Studies of New Physics Related to Neutrinoless Double Beta Decay

Gang Li (李刚)

School of Physics and Astronomy,
Sun Yat-sen University, Zhuhai

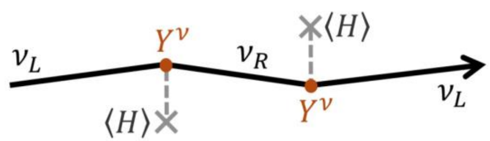
高能理论论坛 (HETH-Forum)

IHEP, CAS, Beijing, Sept. 10, 2025

Neutrino masses

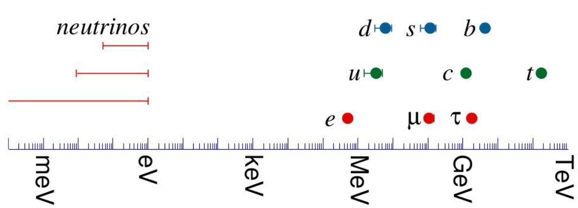
Two ways to generate netrino masses

Dirac mass:



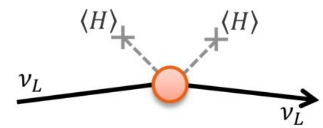
$$\mathcal{L}_D = -(Y^\nu \bar{L} H \nu_R + \text{h.c.})$$

Higgs mechanism



unnaturally small $Y_\nu < 10^{-13}$

Majorana mass:



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

seesaw mechanism

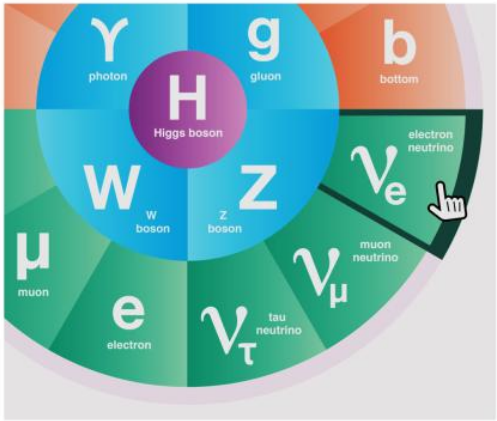
heavy new physics

Neutrino physics

Open questions:

neutrino properties

- Normal or Inverted (sign of Δm^2_{31}?)
- Leptonic CP Violation (δ = ?)
- Octant of θ_{23} (> or < 45°?)
- Absolute Neutrino Masses ($m_{\rm lightest} = 0$?)
- Majorana or Dirac Nature ($\nu = \nu^c$?)
- Majorana CP-Violating Phases (how?)



phenomenology:

- Extra Neutrino Species
- Exotic Neutrino Interactions
- Various LNV & LFV Processes
- Leptonic Unitarity Violation

theories

- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM and/or BAU

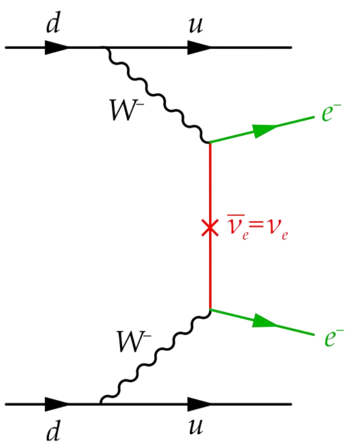
credit: Shun Zhou

neutrinos as a window to new physics

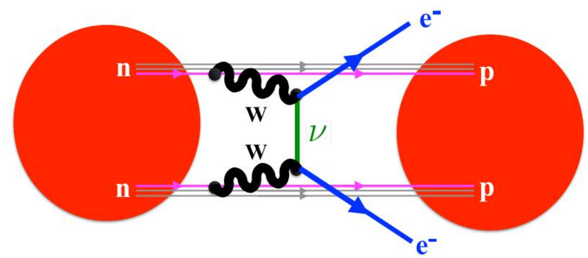
Neutrinoless double beta decay

$0\nu\beta\beta$ decay and Majorana nature of neutrinos

Majorana mass:



$0\nu\beta\beta$ decay:



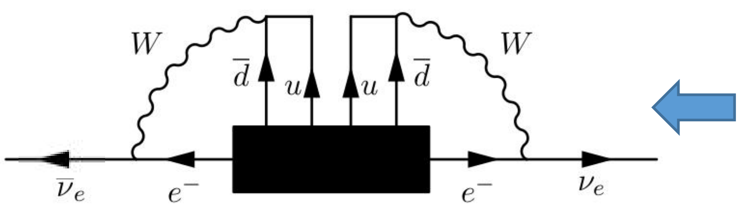
$$(A, Z) \to (A, Z+2) + e^- + e^-$$

M. Goeppert-Mayer, Phys.Rev. 48 (1935) 512
W.H. Furry, Phys. Rev. 56 (1939) 1184

Neutrinoless double beta decay

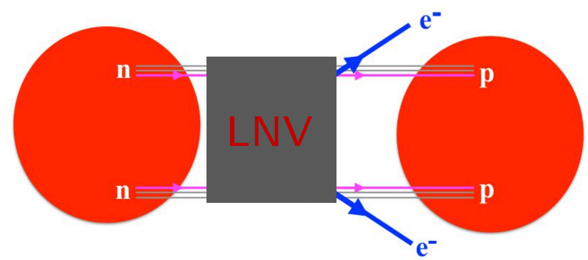
$0\nu\beta\beta$ decay and Majorana nature of neutrinos

Majorana mass:



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

$0\nu\beta\beta$ decay:

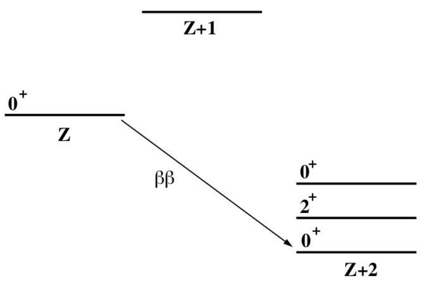


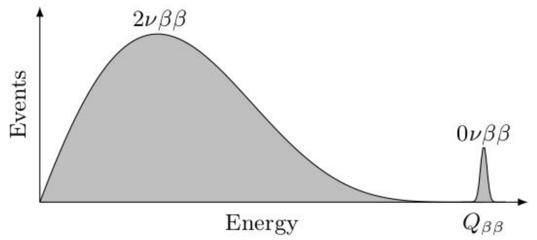
$$(A, Z) \to (A, Z+2) + e^- + e^-$$

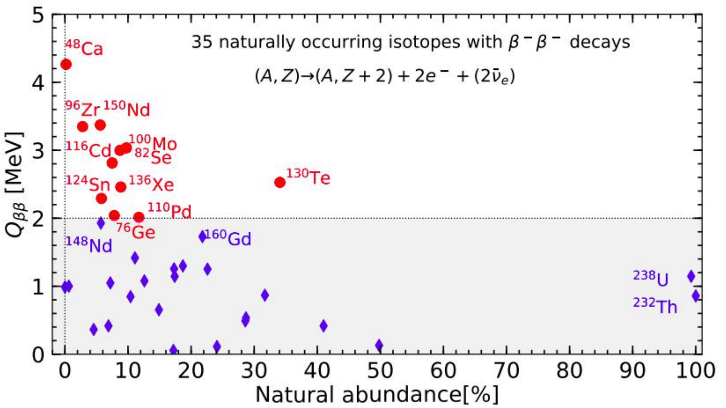
An observation of $0\nu\beta\beta$ decay would undoubtedly imply the Majorana nature of neutrinos and $\Delta L = 2$ LNV interactions in the "black box"

Neutrinoless double beta decay

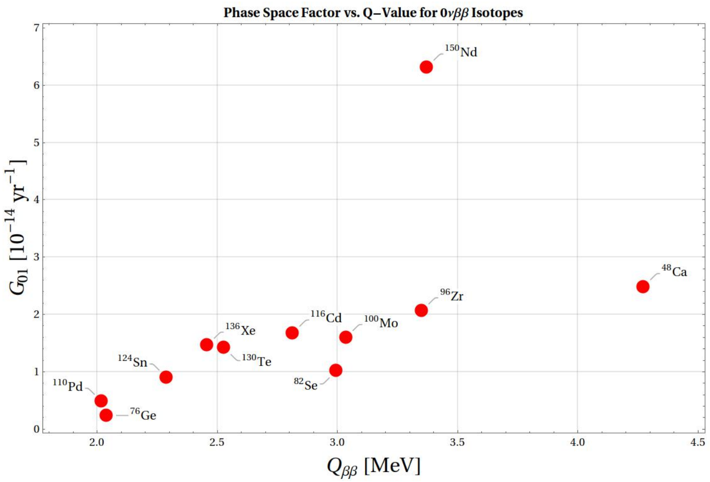
No magic isotopes







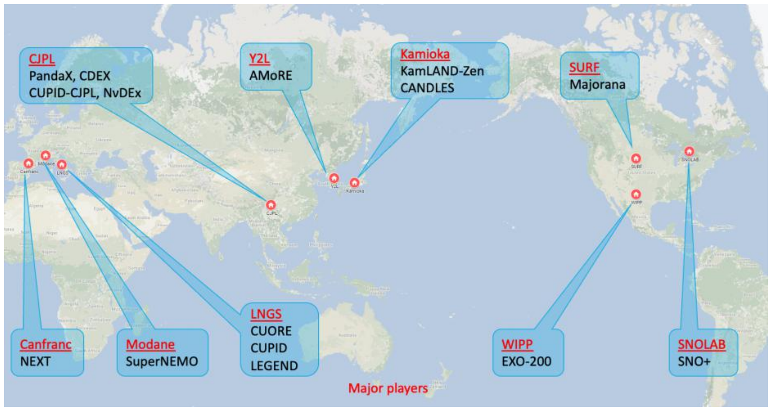
J.M. Yao, et al., 2111.15543 (PPNP)

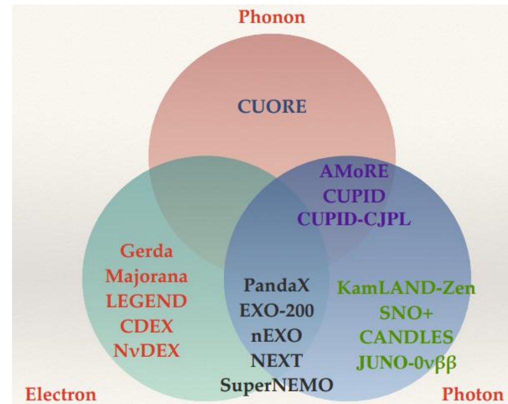


D. Stefanik, R. Dvornicky, F. Simkovic, P. Vogel, 1506.07145 (PRC)

Neutrinoless double beta decay

Global experimental efforts





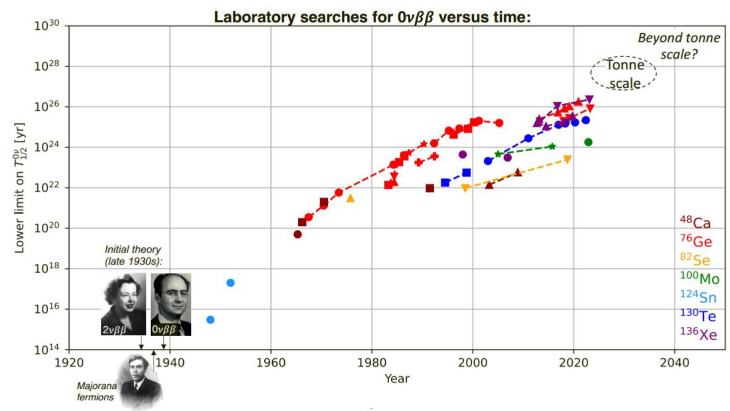
Current limit:

$$T_{1/2}^{0\nu}(\mathrm{Xe}) > 3.8 \times 10^{26} \text{ year}$$

KamLAND-Zen, 2406.11438

Future prospects:

$$T_{1/2}^{0\nu} \gtrsim 10^{28} \text{ year}$$

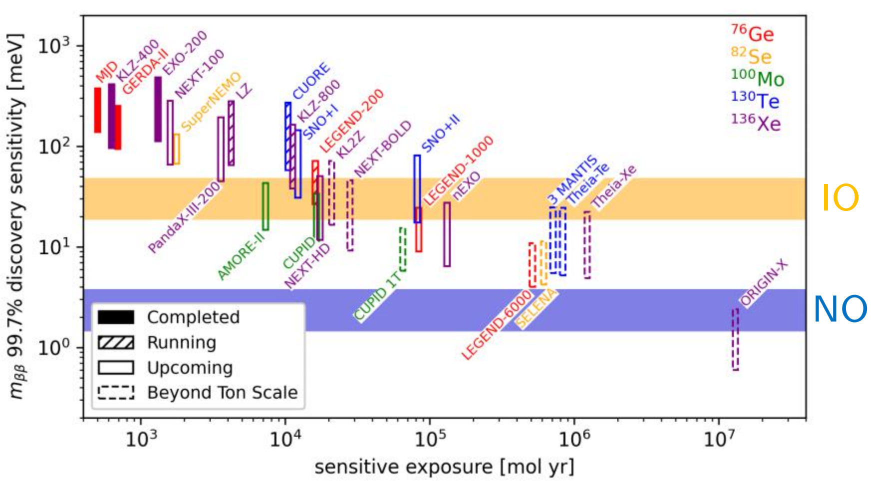


Neutrinoless double beta decay

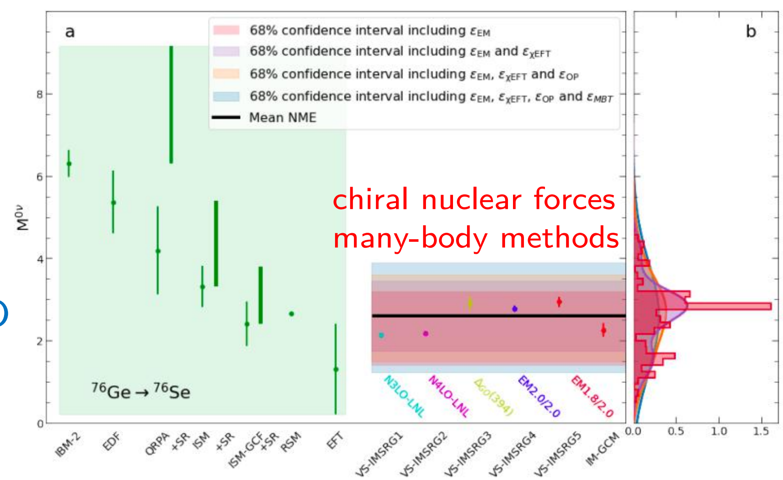
Effective Majorana mass

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

$G_{0\nu}$:	phase space factor (atomic physics)
$M_{0\nu}$:	nuclear matrix element (nuclear physics)
$\langle m_{\beta\beta} \rangle$:	effective Majorana mass (particle physics)



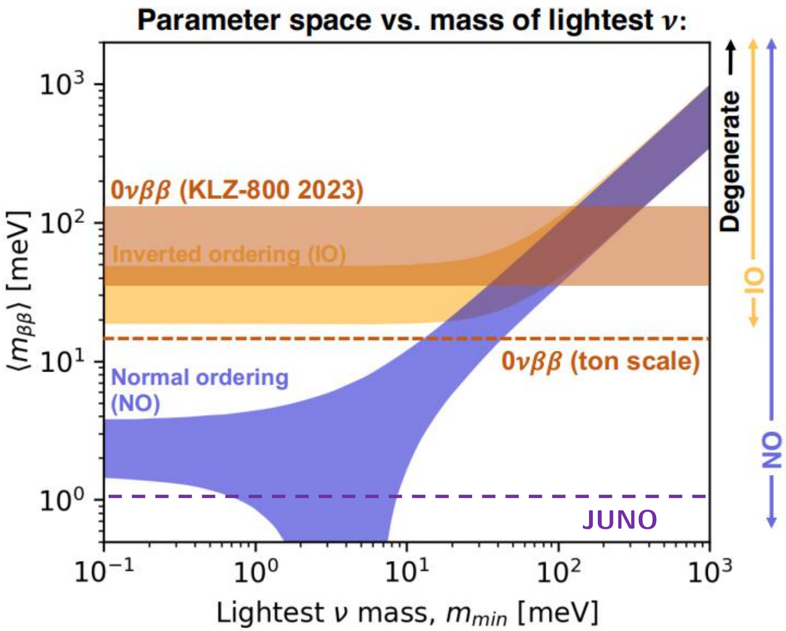
C. Adams, et a., 2212.11099



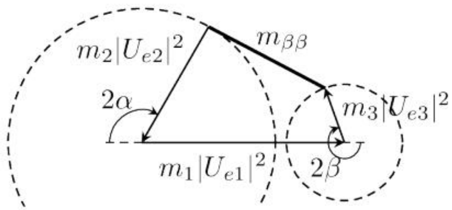
A. Belley, J.M. Yao, et al., 2308.15634 (PRL)

Neutrinoless double beta decay

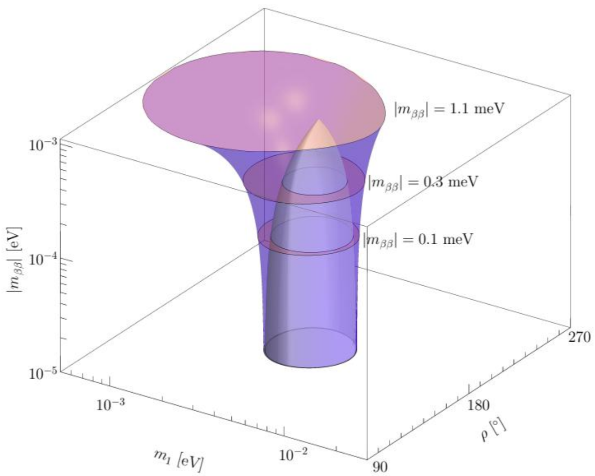
Standard mechanism $\langle m_{\beta\beta}\rangle = |\sum_i m_i U_{ei}^2|$



C. Adams, et a., 2212.11099



Bilenky, Pascoli, Petcov, Phys.Rev.D 64 (2001) 053010



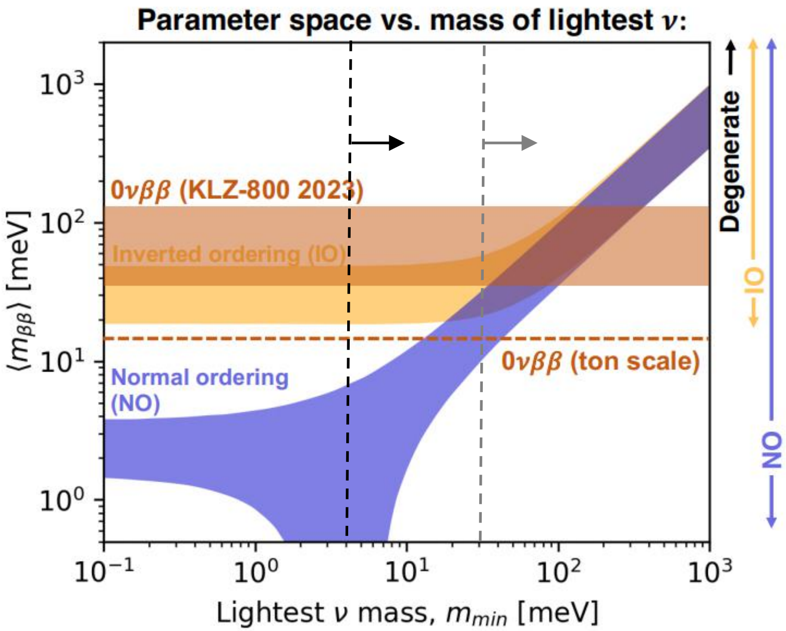
J. Cao, et al., 1908.08355 (CPC)

Neutrinoless double beta decay

Standard mechanism

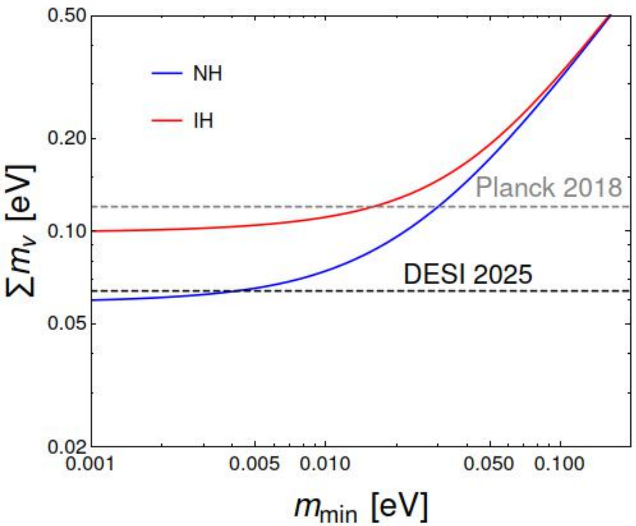
$$\sum m_\nu = m_1 + m_2 + m_3$$

- Planck 2018: $\Sigma m_\nu < 0.12$ eV
- DESI 2025: $\Sigma m_\nu < 0.064$ eV



C. Adams, et a., 2212.11099

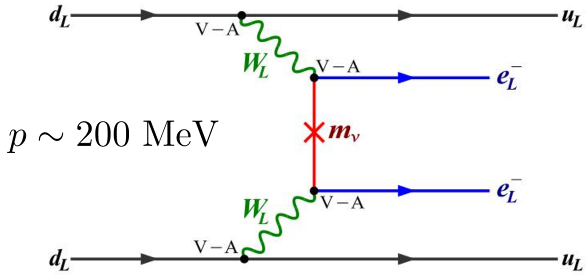
DESI, 2503.14738

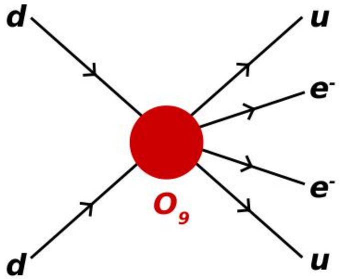


Can tonne-scale experiments discover $0\nu\beta\beta$ decay in the NH?

Non-standard mechanism

Standard vs non-std. mechanisms





$\sim G_F^2 m_\nu^{ee}/p^2$

$\sim c/\Lambda^5$

W. Rodejohann, 1106.1334

Naive estimate:

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

c: new coupling
Λ: new particle mass

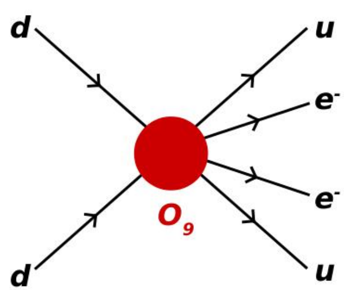
Non-standard mechanism

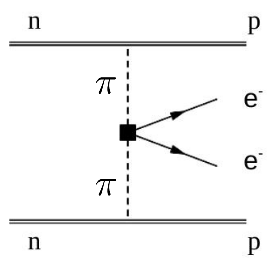
Chiral perturbation theory

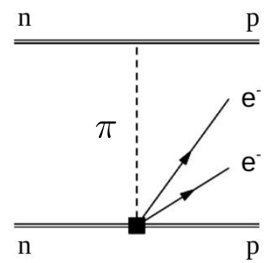
quark level: $d = 9$

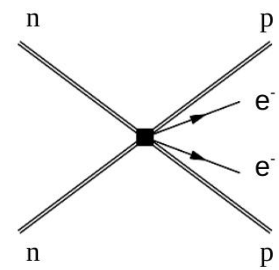
hadronic level: organized in Weinberg power counting

S. Weinberg, Phys. Lett. B 251 (1990) 288; Nucl. Phys. B 363 (1991) 3









p^{-2}, p^0 | p^0 | p^0

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

$\pi^-\pi^-\bar{e}_R e_R^c$ | $(\bar{p}S\cdot\partial\pi^- n)\,\bar{e}_R e_R^c$ | $(\bar{p}n)(\bar{p}n)\bar{e}_R e_R^c$

$\partial_\mu\pi^-\partial^\mu\pi^-\bar{e}_R e_R^c$ | $\bar{p}\left(S\cdot\partial\pi^- n\right)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c$ | $(\bar{p}n)(\bar{p}n)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c$

$R \to L$

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

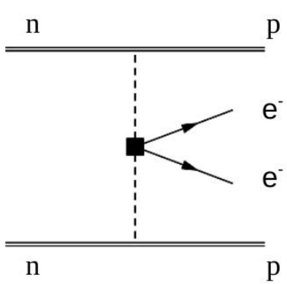
$p^{-2}:\ \frac{\Lambda_\chi}{p^2} \simeq 25$ chiral enhancement

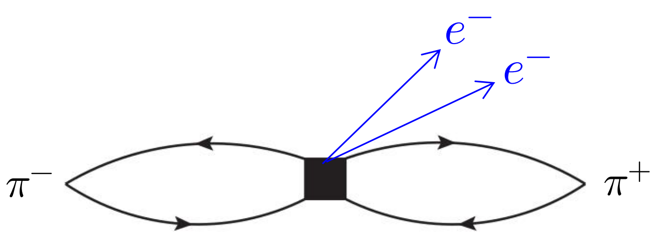
Non-standard mechanism

- However, this formalism depends on low-energy constants (LECs) from non-perturbative QCD effects

$\langle m_{\beta\beta} \rangle \sim$ LECs x Wilson Coeffs   LECs: $g_{V,A}$ (std. mechanism)

- Lattice-QCD calculations:





Nicholson et al., Phys. Rev. Lett. 121, 172501 (2018)

LEC	Value
$g_1^{\pi\pi}$	0.36 ± 0.02
$g_2^{\pi\pi}$	2.0 ± 0.2 GeV^2
$g_3^{\pi\pi}$	$-(0.62 \pm 0.06)$ GeV^2
$g_4^{\pi\pi}$	$-(1.9 \pm 0.2)$ GeV^2
$g_5^{\pi\pi}$	$-(8.0 \pm 0.6)$ GeV^2

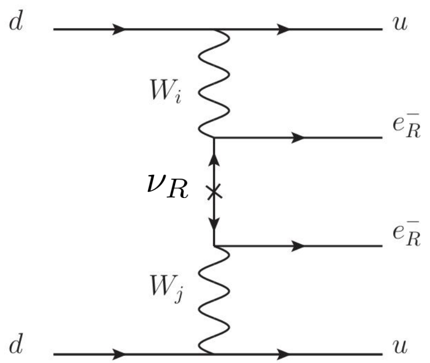
Naive dimensional analysis:

$$g_1^{\pi\pi} = \mathcal{O}(1)$$
$$g_{2,3,4,5}^{\pi\pi} = \mathcal{O}(\Lambda_\chi^2)$$

A. Manohar, H. Georgi, Nucl. Phys. B234, 189 (1984)

Effective field theory approach

Minimal left-right symmetric model



$(i,j) = (R,R)$ $\quad \bar{u}_R\gamma_\mu d_R \bar{u}_R\gamma_\mu d_R \bar{e}_R e_R^c \sim O_1' \bar{e}_R e_R^c$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N}\left(\frac{M_W}{M_{W_R}}\right)^4 p^0$$

$(i,j) = (1,2)$ $\quad \bar{u}_L\gamma_\mu d_L \bar{u}_R\gamma_\mu d_R \bar{e}_R e_R^c \sim O_4 \bar{e}_R e_R^c$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N}\sin 2\beta\left(\frac{M_W}{M_{W_R}}\right)^4 \Lambda_\chi^2 p^{-2}$$

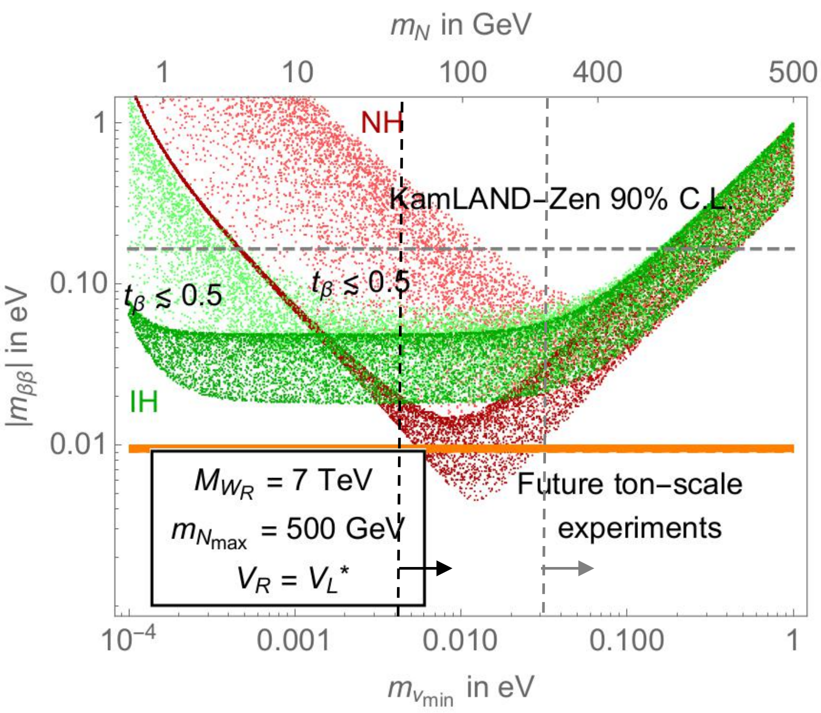
G. Prezeau, M. Ramsey-Musolf, P. Vogel, Phys.Rev.D 68 (2003)

$$O_1' = \bar{q}_R^\alpha \gamma_\mu \tau^+ q_R^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta$$

Left-right mixing: $O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta$

Effective field theory approach

Minimal left-right symmetric model



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

Leading contribution

- Type-II seesaw:

$$M_L = (v_L/v_R)M_R$$

- charge conjugation as the LR symmetry

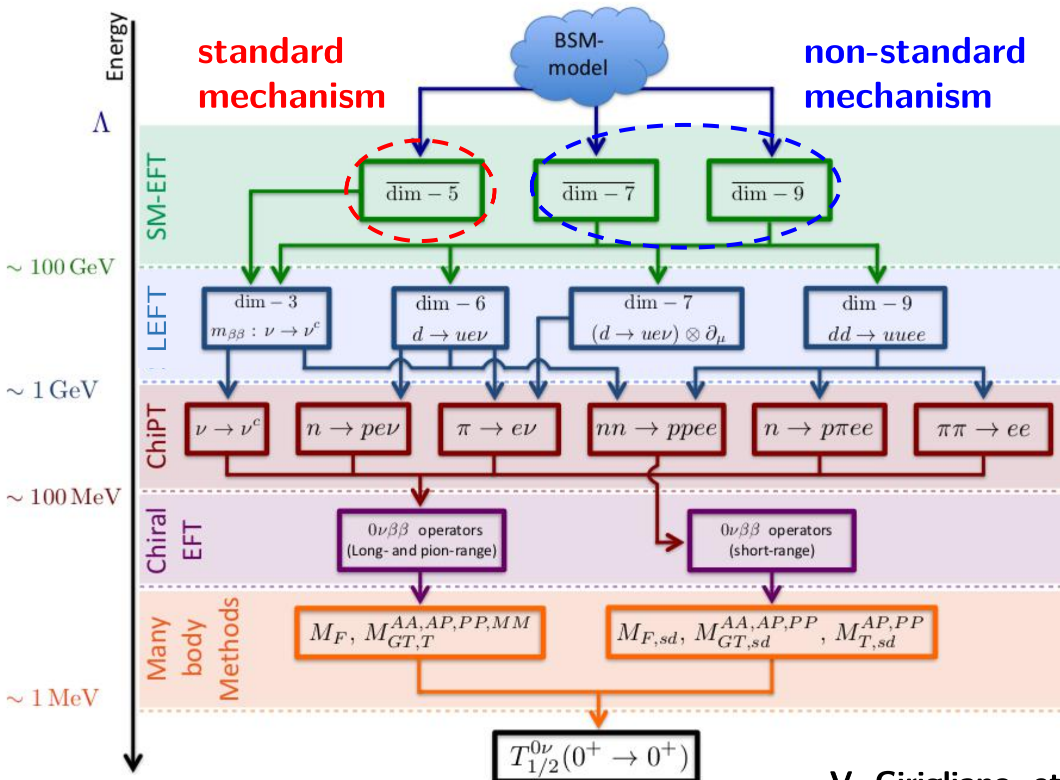
$$V_R = V_L^*$$

- Input parameters in the NH

$$\{M_{W_R}, m_4(m_1), m_6\}$$

Effective field theory approach

End-to-end framework



V. Cirigliano, et al., 2203.12169

Effective field theory approach

Master formula for inverse half-life

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

Bulding blocks:

- For the standard mechanism, 1 phase-space factor, 9+1 NMEs
- For non-standard mechanisms, 6 phase-space factors, 6 NMEs

V. Cirigliano, et al., 1710.01729 (PRC); 1802.10097 (PRL)
V. Cirigliano, et al., 1708.09390 (JHEP); 1806.02780 (JHEP)

Effective field theory approach

- Fundamental NMEs:

NMEs	^{76}Ge			^{82}Se		^{130}Te		^{136}Xe	
	[32]	[33]	[34,35]	[32]	[33]	[32]	[33]	[32]	[33]
M_F	-1.74	-0.59	-0.68	-1.29	-0.55	-1.52	-0.67	-0.89	-0.54
M_{GT}^{AA}	5.48	3.15	5.06	3.87	2.97	4.28	2.97	3.16	2.45
M_{GT}^{AP}	-2.02	-0.94	-0.92	-1.46	-0.89	-1.74	-0.97	-1.19	-0.79
M_{GT}^{PP}	0.66	0.30	0.24	0.48	0.28	0.59	0.31	0.39	0.25
M_{GT}^{MM}	0.51	0.22	0.17	0.37	0.20	0.45	0.23	0.31	0.19
M_T^{AA}	–	–	–	–	–	–	–	–	–
M_T^{AP}	-0.35	-0.01	-0.31	-0.27	-0.01	-0.50	0.01	-0.28	0.01
M_T^{PP}	0.10	0.00	0.09	0.08	0.00	0.16	-0.01	0.09	-0.01
M_T^{MM}	-0.04	0.00	-0.04	-0.03	0.00	-0.06	0.00	-0.03	0.00
$M_{F,\,sd}$	-3.46	-1.46	-1.1	-2.53	-1.37	-2.97	-1.61	-1.53	-1.28
$M_{GT,\,sd}^{AA}$	11.1	4.87	3.62	7.98	4.54	10.1	5.31	5.71	4.25
$M_{GT,\,sd}^{AP}$	-5.35	-2.26	-1.37	-3.82	-2.09	-4.94	-2.51	-2.80	-1.99
$M_{GT,\,sd}^{PP}$	1.99	0.82	0.42	1.42	0.77	1.86	0.92	1.06	0.74
$M_{T,\,sd}^{AP}$	-0.85	-0.05	-0.97	-0.65	-0.05	-1.50	0.07	-0.92	0.05
$M_{T,\,sd}^{PP}$	0.32	0.02	0.38	0.24	0.02	0.58	-0.02	0.36	-0.02

long-range

short-range

Effective field theory approach

Standard mechanism

$$\mathcal{A}_\nu = \frac{m_{\beta\beta}}{m_e}\mathcal{M}_\nu^{(3)}$$

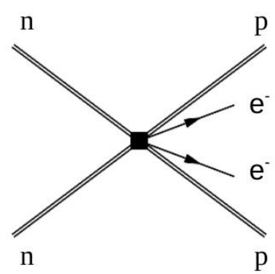
$$\mathcal{M}_\nu^{(3)} = -V_{ud}^2\left(-\frac{1}{g_A^2}M_F + \mathcal{M}_{GT} + \mathcal{M}_T + \boxed{2\frac{m_\pi^2 g_\nu^{NN}}{g_A^2}M_{F,sd}}\right)$$

leading-order contact term

$$\mathcal{M}_{GT} = M_{GT}^{AA} + M_{GT}^{AP} + M_{GT}^{PP} + M_{GT}^{MM}$$

$$\mathcal{M}_T = M_T^{AP} + M_T^{PP} + M_T^{MM}$$

V. Cirigliano, et al., 1802.10097 (PRL)



$p^0 \rightarrow p^{-2}$

- Breakdown of Weinberg power counting, since the NME is an integral of p
- The effect of LO contact term can also be rigorously established in the relativistic framework

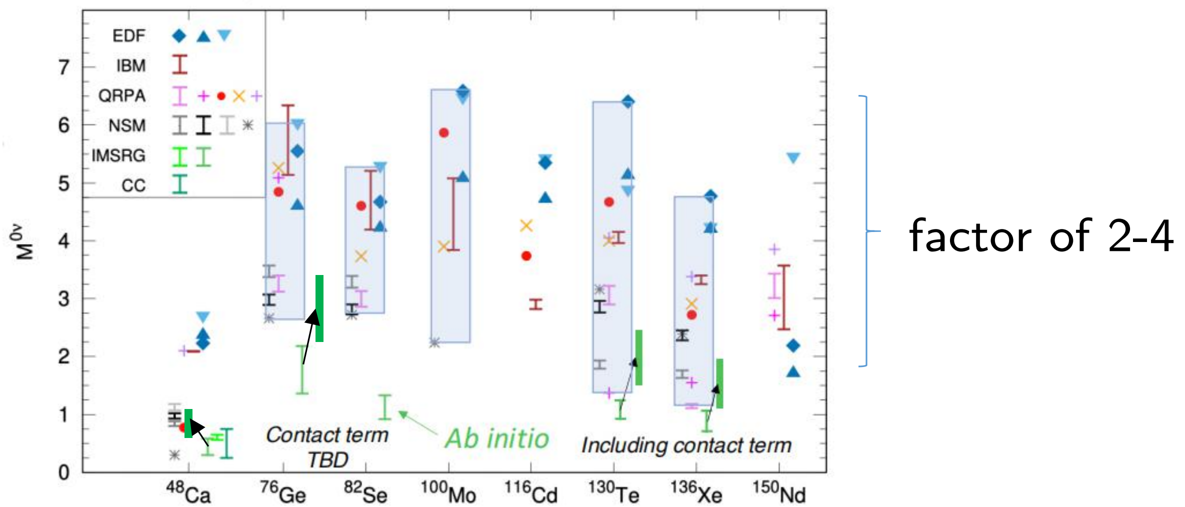
Y.L. Wang, P.W. Zhao, 2308.03356 (PLB)

Effective field theory approach

Standard mechanism

$g_\nu^{\rm NN}({\rm fm}^2)$	Λ (MeV)
-0.67	450
-1.01	550
-1.44	465
-0.91	465
-1.44	349
-1.03	349

L. Jokiniemi, P. Soriano, J. Menéndez, 2107.13354 (PLB)



M. Agostini et al.,, Rev.Mod.Phys. 95 (2023) 2, 025002

^{48}Ca: **R. Wirth, J.M. Yao, H. Hergert,2105.05415 (PRL)**

^{76}Ge: **A. Belley, J.M. Yao, et al., 2308.15634 (PRL)**

Contact term enhances the NME and decay amplitude by $30\% - 50\%$

Effective field theory approach

Non-standard mechanisms

$$\mathcal{A}_\nu = \frac{m_{\beta\beta}}{m_e}\mathcal{M}_\nu^{(3)} + \frac{m_N}{m_e}\mathcal{M}_\nu^{(6)} + \frac{m_N^2}{m_e v}\mathcal{M}_\nu^{(9)}\,,$$

$$\mathcal{A}_R = \frac{m_N^2}{m_e v}\mathcal{M}_R^{(9)}\,,$$

$$\mathcal{A}_E = \mathcal{M}_{E,L}^{(6)} + \mathcal{M}_{E,R}^{(6)}\,,$$

$$\mathcal{A}_{m_e} = \mathcal{M}_{m_e,L}^{(6)} + \mathcal{M}_{m_e,R}^{(6)}\,,$$

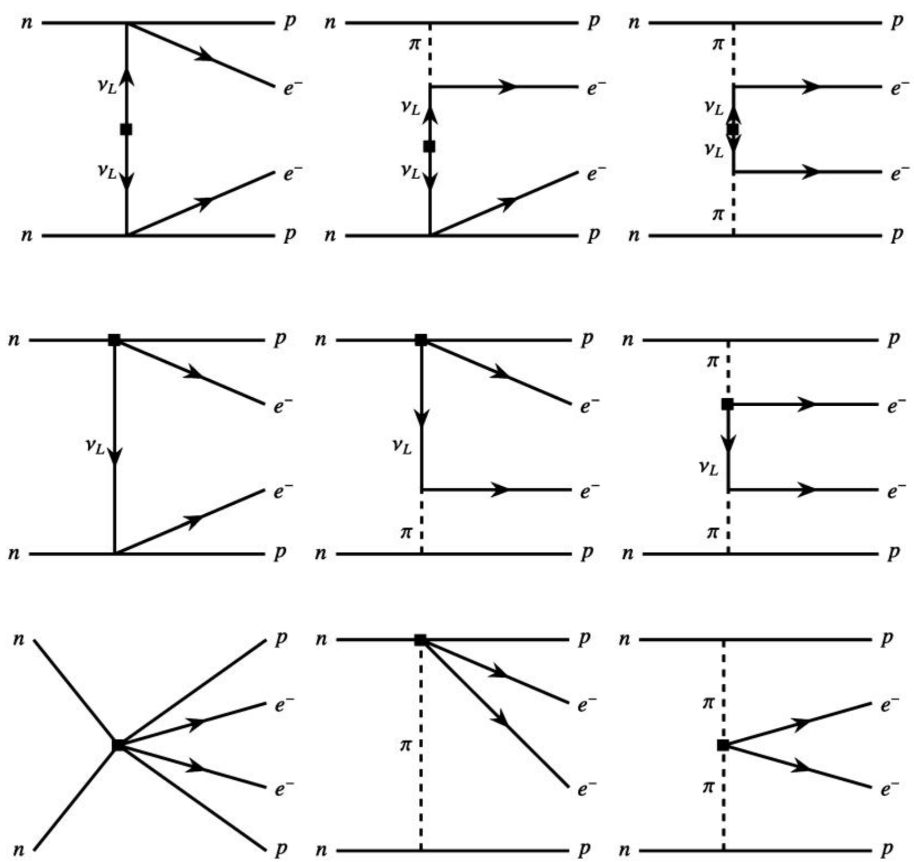
$$\mathcal{A}_M = \frac{m_N}{m_e}\mathcal{M}_M^{(6)} + \frac{m_N^2}{m_e v}\mathcal{M}_M^{(9)}\,.$$

Many combinations of NMEs, which might cancel among each other

$$\mathcal{M}_\nu^{(9)} = -\frac{1}{2m_N^2}C_{\pi\pi\mathrm{L}}^{(9)}\left(\frac{1}{2}M_{GT,sd}^{AP} + M_{GT,sd}^{PP} + \frac{1}{2}M_{T,sd}^{AP} + M_{T,sd}^{PP}\right)$$
$$+\frac{m_\pi^2}{2m_N^2}C_{\pi N\mathrm{L}}^{(9)}\left(M_{GT,sd}^{AP} + M_{T,sd}^{AP}\right) - \frac{2}{g_A^2}\frac{m_\pi^2}{m_N^2}C_{NN\mathrm{L}}^{(9)}M_{F,sd}$$

Effective field theory approach

Three types of diagrams:



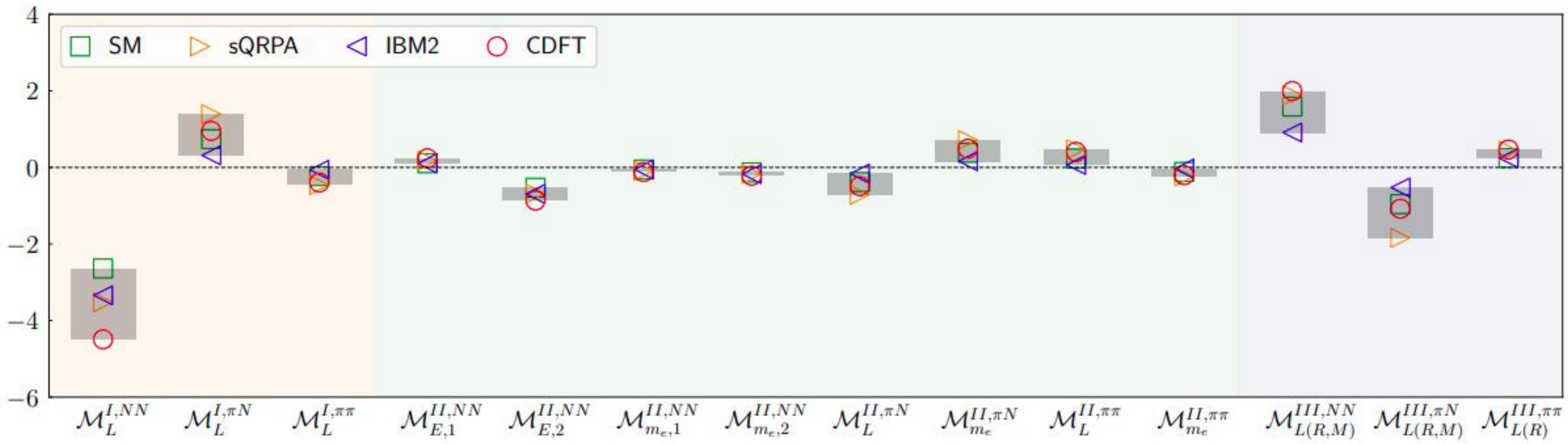
long-range
($d = 5$, standard)

long-range
($d = 7$, non-std.)

short-range
($d = 9$, non-std.)

Effective field theory approach

NMEs categorized in diagrams



- Uncertainties of NMEs in different diagrams are quantified
- For both standard and non-standard mechanisms, the uncertainties are a factor of 2-4

C.R. Ding, GL, J.M. Yao, 2403.17722 (PLB)

Effective field theory approach

- NMEs in $\pi\pi$ and πN diagrams

$$\mathcal{M}_{\nu}^{(9)} = -\frac{1}{2m_N^2} C_{\pi\pi\mathrm{L}}^{(9)} \left(\frac{1}{2} M_{GT,sd}^{AP} + M_{GT,sd}^{PP} + \frac{1}{2} M_{T,sd}^{AP} + M_{T,sd}^{PP} \right) \equiv M_{PS,sd}$$

$$+ \frac{m_\pi^2}{2m_N^2} C_{\pi N\mathrm{L}}^{(9)} \left(M_{GT,sd}^{AP} + M_{T,sd}^{AP} \right) - \frac{2}{g_A^2} \frac{m_\pi^2}{m_N^2} C_{NN\mathrm{L}}^{(9)} M_{F,sd}$$

$$\equiv M_{P,sd}$$

$M_{PS,sd}$	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
QRPA	-0.79	-0.575	-0.78	-0.44
Shell	-0.315	-0.28	-0.32	-0.25
IBM	-0.37			

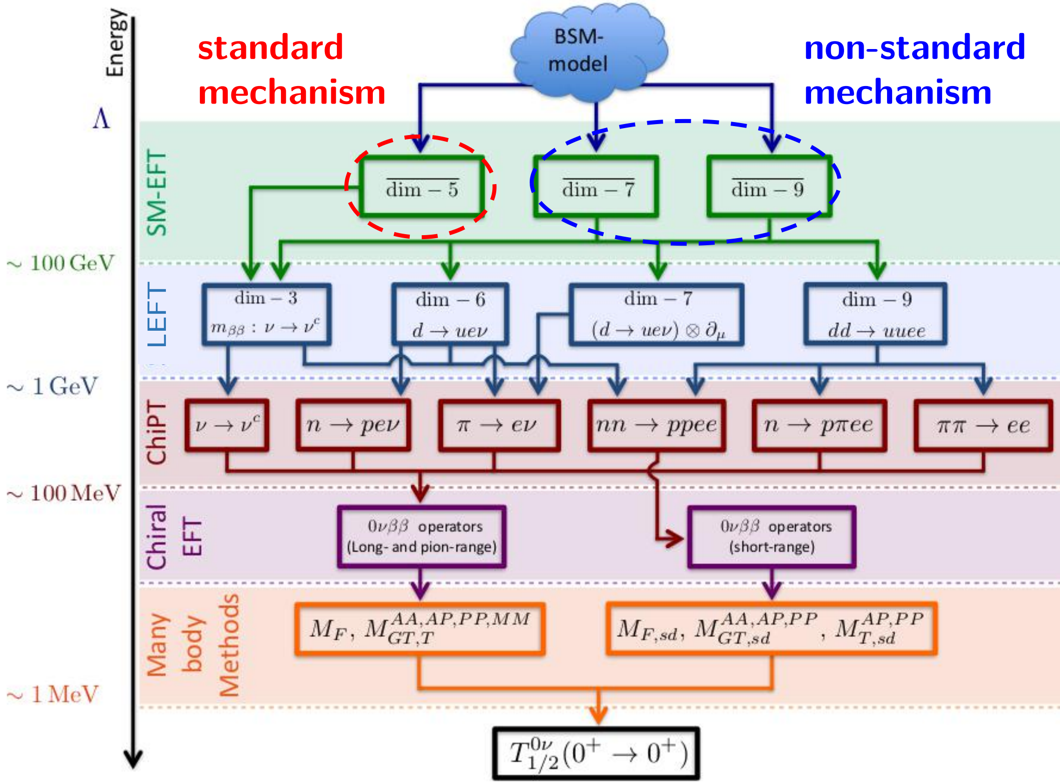
$M_{P,sd}$	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
QRPA	-6.2	-4.47	-6.4	-3.7
Shell	-2.3	-2.1	-2.4	-1.9
IBM	-2.34			

$M_{P,sd}/M_{PS,sd}$	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
QRPA	7.8	7.8	8.3	8.5
Shell	7.3	7.6	7.6	7.8
IBM	6.3			

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

Effective field theory approach

End-to-end framework



sterile neutrinos

$0\nu\beta\beta$ decay with sterile neutrino

EFT with sterile neutrino

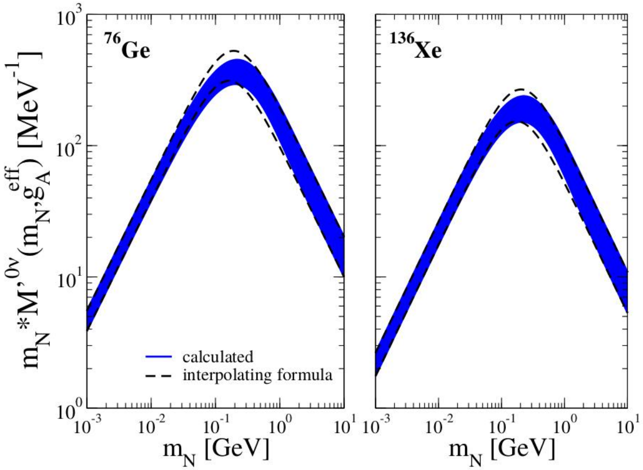
- νSMEFT

Y. Liao, X.-D. Ma, 1612.04527 (PRD)

- νLEFT

T. Li, X.-D. Ma, M. A. Schmidt, 2005.01543 (JHEP)

- NMEs with ν_R



A. Faessler, M. Gonzalez, S. Kovalenko, F. Simkovic, 1408.6077 (PRD)

Interpolation:

$$M_{F\,\mathrm{int}}(m_i) = M_{F,sd}\frac{m_\pi^2}{m_i^2 + m_\pi^2 \frac{M_{F,sd}}{M_F}}$$

$$\lim_{m_i \to 0} M_F(m_i) = M_F$$

$$\lim_{m_i \to \infty} M_F(m_i) = \frac{m_\pi^2}{m_i^2} M_{F,sd}$$

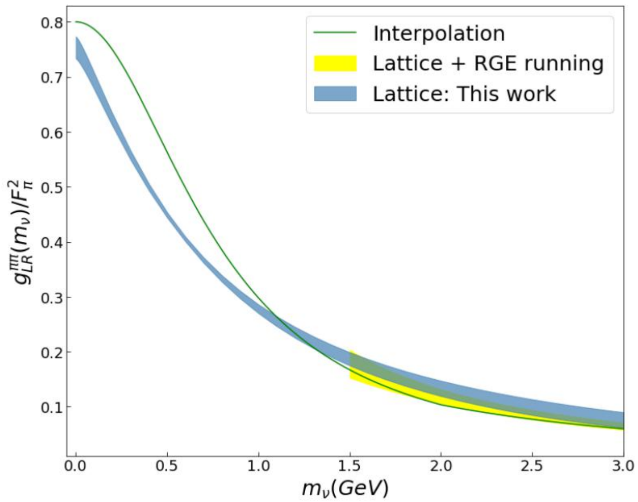
W. Dekens, et al., 2002.07182 (JHEP)

$0\nu\beta\beta$ decay with sterile neutrino

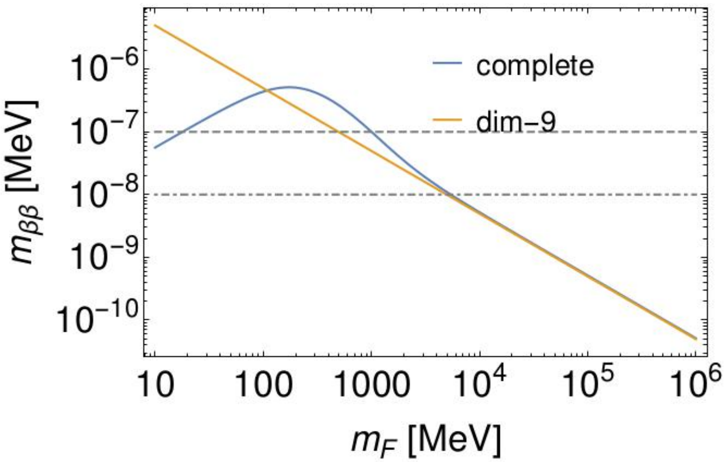
EFT with sterile neutrino

- ChPT with ν_R **W. Dekens, et al., 2002.07182 (JHEP)**

$$g_{\rm LR}^{\pi\pi}(m_i) = \frac{g_{\rm LR}^{\pi\pi}(0)}{1 - m_i^2 \frac{4 g_{\rm LR}^{\pi\pi}(0)}{F_\pi^2} \left[\theta(m_0 - m_i) g_4^{\pi\pi}(m_0) + \theta(m_i - m_0) g_4^{\pi\pi}(m_i)\right]^{-1}}$$



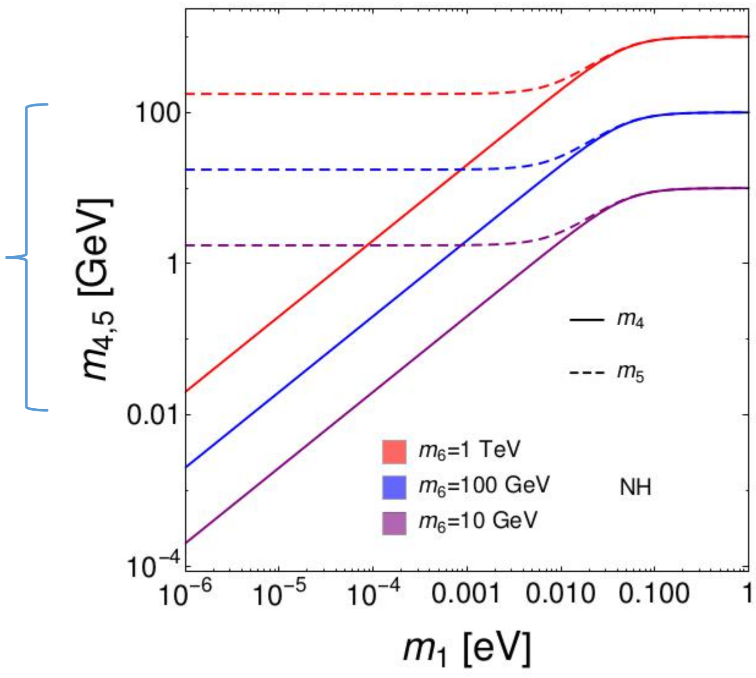
X.-Y. Tuo, X. Feng, L.-C. Jin, 2206.00879 (PRD)



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

$0\nu\beta\beta$ decay with sterile neutrino

Minimal left-right symmetric model



- Type-II seesaw:

$$M_L = (v_L/v_R)M_R$$

- charge conjugation as the LR symmetry

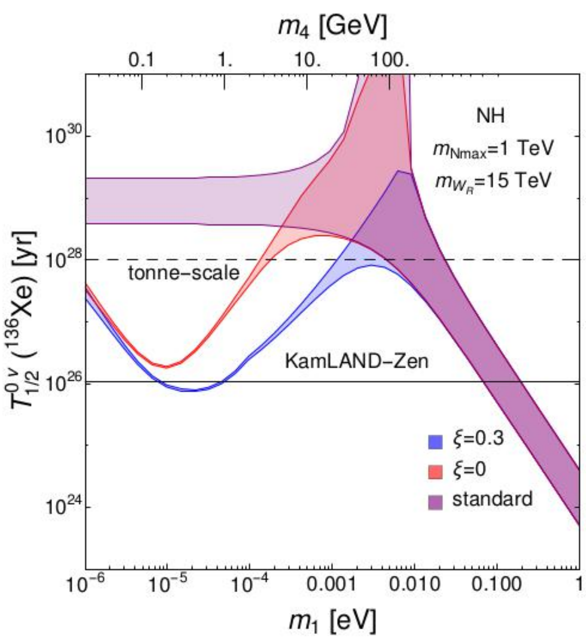
$$V_R = V_L^*$$

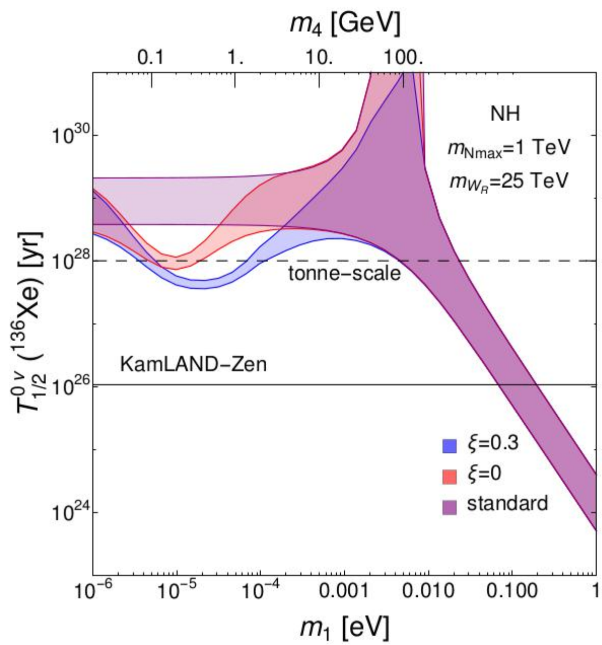
- Input parameters in the NH

$$\{M_{W_R}, m_4(m_1), m_6\}$$

$0\nu\beta\beta$ decay with sterile neutrino

Minimal left-right symmetric model



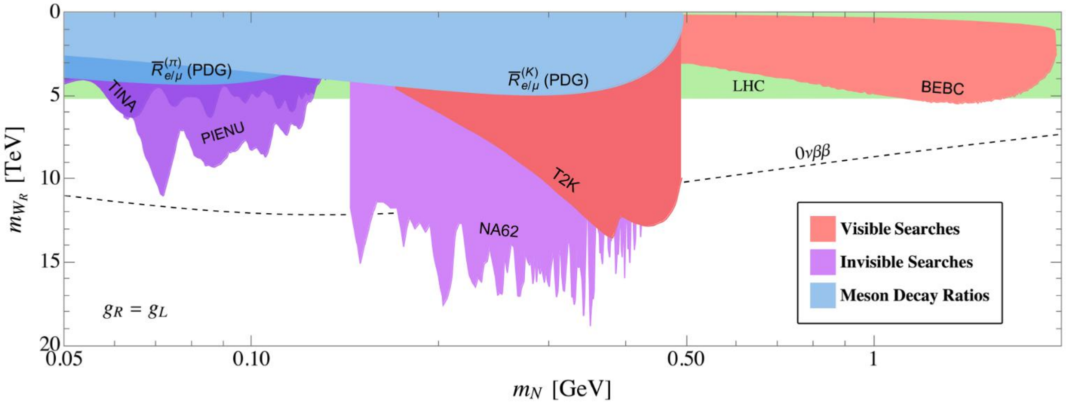


Future tonne-scale experiments are sensitive to M_{W_R} up to 25 TeV

J. de Vries, GL, M. J. Ramsey-Musolf,
J. C. Vasquez, 2209.03031 (JHEP)

Sub-GeV sterile neutrino

Minimal left-right symmetric model



G. F. S. Alves, et al., 2307.04862 (PRL)

The calculation of $0\nu\beta\beta$ decay rate is based on the traditional method, using NMEs that were obtained 27 years ago!

J. D. Vergados, H. Ejiri, F. Simkovic, Rept. Prog. Phys. 75, 106301 (2012)
G. Pantis, F. Simkovic, J. D. Vergados, A. Faessler, Phys. Rev. C 53, 695 (1996)

Sub-GeV sterile neutrino

Minimal left-right symmetric model

- Compared to the traditional method, addtional short-range contribuions arise from the calculation in the cutting-edge EFT approach:

$$\mathcal{A}_L(m_i) = -\frac{m_i}{4m_e}(\mathcal{M}_V + \mathcal{M}_A)\left(C^{(6)}_{\rm VLL}\right)^2_{ei} + \mathcal{A}_L^{(\nu)}(m_i)$$

$$\mathcal{A}_R(m_i) = -\frac{m_i}{4m_e}(\mathcal{M}_V + \mathcal{M}_A)\left(C^{(6)}_{\rm VRR}\right)^2_{e(i-3)} + \mathcal{A}_R^{(\nu)}(m_i)$$

$$\mathcal{A}_L^{(\nu)}(m_i) = -\frac{m_i}{2m_e}\frac{m_\pi^2 g_\nu^{NN}(m_i)}{g_A^2}\left(C^{(6)}_{\rm VLL}\right)^2_{ei} M_{F,sd}$$

$$\mathcal{A}_R^{(\nu)}(m_i) = -\frac{m_i}{2m_e}\frac{m_\pi^2 g_\nu^{NN}(m_i)}{g_A^2}\left(C^{(6)}_{\rm VRR}\right)^2_{e(i-3)} M_{F,sd}$$

W. Dekens, et al., 2002.07182 (JHEP)

$$g_\nu^{NN}(m_i) = g_\nu^{NN}(0)\frac{1+(m_i/\Lambda_\chi)^2}{1+(m_i/\Lambda_\chi)^2(m_i/m_\pi)^2}$$

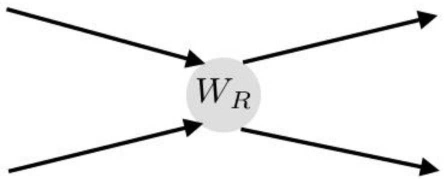
W. Dekens, et al., 2402.07993 (JHEP)

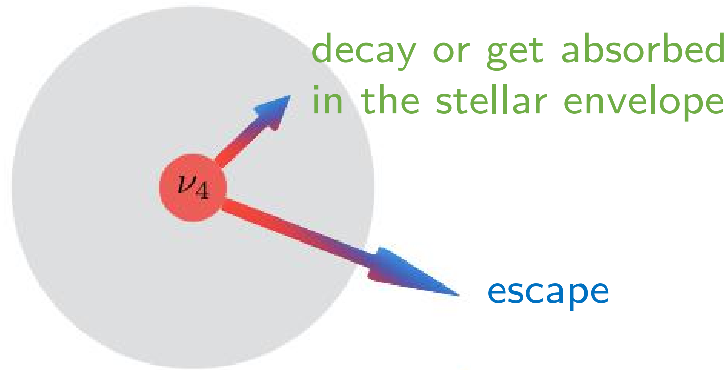
$$g_\nu^{NN}(0) = -(1.055 \pm 0.385)\text{fm}^2$$

L. Jokiniemi, P. Soriano, J. Menéndez, 2107.13354 (PLB)

Sub-GeV sterile neutrino

Supernova bounds:





Production: $e^- + p \to \nu_4 + n$

Decay: $\nu_4 \to \pi^\pm e^\mp$

- The SN1987A cooling bound: sterile neutrinos should not take away too much energy

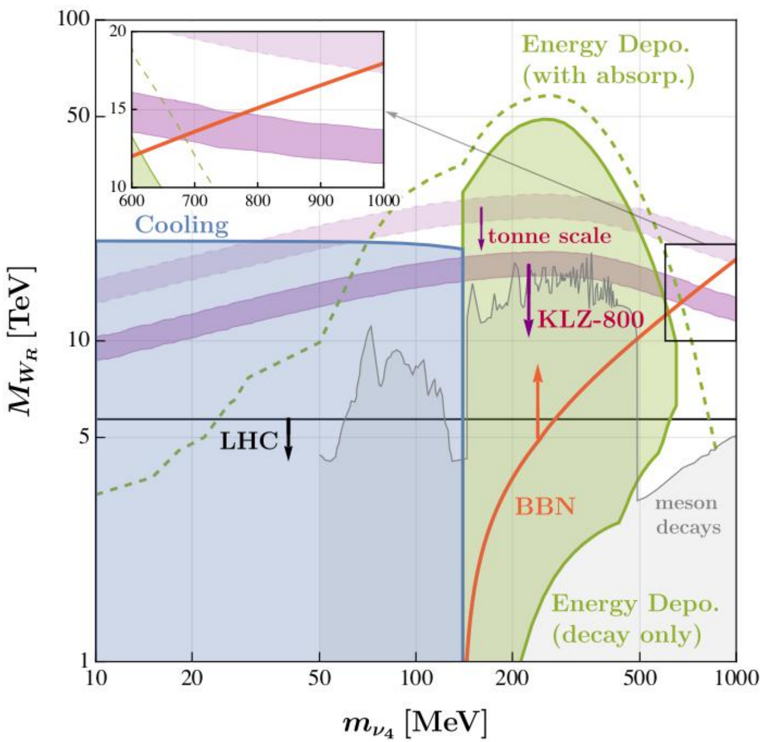
$$M_{W_R} > 23 \text{ TeV} \quad \text{for} \quad m_4 < 10 \text{ MeV}$$

R. Barbieri and R.N. Mohapatra, Phys. Rev. D 39 (1989) 1229

- The energy deposition bound: sterile neutrinos should not inject too much energy inside the stellar envelop

Sub-GeV sterile neutrino

Innovative assessment of the type-II seesaw mechanism



Purple bands: uncertainties from NMEs

- New constraints from SN1987A

  cooling: $m_{\nu_4} \leq m_\pi$
  energy deposition: $m_{\nu_4} \leq$ 650 GeV

- New constraint from BBN

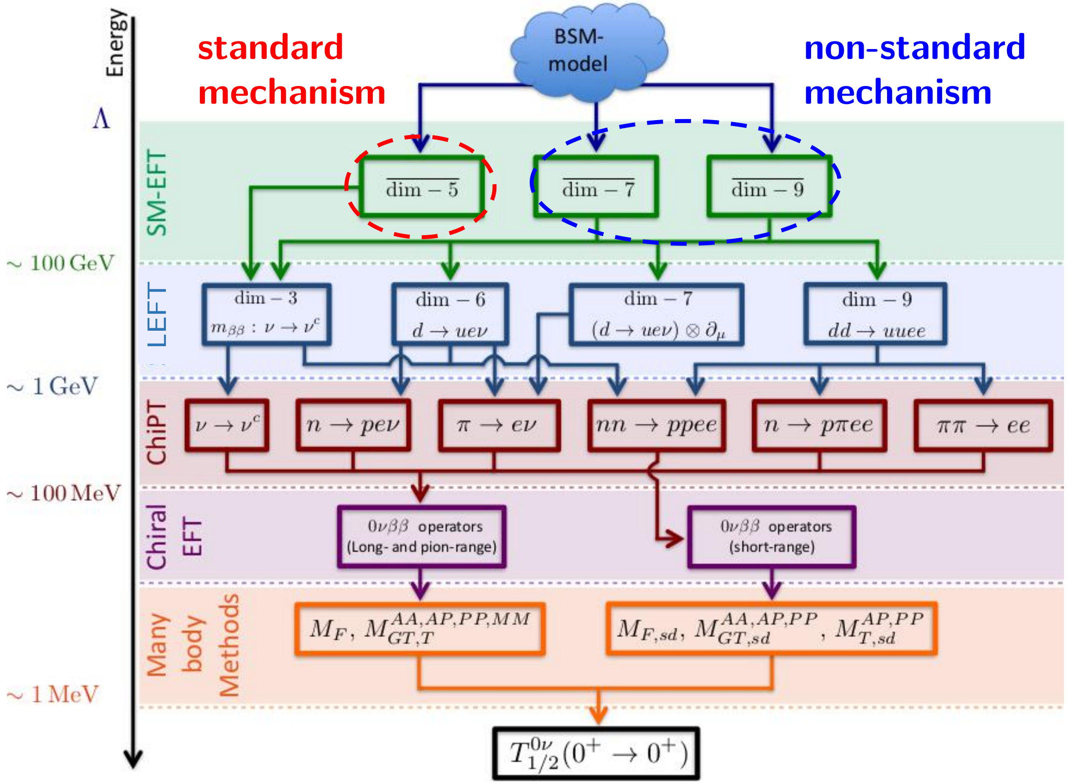
  sterile neutrino lifetime $\tau \lesssim 0.023$ s

- A unique window $700\ \text{MeV} \leq m_{\nu_4} \leq 1\ \text{GeV}$ and $M_{W_R} \sim 20$ TeV, exclusively probed by the future tonne-scale $0\nu\beta\beta$ decay experiments

**GL, Ying-Ying Li, Sida Lu,
Ye-Ling Zhou, 2508.15609**

Effective field theory approach

End-to-end framework

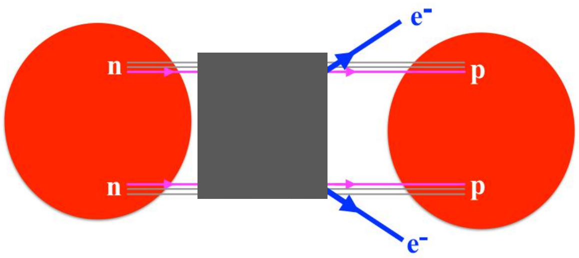


νDoBe: A python program from SMEFT to half-life

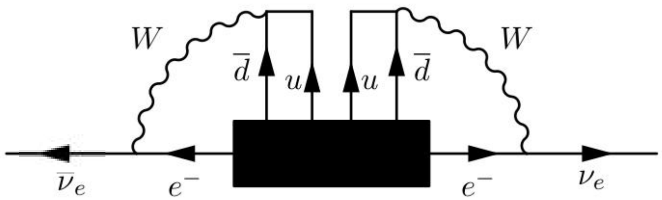
O. Scholer, J. de Vries, L. Gráf 2304.05415 (JHEP)

TeV scale LNV

- From Majorana nature to LNV interactions

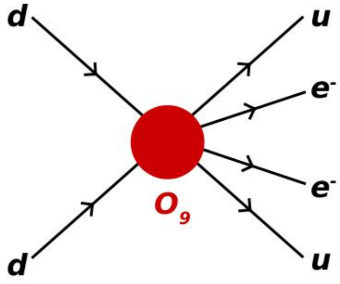


$$(A, Z) \to (A, Z+2) + e^- + e^-$$



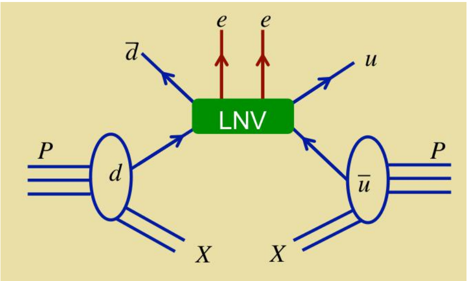
Schechter, Valle, Phys.Rev. D25 (1982) 774

- TeV scale LNV:



✓ uncorrelated with observed neutrino masses

✓ if exists, clear BSM signals at the LHC



same-sign dilepton dijet $(e^{\pm}e^{\pm}jj)$

TeV scale LNV

Chirally enhanced/suppressed mechanism

$$\mathcal{M}_{\nu}^{(9)} = -\frac{1}{2m_N^2} C_{\pi\pi\mathrm{L}}^{(9)} \left(\frac{1}{2} M_{GT,sd}^{AP} + M_{GT,sd}^{PP} + \frac{1}{2} M_{T,sd}^{AP} + M_{T,sd}^{PP} \right) + \frac{m_\pi^2}{2m_N^2} C_{\pi N\mathrm{L}}^{(9)} \left(M_{GT,sd}^{AP} + M_{T,sd}^{AP} \right) - \frac{2}{g_A^2} \frac{m_\pi^2}{m_N^2} C_{NN\mathrm{L}}^{(9)} M_{F,sd}$$

eg. LRSM

$$C_{\pi\pi\,\mathrm{L}}^{(9)} = g_2^{\pi\pi} \left(C_{2\mathrm{L}}^{(9)} + C_{2\mathrm{L}}^{(9)\,\prime} \right) + g_3^{\pi\pi} \left(C_{3\mathrm{L}}^{(9)} + C_{3\mathrm{L}}^{(9)\,\prime} \right) - g_4^{\pi\pi} C_{4\mathrm{L}}^{(9)} - g_5^{\pi\pi} C_{5\mathrm{L}}^{(9)} - \frac{5}{3} g_1^{\pi\pi} m_\pi^2 \left(C_{1\mathrm{L}}^{(9)} + C_{1\mathrm{L}}^{(9)\,\prime} \right),$$

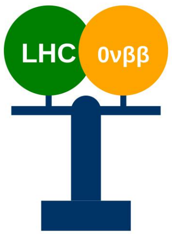
$$C_{\pi N\,\mathrm{L}}^{(9)} = \left(g_1^{\pi N} - \frac{5}{6} g_1^{\pi\pi} \right) \left(C_{1\mathrm{L}}^{(9)} + C_{1\mathrm{L}}^{(9)\,\prime} \right),$$

chirally enhanced

chirally suppressed

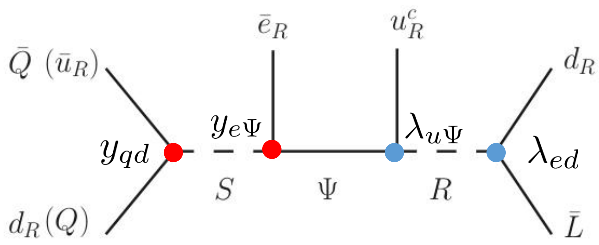
$M_{P,sd}/M_{PS,sd}$	^{76}Ge	^{82}Se	^{130}Te	^{136}Xe
QRPA	7.8	7.8	8.3	8.5
Shell	7.3	7.6	7.6	7.8
IBM	6.3			

How the cancellations among NMEs impact the BSM physics sensitivities of $0\nu\beta\beta$ decay experiments compared to LHC searches?

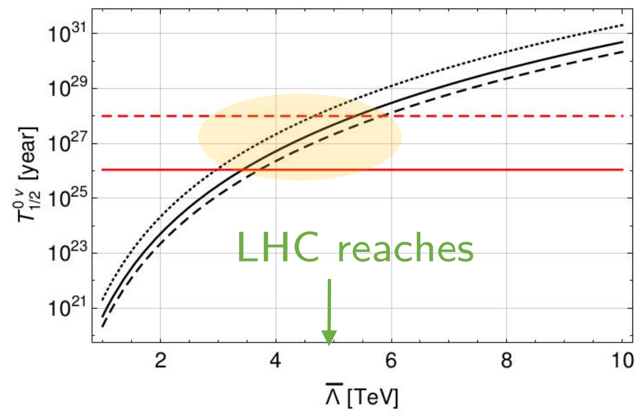


TeV scale LNV

Simplified model for chirally suppressed mechanism

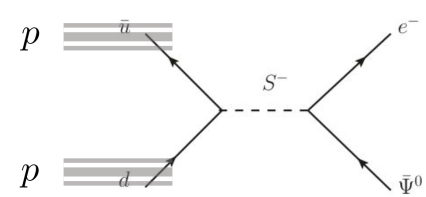


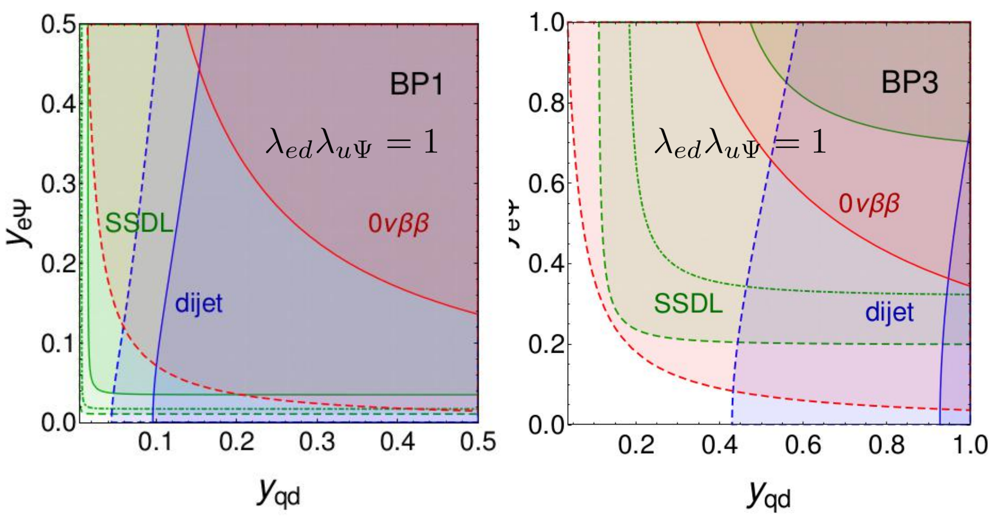
LNV: $\lambda_{ed}\lambda_{u\Psi}y_{qd}y_{e\Psi} \neq 0$



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

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





- The sensitivity of $0\nu\beta\beta$ decay searches is diluted by the chiral suppression
- The reach of LHC searches is increased by the assumed kinematic accessibility

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

TeV scale LNV

Two-step UV completion

BSM model

covariant derivative D_μ

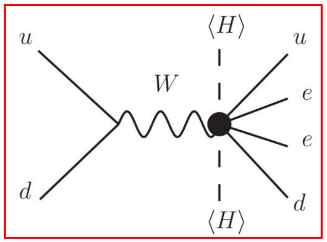
$$\mathcal{O}^{(7)}_{\bar{d}uLLD} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i iD_\mu L_j\right)$$

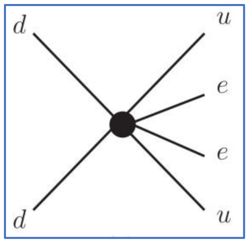
$$\mathcal{O}^{(9)}_1 = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}^c_R e_R\right) H_j D_\mu H_i$$

$$\mathcal{O}^{(9)}_2 = \epsilon^{ik}\left(\bar{d}_R L_j\right)\left(\bar{L}^c_i\gamma^\mu u_R\right) H^{\dagger j} D_\mu H_k$$

$$\mathcal{O}^{(9)}_3 = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i D_\mu L_j\right) H_k H^{\dagger k}$$

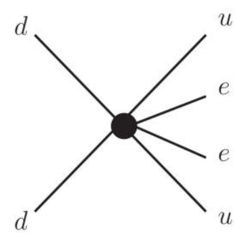
$$\mathcal{O}^{(9)}_4 = \epsilon^{ik}\left(\bar{u}^\alpha_R Q^\beta_j\right)\left(\bar{L}^j d^\alpha_R\right)\left(\bar{L}_i Q^{\beta c}_k\right)$$





broken phase

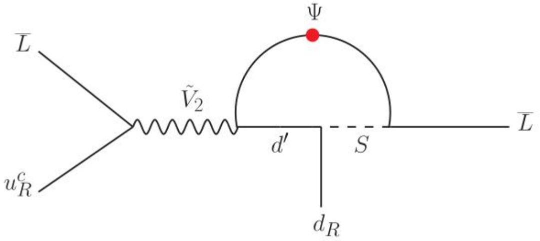
$$O_4 = \bar{q}^\alpha_L\gamma_\mu\tau^+ q^\alpha_L\bar{q}^\beta_R\gamma^\mu\tau^+ q^\beta_R \quad \otimes\left(\bar{e}_L e^c_L, \bar{e}_R e^c_R\right)$$



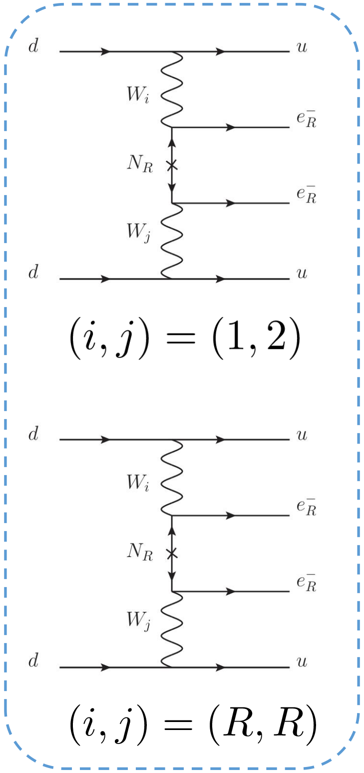
TeV scale LNV

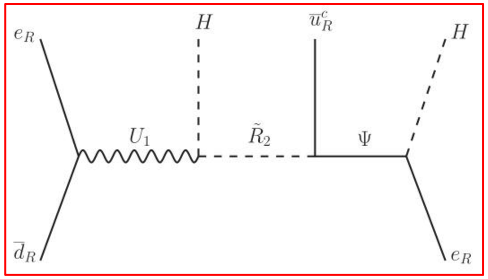
BSM models for chirally enhanced mechanism

$$\mathcal{O}^{(7)}_{\bar{d}uLLD} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i iD_\mu L_j\right)$$



$$\mathcal{O}^{(9)}_1 = \epsilon^{ij}(\bar{d}_R\gamma^\mu e_R)(\bar{u}^c_R e_R)H_j D_\mu H_i$$





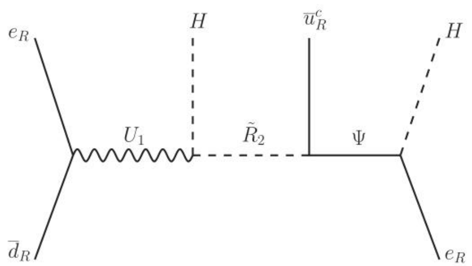
leptoquark model

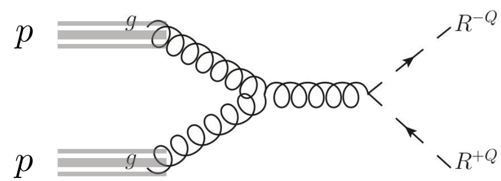
$$\mathcal{O}^{(9)}_4 = \epsilon^{ik}\left(\bar{u}^\alpha_R Q^\beta_j\right)\left(\bar{L}^j d^\alpha_R\right)\left(\bar{L}_i Q^{\beta c}_k\right)$$

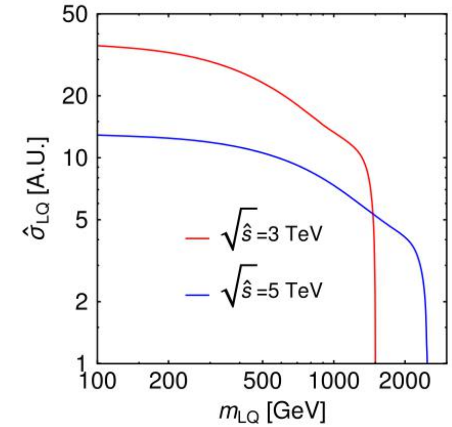
LRSM

TeV scale LNV

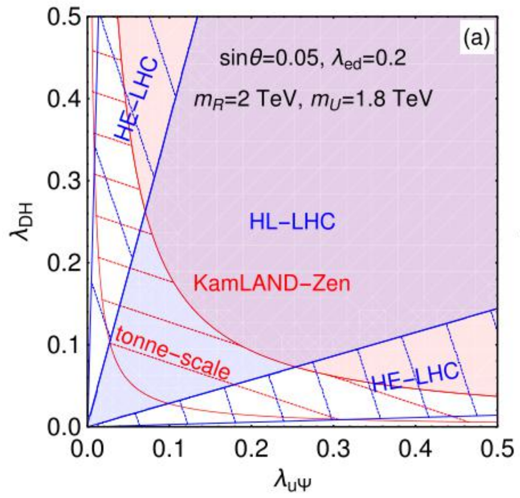
Leptoquark model for chirally enhanced mechanism







LNV: $\lambda_{ed}\lambda_{u\Psi}\lambda_{DH}f_{\Psi e} \neq 0$



sensitive to the leptoquark mass

- BSM model constructed in two-step UV completion
- LHC searches for TeV scale LNV are complementary to $0\nu\beta\beta$ decay searches

GL, J.-H. Yu, X. Zhao, 2202.01237 (JHEP)

Summary

- We investigate benchmark scenarios for new physics related to $0\nu\beta\beta$ decay in the EFT approach
- In the context of left-right symmetric model,
  - The left-right mixing can lead to leading contribution to $0\nu\beta\beta$ decay, due to the chiral enhancement
  - Sub-GeV sterile neutrino can serve as a probe of type-II seesaw mechanism
- Searches at the LHC offer complementary probes of TeV scale LNV, for both chirally enhanced and suppressed mechanisms
- We emphasize that a two-step UV completion is necessary to connect $0\nu\beta\beta$ decay operator to BSM model
- Outlook: flavor effects, leptogenesis, …

Thanks for your attention!