Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Unraveling the Lepton Number Violation

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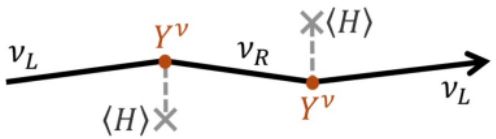
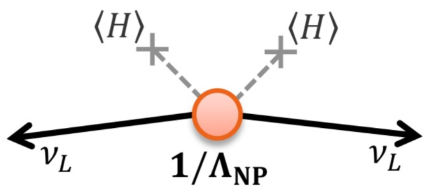
BNL, July 2023

Lepton Number

- non-perturbative SM dynamics: B + L number violated by sphalerons
- B – L number is conserved ↔ non-anomalous global symmetry of the SM → accidental? may be a relict! → violation at low energies subtle ↔ corresponding to B – L preserving gauge symmetry broken at certain high-energy scale
- the manifestation at experimentally accessible scales suppressed by powers of the new-physics scale
- tightly related to the puzzle of neutrino masses and baryon asymmetry of the Universe



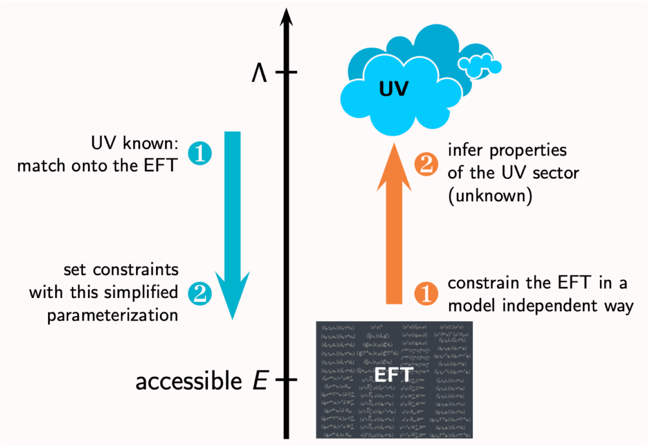
$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$ ✖ $m_M \overline{\nu}_L \nu_L^c$



How to Probe the ν Physics?

- plethora of models for Majorana neutrino mass generation

High-scale	Low-scale
• new particles decoupled • theoretically natural neutrino Yukawa • vanilla scenario of the high-scale leptogenesis	• new particles within reach of experiments • small neutrino Yukawa, loop suppression, approximate LNC • resonant leptogenesis, via oscillations …



What strategy to adopt to probe all the different scenarios?

Effective Field Theory

✔ robust, model independent approach

✖ limitations: e. g. resonant production ➡ simplified models

LNV in Effective Field Theory

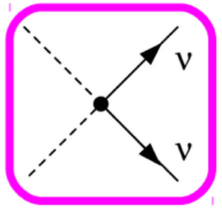
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \boxed{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \boxed{\frac{1}{\Lambda^3}\mathcal{L}_7} + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

odd dimensions

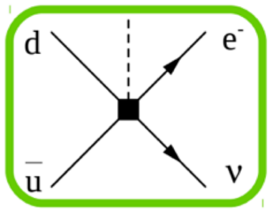
Kobach (2016)

d=5



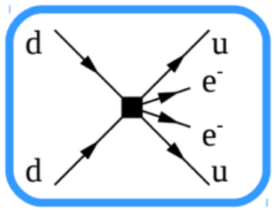
Weinberg (1979)

d=7



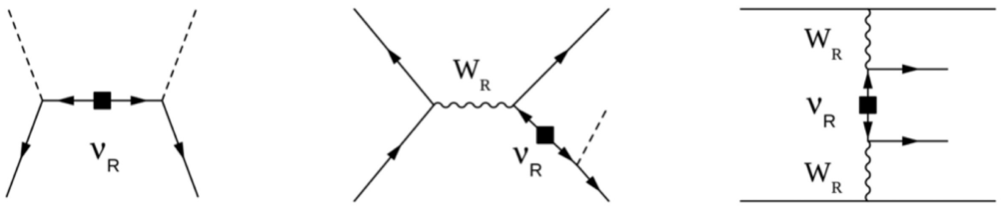
Babu and Leung (2001)
de Gouvea and Jenkins (2008)
Lehman (2014)
Henning, Lu, Melia, Murayama (2015)

d=9



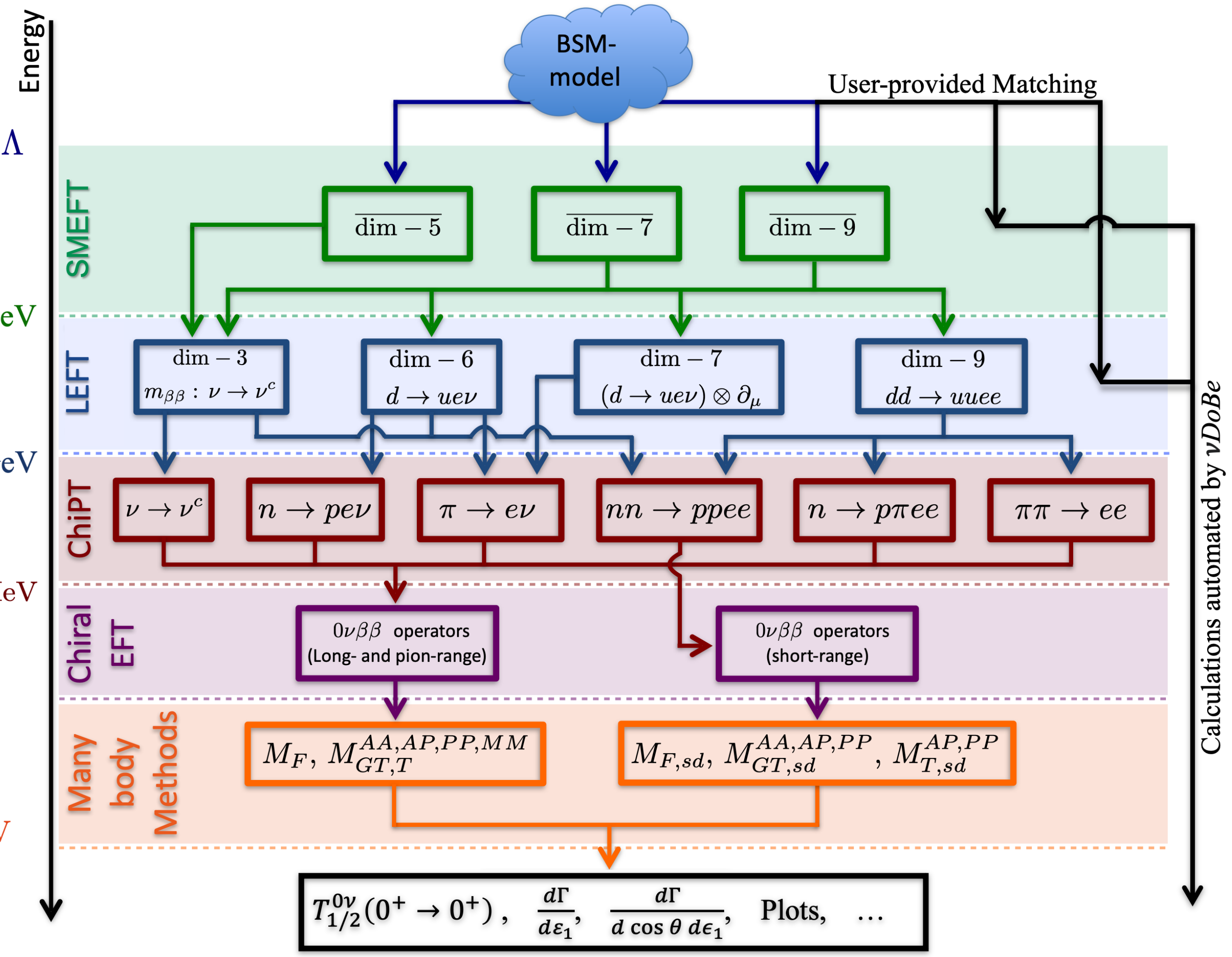
de Gouvea and Jenkins (2008)
Liao and Ma (2020)
Li, Ren, Xiao, Yu, Zheng (2020)

UV example:



Left-Right Symmetric Model

Mohapatra and Pati (1975)
Senjanovic and Mohapatra (1975)



V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 (2018)
O. Scholer, J. de Vries, LG: 2304.05415

Double Beta Decays

- two-neutrino double beta decay

$$2\nu\beta\beta: \ (A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

- neutrinoless double beta decay
  $\to$ LNV, mediated by Majorana neutrinos

$$0\nu\beta\beta: \ (A,Z) \to (A,Z+2) + 2e^-$$

- experiments: $\mathrm{T}_{1/2}^{2\nu\beta\beta} \sim 10^{18}$ - 10^{21} y

$$\mathrm{T}_{1/2}^{0\nu\beta\beta} \sim (0.1 \text{ eV}/m_\nu)^2 \times 10^{26} \text{ y}$$

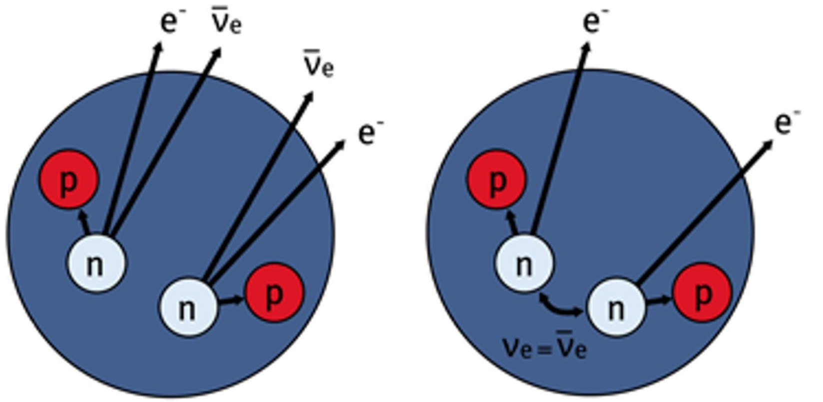
KamLAND-Zen, LEGEND, CUORE, NEMO-3, CUPID, (n)EXO, ...

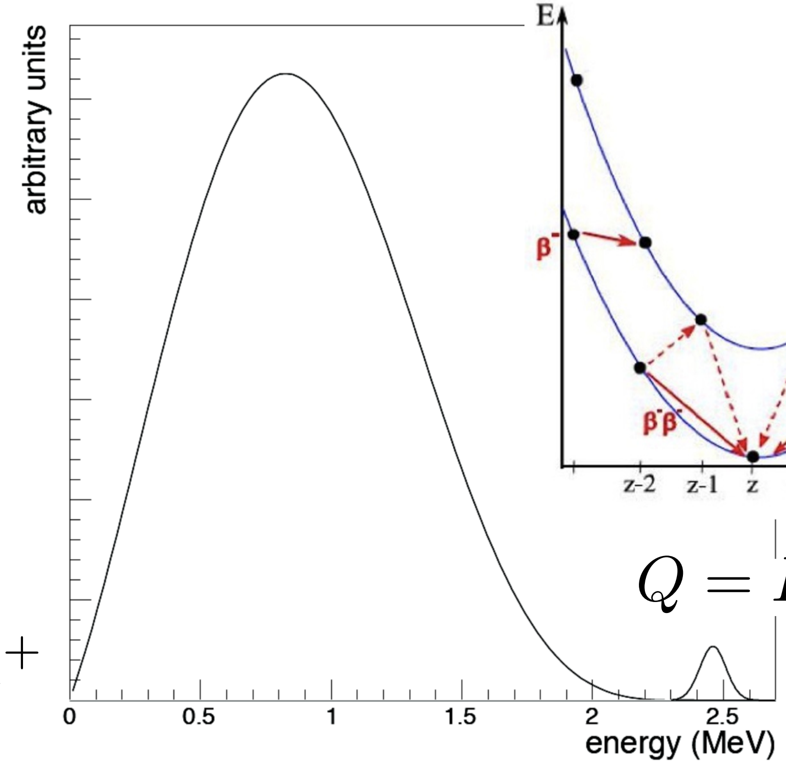
- a variety of isotopes: ^{76}Ge, ^{136}Xe, …

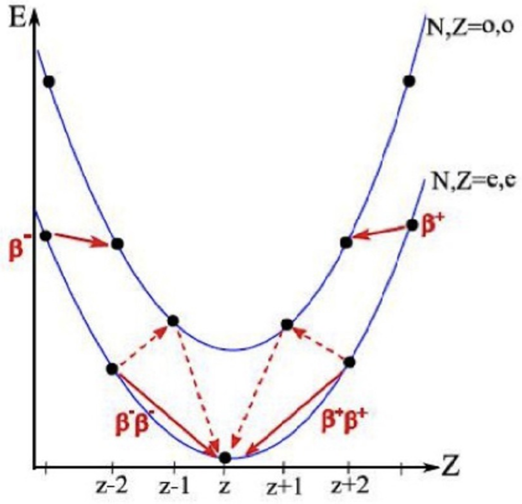
- variants: $0\nu\beta^+\beta^+: \ (A,Z) \to (A,Z-2) + 2e^+$

$$0\nu\beta^+EC: \ (A,Z) + e^- \to (A,Z-2) + e^+$$

$$0\nu ECEC: \ (A,Z) + 2e^- \to (A,Z-2)$$



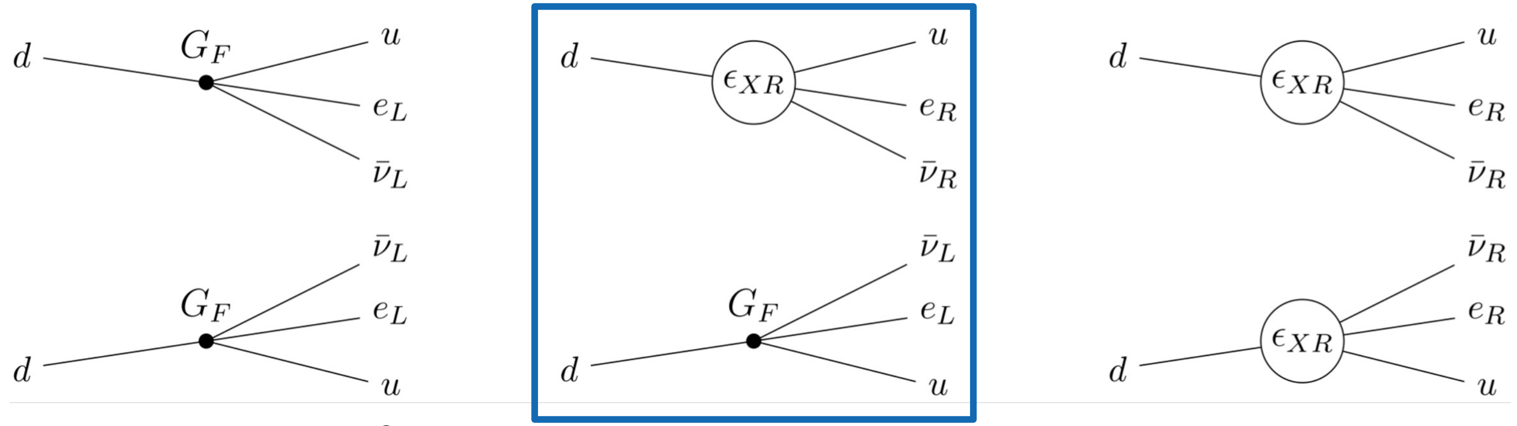




$$Q = E_i - E_f - 2m_e$$

Exotic (2ν)ββ Decay

- double beta decay in presence of right-handed currents?
  → Lagrangian: $\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left((1 + \delta_{\rm SM} + \epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu} \right) + \text{h.c.}$
  with $j^\mu_{L,R} = \bar{e}\gamma^\mu(1 \mp \gamma_5)\nu$, $J^\mu_{L,R} = \bar{u}\gamma^\mu(1 \mp \gamma_5)d$
- contributions:

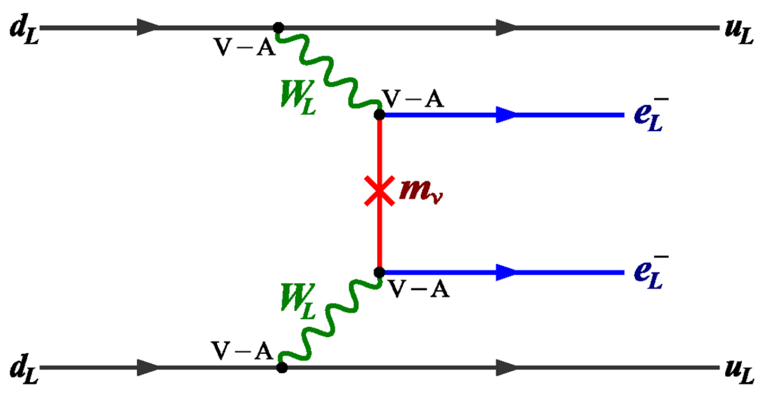


- total rate: $\Gamma^{2\nu} = \epsilon_{XR}^2 G_{2\nu\beta\beta} |M_{2\nu\beta\beta}|^2$
- angular correlation: $\frac{d\Gamma^{2\nu}}{d\cos\theta} = \frac{\Gamma^{2\nu}}{2}\left(1 + K^{2\nu}\cos\theta\right)$ → bound: $\boldsymbol{\epsilon_{XR} \lesssim 2.7 \times 10^{-2}}$
- using existing NEMO-3 data, insensitive to the overall rate, largely insensitive to the nuclear matrix elements

F. F. Deppisch, LG, F. Simkovic: PRL 125 [2003.11836]

Neutrinoless Double Beta Decay

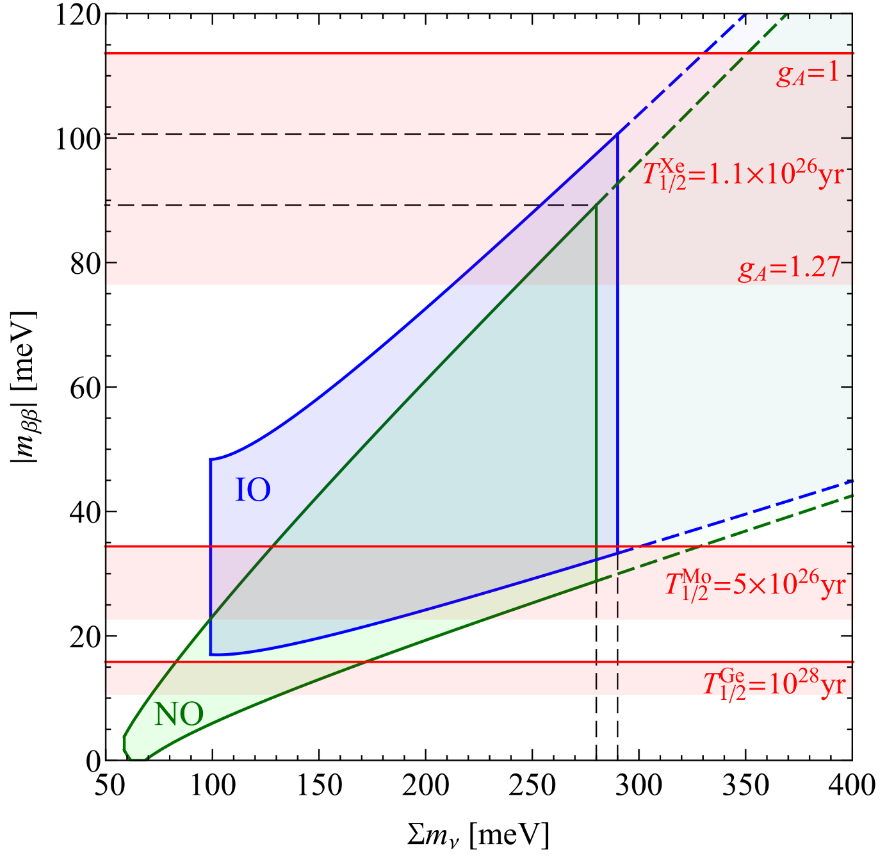
- standard mechanism with light neutrino exchange:



$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 \, \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$$

- half-life limit → bound on effective neutrino mass:

$$\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

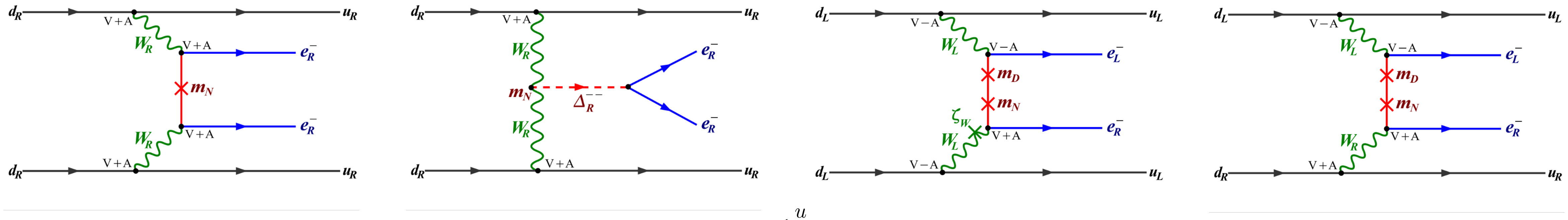


$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_{12}} + m_3 s_{13}^2 e^{i(\phi_{13}-2\delta)}$$

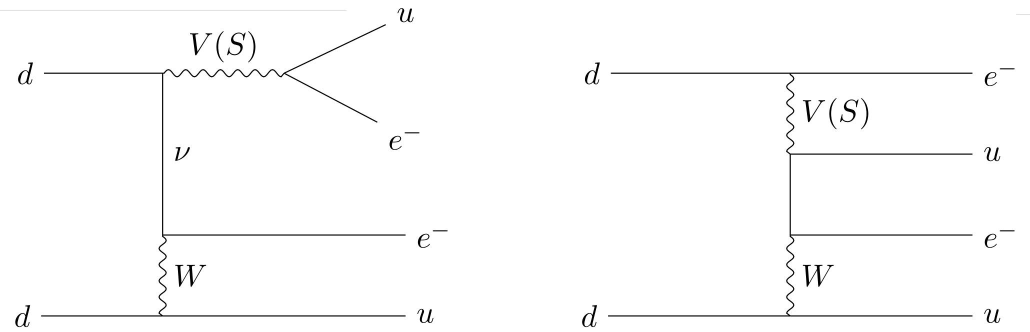
$$A_{\mu\nu}^{\mathrm{lep}} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \bar{e}_2 \gamma_\nu (1-\gamma_5) \frac{q + m_i}{q^2 - m_i^2} (1-\gamma_5)\gamma_\mu e_1^c \approx \bar{e}_2 \frac{\gamma_\nu (1-\gamma_5)\gamma_\mu}{4q^2} e_1^c \boxed{\sum_{i=1}^{3} U_{ei}^2 m_i} \equiv m_{\beta\beta}$$

New Physics & 0νββ

- plethora of New Physics scenarios may be responsible for 0νββ
- left-right symmetric models $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$



- leptoquarks (scalar, vector)

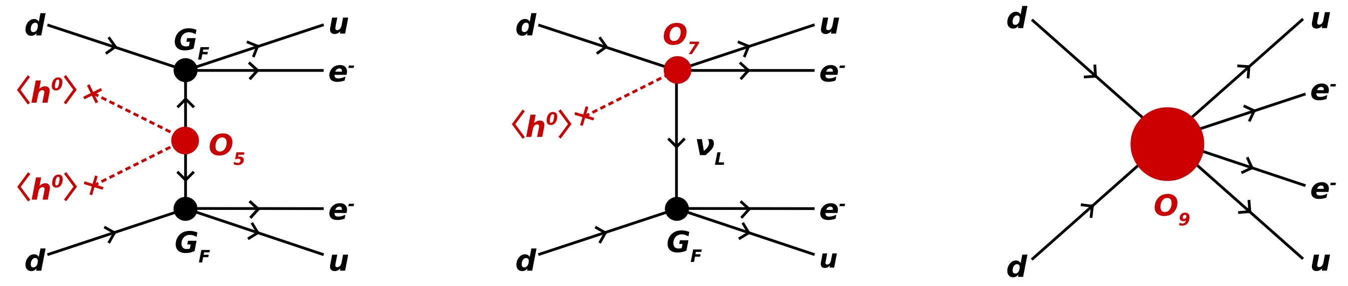


- R-parity violating SUSY, Majorons, Extra Dimensions ...

F. F. Deppisch, M. Hirsch, H. Päs: J. Phys. G 39 (2012), 124007

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range (with neutrino propagator) and short-range mechanisms
- 0νββ half-life limit sets constraints on effective couplings – accurate calculation of nuclear matrix elements and phase-space factors is crucial for estimating these limits
- generally: $T_{1/2}^{-1} = |C|^2 G_{0\nu} |M_{0\nu}|^2$



(a) (b) (c)

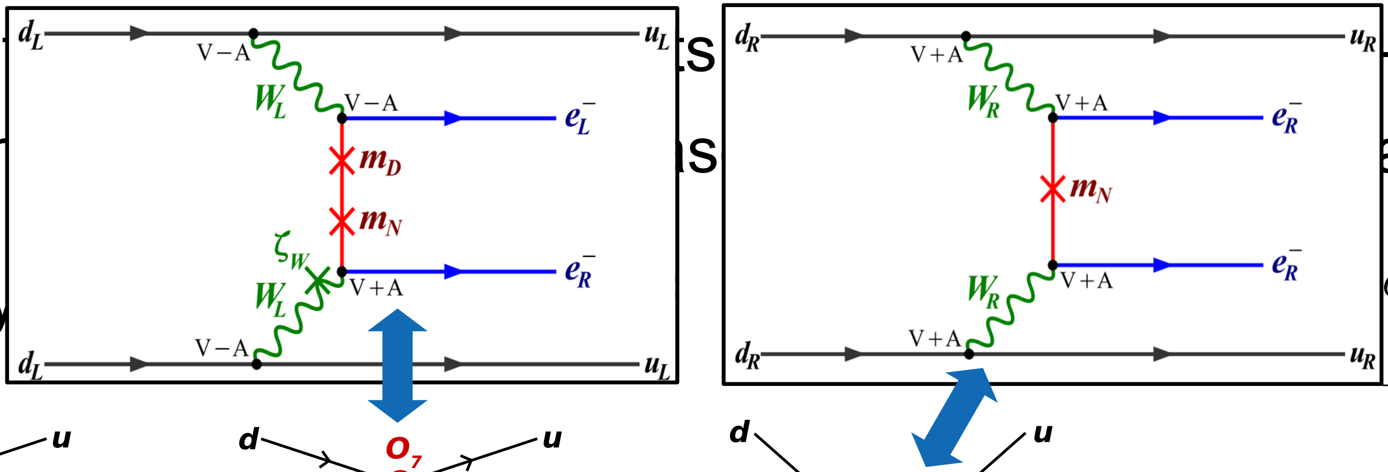
$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}} \Big[C_{\mathrm{VL}}^{(6)} \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right) + C_{\mathrm{VR}}^{(6)} \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right)$$
$$+ C_{\mathrm{SL}}^{(6)} \left(\overline{u_R} d_L\right)\left(\overline{e_L}\nu_L^c\right) + C_{\mathrm{SR}}^{(6)} \left(\overline{u_L} d_R\right)\left(\overline{e_L}\nu_L^c\right)$$
$$+ C_{\mathrm{T}}^{(6)} \left(\overline{u_L}\sigma^{\mu\nu} d_R\right)\left(\overline{e_L}\sigma_{\mu\nu}\nu_L^c\right) \Big] + h.c.$$

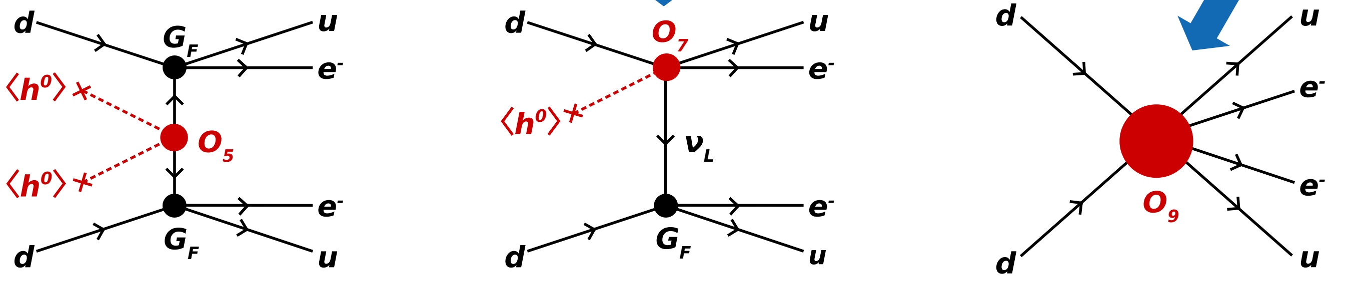
$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v} \Big[C_{\mathrm{VL}}^{(7)} \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c\right) + C_{\mathrm{VR}}^{(7)} \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c\right) \Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5} \sum_i \left[\left(C_{i,R}^{(9)} \left(\overline{e_R} e_R^c\right) + C_{i,L}^{(9)} \left(\overline{e_L} e_L^c\right) \right) \mathcal{O}_i + C_i^{(9)} \left(\overline{e}\gamma_\mu\gamma_5 e^c\right) \mathcal{O}_i^\mu \right]$$

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range (with neutrino propagator) and short-range mechanisms
- 0νββ hal… ts – accurate calculation of nuclear r… s… al for estimating these limits
- generally …





(a) (b) (c)

$$C^{(6)}_{\rm VL}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu\nu^c_L) + C^{(6)}_{\rm VR}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu\nu^c_L)$$

$$+\,C^{(6)}_{\rm SL}\,(\overline{u_R}d_L)\,(\overline{e_L}\nu^c_L) + C^{(6)}_{\rm SR}\,(\overline{u_L}d_R)\,(\overline{e_L}\nu^c_L)$$

$$+\,C^{(6)}_{\rm T}\,(\overline{u_L}\sigma^{\mu\nu}d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu^c_L)\Big] + h.c.$$

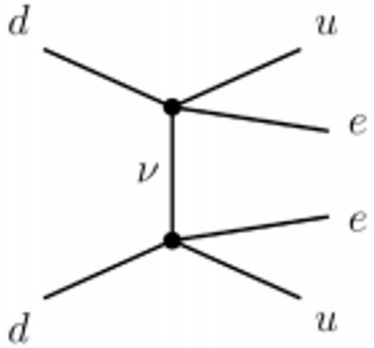
$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big[C^{(7)}_{\rm VL}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu^c_L) + C^{(7)}_{\rm VR}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu^c_L)\Big] + h.c.$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i\Big[\Big(C^{(9)}_{i,R}\,(\overline{e_R}e^c_R) + C^{(9)}_{i,L}\,(\overline{e_L}e^c_L)\Big)\,\mathcal{O}_i + C^{(9)}_i\,(\overline{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}^\mu_i\Big]$$

0νββ Mechanisms

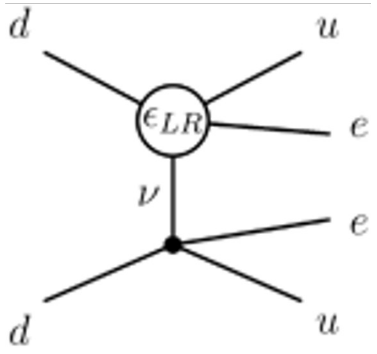
- standard mass mechanism

$$\Gamma^{0\nu\beta\beta}_{m_\nu} \sim m_\nu^2 G_F^4 m_F^2 Q_{\beta\beta}^5 \sim \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^2 (10^{26}\ \mathrm{y})^{-1}$$



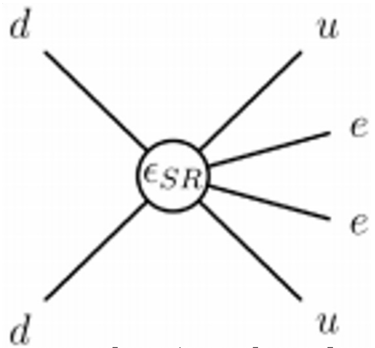
- non-standard long-range mechanisms

$$\Gamma^{0\nu\beta\beta}_{\mathrm{LR}} \sim v^2 \Lambda_{O_7}^{-6} G_F^2 m_F^4 Q_{\beta\beta}^5 \sim \left(\frac{10^5\ \mathrm{GeV}}{\Lambda_{O_7}}\right)^6 (10^{26}\ \mathrm{y})^{-1}$$



- non-standard short-range mechanisms

$$\Gamma^{0\nu\beta\beta}_{\mathrm{SR}} \sim \Lambda_{O_9}^{-10} m_F^6 Q_{\beta\beta}^5 \sim \left(\frac{5\ \mathrm{TeV}}{\Lambda_{O_9}}\right)^{10} (10^{26}\ \mathrm{y})^{-1}$$



- due to the intrinsic helicity flip, non-standard long-range mechanisms in typical scenarios suppressed indirectly by neutrino mass
- e.g. left-right symmetric models: small Yukawa coupling $(y_\nu v = \sqrt{m_\nu M_N})$

$$\Gamma^{0\nu\beta\beta}_{\mathrm{LR}} \sim \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{5\ \mathrm{TeV}}{\Lambda_{\mathrm{LR}}}\right)^5 (10^{26}\ \mathrm{y})^{-1}$$

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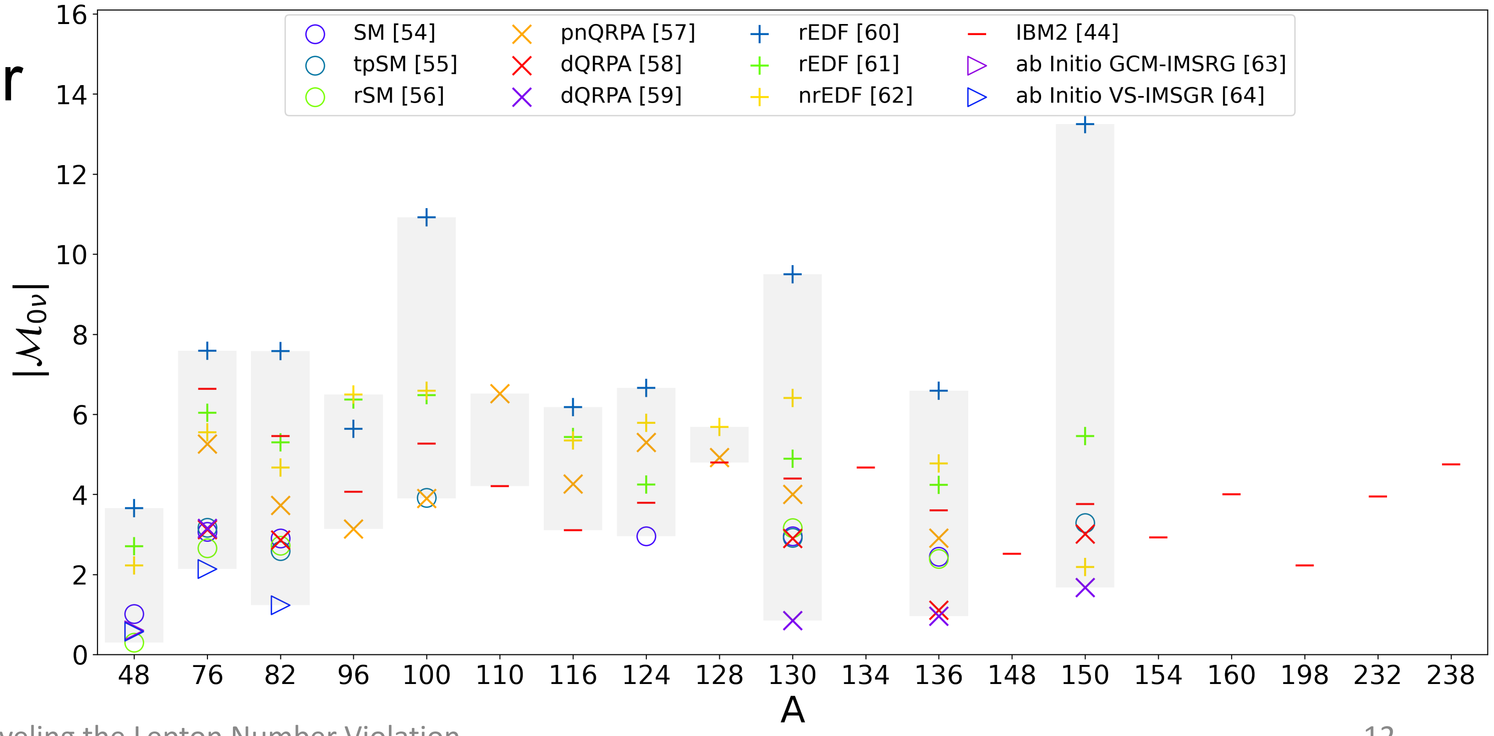
Nuclear Uncertainties

- hadronic currents $J^\mu(q) = g_V\gamma^\mu - g_A\gamma^\mu\gamma^5 + \frac{ig_W}{2m_N}\sigma^{\mu\nu}q_\nu - g_P\gamma^5 q^\mu$
- non-relativistic expansion → nuclear matrix elements

$$\mathcal{M}_{0\nu} = g_A^2\mathcal{M}_{GT} - g_V^2\mathcal{M}_F + g_A^2\mathcal{M}_T$$
$$\mathcal{M}_F = \langle h^F(q^2)\rangle$$
$$\mathcal{M}_{GT} = \langle h^{GT}(q^2)(\sigma_a\cdot\sigma_b)\rangle$$
$$\mathcal{M}_T = \langle h^T(q^2)3(\sigma_a\cdot r_{ab})(\sigma_b\cdot r_{ab}) - (\sigma_a\cdot\sigma_b)\rangle$$

- dependence on isotope and operator
- non-relativistic approx. or chiral EFT
- calculation – many-body problem
- different nuclear structure models, factor of 2-3 difference
- + unknown LECs (or form factors)

Known LECs		Unknown LECs	
g_A	1.271	$\lvert g'_T\rvert$	$\mathcal{O}(1)$
g_S	0.97 [51]	$\lvert g_T^{\pi\pi}\rvert$	$\mathcal{O}(1)$
g_M	4.7	$\lvert g_{1,6,7,8,9}^{\pi N}\rvert$	$\mathcal{O}(1)$
g_T	0.99 [51]	$\lvert g_{VL}^{\pi N}\rvert$	$\mathcal{O}(1)$
B	2.7 GeV	$\lvert g_T^{\pi N}\rvert$	$\mathcal{O}(1)$
$g_1^{\pi\pi}$	0.36 [52]	$\lvert g_{1,6,7}^{NN}\rvert$	$\mathcal{O}(1)$
$g_2^{\pi\pi}$	2.0 [52]	$\lvert g_{2,3,4,5}^{NN}\rvert$	$\mathcal{O}(16\pi^2)$
$g_3^{\pi\pi}$	−0.62 [52]	$\lvert g_{VL}^{NN}\rvert$	$\mathcal{O}(1)$
$g_4^{\pi\pi}$	−1.9 [52]	$\lvert g_T^{NN}\rvert$	$\mathcal{O}(1)$
$g_5^{\pi\pi}$	−8.0 [52]	$\lvert g_{VL,VR}^{E,m_e}\rvert$	$\mathcal{O}(1)$
g_ν^{NN}	$-92.9\,\text{GeV}^{-2} \pm 50\%$ [53–55]		



Distinguishing 0νββ Mechanisms

- phase-space observables – electron energy spectra, angular correlation $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta\,\mathrm{d}\tilde{\epsilon}_1} = a_0\left(1 + \frac{a_1}{a_0}\cos\theta\right)$
- comparison with other ββ modes → β+β+, ECβ+, ECEC - typically suppressed
- decay rate ratios for different isotopes $\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$
    - → ratio of half-lives = ratio of NMEs x ratio of PSFs, the unknown coupling drops out
    - distinguishing 2 specific operators quantified using $\mathrm{R}_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$
- applied to the “master formula” framework of 1806.02780

V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 [1806.02780]

    - PSFs → 4 distinguishable groups of operators
    - ratios: in principle 12 distinguishable groups of operators
        - main issues: nuclear uncertainties: NMEs + unknown low energy constants → solution? hopefully: ab initio + LQCD and/or complementarity

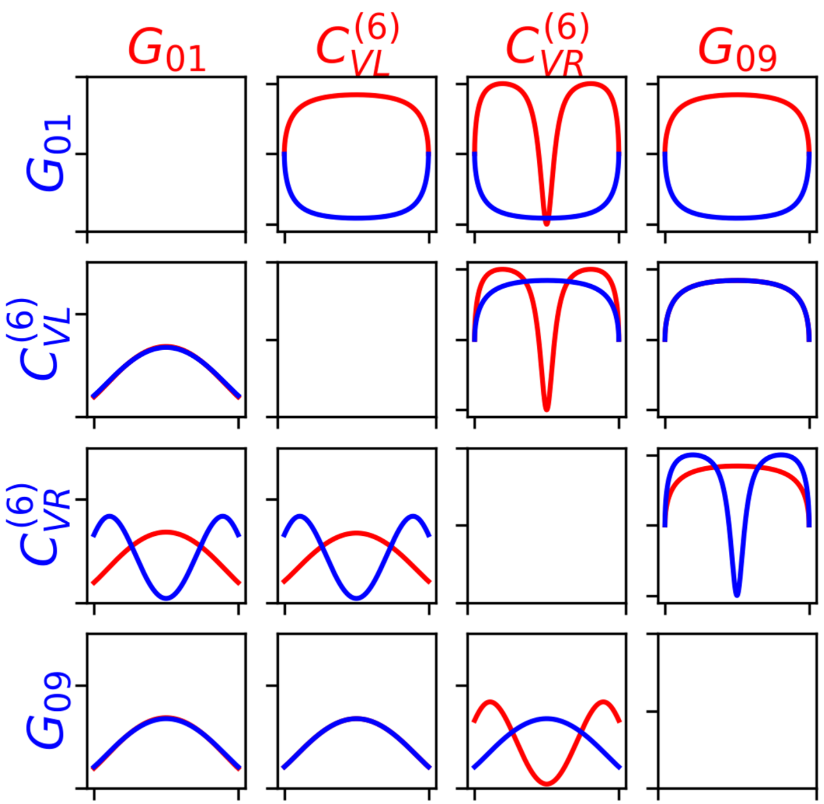
Distinguishing: Phase Space

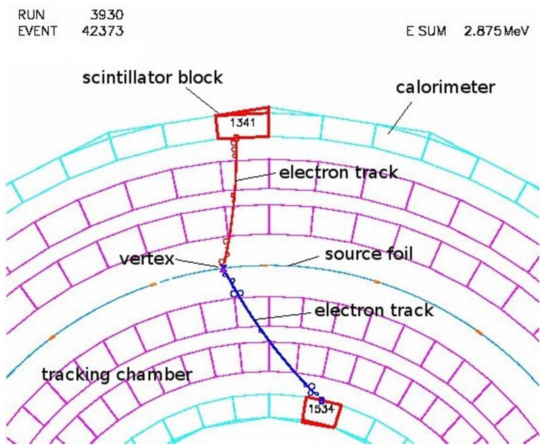
- electron energy spectra and angular correlation of the emitted electrons $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta \mathrm{d}\tilde{\varepsilon}_1} = a_0 \left(1 + \frac{a_1}{a_0}\cos\theta\right)$
- e.g. NEMO-3: thin foils of source material surrounded by a separate tracking calorimeter → better accuracy – reliable detection of 2 electrons coming from the same spot

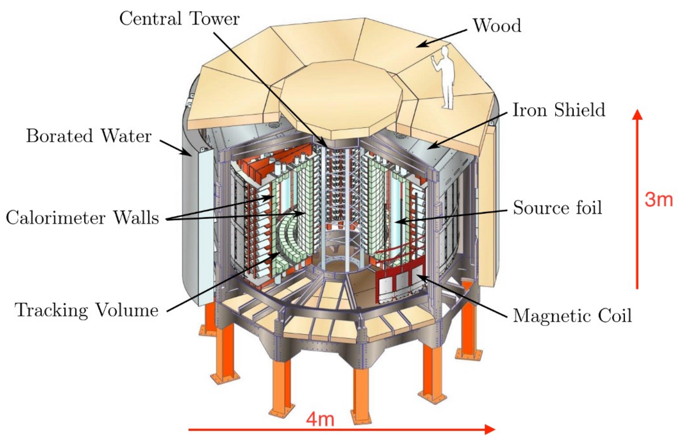
$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big[C^{(6)}_{\mathrm{VL}}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{VR}}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{SL}}\left(\overline{u_R}d_L\right)\left(\overline{e_L}\nu^c_L\right) + C^{(6)}_{\mathrm{SR}}\left(\overline{u_L}d_R\right)\left(\overline{e_L}\nu^c_L\right) + C^{(6)}_{\mathrm{T}}\left(\overline{u_L}\sigma^{\mu\nu} d_R\right)\left(\overline{e_L}\sigma_{\mu\nu}\nu^c_L\right)\Big] + h.c.$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big[C^{(7)}_{\mathrm{VL}}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu^c_L\right) + C^{(7)}_{\mathrm{VR}}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu^c_L\right)\Big] + h.c.$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \Big[\left(C^{(9)}_{i,R}\left(\overline{e_R}e^c_R\right) + C^{(9)}_{i,L}\left(\overline{e_L}e^c_L\right)\right)\mathcal{O}_i + C^{(9)}_i\left(\bar{e}\gamma_\mu\gamma_5 e^c\right)\mathcal{O}^\mu_i\Big]$$







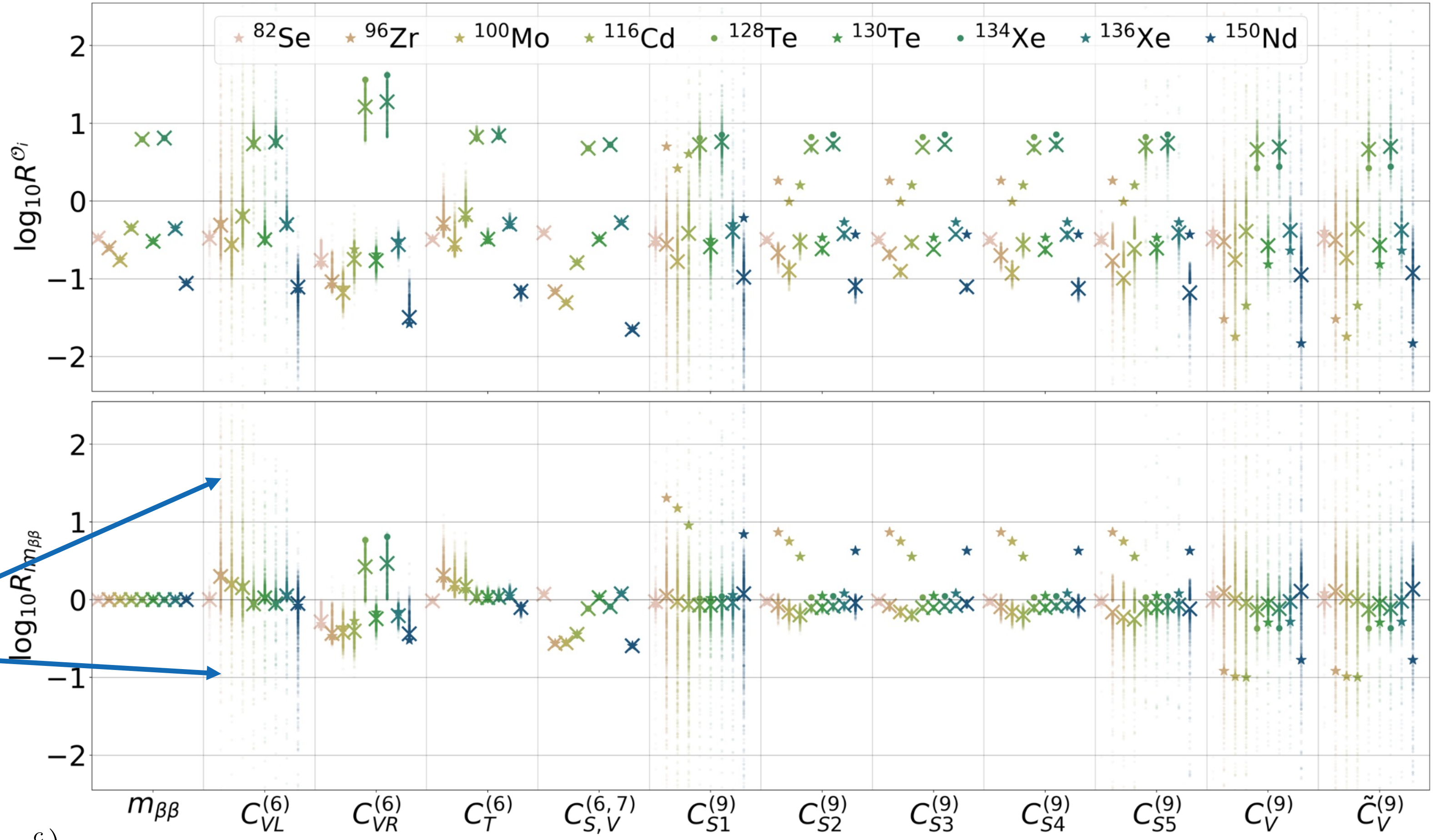
Distinguishing: Half-life Ratios

- distingushing pairs of operators

$$R_{ij}(^AX) = \frac{R^{\mathcal{O}_i}(^AX)}{R^{\mathcal{O}_j}(^AX)}$$

$$\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$$

- most importantly: exotic contribution beyond mass mechanism?
- variation of the unknown LECs gives the spread in values
- → look at the central values



$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}}\Big[C_{\mathrm{VL}}^{(6)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu\nu_L^c) + C_{\mathrm{VR}}^{(6)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu\nu_L^c)$$
$$+ C_{\mathrm{SL}}^{(6)}\,(\overline{u_R}d_L)\,(\overline{e_L}\nu_L^c) + C_{\mathrm{SR}}^{(6)}\,(\overline{u_L}d_R)\,(\overline{e_L}\nu_L^c)$$
$$+ C_{\mathrm{T}}^{(6)}\,(\overline{u_L}\sigma^{\mu\nu}d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu_L^c)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v}\Big[C_{\mathrm{VL}}^{(7)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c) + C_{\mathrm{VR}}^{(7)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5}\sum_i\Big[\Big(C_{i,R}^{(9)}\,(\overline{e_R}e_R^c) + C_{i,L}^{(9)}\,(\overline{e_L}e_L^c)\Big)\,\mathcal{O}_i + C_i^{(9)}\,(\bar{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}_i^\mu\Big]$$

LG, M. Lindner, O. Scholer: PRD 106 (2022)

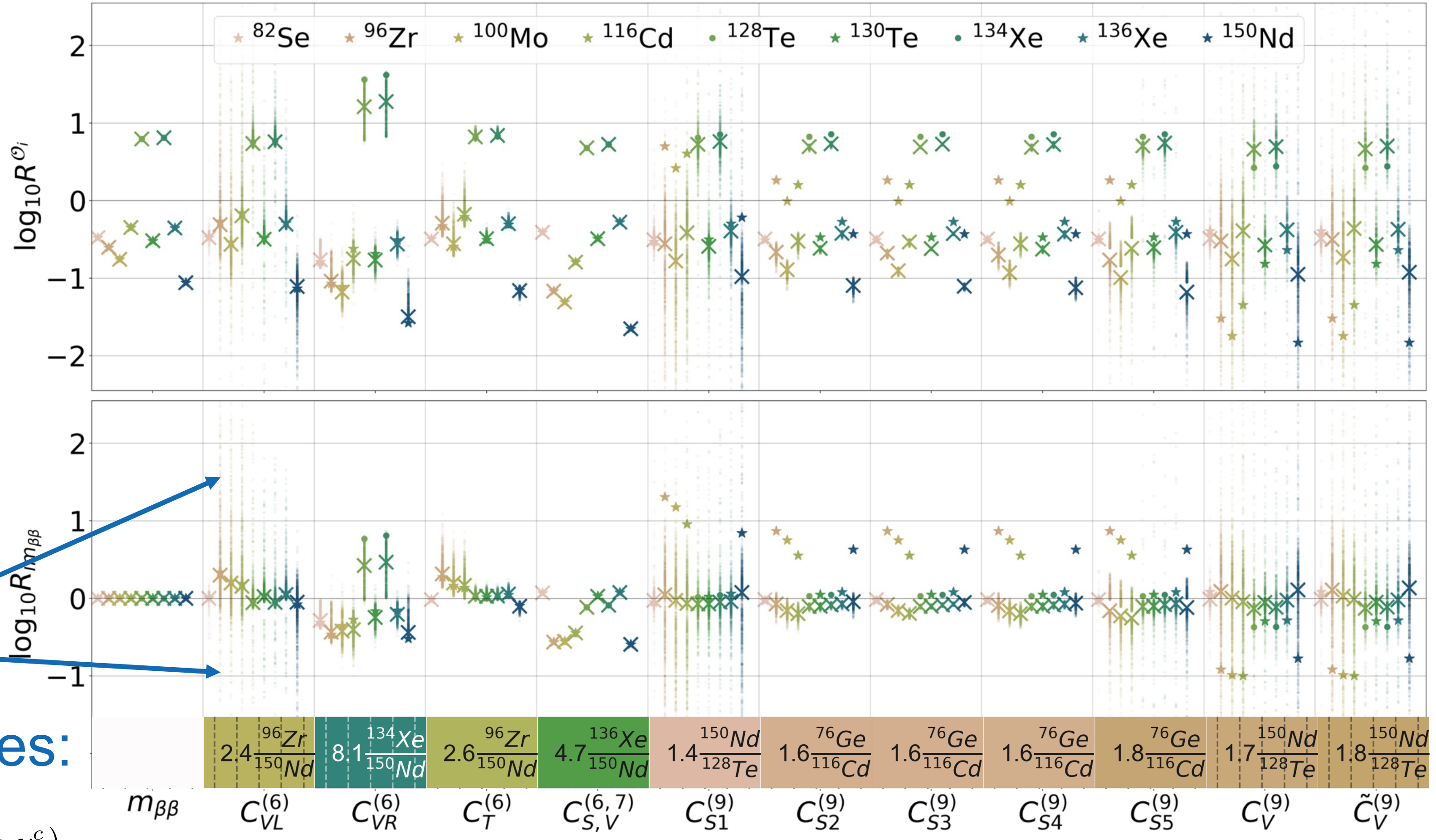
Distinguishing: Half-life Ratios

- distingushing pairs of operators

$$R_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$$

$$\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$$

- most importantly: exotic contri-bution beyond mass mechanism?
- variation of the unknown LECs gives the spread in values



→ best central values:

$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}}\Big[C_{\mathrm{VL}}^{(6)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu \nu_L^c) + C_{\mathrm{VR}}^{(6)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu \nu_L^c) + C_{\mathrm{SL}}^{(6)}\,(\overline{u_R}d_L)\,(\overline{e_L}\nu_L^c) + C_{\mathrm{SR}}^{(6)}\,(\overline{u_L}d_R)\,(\overline{e_L}\nu_L^c) + C_{\mathrm{T}}^{(6)}\,(\overline{u_L}\sigma^{\mu\nu}d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu_L^c)\Big] + h.c.$$

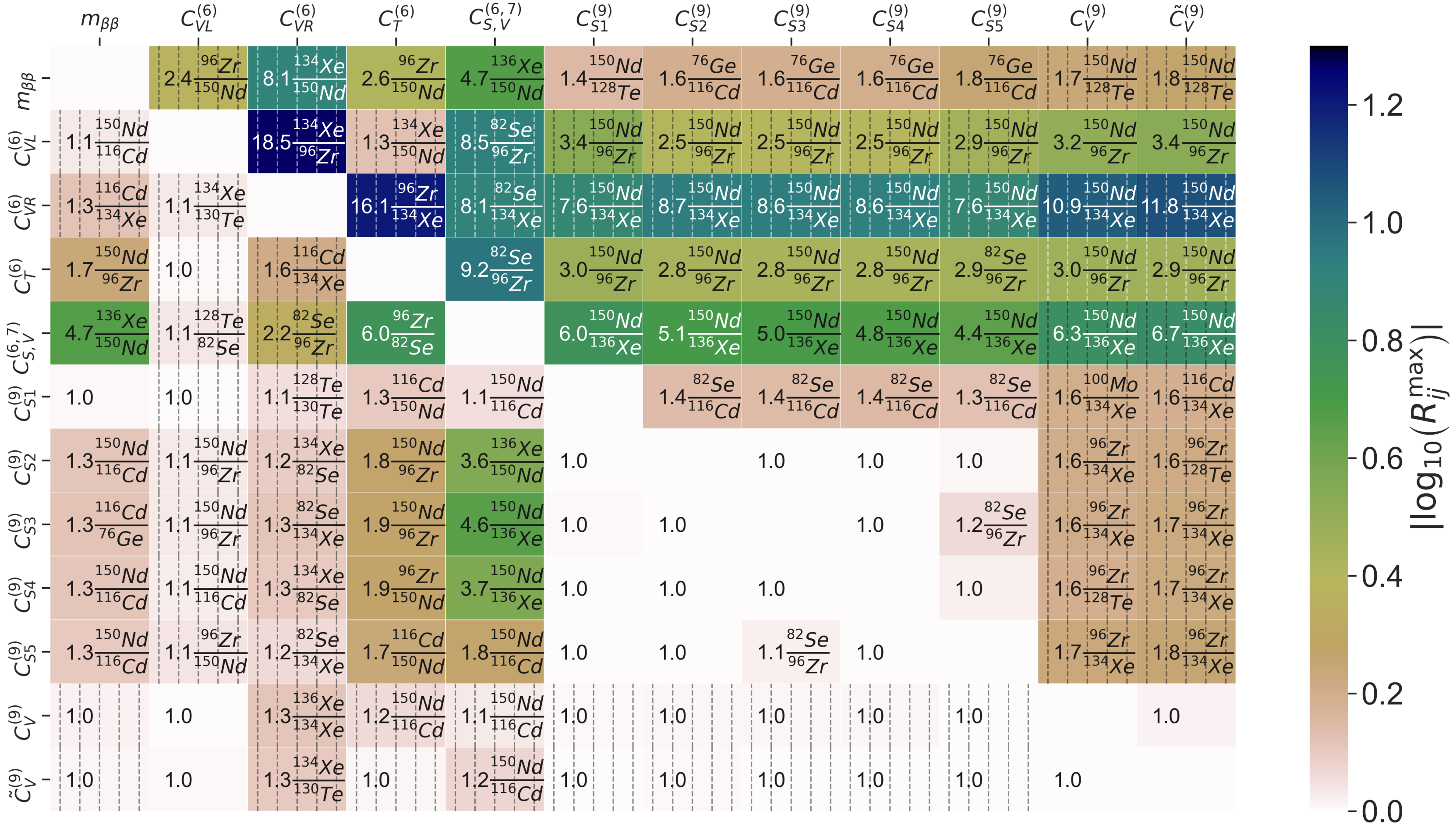
$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v}\Big[C_{\mathrm{VL}}^{(7)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c) + C_{\mathrm{VR}}^{(7)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5}\sum_i \Big[\Big(C_{i,R}^{(9)}\,(\overline{e_R}e_R^c) + C_{i,L}^{(9)}\,(\overline{e_L}e_L^c)\Big)\,\mathcal{O}_i + C_i^{(9)}\,(\bar{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}_i^\mu\Big]$$

LG, M. Lindner, O. Scholer: PRD 106 (2022)

Maximizing Half-life Ratios

- largest ratios – central values vs. worst-case scenario
- the pair of isotopes producing the largest ratio identified
- shading ↔ distinguishable based on the phase space
- uncertainties crucial, most likely correlated → worst case rather pessimistic



$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}}\Big[C_{\rm VL}^{(6)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu\nu_L^c) + C_{\rm VR}^{(6)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu\nu_L^c) + C_{\rm SL}^{(6)}\,(\overline{u_R}d_L)\,(\overline{e_L}\nu_L^c) + C_{\rm SR}^{(6)}\,(\overline{u_L}d_R)\,(\overline{e_L}\nu_L^c) + C_{\rm T}^{(6)}\,(\overline{u_L}\sigma^{\mu\nu}d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu_L^c)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v}\Big[C_{\rm VL}^{(7)}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c) + C_{\rm VR}^{(7)}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5}\sum_i\Big[\Big(C_{i,R}^{(9)}\,(\overline{e_R}e_R^c) + C_{i,L}^{(9)}\,(\overline{e_L}e_L^c)\Big)\,\mathcal{O}_i + C_i^{(9)}\,(\overline{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}_i^\mu\Big]$$

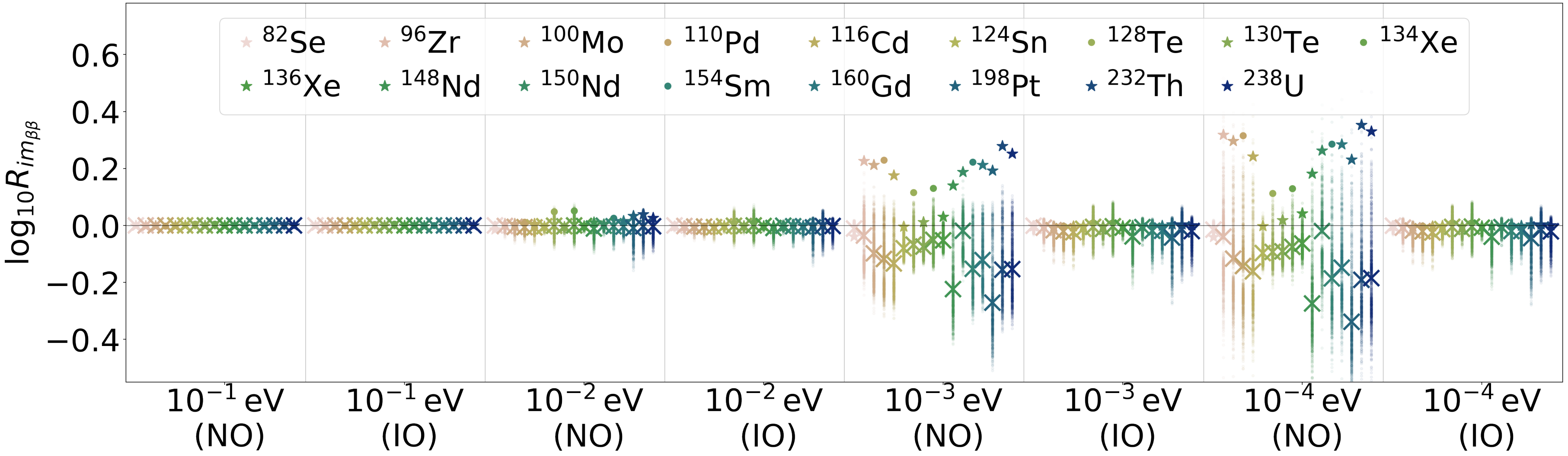
LG, M. Lindner, O. Scholer: PRD 106 (2022)

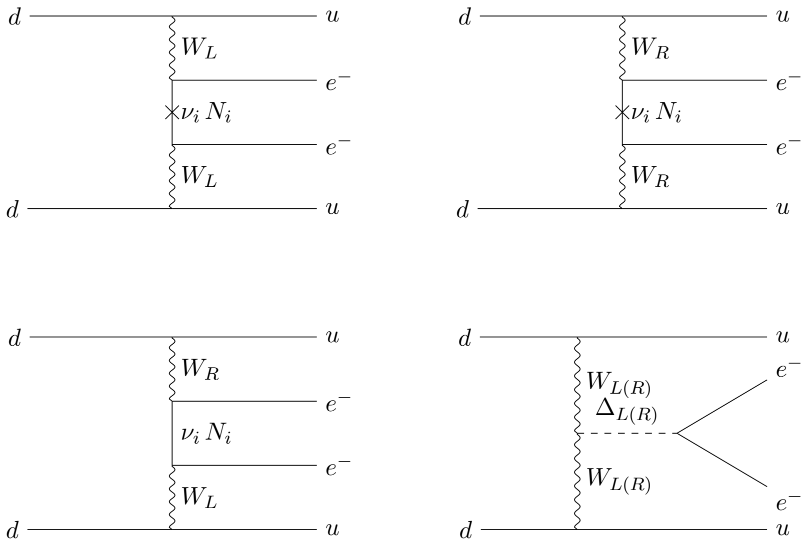
Models: mLRSM

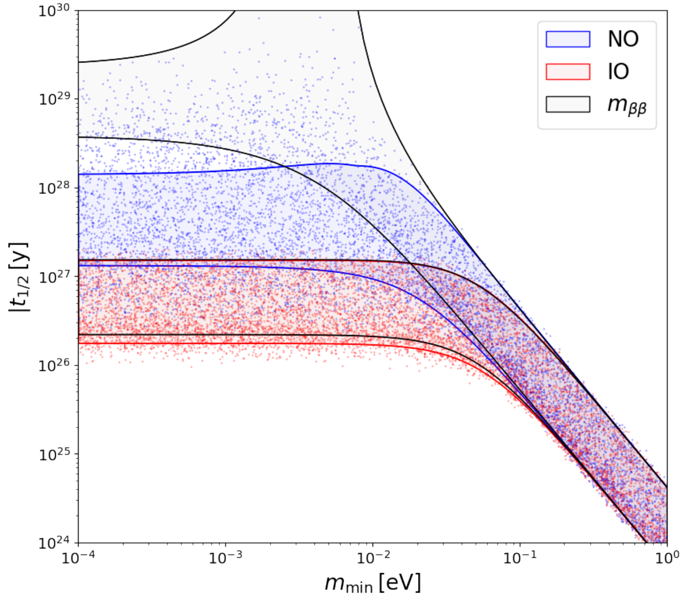
- UV scenario: minimal left-right symmetric model

$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

- minor variations for inverted ordering (IO)
- assuming normal ordering (NO) can result in ratios altered more significantly for small minimal neutrino mass
- small ratios ↔ dominance of short-range contributions at χEFT level

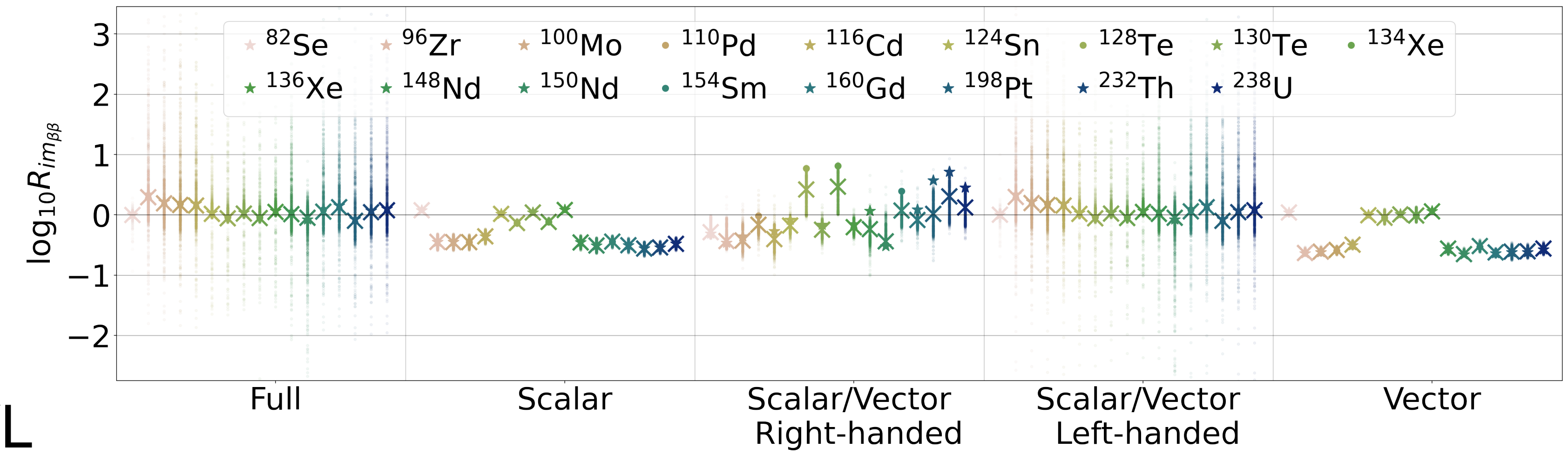






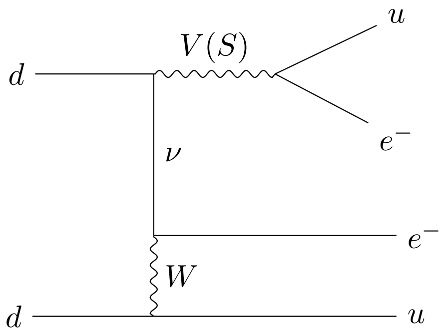
Models: Leptoquarks

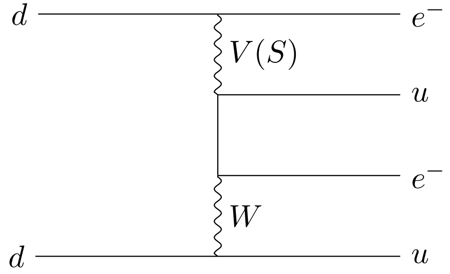
- considered scenarios give distinguishable spectra
- central values match the case with order-of-magnitude estimates of the LECs
- spread for the full model, SL, VL

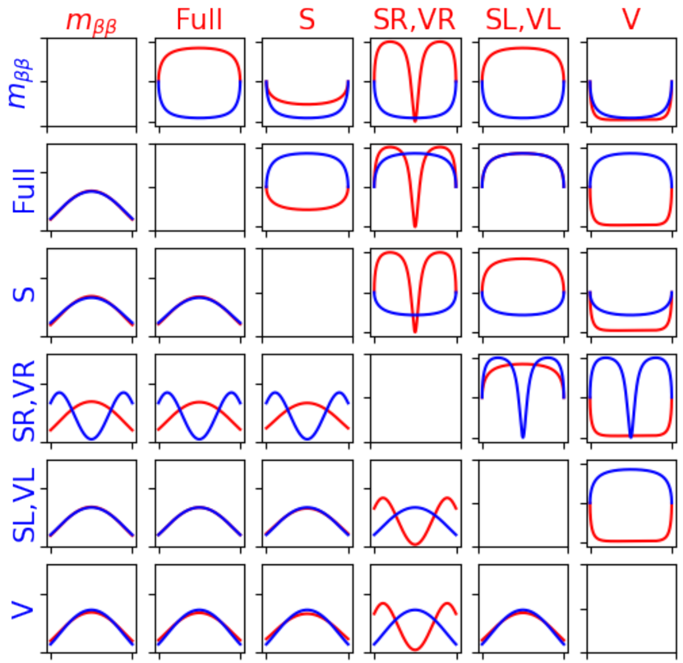


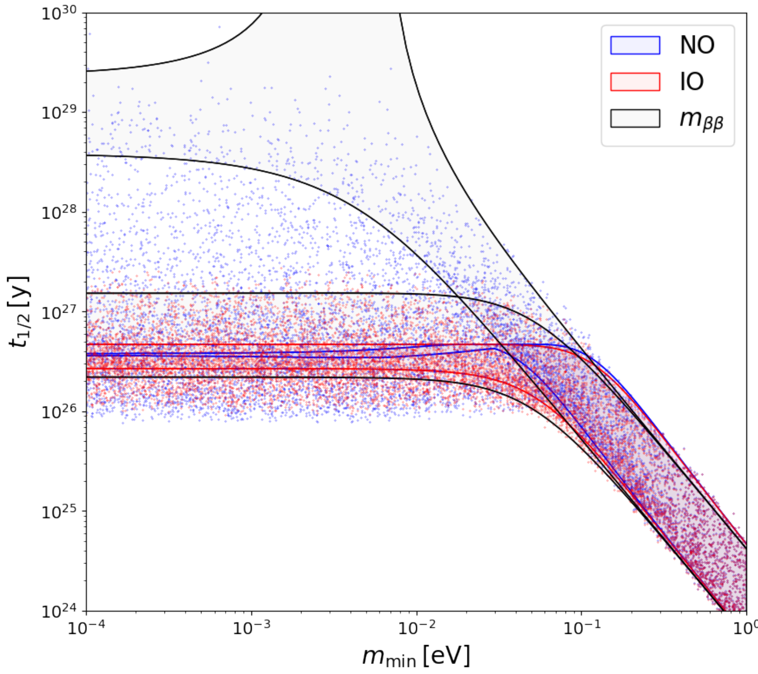
$$\mathcal{L}_{LQ} = [\bar{e} P_L \nu^c]\left\{\frac{\epsilon_S}{M_S^2}[\bar{u} P_R d] + \frac{\epsilon_V}{M_V^2}[\bar{u} P_L d]\right\}$$
$$- [\bar{e}\gamma^\mu P_L \nu^c]\left\{\left(\frac{\alpha_S^R}{M_S^2}+\frac{\alpha_V^R}{M_V^2}\right)[\bar{u}\gamma_\mu P_R d] - \sqrt{2}\left(\frac{\alpha_S^L}{M_S^2}+\frac{\alpha_V^L}{M_V^2}\right)[\bar{u}\gamma_\mu P_L d]\right\} + \text{h.c.},$$

M. Hirsch, H. V. Klapdor-Kleingrothaus, S. G. Kovalenko (PRD, 1996)





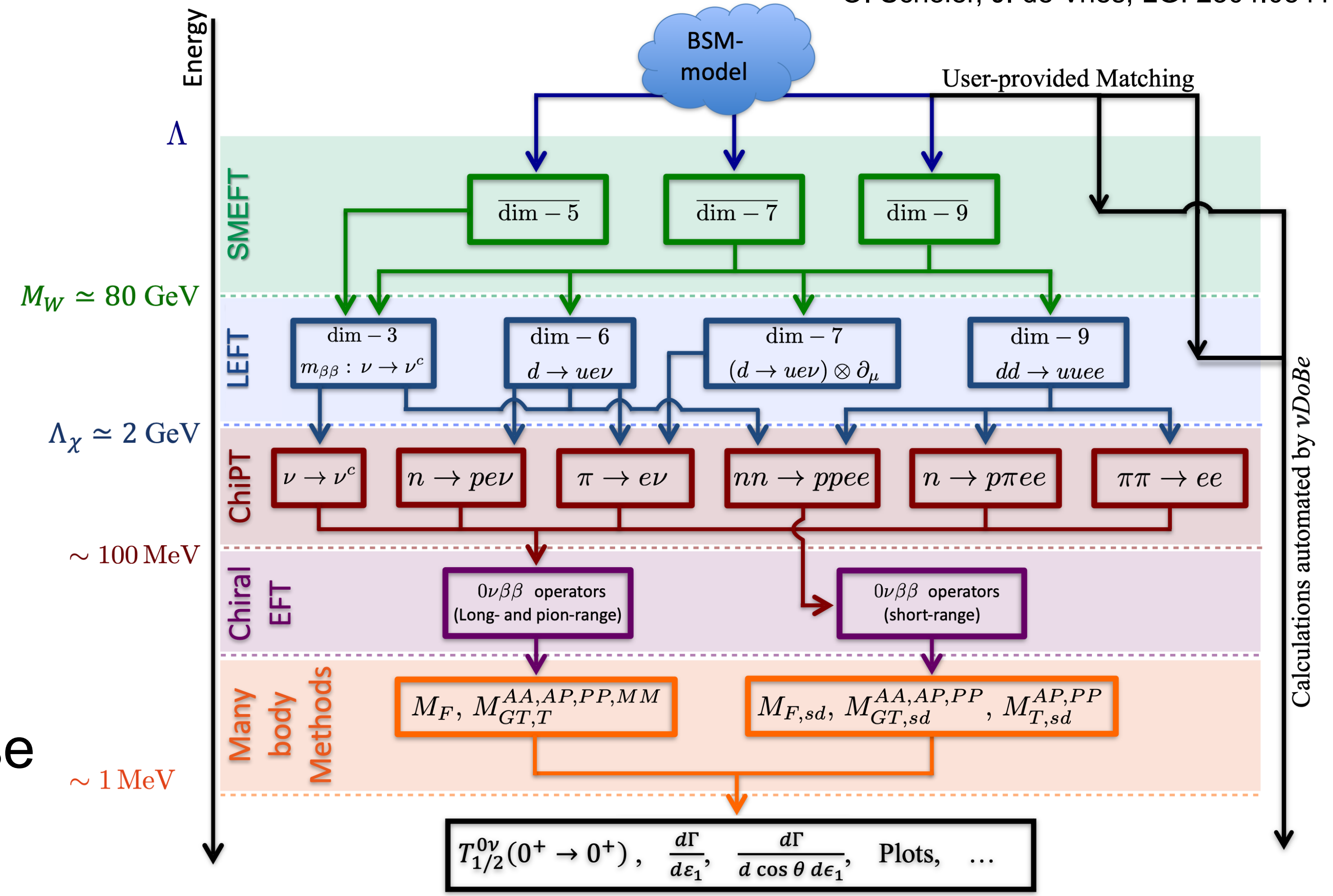




vDoBe: A Python Tool for 0νββ

O. Scholer, J. de Vries, LG: 2304.05415

- user inputs:
  - scale + selection of operators
  - isotope(s), type of NMEs
- data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants
- outputs:
  - half-life formula for the given case
  - limits on selected couplings
  - $m_{\beta\beta}$ vs. m_ν plots, etc.
  - chosen contour plots showing correlations of different parameters, …



download: https://github.com/OScholer/nudobe
online tool: https://oscholer-nudobe-streamlit-4foz22.streamlit.app/

Unraveling the signal: other probes of LNV?

LNV at Dimension 7 in SMEFT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + C_5 \mathcal{O}_5 + \sum C_7^i \mathcal{O}_7^i + \sum C_9^i \mathcal{O}_9^i + \dots .$$

- let's consider the basis of the 12 dimension-7 ΔL = 2 SMEFT operators
- Lehman PRD (2014) → 20 independent operators (13 conserving B but ΔL = 2 and 7 violating both by one unit, ΔB = −ΔL = −1)
- further reduced in Liao, Ma JHEP (2017) to 18 = 12 + 6 (independent structures)

Type	$\mathcal{O}$	Operator
$\Psi^2 H^4$	$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}} L_r^m\right) H^j H^n \left(H^\dagger H\right)$
$\Psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}} \gamma_\mu e_r\right) H^j \left(H^m iD^\mu H^n\right)$
$\Psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}} D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
	$\mathcal{O}_{LHD2}^{pr}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{L_p^{ci}} D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\Psi^2 H^2 X$	$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}} \sigma_{\mu\nu} L_r^m\right) H^j H^n B^{\mu\nu}$
	$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L_p^{ci}} \sigma_{\mu\nu} L_r^m\right) H^j H^n W^{I\mu\nu}$
$\Psi^4 D$	$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^{ci}} iD^\mu L_t^j\right)$
$\Psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p} L_r^i\right)\left(\overline{L_s^{cj}} L_t^m\right) H^n$
	$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p} L_r^i\right)\left(\overline{u_s^c} e_t\right) H^j$
	$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^{cj}} L_t^m\right) H^n$
	$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^{cj}} L_t^m\right) H^n$
	$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}\left(\overline{Q_p} u_r\right)\left(\overline{L_s^c} L_t^i\right) H^j$

LNV at Dimension 7 in SMEFT

Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

- bottom-up approach:

Experimental observable

↓

Constraints on LEFT
(single operator dominance)

↓

Constraints on SMEFT
(using matching relations)

↓

UV theory

- caveat: simplified, could be correlations/cancellations

$\mathcal{O}$	Operator	Matching
$\mathcal{O}^{S,prst}_{e\nu;LL}$	$(\overline{e_{Rp}} e_{Lr})(\overline{\nu^c_s} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{e\nu;LL} = -\frac{\sqrt{2}v}{8}\left(2C^{prst}_{\bar{e}LLLH} + C^{psrt}_{\bar{e}LLLH} + s \leftrightarrow t\right)$
$\mathcal{O}^{S,prst}_{e\nu;RL}$	$(\overline{e_{Lp}} e_{Rr})(\overline{\nu^c_s} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{e\nu;RL} = -\frac{\sqrt{2}v}{2}\left(C^{sr}_{LeHD}\delta^{tp} + C^{tr}_{LeHD}\delta^{sp}\right)$
$\mathcal{O}^{T,prst}_{e\nu;LL}$	$(\overline{e_{Rp}} \sigma_{\mu\nu} e_{Lr})(\overline{\nu^c_s} \sigma^{\mu\nu} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{T,prst}_{e\nu;LL} = +\frac{\sqrt{2}v}{32}\left(C^{psrt}_{\bar{e}LLLH} - C^{ptrs}_{\bar{e}LLLH}\right)$
$\mathcal{O}^{S,prst}_{d\nu;LL}$	$(\overline{d_{Rp}} d_{Lr})(\overline{\nu^c_s} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{8} V_{xr}\left(C^{ptxs}_{\bar{d}LQLH1} + C^{psxt}_{\bar{d}LQLH1}\right)$
$\mathcal{O}^{T,prst}_{d\nu;LL}$	$(\overline{d_{Rp}} \sigma_{\mu\nu} d_{Lr})(\overline{\nu^c_s} \sigma^{\mu\nu} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{T,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{32} V_{xr}\left(C^{ptxs}_{\bar{d}LQLH1} - C^{psxt}_{\bar{d}LQLH1}\right)$
$\mathcal{O}^{S,prst}_{u\nu;RL}$	$(\overline{u_{Lp}} u_{Rr})(\overline{\nu^c_s} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{u\nu;RL} = +\frac{\sqrt{2}v}{4}\left(C^{prst}_{\bar{Q}uLLH} + C^{prts}_{\bar{Q}uLLH}\right)$
$\mathcal{O}^{S,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}} u_{Lr})(\overline{\nu^c_s} e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{du\nu e;LL} = +\frac{\sqrt{2}v}{8}\left(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} - C^{psrt}_{\bar{d}LQLH2}\right)$
$\mathcal{O}^{S,prst}_{du\nu e;RL}$	$(\overline{d_{Lp}} u_{Rr})(\overline{\nu^c_s} e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c^{S,prst}_{du\nu e;RL} = +\frac{\sqrt{2}v}{2} V^*_{xp} C^{xrts}_{\bar{Q}uLLH}$
$\mathcal{O}^{T,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}} \sigma_{\mu\nu} u_{Lr})(\overline{\nu^c_s} \sigma^{\mu\nu} e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c^{T,prst}_{du\nu e;LL} = +\frac{\sqrt{2}v}{32}\left(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} + C^{psrt}_{\bar{d}LQLH2}\right)$
$\mathcal{O}^{V,prst}_{du\nu e;LR}$	$(\overline{d_{Lp}} \gamma_\mu u_{Lr})(\overline{\nu^c_s} \gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}} c^{V,prst}_{du\nu e;LR} = +\frac{\sqrt{2}v}{2} V^*_{rp} C^{st}_{LeHD}$
$\mathcal{O}^{V,prst}_{du\nu e;RR}$	$(\overline{d_{Rp}} \gamma_\mu u_{Rr})(\overline{\nu^c_s} \gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}} c^{V,prst}_{du\nu e;RR} = +\frac{\sqrt{2}v}{4} C^{psrt}_{\bar{d}LueH}$
$\mathcal{O}^{S,prst}_{d\nu;RL}$	$(\overline{d_{Lp}} d_{Rr})(\overline{\nu^c_s} \nu_t)$	Not induced by $d = 7$ $\Delta L = 2$ SMEFT operators
$\mathcal{O}^{S,prst}_{u\nu;LL}$	$(\overline{u_{Rp}} u_{Lr})(\overline{\nu^c_s} \nu_t)$	
$\mathcal{O}^{T,prst}_{u\nu;LL}$	$(\overline{u_{Rp}} \sigma_{\mu\nu} u_{Lr})(\overline{\nu^c_s} \sigma^{\mu\nu} \nu_t)$	

LNV at Dimension 7 in SMEFT

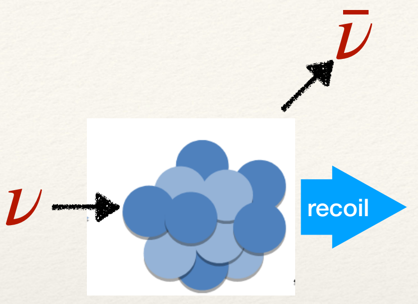
- clearly, neutrinoless double beta decay is the best probe
- but: sensitive to LNV only in the electron flavour
- if observed, not enough info to distinguish the dominant mechanism and therefore, the underlying new physics (also nuclear uncertainties …)

→ complementary probes vital

LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV^{-3}]	Λ_{NP} [TeV]
$c^{S}_{du\nu e;LL}$	$1.86 \cdot 10^{-10}$	$C_{\bar{d}LQLH1}$	$7.06 \cdot 10^{-8}$	242
$c^{S}_{du\nu e;RL}$	$1.86 \cdot 10^{-10}$	$C_{\bar{Q}uLLH}$	$3.62 \cdot 10^{-8}$	302
$c^{V}_{du\nu e;LR}$	$8.20 \cdot 10^{-10}$	C_{LeHD}	$1.55 \cdot 10^{-7}$	186
$c^{V}_{du\nu e;RR}$	$5.93 \cdot 10^{-8}$	$C_{\bar{d}LueH}$	$1.12 \cdot 10^{-5}$	44.7
$c^{T}_{du\nu e;LL}$	$4.51 \cdot 10^{-10}$	$C_{\bar{d}LQLH1}$	$6.83 \cdot 10^{-7}$	114
		$C_{\bar{d}LQLH2}$	$3.41 \cdot 10^{-7}$	143
$c^{(7)V}_{du\nu e;LL}$	$9.87 \cdot 10^{-6}$	C_{LHD1}	$1.36 \cdot 10^{-3}$	9.03
		C_{LHD2}	$2.71 \cdot 10^{-3}$	7.17
		C_{LHW}	$3.39 \cdot 10^{-4}$	14.3
$c^{(7)V}_{du\nu e;RL}$	$9.87 \cdot 10^{-6}$	$C_{\bar{d}uLLD}$	$1.32 \cdot 10^{-3}$	9.11
$c^{(9);ij}_{V;LL}$	$1.40 \cdot 10^{-5}$	C_{LHD1}	$9.91 \cdot 10^{-4}$	10.0
		C_{LHW}	$2.48 \cdot 10^{-4}$	15.9
$c^{(9);ij}_{V;LR}$	$2.66 \cdot 10^{-8}$	$C_{\bar{d}uLLD}$	$1.83 \cdot 10^{-6}$	81.7

Complementary Probes

- neutral current LNV NSI @CEvNS experiments
  - first observation
    Akimov er al.: Science (2017)
  - neutrino scatters elastically off the entire nucleus



$$E_\nu \lesssim \frac{hc}{R_N} \sim \mathcal{O}(10\ \mathrm{MeV})$$

LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV^{-3}]	Λ_{NP} [TeV]	Experiment
Current Bound				
$c^{S,11\mu\mu}_{d\nu;LL(LR)}$	0.030	11.3	0.4	COHERENT
$c^{T,11st}_{d\nu;LL}$	0.178	540.2	0.1	COHERENT
Future Sensitivity				
$c^{S,11\alpha\alpha}_{d\nu;LL(LR)}$	0.008	3.0	0.7	Ge
$c^{T,11st}_{d\nu;LL}$	0.062	186.9	0.2	Ge

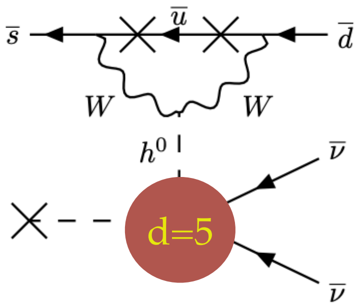
- charged current LNV NSI @LBL oscillation exp.
  Bolton, Deppisch: PRD 99 (2019)
  - production charge blind
  - detection sensitive to outgoing lepton charge

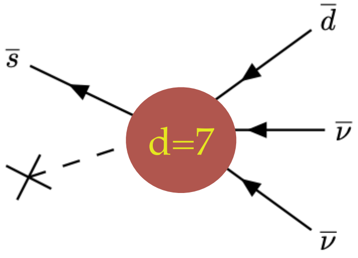
LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV^{-3}]	Λ_{NP} [TeV]	Experiment
$c^{V,11ee(e\mu)}_{du\nu e;LR}$	0.017	$C^{ee(e\mu)}_{LeHD}$	3.2	0.7	KamLAND
$c^{V,11ee(e\mu)}_{du\nu e;RR}$	0.017	$C^{1e1e(1e1\mu)}_{\bar{d}LueH}$	6.4	0.5	KamLAND
$c^{V,11e\tau}_{du\nu e;LR}$	0.015	$C^{ee(e\tau)}_{LeHD}$	2.8	0.7	KamLAND
$c^{V,11e\tau}_{du\nu e;RR}$	0.015	$C^{1e1\tau}_{\bar{d}LueH}$	5.7	0.6	KamLAND
$c^{V,11\mu e}_{du\nu e;LR}$	$0.22-3.47$	$C^{\mu e}_{LeHD}$	41.7-658.1	0.1-0.3	MINOS
$c^{V,11\mu e}_{du\nu e;RR}$	$0.22-3.47$	$C^{1\mu 1e}_{\bar{d}LueH}$	83.4-1316.2	0.1-0.2	MINOS
$c^{V,11\mu\mu}_{du\nu e;LR}$	$0.16-0.63$	$C^{\mu\mu}_{LeHD}$	30.3-119.5	0.2-0.3	MINOS
$c^{V,11\mu\mu}_{du\nu e;RR}$	$0.16-0.63$	$C^{1\mu 1\mu}_{\bar{d}LueH}$	60.7-239.0	0.2-0.3	MINOS
$c^{V,11\mu\tau}_{du\nu e;LR}$	$0.16-0.71$	$C^{\mu\tau}_{LeHD}$	30.3-134.7	0.2-0.3	MINOS
$c^{V,11\mu\tau}_{du\nu e;RR}$	$0.16-0.71$	$C^{1\mu 1\tau}_{\bar{d}LueH}$	60.7-269.31	0.2-0.3	MINOS

Complementary Probes

Deppisch, Fridell, Harz: JHEP 12 (2020)
Felkl, Li, Schmidt: JHEP 12 (2021)
Li, Ma, Schmidt: PRD 101 (2020)

- LNV dim-7 SMEFT can be probed with rare meson decays and rare tau decays
- very weak constraints from $K^+ \to \pi^- \ell^+ \ell^+$, $\tau^\pm \to \ell^\mp_\alpha P^\pm_i P^\pm_j$
- $M' \to M\nu\nu$ well discussed in literature in the context of dim-7 SMEFT
- charged Kaon decays @NA62 provide the best limits
- dipole type of contributions can be present, but are suppressed





LEFT Wilson Coefficient	Current Bound Value	$C_{\bar{d}LQLH1}$ [TeV^{-3}]	$\Lambda_{\rm NP}$ [TeV]	Observable
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	1.3×10^{-6}	4.8×10^{-4}	12.8	$K_L \to \nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	2.5×10^{-7}	9.6×10^{-5}	21.8	$K^+ \to \pi^+\nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	2.6×10^{-7}	9.9×10^{-5}	21.6	$K^0 \to \pi^0\nu\nu$
Future Sensitivity				
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	8.4×10^{-8}	3.2×10^{-5}	31.5	$K^+ \to \pi^+\nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	1.4×10^{-7}	5.2×10^{-5}	26.8	$K^0 \to \pi^0\nu\nu$

LEFT Wilson Coefficient	Current Bound Value	$C_{\bar{d}LQLH1}$ [TeV^{-3}]	$\Lambda_{\rm NP}$ [TeV]	Observable
$c^{S,sb\gamma\gamma}_{d\nu;LL}$	3.6×10^{-4}	0.14	1.9	$B \to K^{(*)}\nu\nu$
$c^{S,sb\gamma\delta}_{d\nu;LL}$	2.7×10^{-4}	0.21	1.7	$B \to K^{(*)}\nu\nu$
$c^{T,sb\gamma\delta}_{d\nu;LL}$	0.6×10^{-4}	0.18	1.75	$B \to K^*\nu\nu$
Future Sensitivity (50 ab^{-1})				
$c^{S,sb\gamma\gamma}_{d\nu;LL}$	0.6×10^{-4}	0.02	3.5	$B \to K\nu\nu$
$c^{S,sb\gamma\delta}_{d\nu;LL}$	0.6×10^{-4}	0.05	2.8	$B \to K\nu\nu$
$c^{T,sb\gamma\delta}_{d\nu;LL}$	0.3×10^{-4}	0.08	2.3	$B \to K^*\nu\nu$

Complementary Probes

- non-standard muon decay – eLLLH does not contribute at tree level to 0vbb
- at LEFT level:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\Big\{ c^{S,\mu ee\mu}_{e\nu;LL}\left(\overline{\mu_R} e_L\right)\left(\bar{\nu^c_e}\nu_\mu\right) + c^{S,e\mu e\mu}_{e\nu;LL}\left(\overline{e_R}\mu_L\right)\left(\bar{\nu^c_e}\nu_\mu\right)$$
$$+ c^{T,\mu ee\mu}_{e\nu;LL}\left(\overline{\mu_R}\sigma_{\mu\nu} e_L\right)\left(\bar{\nu^c_e}\sigma^{\mu\nu}\nu_\mu\right) + c^{T,e\mu e\mu}_{e\nu;LL}\left(\overline{e_R}\sigma_{\mu\nu}\mu_L\right)\left(\bar{\nu^c_e}\sigma^{\mu\nu}\nu_\mu\right)\Big\} + \text{h.c.}$$

  - only the highlighted terms can mediate the experimentally probed $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_\mu$
  - CC process $p\,\bar{\nu}_e \to e^+ n$ was used to identify electron antineutrino

B. Armbruster et al.: PRL 90 (2003)

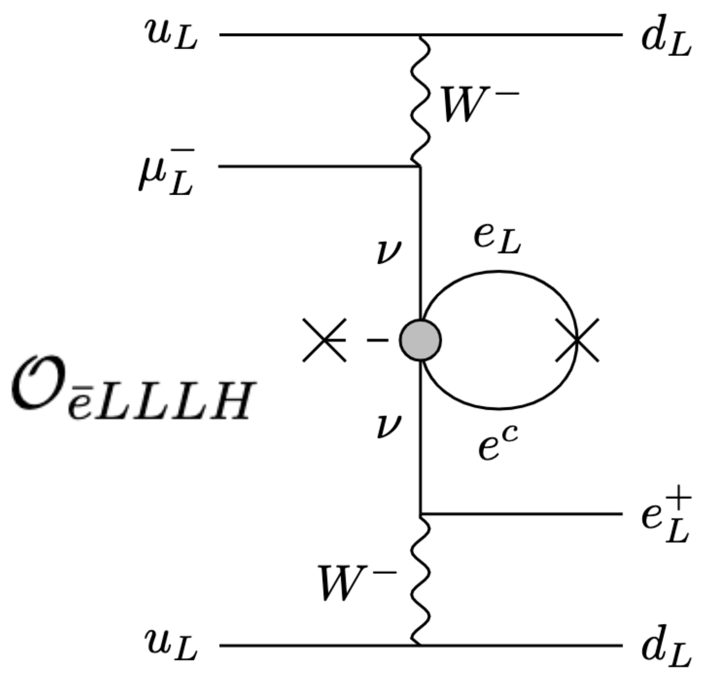
LEFT Wilson Coefficient	Value	Current Bound $C_{\bar{e}LLLH}$ [TeV^{-3}]	Current Bound Λ_{NP} [TeV]	Observable
$c^{S,\mu ee\mu}_{e\nu;LL}$	0.06	15.2	0.4	$\mu^+ \to e^+\bar{\nu}_e\bar{\nu}_\mu, \tilde{\rho} = 0.75$
$c^{T,\mu ee\mu}_{e\nu;LL}$	0.04	121.6	0.2	$\mu^+ \to e^+\bar{\nu}_e\bar{\nu}_\mu, \tilde{\rho} = 0.25$

Complementary Probes

- μ^- to e^+ conversion

$$R_{\mu^- e^+} \equiv \frac{\Gamma(\mu^- + \mathrm{N} \to e^+ + \mathrm{N}')}{\Gamma(\mu^- + \mathrm{N} \to \nu_\mu + \mathrm{N}'')}$$

  - best limits: SINDRUM II, upcoming Mu2e, COMET
  - small contributions from dim-7 SMEFT, for Λ ~ 1 TeV: R ~ 10^{-24}



Berryman, de Gouvêa et al.: PRD (2017)

- neutrino magnetic moment

$$\mathcal{L}_M \supset \frac{1}{2}\begin{pmatrix}\nu_1 & \nu_2 & \nu_3\end{pmatrix}\sigma_{\mu\nu}\begin{pmatrix}0 & \mu_{12} & \mu_{13}\\ -\mu_{12} & 0 & \mu_{23}\\ -\mu_{13} & -\mu_{23} & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}F^{\mu\nu} + \mathrm{h.c.}$$

$$c^{5\gamma}_{\nu\nu F}/e \equiv \mu_{ij} = \frac{1}{2v}\left(v^3 C^{ij}_{LHB} - v^3\frac{C^{ij}_{LHW} - C^{ji}_{LHW}}{2}\right)$$

  - solar: Borexino; reactor: GEMMA, TEXONO, CONUS; accelerator: LSND, DUNE
  - Λ > 10 TeV, competitive with 0vbb

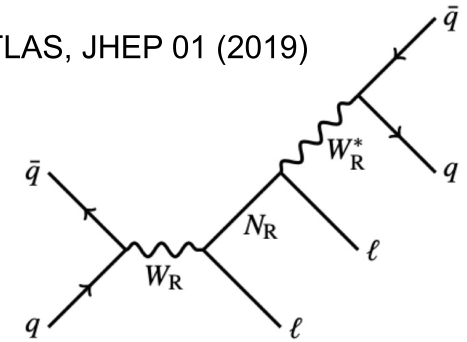
$$|C^{ij}_{LHB} - C^{ij}_{LHW}|_{i\neq j} \lesssim \frac{10^{-11}}{4 m_e v^2}$$

V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 (2017)

SMEFT Dim-7 LNV at Colliders

- main mode of interest: $pp \to \ell^\pm \ell^\pm jj$
- recasting of the search for the Keung-Senjanović process by ATLAS

ATLAS, JHEP 01 (2019)

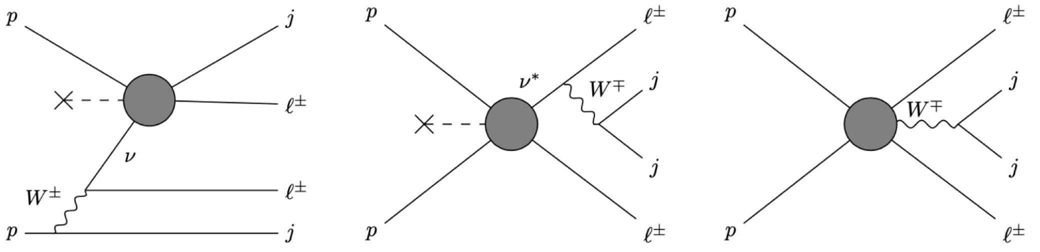


- study along the lines of the analysis for Weinberg operator

Fuks, Neundorf, Peters, Ruiz, Saimpert, PRD 103 (2021)
CMS, JHEP 03 (2022)

- caveats: resonant production, validity of EFT

Graesser, Li, Ramsey-Musolf, Shen, Quiroga, JHEP 10 (2022)
Busoni, De Simone, Morgante, Riotto, PLB 728 (2014)

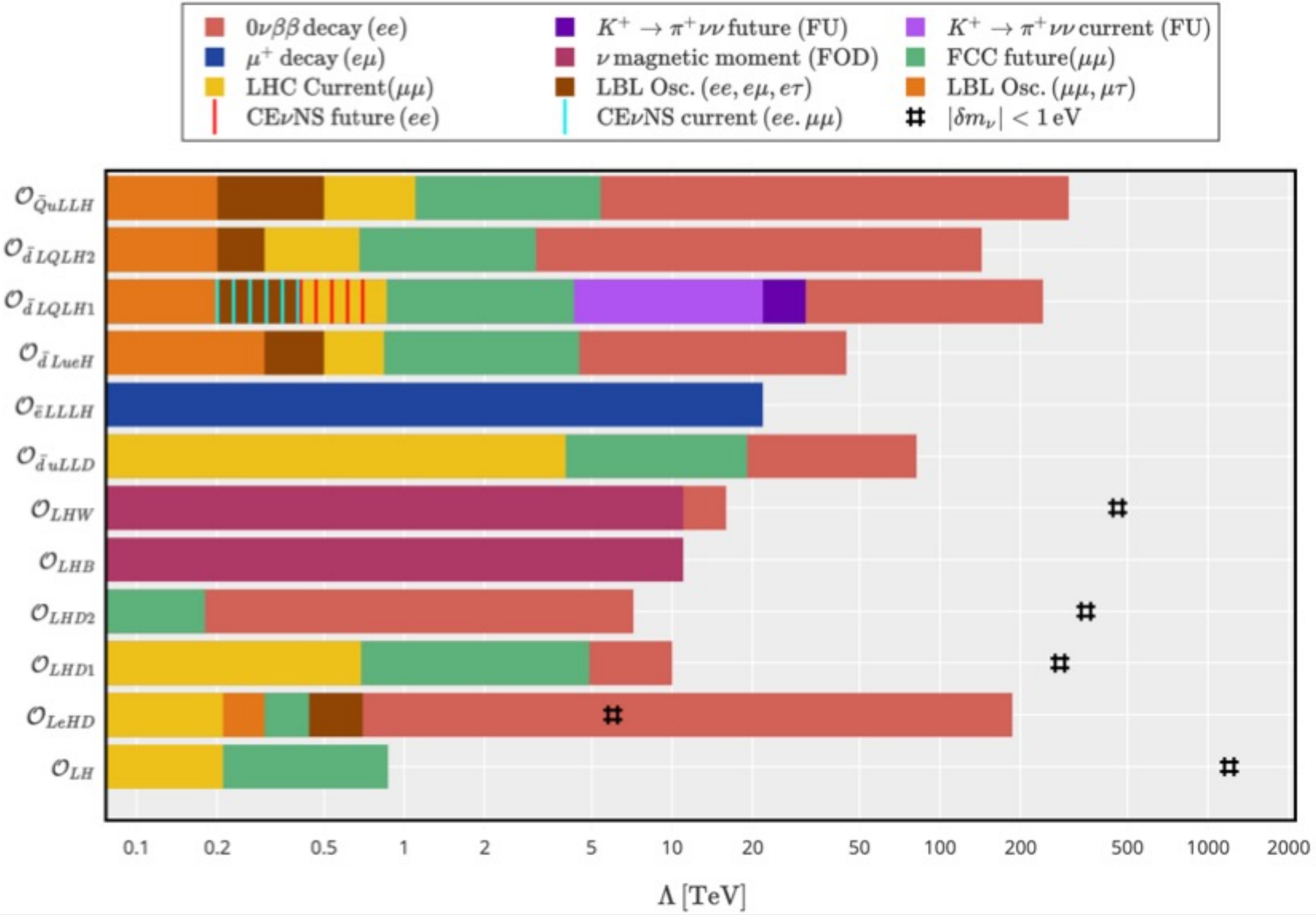


Operator	$\sigma(pp \to \mu^\pm\mu^\pm jj)$ (pb) LHC	FCC	Λ_{LNV} [TeV]	$\Lambda_{\mathrm{LNV}}^{\mathrm{future}}$ [TeV]
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.1	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.68	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	0.86	4.3
$\mathcal{O}_{\bar{d}LueH}$	5.7×10^{-5}	0.035	0.84	4.5
$\mathcal{O}_{\bar{d}uLLD}$	0.64	210	4.0	19
$\mathcal{O}_{LDH2}$	2.7×10^{-12}	1.7×10^{-10}	0.050*	0.18
$\mathcal{O}_{LDH1}$	1.9×10^{-5}	0.061	0.69	4.9
$\mathcal{O}_{LeHD}$	1.2×10^{-8}	3.1×10^{-8}	0.21*	0.44
$\mathcal{O}_{LH}$	1.5×10^{-8}	2.0×10^{-6}	0.21*	0.87

K. Fridell, LG, J. Harz, C. Hati: 2306.08709

Complementary Probes @SMEFT dim 7

$\mathcal{O}$	Operator
$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^{i} L_r^m\right) H^j H^n \left(H^\dagger H\right)$
$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^{i}\gamma_\mu e_r\right) H^j \left(H^m i D^\mu H^n\right)$
$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^{i} D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\mathcal{O}_{LHD2}^{pr}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{L_p^{c}}^{i} D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^{i}\sigma_{\mu\nu} L_r^m\right) H^j H^n B^{\mu\nu}$
$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L_p^{c}}^{i}\sigma_{\mu\nu} L_r^m\right) H^j H^n W^{I\mu\nu}$
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^{c}}^{i} i D^\mu L_t^j\right)$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p} L_r^i\right)\left(\overline{L_s^{c}}^{j} L_t^m\right) H^n$
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p} L_r^i\right)\left(\overline{u_s^{c}} e_t\right) H^j$
$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^{c}}^{j} L_t^m\right) H^n$
$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^{c}}^{j} L_t^m\right) H^n$
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}\left(\overline{Q_p} u_r\right)\left(\overline{L_s^{c}} L_t^i\right) H^j$



K. Fridell, LG, J. Harz, C. Hati: 2306.08709

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PHYSICS FRONTIER CENTER

Complementary Probes @SMEFT dim 7

$\mathcal{O}$	Operator
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$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^c}{}^i \gamma_\mu e_r\right)H^j \left(H^m iD^\mu H^n\right)$
$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^c}{}^i D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
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$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^c}{}^i \sigma_{\mu\nu} L_r^m\right)H^j H^n B^{\mu\nu}$
$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L_p^c}{}^i \sigma_{\mu\nu} L_r^m\right)H^j H^n W^{I\mu\nu}$
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^c}{}^i iD^\mu L_t^j\right)$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p} L_r^i\right)\left(\overline{L_s^c}{}^j L_t^m\right)H^n$
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p} L_r^i\right)\left(\overline{u_s^c} e_t\right)H^j$
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$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^c}{}^j L_t^m\right)H^n$
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}\left(\overline{Q_p} u_r\right)\left(\overline{L_s^c} L_t^i\right)H^j$

Operator	Collider	$0\nu\beta\beta$	LBL Osc.	μ_ν	μ^+-decay	CEνNS	Meson decay
$\mathcal{O}_{LH}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LeHD}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{LDH1}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LDH2}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LHB}$	-	-	-	✓	-	-	-
$\mathcal{O}_{LHW}$	-	✓	-	✓	-	-	-
$\mathcal{O}_{\bar{d}uLLD}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{\bar{e}LLLH}$	-	-	-	-	✓	-	-
$\mathcal{O}_{\bar{d}LueH}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{d}QLLH1}$	✓	✓	✓	-	-	✓	✓
$\mathcal{O}_{\bar{d}QLLH2}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{Q}uLLH}$	✓	✓	✓	-	-	-	-

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Conclusion & Outlook

- $0\nu\beta\beta$ – complex process, access to new physics – a variety of different mechanisms besides the standard light neutrino exchange can contribute to $0\nu\beta\beta$ → effective description
- to unravel the underlying new physics – necessary to distinguish the dominant LNV interaction
- using only $0\nu\beta\beta$ – challenging task: other modes, energy spectrum, angular correlation, isotope ratios – main issue: unknown LECs + uncertain NMEs
- hard to pin down a specific operator, but at least distinguish any exotic contribution
- combining various contributions → involved, tedious calculations with a variety of inputs → νDoBe tool developed and available online
- complementarity could help with unraveling the LNV physics → other low-energy experiments, but also high-energy data useful
- LNV at colliders: same-sign dileptons, stringent limits for muon flavour
- next: from EFT to simplified models, νSMEFT

Conclusion & Outlook

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Thank you!