Probing Lepton Number Violation from Low to High Energies

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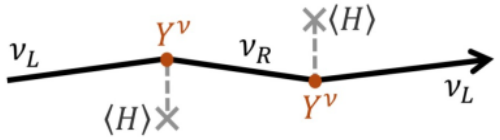
BCVSPIN conference, Kathmandu, December 2024

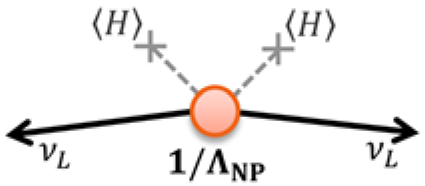
Lepton Number (Violation)

- non-perturbative Standard Model (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



$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$

$m_M \overline{\nu}_L \nu_L^c$



Dirac mass → as other fermions, but tiny

Majorana mass → lepton number violation

Double Beta Decays

- two-neutrino double beta decay

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

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

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

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

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

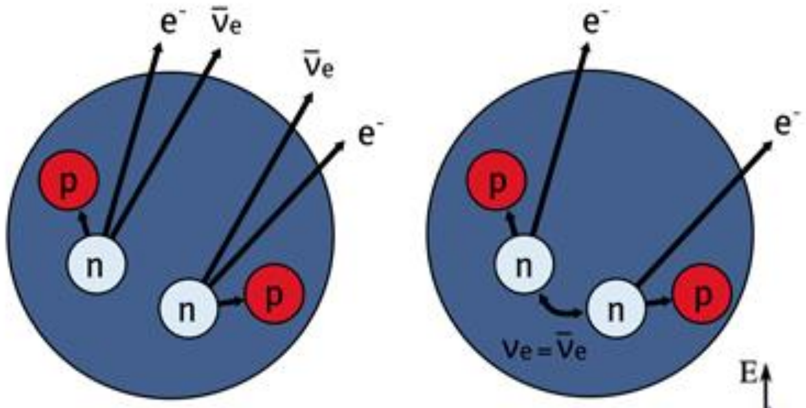
KamLAND-Zen, LEGEND, CUORE, NEMO-3, CUPID, (n)EXO, …

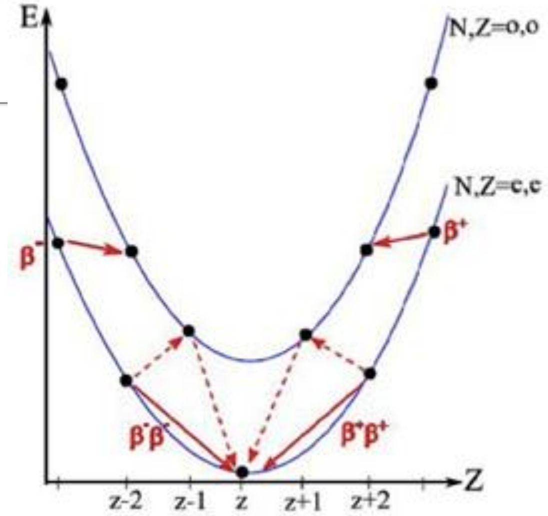
- a variety of isotopes: ^{76}Ge, ^{136}Xe, …

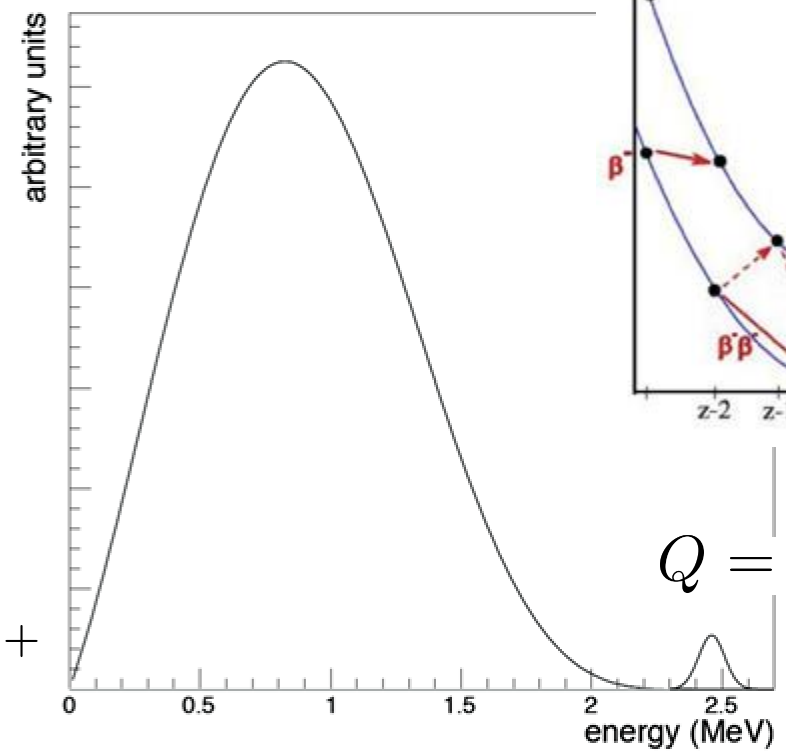
- variants: $0\nu\beta^+\beta^+ : \ (A,Z) \rightarrow (A,Z-2) + 2e^+$

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

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



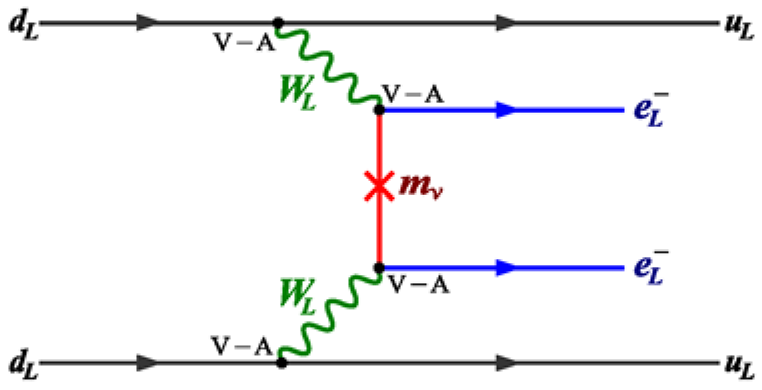




$$Q = E_i - E_f - 2m_e$$

Neutrinoless Double Beta Decay

- standard mechanism with light neutrino exchange:

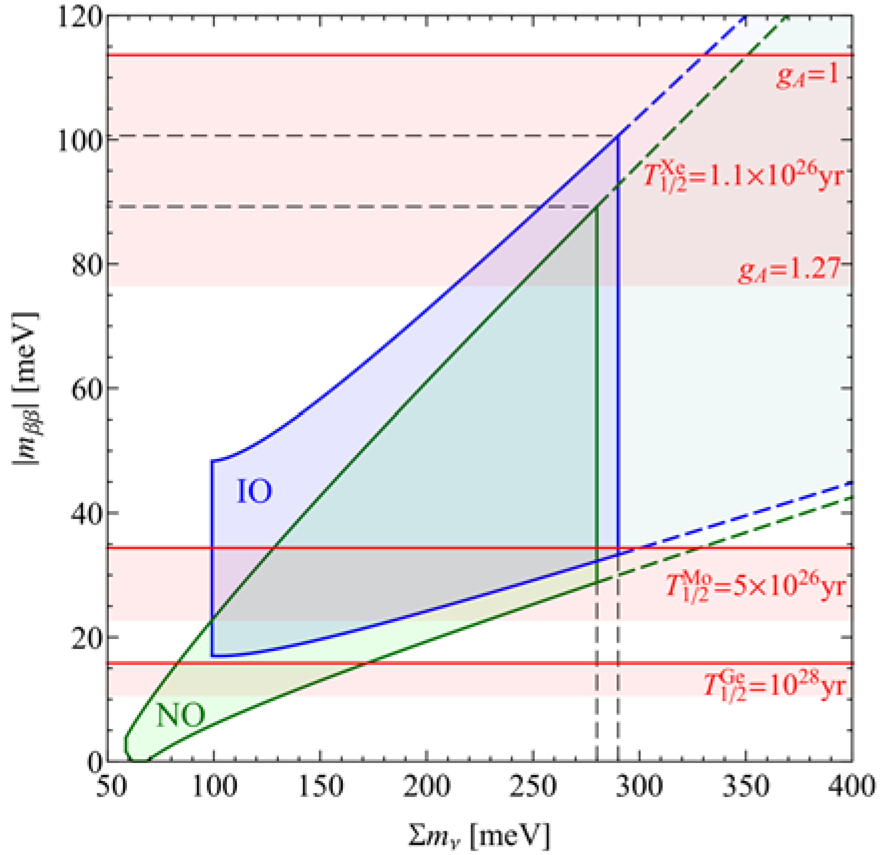


$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 \, \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$$

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

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

F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]



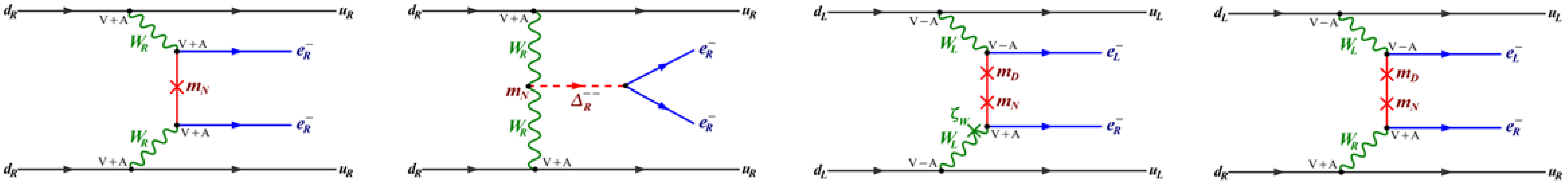
$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_{12}} + m_3 s_{13}^2 e^{i(\phi_{13}-2\delta)}$$

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

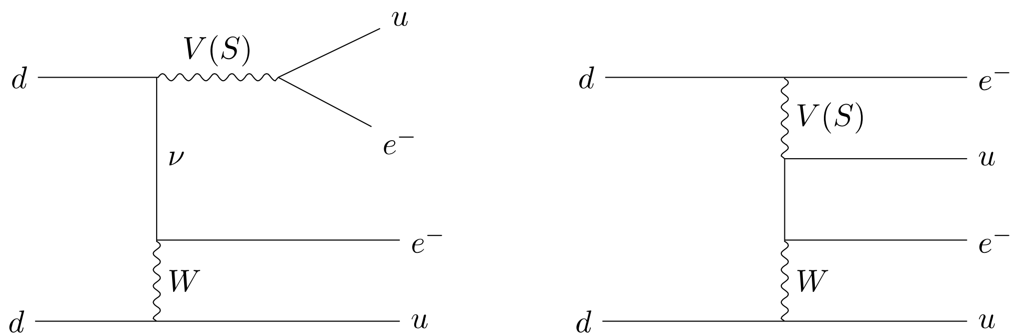
New Physics & 0νββ

- 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 ...

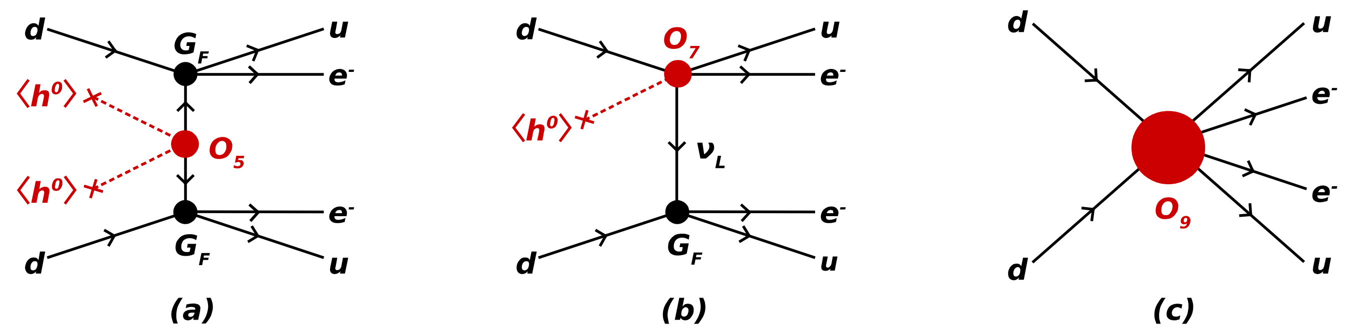
F. F. Deppisch, M. Hirsch, H. Päs: J. Phys. G 39 (2012), 124007

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 9804374, 0008182, 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range 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: $T_{1/2}^{-1} = |C|^2 G_{0\nu} |M_{0\nu}|^2$



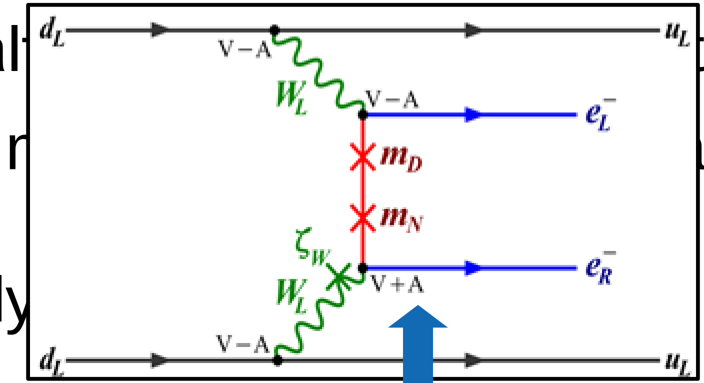
$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}} \Big[C^{(6)}_{\rm VL} \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right) + C^{(6)}_{\rm VR} \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right) + C^{(6)}_{\rm SL} \left(\overline{u_R}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

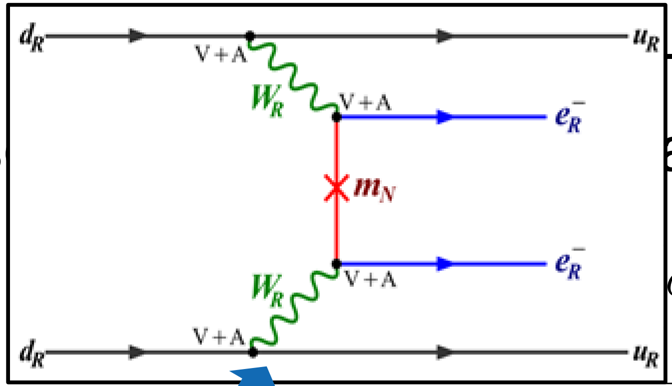
$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v} \Big[C^{(7)}_{\rm VL} \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c\right) + C^{(7)}_{\rm VR} \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu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

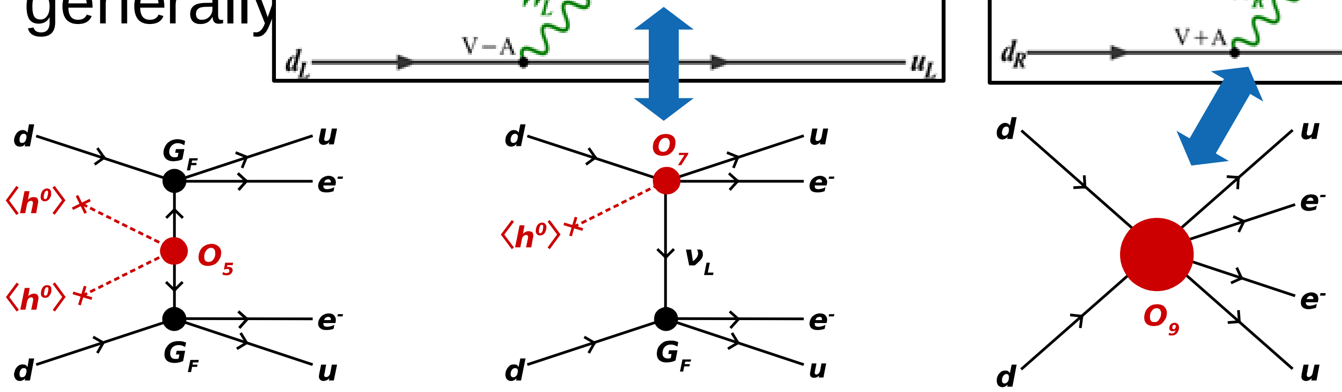
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5} \sum_i \Big[\Big(C^{(9)}_{i,R} \left(\overline{e_R} e_R^c\right) + C^{(9)}_{i,L} \left(\overline{e_L} e_L^c\right) \Big) \mathcal{O}_i + C^{(9)}_i \left(\bar{e}\gamma_\mu \gamma_5 e^c\right) \mathcal{O}_i^\mu \Big]$$

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 9804374, 0008182, 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range and short-range mechanisms
- 0νββ hal … ts – accurate calculation of nuclear r … s … al for estimating these limits
- generally







(a) (b) (c)

$$C_{\rm VL}^{(6)}\left(\overline{u_L}\gamma^{\mu}d_L\right)\left(\overline{e_R}\gamma_{\mu}\nu_L^c\right)+C_{\rm VR}^{(6)}\left(\overline{u_R}\gamma^{\mu}d_R\right)\left(\overline{e_R}\gamma_{\mu}\nu_L^c\right)$$

$$+C_{\rm SL}^{(6)}\left(\overline{u_R}d_L\right)\left(\overline{e_L}\nu_L^c\right)+C_{\rm SR}^{(6)}\left(\overline{u_L}d_R\right)\left(\overline{e_L}\nu_L^c\right)$$

$$+C_{\rm T}^{(6)}\left(\overline{u_L}\sigma^{\mu\nu}d_R\right)\left(\overline{e_L}\sigma_{\mu\nu}\nu_L^c\right)\Big]+h.c.$$

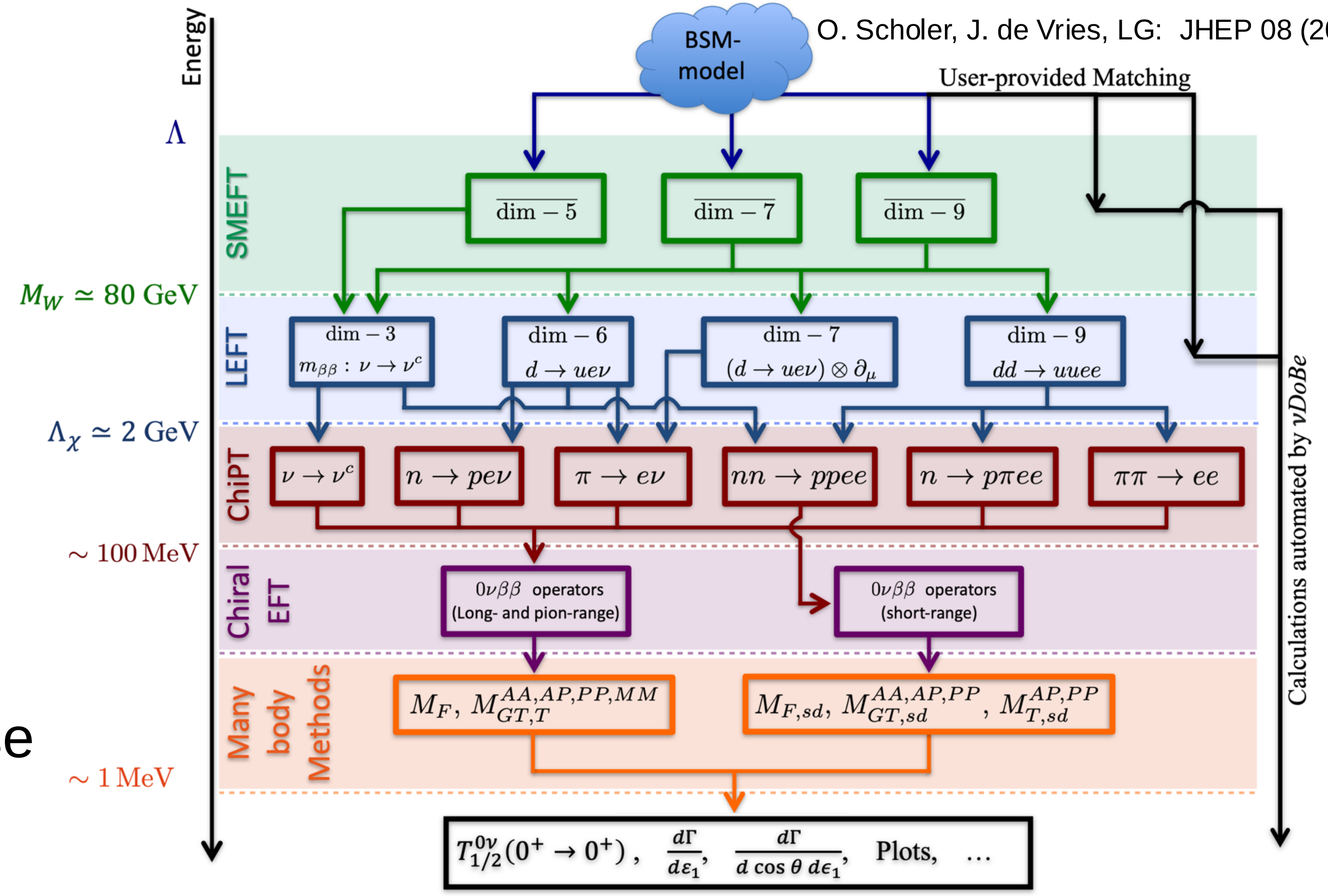
$$\mathcal{L}_{\Delta L=2}^{(7)}=\frac{2G_F}{\sqrt{2}v}\left[C_{\rm VL}^{(7)}\left(\overline{u_L}\gamma^{\mu}d_L\right)\left(\overline{e_L}\overleftrightarrow{\partial}_{\mu}\nu_L^c\right)+C_{\rm VR}^{(7)}\left(\overline{u_R}\gamma^{\mu}d_R\right)\left(\overline{e_L}\overleftrightarrow{\partial}_{\mu}\nu_L^c\right)\right]+h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)}=\frac{1}{v^5}\sum_i\left[\left(C_{i,R}^{(9)}\left(\overline{e_R}e_R^c\right)+C_{i,L}^{(9)}\left(\overline{e_L}e_L^c\right)\right)\mathcal{O}_i+C_i^{(9)}\left(\bar{e}\gamma_{\mu}\gamma_5e^c\right)\mathcal{O}_i^{\mu}\right]$$

νDoBe: A Python Tool for 0νββ

- 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, ...

O. Scholer, J. de Vries, LG: JHEP 08 (2023) 043



download: https://github.com/OScholer/nudobe
online tool: https://nudobe.streamlit.app

https://nudobe.streamlit.app

νDoBe - Online

If you use results of this tool in your scientific work, please add a citation to: arxiv:2304.05415.
For more advanced analyses, you can download the full code from gitHub.
You have any suggestions/comments on how to improve the tool?
=> Contact:
Oliver Scholer: scholer@mpi-hd.mpg.de
Lukas Graf: lukas.graf@berkeley.edu
Jordy de Vries: j.devries4@uva.nl

Please specify what you would like to do:

-

-

Define a model

Study operator limits

Which NME approximation do you want to use?

IBM2

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

-

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If you want you can give your model name. This name will be displayed in all plots

Model

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IBM2

- IBM2
- QRPA
- SM

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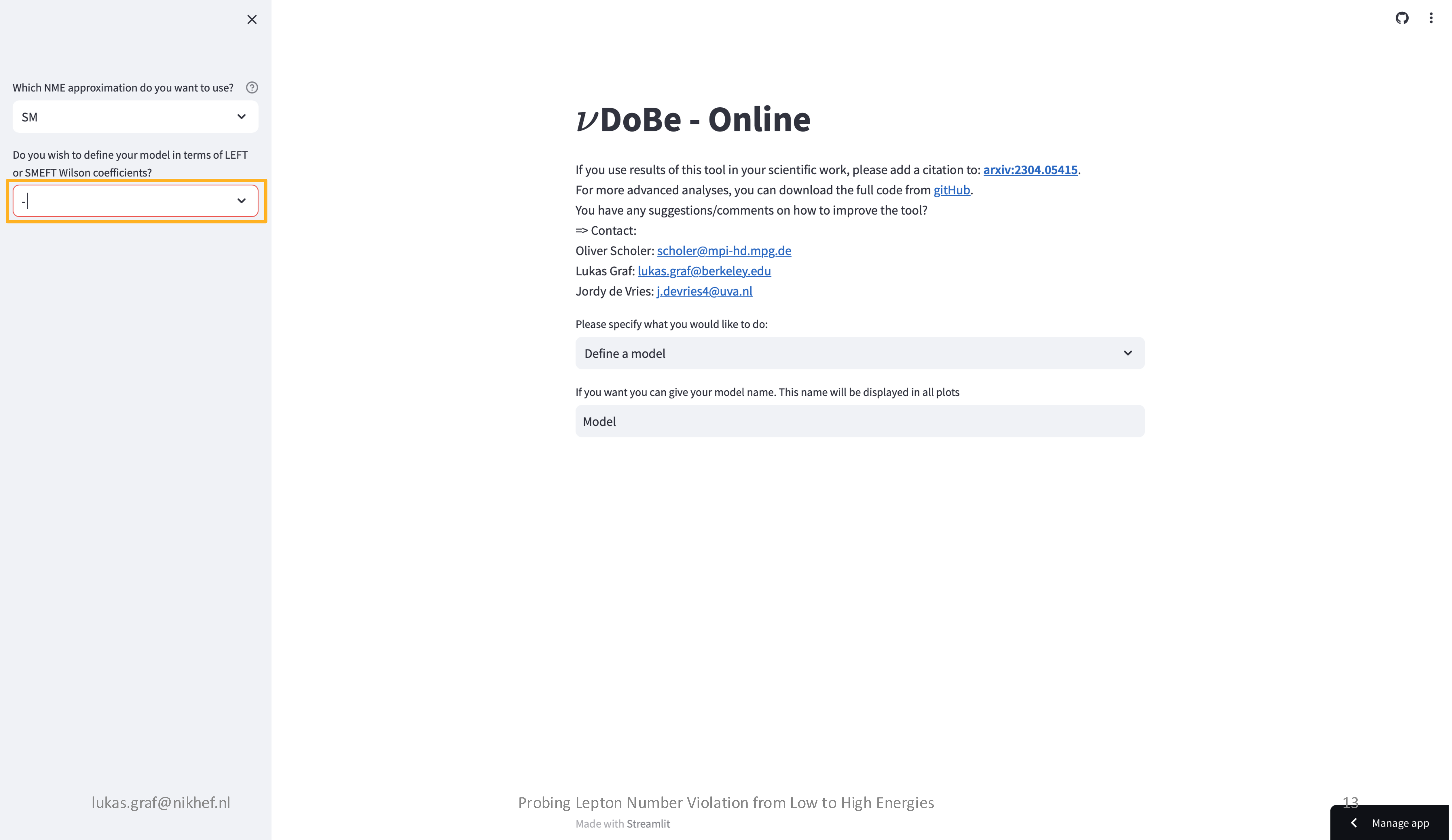
Which NME approximation do you want to use?
SM
Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?
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Manage app

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SM

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

-

-

LEFT

SMEFT

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Which NME approximation do you want to use?

SM

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

SMEFT

Allow for complex phases?

Does your model generate SMEFT operators at multiple scales? If 'Yes' you will need to define a scale for each operator.

No

Set the scale at which your SMEFT model is generated [TeV].

50

Set the dimensionless Wilson coefficients:

Dimension 5

LH(5) [1e-12]

1,00

Dimension 7

LH(7)

0,00

LHD1(7)

0,00

νDoBe - Online

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Model

Half-lives

Download half-lives as .csv or as .tex file.

	10^24 years
48Ca	431,000.0000
76Ge	651,000.0000
82Se	170,000.0000
124Sn	146,000.0000
130Te	88,500.0000
136Xe	129,000.0000

Angular correlation

$$\frac{d\Gamma}{d\cos\theta d\bar{\epsilon}_1} = a_0\left(1 + \frac{a_1}{a_0}\cos\theta\right)$$

Manage app

Which NME approximation do you want to use?

SM

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

SMEFT

Allow for complex phases?

Does your model generate SMEFT operators at multiple scales? If 'Yes' you will need to define a scale for each operator.

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50

Set the dimensionless Wilson coefficients:

Dimension 5

LH(5) [1e-12]

1,00

Dimension 7

LH(7)

0,00

LHD1(7)

0.00

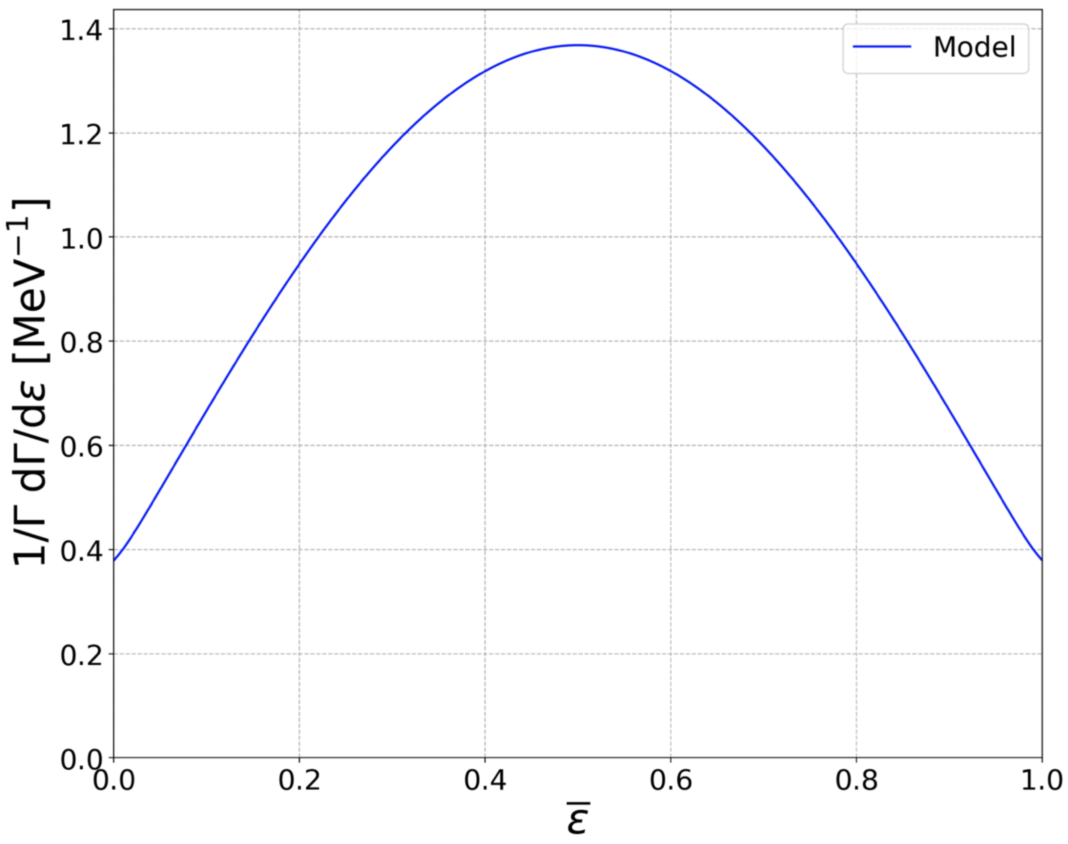
Normalized single electron spectrum

$$\frac{d\Gamma}{d\epsilon_1}(\{C_i\},\bar{\epsilon}) \propto \sum_k g_{0k}(\epsilon, \Delta M - \epsilon, R) \left|A_k(\{C_i\})\right|^2 p_1 p_2 \epsilon (\Delta M - \epsilon)$$

Choose an isotope:

76Ge

Compare to mass mechanism?



Half-life ratios

Choose the reference isotope:

76Ge

Compare to mass mechanism?

Vary unknown LECs?

Manage app

Unraveling the signal:
source of LNV?

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

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

Complementary Probes

- 0νββ usually the best test, but what about other flavours? Can other probes help to pinpoint the LNV mechanism?

- rare meson decays → lepton number violating B or K decays
  Deppisch, Fridell, Harz: JHEP 12 (2020)
  Felkl, Li, Schmidt: JHEP 12 (2021)

- neutral current LNV NSI @CEvNS, charged current LNV NSI @LBL oscillation exp.
  Bolton, Deppisch: PRD 99 (2019)

- lepton number violating tau decays Li, Ma, Schmidt: PRD 101 (2020)

- non-standard muon decay, μ^- to e^+ conversion Berryman, de Gouvêa et al.: PRD (2017)
  B. Armbruster et al.: PRL 90 (2003)

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

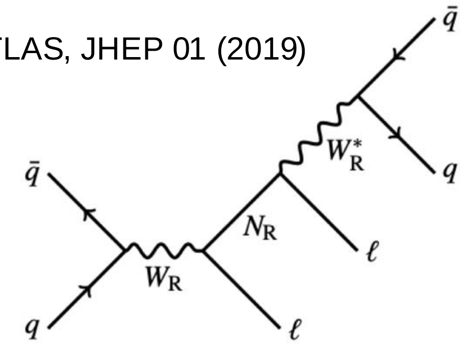
- colliders – LNV probed by same-sign dilepton searches, or individual models
  K. Fridell, LG, J. Harz, C. Hati: 2306.08709

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)

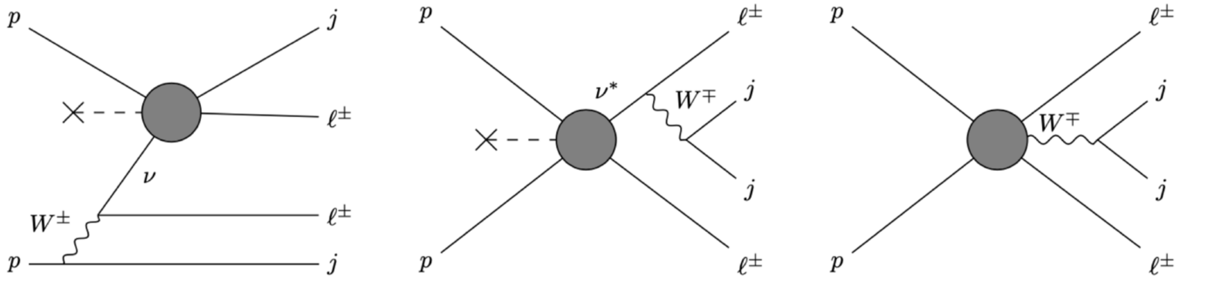
- study along the lines of the analysis for Weinberg operator



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)

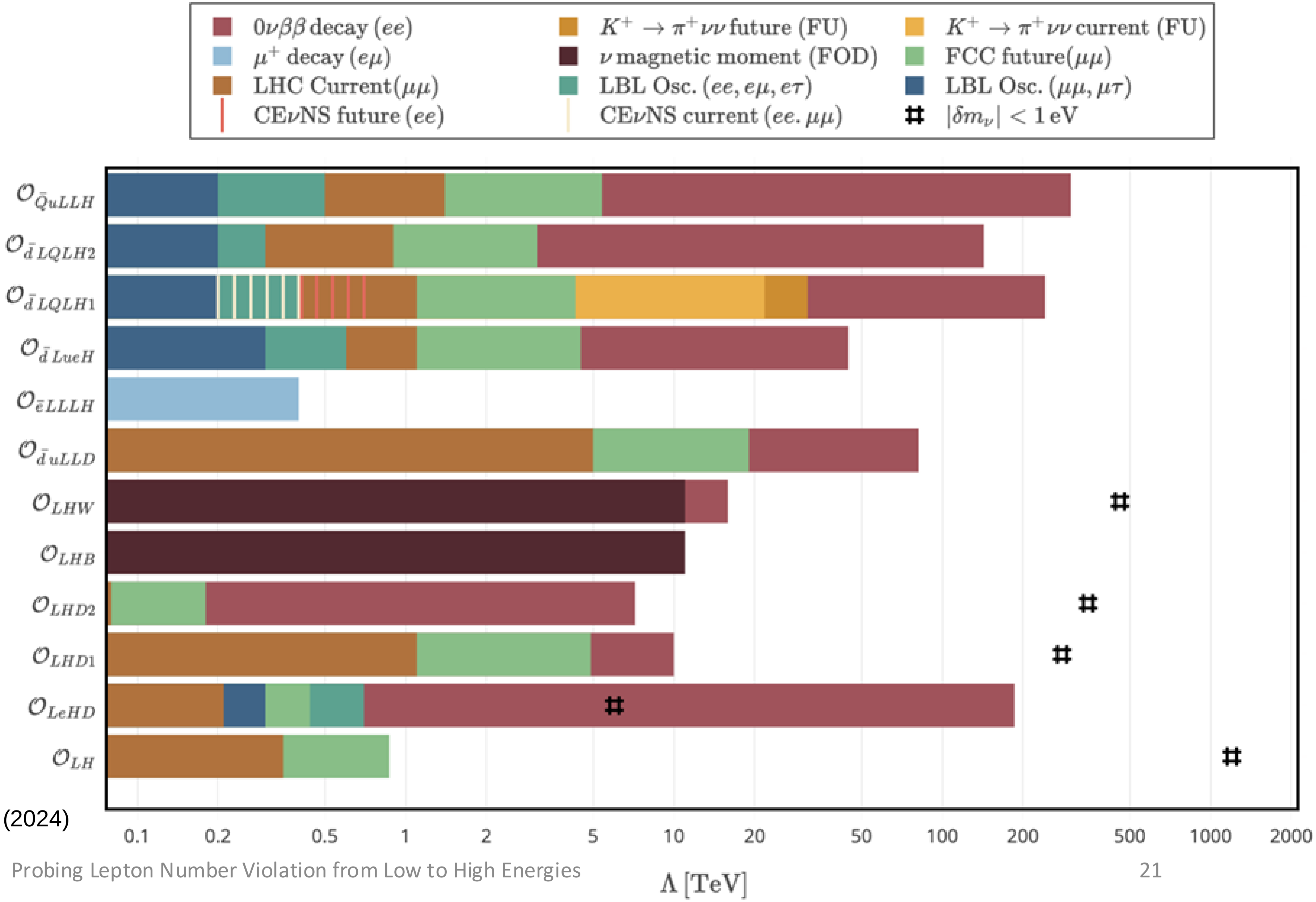


Operator	$\sigma(pp \to \mu^{\pm}\mu^{\pm}jj)$ (pb) LHC	FCC	Λ_{LNV} [TeV]	$\Lambda_{\text{LNV}}^{\text{future}}$ [TeV]
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.4	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.90	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	1.1	4.3
$\mathcal{O}_{\bar{d}LueH}$	5.7×10^{-5}	0.035	1.1	4.5
$\mathcal{O}_{\bar{d}uLLD}$	0.64	210	5.0	19
$\mathcal{O}_{LHD2}$	2.7×10^{-12}	1.7×10^{-10}	0.075*	0.18
$\mathcal{O}_{LHD1}$	1.9×10^{-5}	0.061	1.1	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}	0.35*	0.87

K. Fridell, LG, J. Harz, C. Hati, JHEP 05 (2024)

Complementary Probes @SMEFT dim 7

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



K. Fridell, LG, J. Harz, C. Hati, JHEP 05 (2024)

From EFT to Simplified Models: Neutrino Mass

- classification of different (simplified) UV completions based on generated neutrino mass topology

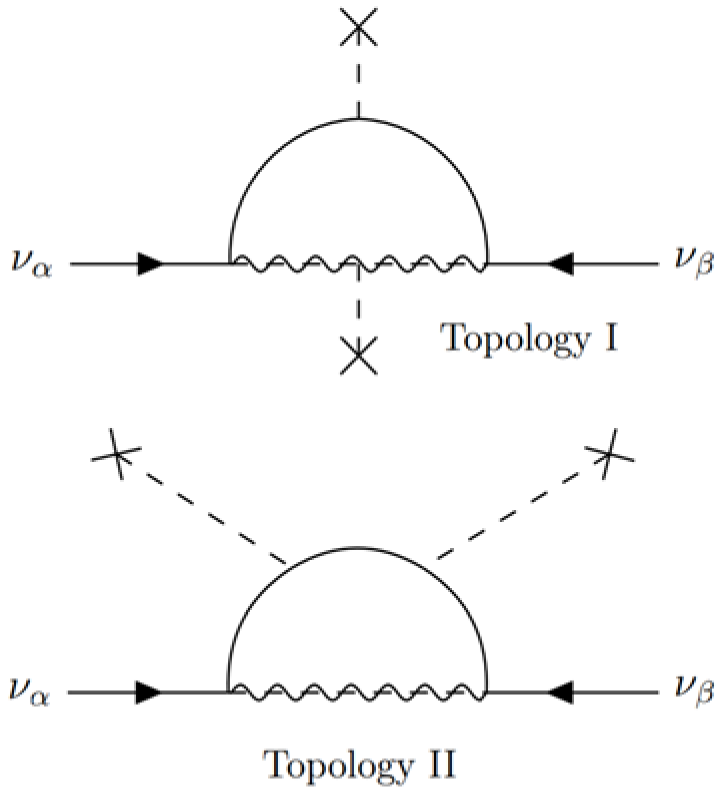
$$\mathcal{O}_{\bar{Q}uLLH} = \epsilon_{ij}\left(\overline{Q_p}u_r\right)\left(\overline{L_s^c}L_t^i\right)H^j$$

	Δ	φ	N	Σ	Q_7	$T_1^\dagger$	U_1	$\bar{V}_2^\dagger$	U_3
Δ		●			●	●			
φ	●		○	○					
N		○					○	○	
Σ		○						○	○
Q_7	●						II		II
$T_1^\dagger$	●							II	
U_1			○		II			I	
$\bar{V}_2^\dagger$			○	○		II	I		I
U_3				○	II			I	

○ = Generates the dimension-5 LNV operator

$$(SU(3)_c, SU(2)_L, U(1)_Y)(3B)$$

Field	Rep
Δ	$S(1,3,1)(0)$
φ	$S(1,2,1/2)(0)$
N	$F(1,1,0)(0)$
Σ	$F(1,3,0)(0)$
Q_7	$F(3,2,7/6)(1)$
T_1	$F(3,3,-1/3)(1)$
U_1	$V(3,1,2/3)(1)$
$\bar{V}_2$	$V(\bar{3},2,-1/6)(-1)$
U_3	$V(3,3,2/3)(1)$



K. Fridell, LG, J. Harz, C. Hati, arXiv: 2412:XXXXX

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
- combining various contributions → involved, tedious calculations with a variety of inputs → νDoBe tool developed and available online
- 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
- 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

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Thank you!