Testing lepton number violation beyond the approach of EFTs

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Neutrinos and lepton number violation

- The unknown of neutrinos:
  - How do neutrinos get their masses? *S. Zhou's talk*
  - Are they Dirac or Majorana fermions?

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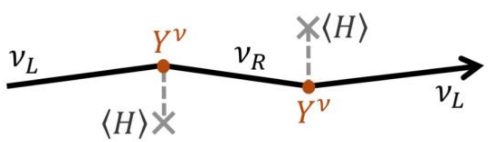
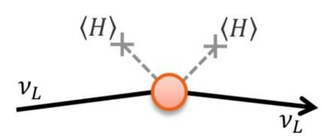
Dirac mass:



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

very small coupling

Majorana mass:



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

(very) large scale

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

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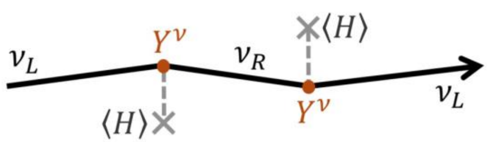

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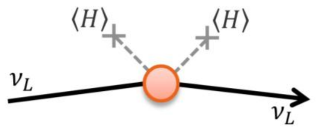


$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

(very) large scale

$\Delta L = 2$ LNV

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

clear evidence for BSM, connected to BAU **Fukugita, Yanagida 1986**

Neutrinos and lepton number violation

- The unknown of neutrinos:
  - How do neutrinos get their masses?
  - **Are they Dirac or Majorana fermions?**

S. Zhou's talk

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

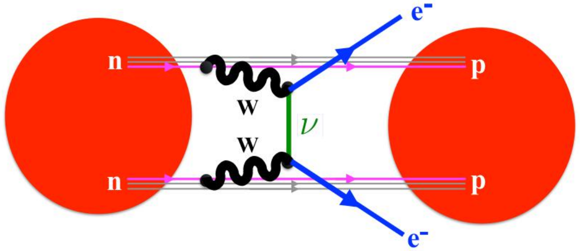
W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four

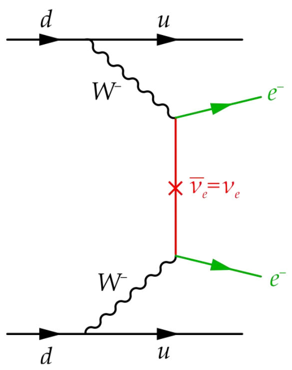
The most promising process to assess the Majorana nature of neutrinos

Neutrinoless double beta decay

- $0\nu\beta\beta$ decay in nuclei
  - at nuclear level: $(A, Z) \to (A, Z+2) + e^- + e^-$
  - at nucleon level: $nn \to ppe^-e^-$
  - at quark level: $dd \to uue^-e^-$



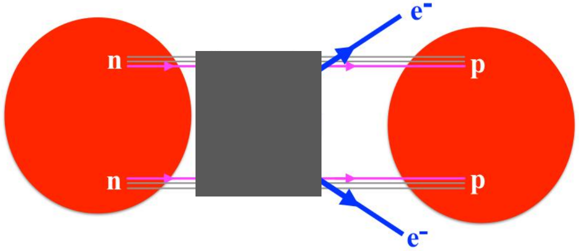
Furry, Phys. Rev. 56 (1939) 1184

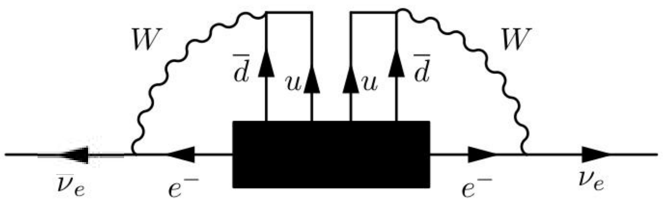


Neutrinoless double beta decay

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

Schechter-Valle theorem





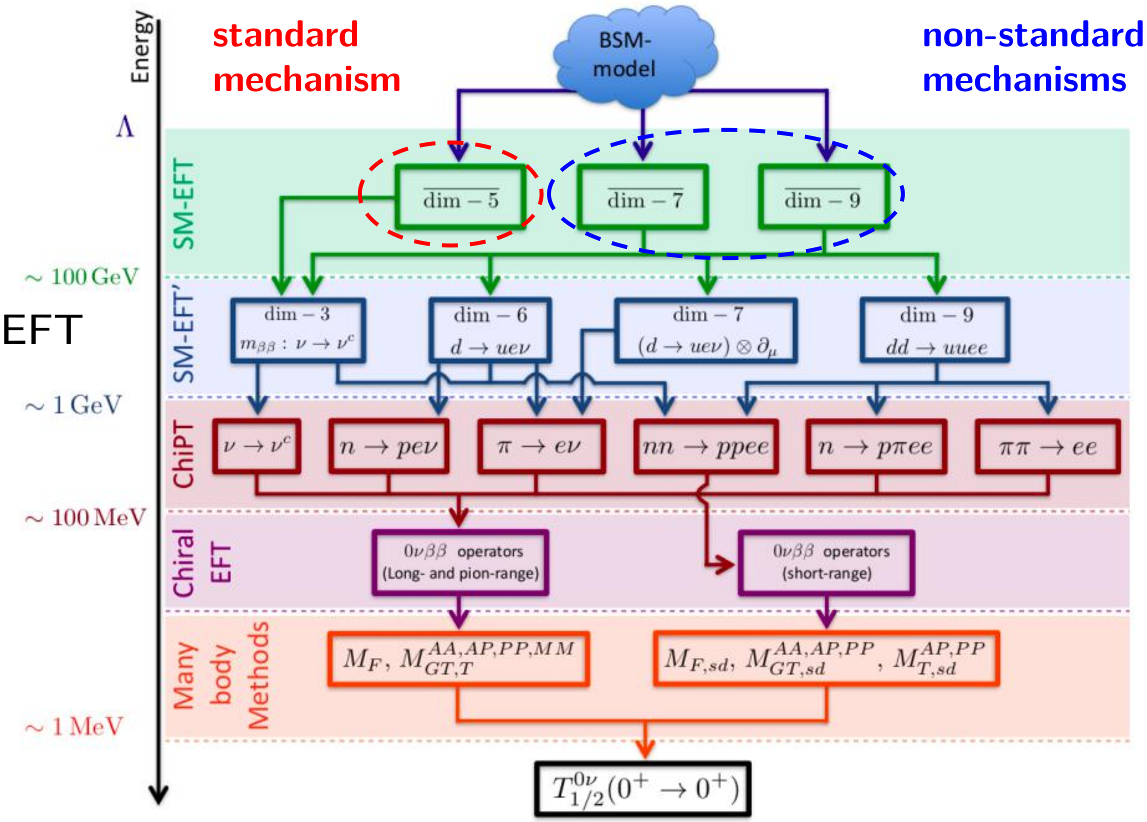
Schechter, Valle, Phys.Rev. D25 (1982) 774

Black box: various $\Delta L = 2$ LNV interactions

Effective field theory approach

- A systematic description of all $\Delta L = 2$ LNV sources

or LEFT



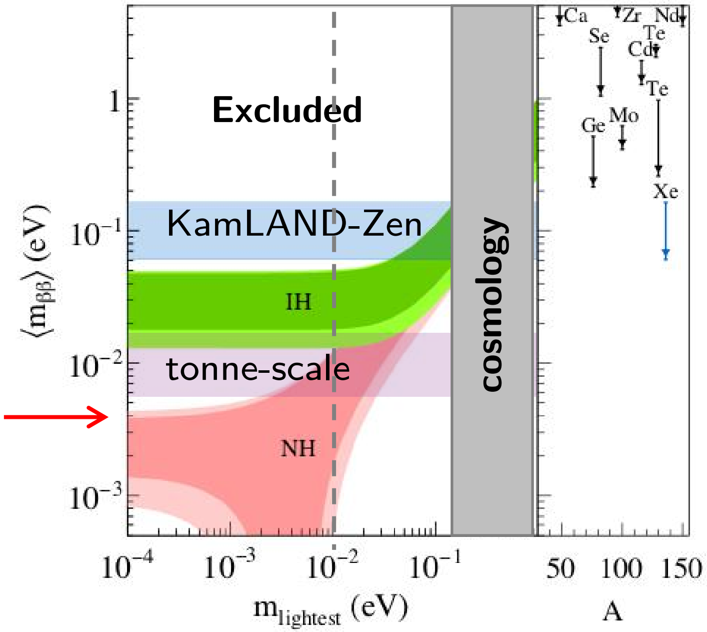
V. Cirigliano et al., 2203.12169, Snowmass 2021

Y. Liao's talk for

$K^{\pm} \to \pi^{\mp} l^{\pm} l^{\pm}$

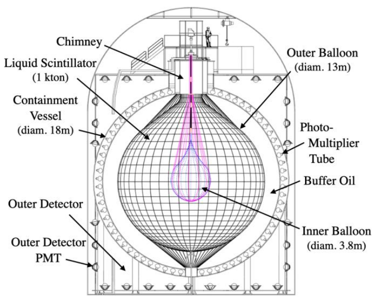
Standard mechanism

The status



combined w/ neutrino oscillation and cosmological measurements

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



$$T^{0\nu}_{1/2}(\mathrm{Xe}) > 2.3 \times 10^{26} \text{ year}$$

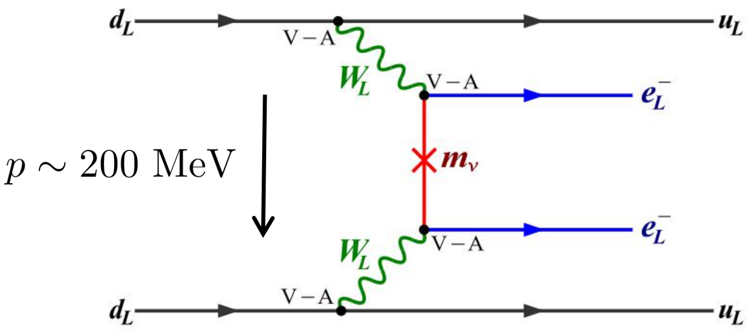
half-life effective Majorana mass

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

- $\langle m_{\beta\beta} \rangle$ is altered by involking non-standard mechanisms
- The relation is valid w/ or w/o non-std. contributions

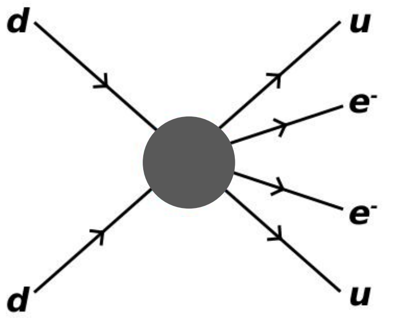
Non-standard mechanisms

Standard mechanism:



$$\sim G_F^2 m_\nu / p^2$$

Non-standard mechanisms:



$$\sim c/\Lambda^5$$

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

c: new coupling
Λ: new particle mass

A master formula

The interpretation 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)

The effective Majorana mass is a sum of

$\langle m_{\beta\beta}\rangle$ ~ LECs x Wilson Coeffs

non-perturbative QCD effects

Two ways...

- Top-down: given BSM model

    Easy to handle

    Integrate out the BSM fields → SMEFT → LEFT → ...

- Bottom-up: given EFT basis

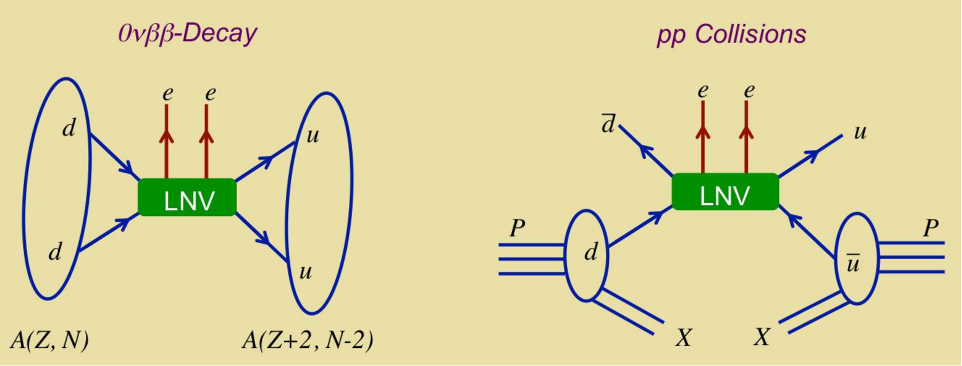
    Hard to do *Q.-H. Cao's talk*

    (1) which operator(s)?

    (2) which UV?

Beyond the EFTs

- Correlation of processes



+

LNC	direct searches
LNV	eg. $K^\pm \to \pi^\mp l^\pm l^\pm$

Y. Liao, X.-D. Ma, 1909.06272 (JHEP), 2001.07378 (JHEP)

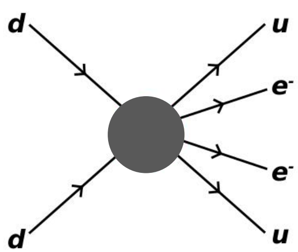
Beyond the EFTs

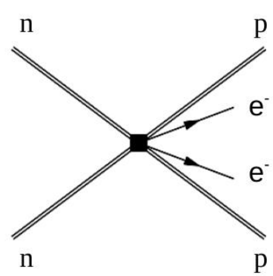
- LECs as the weights

$$\langle m_{\beta\beta}\rangle \sim \text{LECs} \times \text{Wilson Coeffs}$$

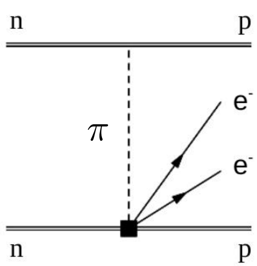
$\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$ → hadronic operators with different chiral power counting $\left(\frac{\Lambda_\chi}{p}\right)^2 \sim 25$

$\sim \Lambda_\chi$

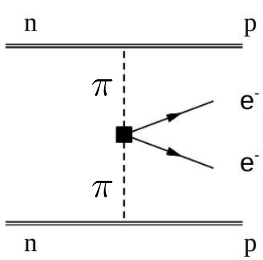




p^0



p^0



p^{-2}, p^0

Dim-9 LEFT operators

- lepton bilinear

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

- quark biliners

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

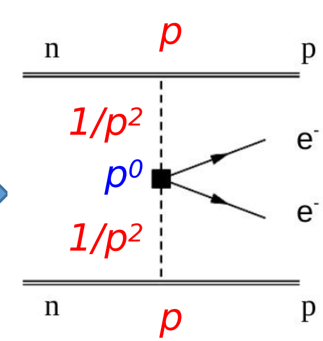
$$O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta \,, \qquad O_1' = \bar{q}_R^\alpha \gamma_\mu \tau^+ q_R^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \,,$$

$$O_2 = \bar{q}_R^\alpha \tau^+ q_L^\alpha \; \bar{q}_R^\beta \tau^+ q_L^\beta \,, \qquad O_2' = \bar{q}_L^\alpha \tau^+ q_R^\alpha \; \bar{q}_L^\beta \tau^+ q_R^\beta \,,$$

$$O_3 = \bar{q}_R^\alpha \tau^+ q_L^\beta \; \bar{q}_R^\beta \tau^+ q_L^\alpha \,, \qquad O_3' = \bar{q}_L^\alpha \tau^+ q_R^\beta \; \bar{q}_L^\beta \tau^+ q_R^\alpha \,,$$

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \,,$$

$$O_5 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha \,,$$



$$O_6^\mu = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L \tau^+ q_R\right) \,, \qquad O_6^{\mu\prime} = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R \tau^+ q_L\right) \,,$$

$$O_7^\mu = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L t^a \tau^+ q_R\right) \,, \qquad O_7^{\mu\prime} = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R t^a \tau^+ q_L\right) \,,$$

$$O_8^\mu = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R \tau^+ q_L\right) \,, \qquad O_8^{\mu\prime} = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L \tau^+ q_R\right) \,,$$

$$O_9^\mu = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R t^a \tau^+ q_L\right) \,, \qquad O_9^{\mu\prime} = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L t^a \tau^+ q_R\right) \,,$$

From EFTs to BSM models

A detection of $0\nu\beta\beta$ decay raises further questions. Foremost is the "inverse problem":

i) Are Majorana neutrino masses the correct physical explanation for such a detection? If so, what are the implications of such a detection for theoretical models of neutrino masses? If not, what are alternative interpretations? How can they be excluded?

The interpretation of $0\nu\beta\beta$ experiments and, in case of an observation, the solution of the "inverse problem" of identifying the microscopic mechanism behind a signal demand an ambitious theoretical program to: *a*) further develop particle-physics models of LNV, including simplified models that go beyond the Majorana neutrino-mass paradigm, and test them against the results of current and future $0\nu\beta\beta$ experiments, the Large Hadron Collider (LHC), and astrophysics and cosmology; *b*) compute $0\nu\beta\beta$ rates with minimal model dependence and quantifiable theoretical

V. Cirigliano et al., 2203.12169, Snowmass 2021

From EFTs to BSM models

The lesson we learn:

chPT/chiral EFT may shed light on BSM models at work

The questions we address for $0\nu\beta\beta$ decay:

1) well-motivated scenarios for chirally enhanced mechanisms

2) sensitivities to chirally suppressed mechanisms

3) different UV completions of LEFT operators

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Left-right symmetric model

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Doublets:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$$

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

Bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$

$$\boxed{\tan\beta = \frac{v_2}{v_1}}$$

Triplets:

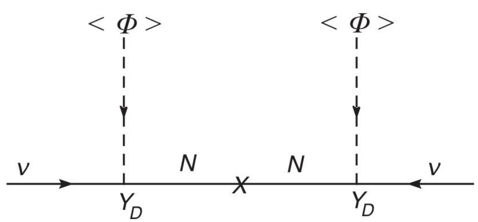
$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

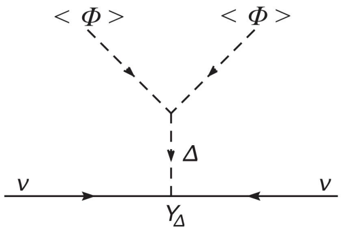
$$\Rightarrow \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

Left-right symmetric model

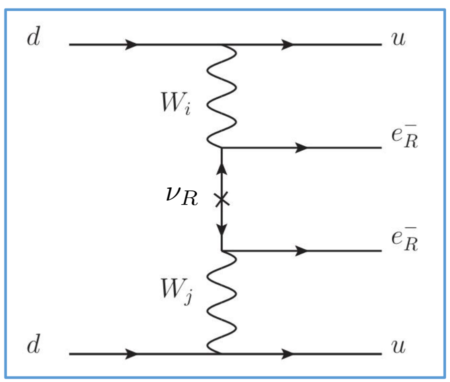
Well-motivated scenarios:

- complete model that provides natural origin of neutrino masses





- Contributions to $0\nu\beta\beta$ decay



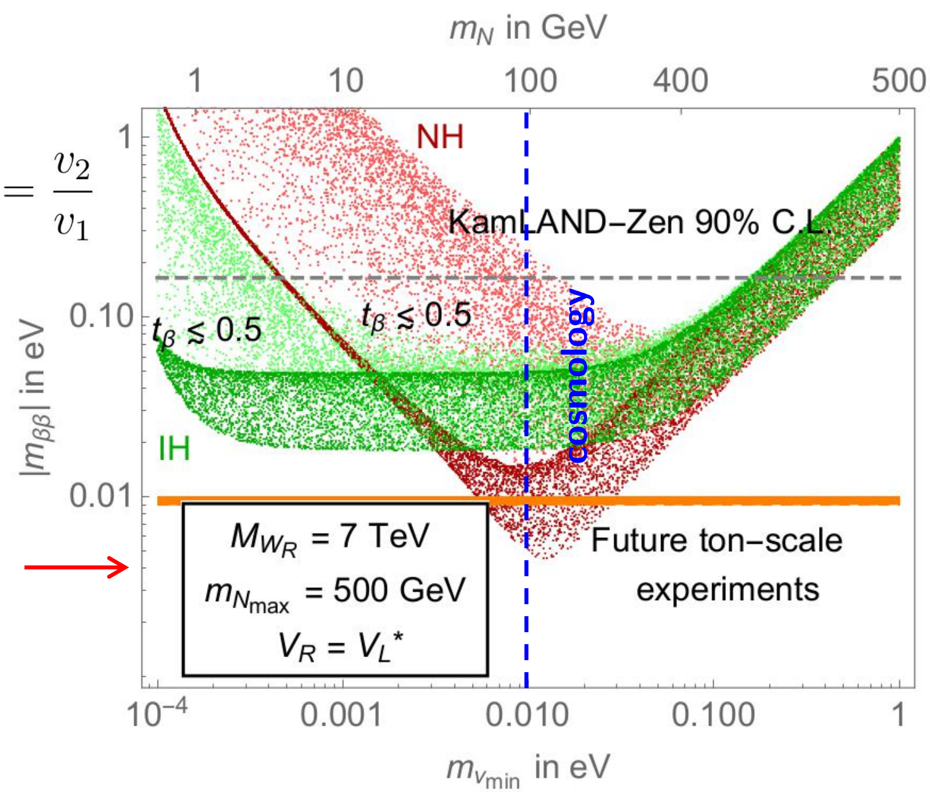
left-right mixing $\tan\zeta = \frac{M_W^2}{M_{W_R}^2}\sin(2\beta)$

chirally enhanced: $O_4 \bar{e}_R e_R^c$

Left-right symmetric model

The left-right symmetry is imposed in the Yukawa sector

$$\tan\beta = \frac{v_2}{v_1}$$



std. →

mass correlation:

$$m_N = \frac{m_1}{m_3} m_{N_{\rm max}} \quad \text{(NH)}$$

$$m_N \simeq 100 \text{ GeV} \cdot \frac{m_1}{0.01 \text{ eV}} \cdot \frac{m_{N_{\rm max}}}{500 \text{ GeV}}$$

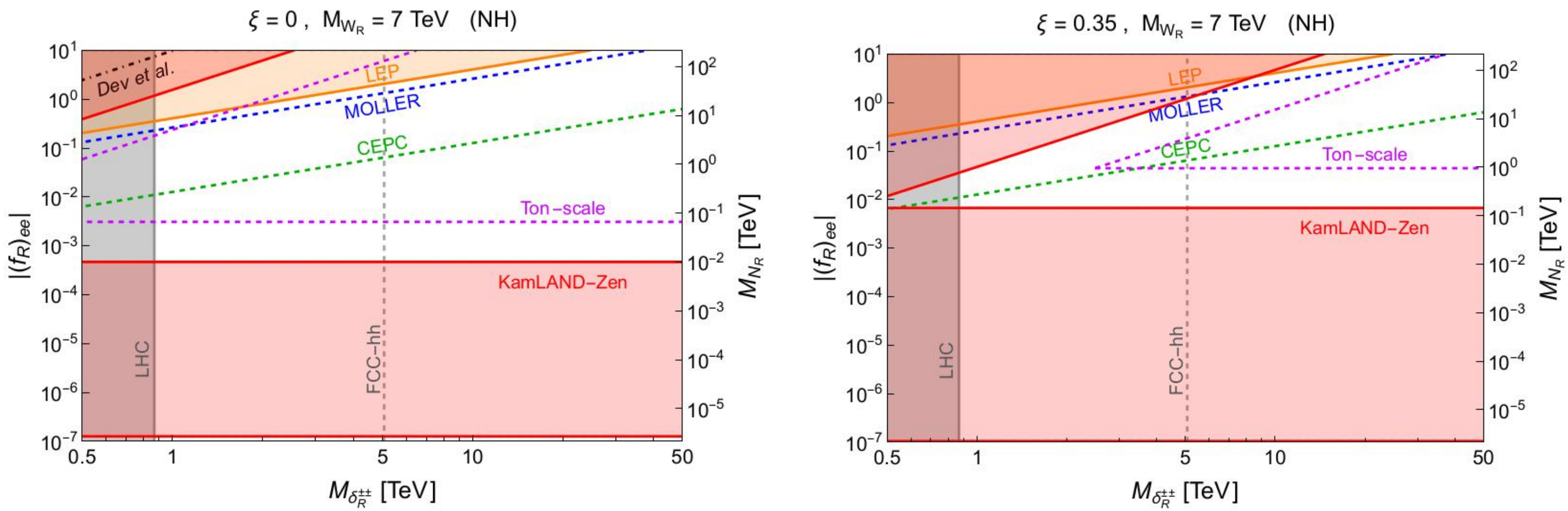
turning point at $m_{\nu_{\rm min}} \sim 0.01$ eV

- **R**: std. mechanism
- **L**: non-std. mechanism

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

Left-right symmetric model

The left-right symmetry is not imposed in the Yukawa sector



- Non-std. mechanism: doubly-charged scalar exchange can be significant
- Searches and measurements at colliders: LHC, FCC-hh, LEP, CEPC
- Low-energy precision measurements: MOLLER

GL, M. J. Ramsey-Musolf, J. C. Vasquez, S. Urrutia-Quiroga, to appear

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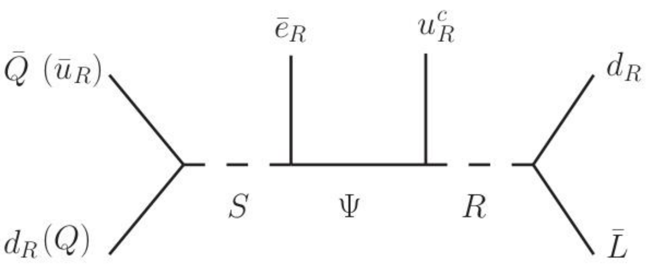
Simplified model

The Lagrangian:

$$\mathcal{L}_{\rm int} = y_{qd}\bar{Q}Sd_R + y_{qu}\bar{u}_R S^T\epsilon Q + y_{e\Psi}\bar{e}_R S^\dagger \Psi_L + \lambda_{ed}\bar{L}\epsilon R^* d_R + \lambda_{u\Psi}\bar{\Psi}_R R u_R^c + \lambda_{d\Psi}\epsilon\bar{\Psi}_L R^* d_R + y'_{e\Psi}\bar{\Psi}_L H e_R + \text{h.c.}\,,$$



scalar $S \in (1,2)_{1/2}$, leptoquark $R \in (3,2)_{1/6}$
Dirac fermion $\Psi \in (1,2)_{-1/2}$

chirally suppressed: $O^{\mu\prime}_{6,8}\bar{e}\gamma_\mu\gamma_5 e^c$

$$\frac{\mathcal{A}_{\rm vector}}{\mathcal{A}_{\rm scalar}} \simeq \frac{m_\pi^2}{m_N^2}\frac{M_{P,sd}}{M_{PS,sd}}$$

chiral power counting

$\sim 1/25$

$M_{P,sd}/M_{PS,sd}$	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
QRPA	7.8	7.8	8.3	8.5
Shell	7.3	7.6	7.6	7.8
IBM	6.3			

M. L. Graesser, **GL**, M. J. Ramsey-Musolf, T. Shen, S. Urrutia-Quiroga, 2202.01237 (JHEP)
M. Agostini et al., 2202.01787 (Rev. Mod. Phys.)

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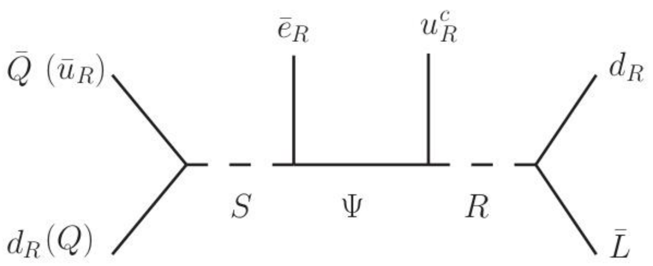

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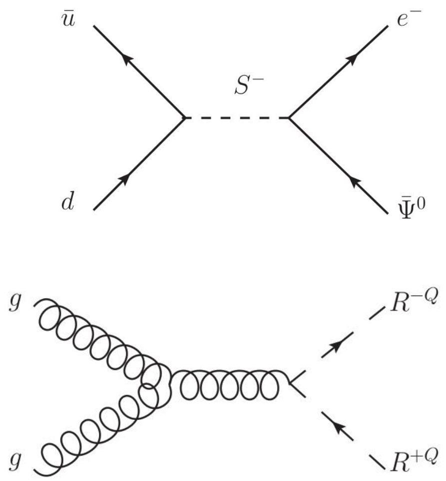
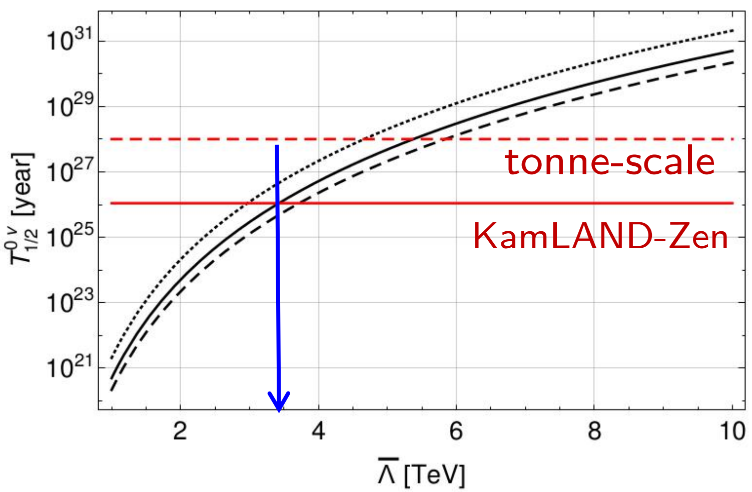
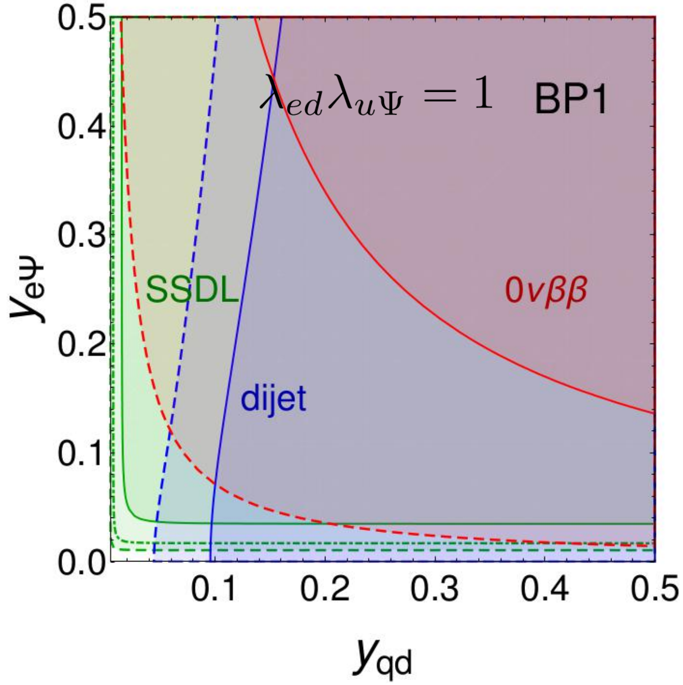
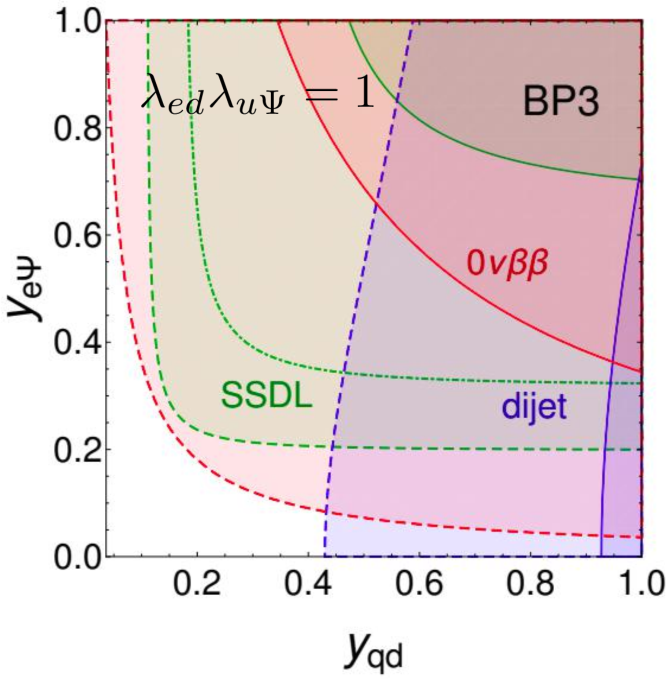




Simplified model

$0\nu\beta\beta$ decay and LHC searches





$$\text{BP1}: m_\Psi = 1.0\ \text{TeV}, m_S = 2.0\ \text{TeV}, m_R = 2.0\ \text{TeV};$$
$$\text{BP3}: m_\Psi = 1.0\ \text{TeV}, m_S = 4.5\ \text{TeV}, m_R = 2.0\ \text{TeV}.$$

M. L. Graesser, **GL**, M. J. Ramsey-Musolf, T. Shen, S. Urrutia-Quiroga, 2202.01237 (JHEP)

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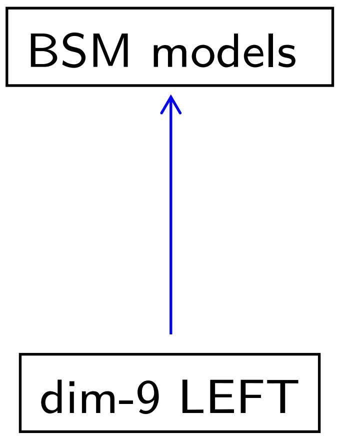
UV completion

Build up BSM models for $0\nu\beta\beta$ decay



($\Delta L = 2$ six-femion operators)

- Tree level:

  Bonnet, Hirsch, Ota, Winter, 1212.3045 (JHEP)

- One-loop level:

  Chen, Ding, Yao, 2110.15347 (JHEP)

The possibility of left-right symmetric model as the **tree-level** realization of chirally enhanced $0\nu\beta\beta$ decay operator is missing!

UV completion

Build up BSM models for $0\nu\beta\beta$ decay

BSM models

↑

dim-7, 9 SMEFT

↑

dim-9 LEFT

($\Delta L = 2$ six-femion operators)

Operator bases: **Lehman 2014; Liao & Ma 2016, 2020; Li et al, 2020**

Tree-level UV completion can be performed more systematically

X.-X. Li, J.-H. Yu, 2307.10380
H.-L. Li et al., 2204.03660 (JHEP)

UV completion

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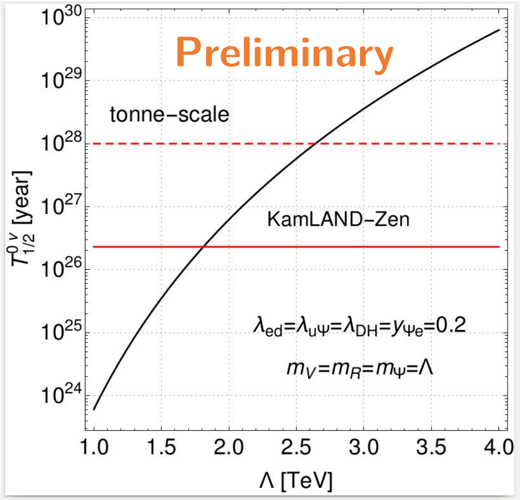
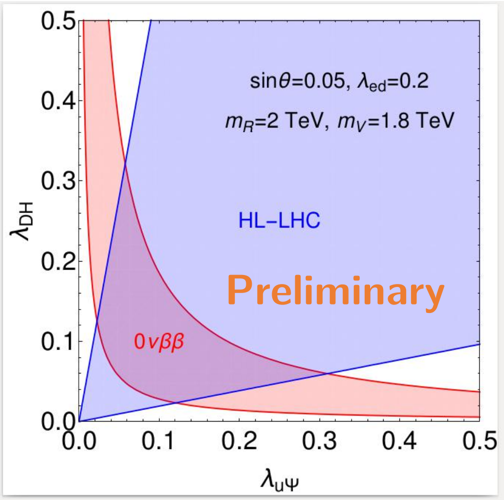
$$O_4 \bar{e}_R e_R^c \qquad\qquad O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta$$

- left-right symmetric model
- simplified models: eg. leptoquark $V \in (3,1)_{2/3}$, leptoquark $R \in (3,2)_{1/6}$
  Dirac fermion $\Psi \in (1,2)_{-1/2}$





GL, Jiang-Hao Yu, Xiang Zhao, in preparation

Summary

- EFTs provide a systematic description of $0\nu\beta\beta$ decay of BSM models of LNV

$$\mathcal{L}_{\Delta L=2} \supset \frac{C^{(5)}}{\Lambda} O^{(5)} + \frac{C^{(7)}}{\Lambda^3} O^{(7)} + \frac{C^{(9)}}{\Lambda^5} O^{(9)+\cdots}$$

- Going beyond the EFTs to test LNV enables complementary assessment of non-standard $0\nu\beta\beta$-decay mechanisms

- We address the following questions for $0\nu\beta\beta$ decay:

    1) well-motivated scenarios for chirally enhanced mechanisms

    2) sensitivities to chirally suppressed mechanisms

    3) different UV completions of LEFT operators