Lepton Number Violation: from $0\nu\beta\beta$ decay to collider searches

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Outline

- Neutrinos and lepton number violation (LNV)
- LNV: $0\nu\beta\beta$ decay and collider searches
- Effective field theory (EFT) approach to $0\nu\beta\beta$ decay
- Two case studies in the framework of simplified models:
  - chirally enhanced $0\nu\beta\beta$ decay and displaced searches
  - chirally suppressed $0\nu\beta\beta$ decay and prompt searches

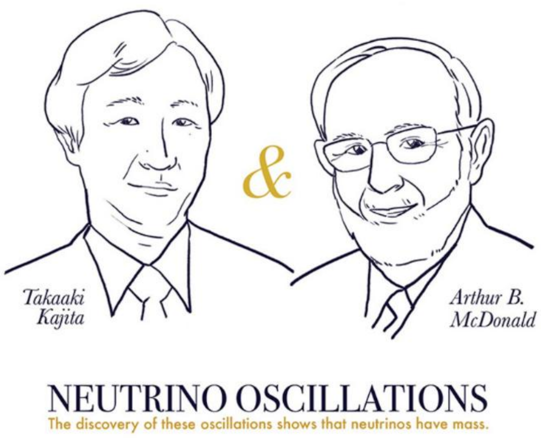
Neutrinos: what we know

- Neutrinos in the SM are **massless**

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad m_\nu = 0$$

- Neutrino mixing

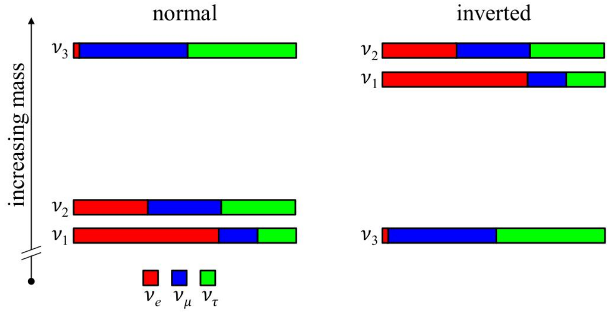
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Neutrino oscillations require **massive** neutrinos

$$P(\nu_i \to \nu_j) \propto \Delta m^2_{ij} \qquad \begin{aligned} \Delta m^2_{21} &\approx 7.5 \times 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m^2_{31}| &\approx 2.5 \times 10^{-3}\ \mathrm{eV}^2 \end{aligned}$$

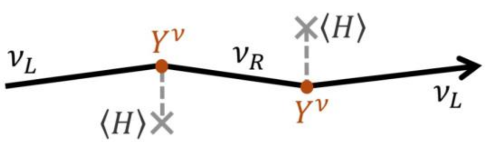
- Normal vs inverted hierarchy



Neutrinos: what we do not know

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

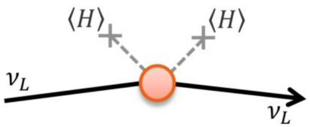
Dirac mass:



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

very small coupling

Majorana mass:



"Weinberg operator"

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

(very) large scale

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

Neutrinos and lepton number violation

- How can we test if neutrinos are Dirac or Majorana fermions?

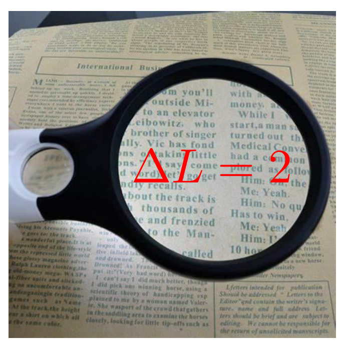
Dirac mass:

$$\mathcal{L}_D = -(Y^\nu \underset{-1}{\bar{L}} H \underset{+1}{\nu_R} + \text{h.c.})$$

Majorana mass:

$$\mathcal{L}_M = \frac{C_5}{\Lambda} \underset{+1}{(\bar{L}^c \tilde{H}^*)} \underset{+1}{(\tilde{H}^\dagger L)} + \text{h.c.}$$

Lepton number is violated by two units $\Delta L = 2$ if there exists Majorana neutrino mass term

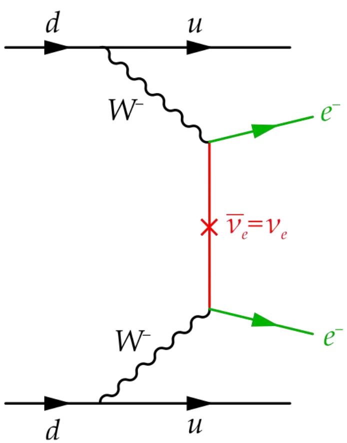


Neutrinoless double beta decay

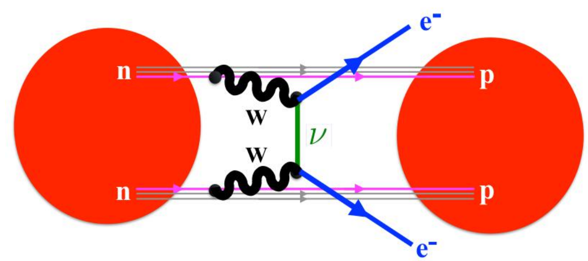
- Why search for $0\nu\beta\beta$ decay?

If neutrino is Majorana fermion, $0\nu\beta\beta$ decay process is induced

Majorana mass:



$0\nu\beta\beta$ decay:



$$(A, Z) \to (A, Z+2) + e^- + e^-$$

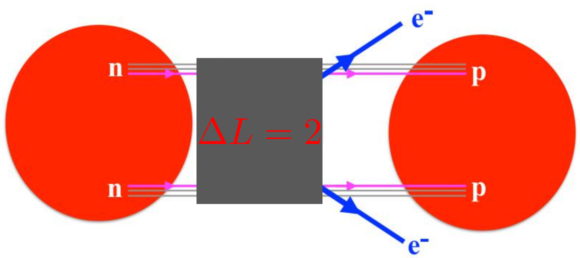
Furry, Phys. Rev. 56 (1939) 1184

Neutrinoless double beta decay

- Why search for $0\nu\beta\beta$ decay?

An observation of $0\nu\beta\beta$ decay implies LNV $\Delta L = 2$ and Majorana neutrino mass

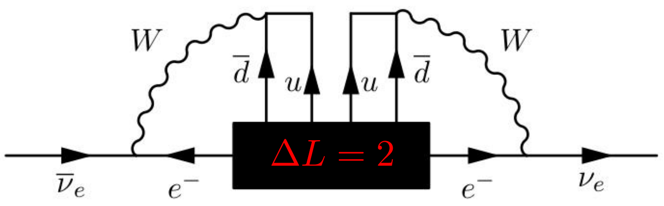
$0\nu\beta\beta$ decay:



$$(A, Z) \to (A, Z+2) + e^- + e^-$$

Majorana mass:

"Black box theorem"

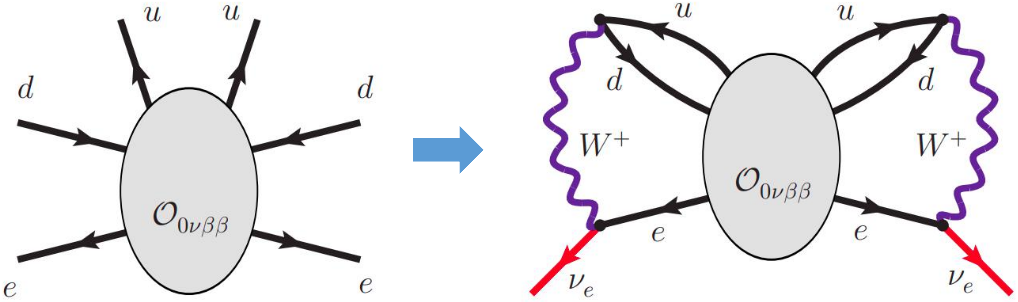


Schechter, Valle, Phys.Rev. D25 (1982) 774

Solid theoretical motivations for studying $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay and neutrino masses

- Caveat:



$$\delta m_\nu = \mathcal{O}(10^{-28}\ \mathrm{eV})$$

M. Duerr, M. Lindner, A. Merle, 1105.0901 (JHEP)
J.-H. Liu, J. Zhang, S. Zhou, 1606.04886 (PLB)

$0\nu\beta\beta$ decay operators only give a tiny contribution to the observed neutrino masses

$0\nu\beta\beta$ decay and neutrino masses

- Way out:

1) Observed neutrino masses are generated at **lower** loop order or even **tree** level

   GL, Ramsey-Musolf, Su, Vasquez, 2109.08172 (PRD)

   GL, Michael J. Ramsey-Musolf, Juan Carlos Vasquez, 2009.01257 (PRL); 2202.01789 (PRD)

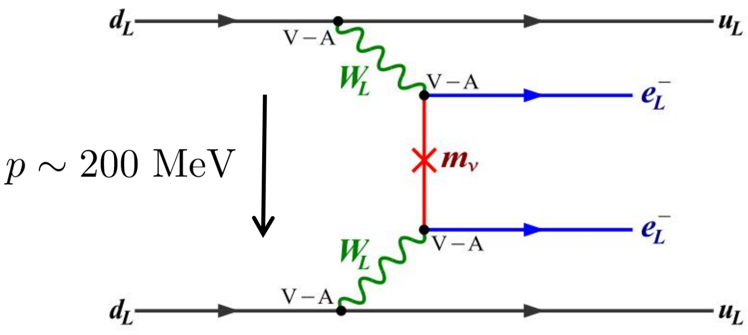
2) LNV responsible for $0\nu\beta\beta$ decay **partially** contributes to the observed neutrino masses

   Graesser, **GL**, Ramsey-Musolf, Shen, Urrutia-Quiroga, 2202.01237 (JHEP)

$0\nu\beta\beta$ decay and observed neutrino masses may or <u>may not</u> be correlated

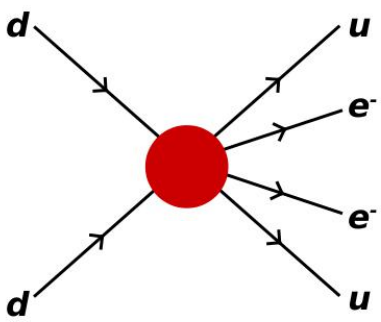
$0\nu\beta\beta$ decay mechanisms

Standard mechanism:



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

Non-standard mechanisms:



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

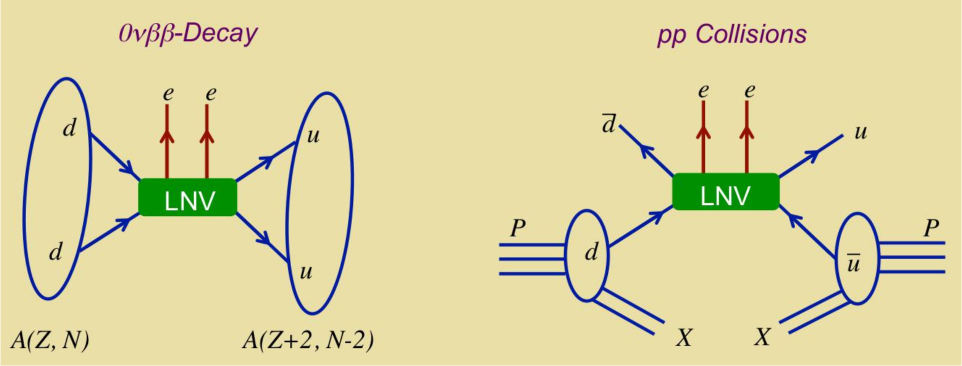
$$\boxed{\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee}/p^2} = c(\frac{3.3\ \mathrm{TeV}}{\Lambda})^5 \frac{0.1\ \mathrm{eV}}{m_\nu^{ee}}}$$

c: new coupling
Λ: heavy particle mass

Contributions from non-standard mechanisms and standard mechanism are comparable if $c \sim \mathcal{O}(1), \Lambda \sim \mathcal{O}(\mathrm{TeV})$

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

- What's the relation with LHC?
  - By itself, an observation of $0\nu\beta\beta$ decay would not point to the underlying mechanism
  - We need complementary probes:



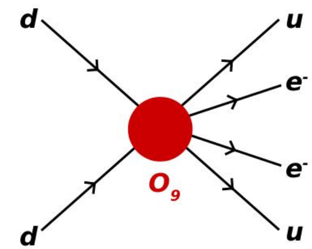
M. Ramsey-Musolf

EFT approach to $0\nu\beta\beta$ decay

Describe all $\Delta L = 2$ LNV sources systematically and consistently

Λ		
	LNV BSM models	integrate out BSM fields
? TeV		
	SM EFT	integrate out heavy SM fields
~100 GeV		
	low-energy EFT $\mathcal{L}(u, d, \nu, e)$	lattice QCD input
~1 GeV		
	chiral EFT $\mathcal{L}(N, \pi, \nu, e)$	construct two-nucleon $0\nu\beta\beta$-decay operators
~100 MeV		
	many-body methods	nuclear matrix elements
~1 MeV		
	$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$	

EFT approach to $0\nu\beta\beta$ decay



Below the EW scale, $SU(3)_C \times U(1)_{\mathrm{em}}$ invariant operators

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

scalar operators

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

vector operators

$$\begin{aligned}
O_6^\mu &= \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L \tau^+ q_R\right) \,, & O_6^{\mu\,\prime} &= \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R \tau^+ q_L\right) \,, \\
O_7^\mu &= \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L t^a \tau^+ q_R\right) \,, & O_7^{\mu\,\prime} &= \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R t^a \tau^+ q_L\right) \,, \\
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\end{aligned}$$

G. Prezeau, M. Ramsey-Musolf, P. Vogel, Phys.Rev.D 68 (2003) 034016; M. Graesser JHEP 08 (2017) 099; V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, E. Mereghetti 1806.02780 (JHEP)

EFT approach to $0\nu\beta\beta$ decay

At $\Lambda_\chi \sim 1$ GeV scale, match quark operators to hadronic operators using chiral effective field theory

scalar operators

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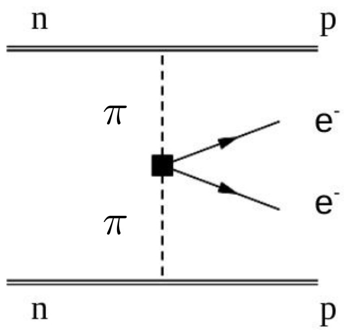
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \, \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha \,,
\end{aligned}
$$



■ LNV interaction

Based on chiral transformation property:

$$O_{2,3,4,5},\ O_{2,3}' : \quad \pi\pi ee$$

$$O_1,\ O_1' : \quad \partial_\mu \pi \partial^\mu \pi ee$$

EFT approach to $0\nu\beta\beta$ decay

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<u>*scalar operators*</u>

$$
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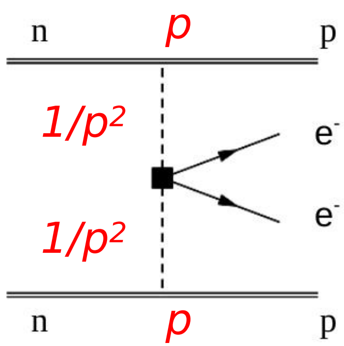
\end{aligned}
$$



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

In chiral power counting:

chirally enhanced/suppressed

$$O_{2,3,4,5},\ O'_{2,3}:\quad \pi\pi ee \qquad \Rightarrow \qquad \mathcal{A}_{0\nu\beta\beta} \sim p^{-2}$$

$$O_1,\ O'_1:\quad \partial_\mu\pi\partial^\mu\pi ee \qquad \Rightarrow \qquad \mathcal{A}_{0\nu\beta\beta} \sim p^{0}$$

$$\boxed{\frac{\Lambda_\chi^2}{p^2} \simeq 25}$$

EFT approach to $0\nu\beta\beta$ decay

At $\Lambda_\chi \sim 1$ GeV scale, match quark operators to hadronic operators using chiral effective field theory

scalar operators

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\end{aligned}
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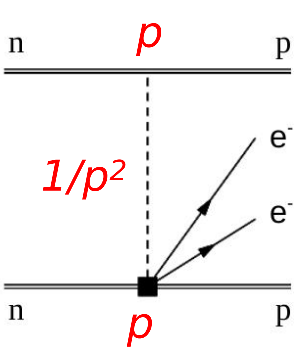
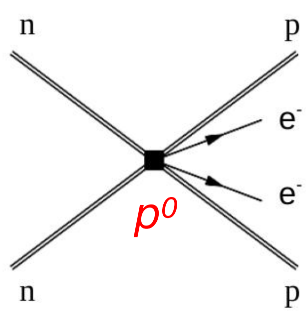
chirally suppressed





$$\mathcal{A}_{0\nu\beta\beta} \sim p^0$$

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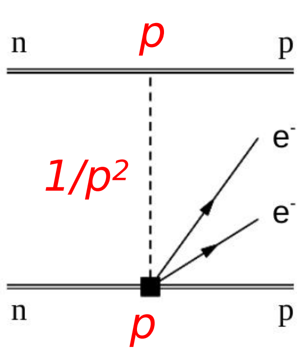
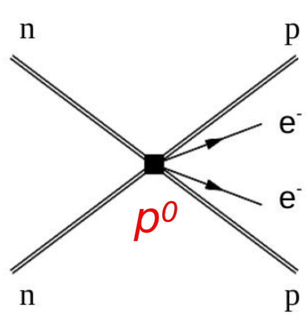
O_9^\mu &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)(\bar{q}_R t^a \tau^+ q_L) \,, & O_9^{\mu\prime} &= (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)(\bar{q}_L t^a \tau^+ q_R) \,,
\end{aligned}
$$

In chiral power counting:

chirally suppressed





$$\mathcal{A}_{0\nu\beta\beta} \sim p^0$$

A case study

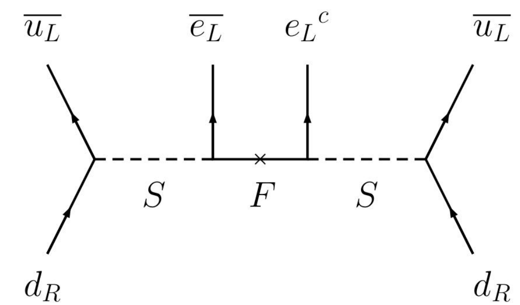
Simplified model that induces chirally **enhanced** $0\nu\beta\beta$ decay

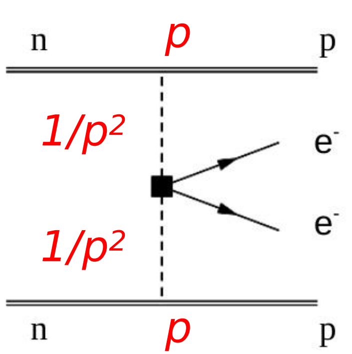
$$\mathcal{L} = (\partial_\mu S)^\dagger \partial^\mu S - m_S^2 S^\dagger S + \frac{1}{2}\bar{F}^c(i\partial\!\!\!/ - m_F)F + g_Q \bar{Q}_L S d_R + g_L \bar{L}\tilde{S}F + \text{h.c.}$$

doublet scalar S: $(1,2)_{1/2}$ -- slepton

Majorana fermion F: $(1,1)_0$ -- neutralino

RPV SUSY





scalar operators

$$\boxed{O_2' = \bar{q}_L^\alpha \tau^+ q_R^\alpha \; \bar{q}_L^\beta \tau^+ q_R^\beta}$$

$$O_2' : \quad \pi\pi ee \quad \Rightarrow \quad \mathcal{A}_{0\nu\beta\beta} \sim p^{-2}$$

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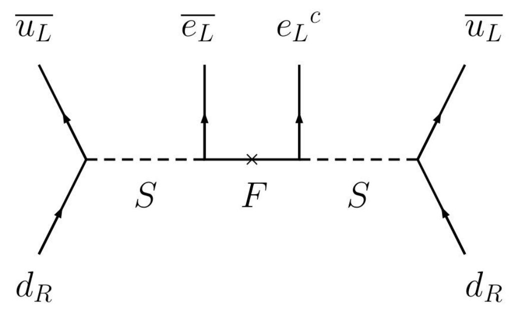
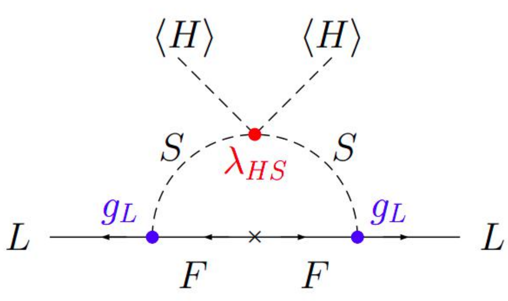
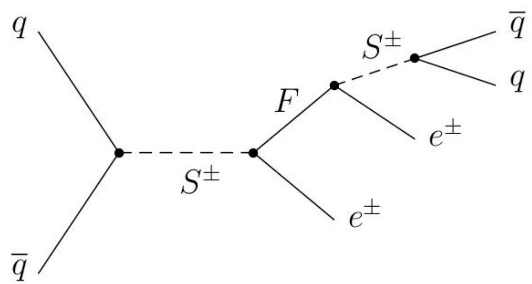


Lepton number is violated by the mass term of F

neutrino mass at one-loop level:
$\lambda_{HS} \to 0$



LHC searches:

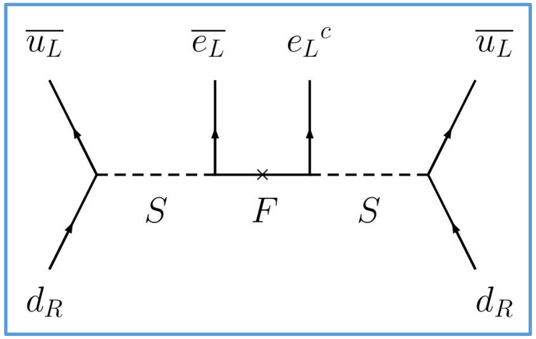


A case study

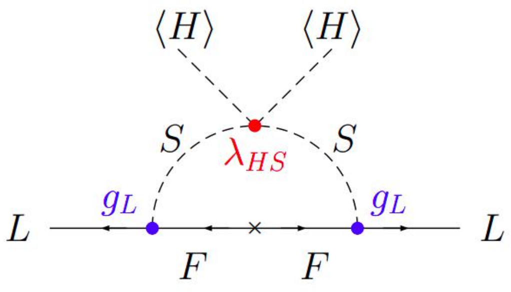
Simplified model that induces chirally **enhanced** $0\nu\beta\beta$ decay

$$\mathcal{L} = (\partial_\mu S)^\dagger \partial^\mu S - m_S^2 S^\dagger S + \frac{1}{2}\bar{F}^c(i\not\partial - m_F)F$$
$$+ g_Q \bar{Q}_L S d_R + g_L \bar{L}\tilde{S}F + \text{h.c.}$$

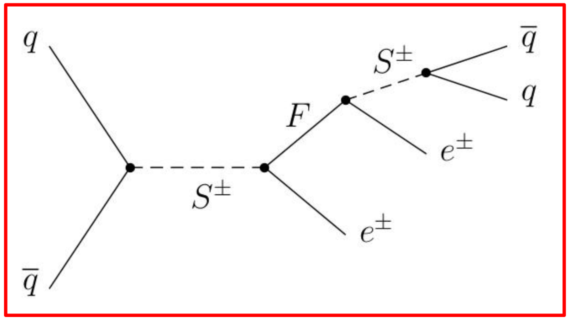
Lepton number is violated by the mass term of F



neutrino mass at one-loop level:
$\lambda_{HS} \to 0$

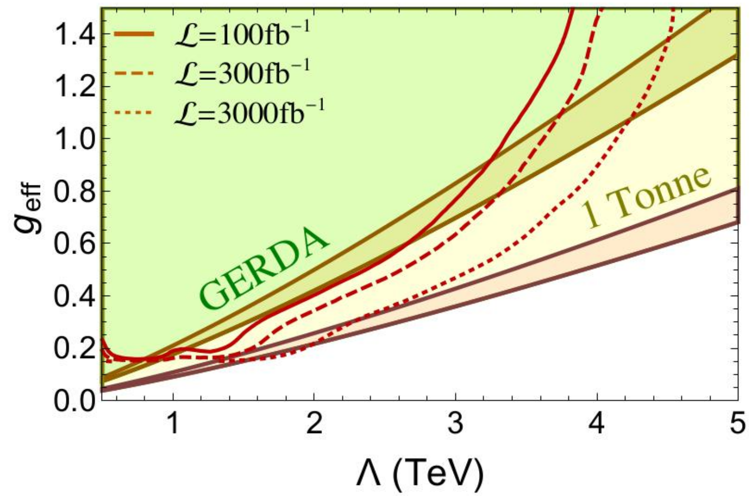


LHC searches:



A case study

LNV in different regimes

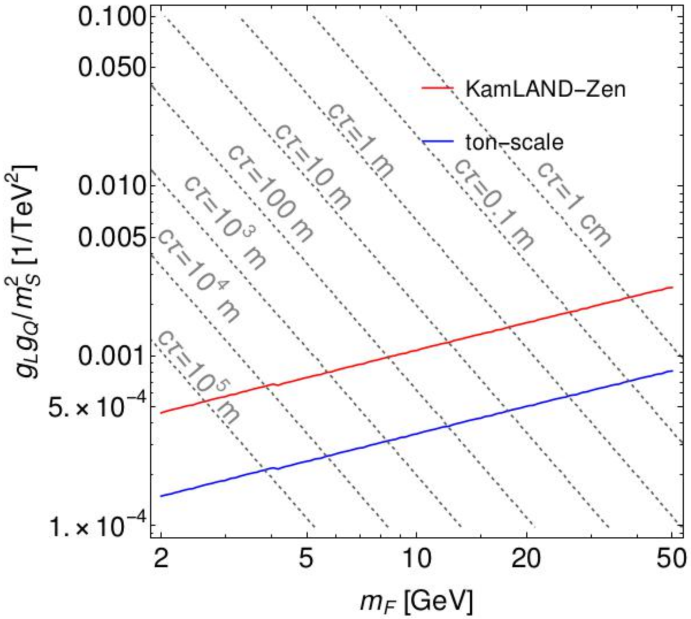


$g_{\text{eff}} = g_L g_Q$

$\Lambda = m_S = m_F$

T. Peng, M. Ramsey-Musolf, P. Winslow, 1508.04444 (PRD)

proper decay length $c\tau$



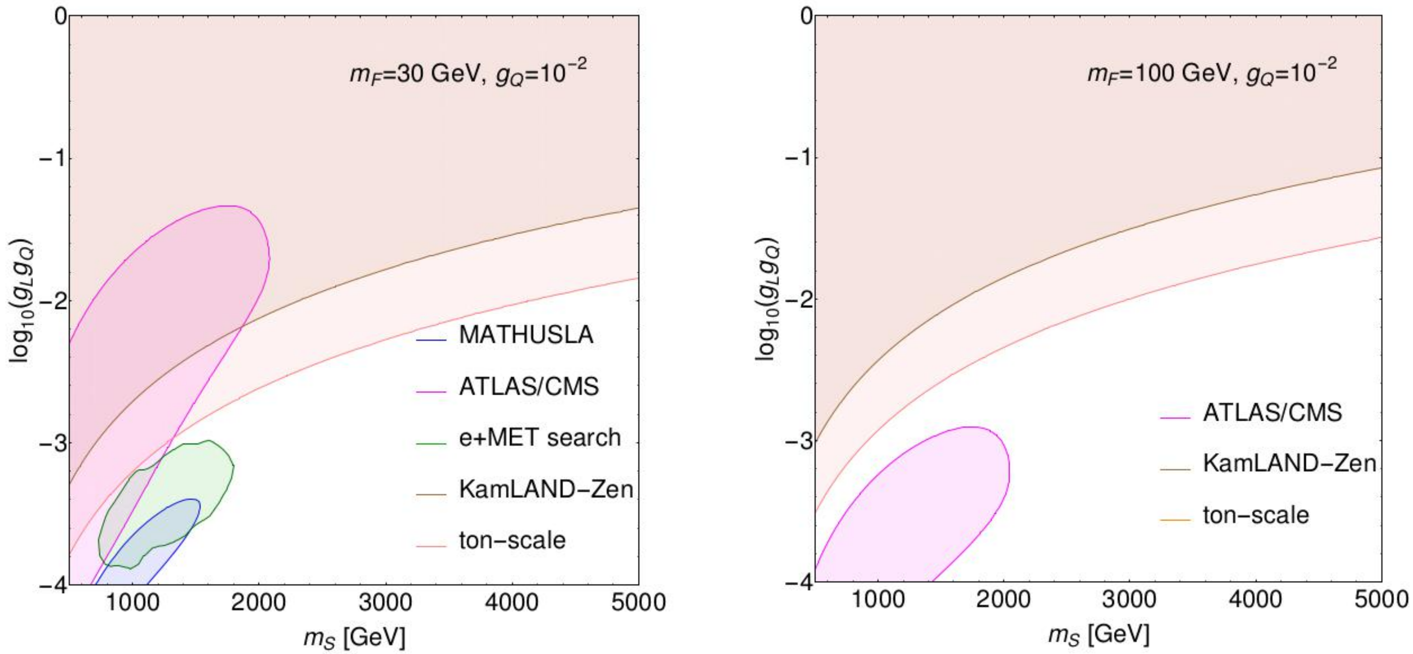
$\Lambda = m_S \gg m_F$

GL, M. J. Ramsey-Musolf, S. Su, J. C. Vasquez, 2109.08172 (PRD)

F is a long-lived particle

A case study

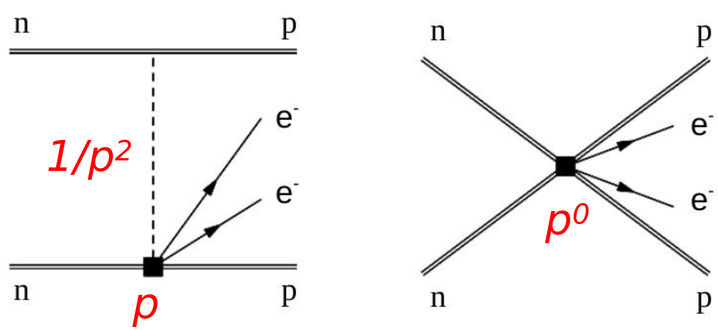
$0\nu\beta\beta$ decay and displaced searches at the LHC for LNV



GL, M. J. Ramsey-Musolf, S. Su, J. C. Vasquez, 2109.08172 (PRD)

$0\nu\beta\beta$ decay for vector operators

The contributions of vector operators to $0\nu\beta\beta$ decay are chirally suppressed respect to the scalar operators (except for O_1, O_1')



$\sim p^0$

However, we find that the ratio of amplitudes also depends on the NMEs

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

$M_{P,sd}/M_{PS,sd}$	^{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			

chiral power counting

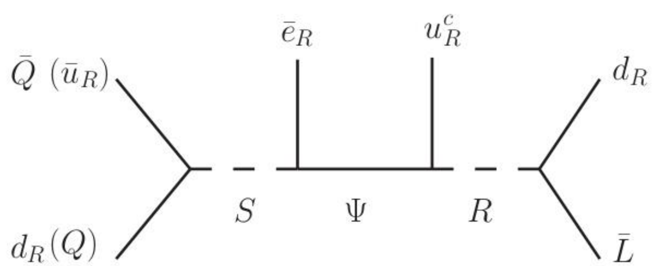
$\sim 1/25$

M. L. Graesser, **GL**, M. J. Ramsey-Musolf, T. Shen, S. Urrutia-Quiroga, 2202.01237 (JHEP)
M. Agostini, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani, 2202.01787 (JHEP)

Yet another case study

Simplified model that induces chirally **suppressed** $0\nu\beta\beta$ decay

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



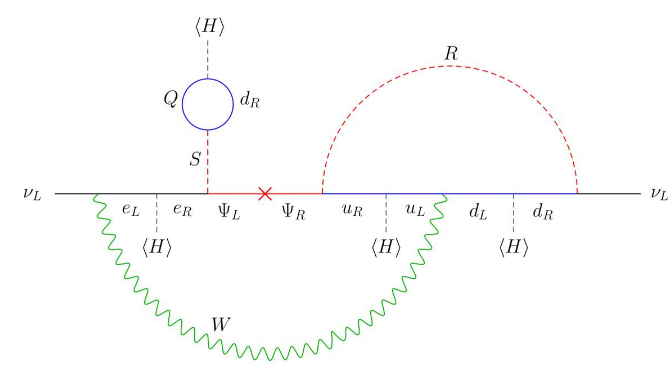
scalar $S \in (1,2)_{1/2}$, leptoquark $R \in (3,2)_{1/6}$
Dirac fermion $\Psi \in (1,2)_{-1/2}$

vector operators

$$O_6^{\mu\,\prime} = \left(\bar{q}_R\tau^+\gamma^\mu q_R\right)\left(\bar{q}_R\tau^+ q_L\right)\ ,$$
$$O_7^{\mu\,\prime} = \left(\bar{q}_R t^a\tau^+\gamma^\mu q_R\right)\left(\bar{q}_R t^a\tau^+ q_L\right)\ ,$$
$$O_8^{\mu\,\prime} = \left(\bar{q}_R\tau^+\gamma^\mu q_R\right)\left(\bar{q}_L\tau^+ q_R\right)\ ,$$
$$O_9^{\mu\,\prime} = \left(\bar{q}_R t^a\tau^+\gamma^\mu q_R\right)\left(\bar{q}_L t^a\tau^+ q_R\right)\ ,$$

Lepton number is violated by the leptoquark interactions

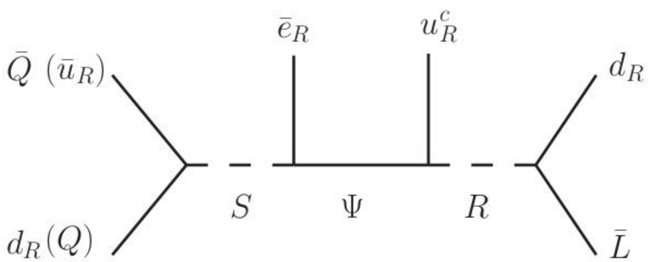
neutrino mass at three-loop level:



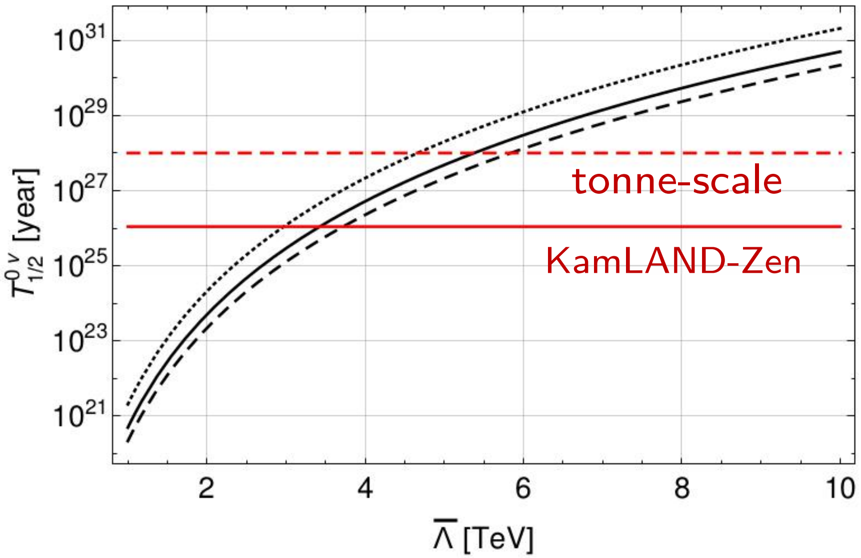
Yet another case study

Simplified model that induces chirally **suppressed** $0\nu\beta\beta$ decay

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



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



$0\nu\beta\beta$ decay can probe the LNV scale

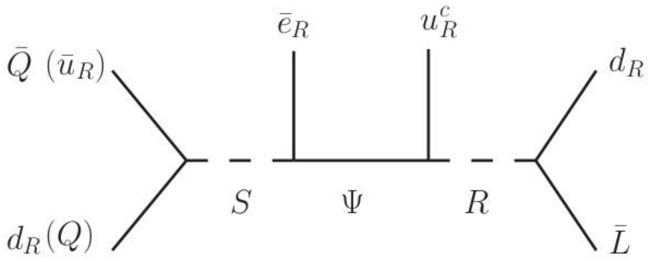
$$\bar{\Lambda} \lesssim 4.5 - 6 \text{ TeV}$$

which is in the reach of LHC

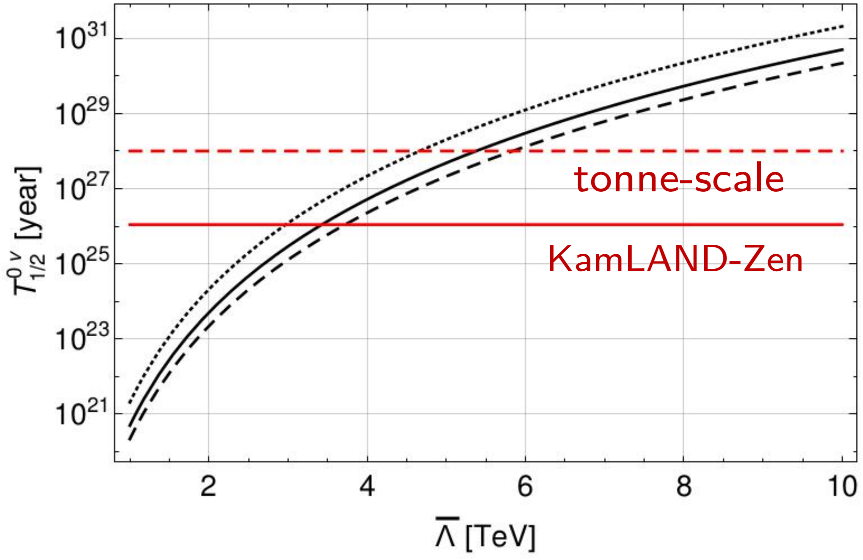
Yet another case study

Simplified model that induces chirally **suppressed** $0\nu\beta\beta$ decay

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



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

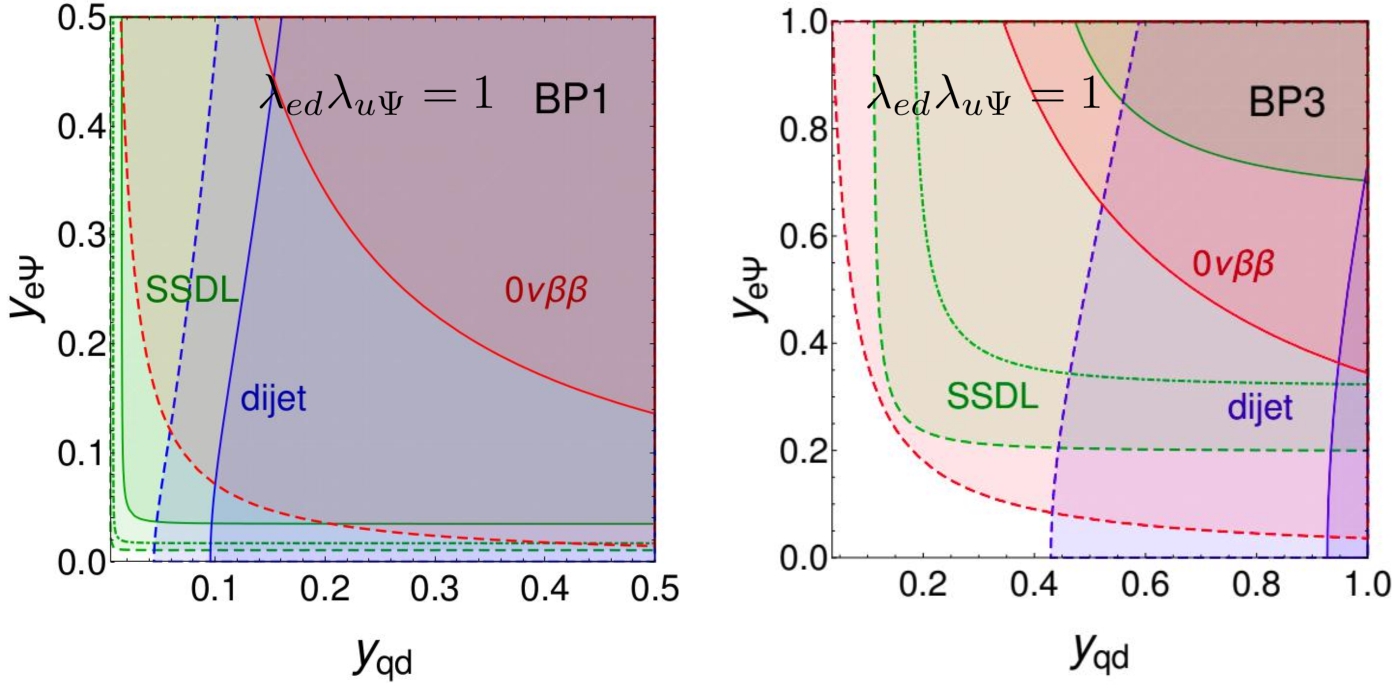


LHC searches:

- same-sign dilepton search
- dijet search
- leptoquark search

Yet another case study

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



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

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

Summary

- LNV $\Delta L = 2$ is of great interest from both theoretical and experimental aspects

- $0\nu\beta\beta$ decay can be induced by effective operators, which may be uncorrelated with observed neutrino masses

- LHC searches can help to uncover the underlying mechanisms of $0\nu\beta\beta$ decay and may point to possible physics beyond the SM