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

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Gang Li, Jiang-Hao Yu, Xiang Zhao 2311.10079(PRD).

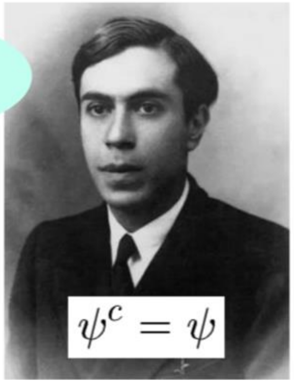
第五届粒子物理前沿研讨会

Dirac vs Majorana neutrino

What is the Majorana nature?

The antiparticle of a free fermion is itself.

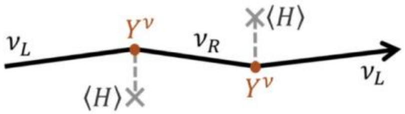
1937



$$\mathcal{L}_m = \underbrace{m_D\, \overline{\psi_R}\psi_L}_{\text{Dirac term}} + \underbrace{\frac{1}{2}m_L\, \overline{\psi_L^c}\psi_L + \frac{1}{2}m_R\, \overline{\psi_R}\psi_R^c}_{\text{Majorana terms}} + \text{h.c.}$$

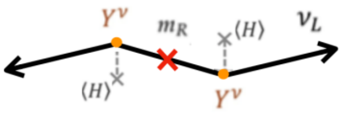
$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix}$$

$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$



$$m_\nu = Y^\nu v_{\rm EW}$$

Tiny Yukawa coupling



$$m_\nu = \frac{(Y^\nu v_{\rm EW})^2}{m_R}$$

Yukawa coupling not small, but mR heavy

The Majorana mass term is allowed.

Lepton number violation

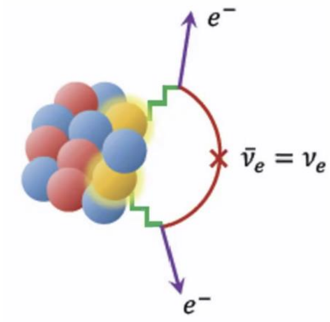
credit: Jiang-Hao Yu

Introduction of Neutrinoless double beta decay

➢ What is $0\nu\beta\beta$?

$$d + d \rightarrow u + u + e^- + e^-$$

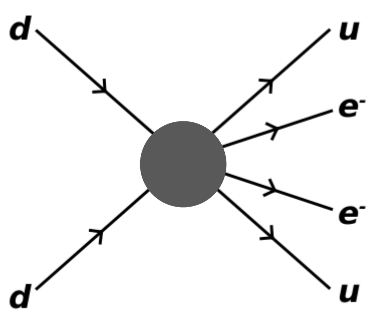
$$n + n \rightarrow p + p + e^- + e^-$$



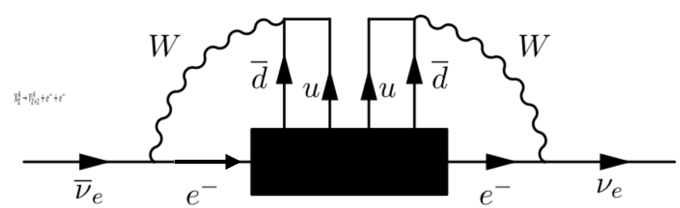
- Two neutrons decay into two protons, only two electrons emit
- Lepton number violation ($\Delta L = 2$) weak-interaction process

➢ Why is $0\nu\beta\beta$?

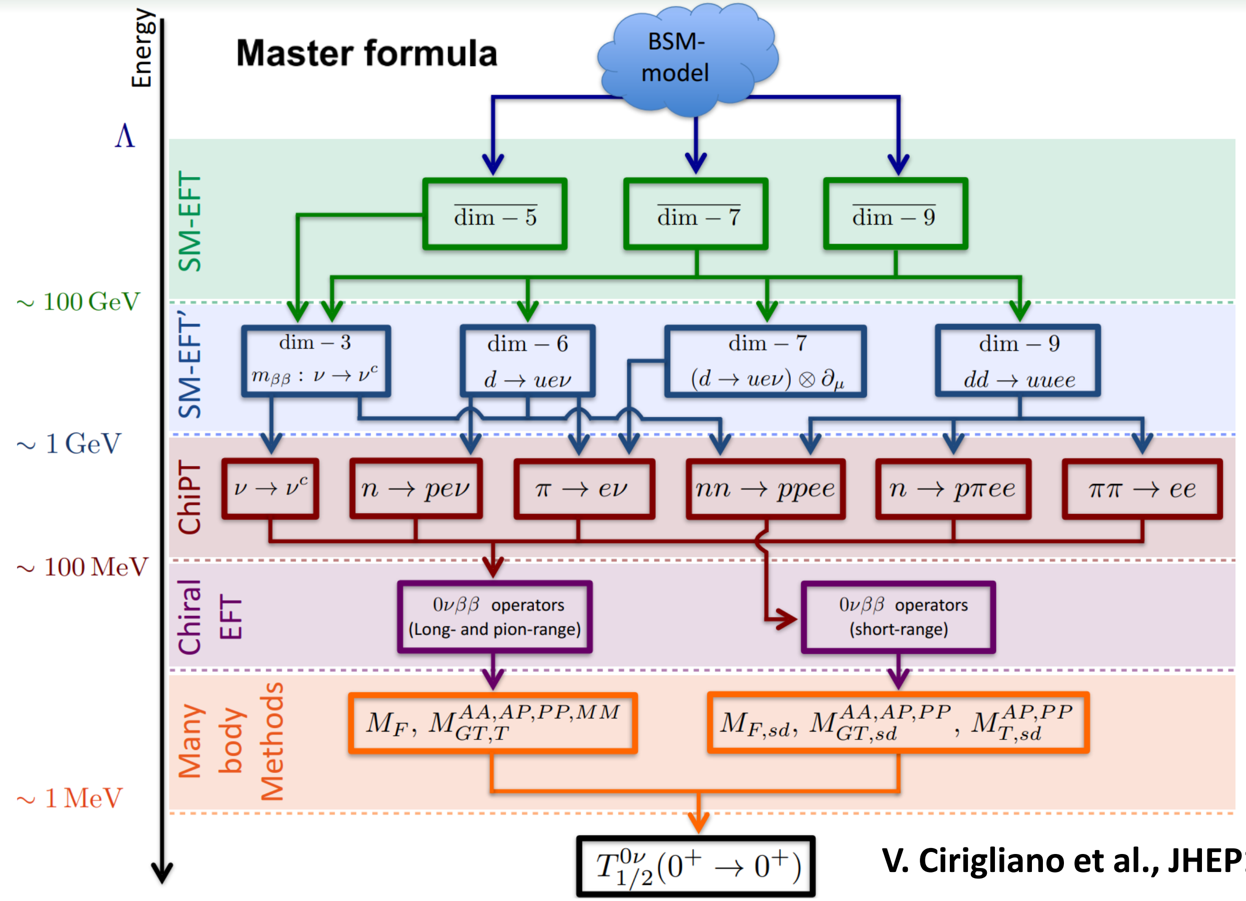
- If the 0νββ process is observed, neutrinos must have Majorana masses.



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



Framework of Effective field theory



UV theories

$SU(3)_c \times SU(2)_L \times U(1)_Y$
e,ν,u,d,t,W,Z……
(SMEFT)

$SU(3)_c \times U(1)_{em}$
e,ν,u,d (LEFT)

e,ν,p,n,π (χEFT)

Construct the $0\nu\beta\beta$ operators

NMEs

Phase space integrals

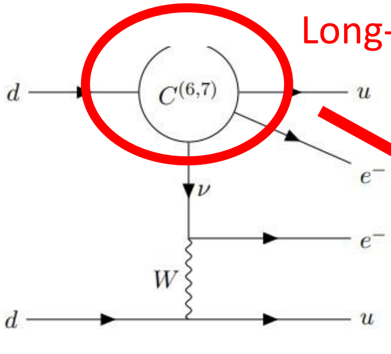
V. Cirigliano et al., JHEP12(2018)097

$\mathcal{A}$ = ∑ (SMEFT WC)×(LEC) ×(NME)

High-energy contribution ⟷ decouple ⟷ Low-energy contribution

Low-energy effective field theory

Long-range

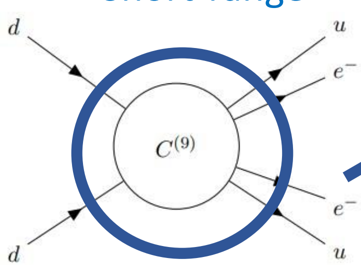


V. Cirigliano et al.,1806.02780(JHEP)

$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big(C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j}$$
$$+\,C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^T_{L,j}\Big)$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big(C^{(7)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j} + C^{(7)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j}\Big)$$

Short-range



$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i\Big[\Big(C^{(9)}_{i\,\mathrm{R}}\,\bar{e}_R C\bar{e}^T_R + C^{(9)}_{i\,\mathrm{L}}\,\bar{e}_L C\bar{e}^T_L\Big)\,O_i + C^{(9)}_i\bar{e}\gamma_\mu\gamma_5 C\bar{e}^T\,O^\mu_i\Big],$$

$$\begin{aligned} O_1 &= \bar{q}^\alpha_L\gamma_\mu\tau^+q^\alpha_L\;\bar{q}^\beta_L\gamma^\mu\tau^+q^\beta_L\,, & O'_1 &= \bar{q}^\alpha_R\gamma_\mu\tau^+q^\alpha_R\;\bar{q}^\beta_R\gamma^\mu\tau^+q^\beta_R\,,\\ O_2 &= \bar{q}^\alpha_R\tau^+q^\alpha_L\;\bar{q}^\beta_R\tau^+q^\beta_L\,, & O'_2 &= \bar{q}^\alpha_L\tau^+q^\alpha_R\;\bar{q}^\beta_L\tau^+q^\beta_R\,,\\ O_3 &= \bar{q}^\alpha_R\tau^+q^\beta_L\;\bar{q}^\beta_R\tau^+q^\alpha_L\,, & O'_3 &= \bar{q}^\alpha_L\tau^+q^\beta_R\;\bar{q}^\beta_L\tau^+q^\alpha_R\,,\\ O_4 &= \bar{q}^\alpha_L\gamma_\mu\tau^+q^\alpha_L\;\bar{q}^\beta_R\gamma^\mu\tau^+q^\beta_R\,, \\ O_5 &= \bar{q}^\alpha_L\gamma_\mu\tau^+q^\beta_L\;\bar{q}^\beta_R\gamma^\mu\tau^+q^\alpha_R\,, \end{aligned}$$

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2}(m_\nu)_{ij}\,\nu^T_{L,i}C\nu_{L,j} + \mathcal{L}^{(6)}_{\Delta L=2} + \mathcal{L}^{(7)}_{\Delta L=2} + \mathcal{L}^{(9)}_{\Delta L=2}$$

Long-range

Short range

From Low-energy EFT to Chiral EFT

LEFT

$$
\begin{aligned}
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha \; \bar{q}_R^\beta \tau^+ q_L^\beta \,, \\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta \; \bar{q}_R^\beta \tau^+ q_L^\alpha \,, \\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha
\end{aligned}
$$

$$
O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta
$$

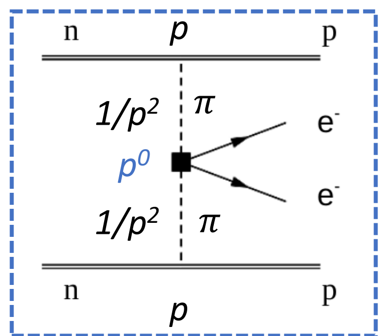
G. Prezeau, M. Ramsey-Musolf, and P. Vogel, 2003

Chiral EFT

V. Cirigliano et al.,1806.02780(JHEP)

$$
\begin{aligned}
\mathcal{L}_\pi^{\text{scalar}} &= \frac{F_0^4}{4}\left[\frac{5}{3} g_1^{\pi\pi} C_{1\text{L}}^{(9)} L_{21}^\mu L_{21\,\mu} + \left(g_2^{\pi\pi} C_{2\text{L}}^{(9)} + g_3^{\pi\pi} C_{3\text{L}}^{(9)}\right) \text{Tr}\left(U\tau^+ U\tau^+\right)\right. \\
&\quad \left. + \left(g_4^{\pi\pi} C_{4\text{L}}^{(9)} + g_5^{\pi\pi} C_{5\text{L}}^{(9)}\right) \text{Tr}\left(U\tau^+ U^\dagger \tau^+\right)\right] \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) \\
&= \frac{F_0^2}{2}\left[\frac{5}{3} g_1^{\pi\pi} C_{1\text{L}}^{(9)} \partial_\mu \pi^- \partial^\mu \pi^- + \left(g_4^{\pi\pi} C_{4\text{L}}^{(9)} + g_5^{\pi\pi} C_{5\text{L}}^{(9)} - g_2^{\pi\pi} C_{2\text{L}}^{(9)} - g_3^{\pi\pi} C_{3\text{L}}^{(9)}\right) \pi^- \pi^-\right] \\
&\quad \times \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots \,,
\end{aligned}
$$

Chiral enhancement



$\sim p^{-2}$

Most important at low energy!

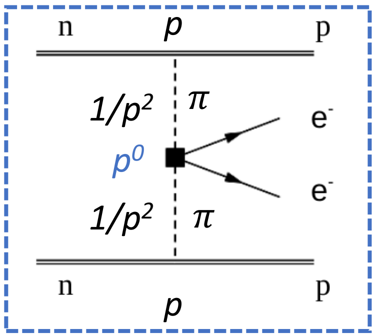
From Low-energy EFT to Chiral EFT

Low-energy EFT

Focus on O_4

$$
\begin{aligned}
O_2 &= \bar{q}_R^{\alpha}\tau^+ q_L^{\alpha}\, \bar{q}_R^{\beta}\tau^+ q_L^{\beta}\,, \\
O_3 &= \bar{q}_R^{\alpha}\tau^+ q_L^{\beta}\, \bar{q}_R^{\beta}\tau^+ q_L^{\alpha}\,, \\
O_4 &= \bar{q}_L^{\alpha}\gamma_\mu\tau^+ q_L^{\alpha}\, \bar{q}_R^{\beta}\gamma^\mu\tau^+ q_R^{\beta} \\
O_5 &= \bar{q}_L^{\alpha}\gamma_\mu\tau^+ q_L^{\beta}\, \bar{q}_R^{\beta}\gamma^\mu\tau^+ q_R^{\alpha}
\end{aligned}
$$

Chiral EFT



$\sim p^{-2}$

Most important at low energy!

How to find its UV theories?

$$
\mathcal{O}_{4L}^{(9)} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_L}e_L^c)
$$

$$
\mathcal{O}_{4R}^{(9)} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_R}e_R^c)
$$

W_L W_R or Leptoquarks

To find the UV theories, we should restore the standard model symmetry firstly.

From Low-energy EFT to Standard model EFT

LEFT

$$\mathcal{O}_{4L}^{(9)} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_L}e_L^c)$$

$$\mathcal{O}_{4R}^{(9)} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_R}e_R^c)$$

W_L $\quad$ W_R or Leptoquarks

Step 1 → SMEFT: dim-7 dim-9 SMEFT operators **Step 2** → UV theory

SMEFT

Six-fermion operators

$$\mathcal{O}_4^{(9)} = \epsilon^{ik}(\bar{u}_R^\alpha Q_j^\beta)(\bar{L}^j d_R^\alpha)(\bar{L}_i Q_k^{\beta c})\ .$$

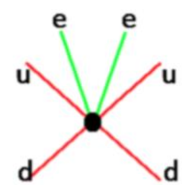
Operators involving derivative

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

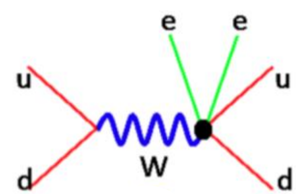
$$\mathcal{O}_1^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}_R^c e_R\right) H_j D_\mu H_i\ ,$$

$$\mathcal{O}_2^{(9)} = \epsilon^{ik}\left(\bar{d}_R L_j\right)\left(\bar{L}_i^c\gamma^\mu u_R\right) H^{\dagger j} D_\mu H_k$$

$$\mathcal{O}_3^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}_i^c D_\mu L_j\right) H_k H^{\dagger k}$$



Dim-9



Dim-7, 9

Dim-7: one-loop

$$C_{SMEFT}^{(7)} = \frac{v^3}{\Lambda^3}\times\frac{1}{16\pi^2}$$

Dim-9: Tree-level

$$C_{SMEFT}^{(9)} = \frac{v^5}{\Lambda^5}$$

credit: Jiang-Hao Yu

Y. Liao, X.-D. Ma, 1612.04527 (PRD)
L. Lehman, 1410.4193 (PRD)
Y. Liao, X.-D. Ma, 2007.08125 (JHEP)
H.-L. Li et al., 2007.07899 (PRD)

UV completion

dim-7, 9 SMEFT → **Step2** → UV models

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

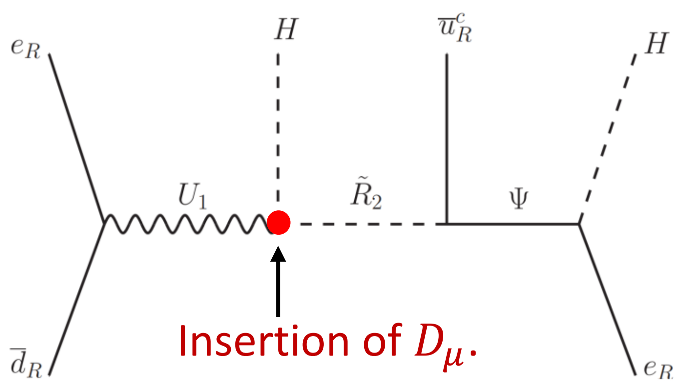
Tree-level

$$C_{SMEFT}^{(9)} \sim \frac{v^5}{\Lambda^5}$$

One-loop level

$$C_{SMEFT}^{(7)} \sim \frac{v^3}{\Lambda^3} \times \frac{1}{16\pi^2}$$

$$\mathcal{O}_1^{(9)} = \epsilon^{ij}\left(\bar{d}_R \gamma^\mu e_R\right)\left(\bar{u}_R^c e_R\right) H_j D_\mu H_i$$

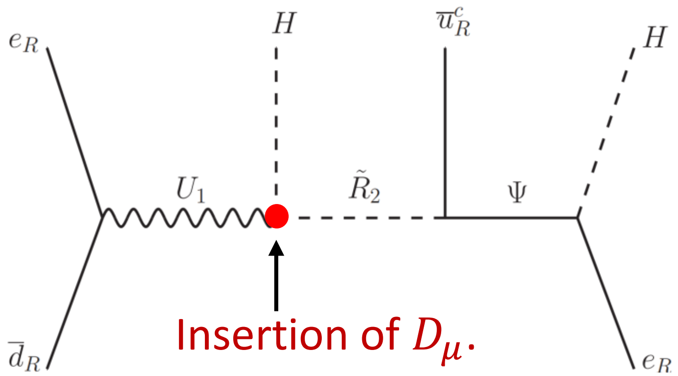


$$\mathcal{L} \supset \lambda_{ed}\left(\bar{d}_R \gamma_\mu e_R\right) U_1^\mu + \lambda_{u\Psi} \tilde{R}_2^* \bar{u}_R^c \Psi_R + \lambda_{DH} U_1^{\mu\dagger} \tilde{R}_2 \epsilon \left(iD_\mu H\right) + f_{\Psi e} \bar{\Psi}_L H e_R + \text{h.c.}$$

Gang Li, Jiang-Hao Yu, XZ, 2311.10079 (PRD).

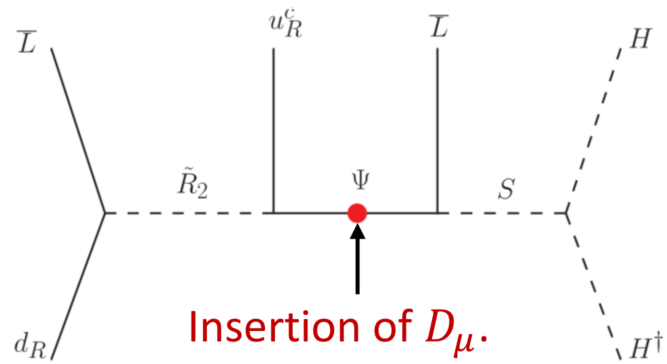
UV completion

$$\mathcal{O}_1^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}_R^c e_R\right) H_j D_\mu H_i$$



$U_1^\mu \tilde{R}_2 (D_\mu H)$ Dim=4

$$\mathcal{O}_3^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}_i^c D_\mu L_j\right) H_k H^{\dagger k}$$



$V^\mu(\bar{\Psi} D_\mu L)$ Dim>4

How to obtain $D_\mu L$?

$$\frac{i}{\not{p} - m} = \frac{\not{p} + m}{p^2 - m^2} \approx \boxed{\frac{\not{p}}{m^2}} + \frac{1}{m}$$

$$\begin{aligned}\Psi_R &= -\frac{1}{m_\Psi^2} i\not{D}\left(\lambda_{u\Psi} u_R^c \tilde{R}_2 + f_{L\Psi} L S^*\right) \\ &= \frac{1}{m_\Psi^2} i\not{D}\Big[-\frac{\lambda_{u\Psi}\lambda_{Ld}}{m_R^2} u_R^c(\epsilon \bar{L} d_R) \\ &\quad + \frac{f_{L\Psi}\mu}{m_S^2} L(H^\dagger H)\Big] .\end{aligned}$$

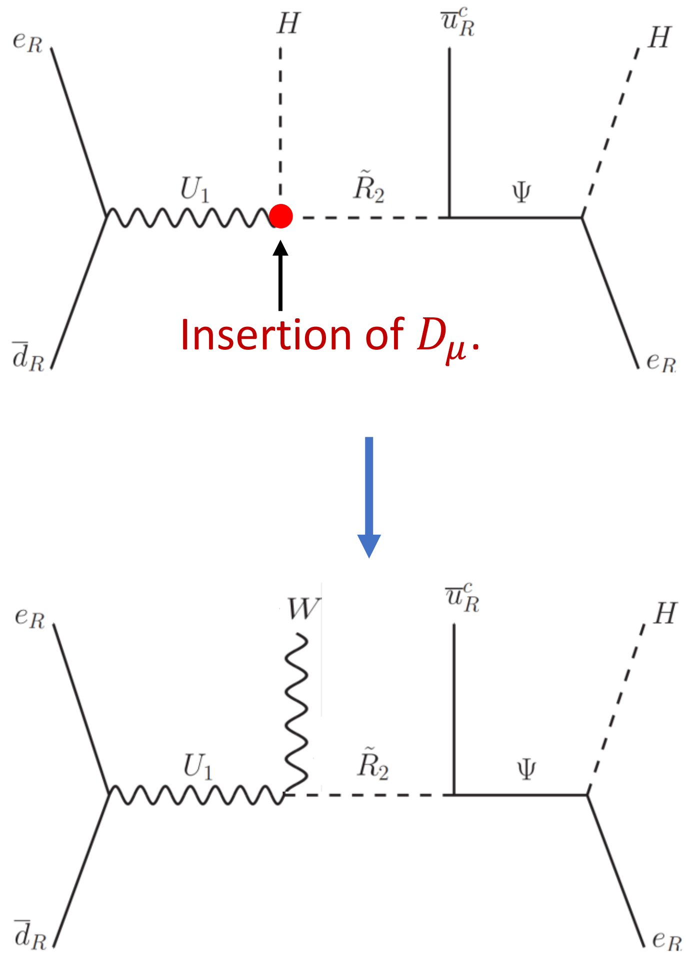
$D_\mu L$ appears

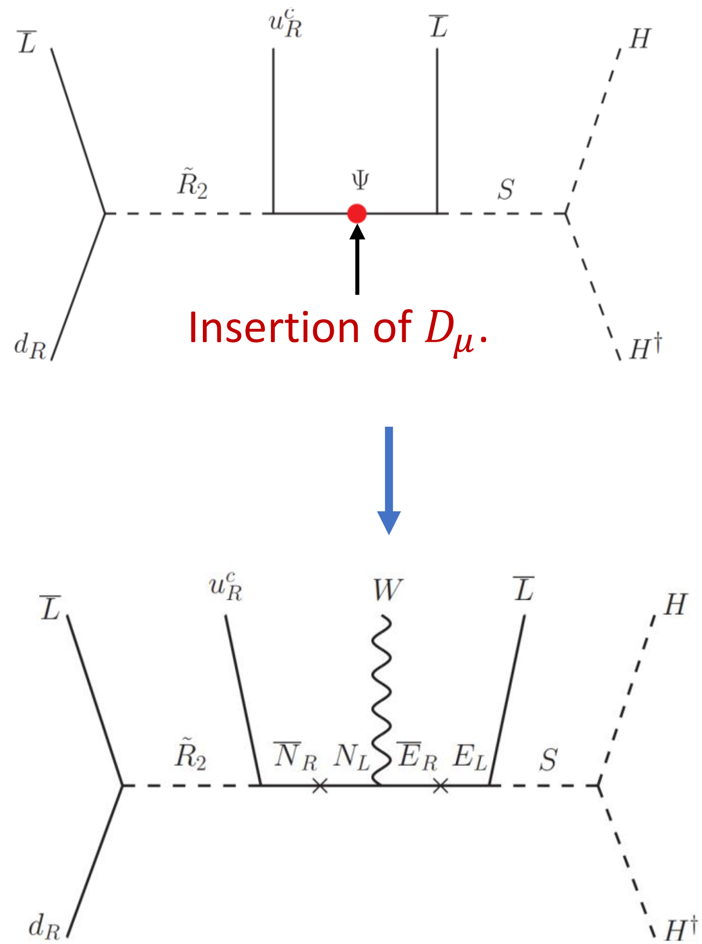
Gang Li, Jiang-Hao Yu, XZ, 2311.10079 (PRD).

UV completion

$$\mathcal{O}_1^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}_R^c e_R\right) H_j D_\mu H_i$$

$$\mathcal{O}_3^{(9)} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}_i^c D_\mu L_j\right) H_k H^{\dagger k}$$





Gang Li, Jiang-Hao Yu, XZ, 2311.10079 (PRD).

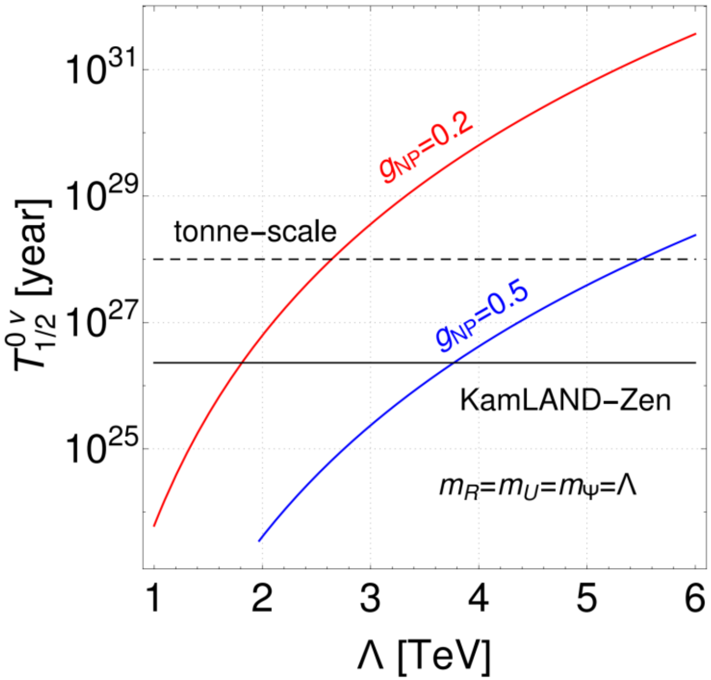
Indirect searches in $0\nu\beta\beta$ decay experiments

KamLAND-Zen experiment

$T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ year

The future tonne-scale experiments

$T_{1/2}^{0\nu} \sim 10^{28}$ year



0νββ-decay experiments are sensitive to $\Lambda \sim$2 - 3 TeV for $g_{NP} = 0.2$, which is in the reach of LHC searches.

Half-life of $0\nu\beta\beta$

$$(T_{1/2}^{0\nu})^{-1} = g_A^4[G_{01}(|A_L|^2 + |A_R|^2) - 2(G_{01} - G_{04})Re A_L^* A_R]$$

Amplitude
$$A_X = \frac{1}{2m_e v} C_{\pi\pi X}^{(9)} \sum (\frac{1}{2} M_{i,sd}^{AP} + M_{i,sd}^{PP})$$

Hign-energy Low-energy

Wilson coefficient
$$C_{\pi\pi X}^{(9)} = -g_4^{\pi\pi} C_{4X}^{(9)} - g_5^{\pi\pi} C_{5X}^{(9)}$$

$$C_{4R}^{(9)}(m_W) = \frac{i}{2} V_{ud} \frac{v^5}{\Lambda^5} C_1^{(9)*} \qquad \frac{C_1^{(9)}}{\Lambda^5} = i\frac{\lambda_{ed}\lambda_{u\Psi}\lambda_{DH} f_{\Psi e}}{m_U^2 m_R^2 m_\Psi}$$

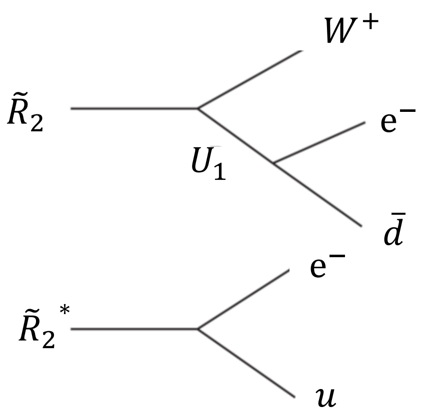
Nuclear matrix elements

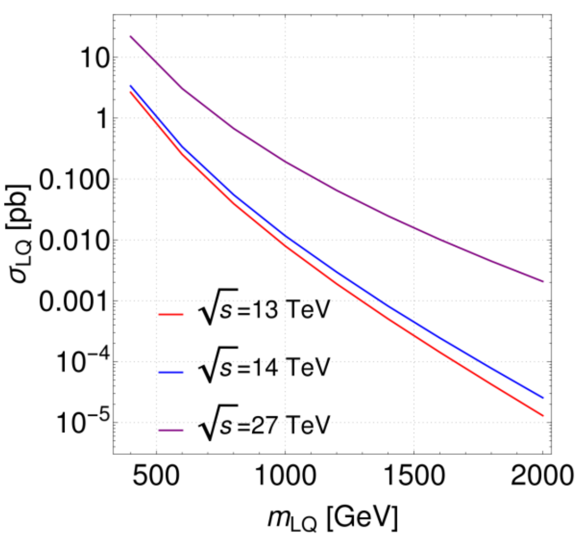
$$M_{GT,sd}^{AP} = -2.8\,, \qquad M_{GT,sd}^{PP} = 1.06\,,$$
$$M_{T,sd}^{AP} = -0.92\,, \qquad M_{T,sd}^{PP} = 0.36\,,$$

Phase-space factor $^{136}\mathrm{Xe}$ $G_{01} = 1.5 \times 10^{15} yr^{-1}$

Direct searches at the LHC

Signal proceess: SSDL and at least two jets





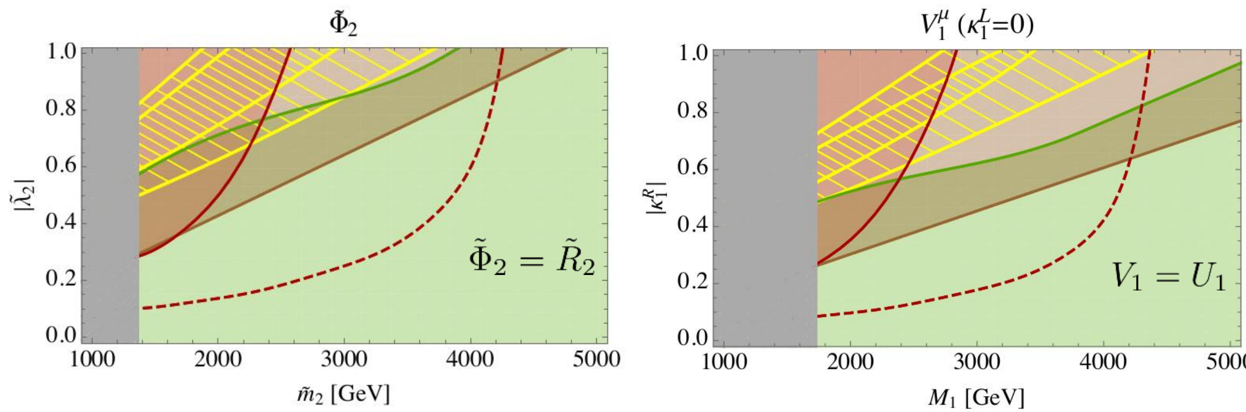
Recast the Atlas search(2304.09553):

$$p_T^{e1(2)} > 40\ (25)\ \text{GeV}\ , \qquad |\ \eta_e\ | < 2.47\ ,$$
$$p_T^{j} > 100\ \text{GeV}\ , \qquad |\ \eta_j\ | < 2.5\ ,$$

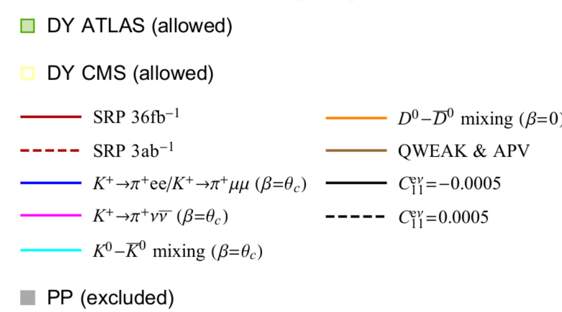
Impose $H_T > 3$TeV to reject most of the SM backgrounds.

The number of signal events: $n_s = \sigma_s \epsilon_s \mathcal{L}$ $\epsilon_s \approx 0.3$

exclusion limits $n_S = 3$ with no SM background.

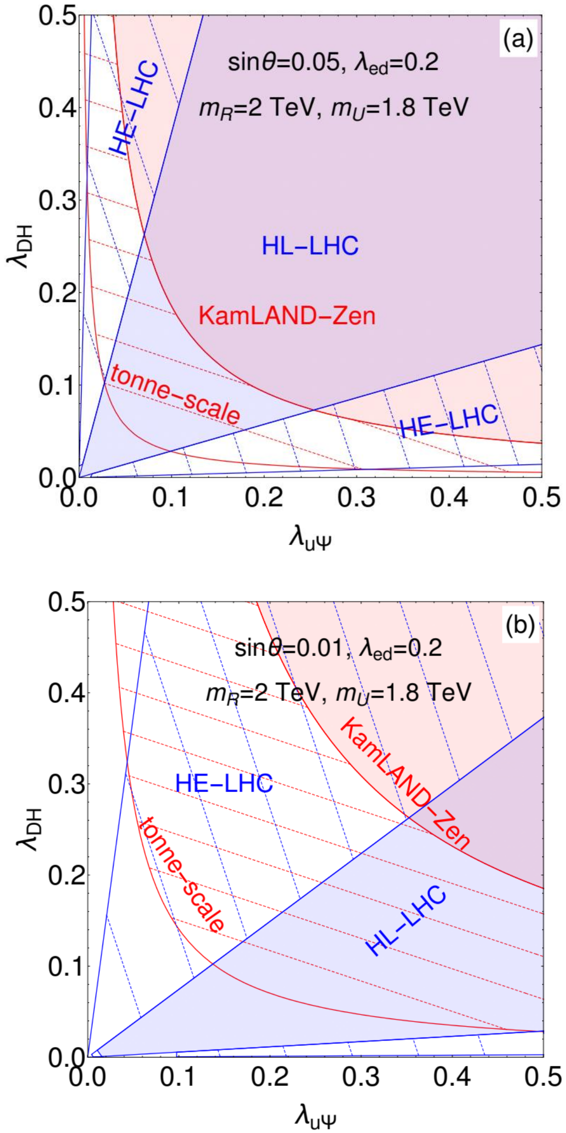


A. Crivellin, L. Schnell, 2104.06417 (PRD)



Gang Li, Jiang-Hao Yu, XZ, 2311.10079 (PRD).

Results



$$\sin\theta = f_{\Psi e} v / (\sqrt{2} m_\Psi)$$

$$\left(T_{1/2}^{0\nu}\right)^{-1/2} \propto \frac{\lambda_{ed}\lambda_{DH}\lambda_{u\Psi}\sin\theta}{m_U^2 m_R^2} \qquad \sigma_s^{1/2} \propto \frac{\lambda_{DH}\lambda_{u\Psi}\sin\theta}{(\sin\theta\lambda_{u\Psi})^2 + (0.05\lambda_{DH})^2}$$

- $0\nu\beta\beta$ decay and the LHC are complementary to each other.
- HE-LHC are much improved compared to the HL-LHC.
- For a larger m_Ψ or smaller $f_{\Psi e}$, the HE-LHC and tonne-scale 0νββ experiments are crucial to probe the couplings of the LQs.
- Most of the parameter space is in the reach of HE-LHC and tonne-scale $0\nu\beta\beta$ decay experiments.

Summary

- The EFT framework is used to study $0\nu\beta\beta$ decay, while promising UV completions are classified -- left-right symmetric model, leptoquark models.
- Chirally enhanced LNV operators at low energy--stronger constraint from $0\nu\beta\beta$ decay experiments.
- SMEFT operators: To find the UV theories of the LEFT, we search for the corresponding SMEFT operators firstly — dim-7 SMEFT at one-loop, dim-9 at tree-level.
- LHC search — LHC and 0νββ decay experiments are complementary.

Thank you for your attention!

Appendix

LEFT

$$\mathcal{O}^{(9)}_{4L} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_L}e^c_L)$$
$$\mathcal{O}^{(9)}_{4R} = (\overline{q_L}\gamma_\mu q_L)(\overline{q_R}\gamma^\mu q_R)(\overline{e_R}e^c_R)$$

SMEFT

Six-fermion operators

$$\mathcal{O}^{(9)}_4 = \epsilon^{ik}(\bar{u}^\alpha_R Q^\beta_j)(\bar{L}^j d^\alpha_R)(\bar{L}_i Q^{\beta c}_k)\ .$$

Operators involving derivative

$$\mathcal{O}^{(7)}_{\bar{d}uLLD} = \epsilon^{ij}\,(\bar{d}_R\gamma^\mu u_R)\,(\bar{L}^c_i iD_\mu L_j)$$
$$\mathcal{O}^{(9)}_1 = \epsilon^{ij}\,(\bar{d}_R\gamma^\mu e_R)\,(\bar{u}^c_R e_R)\,H_j D_\mu H_i\ ,$$
$$\mathcal{O}^{(9)}_2 = \epsilon^{ik}\,(\bar{d}_R L_j)\,(\bar{L}^c_i\gamma^\mu u_R)\,H^{\dagger j} D_\mu H_k$$
$$\mathcal{O}^{(9)}_3 = \epsilon^{ij}\,(\bar{d}_R\gamma^\mu u_R)\,(\bar{L}^c_i D_\mu L_j)\,H_k H^{\dagger k}$$

$$D_\mu H = \partial_\mu H + \frac{ig}{2}W^a_\mu\tau^a H - \frac{1}{2}ig' B_\mu H$$

$$W^+_\mu \simeq -\frac{g}{\sqrt{2}}\frac{1}{m^2_W}\left(\bar{e}_L\gamma_\mu\nu_L + V^\dagger_{ud}\bar{d}_L\gamma_\mu u_L\right)$$

W boson derives from $D_\mu L$ or $D_\mu H$.