# Complementary LHC searches for UV resonances of the 0νββ decay operators

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第27届LHC Mini-Workshop

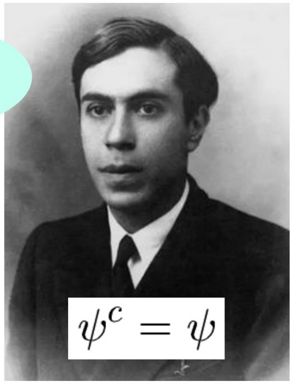
# Introduction of Neutrinoless double beta decay

# Dirac vs Majorana neutrino

What is the Majorana nature?

The antiparticle of a free fermion is itself.

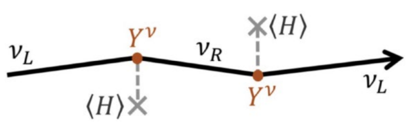
1937




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

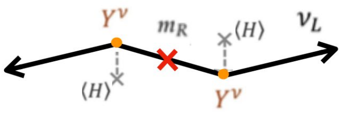
$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix}$$

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




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

**Tiny Yukawa coupling**




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

**Yukawa coupling not small, but mR heavy**

How to forbid the Majorana term?
Lepton number conservation

The Majorana term is allowed
Lepton number violation

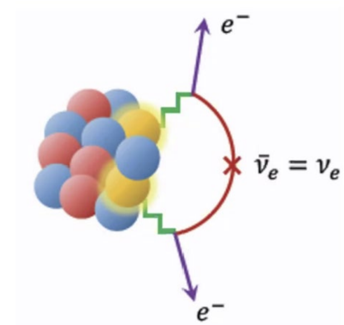
credit:Jiang-Hao Yu

# Introduction of Neutrinoless double beta decay

## ➢ What is $0\nu\beta\beta$?

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

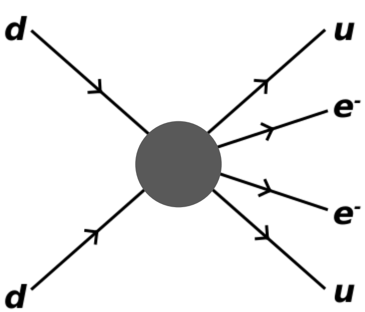
$$n + n \rightarrow p + p + e^- + e^-$$



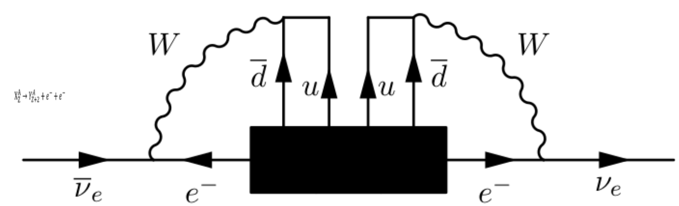

- Two neutrons decay into two protons, only two electrons emit
- Lepton number violation ($LNV = 2$) weak-interaction process

## ➢ Why is $0\nu\beta\beta$?

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

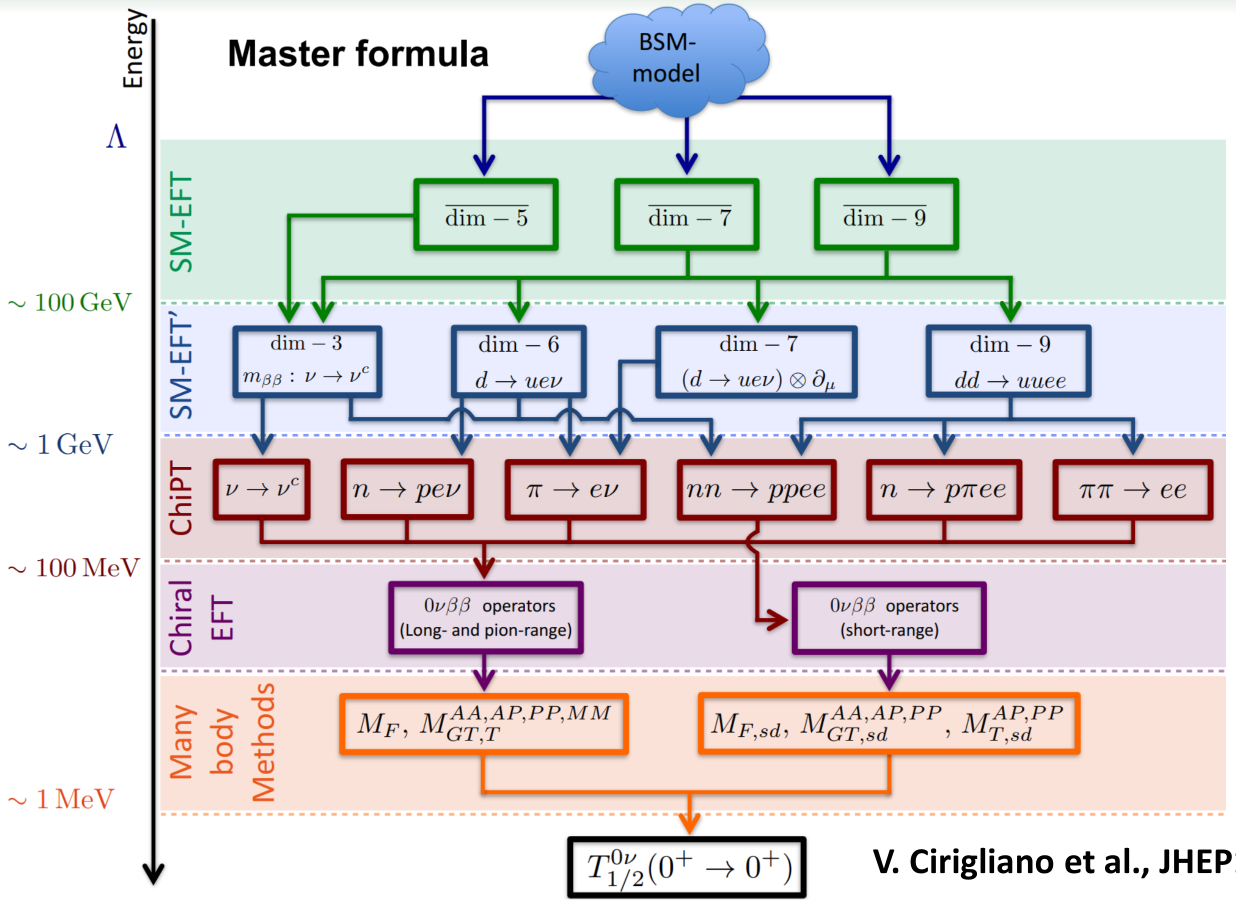



Schechter, Valle, Phys.Rev. D25 (1982) 774



# Nonstandard mechanisms in EFT framework

# Framework of Effective field theory




UV theories

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

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

e,$\nu$,p,n,$\pi$ ($\chi EFT$)

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

**NMEs**

**Phase space integrals**

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

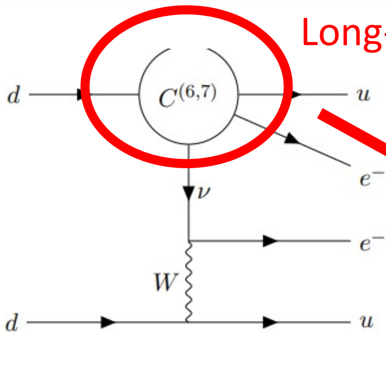
$\mathcal{A} = \sum$ (SMEFT WC)×(LEC) ×(NEM)

High-energy contribution ⟵ decouple ⟶ Low-energy contribution

# Low-energy effective field theory

**V. Cirigliano et al.,1806.02780(JHEP)**

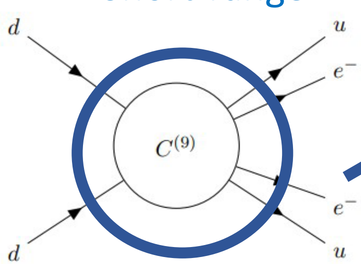
Long-range




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

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big( C^{(7)}_{\rm VL,\it ij}\,\bar u_L\gamma^\mu d_L\,\bar e_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar\nu^T_{L,j} + C^{(7)}_{\rm VR,\it ij}\,\bar u_R\gamma^\mu d_R\,\bar e_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar\nu^T_{L,j}\Big)$$

Short-range




$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i\Big[\Big(C^{(9)}_{i\rm R}\,\bar e_R C\bar e_R^T + C^{(9)}_{i\rm L}\,\bar e_L C\bar e_L^T\Big)\,O_i + C^{(9)}_i\bar e\gamma_\mu\gamma_5 C\bar e^T\,O_i^\mu\Big],$$

$$\begin{aligned}
O_1 &= \bar q_L^\alpha\gamma_\mu\tau^+ q_L^\alpha\ \bar q_L^\beta\gamma^\mu\tau^+ q_L^\beta\,, & O_1' &= \bar q_R^\alpha\gamma_\mu\tau^+ q_R^\alpha\ \bar q_R^\beta\gamma^\mu\tau^+ q_R^\beta\,,\\
O_2 &= \bar q_R^\alpha\tau^+ q_L^\alpha\ \bar q_R^\beta\tau^+ q_L^\beta\,, & O_2' &= \bar q_L^\alpha\tau^+ q_R^\alpha\ \bar q_L^\beta\tau^+ q_R^\beta\,,\\
O_3 &= \bar q_R^\alpha\tau^+ q_L^\beta\ \bar q_R^\beta\tau^+ q_L^\alpha\,, & O_3' &= \bar q_L^\alpha\tau^+ q_R^\beta\ \bar q_L^\beta\tau^+ q_R^\alpha\,,\\
O_4 &= \bar q_L^\alpha\gamma_\mu\tau^+ q_L^\alpha\ \bar q_R^\beta\gamma^\mu\tau^+ q_R^\beta\,, & &\\
O_5 &= \bar q_L^\alpha\gamma_\mu\tau^+ q_L^\beta\ \bar q_R^\beta\gamma^\mu\tau^+ q_R^\alpha\,, & &
\end{aligned}$$

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

Long-range

Short range

# Chiral effective field theory

**V. Cirigliano et al.,1806.02780(JHEP)**

LEFT

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

Focus on $O_4$

ChiPT

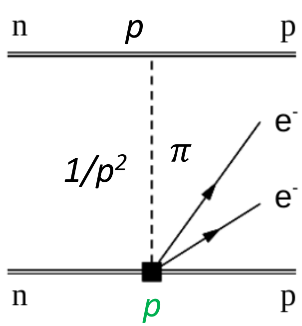
$$
\begin{aligned}
\mathcal{L}_\pi^{\text{scalar}} &= \frac{F_0^4}{4}\Big[\frac{5}{3} g_1^{\pi\pi} C_{1\text{L}}^{(9)} L_{21}^\mu L_{21\,\mu} + \left(g_2^{\pi\pi} C_{2\text{L}}^{(9)} + g_3^{\pi\pi} C_{3\text{L}}^{(9)}\right) \text{Tr}\left(U\tau^+ U\tau^+\right) \\
&\quad + \left(g_4^{\pi\pi} C_{4\text{L}}^{(9)}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

Chiral enhancement

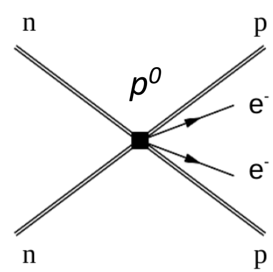
$$
O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \, \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta
$$

$$
\begin{aligned}
\mathcal{L}_{\pi N}^{\text{scalar}} &= g_A g_1^{\pi N} C_{1\text{L}}^{(9)} F_0^2 \left[\bar{N} S^\mu u^\dagger \tau^+ u N \, \text{Tr}\left(u_\mu u^\dagger \tau^+ u\right)\right] \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) \\
&= \sqrt{2} g_A g_1^{\pi N} C_{1\text{L}}^{(9)} F_0 \left[\bar{p}\, S \cdot (\partial \pi^-) n\right] \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots \,,
\end{aligned}
$$

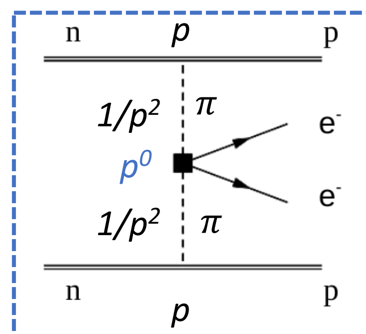
**G. Prezeau, M. Ramsey-Musolf, and P. Vogel, 2003**




$p^0$




$p^0$




$\sim p^{-2}$

Most important at low energy!

# Effective field theory approach

LEFT

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

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

$W_L$ $W_R$ or Leptoquarks

**Step 1** →

SMEFT

dim-7 dim-9 SMEFT operators

**Step 2** →

UV theory

SMEFT

Six-fermion operators

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

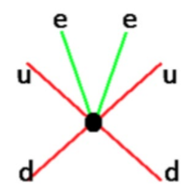
Operators involving derivative

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

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

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

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



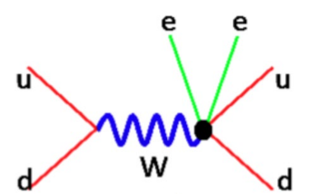

Dim-9

Dim-7: one-loop

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

Dim-9: Tree-level

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




Dim-7, 9

SMEFT in broken phase

credit: Jiang-Hao Yu

**Y. Liao, X.-D. Ma, 1612.04527 (PRD)**
**L. Lehman, 1410.4193 (PRD)**
**Y. Liao, Xiao-Dong Ma, 2007.08125 (JHEP)**
**Hao-Lin Li et al., 2007.07899 (PRD)**

# UV completion

dim-7, 9 SMEFT —Step2→ UV models

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

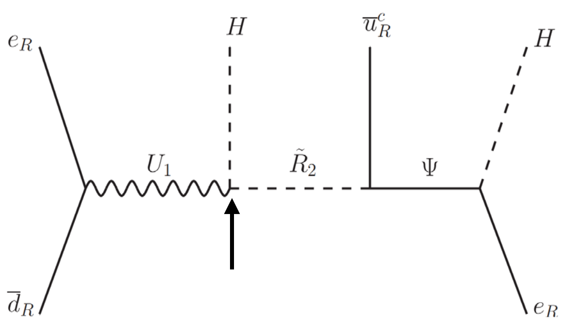
Tree-level

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

One-loop level

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

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



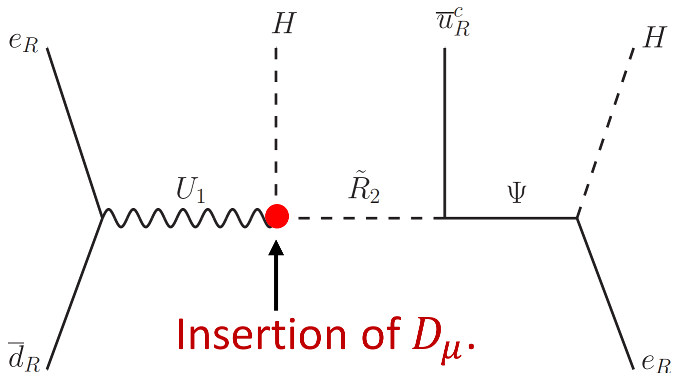

Insertion of $D_\mu$.

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

Gang Li, Jiang-Hao Yu, XZ, 2311.10079

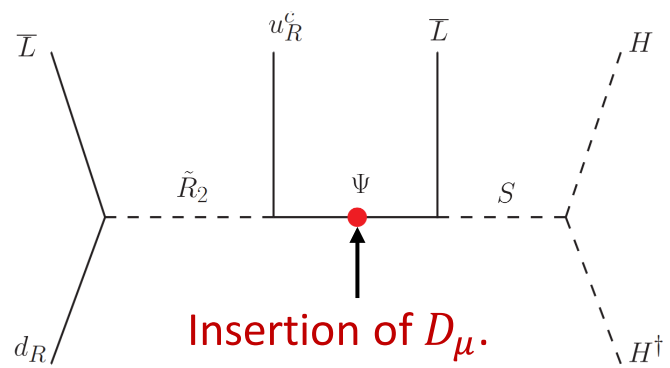
# UV completion

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




$V^\mu R(D_\mu H)$ 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 produce $D_\mu L$

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

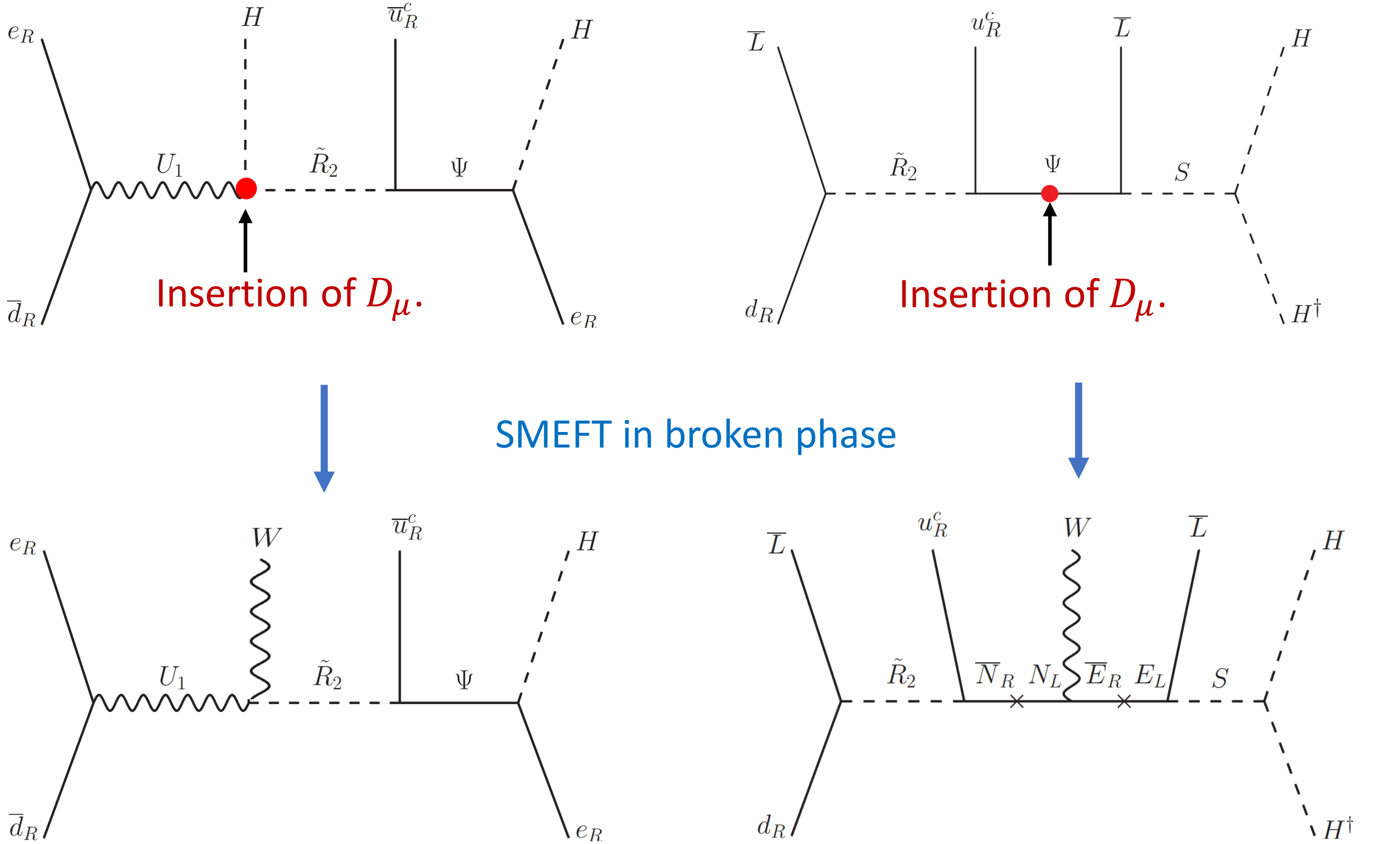
$$\begin{aligned}\Psi_R &= -\frac{1}{m_\Psi^2} i\not{D}\left(\lambda_{u\Psi} u_R^c \tilde{R}_2 + f_{L\Psi} L S^*\right) \\ &= \frac{1}{m_\Psi^2} i\not{D}\left[-\frac{\lambda_{u\Psi}\lambda_{Ld}}{m_R^2} u_R^c(\epsilon \bar{L} d_R) + \frac{f_{L\Psi}\mu}{m_S^2} L(H^\dagger H)\right].\end{aligned}$$

$D_\mu L$ appears

**Gang Li, Jiang-Hao Yu, XZ, 2311.10079**

# UV completion

$$\mathcal{O}_1^{(9)} = \epsilon^{ij} \left(\bar{d}_R \gamma^\mu e_R\right) \left(\bar{u}_R^c e_R\right) H_j D_\mu H_i \qquad \mathcal{O}_3^{(9)} = \epsilon^{ij} \left(\bar{d}_R \gamma^\mu u_R\right) \left(\bar{L}_i^c D_\mu L_j\right) H_k H^{\dagger k}$$




**Gang Li, Jiang-Hao Yu, XZ, 2311.10079**

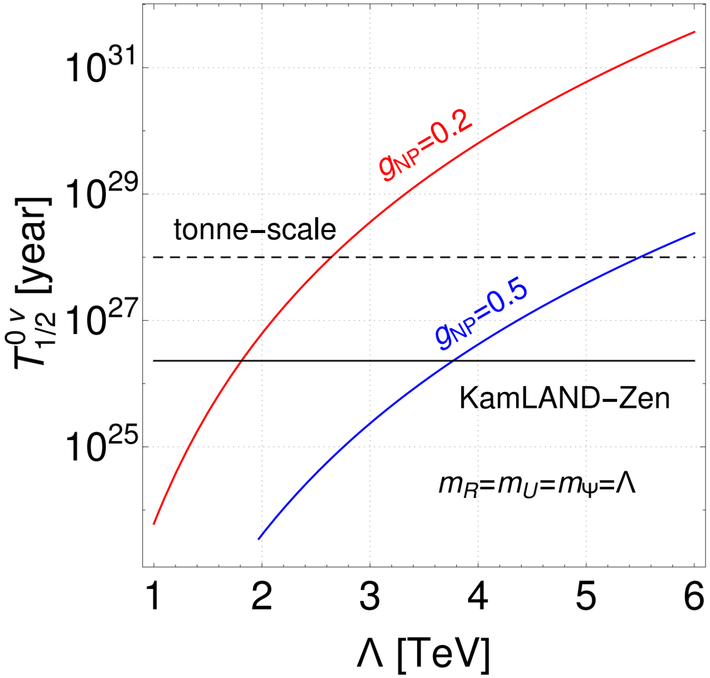
# Indirect searches in $0\nu\beta\beta$ decay experiments

KamLAND-Zen experiment

$T_{1/2}^{0\nu} > 2.3\times10^{26}$ 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 $$C_{\pi\pi X}^{(9)} = -g_4^{\pi\pi}C_{4X}^{(9)} - g_5^{\pi\pi}C_{5X}^{(9)}$$

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

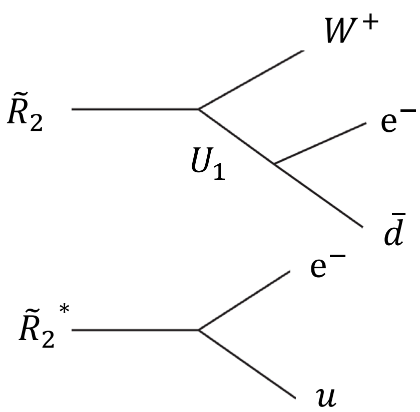
Nuclear matrix elements

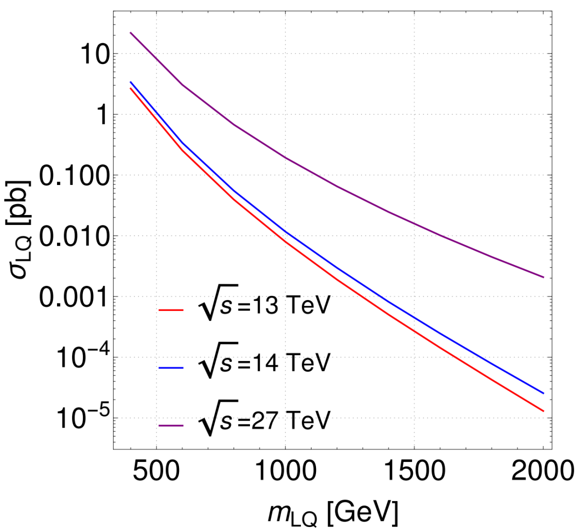
$$M_{GT,sd}^{AP} = -2.8\,, \qquad M_{GT,sd}^{PP} = 1.06\,,$$
$$M_{T,sd}^{AP} = -0.92\,, \qquad M_{T,sd}^{PP} = 0.36\,,$$

Phase-space factor $^{136}$Xe G01 =$1.5\times10^{15} yr^{-1}$

# Direct searches at the LHC

Signal proceess: SSDL and at least two jets



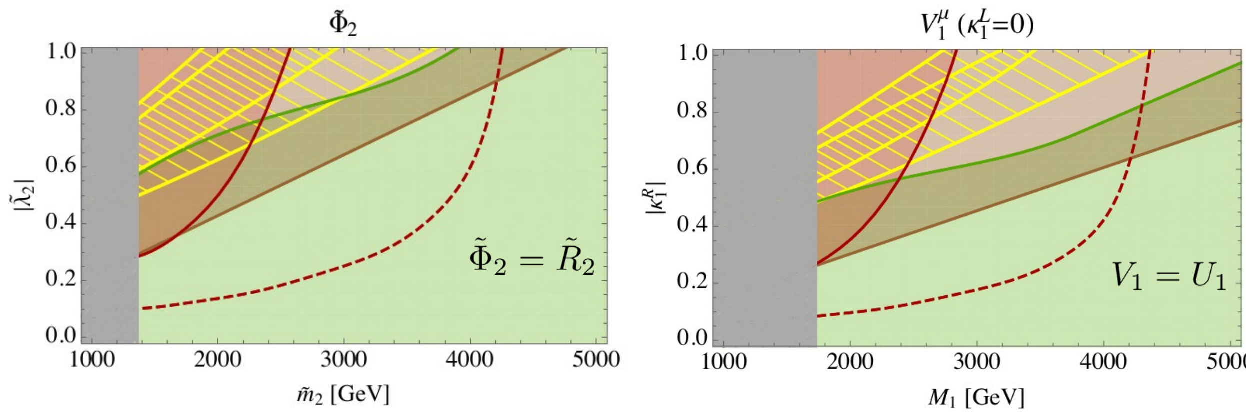

Cut used by ATLAS:

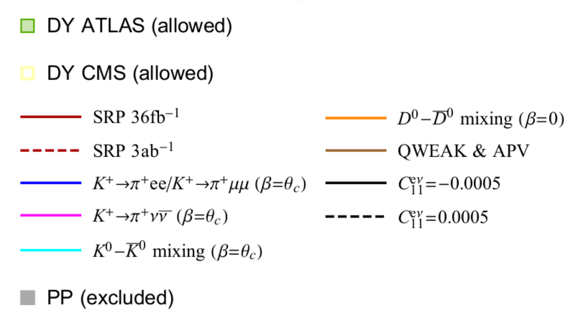
$$p_T^{e1(2)} > 40\ (25)\ \text{GeV}\ , \qquad |\ \eta_e\ | < 2.47\ ,$$
$$p_T^{j} > 100\ \text{GeV}\ , \qquad |\ \eta_j\ | < 2.5\ ,$$

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

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

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

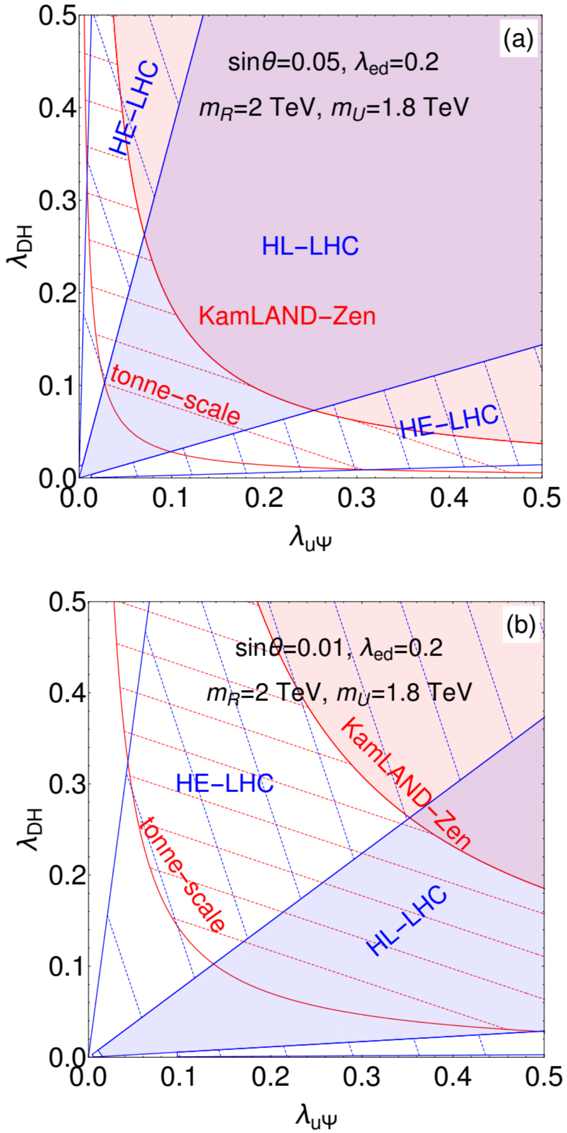



**A. Crivellin, L. Schnell, 2104.06417 (PRD)**

**Gang Li, Jiang-Hao Yu, XZ, 2311.10079**

# 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 $m_\Psi$ 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: dim-7 at one-loop, dim-9 at tree-level—comparable.
- LHC search-- LHC and 0νββ decay experiments are complementary.

**Thank you for your attention!**

# Appendix

LEFT

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

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

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

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

$$W_\mu^+ \simeq -\frac{g}{\sqrt{2}}\frac{1}{m_W^2}\left(\bar{e}_L\gamma_\mu\nu_L + V_{ud}^\dagger\bar{d}_L\gamma_\mu u_L\right)$$

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