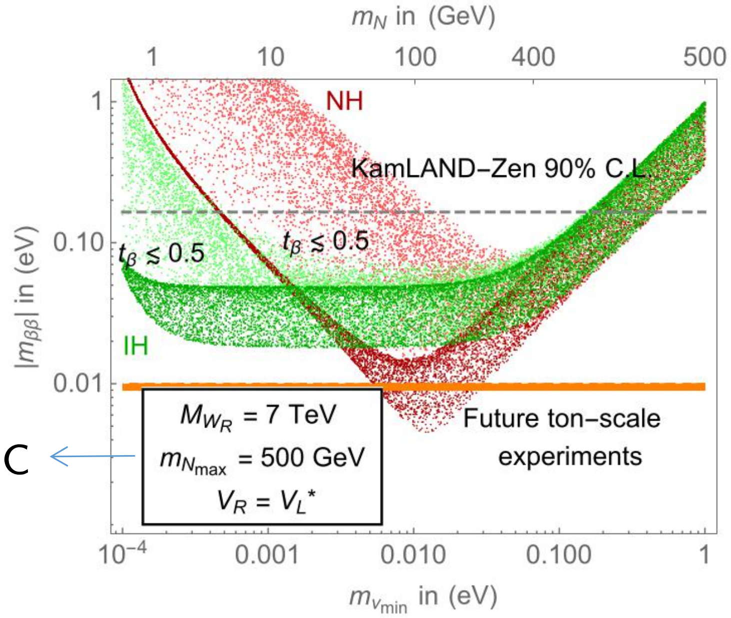
Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016

UV completions

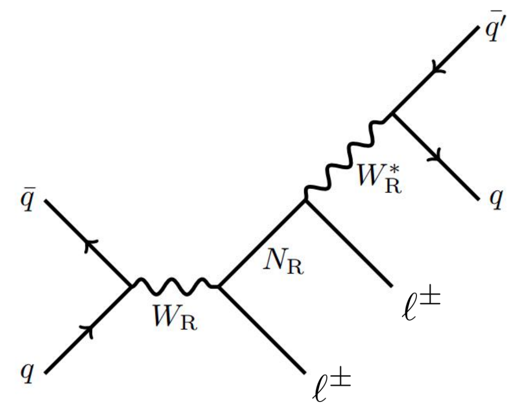
- TeV scale LNV correlated with observed neutrino masses

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \qquad \bar{e}_L e_L^c, \bar{e}_R e_R^c$$

HL-LHC



GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL)



UV completions

- TeV scale LNV uncorrelated with observed neutrino masses

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \qquad \bar{e}_L e_L^c, \bar{e}_R e_R^c$$

  - Contributions to Majorana masses of neutrinos are non-zero but **negligible**
  - Possible if neutrino have **different mass origins**
  - Other kinds of UV scenarios

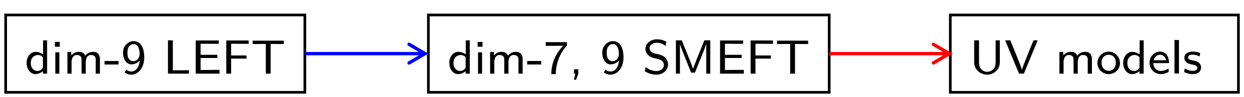
UV completions

- TeV scale LNV uncorrelated with observed neutrino masses

$$O_4 = \bar{q}_L^{\alpha}\gamma_{\mu}\tau^{+}q_L^{\alpha}\bar{q}_R^{\beta}\gamma^{\mu}\tau^{+}q_R^{\beta} \qquad \bar{e}_L e_L^c, \bar{e}_R e_R^c$$

  - Contributions to Majorana masses of neutrinos are non-zero but **negligible**
  - Possible if neutrino have **different mass origins**
  - Other kinds of UV scenarios

- Two-step UV completions **Li, Ni, Xiao, Yu, 2204.03660 (JHEP)**



Lehman 2014; Liao & Ma 2016, 2020; Li et al, 2020

UV completions

- Step 1

Dim-7 SMEFT operator:

$$\mathcal{O}^{(7)}_{\bar{d}uLLD} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i iD_\mu L_j\right)$$

Dim-9 SMEFT operators:

$$\mathcal{O}^{(9)}_1 = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}^c_R e_R\right) H_j D_\mu H_i \ ,$$
$$\mathcal{O}^{(9)}_2 = \epsilon^{ik}\left(\bar{d}_R L_j\right)\left(\bar{L}^c_i\gamma^\mu u_R\right) H^{\dagger j} D_\mu H_k \ ,$$
$$\mathcal{O}^{(9)}_3 = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i D_\mu L_j\right) H_k H^{\dagger k} \ ,$$
$$\mathcal{O}^{(9)}_4 = \epsilon^{ik}(\bar{u}^\alpha_R Q^\beta_j)(\bar{L}^j d^\alpha_R)(\bar{L}_i Q^{\beta c}_k) \ .$$

5 SMEFT operators up to dim-9 level are related

GL, Jiang-Hao Yu, Xiang Zhao, 2311.10079
O. Scholer, J. de Vries, L. Gráf, 2304.05415 (JHEP)

UV completions

- Step 2: tree or one-loop level

UV models:

operator	leptoquark(s)		vector-like fermions	singlet scalar
$\mathcal{O}_1^{(9)}$	$\tilde{R}_2 \in (3,2,1/6)$	$U_1 \in (3,1,2/3)$	$\Psi_{L,R} \in (1,2,-1/2)$	/
$\mathcal{O}_2^{(9)}$	$\bar{S}_1 \in (\bar{3},1,-2/3)$	$\tilde{V}_2 \in (\bar{3},2-1/6)$	$E'_{L,R} \in (1,1,-1)$	/
$\mathcal{O}_3^{(9)}$	$\tilde{R}_2 \in (3,2,1/6)$	/	$\Psi_{L,R} \in (1,2-1/2)$	$S \in (1,1,0)$
$\mathcal{O}_4^{(9)}$	$\tilde{R}_2 \in (3,2,1/6)$	$S_1 \in (\bar{3},1,1/3)$	$\Psi_{L,R} \in (1,2-1/2)$	/
$O_{\bar{d}uLLD}^{(7)}$	$\tilde{V}_2 \in (\bar{3},2-1/6)$	/	$\Psi_{L,R} \in (1,2,-1/2)$, $d'_{L,R} \in (3,1,-1/3)$	$S \in (1,1,0)$

tree (operators $\mathcal{O}_1^{(9)}$–$\mathcal{O}_4^{(9)}$)

one-loop ← ($O_{\bar{d}uLLD}^{(7)}$)

dim-7: $\sim 1/16\pi^2 \; v^3/\Lambda^3$

GL, Jiang-Hao Yu, Xiang Zhao, 2311.10079

dim-9: $\sim v^5/\Lambda^5$

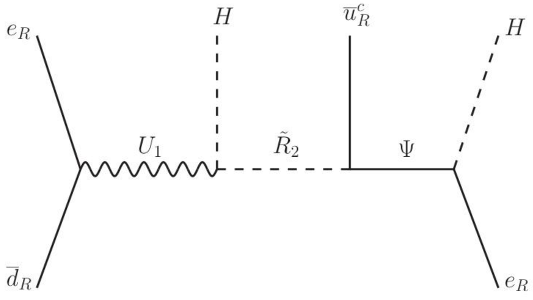
compable if $\Lambda \sim 2-3$ TeV

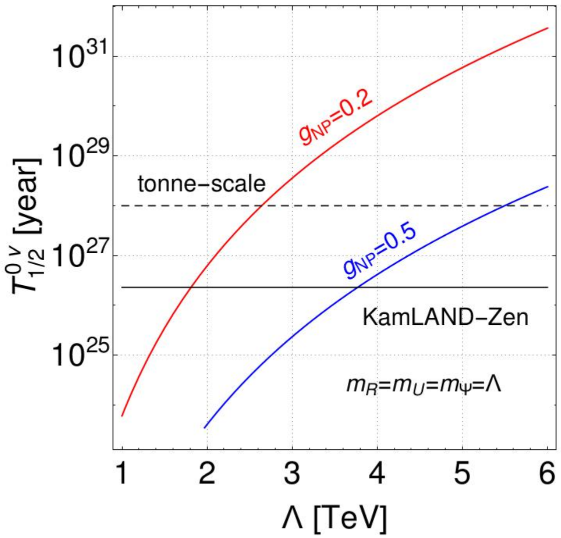
Complementary searches

- Indirect searches in $0\nu\beta\beta$ decay experiments

operator	leptoquark(s)		vector-like fermions
$\mathcal{O}_1^{(9)}$	$\tilde{R}_2 \in (3,2,1/6)$	$U_1 \in (3,1,2/3)$	$\Psi_{L,R} \in (1,2,-1/2)$

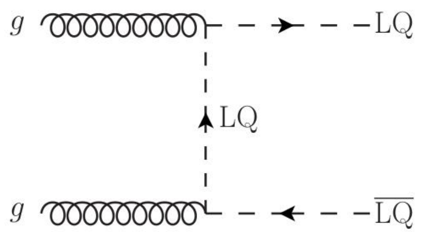
$$\mathcal{L} \supset \lambda_{ed}\left(\bar{d}_R\gamma_\mu e_R\right)U_1^\mu + \lambda_{u\Psi}\tilde{R}_2^*\bar{u}_R^c\Psi_R + \lambda_{DH}U_1^{\mu\dagger}\tilde{R}_2\epsilon\left(iD_\mu H\right) + f_{\Psi e}\bar{\Psi}_L H e_R + \text{h.c.}$$

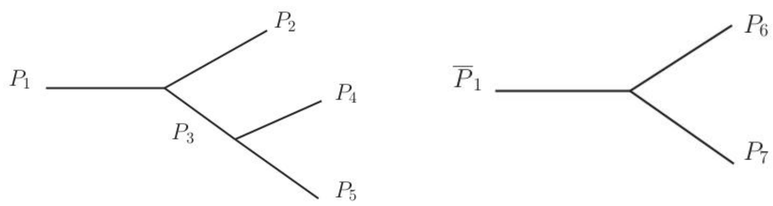




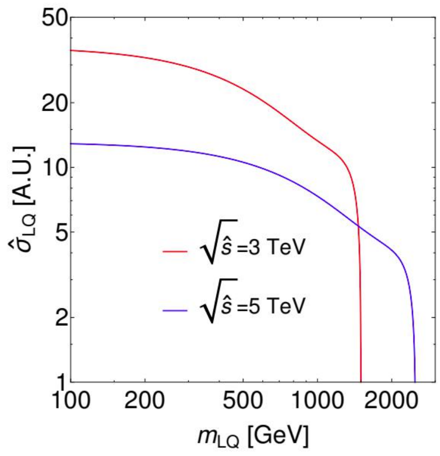
Complementary searches

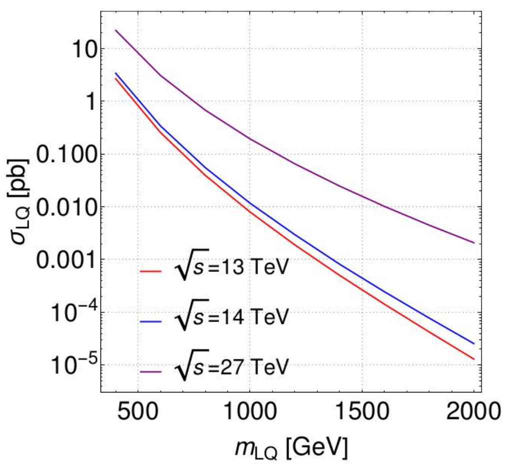
- Direct searches at the LHC





operator	P_1	P_2	P_3	P_4	P_5	P_6	P_7
$\mathcal{O}_1^{(9)}$	$\tilde{R}_2^{-1/3}$	W^-	$U_1^{2/3}$	e^+	d	e^+	$\bar{u}$
	$U_1^{-2/3}$	W^-	$\tilde{R}_2^{+1/3}$	e^+	$\bar{u}$	e^+	d





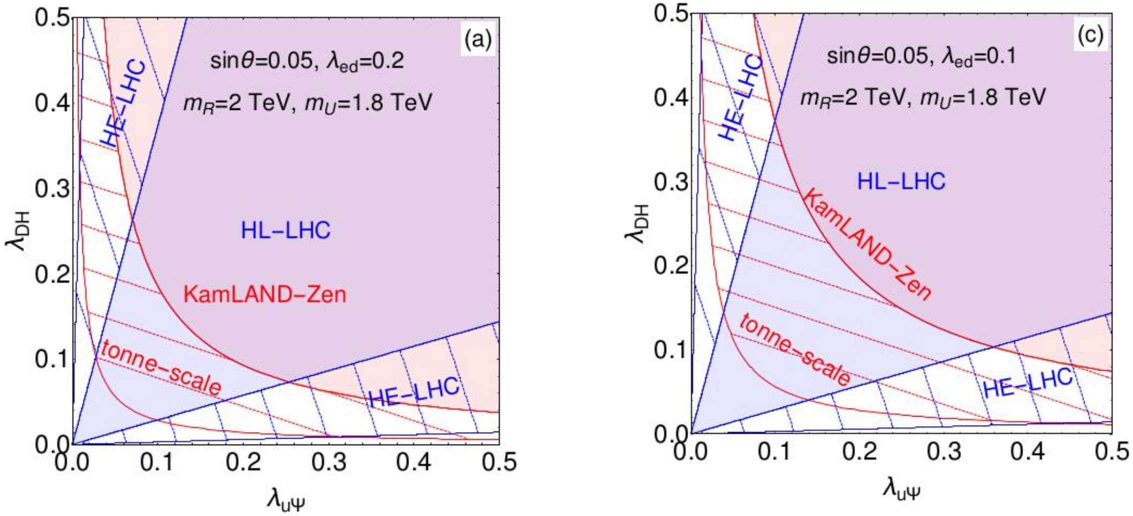
$pp \to e^{\pm}e^{\pm}jjW^{\mp}$

HE-LHC

HL-LHC

Complementary searches

- Direct searches at the LHC



GL, Jiang-Hao Yu, Xiang Zhao, 2311.10079

Searches at the LHC and $0\nu\beta\beta$ decay experiments are very complementary to uncover the UV completions

Summary

- The Majorana nature of neutrino is the key to understanding the origin of neutrino masses
- $0\nu\beta\beta$ decay, which could undoubtedly assess the Majorana nature, might receive contributions beyond the standard mechanisms
- TeV scale LNV responsible for $0\nu\beta\beta$ decay provides a good opportunity for complementary searches at the LHC
- We concentrate on a chirally enhanced contribution to $0\nu\beta\beta$ decay and the related operators in the standard model effective field theory
- The UV completions with leptoquarks strongly motivate experimental searches for LNV at the HL-LHC and HE-LHC

Thanks for your attention!