

Probing Nuclear and New Physics with Double Beta Decays

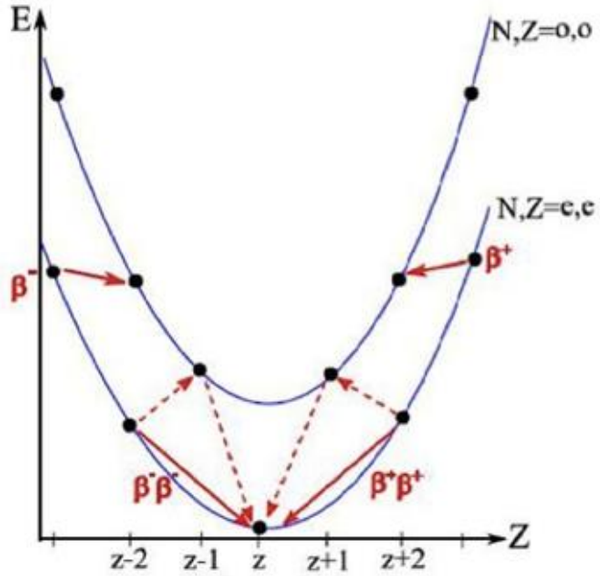
Lukáš Gráf

Charles University, Prague

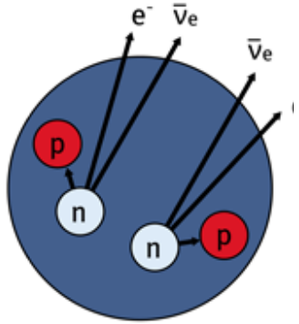
DISCRETE 2026, Bratislava

Double Beta & Double M Backstory

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



- one of the rarest processes ever observed in Nature (age of the Universe ~ 10^{10} y) $T_{1/2}^{2\nu\beta\beta} \sim 10^{18}$ - 10^{21} y



- first proposed by Maria Goeppert Mayer in 1935
  - born in Katowice (Prussia) in 1906
  - studied in Goettingen, PhD in 1931 (Max Born)
  - Johns Hopkins, Columbia, Sarah Lawrence College (NY, teaching science, part-time), Chicago (voluntary (!) associate professor), Argonne, UCSD (professor 1960)

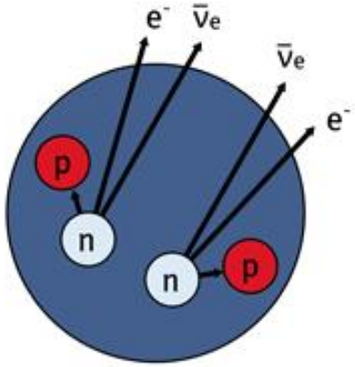


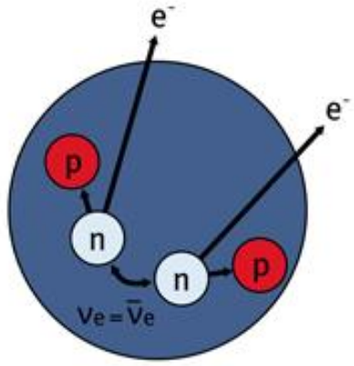
- NP for physics in 1963 (shell model)

Double Beta Decay

- Majorana's idea (1937): neutral fermion = antifermion
- Furry (1939): $0\nu\beta\beta: \ (A,Z) \rightarrow (A,Z+2) + 2e^-$







- neutrinoless double beta decay
  → mediated by Majorana neutrinos
  → lepton number violation



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

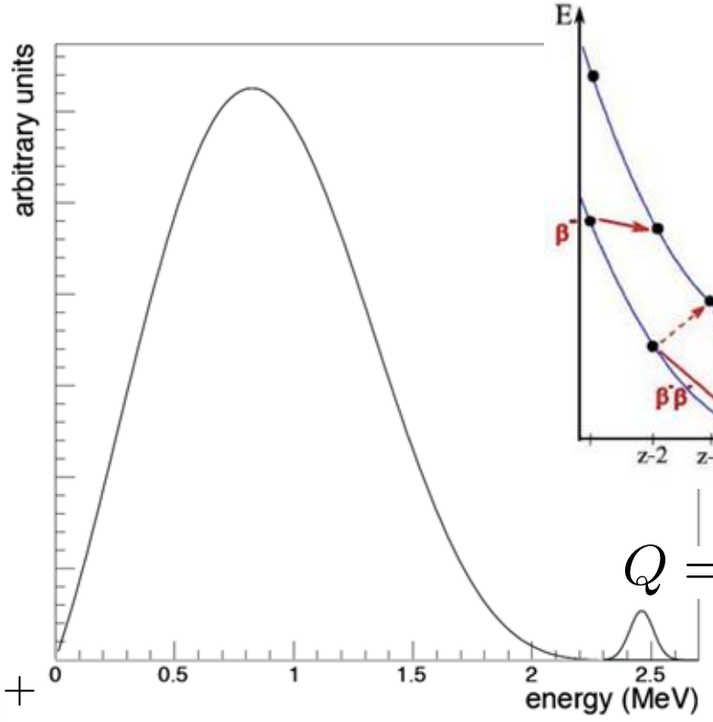
  $\mathrm{T}^{0\nu\beta\beta}_{1/2} \sim (0.1 \text{ eV}/m_\nu)^2 \times 10^{26}$ y

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

- a variety of isotopes: ^{76}Ge, ^{136}Xe, …
- variants: $0\nu\beta^+\beta^+: \ (A,Z) \rightarrow (A,Z-2) + 2e^+$

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

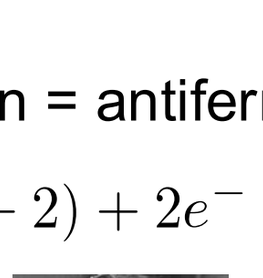
  $0\nu ECEC: \ (A,Z) + 2e^- \rightarrow (A,Z-2)$



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

Double Beta Decay

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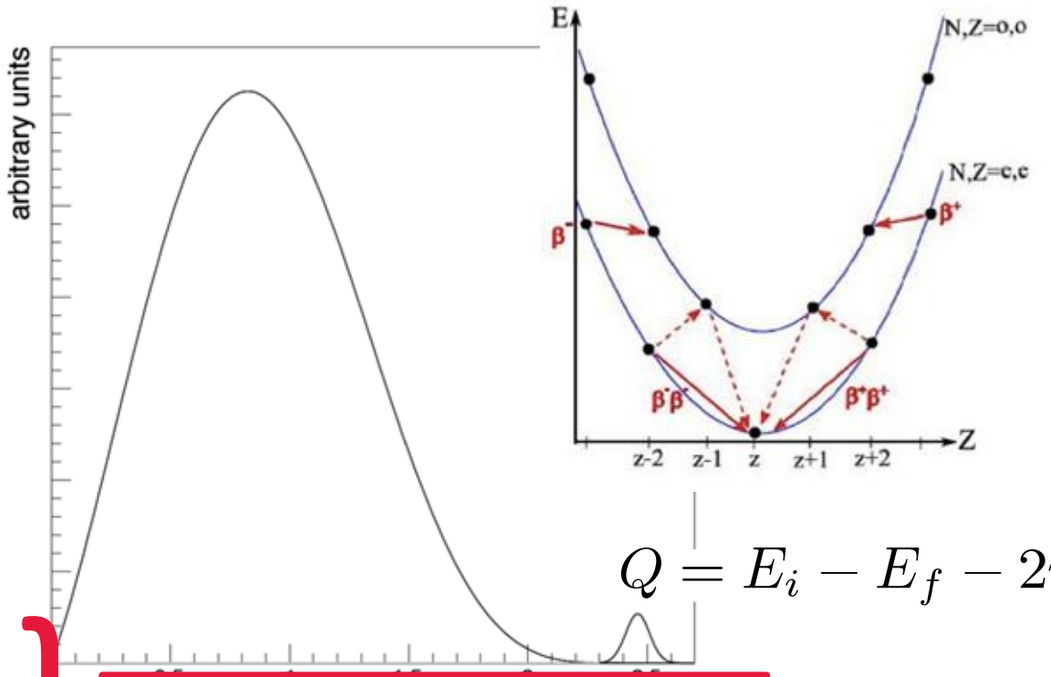
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  $0\nu\beta^+EC: \ (A,Z) + e^- \rightarrow (A,Z-2) + e^+$

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



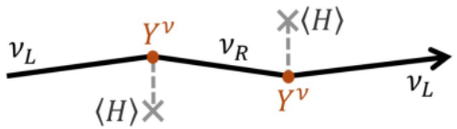
$$Q = E_i - E_f - 2m_e$$

LG, J. Kotila, O. Scholer: 2606.26097

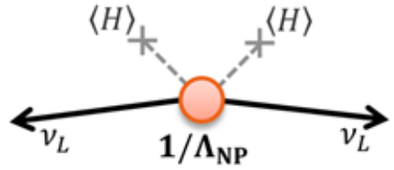
Neutrino Mass

- observation of neutrino oscillations requires neutrino mixing and non-zero neutrino mass
  → evidence for physics beyond the Standard Model





Dirac mass → as other fermions, but tiny Yukawas



Majorana mass → unique



- if we add right-handed neutrinos to the SM content, we can write both types of mass terms for them $\mathcal{L} = \mathcal{L}_{SM} + i\overline{N_R}\partial\!\!\!/ N_R - \frac{1}{2}\overline{N_R} M_R N_R^c - \left[Y_\nu \overline{N_R} \tilde{\Phi}_H^\dagger L_L + h.c. \right]$

- hence, the mass of the active neutrinos:

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad m_\nu = -m_D \, M_R^{-1} \, m_D^T$$

$\leftrightarrow$ seesaw mechanism (type-I)

Neutrino Mass

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  → evidence fo



Dira violation

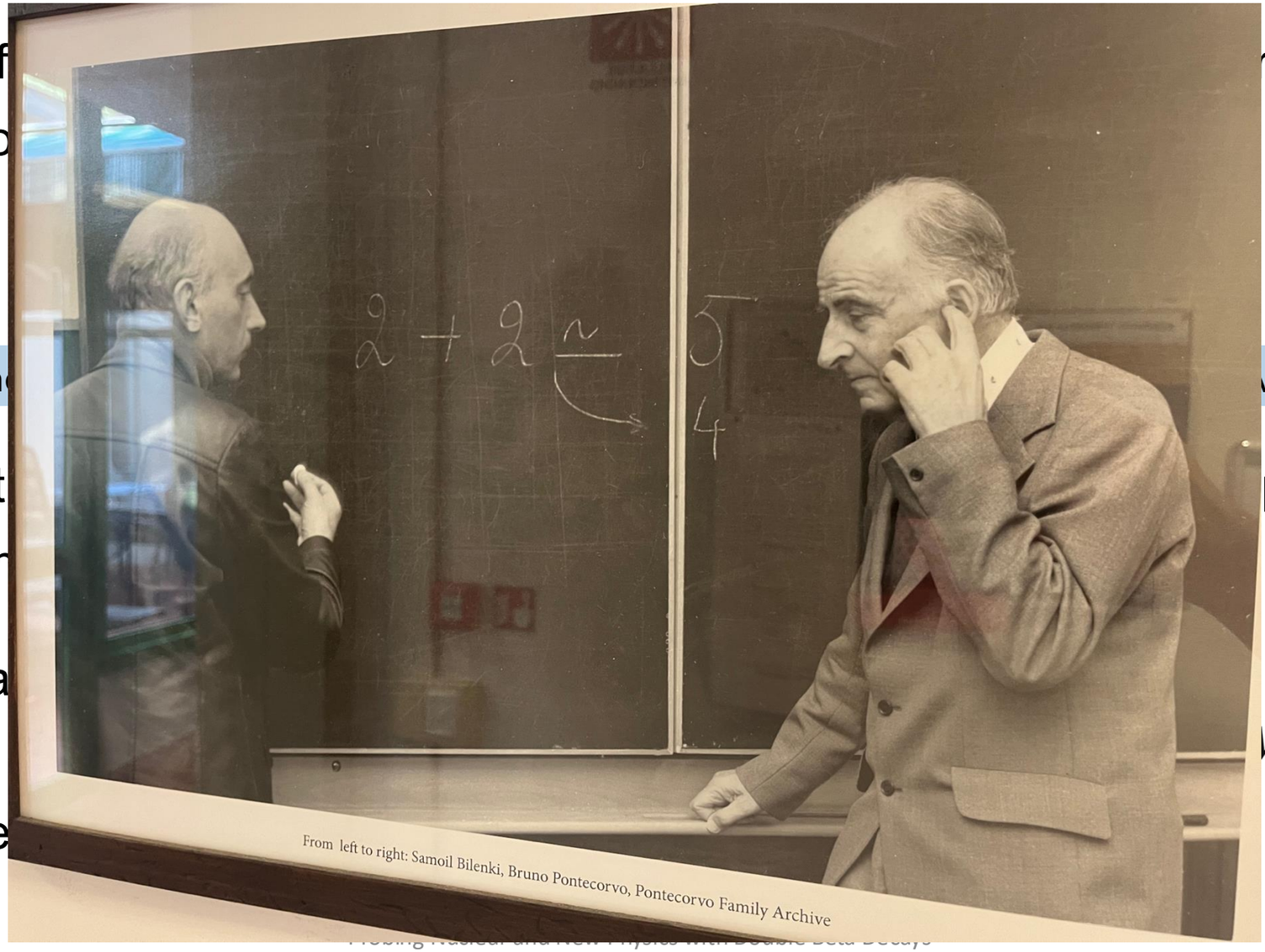


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$$M_R^{-1}\, m_D^T$$

  ↔ seesaw me

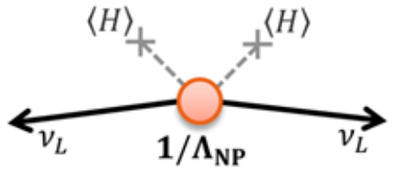


Lepton Number (Violation)

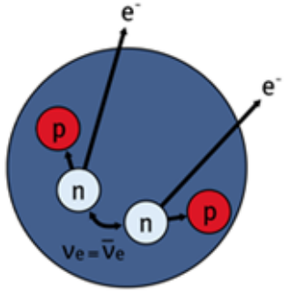
- non-perturbative Standard Model (SM) dynamics: B + L number violated by sphalerons
- B – L number is conserved ↔ non-anomalous global symmetry of the SM
  → accidental? may be a relict! → violation at low energies subtle ↔ corresponding to B – L preserving gauge symmetry broken at certain high-energy 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

$$\begin{array}{ccc} (\nu_L & \leftarrow \text{CPT} \rightarrow & \bar{\nu}_R) \\ & \updownarrow \quad \text{“Lorentz”} & \\ (\bar{\nu}_R & \leftarrow \text{CPT} \rightarrow & \nu_L) \end{array}$$





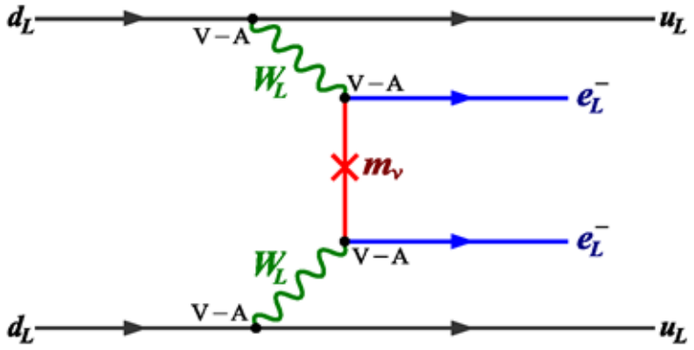
Majorana mass → lepton number violation



Neutrinoless Double Beta Decay

- standard mechanism with light neutrino exchange:

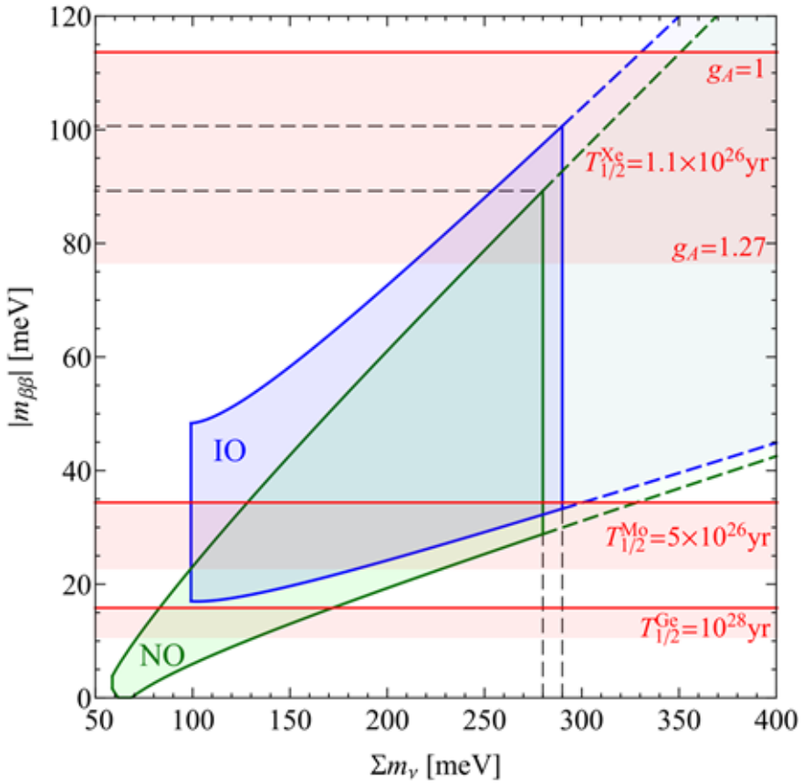
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 \, \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$$



- 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]



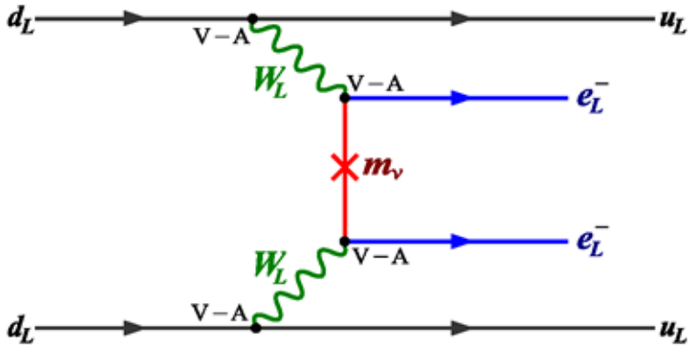
$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_{12}} + m_3 s_{13}^2 e^{i(\phi_{13} - 2\delta)}$$

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

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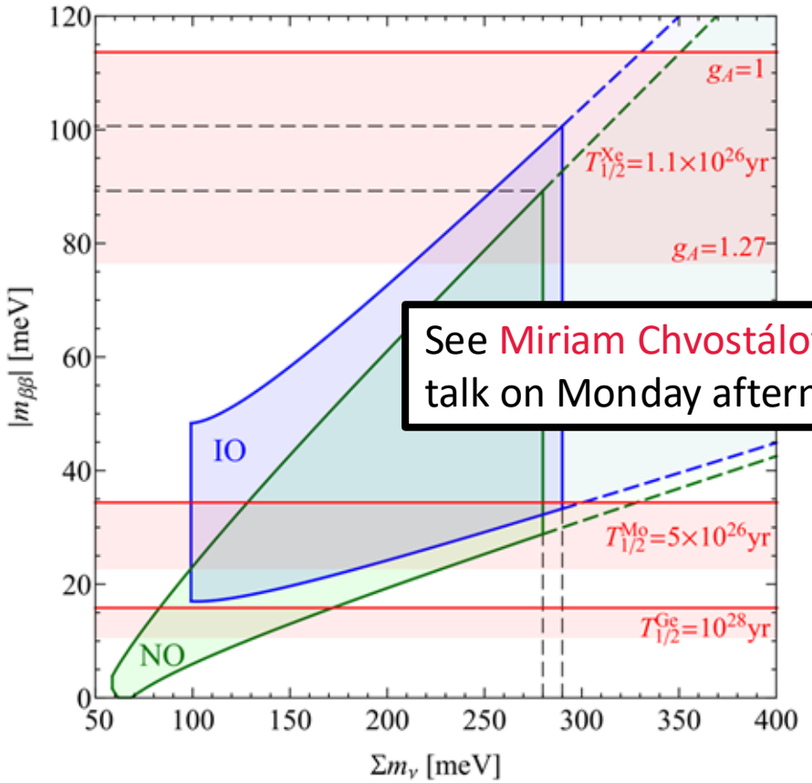
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F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]



See Miriam Chvostálová's talk on Monday afternoon!

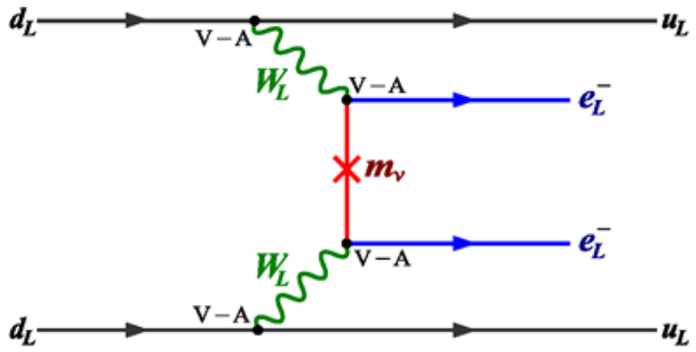
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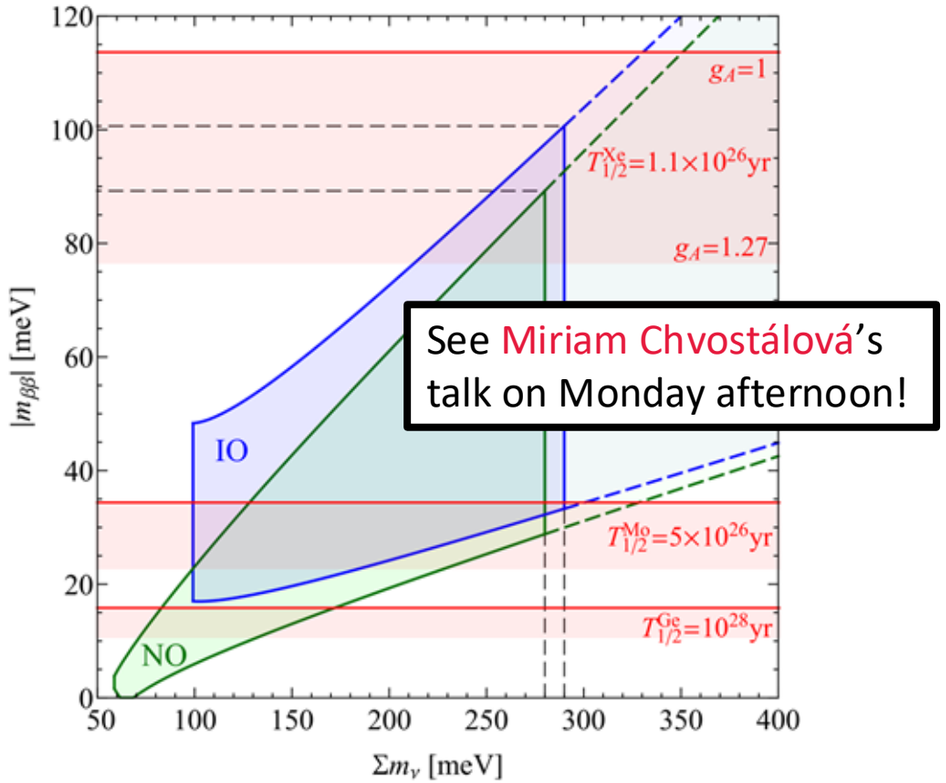
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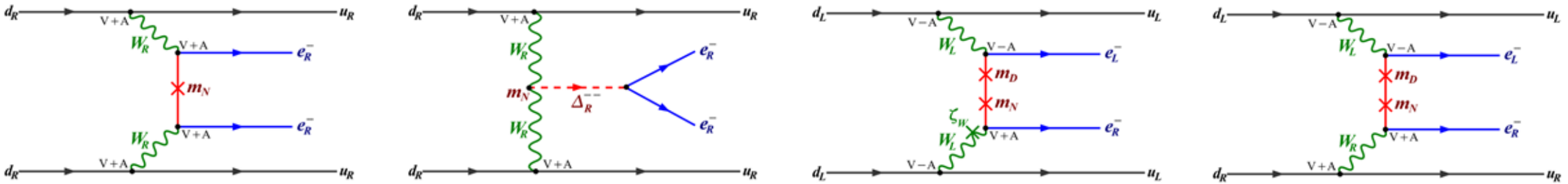
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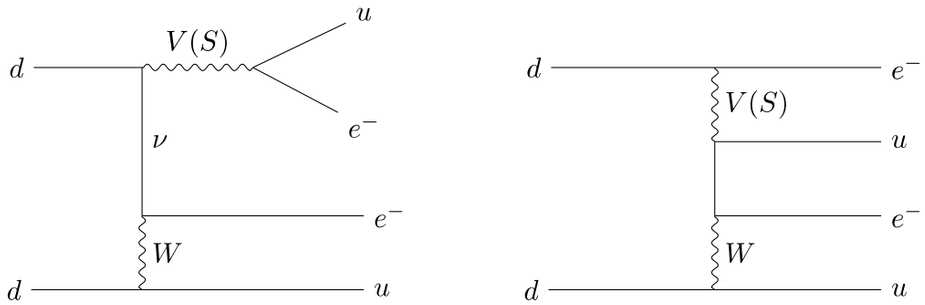
$$\frac{+ m_i}{- m_i^2}(1-\gamma_5)\gamma_\mu e_1^c \approx \bar{e}_2 \frac{\gamma_\nu(1-\gamma_5)\gamma_\mu}{4q^2} e_1^c \sum_{i=1}^{3} U_{ei}^2 m_i \equiv m_{\beta\beta}$$

New Physics & 0νββ

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



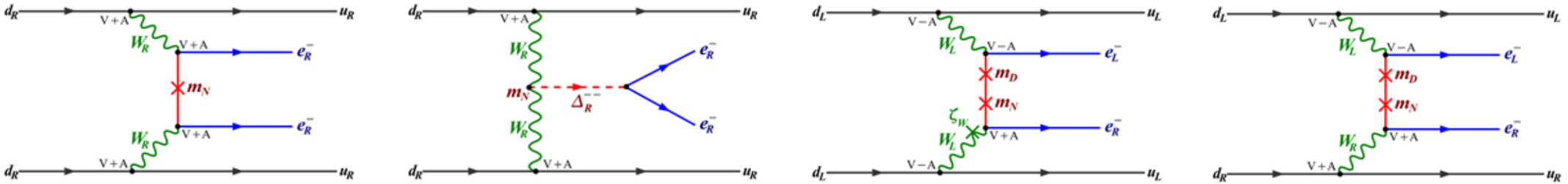
- leptoquarks (scalar, vector)



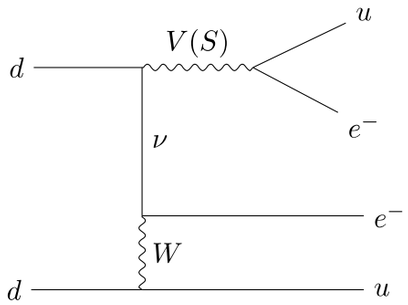
- R-parity violating SUSY, Majorons, etc. ...

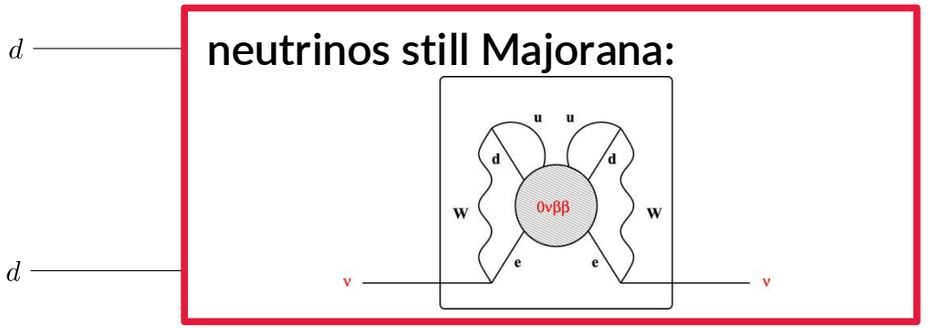
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J. Schechter, J. W. F. Valle: PRD 25 (1982) 2951

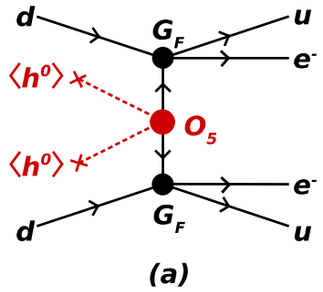
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Effective Approach to 0νββ

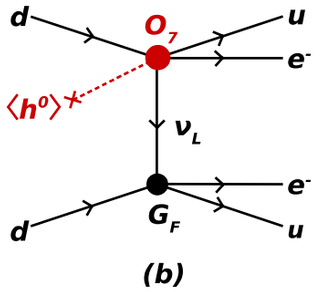
- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 9804374, 0008182, 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range and short-range mechanisms

- 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

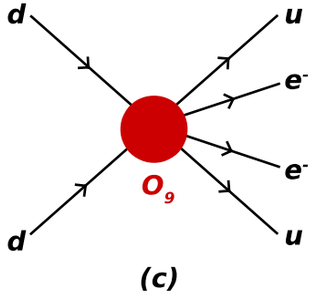
- generally: $T_{1/2}^{-1} = \boxed{|C|^2} G_{0\nu} |M_{0\nu}|^2$



(a)



(b)



(c)

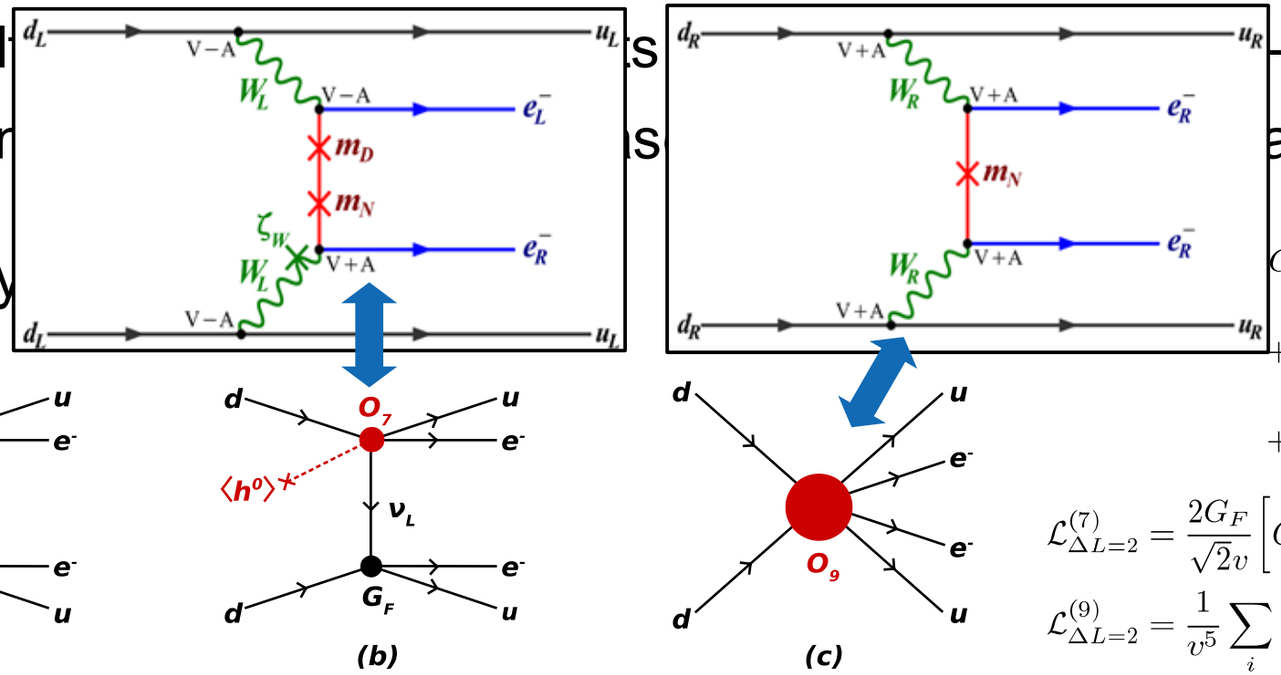
$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}} \Big[C^{(6)}_{\mathrm{VL}} \left(\overline{u_L}\gamma^\mu d_L\right) \left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{VR}} \left(\overline{u_R}\gamma^\mu d_R\right) \left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{SL}}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

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

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

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- generally



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

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

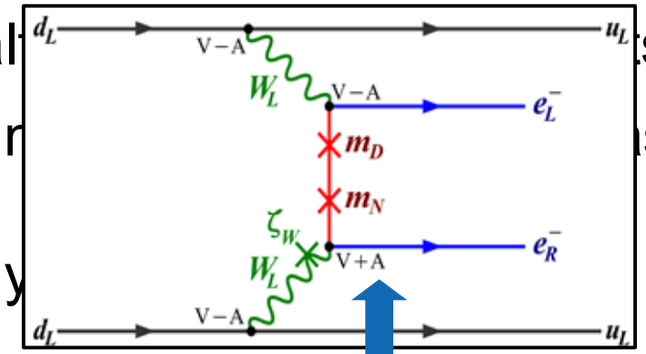
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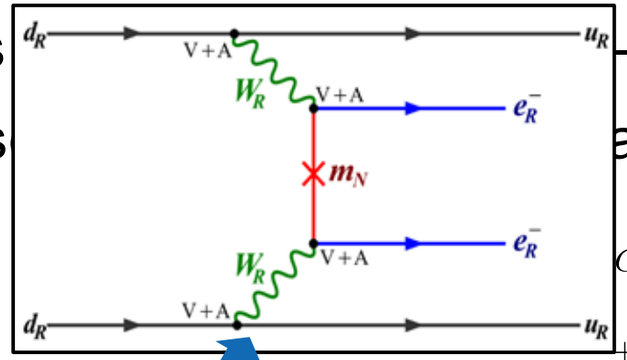
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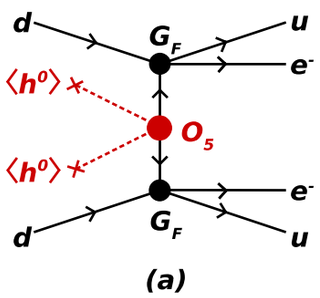
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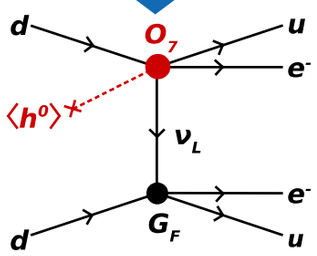
Systematic approach to "opening-up" the effective operators and search for models, in which the higher-dimensional ones "matter":
F. Esser, LG, C. Hati, JHEP [2602.18395]
See talk by Fabian Esser on Monday afternoon!



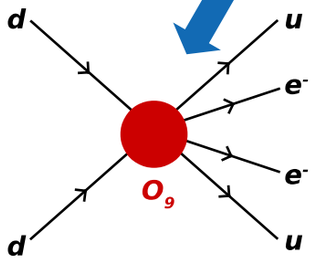




(a)



(b)



(c)

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

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

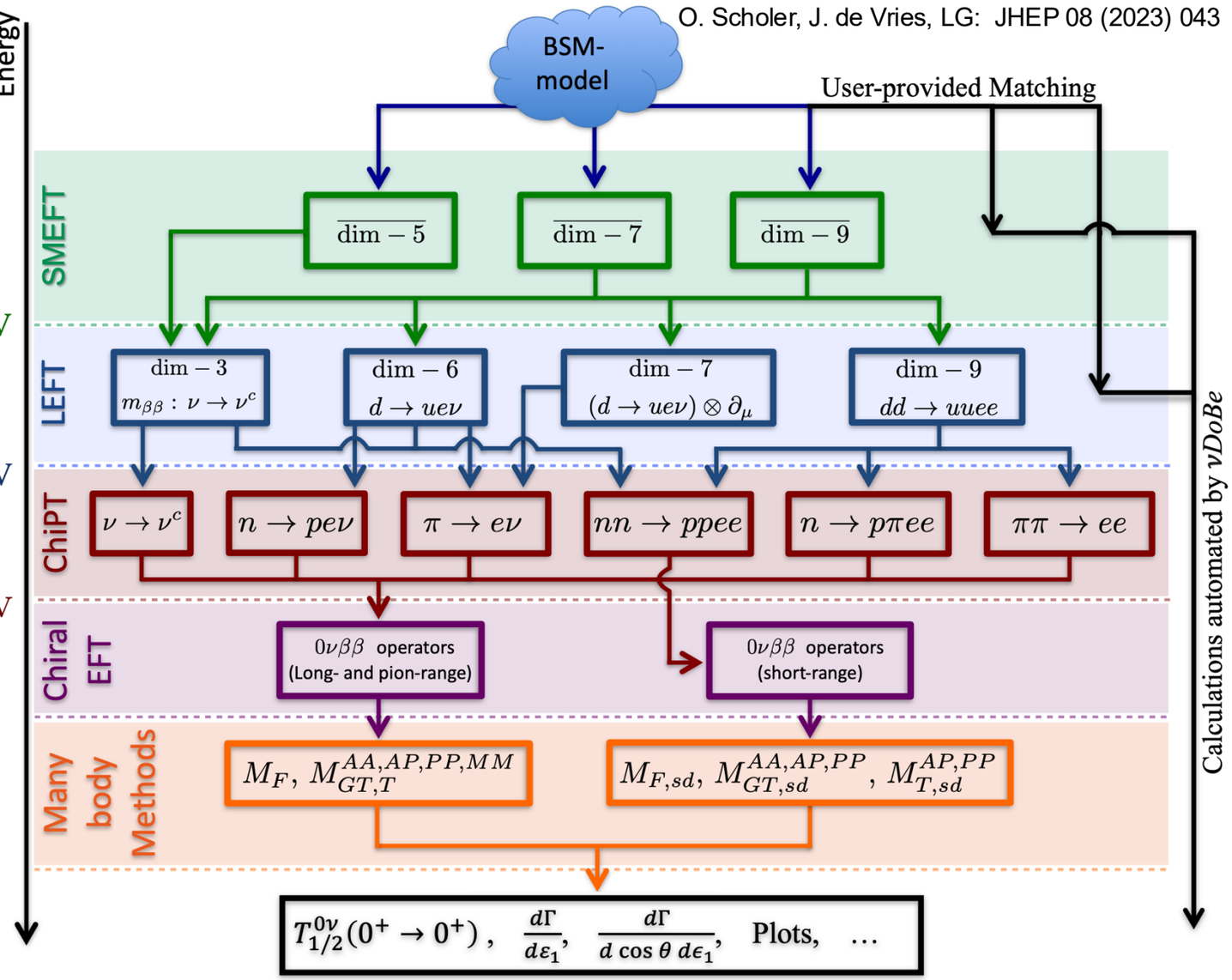
$$+ C_{\mathrm{T}}^{(6)} \left(\overline{u_L}\sigma^{\mu\nu} d_R\right) \left(\overline{e_L}\sigma_{\mu\nu}\nu_L^c\right)\Big] + h.c.$$

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

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

0νββ Constraints for (almost) Any Model

- model inputs:
  - scale + selection of operators – result of the matching
- computation/data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants
  - isotope (experiment) choice



also a tool: https://github.com/OScholer/nudobe

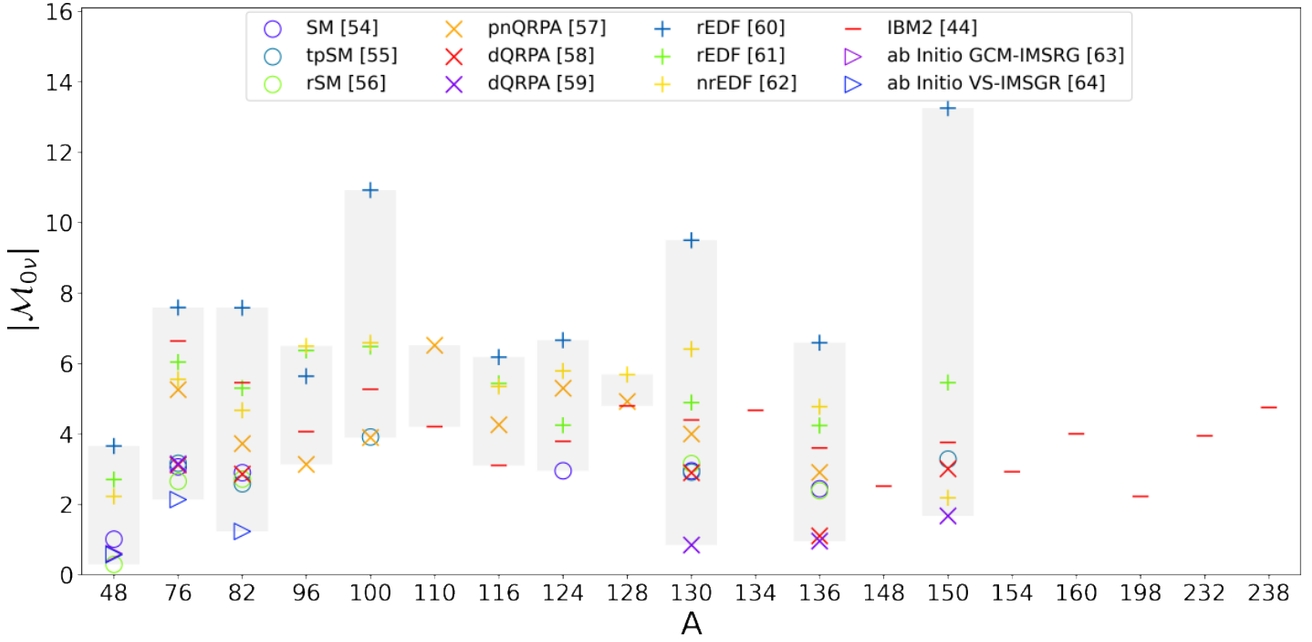
Nuclear Uncertainties

- 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 limit → nuclear matrix elements

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

- dependence on isotope and operator
- 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}	$-92.9\,\mathrm{GeV}^{-2} \pm 50\%$ [53–55]		



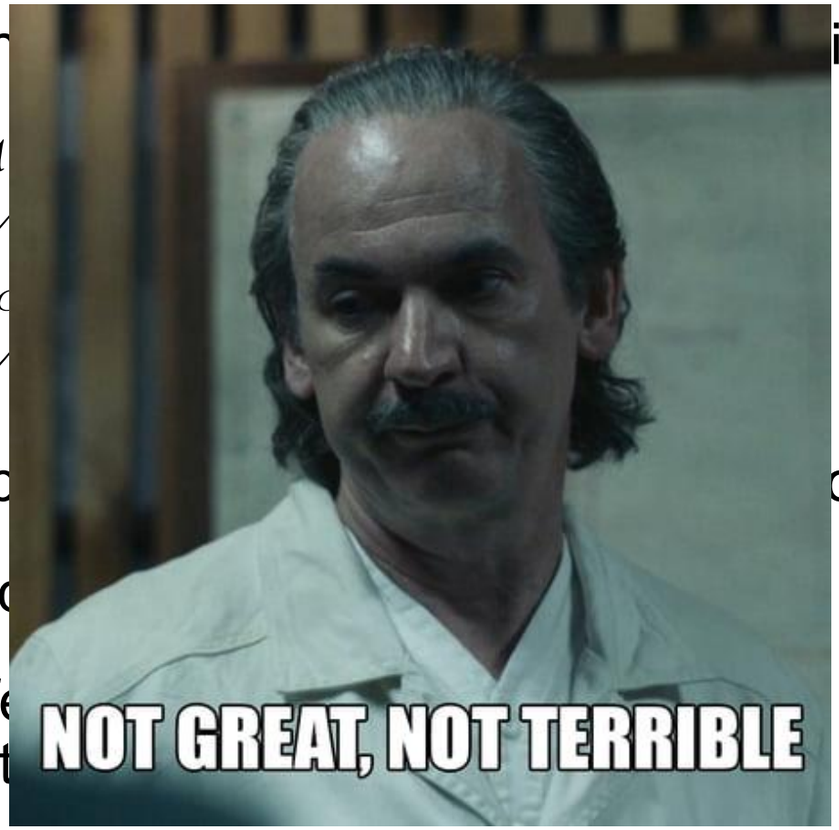
LG, M. Lindner, O. Scholer: PRD 106 (2022)

Nuclear Uncertainties

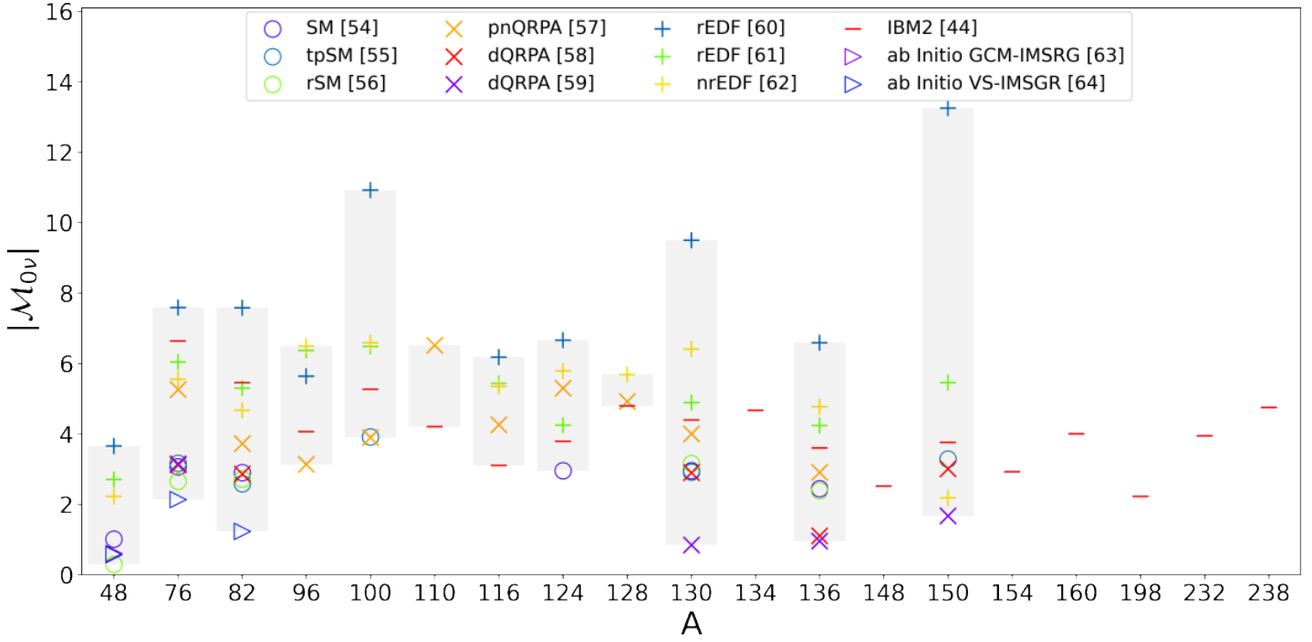
- hadronic currents $J^\mu(q) = g_V\gamma^\mu - g_A\gamma^\mu\gamma^5 + \frac{ig_W}{2m_N}\sigma^{\mu\nu}q_\nu - g_P\gamma^5 q^\mu$
- non ix elements

$\mathcal{M}$
$\mathcal{M}$
$\mathcal{M}_C$
$\mathcal{M}$

- dep or
- calc
- diff fact
- + unknown LECs (or form factors)



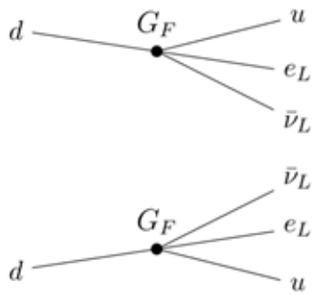
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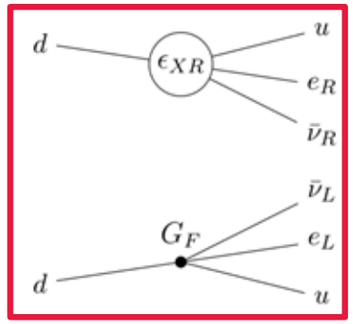


LG, M. Lindner, O. Scholer: PRD 106 (2022)

Exotic (2ν)ββ Decay







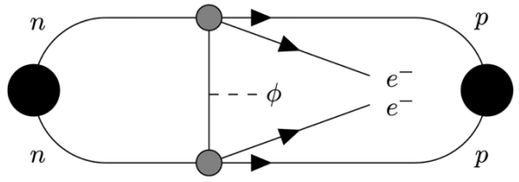
- exotic contributions to double beta decay?
- e.g. in presence of right-handed currents:

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left((1 + \delta_{\mathrm{SM}} + \epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu} \right) + \mathrm{h.c.}$$

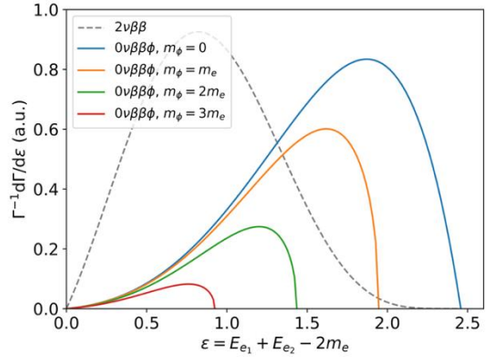
- → contribution to the rate: $\Gamma^{2\nu} = \epsilon_{XR}^2 G_{2\nu\beta\beta} |M_{2\nu\beta\beta}|^2$, angular correlation: $\frac{\mathrm{d}\Gamma^{2\nu}}{\mathrm{d}\cos\theta} = \frac{\Gamma^{2\nu}}{2} \left(1 + K^{2\nu} \cos\theta\right)$
  → bound: $\epsilon_{XR} \lesssim 2.7 \times 10^{-2}$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

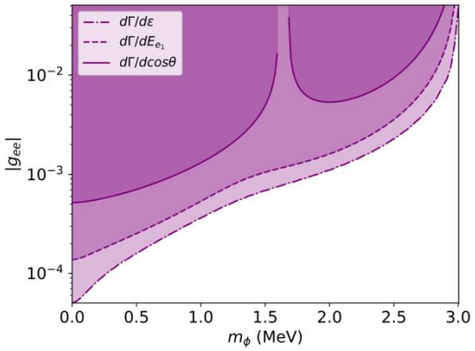
F. F. Deppisch, LG, F. Simkovic: PRL 125 [2003.11836]

- e.g. scalar (Majoron) emission
- → distortion of the spectrum



J. de Vries, LG, V. Plakkot, D. Starý: JHEP 03 [2511.19173]





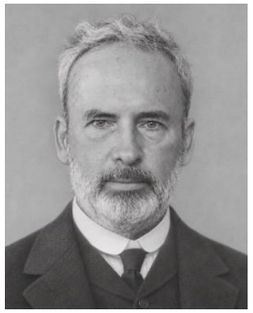
Towards Precision Double Beta Decay Spectrum

- double beta decay spectrum: upcoming experiments aim to reach (sub-)percent level precision
- theoretical description not as accurate → efforts to match the precision necessary
- electron wave functions – Fermi function, realistic wave functions in central field

  Kotila, Iachello: PRC [1209.5722]
  Neascu, Horoi: PRC [1510.00882]
- expansion in the leptonic energies Šimkovic, Dvornicky, Stefanik, Faessler: PRC [1804.04227]
- corrections at the level of heavy baryon chiral effective field theory – pion exchanges, weak magnetism El Morabit, Bouabid, Cirigliano, de Vries, LG, Mereghetti: JHEP [2412.14160]
- atomic effects: screening, exchange corrections, etc. Kotila, Iachello: PRC [1209.5722]
  Niţescu, Šimkovic: PRC [2411.05405]
- radiative corrections (Sirlin function and beyond) Niţescu, Šimkovic: PRC [2411.05405]
  de Vries, El Morabit, Mereghetti, Sandner: PRL [2603.23592]

See Ovidiu Nitescu's talk on Monday afternoon!

Taylor Expansion in Leptonic Energies



- Šimkovic et al.: improved description of 2vββ — Šimkovic, Dvornicky, Stefanik, Faessler: PRC [1804.04227]
- expansion in small leptonic energies allows for separation of nuclear and leptonic parts, works very well

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon_{K,L}^2}$$

$$\varepsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2,$$
$$\varepsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2.$$

$$\mathcal{A}_0^{2\nu} = 1, \quad \mathcal{A}_2^{2\nu} = \frac{\varepsilon_K^2 + \varepsilon_L^2}{(2m_e)^2},$$
$$\mathcal{A}_{22}^{2\nu} = \frac{\varepsilon_K^2 \varepsilon_L^2}{(2m_e)^4}, \quad \mathcal{A}_4^{2\nu} = \frac{\varepsilon_K^4 + \varepsilon_L^4}{(2m_e)^4}$$

$$M_{GT-1}^{2\nu} \equiv M_{GT}^{2\nu}$$
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4\, m_e^3}{(E_n - (E_i + E_f)/2)^3}$$
$$M_{GT-5}^{2\nu} = \sum_n M_n \frac{16\, m_e^5}{(E_n - (E_i + E_f)/2)^5}$$

$$M_n = \langle 0_f^+ \parallel \sum_m \tau_m^- \sigma_m \parallel 1_n^+ \rangle \langle 1_n^+ \parallel \sum_m \tau_m^- \sigma_m \parallel 0_i^+ \rangle$$

$$G_N^{2\nu} = \frac{c_{2\nu}}{m_e^{11}} \int_{m_e}^{E_i - E_f - m_e} F_0(Z_f, E_{e_1}) p_{e_1} E_{e_1} dE_{e_1}$$
$$\times \int_{m_e}^{E_i - E_f - E_{e_1}} F_0(Z_f, E_{e_2}) p_{e_2} E_{e_2} dE_{e_2} \qquad (14)$$
$$\times \int_0^{E_i - E_f - E_{e_1} - E_{e_2}} E_{\nu_1}^2 E_{\nu_2}^2 \mathcal{A}_N^{2\nu} dE_{\nu_1}, \quad (\mathrm{N}{=}0,\ 2,\ 4,\ 22)$$

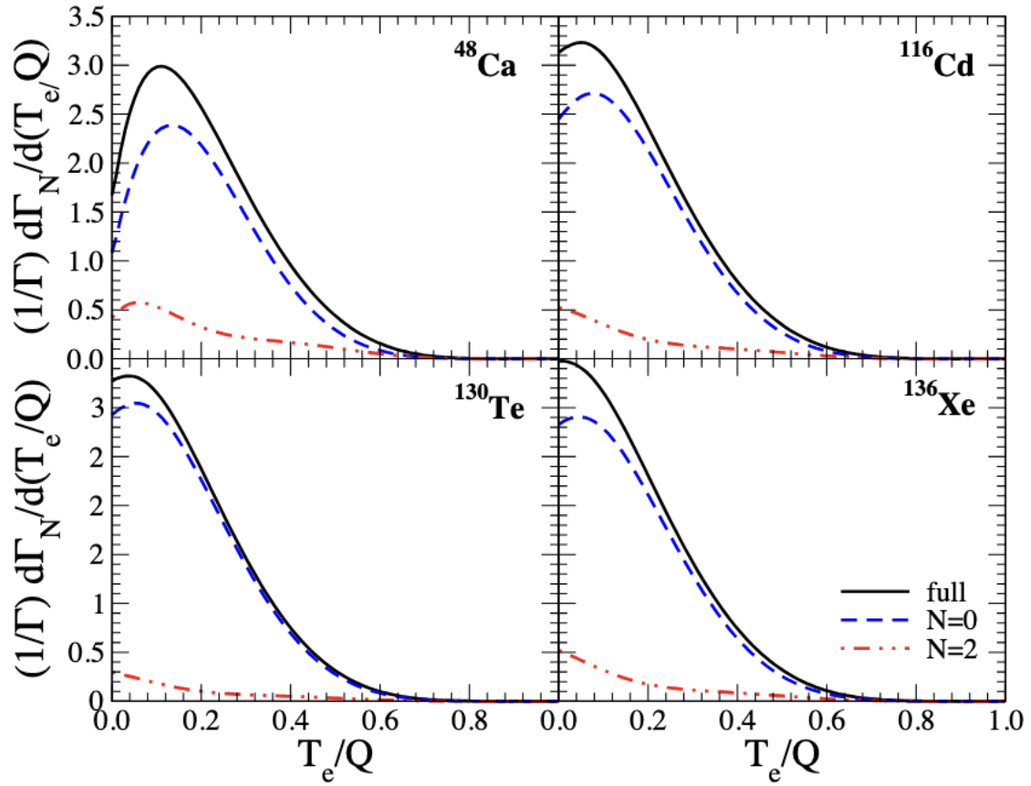
$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}, \quad \xi_{51}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}$$

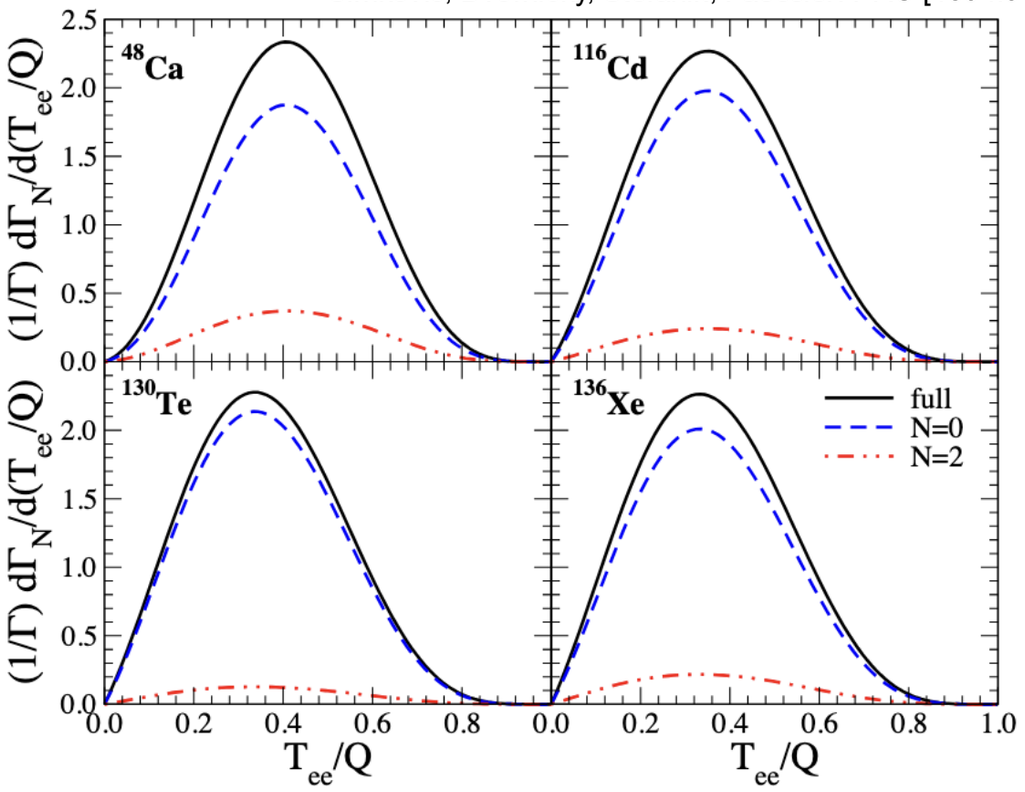
$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} = \left(g_A^{\mathrm{eff}}\right)^4 \left|M_{GT-1}^{2\nu}\right|^2 \left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu} + \frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 G_{22}^{2\nu} + \left(\frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 + \xi_{51}^{2\nu}\right) G_4^{2\nu}\right),$$

Taylor Expansion in Leptonic Energies

- Šimkovic et al.: improved description of 2νββ – spectra:

Šimkovic, Dvornicky, Stefanik, Faessler: PRC [1804.04227]



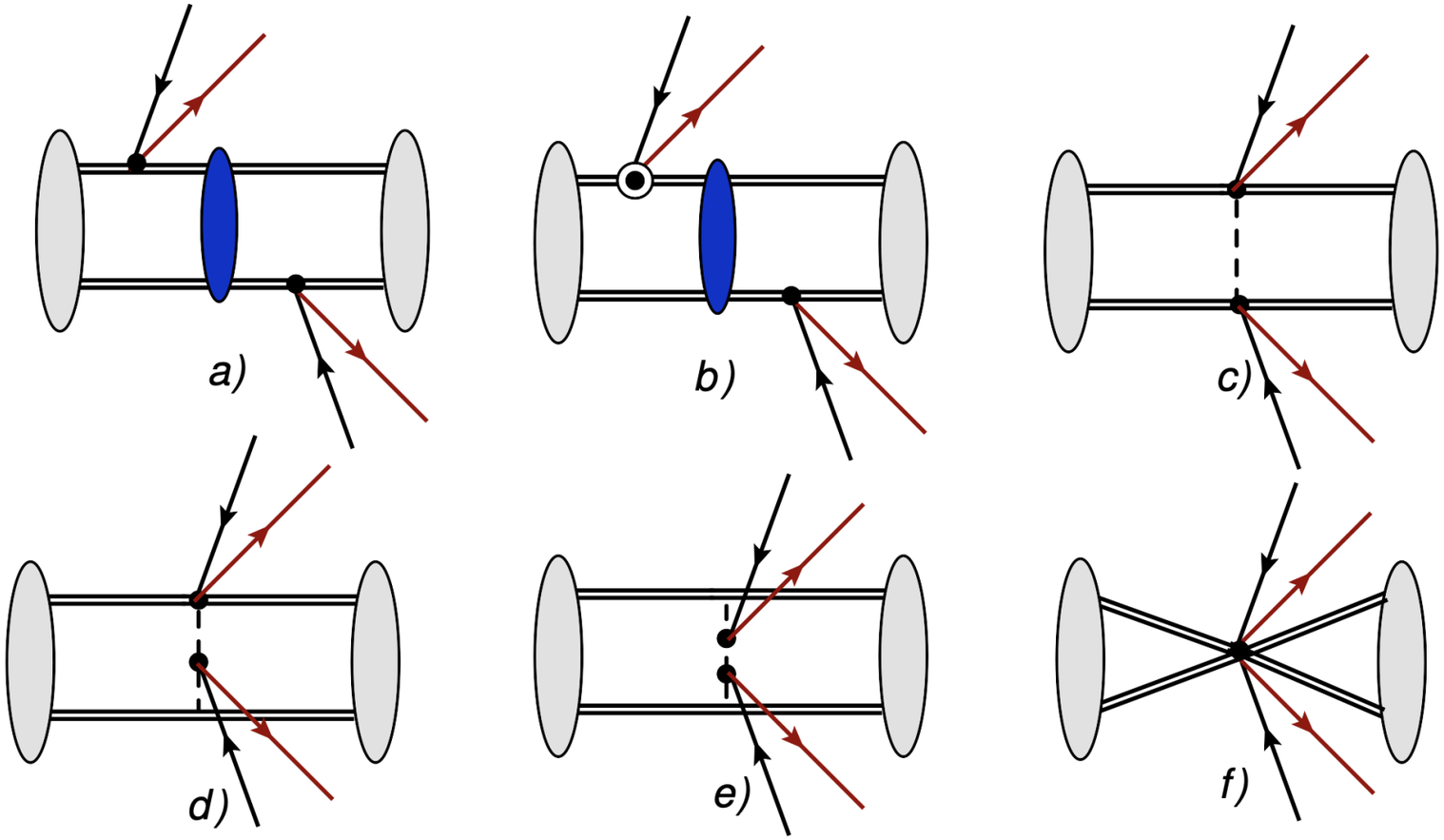


- fitted by experiments:

Experiment	Isotope	ξ_{31}	Source
KamLAND-ZEN	^{136}Xe	-0.26 ± 0.28	Phys. Rev. Lett. 122, 192501
CUPID-Mo	^{100}Mo	0.45 ± 0.06	Phys. Rev. Lett. 131, 162501
CUORE	^{130}Te	0.15 ± 0.15	Phys. Rev. Lett. 135, 082501

Chiral Corrections to the Spectrum

- corrections determined at the level of heavy baryon chiral effective field theory: pion exchanges, weak magnetic term (~ g_M)



El Morabit, Bouabid, Cirigliano, de Vries, LG, Mereghetti: JHEP 03 [2412.14160]

Weak Magnetism

- corrections at the level of heavy baryon chiral EFT: weak magnetic term (~ g_M)

$$\frac{\Gamma^{2\nu}}{\ln 2} \simeq (g_A^{\text{eff}})^4 |\mathcal{M}^{2\nu}_{GT-1}|^2 \Delta_0 \left[G^{2\nu}_0 + \xi_{31} \frac{\Delta_2}{\Delta_0} G^{2\nu}_2 + \frac{1}{3}\xi^2_{31} G^{2\nu}_{22} + \left(\frac{1}{3}\xi^2_{31} + \xi_{51} \frac{\Delta_2}{\Delta_0} \right) G^{2\nu}_4 + \frac{G^{2\nu}_M}{\Delta_0} \right]$$

- arising from term: $(ig_M/m_N)\epsilon^{\mu\nu\rho\sigma} v_\rho S_\sigma q_\nu$ with g_M = 4.7

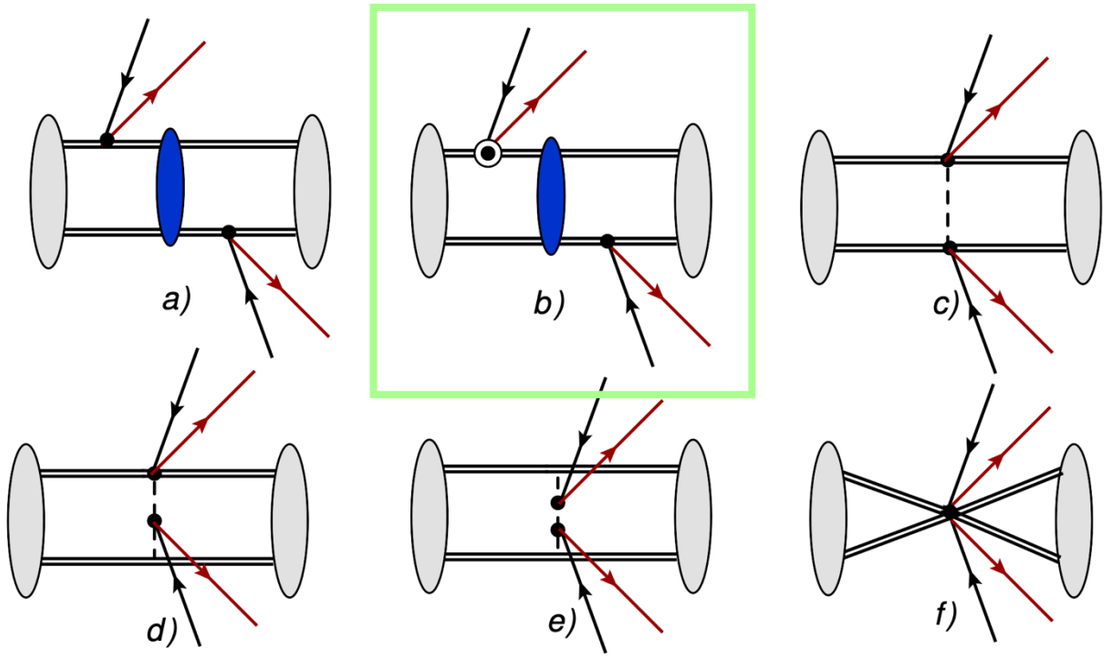
- resembles QED magnetic coupling, with W instead of photon

$$\Delta_0 = 1 + \frac{4}{g_A^2} \frac{(3\epsilon_{GT} - \epsilon_F)}{M^{(-1)}_{GT}} - \frac{2g_M}{3m_N g_A}(\mathcal{Q} + 2m_e),$$

$$\Delta_2 = 1 + \frac{2}{g_A^2} \frac{(3\epsilon_{GT} - \epsilon_F)}{M^{(-1)}_{GT}}.$$

- new phase-space term distortion

$$\mathcal{A}^{2\nu}_M = \frac{2g_M}{3m_N g_A^{\text{eff}}} \frac{(E_{e1} + E_{e2})(2E_{e1}E_{e2} - m_e^2)}{E_{e1}E_{e2}}$$



El Morabit, Bouabid, Cirigliano, de Vries, LG, Mereghetti: JHEP 03 [2412.14160]

Pion-Exchange Contributions

- corrections at the level of heavy baryon chiral EFT: pion exchanges

$$\frac{\Gamma^{2\nu}}{\ln 2} \simeq (g_A^{\text{eff}})^4 |\mathcal{M}^{2\nu}_{GT-1}|^2 \Delta_0 \left[G_0^{2\nu} + \xi_{31} \frac{\Delta_2}{\Delta_0} G_2^{2\nu} + \frac{1}{3}\xi_{31}^2 G_{22}^{2\nu} + \left(\frac{1}{3}\xi_{31}^2 + \xi_{51} \frac{\Delta_2}{\Delta_0} \right) G_4^{2\nu} + \frac{G_M^{2\nu}}{\Delta_0} \right]$$

$$V_{2\nu}(\vec{q}) = -\frac{(8G_F^2 V_{ud}^2)}{2F_\pi^2} (\tau_1^+ \tau_2^+) \frac{1}{\vec{q}^2 + m_\pi^2} (L_{11}^\mu L_{22}^\nu - L_{12}^\mu L_{21}^\nu) \left\{ g_V^2 \delta^{\mu 0}\delta^{\nu 0} + \frac{g_A^2}{3}\delta^{\mu i}\delta^{\nu i} \right.$$

$$\left. \times \left[\vec{\sigma}_1 \cdot \vec{\sigma}_2 \left(1 + \frac{4}{3}\frac{\vec{q}^2}{\vec{q}^2 + m_\pi^2} + \frac{4}{3}\left(\frac{\vec{q}^2}{\vec{q}^2 + m_\pi^2} \right)^2 \right) - \frac{4}{3} S_{12} \frac{\vec{q}^2}{\vec{q}^2 + m_\pi^2} \left(1 + \frac{\vec{q}^2}{\vec{q}^2 + m_\pi^2} \right) \right] \right\}$$

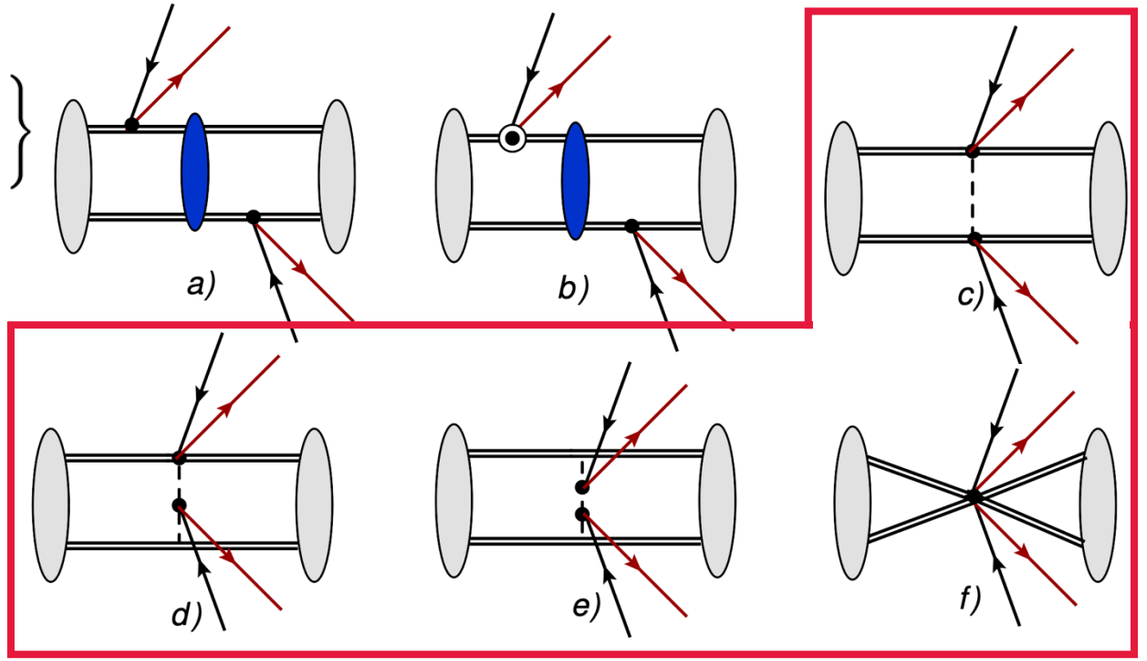
$$\Delta_0 = 1 + \frac{4}{g_A^2} \frac{(3\epsilon_{GT} - \epsilon_F)}{M_{GT}^{(-1)}} - \frac{2 g_M}{3 m_N g_A} (\mathcal{Q} + 2m_e),$$

$$\Delta_2 = 1 + \frac{2}{g_A^2} \frac{(3\epsilon_{GT} - \epsilon_F)}{M_{GT}^{(-1)}}$$

$$\epsilon_F = \frac{m_e g_V^2}{2F_\pi^2} \frac{1}{4\pi R_A} \left(M_F(m_\pi) + \frac{m_\pi^2}{F_\pi^2} g_{2\nu,\text{F}}^{\text{NN}} M_{F,sd} \right)$$

$$\epsilon_{GT} = \frac{m_e g_A^2}{6F_\pi^2} \frac{1}{4\pi R_A} \left(M_{GT}^{AA}(m_\pi) - 2M_{GT}^{AP}(m_\pi) + 4M_{GT}^{PP}(m_\pi) - \frac{3m_\pi^2}{g_A^2 F_\pi^2} g_{2\nu,\text{GT}}^{\text{NN}} M_{F,sd} \right)$$

El Morabit, Bouabid, Cirigliano, de Vries, LG, Mereghetti: JHEP 03 [2412.14160]



- just like 0νββ NMEs for sterile-neutrino exchange with $M_N = m_\pi$!

Differential Decay Rate & Spectral Shape

- differential decay rate – additional fit parameter

$$\frac{d\Gamma}{d\epsilon} = g_A^4 \left(M_{GT}^{(-1)}\right)^2 \Delta_0 \left[\frac{dG_0^{2\nu}}{d\epsilon} + \frac{dG_2^{2\nu}}{d\epsilon}\xi_{31}\frac{\Delta_2}{\Delta_0} + \frac{dG_4^{2\nu}}{d\epsilon}\left(\xi_{51}\frac{\Delta_2}{\Delta_0} + \frac{1}{3}\xi_{31}^2\right) + \frac{dG_{22}^{2\nu}}{d\epsilon}\frac{1}{3}\xi_{31}^2 + \frac{dG_M^{2\nu}}{d\epsilon}\right]$$

- differential phase-space factors

$$\frac{dG_i^{2\nu}}{d\epsilon} = \frac{1}{\ln 2}\frac{(G_F V_{ud})^4}{8\pi^7 m_e^2}\int_{-\epsilon/2}^{\epsilon/2} d\Delta \int_0^{\mathcal{Q}-\epsilon} dE_{\nu 1}\, E_{e1}p_{e1}E_{e2}p_{e2}E_{\nu 1}^2 E_{\nu 2}^2 \times F(E_{e1}, Z_f) \times F(E_{e2}, Z_f) \times \mathcal{A}_i$$

where: $\mathcal{A}_0 = 1\,, \qquad \mathcal{A}_2 = \frac{\epsilon_K^2 + \epsilon_L^2}{(2m_e)^2}\,, \qquad \mathcal{A}_4 = \frac{\epsilon_K^4 + \epsilon_L^4}{(2m_e)^4}\,, \qquad \mathcal{A}_{22} = \frac{\epsilon_K^2 \epsilon_L^2}{(2m_e)^4}$

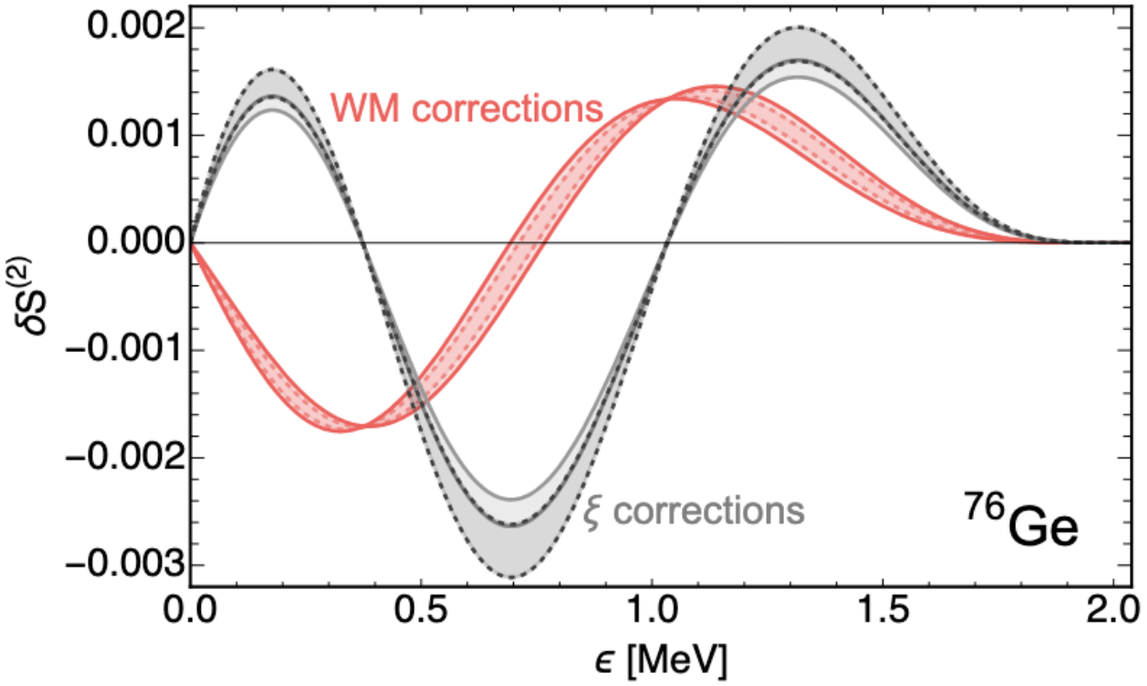
$$\mathcal{A}_M = \frac{2g_M}{3m_N g_A}\frac{(E_{e1}+E_{e2})(2E_{e1}E_{e2} - m_e^2)}{E_{e1}E_{e2}}\,,$$

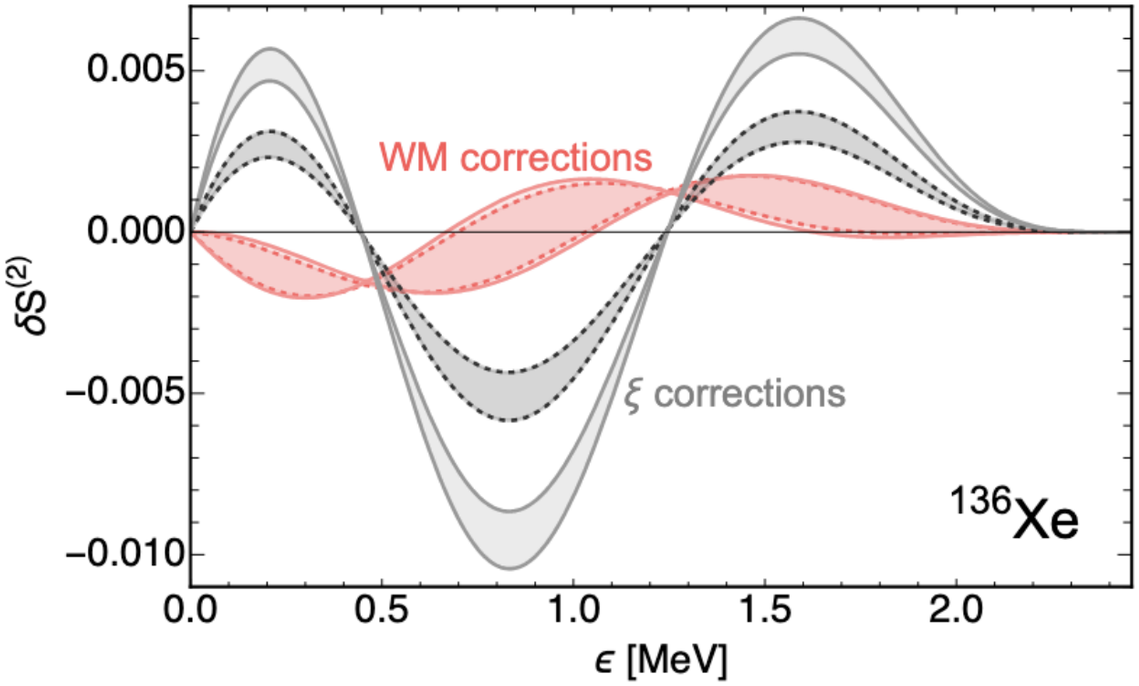
- we study the effects in terms of the shape factors S and their deviations δS

$$S(\epsilon) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\epsilon} \qquad \delta S_i^{(m)}(\epsilon) = S_i^{(m)}(\epsilon) - S_0^{(m)}(\epsilon)\,, \quad \delta \bar{S}_i^{(m)}(\epsilon) = \delta S_i^{(m)}(\epsilon)/S_0^{(m)}(\epsilon)$$

Spectral Shape – WM vs ξ

- compare the effect of the ξ corrections (leptonic energies) with the WM effect
- using both QRPA (lighter, solid) and NSM (darker, dashed); “nodes” for $\frac{dG_2^{2\nu}}{d\epsilon} \simeq \frac{G_2^{2\nu}}{G_0^{2\nu}} \frac{dG_0^{2\nu}}{d\epsilon}$





$$S(\epsilon) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\epsilon} \qquad \delta S_i^{(m)}(\epsilon) = S_i^{(m)}(\epsilon) - S_0^{(m)}(\epsilon)$$

Spectral Shape – Tensor Current

- contribution from exotic tensor current $\epsilon_T \bar{e}_R \sigma^{\mu\nu} \nu_L \, \bar{u}_R \sigma_{\mu\nu} d_L$

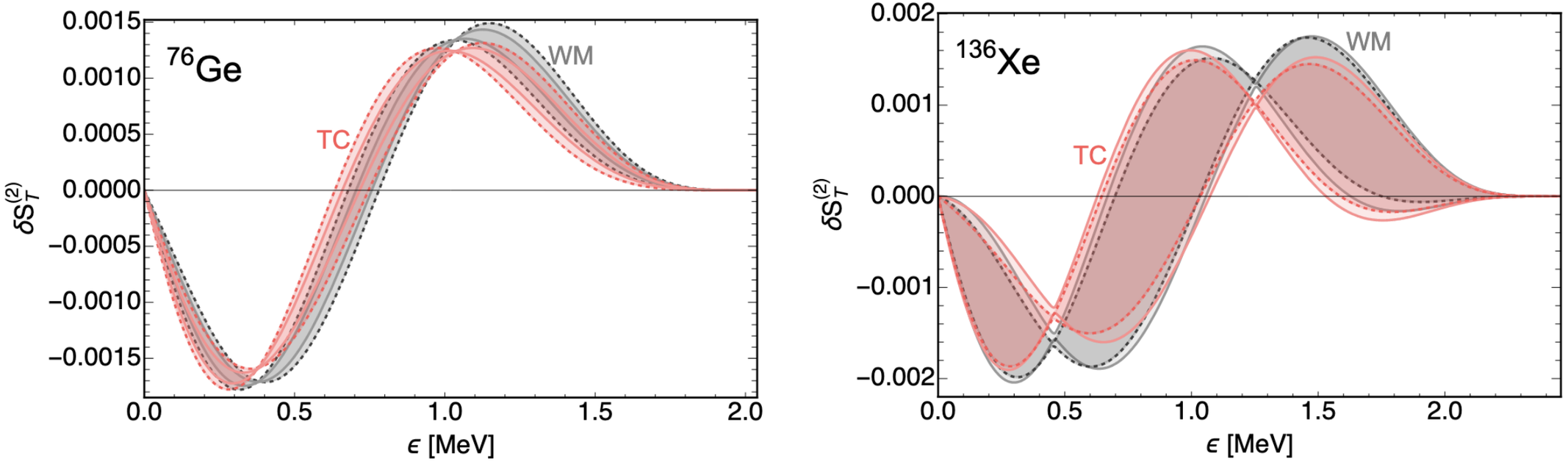


Figure 10: Shape-factor deviations δS induced by the BSM tensor current (TC) with $\epsilon_T = -0.0014$ in comparison with the deviations caused by the weak magnetism (WM) correction term.

$$C_{2\nu}^{\mathrm{BSM}} = \frac{8 g_A^4}{3} \left\{ \epsilon_T \frac{g_T}{g_A} \left[(M_{GT}^K)^2 + (M_{GT}^L)^2 + M_{GT}^K M_{GT}^L \right] \frac{m_e (E_{e1} + E_{e2})}{E_{e1} E_{e2}} \right\}$$

El Morabit, Bouabid, Cirigliano, de Vries, LG, Mereghetti: JHEP 03 [2412.14160]

Conclusion & Outlook

- rare nuclear processes, such as double beta decays, can help to unravel new particle physics; calculations can be complex
- 0νββ – best probe of lepton number violation; generally, a variety of different mechanisms besides the standard light neutrino exchange can contribute to 0νββ
- combining various contributions within a new model → can be involved, tedious calculation with a variety of inputs
  → vDoBe tool developed and available online
- understanding 2νββ crucial for understanding upcoming experiments; can help with searches, but also theory, for 0νββ and its other variants (Majorons)
- new physics can be also probed with 2νββ itself

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Thank you!