Testing lepton number violation beyond the approach of EFTs

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Based on

2009.01257, 2109.08172, 2202.01237 + work in progress

Topics of Particle, Astro and Cosmo Frontiers (TOPAC 2023)

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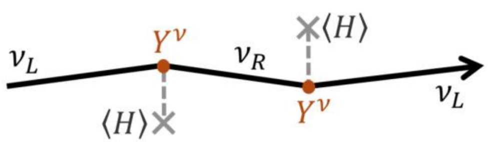
Neutrinos and lepton number violation

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

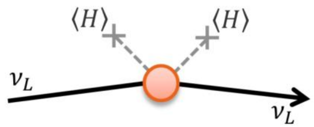
Dirac mass:



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

very small coupling

Majorana mass:



"Weinberg operator"

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

(very) large scale

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

$\Delta L = 2$ LNV

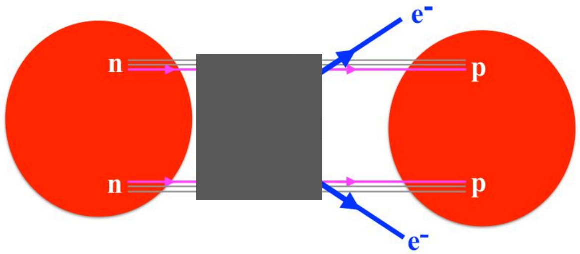
clear evidence for BSM, connected to BAU

Neutrinoless double beta decay

- Schechter-Valle theorem:

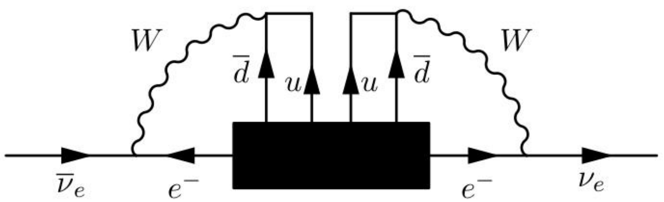
  An observation of $0\nu\beta\beta$ decay undoubtedly implies the Majorana nature of neutrinos

$0\nu\beta\beta$ decay:



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

Majorana mass:

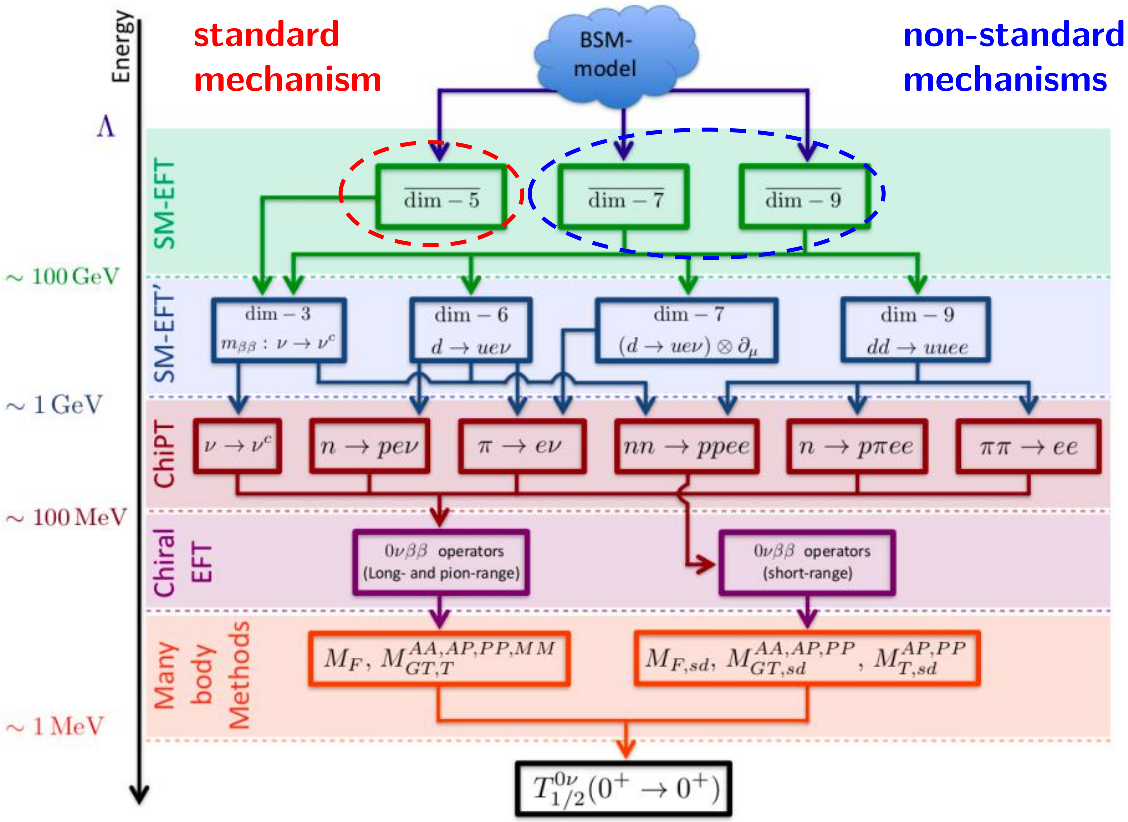


Schechter, Valle, Phys.Rev. D25 (1982) 774

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

Effective field theory approach

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

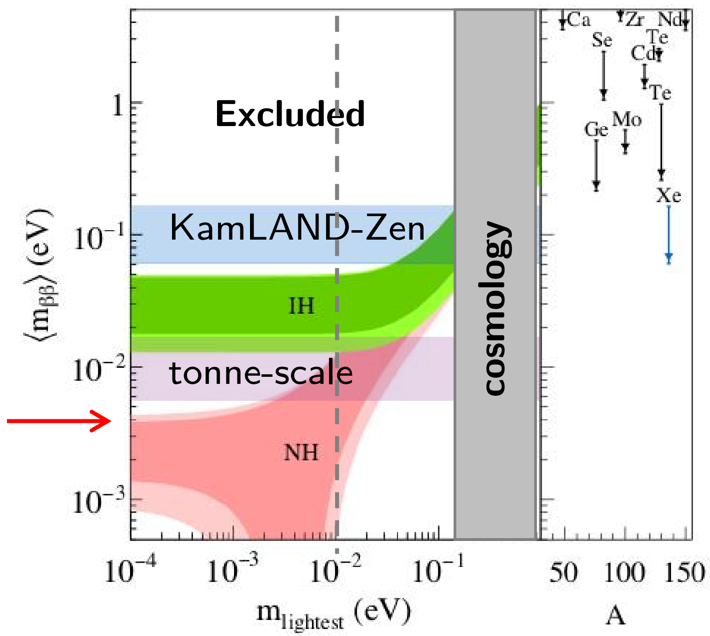


V. Cirigliano et al., 2203.12169, Snowmass 2021

Standard mechanism

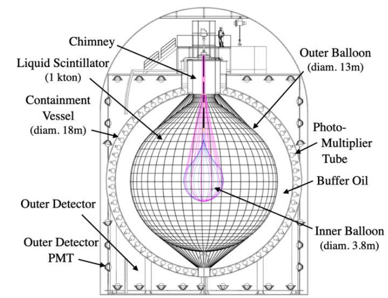
The status

see Ke Han's talk



combined w/ neutrino oscillation and cosmological measurements

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



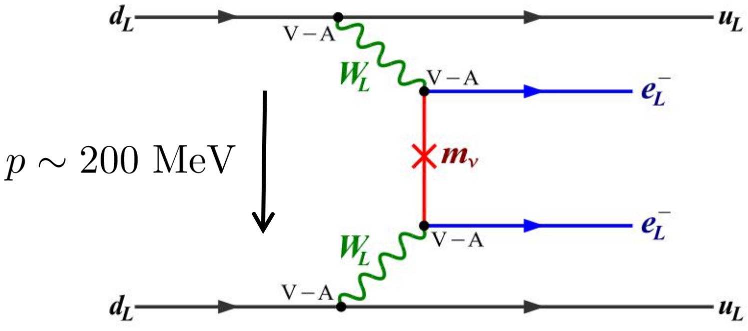
$$T^{0\nu}_{1/2}(\mathrm{Xe}) > 1.07 \times 10^{26} \text{ year}$$

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

$\langle m_{\beta\beta}\rangle$ is altered by involking non-standard mechanism(s)

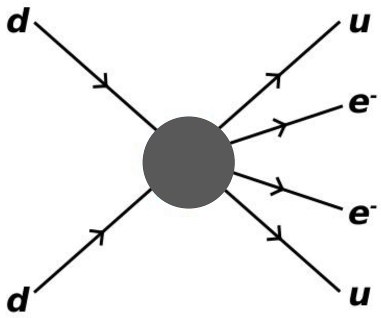
Non-standard mechanisms

Standard mechanism:



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

Non-standard mechanisms:



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

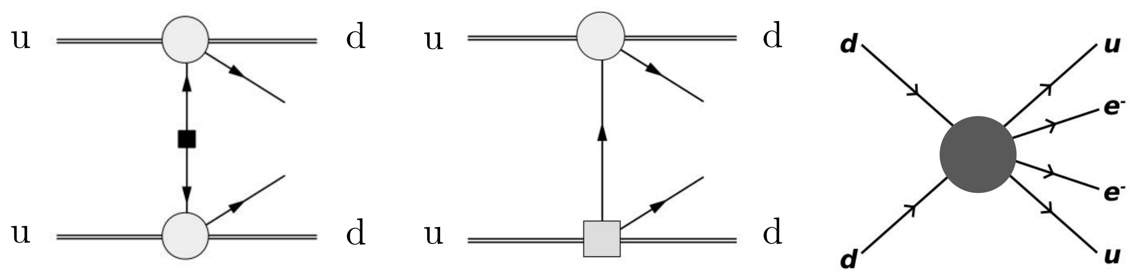
An estimate:

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

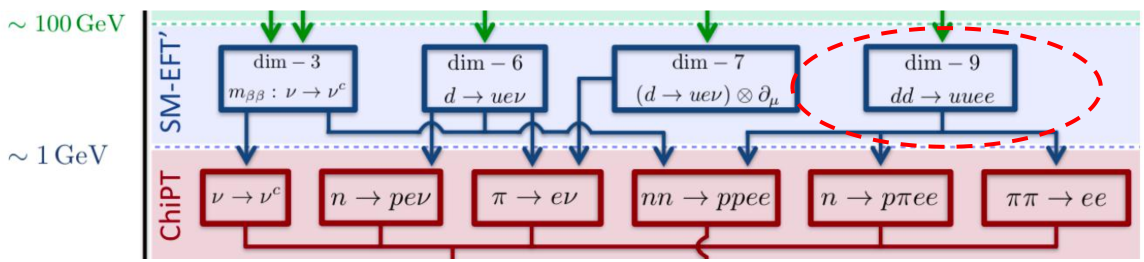
c: new coupling
Λ: new particle mass

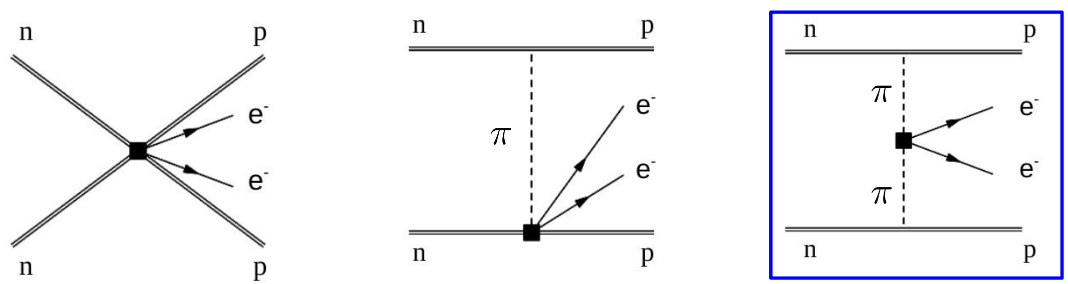
Non-standard mechanisms

In the EFTs below the weak scale



$$\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$$





chirally enhanced

$$\left(\frac{\Lambda_\chi}{p}\right)^2 \sim 25$$

Non-standard mechanisms

Dim-9 LNV operators in SM-EFT' (LEFT)

- 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

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

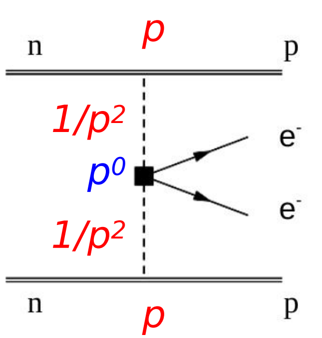
$$O_1 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L \; \bar{q}^\beta_L \gamma^\mu \tau^+ q^\beta_L \,, \qquad O'_1 = \bar{q}^\alpha_R \gamma_\mu \tau^+ q^\alpha_R \; \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R \,,$$

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

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

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

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



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

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

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

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

From EFTs to BSM models

The interpretation for $0\nu\beta\beta$ decay in the EFT approach

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

"master formula"

V. Cirigliano et al, 1708.09390 (JHEP), 1806.02780 (JHEP)

- Different constraints on $\langle m_{\beta\beta}\rangle$ or Wilson coefficients are obtained

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

- The EFTs sheld light on possible BSM models at work

well-motivated scenarios? observed neutrino masses?

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

Neutrinoless Double-Beta Decay:
A Roadmap for Matching Theory to Experiment

V. Cirigliano et al., 2203.12169, Snowmass 2021

Vincenzo Cirigliano,[1] Zohreh Davoudi,[2,*] Wouter Dekens,[1] Jordy de Vries,[3,4] Jonathan Engel,[5,†] Xu Feng,[6,7,8] Julia Gehrlein,[9,‡] Michael L. Graesser,[10,§] Lukáš Gráf,[11,12] Heiko Hergert,[13,¶] Luchang Jin,[14,15] Emanuele Mereghetti,[10,**] Amy Nicholson,[16,††] Saori Pastore,[17,18] Michael J. Ramsey-Musolf,[19,20,‡‡] Richard Ruiz,[21] Martin Spinrath,[22,23] Ubirajara van Kolck,[24,25] and André Walker-Loud[26]

From EFTs to BSM models

Going beyond the EFTs enables comlementary tests of LNV

$0\nu\beta\beta$ decay $\xleftrightarrow{?}$ m_ν

$\upharpoonleft\downharpoonright$

other probes

model 1: compete model

- chirally enhanced contributions to $0\nu\beta\beta$ decay $\left(\frac{\Lambda_\chi}{p}\right)^2 \sim 25$
- correlated with m_ν
- interplay with cosmology, collider searches, precision meas.

Model 1

The 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:

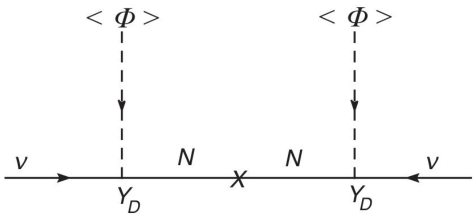
$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

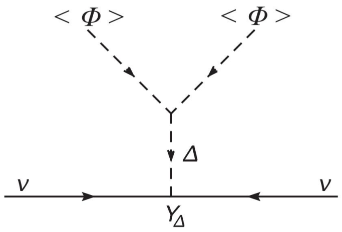
$$\Rightarrow \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

Model 1

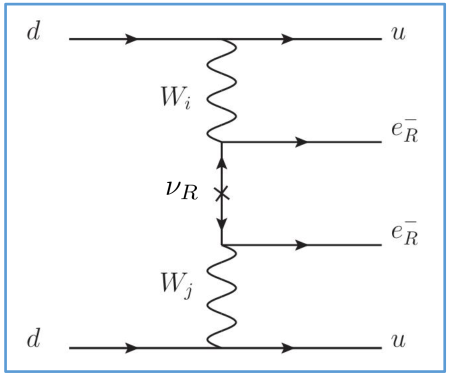
Well-motivated scenarios:

- complete model that provides natural origin of neutrino masses





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



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

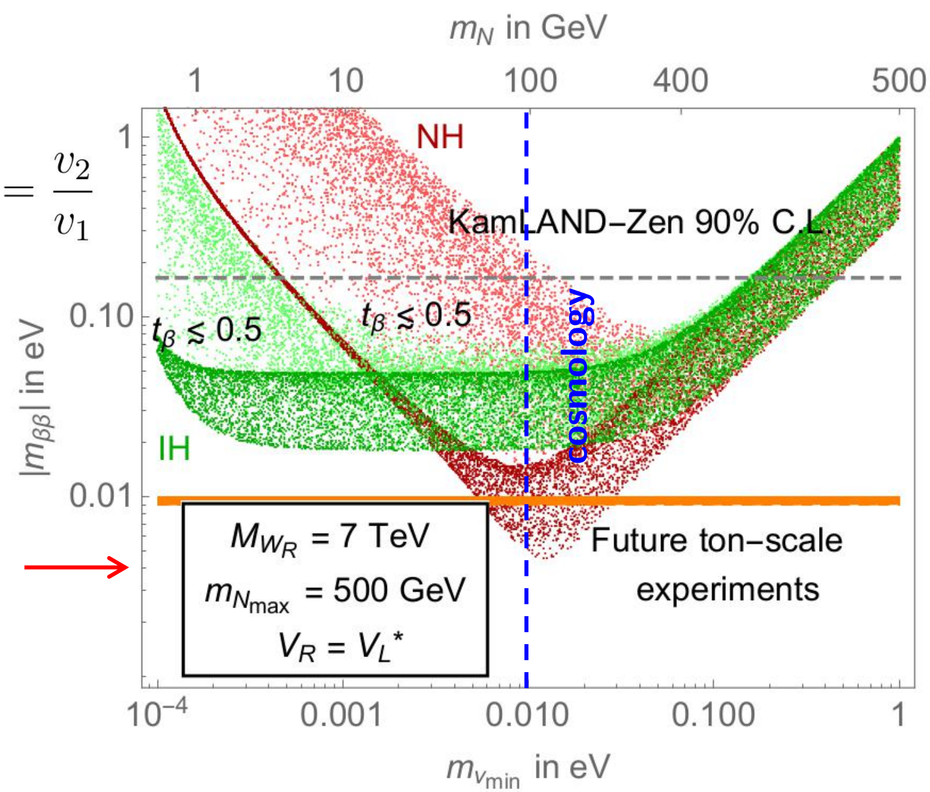
chirally enhanced: $O_4 \bar{e}_R e_R^c$

Model 1

Generalized parity or charge conjugation as the left-right symmetry

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

std. →



mass correlation:

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

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

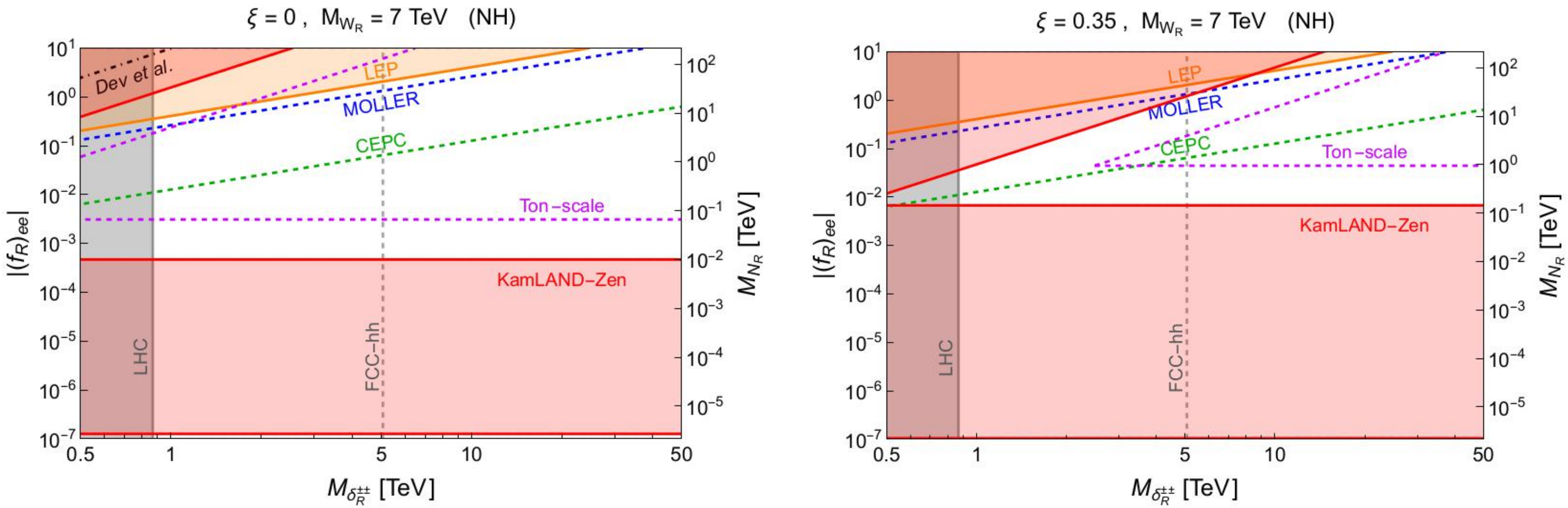
turning point at $m_{\nu_{\min}} \sim 0.01$ eV

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

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

Model 1

Left-right symmetry is not assumed



searches and measurements at colliders: LHC, LEP, CEPC
low-energy precision measurements: MOLLER

GL, M. J. Ramsey-Musolf, J. C. Vasquez, S. Urrutia-Quiroga, 2306.xxxx

From EFTs to BSM models

Going beyond the EFTs enables comlementary tests of LNV

$0\nu\beta\beta$ decay $\overset{?}{\longleftrightarrow}$ m_ν

$\rightleftharpoons$

other probes

model 2: simplified model

- chirally enhanced contributions to $0\nu\beta\beta$ decay
- uncorrelated with m_ν
- interplay with LHC searches (long-lived particle)

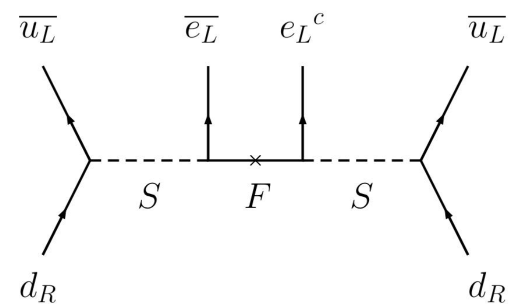
$$\left(\frac{\Lambda_\chi}{p}\right)^2 \sim 25$$

Model 2

Simplified model inspired by RPV SUSY

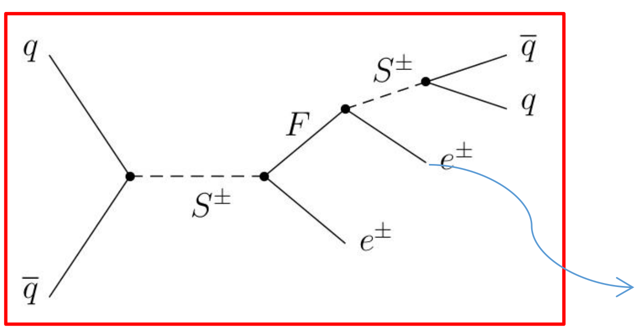
$$\mathcal{L} = (\partial_\mu S)^\dagger \partial^\mu S - m_S^2 S^\dagger S + \frac{1}{2}\bar{F}^c(i\partial\!\!\!/ - m_F)F$$
$$+ g_Q \bar{Q}_L S d_R + g_L \bar{L}\tilde{S}F + \text{h.c.}$$

doublet scalar (slepton) S: $(1{,}2)_{1/2}$,
Majorana fermion (neutralino) F: $(1{,}1)_0$



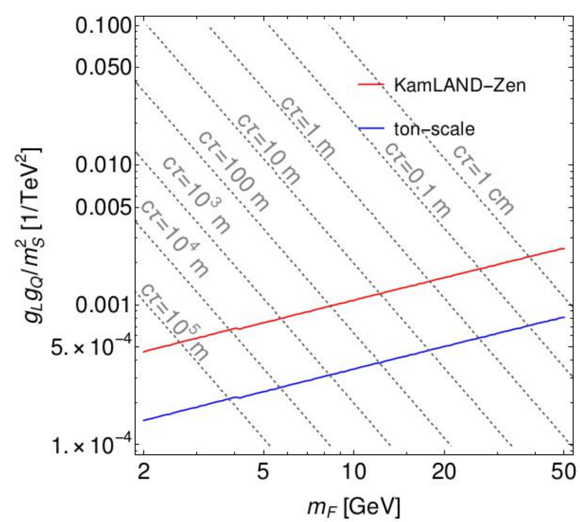
chirally enhanced: $O_2' \bar{e}_L e_L^c$

$$pp \to e^\pm e^\pm jj$$



displaced

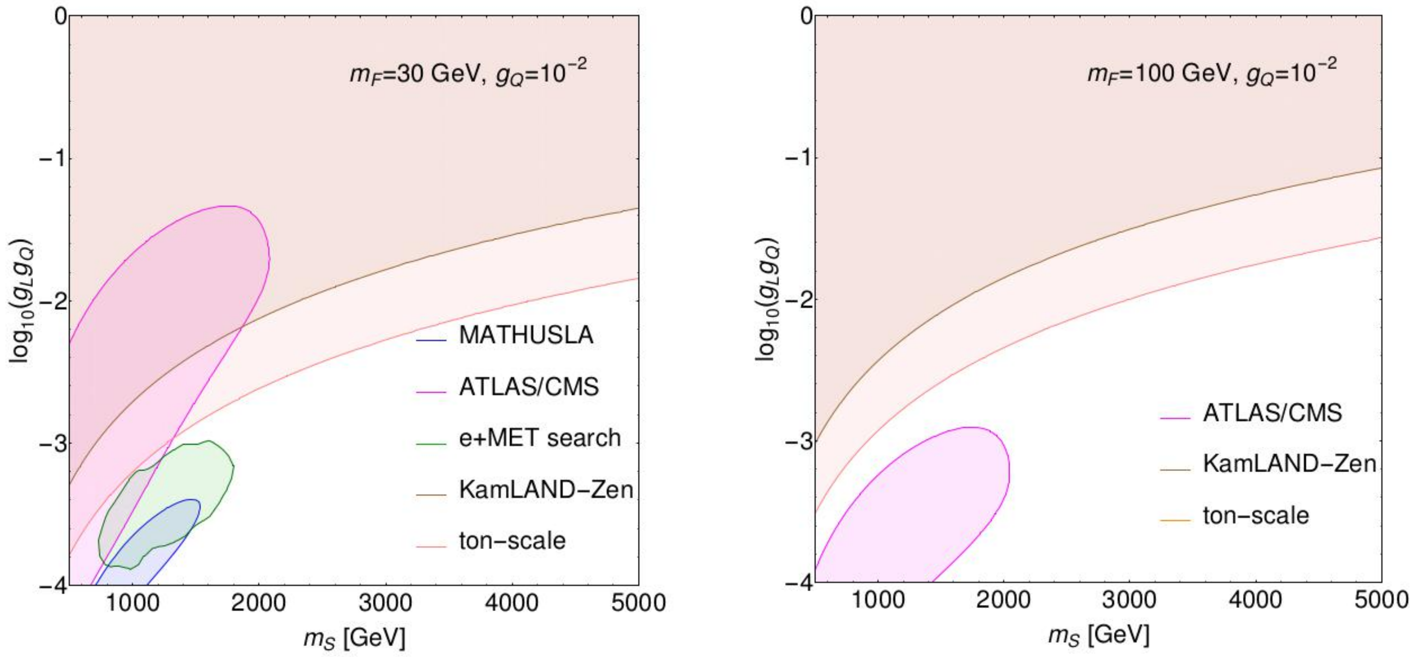
F is a long-lived particle



$\Lambda = m_S \gg m_F$

Model 2

$0\nu\beta\beta$ decay and long-lived particle searches at the LHC for LNV



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

From EFTs to BSM models

Going beyond the EFTs enables comlementary tests of LNV

$0\nu\beta\beta$ decay $\overset{?}{\longleftrightarrow}$ m_ν

$\upharpoonleft\downharpoonright$

other probes

model 3: simplified model

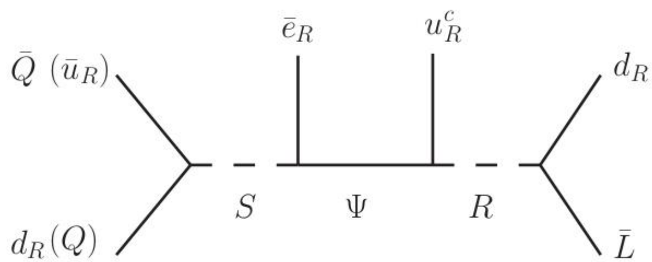
- chirally suppressed contributions to $0\nu\beta\beta$ decay
- uncorrelated with m_ν
- interplay with LHC searches

Model 3

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

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

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



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

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

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, G. Benato, J. A. Detwiler, J. Menéndez, F. Vissani, 2202.01787 (JHEP)

Model 3

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

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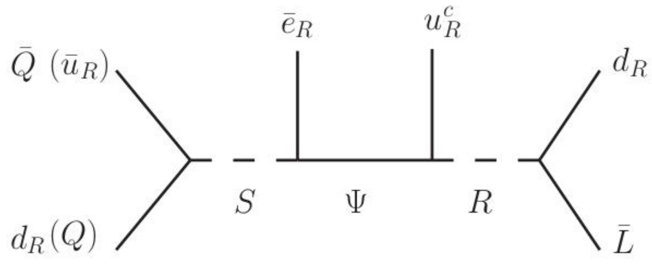
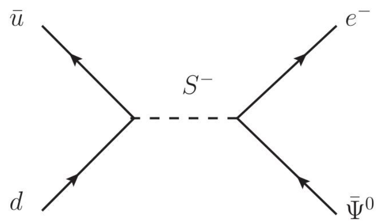
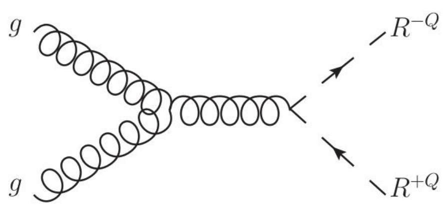
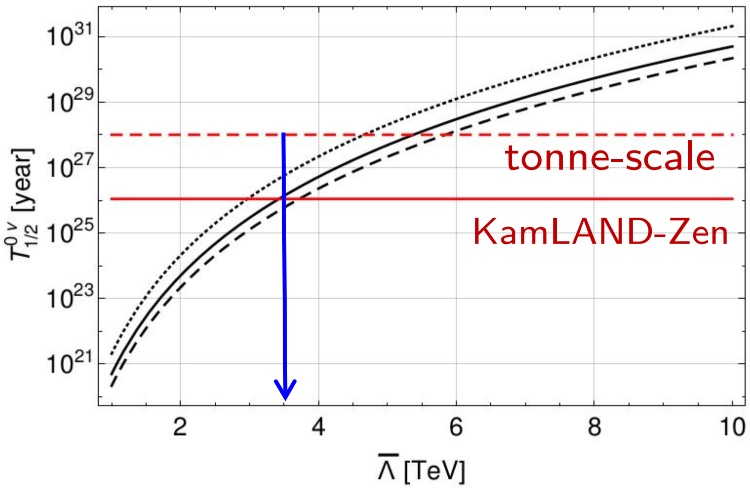


scalar $S \in (1{,}2)_{1/2}$, leptoquark $R \in (3{,}2)_{1/6}$
Dirac fermion $\Psi \in (1{,}2)_{-1/2}$

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

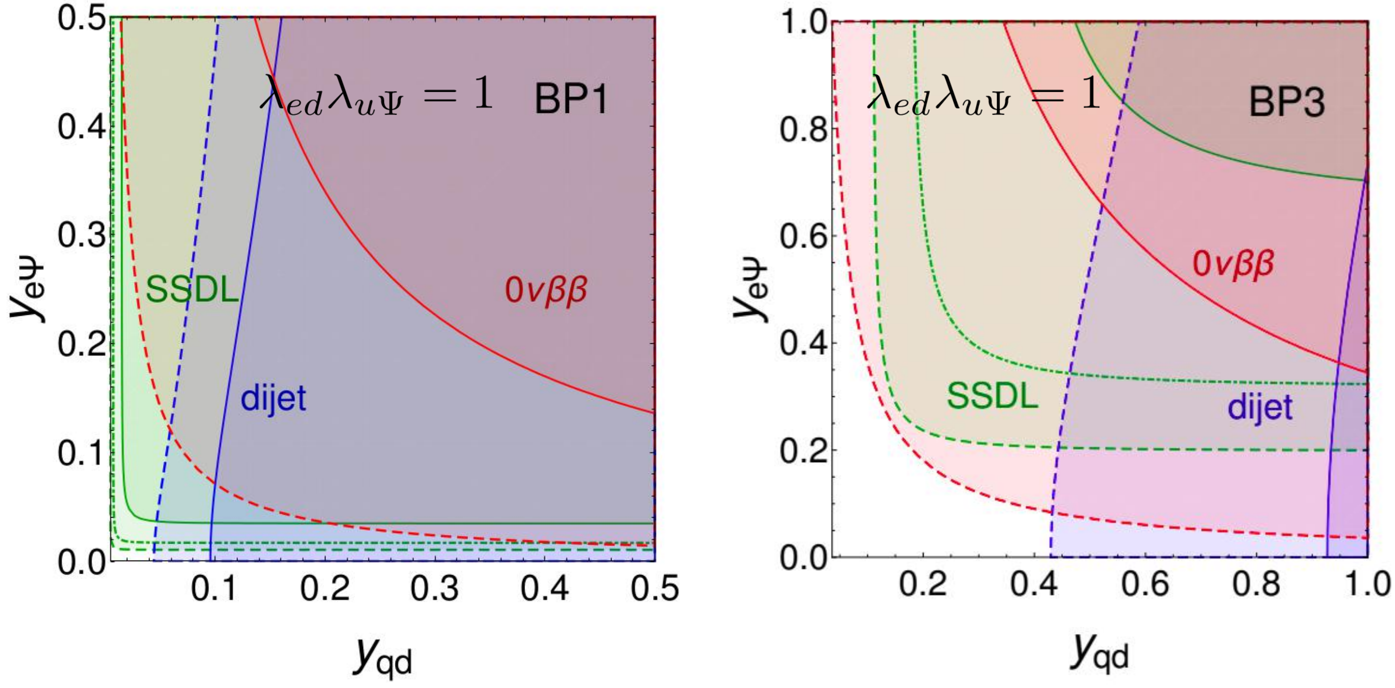






Model 3

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

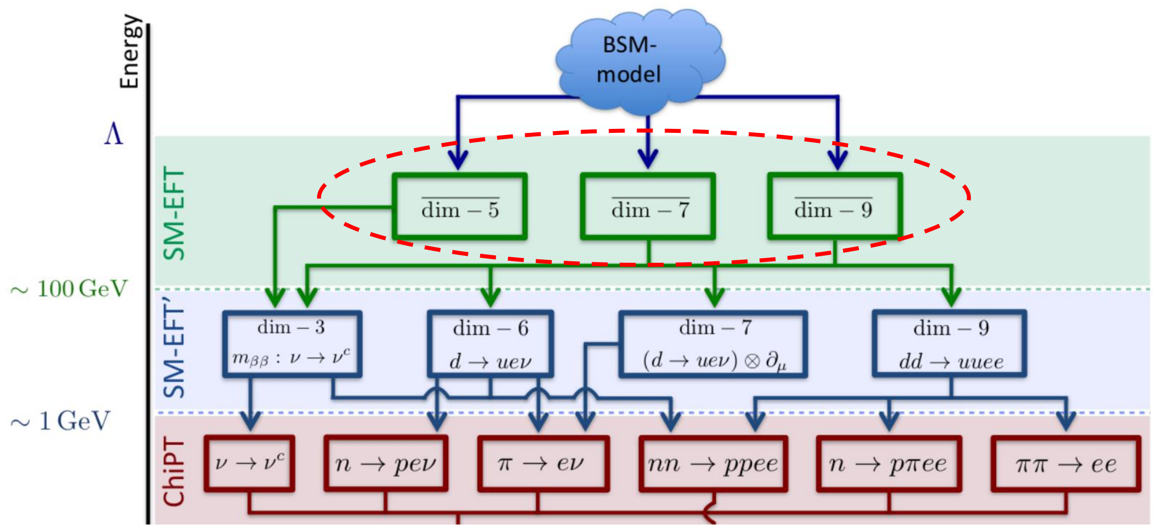


$$\text{BP1}: m_\Psi = 1.0 \text{ TeV}, m_S = 2.0 \text{ TeV}, m_R = 2.0 \text{ TeV};$$
$$\text{BP3}: m_\Psi = 1.0 \text{ TeV}, m_S = 4.5 \text{ TeV}, m_R = 2.0 \text{ TeV}.$$

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

UV completion

In the EFTs above the EW scale



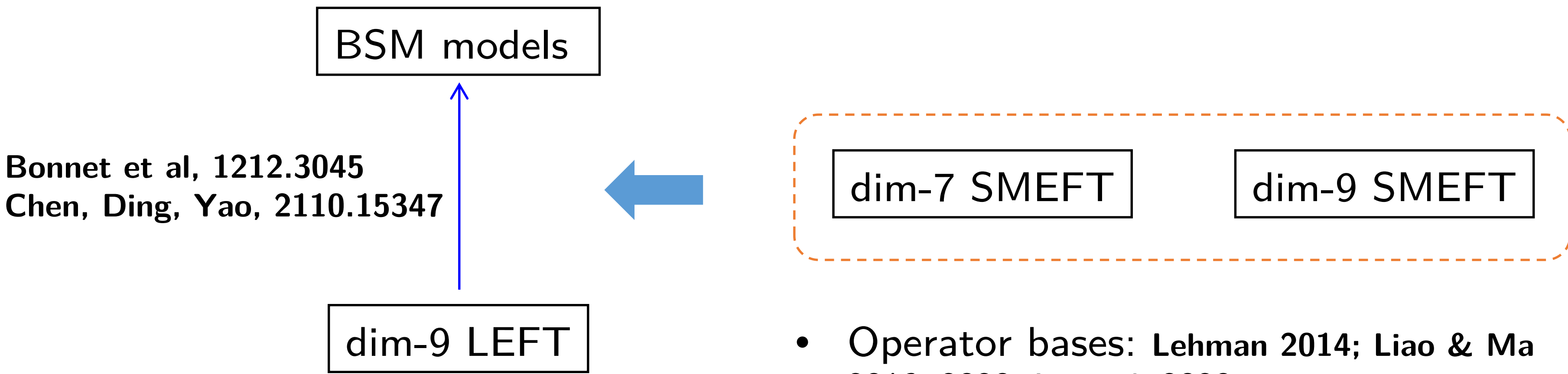
From BSM model to dim-9 LNV LEFT operators:

- model 1: one-step, and two-step integration
- model 2, 3: one-step integration†

† operators in the SMEFT and LEFT are the same

UV completion

Build up the BSM models of LNV



- Operator bases: **Lehman 2014; Liao & Ma 2016, 2020; Li et al, 2020**
- UV completion: **GL**, J.-H. Yu, X. Zhao, work in progress

Summary

- EFTs provide a systematic description of $0\nu\beta\beta$ decay of BSM models of LNV, and sheld light on possible UV completion

- Going beyond the EFTs enables to test LNV with $0\nu\beta\beta$ decay and other probes

- We study three representative models with enhanced/suppressed contributions to $0\nu\beta\beta$ decay being obtained, which interplay with cosmology, collider searches, precision meas.

- From the bottom-up approach, other BSM models of LNV are expected