Theory overview of neutrinoless double beta decay

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NuPhys 2019, London

Technische Universität München

Neutrinos – what do we know?

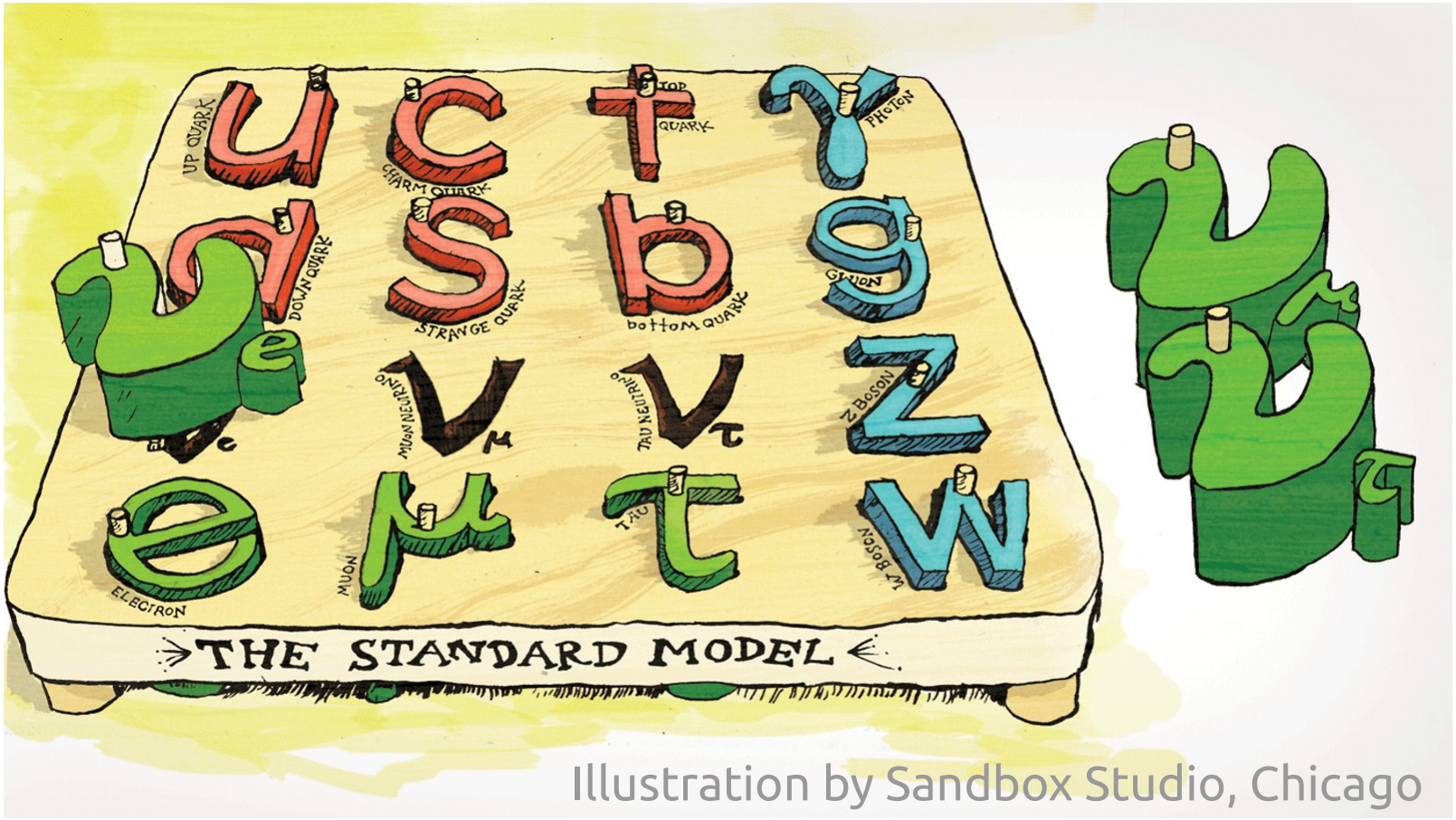


Illustration by Sandbox Studio, Chicago

“Neutrinos, the Standard Model misfits”

Neutrinos – what do we know?

- Neutrinos in the Standard Model are **massless**

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad m_\nu = 0$$

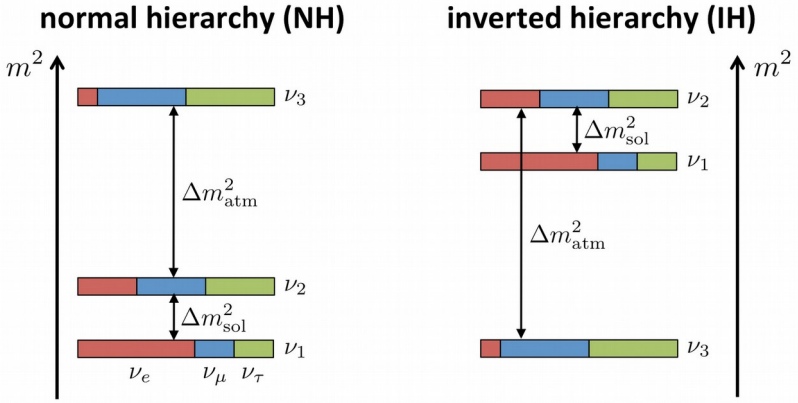
- Neutrino **mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino **oscillations** require **massive** neutrinos

$$P(\nu_i \to \nu_j) \propto \Delta m^2_{ij}$$

$$\Delta m^2_{12} \sim 7.59 \times 10^{-5}\text{eV}^2$$
$$\Delta m^2_{23} \sim \Delta m^2_{31} \sim 2.3 \times 10^{-3}\text{eV}^2$$



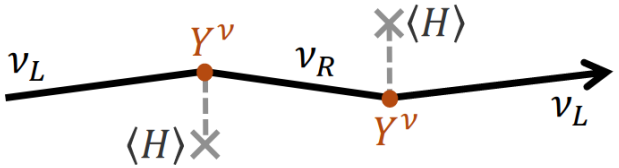
- **Normal** vs. **inverted** hierarchy

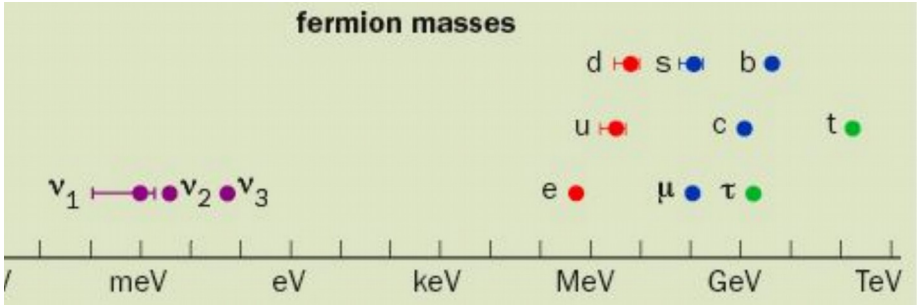
What generates the neutrino mass?

Neutrinos – how do they get their mass?

Dirac

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi = M_D^{ij} \nu_i N_j$$



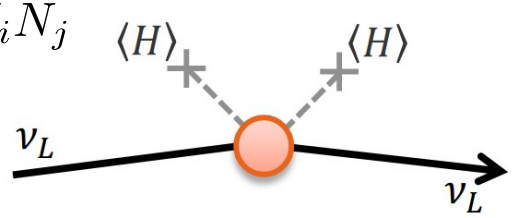


$$Y_t / Y_\nu \sim 10^{12-15}$$

"*unnaturally*" small neutrino masses

Majorana

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi + M^{ij} N_i N_j$$
$$= M_D^{ij} \nu_i N_j + M_M^{ij} N_i N_j$$



$$\mathrm{M}_\nu = \begin{pmatrix} \delta m_\nu^{1loop} & M_D \\ M_D^T & M_M \end{pmatrix}$$

$$\mathrm{m}_\nu \sim M_D^T M_M^{-1} M_D \sim v^2 Y M_M^{-1} Y^T$$

$\nu \simeq \nu_L + \theta v_R^c$ mainly **active** SU(2)$_L$ doublet states with **light** masses

$\mathrm{m}_N \sim M_M$

$N \simeq \nu_R + \theta^T v_L^c$ mainly **sterile** singlet states with **heavy** masses

Seesaw type I

"*naturally*" small neutrino masses

How can one test if neutrinos have a Majorana or Dirac nature?

A Brief History of Neutrinoless Double Beta Decay

WORLD RENOWNED—Dr. Maria Goeppert Mayer, 57, holds the slide rule she uses in the study of nuclear physics that won her a Nobel Prize today. She is a University of California professor here.

S.D. Mother Wins Nobel Physics Prize

Dr. Mayer 1st Woman in U.S., 2nd in History So Honored

By FRANK HOGAN

Dr. Maria Goeppert Mayer, 57, a research physicist at the University of California here, today was named 1963 Nobel Prize winner in physics.

The red-haired college professor, mother of two, is the first woman residing in America to win a Nobel

A Brief History of Neutrinoless Double Beta Decay

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLU

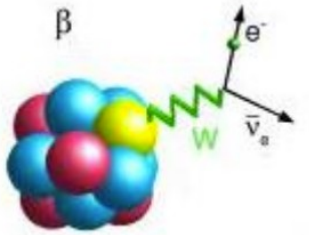
Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

Single beta decay



$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

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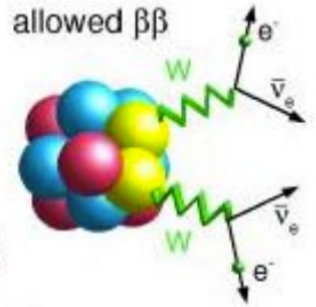
Double beta decay



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

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DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

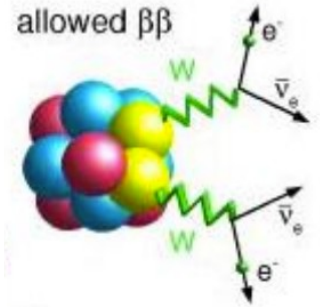
On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

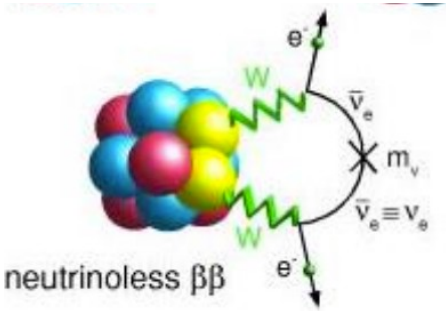
The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1,0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

Double beta decay



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

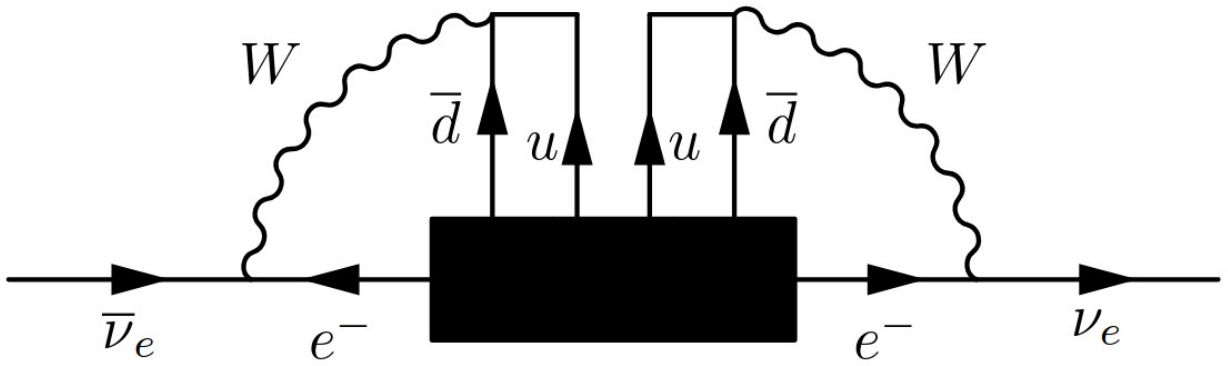
Neutrinoless double beta decay



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

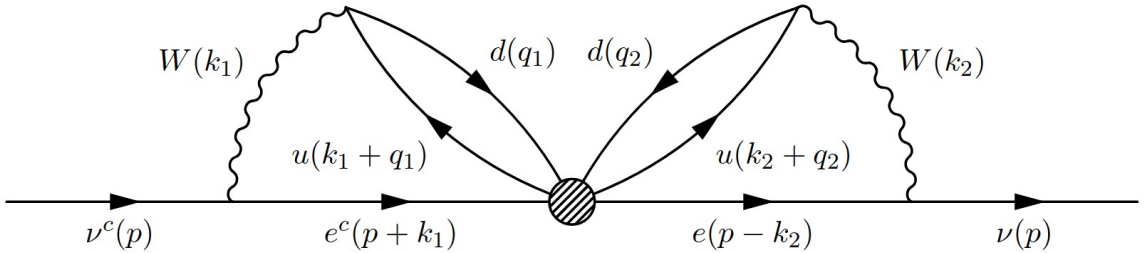
Lepton Number violating (LNV) ΔL = 2

Schechter-Valle Theorem – Black Box Theorem



Schechter, Valle (1982)

Any ΔL = 2 operator that leads to 0vbb will induce a **Majorana mass contribution** via loop



9-dim ΔL = 2 operator will lead to 0vbb but only **tiny contribution** to neutrino mass

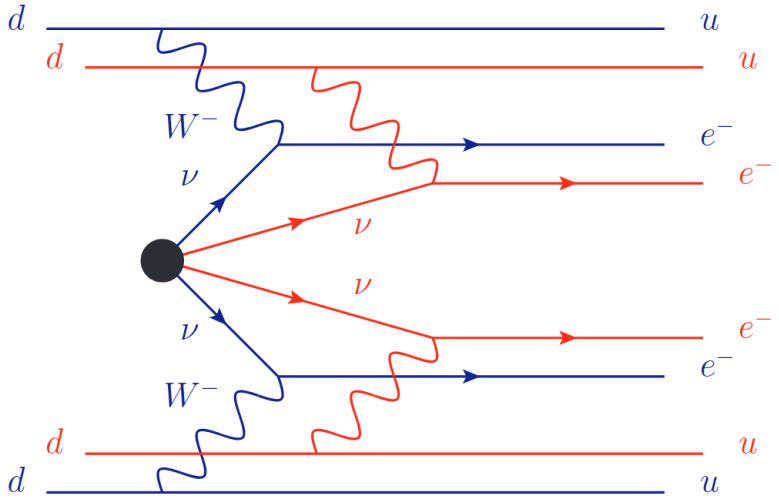
$$\delta m_\nu = 10^{-28}\text{eV}$$

Dürr, Merle, Lindner (2011)

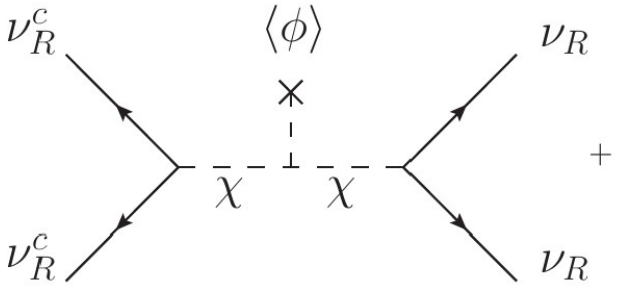
Is LNV only possible with Majorana particles?

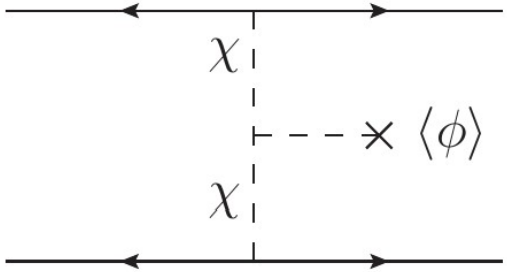
Neutrinoless Quadruple Decay

$$(A, Z) \to (A, Z+4) + 4e^-$$



$$\Delta(B-L) = 4$$





$$\frac{\tau_{1/2}^{0\nu4\beta}}{\tau_{1/2}^{2\nu2\beta}} \simeq \left(\frac{Q_{0\nu2\beta}}{Q_{0\nu4\beta}}\right)^{11} \left(\frac{\Lambda^4}{q^{12} G_F^4}\right) \simeq 10^{46} \left(\frac{\Lambda}{\text{TeV}}\right)^4$$

pessimistic estimate – light mediators, resonances…

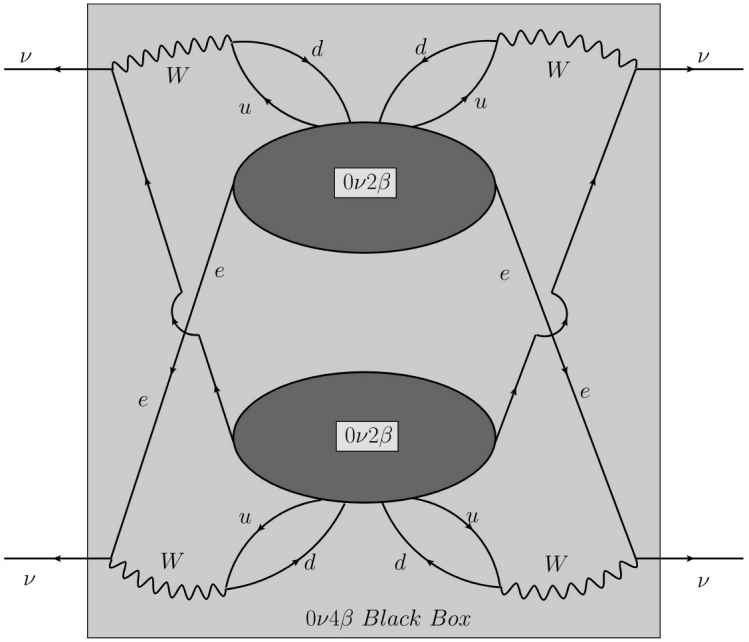
Majorana Neutrinos are **not** generally a pre-requisite for LNV

NO!

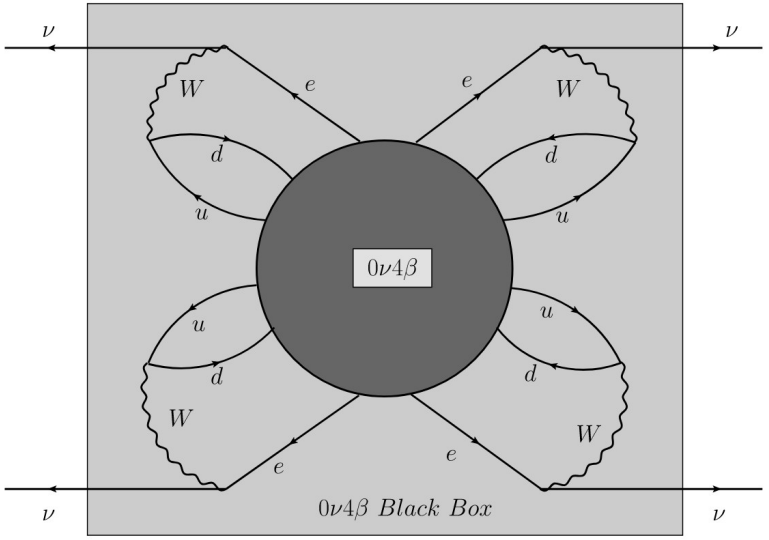
LNV with **Dirac neutrinos** @ Neutrinoless Quadruple Decay! **(ΔL = 4)**

Heeck, Rodejohann (2013)

Can one ever prove neutrinos are Dirac?



$$R = \frac{\Gamma_{0\nu2\beta}}{\Gamma_{0\nu4\beta}}$$



$$R = \frac{Q_{\beta\beta}^{5}(\frac{1}{\Lambda^5})^2 q^6}{Q_{4\beta}^{11}(\frac{1}{\Lambda^{14}})^2 q^{18}} \sim 10^{82}$$

Should a **0v4β decay** signal ever be established, **unaccompanied by 0v2β** decays, then one would **rule out Majorana neutrinos**

Caveats may exist?

Hirsch, Srivastava, Valle (2018)

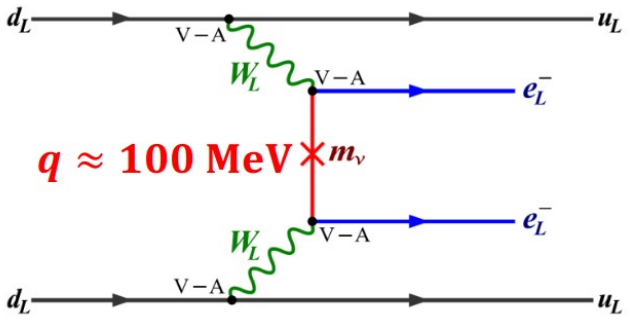
Half life of Neutrinoless Double Beta Decay

$$T_{1/2}^{-1} = \mid m_{\beta\beta} \mid^2 G^{0\nu} \mid M^{0\nu} \mid^2$$

particle physics

atomic physics

nuclear physics



$$A_{\mu\nu}^{\text{lep}} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu(1+\gamma_5)\frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5)$$

$$\approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \qquad m_{\beta\beta}$$

Most stringent limits are currently set by GERDA and Kamland-Zen:

$$T_{1/2}^{\text{Ge}} \geq 8.0 \times 10^{25}\ \text{y} \qquad T_{1/2}^{\text{Xe}} \geq 1.07 \times 10^{26}\ \text{y}$$

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

Experiment	Iso.	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]
LEGEND 200 [60, 61]	^{76}Ge	$8.4 \cdot 10^{26}$	40–73
LEGEND 1k [60, 61]	^{76}Ge	$4.5 \cdot 10^{27}$	17–31
SuperNEMO [67, 68]	^{82}Se	$6.1 \cdot 10^{25}$	82–138
CUPID [57, 58, 69]	^{82}Se	$1.8 \cdot 10^{27}$	15–25
CUORE [51, 52]	^{130}Te	$5.4 \cdot 10^{25}$	66–164
CUPID [57, 58, 69]	^{130}Te	$2.1 \cdot 10^{27}$	11–26
SNO+ Phase I [65, 70]	^{130}Te	$1.1 \cdot 10^{26}$	46–115
SNO+ Phase II [66]	^{130}Te	$4.8 \cdot 10^{26}$	22–54
KamLAND-Zen 800 [59]	^{136}Xe	$1.6 \cdot 10^{26}$	47–108
KamLAND2-Zen [59]	^{136}Xe	$8.0 \cdot 10^{26}$	21–49
nEXO [71]	^{136}Xe	$4.1 \cdot 10^{27}$	9–22
NEXT 100 [63, 72]	^{136}Xe	$5.3 \cdot 10^{25}$	82–189
PandaX-III 200 [64]	^{136}Xe	$8.3 \cdot 10^{25}$	65–150
PandaX-III 1k [64]	^{136}Xe	$9.0 \cdot 10^{26}$	20–46

Uncertainties of Nuclear Matrix Elements

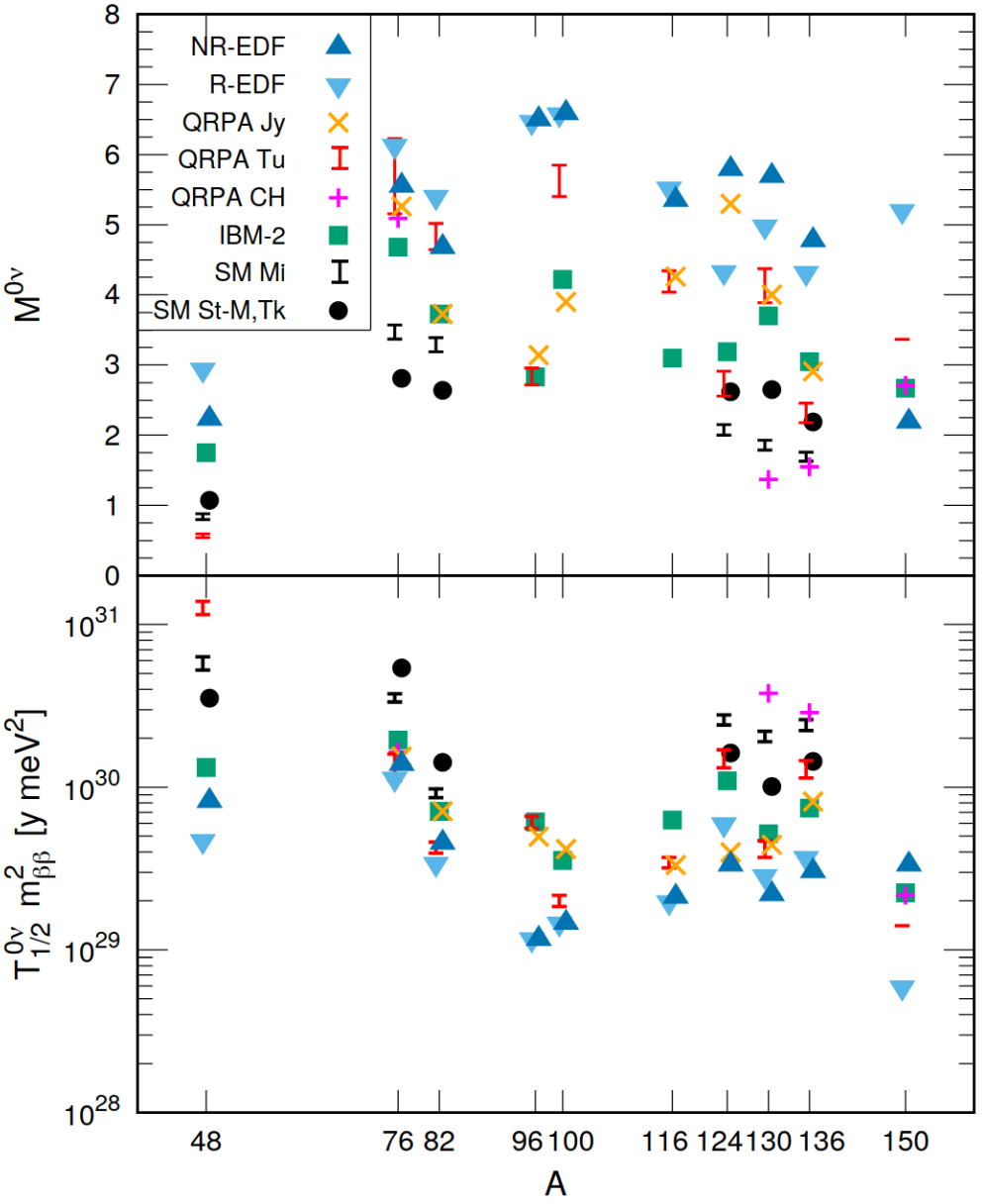
$$T_{1/2}^{-1} = \mid m_{\beta\beta} \mid^2 G^{0\nu} \mid M^{0\nu} \mid^2$$

nuclear physics

- **Dependence** on isotope and specific operator
- Differences between different **nuclear models**
- "**the g_A problem**" quenching of the axial-vector coupling?

$$\mathcal{M} = \mathcal{M}_{GT} - \frac{g_V^2}{g_A^2}\mathcal{M}_F + \mathcal{M}_T$$

→ **More details:**
Next talk by Jouni Suhonen



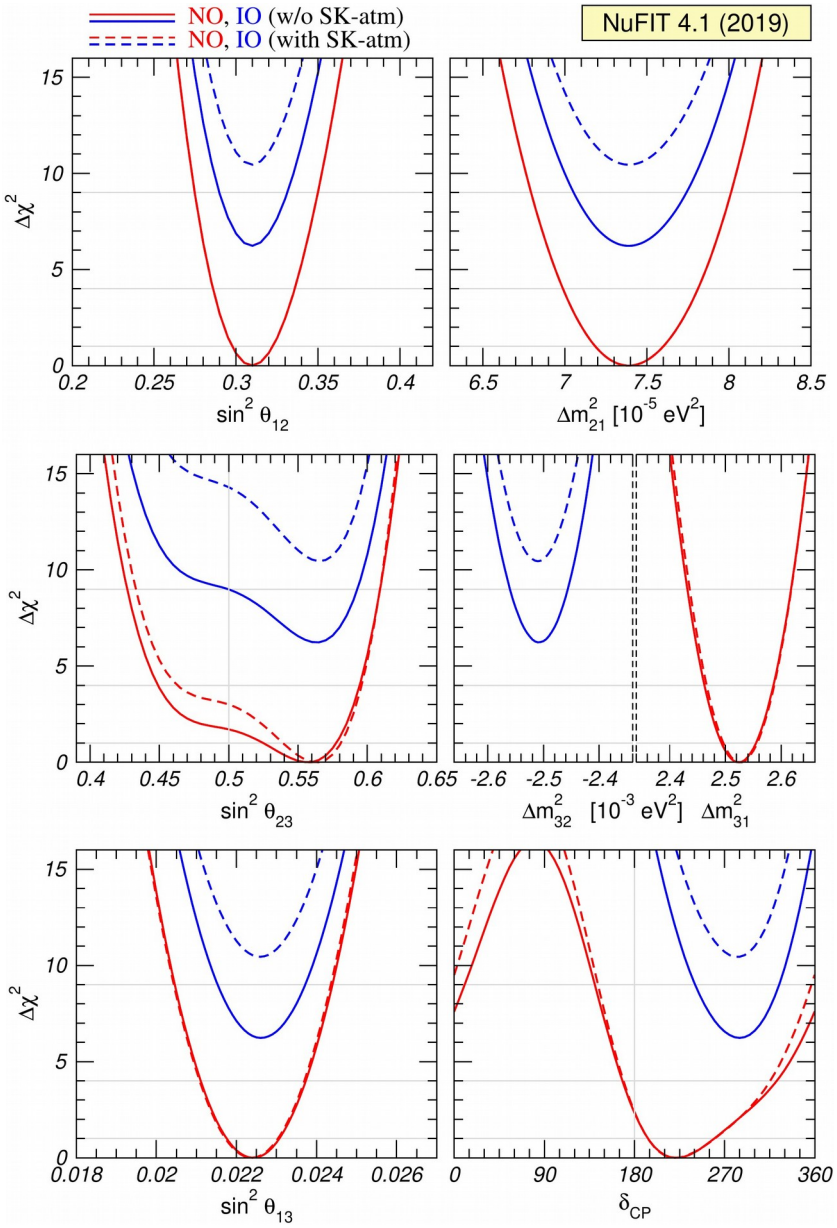
Engel, Menendez (2016)

Neutrino Oscillations & 0νββ

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$\|\nu_\alpha\rangle$	flavour eigenstates
$\|\nu_i\rangle$	mass eigenstates
$U_{\alpha i}$	Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

- **Solar experiments**
  Homestake, Chlorine, Gallex/GNO, SAGE, (Super) Kamiokande, SNO, Borexino
- **Atmospheric experiments**
  IceCube, ANTARES, DeepCore, Super-Kamiokande
- **Reactor experiments**
  KamLAND, Double Chooz, Daya Bay
- **Accelerator experiments**
  T2K, MINOS, NOvA

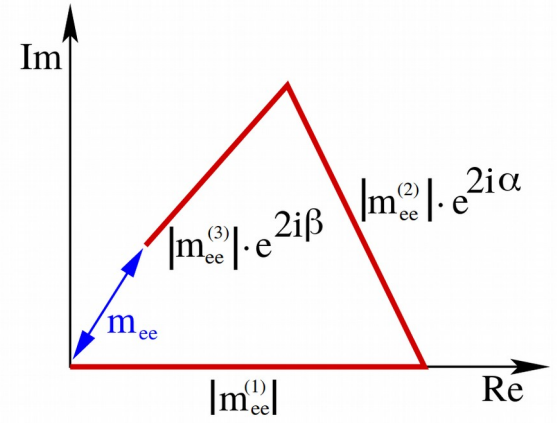


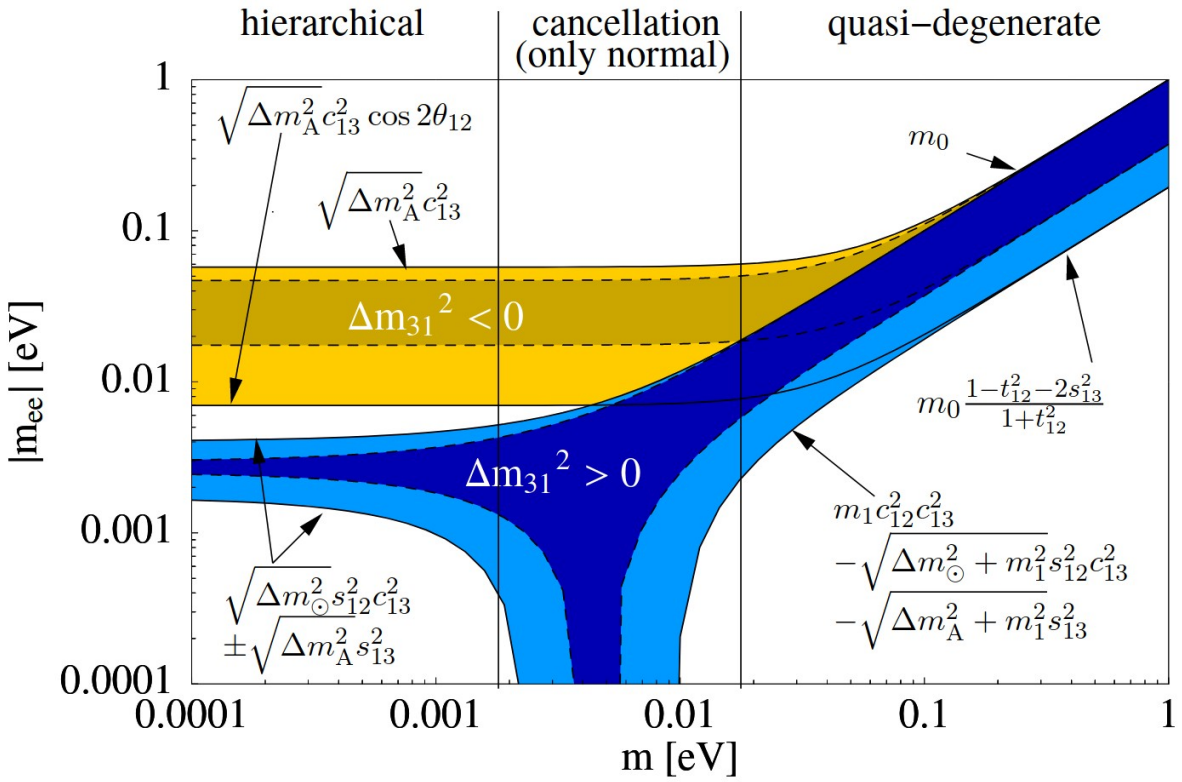
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Oscillations & 0νββ

$$\langle m_{ee} \rangle = \left| c_{12}^2 c_{13}^2 \, m_1 + s_{12}^2 c_{13}^2 \, m_2 \, e^{2i\phi_{12}} + s_{13}^2 \, m_3 \, e^{2i\phi_{13}} \right|$$

- Uncertainty from **unknown Majorana phase**
- **Quasi-degenerate** region above 0.2 eV
- Accidental **cancellation** for NO

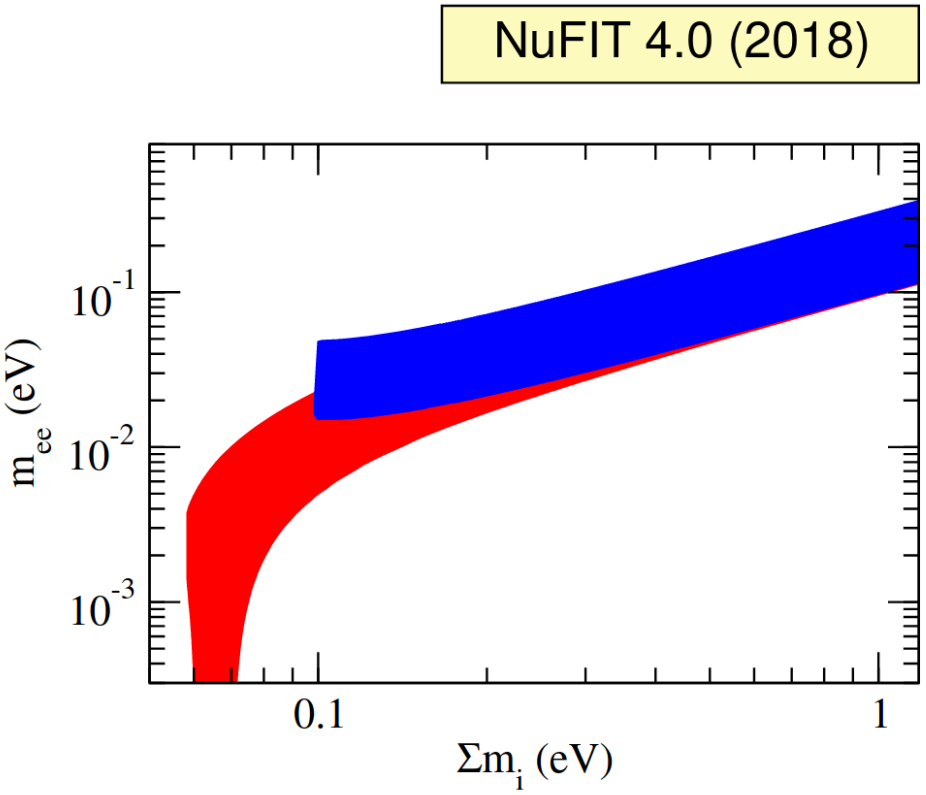




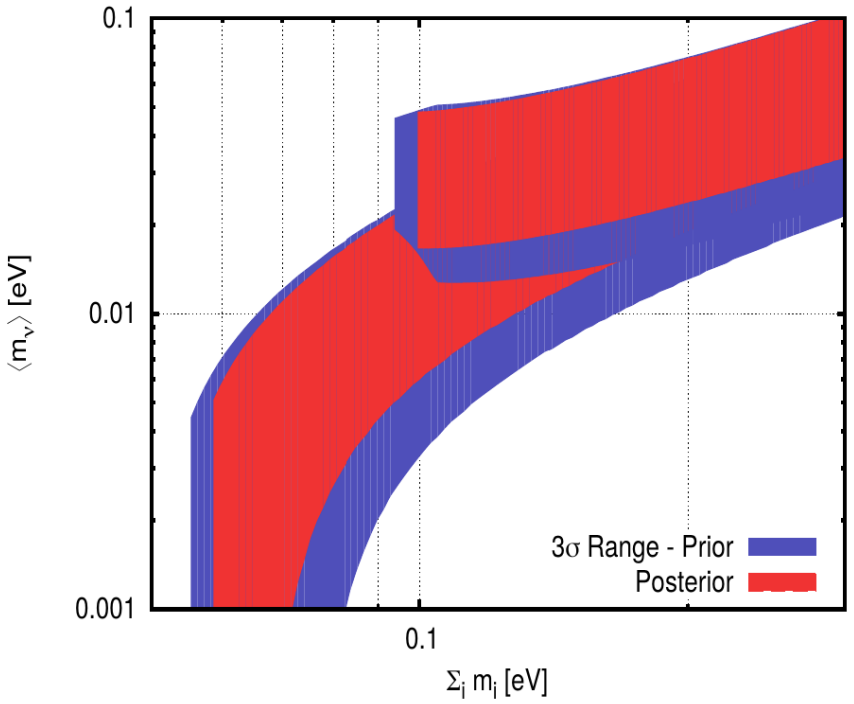
Lindner, Merle, Rodejohann (2006)

Neutrino Oscillations & 0νββ

Latest combined fit



Future projection with JUNO



$$\langle m_\nu \rangle^{\mathrm{IO}}_{\mathrm{min}} \rightarrow \sqrt{\Delta m^2_a}(c_s^2 - s_s^2)c_r^2$$

JUNO can determine **minimal value** of the effective mass with **almost no uncertainty** → fixes the half life that needs to be addressed

Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz (2018+)
Anamiati, Romeri, Hirsch, Ternes, Tortola (2019+)
Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo (2017+)
Ge, Rodejohann (2018)

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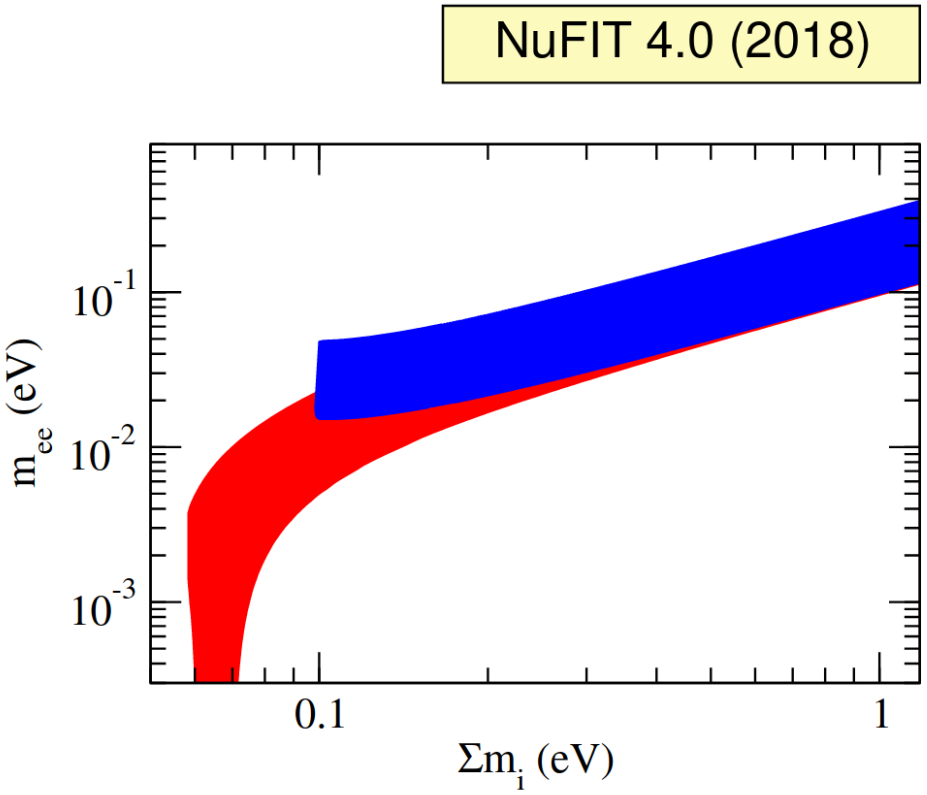

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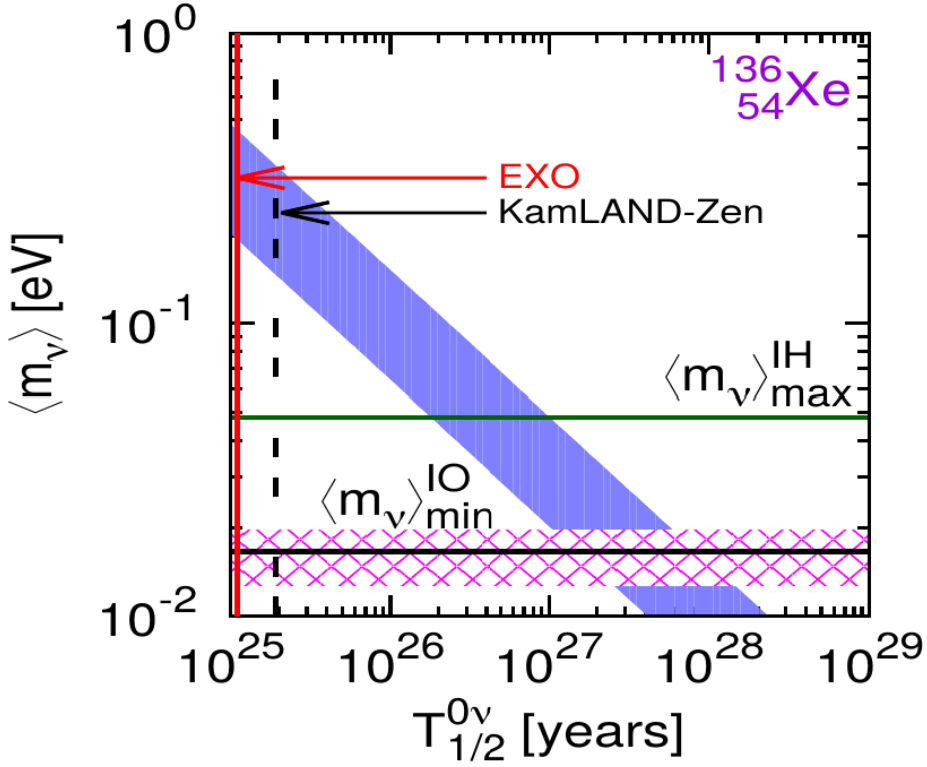

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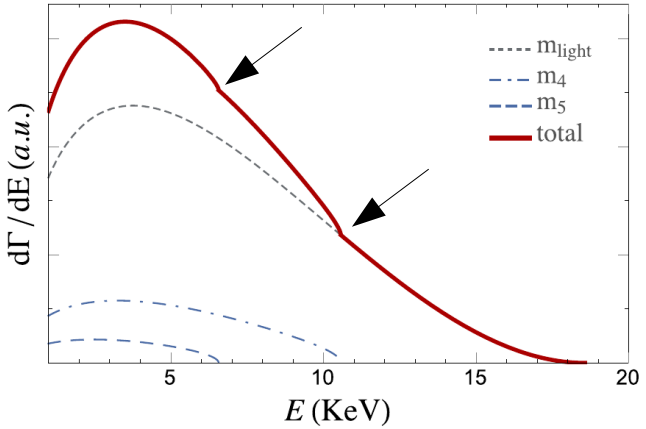
Ge, Rodejohann (2015+)

Light Sterile Neutrinos – Interplay 0νββ & KATRIN

Hypothesis: KATRIN sees a kink

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

$$m_4 \in [1\ \mathrm{KeV}, 18.5\ \mathrm{KeV}]\,, \quad |U_{e4}|^2 > 10^{-6}\,.$$



$$\frac{d\Gamma}{dE} = \Theta\left(E_0 - E - m_\beta\right)\left(1 - |U_{e4}|^2\right)\frac{d\Gamma}{dE}\left(m_\beta\right) + \Theta\left(E_0 - E - m_4\right)|U_{e4}|^2\,\frac{d\Gamma}{dE}\left(m_4\right)$$

Assumption: 3 active + 1 sterile neutrino:

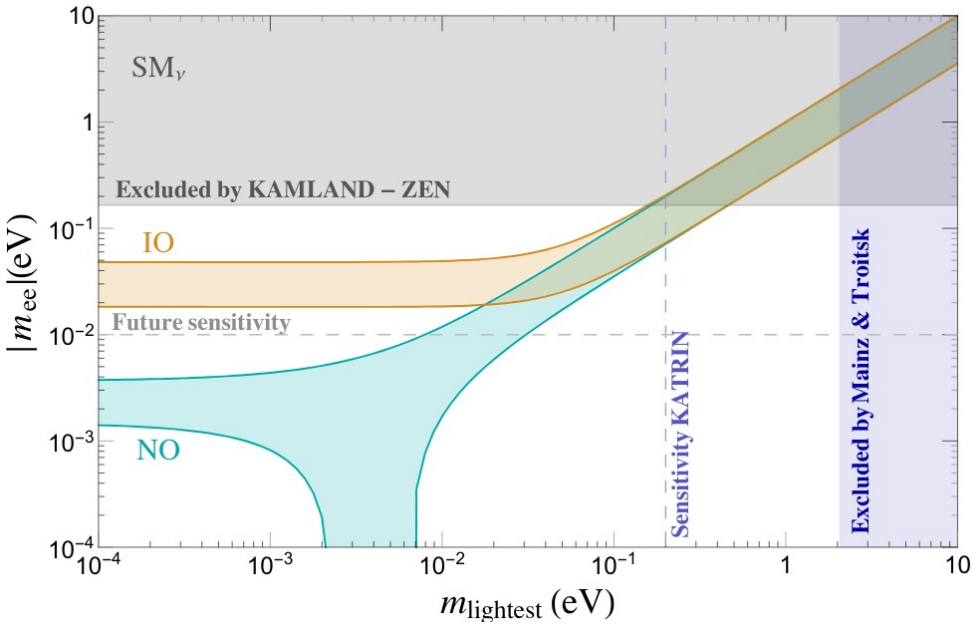
$$-\mathcal{L}_{\mathrm{cc}} = \frac{g}{\sqrt{2}} U_{ji}\bar{\ell}_j\gamma^\mu P_L\nu_i W_\mu^- + \mathrm{H.c.}$$

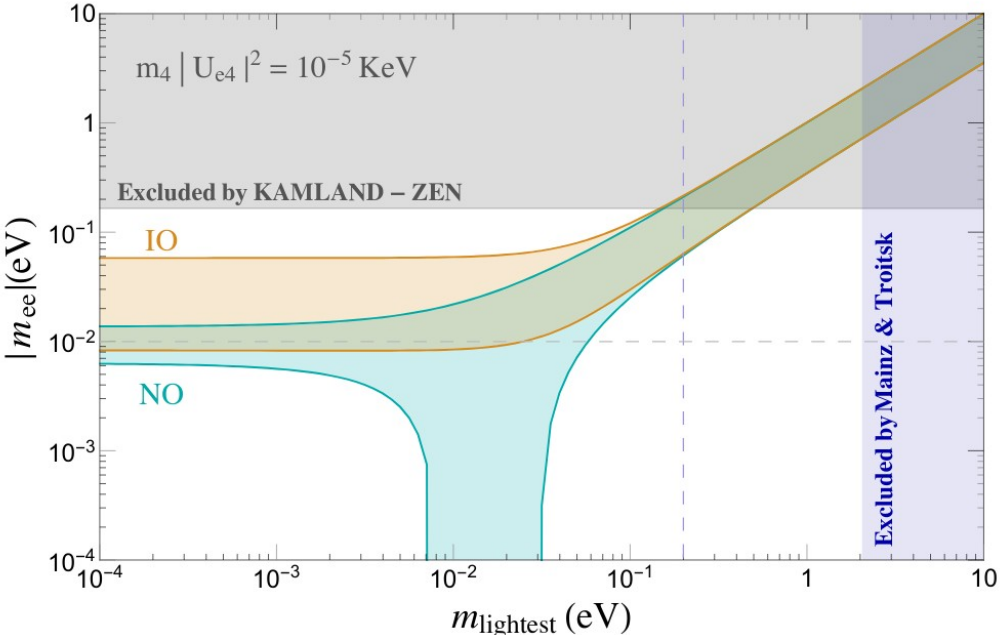
Impact on neutrinoless double beta decay:

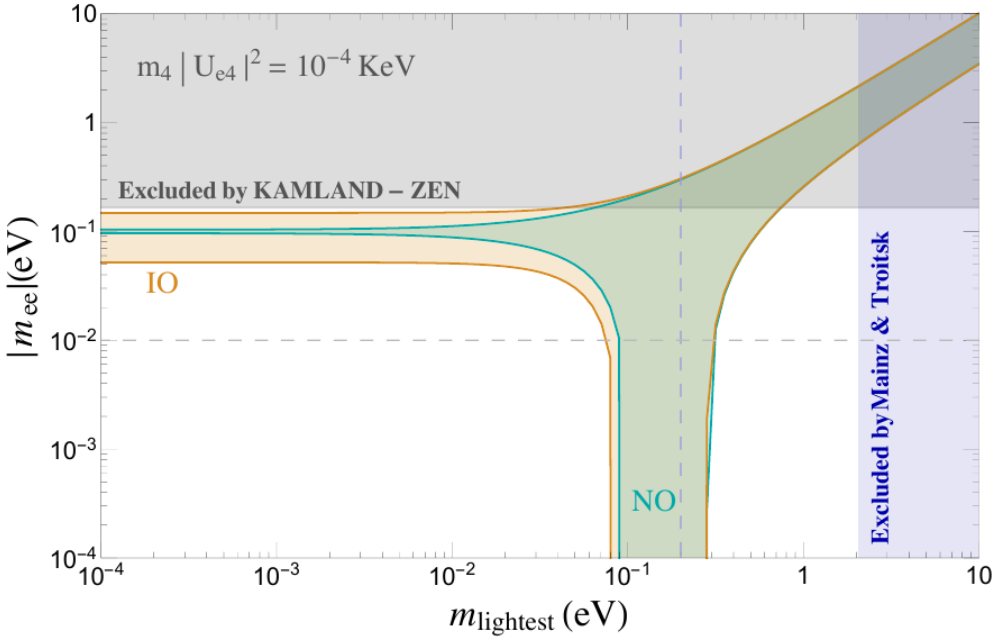
$$m_{ee}^{(3+1)} = \sum_{i=1}^{4} U_{ei}^2\, p^2 \frac{m_i}{p^2 - m_i^2} \simeq \sum_{i=1}^{4} U_{ei}^2\, m_i \equiv m_{ee}^{(\mathrm{SM}_\nu)} + m_4 U_{e4}^2$$

Abada, Hernandez-Cabezudo, Marcano (2019)

Light Sterile Neutrinos – Interplay 0νββ & KATRIN







- possible kink @ KATRIN would imply that IO and NO might **not be distinguishable** anymore with 0νββ
- **Observation** of 0νββ would not necessarily imply IO
- **Non-observation** would not rule out IO due to cancellations for large enough $m_4 U^2_{e4}$

Abada, Hernandez-Cabezudo, Marcano (2019)

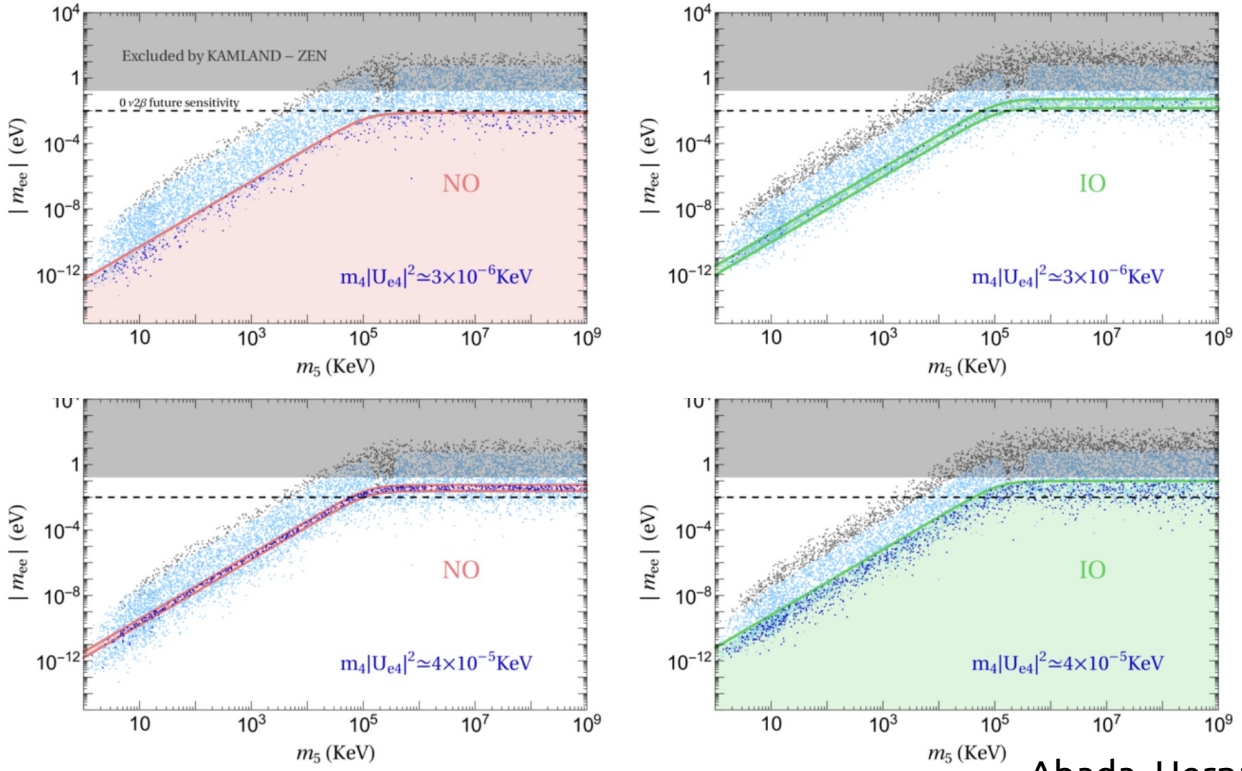
Light Sterile Neutrinos – Interplay 0νββ & KATRIN

Assumption: 3 active + 2 sterile neutrinos (See saw type-I):

$$m_{ee} = \sum_{i=1}^{5} U_{ei}^2\, p^2 \frac{m_i}{p^2 - m_i^2} \simeq m_{ee}^{(3+1)} + U_{e5}^2\, m_5 \frac{p^2}{p^2 - m_5^2}$$

1st sterile neutrino in KATRIN reach, 2nd variable

$$m_{ee} \simeq m_{ee}^{(3+1)} \times \left[1 - \frac{p^2}{p^2 - m_5^2}\right]$$



Abada, Hernandez-Cabezudo, Marcano (2019)

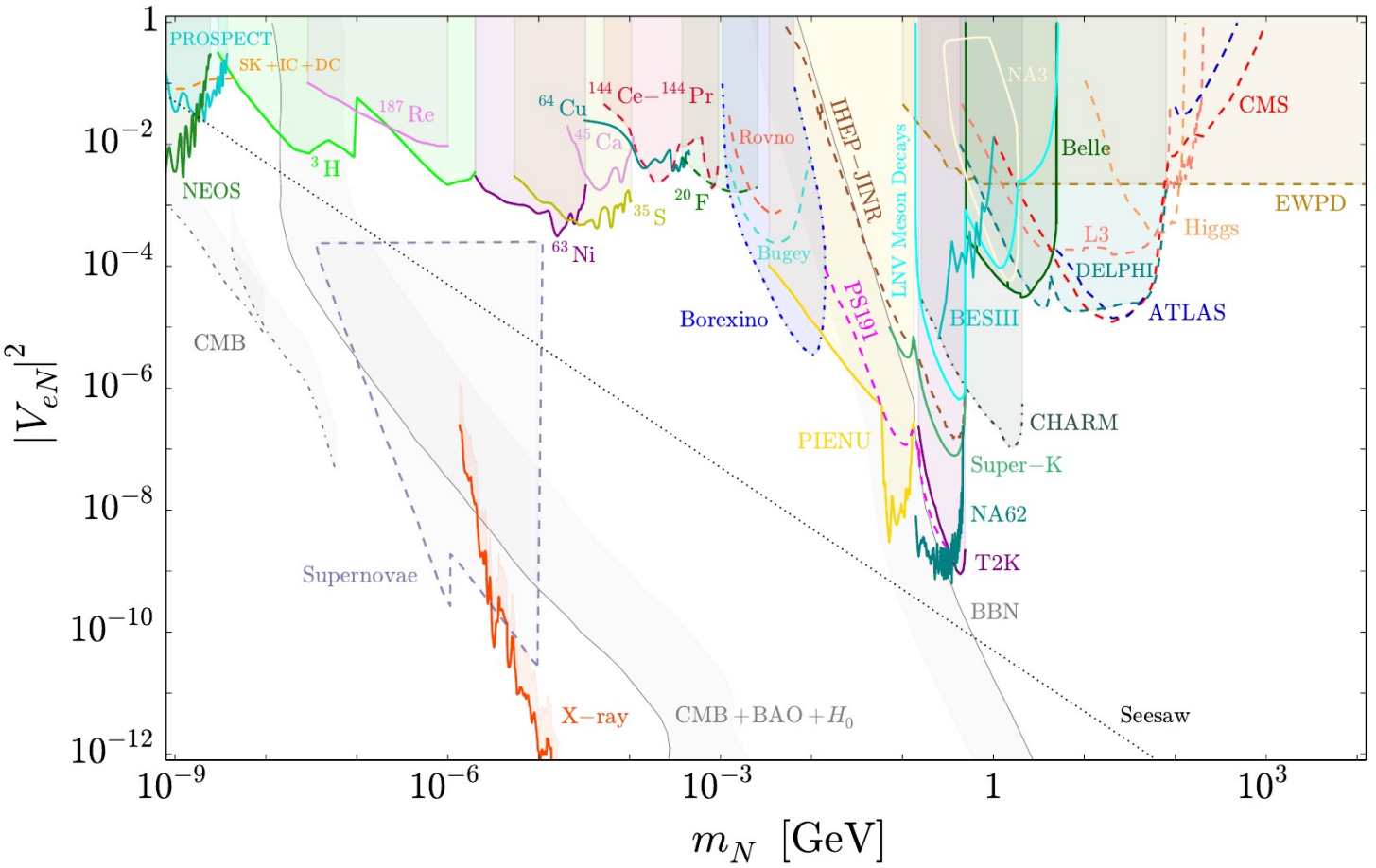
Interesting interplay between KATRIN & 0νbb prospects

Isotope dependent cancellation between two **different** exchange mechanisms (two different NMEs)

Pascoli, Mitra, Wong (2014)

Heavy Sterile Neutrinos

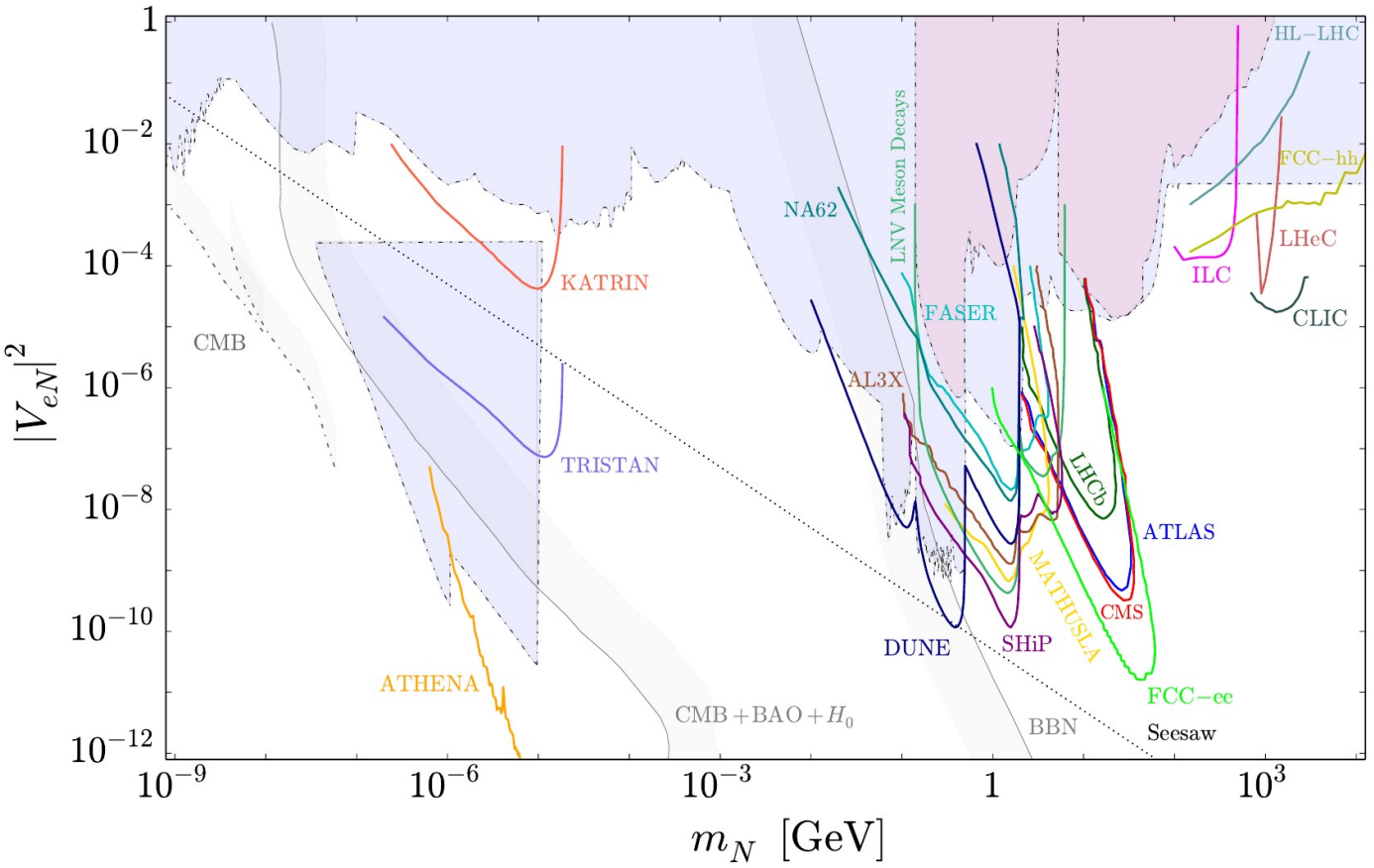
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}^{0\nu}_N|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



Bolton, Deppisch, Dev (2019)
Atre, Han, Pascoli, Zhang (2009)

Heavy Sterile Neutrinos

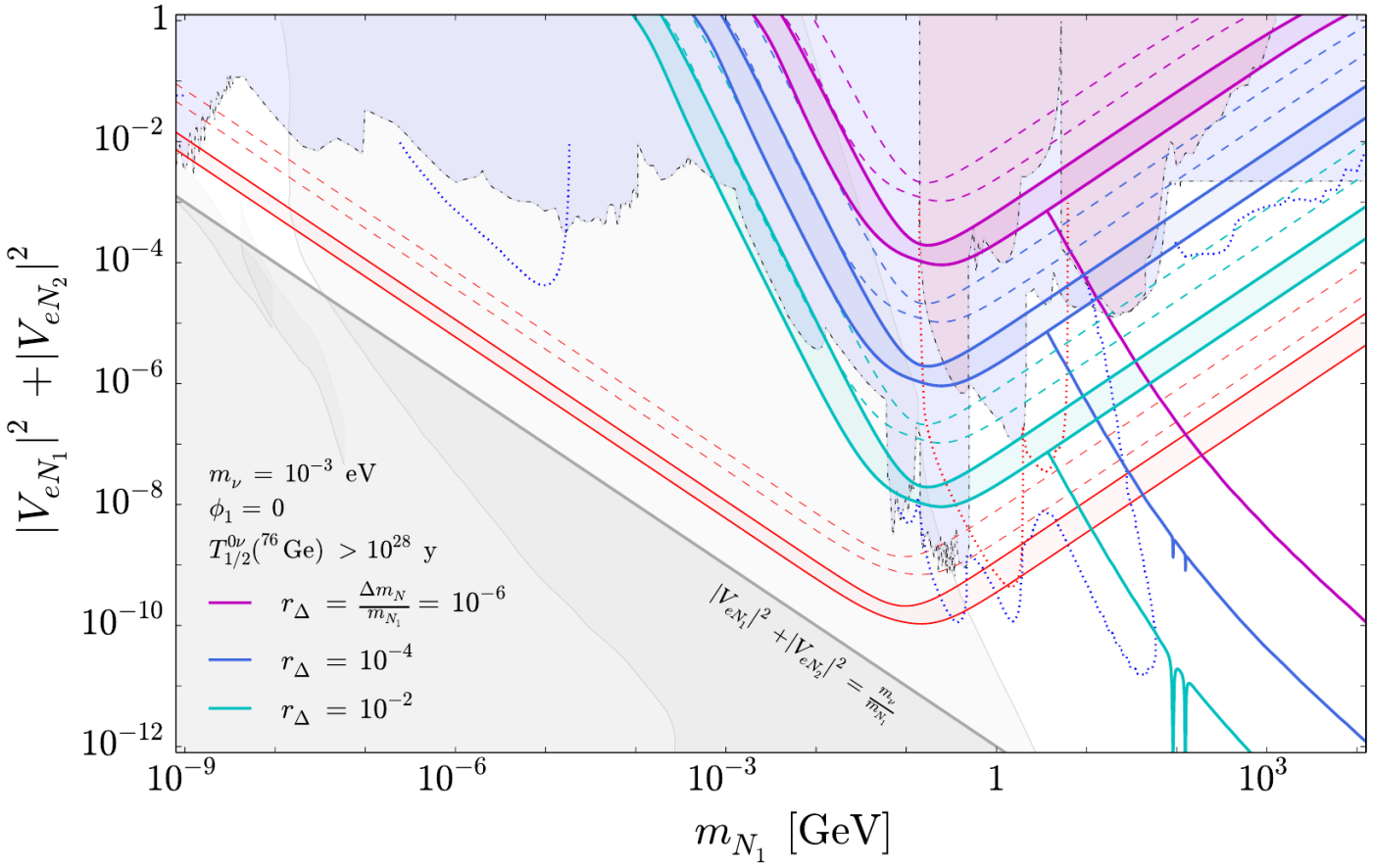
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}^{0\nu}_N|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



Bolton, Deppisch, Dev (2019)

Heavy Sterile Neutrinos

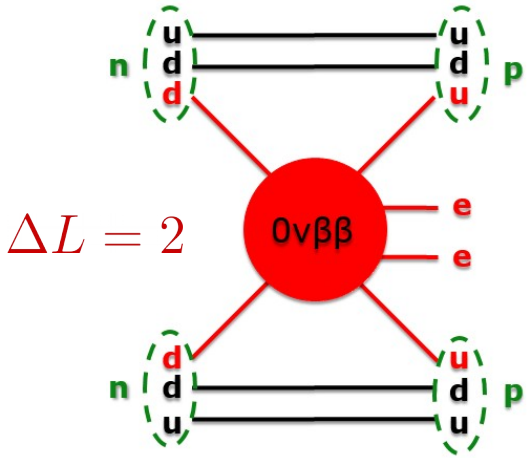
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}^{0\nu}_N|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



Δr → 0 leads to **pseudo-Dirac limit** where lepton number is approximately conserved and 0νββ forbidden

Bolton, Deppisch, Dev (2019)

Non-standard contributions



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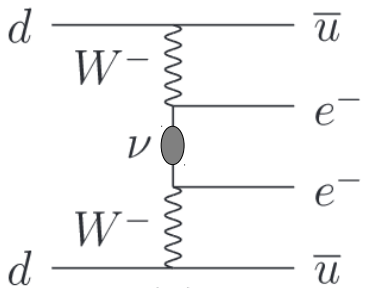
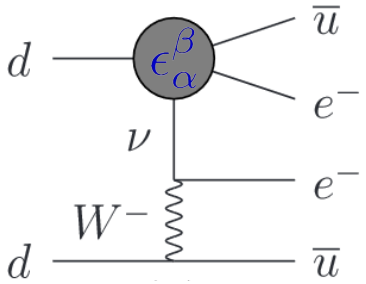
standard mass mechanism



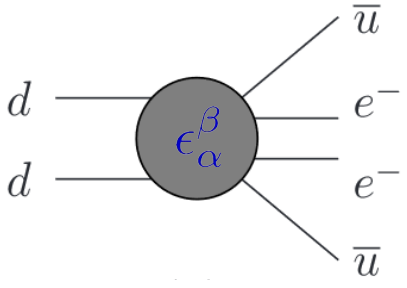
$\mathcal{O}_5$

long range contribution



$\mathcal{O}_7$

short range contribution



$\mathcal{O}_9$

All ΔL=2 LNV operators contribute to 0vbb

The inverse half life can be expressed in terms of effective couplings:

$$T_{1/2}^{-1} = G_{0\nu} \mid \mathcal{M} \mid^2 \mid m_{\beta\beta} \mid^2$$

$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$

Non-standard contributions

$\mathcal{O}$	Operator
1	$L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$
2	$L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$
3_a	$L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}$
3_b	$L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}$
5	$L^i L^j Q^k d^c H^l H^m \overline{H}_i \epsilon_{jl}\epsilon_{km}$
6	$L^i L^j \overline{Q}_k \bar{u}^c H^l H^k \overline{H}_i \epsilon_{jl}$
7	$L^i Q^j \bar{e}^c \overline{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm}$
8	$L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$
9	$L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}$
10	$L^i L^j L^k e^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$
11_a	$L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$
11_b	$L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$
12_a	$L^i L^j \overline{Q}_i \bar{u}^c \overline{Q}_j \bar{u}^c$
12_b	$L^i L^j \overline{Q}_k \bar{u}^c \overline{Q}_i \bar{u}^c \epsilon_{ij}\epsilon^{kl}$
13	$L^i L^j \overline{Q}_i \bar{u}^c L^l e^c \epsilon_{jl}$
14_a	$L^i L^j \overline{Q}_k \bar{u}^c Q^k d^c \epsilon_{ij}$
14_b	$L^i L^j \overline{Q}_i \bar{u}^c Q^l d^c \epsilon_{jl}$
15	$L^i L^j L^k d^c \overline{L}_i \bar{u}^c \epsilon_{jk}$
16	$L^i L^j e^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}$
17	$L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij}$
18	$L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij}$
19	$L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}$
20	$L^i d^c \overline{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c$
21_a	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$
21_b	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$
22	$L^i L^j L^k e^c \overline{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
23	$L^i L^j L^k e^c \overline{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
24_a	$L^i L^j Q^k d^c Q^l d^c H^m \overline{H}_i \epsilon_{jk}\epsilon_{lm}$
24_b	$L^i L^j Q^k d^c Q^l d^c H^m \overline{H}_i \epsilon_{jm}\epsilon_{kl}$
25	$L^i L^j Q^k d^c Q^l u^c H^m H^n \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$
26_a	$L^i L^j Q^k d^c \overline{L}_l \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km}$
26_b	$L^i L^j Q^k d^c \overline{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
27_a	$L^i L^j Q^k d^c \overline{Q}_l \bar{d}^c H^l H^m \epsilon_{jl}\epsilon_{km}$
27_b	$L^i L^j Q^k d^c \overline{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
28_a	$L^i L^j Q^k d^c \overline{Q}_j \bar{u}^c H^l \overline{H}_i \epsilon_{kl}$
28_b	$L^i L^j Q^k d^c \overline{Q}_k \bar{u}^c H^l \overline{H}_i \epsilon_{jl}$
28_c	$L^i L^j Q^k d^c \overline{Q}_l \bar{u}^c H^l \overline{H}_i \epsilon_{jk}$
29_a	$L^i L^j Q^k u^c \overline{Q}_k \bar{u}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
29_b	$L^i L^j Q^k u^c \overline{Q}_l \bar{u}^c H^l H^m \epsilon_{ik}\epsilon_{jm}$
30_a	$L^i L^j \overline{L}_l e^c \overline{Q}_k \bar{u}^c H^k H^l \epsilon_{jl}$
30_b	$L^i L^j \overline{L}_m e^c \overline{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
31_a	$L^i L^j \overline{Q}_l d^c \overline{Q}_k \bar{u}^c H^k H^l \epsilon_{jl}$

$\mathcal{O}$	Operator
31_b	$L^i L^j \overline{Q}_m d^c \overline{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
32_a	$L^i L^j \overline{Q}_j \bar{u}^c \overline{Q}_k \bar{u}^c H^k \overline{H}_i$
32_b	$L^i L^j \overline{Q}_m \bar{u}^c \overline{Q}_n \bar{u}^c H^k \overline{H}_i \epsilon_{jk}\epsilon^{mn}$
33	$\bar{e}^c \bar{e}^c L^i L^j e^c e^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
34	$\bar{e}^c \bar{e}^c L^i Q^j e^c d^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
35	$\bar{e}^c \bar{e}^c L^i e^c \overline{Q}_j \bar{u}^c H^j H^k \epsilon_{ik}$
36	$\bar{e}^c \bar{e}^c Q^i d^c Q^j d^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
37	$\bar{e}^c \bar{e}^c Q^i d^c \overline{Q}_j \bar{u}^c H^j H^k \epsilon_{ik}$
38	$\bar{e}^c \bar{e}^c \overline{Q}_i \bar{u}^c \overline{Q}_j \bar{u}^c H^i H^j$
39_a	$L^i L^j L^k L^l \overline{L}_i \overline{L}_j H^m H^n \epsilon_{km}\epsilon_{ln}{}^\dagger$
39_b	$L^i L^j L^k L^l \overline{L}_m \overline{L}_n H^m H^n \epsilon_{ij}\epsilon_{kl}$
39_c	$L^i L^j L^k L^l \overline{L}_i \overline{L}_m H^m H^n \epsilon_{jk}\epsilon_{ln}$
39_d	$L^i L^j L^k L^l \overline{L}_p \overline{L}_q H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
40_a	$L^i L^j L^k Q^l \overline{L}_i \overline{Q}_j H^m H^n \epsilon_{km}\epsilon_{ln}$
40_b	$L^i L^j L^k Q^l \overline{L}_i \overline{Q}_l H^m H^n \epsilon_{jm}\epsilon_{kn}$
40_c	$L^i L^j L^k Q^l \overline{L}_l \overline{Q}_i H^m H^n \epsilon_{jm}\epsilon_{kn}$
40_d	$L^i L^j L^k Q^l \overline{L}_i \overline{Q}_m H^m H^n \epsilon_{jk}\epsilon_{ln}$
40_e	$L^i L^j L^k Q^l \overline{L}_i \overline{Q}_m H^m H^n \epsilon_{jl}\epsilon_{kn}$
40_f	$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_i H^m H^n \epsilon_{jk}\epsilon_{ln}$
40_g	$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_i H^m H^n \epsilon_{jl}\epsilon_{kn}$
40_h	$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^m H^n \epsilon_{ij}\epsilon_{kl}$
40_i	$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^p H^q \epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn}$
40_j	$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^p H^q \epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}$
41_a	$L^i L^j L^k d^c \overline{L}_i \bar{d}^c H^l H^m \epsilon_{jl}\epsilon_{km}$
41_b	$L^i L^j L^k d^c \overline{L}_l \bar{d}^c H^l H^m \epsilon_{ij}\epsilon_{km}$
42_a	$L^i L^j L^k u^c \overline{L}_i \bar{u}^c H^l H^m \epsilon_{jl}\epsilon_{km}$
42_b	$L^i L^j L^k u^c \overline{L}_l \bar{u}^c H^l H^m \epsilon_{ij}\epsilon_{km}$
43_a	$L^i L^j L^k d^c \overline{L}_l \bar{u}^c H^l \overline{H}_i \epsilon_{jk}$
43_b	$L^i L^j L^k d^c \overline{L}_j \bar{u}^c H^l \overline{H}_i \epsilon_{kl}$
43_c	$L^i L^j L^k d^c \overline{L}_l \bar{u}^c H^m \overline{H}_n \epsilon_{ij}\epsilon_{km}\epsilon^{ln}$
44_a	$L^i L^j Q^k e^c \overline{Q}_i \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km}$
44_b	$L^i L^j Q^k e^c \overline{Q}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}$
44_c	$L^i L^j Q^k e^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ij}\epsilon_{km}$
44_d	$L^i L^j Q^k e^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ik}\epsilon_{jm}$
45	$L^i L^j e^c d^c \bar{e}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
46	$L^i L^j e^c u^c e^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
47_a	$L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_j H^m H^n \epsilon_{km}\epsilon_{ln}$

$\mathcal{O}$	Operator
47_b	$L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_k H^m H^n \epsilon_{jm}\epsilon_{ln}$
47_c	$L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_l H^m H^n \epsilon_{im}\epsilon_{jn}$
47_d	$L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_m H^m H^n \epsilon_{jk}\epsilon_{ln}$
47_e	$L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_m H^m H^n \epsilon_{jn}\epsilon_{kl}$
47_f	$L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_m H^m H^n \epsilon_{ij}\epsilon_{ln}$
47_g	$L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_m H^m H^n \epsilon_{il}\epsilon_{jn}$
47_h	$L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
47_i	$L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq}$
47_j	$L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}$
48	$L^i L^j d^c d^c \bar{d}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
49	$L^i L^j d^c u^c d^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
50	$L^i L^j d^c d^c \bar{d}^c \bar{u}^c H^k \overline{H}_i \epsilon_{jk}$
51	$L^i L^j u^c u^c \bar{u}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
52	
53	
54_a	
54_b	
54_c	
54_d	$L^i Q^j Q^k d^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ij}\epsilon_{km}$
55_a	$L^i Q^j \overline{Q}_i \overline{Q}_k \bar{e}^c \bar{u}^c H^k H^l \epsilon_{jl}$
55_b	$L^i Q^j \overline{Q}_j \overline{Q}_k \bar{e}^c \bar{u}^c H^k H^l \epsilon_{il}$
55_c	$L^i Q^j \overline{Q}_m \overline{Q}_n \bar{e}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
56	$L^i Q^j d^c d^c \bar{e}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl}$
57	$L^i d^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{d}^c H^j H^k \epsilon_{ik}$
58	$L^i u^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j H^k \epsilon_{ik}$
59	$L^i Q^j d^c d^c \bar{e}^c \bar{u}^c H^k \overline{H}_i \epsilon_{jk}$
60	$L^i d^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j \overline{H}_i$
61	$L^i L^j H^k H^l L^r e^c \overline{H}_r \epsilon_{ik}\epsilon_{jl}$
62	$L^i L^j L^k e^c H^l L^r e^c \overline{H}_r \epsilon_{ij}\epsilon_{kl}$
63_a	$L^i L^j Q^k d^c H^l L^r e^c \overline{H}_r \epsilon_{ij}\epsilon_{kl}$
63_b	$L^i L^j Q^k d^c H^l L^r e^c \overline{H}_r \epsilon_{ik}\epsilon_{jl}$
64_a	$L^i L^j \overline{Q}_i \bar{u}^c H^k L^r e^c \overline{H}_r \epsilon_{jk}$
64_b	$L^i L^j \overline{Q}_k \bar{u}^c H^k L^r e^c \overline{H}_r \epsilon_{ij}$
65	$L^i \bar{e}^c \bar{u}^c d^c H^j L^r e^c \overline{H}_r \epsilon_{ij}$
66	$L^i L^j H^k H^l \epsilon_{ik} Q^r d^c \overline{H}_r \epsilon_{jl}$
67	$L^i L^j L^k e^c H^l Q^r d^c \overline{H}_r \epsilon_{ij}\epsilon_{kl}$
68_a	$L^i L^j Q^k d^c H^l Q^r d^c \overline{H}_r \epsilon_{ij}\epsilon_{kl}$
68_b	$L^i L^j Q^k d^c H^l Q^r d^c \overline{H}_r \epsilon_{ik}\epsilon_{jl}$
69_a	$L^i L^j \overline{Q}_i u^c H^k Q^r d^c \overline{H}_r \epsilon_{jk}$
69_b	$L^i L^j \overline{Q}_k \bar{u}^c H^k Q^r d^c \overline{H}_r \epsilon_{ij}$

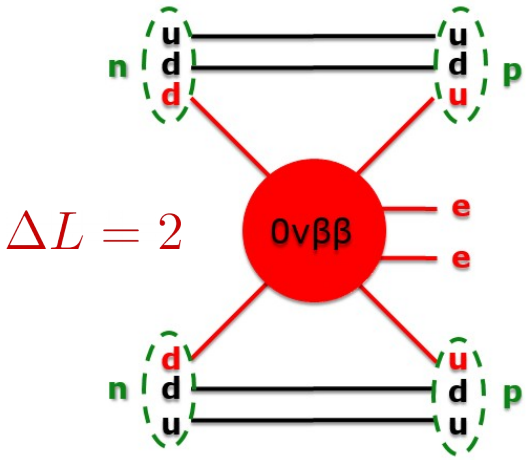
$\mathcal{O}$	Operator
70	$L^i \bar{e}^c \bar{u}^c d^c H^j Q^r d^c \overline{H}_r \epsilon_{ij}$
71	$L^i L^j H^k H^l Q^r u^c H^s \epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
72	$L^i L^j L^k e^c H^l Q^r u^c H^s \epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_a	$L^i L^j Q^k d^c H^l Q^r u^c H^s \epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_b	$L^i L^j Q^k d^c H^l Q^r u^c H^s \epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
74_a	$L^i L^j \overline{Q}_i \bar{u}^c H^k Q^r u^c H^s \epsilon_{rs}\epsilon_{jk}$
74_b	$L^i L^j \overline{Q}_k \bar{u}^c H^k Q^r u^c H^s \epsilon_{rs}\epsilon_{ij}$
75	$L^i \bar{e}^c \bar{u}^c d^c H^j Q^r u^c H^s \epsilon_{rs}\epsilon_{ij}$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_5}\mathcal{O}_5 + \sum_i \frac{1}{\Lambda_{7_i}^3}\mathcal{O}_7^i + \sum_i \frac{1}{\Lambda_{9_i}^5}\mathcal{O}_9^i + \sum_i \frac{1}{\Lambda_{11_i}^7}\mathcal{O}_{11}^i$$

Babu, Leung (2001)
Gouvea, Jenkins (2008)
Graf, JH, Deppisch, Huang (2018)

Long-range contributions to 0νββ

$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$

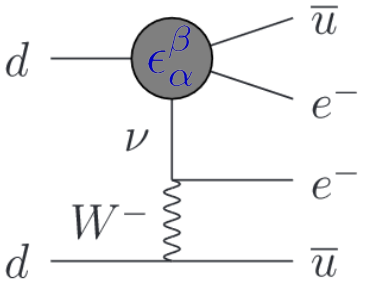


$\Delta L = 2$

?

=

long range contribution



$\mathcal{O}_7$

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{j_{V-A}^\mu J_{V-A,\mu}^\dagger + \sum_{\alpha,\beta}\epsilon_\alpha^\beta j_\beta J_\alpha^\dagger\}$$

Leptonic and hadronic current with different chirality structure:

$$j_\beta = \bar{e}\mathcal{O}_\beta\nu$$
$$J_\alpha^\dagger = \bar{u}\mathcal{O}_\alpha d$$

with

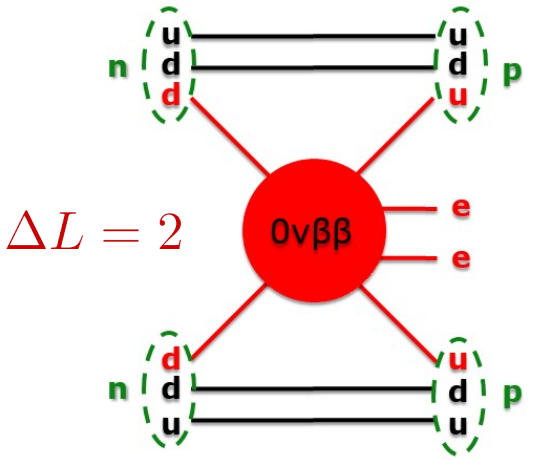
$$\mathcal{O}_{V\pm A} = \gamma^\mu(1\pm\gamma_5)$$
$$\mathcal{O}_{S\pm P} = (1\pm\gamma_5)$$
$$\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_\mu,\gamma_\nu](1\pm\gamma_5)$$

$\lvert\epsilon\rvert \times 10^8$	ϵ_ν	ϵ_{V-A}^{V+A}	ϵ_{V+A}^{V+A}	$\epsilon_{S\pm P}^{S+P}$	$\epsilon_{T_R}^{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Deppisch, Hirsch, Päs (2012)

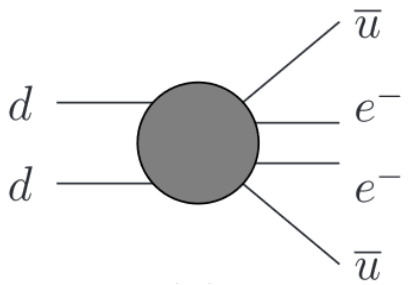
Short-range contributions to 0νββ

$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$



?

short range contribution



$\mathcal{O}_9$

$$\mathcal{L}^{\text{eff}} = \frac{G_F^2}{2} m_P^{-1} \left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu\right]$$

Leptonic and hadronic current with different chirality structure:

$$J = \bar{u}(1 \pm \gamma_5)d,\ J^\mu = \bar{u}\gamma^\mu(1 \pm \gamma_5)d,\ J^{\mu\nu} = \bar{u}\tfrac{i}{2}[\gamma^\mu, \gamma^\nu](1 \pm \gamma_5)d$$

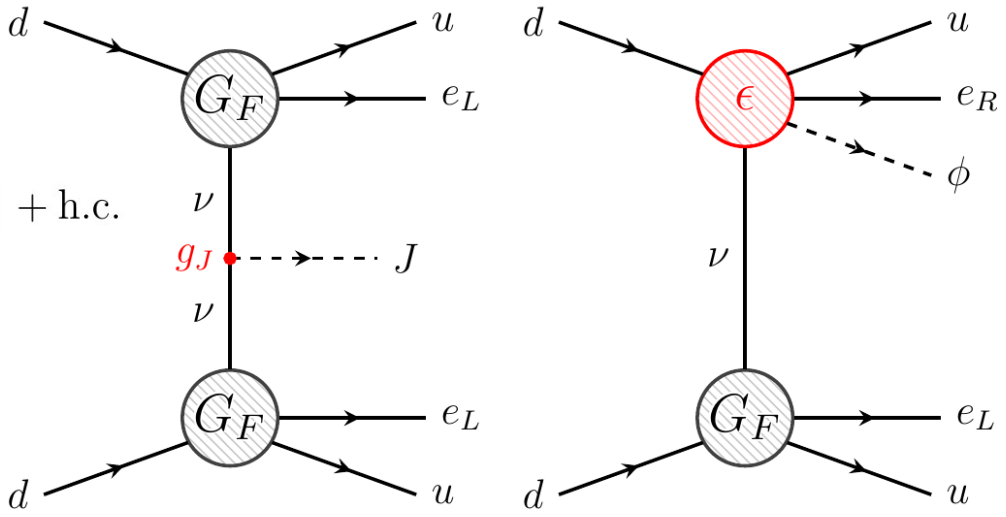
$$j = \bar{e}(1 \pm \gamma_5)e^C,\ j^\mu = \bar{e}\gamma^\mu(1 \pm \gamma_5)e^C$$

^{A}X	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz(RRz)}\rvert$	$\lvert\epsilon_3^{LRz(RLz)}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
^{76}Ge	$3.0 \cdot 10^{-7}$	$1.7 \cdot 10^{-9}$	$2.1 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$1.4 \cdot 10^{-7}$
^{136}Xe	$2.4 \cdot 10^{-7}$	$1.3 \cdot 10^{-9}$	$1.0 \cdot 10^{-8}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-7}$

Deppisch, Hirsch, Päs (2012)

Non-standard Majoron Emission

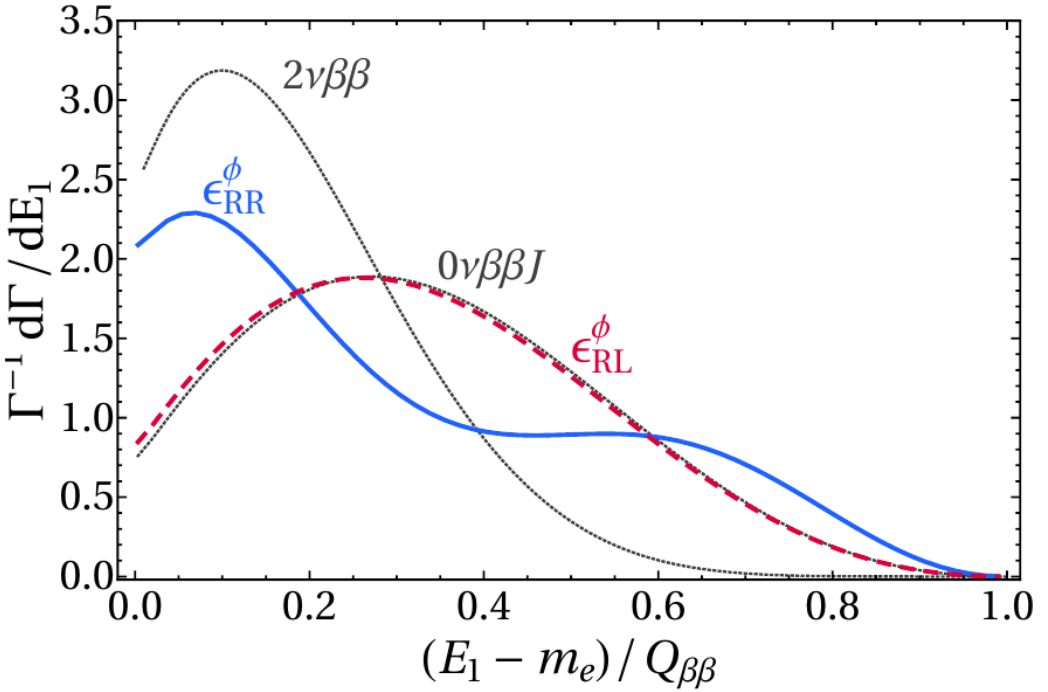
$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$



Isotope	$T_{1/2}$ [y]	$\lvert\epsilon_{RL}^\phi\rvert$	$\lvert\epsilon_{RR}^\phi\rvert$
^{82}Se	3.7×10^{22} [14]	4.1×10^{-4}	4.6×10^{-2}
^{136}Xe	2.6×10^{24} [13]	1.1×10^{-4}	1.1×10^{-2}
^{82}Se	1.0×10^{24}	8.0×10^{-5}	8.8×10^{-3}
^{136}Xe	1.0×10^{25}	5.7×10^{-5}	5.8×10^{-3}

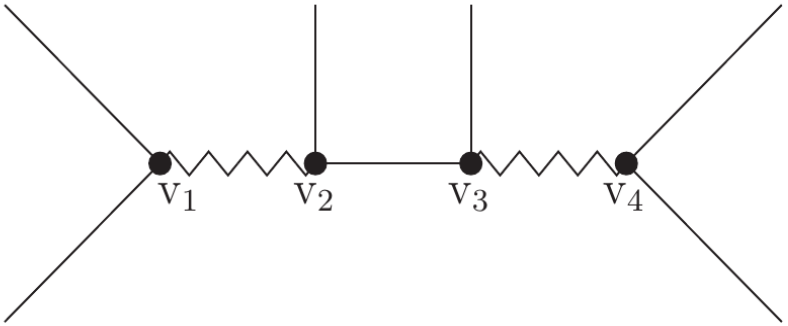
$$\Lambda_{\text{NP,RL}}^{\text{fut}} \approx 1.3\text{TeV}$$
$$\Lambda_{\text{NP,RR}}^{\text{fut}} \approx 270\text{GeV}$$

New type of interaction distinguishable from background

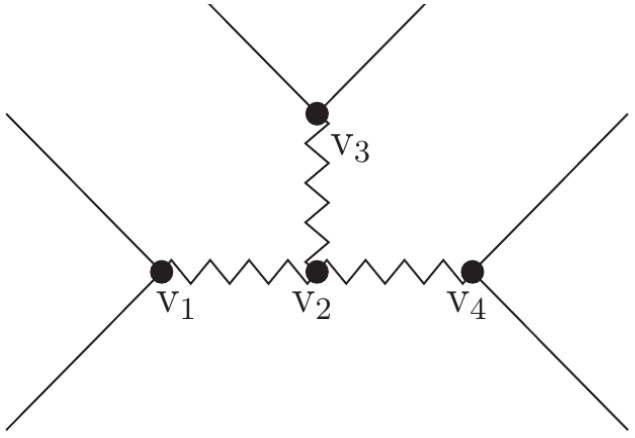


Cepedello, Deppisch, Gonzalez, Hati, Hirsch, Päs (2019)

Topologies for Neutrinoless Double Beta Decay



Topology I

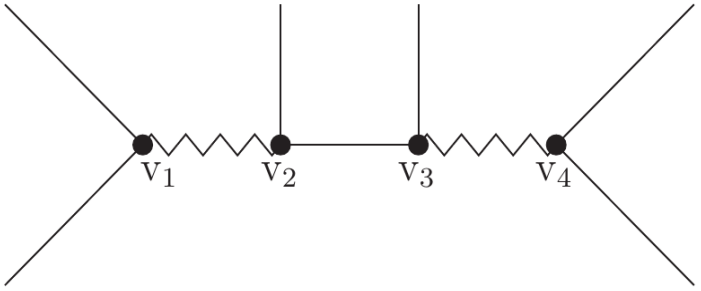


Topology II

#	Decomposition	Long Range?	Mediator $(U(1)_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62,63] [64]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

Bonnet, Hirsch, Ota, Winter (2014)

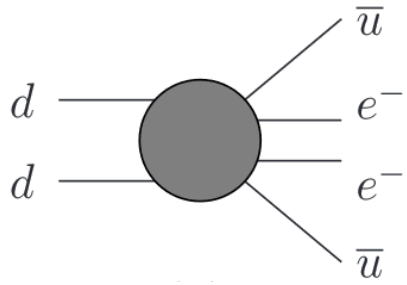
Neutrinoless Double Beta Decay at the LHC



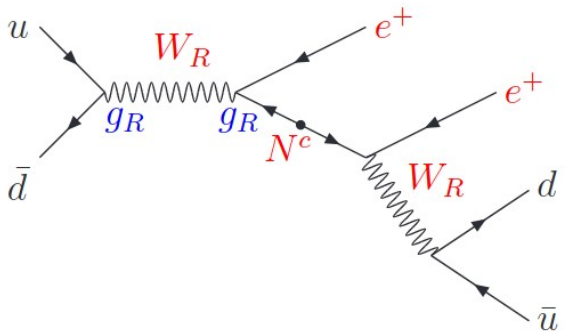
Topology I

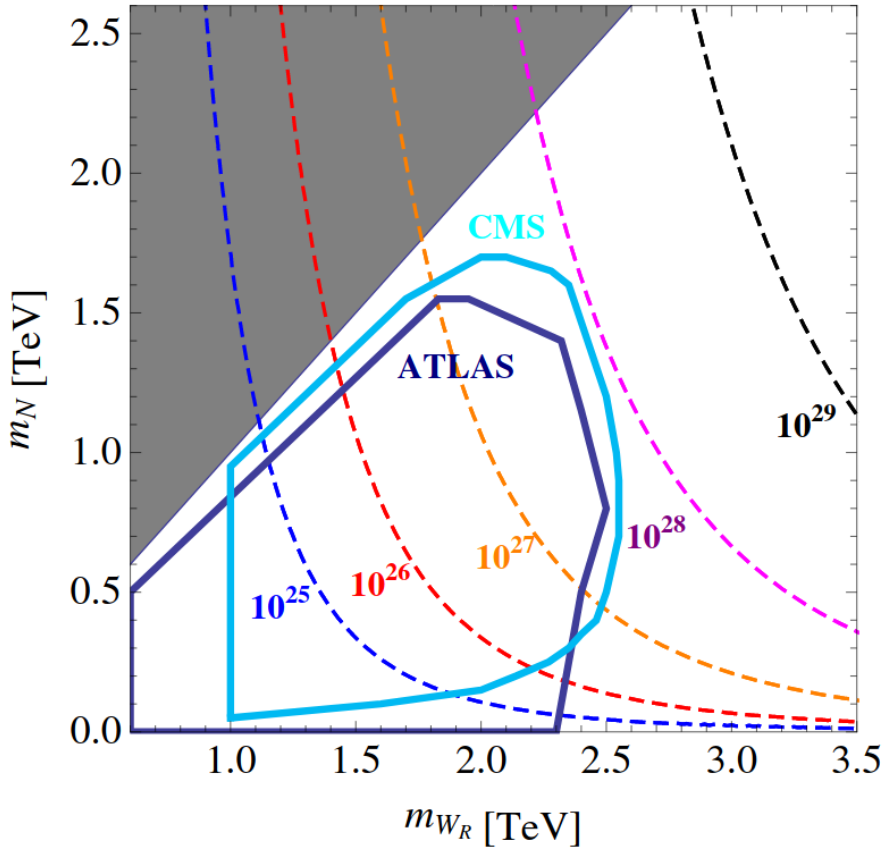
$$\mathcal{O}_9 = \frac{c_9}{\Lambda^5}\bar{u}\bar{u}\bar{d}\bar{d}\bar{e}\bar{e}$$

$$\Lambda \geq (1.2 - 3.2) g_{\text{eff}}^{4/5} \text{TeV}$$



Example: Left-Right Symmetric Model

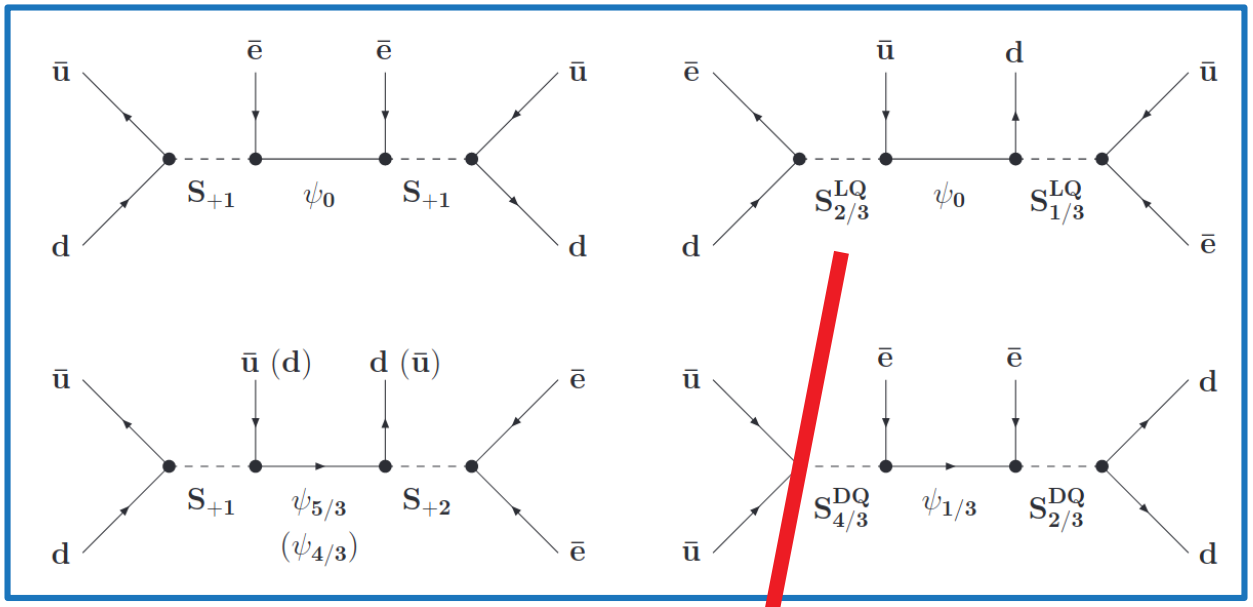


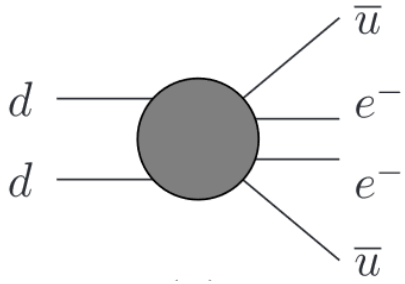


Helo, Kovalenko, Hirsch, Päs (2013)

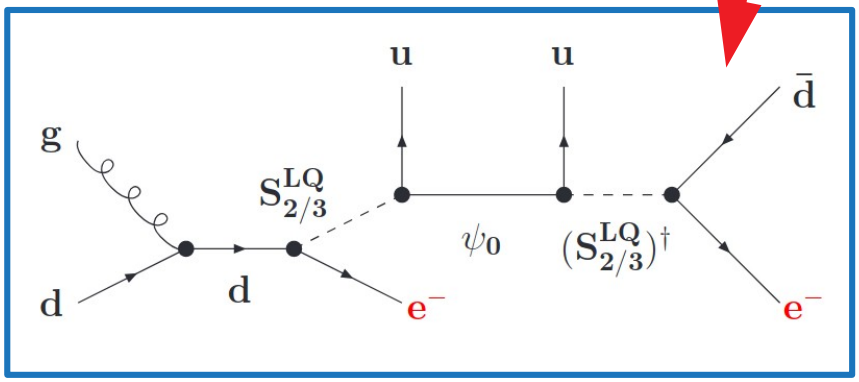
Neutrinoless Double Beta Decay at the LHC

Different possible contributions to 0vbb:





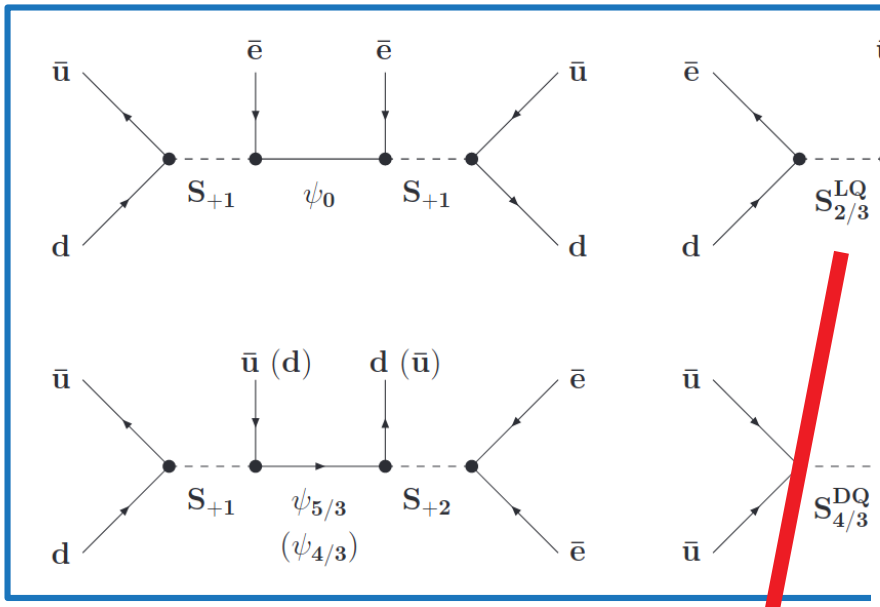
Corresponding process at LHC:

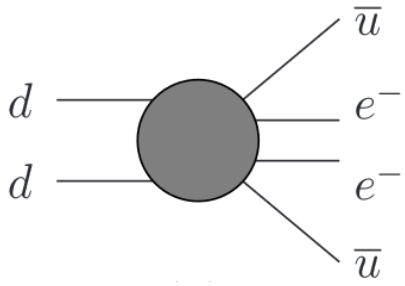


Helo, Kovalenko, Hirsch, Päs (2013)

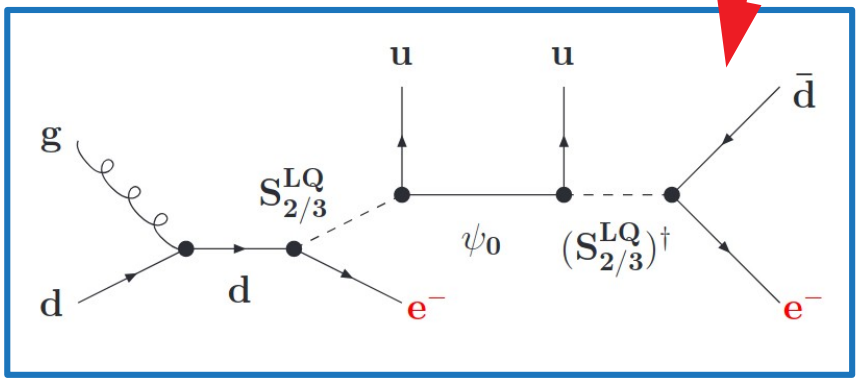
Neutrinoless Double Beta Decay at the LHC

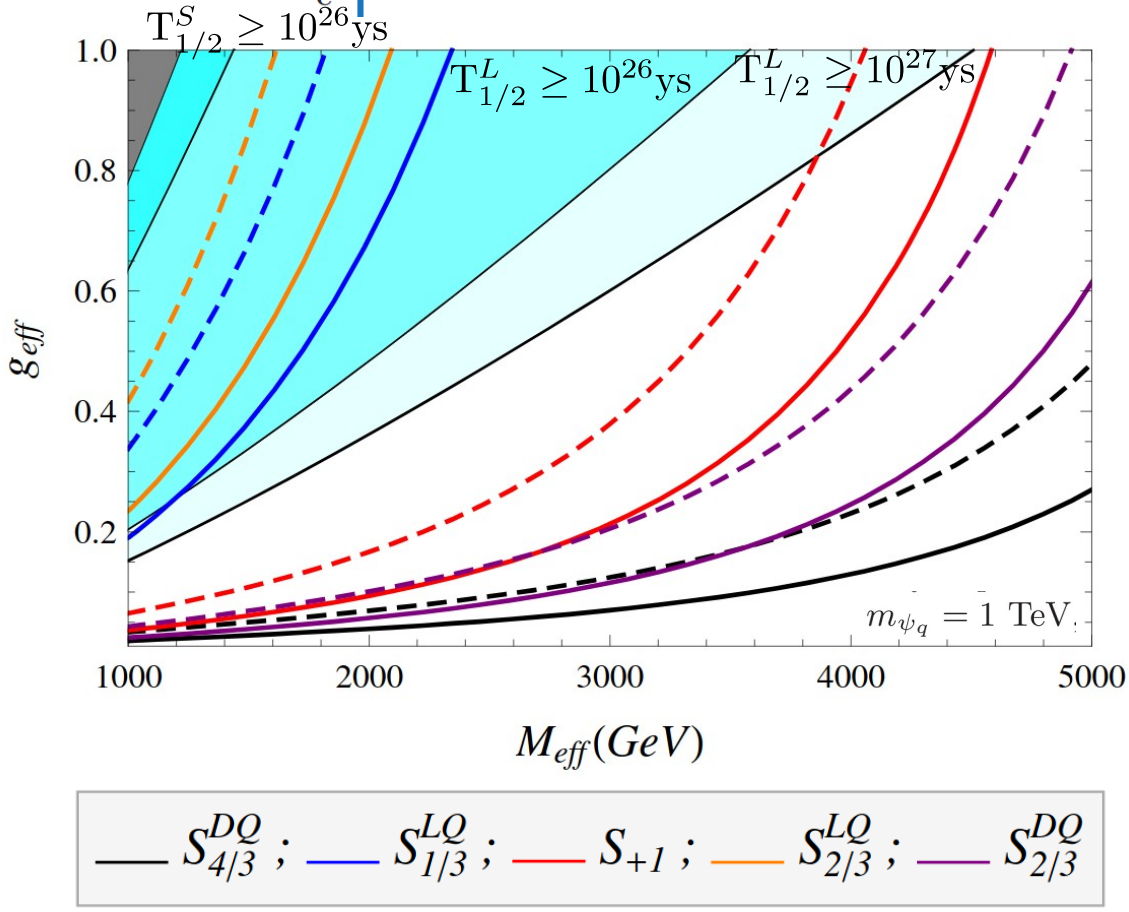
Different possible contributions to 0vbb:





Corresponding process at LHC:



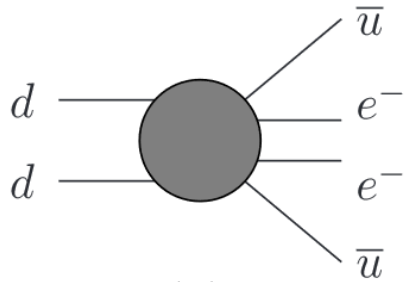


Helo, Kovalenko, Hirsch, Päs (2013)

Neutrinoless Double Beta Decay at the LHC

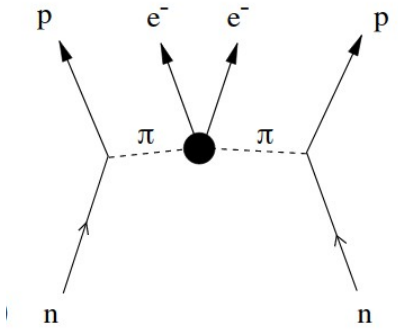
Refined study of one model:

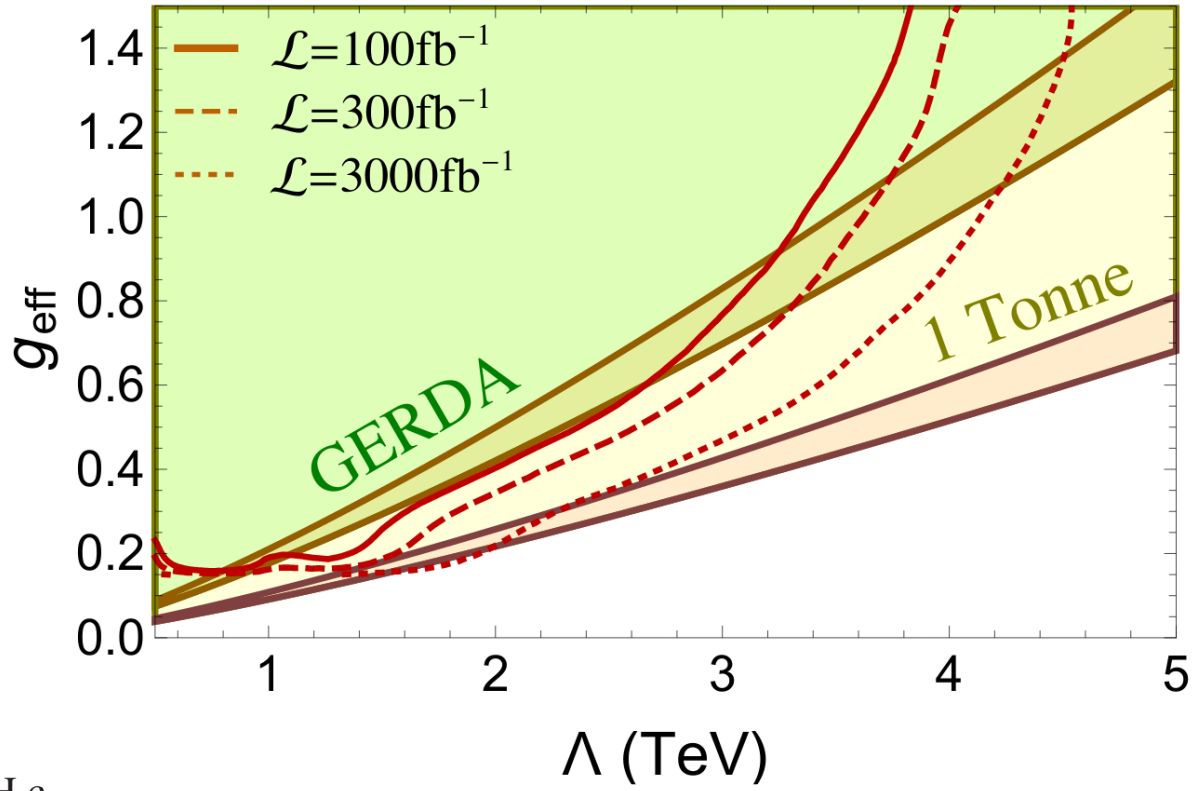
$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^\alpha d^\alpha S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$



Including:

- SM + detector background
- running of the operators
- long distance contributions



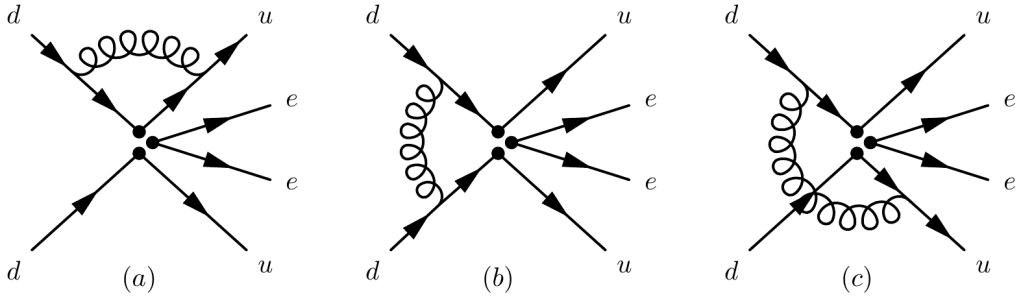


$$\frac{C_{\rm eff}}{\Lambda} \mathcal{O}_{2+}^{++} \bar{e}_L e_R^c + \text{H.c.} \to \frac{C_{\rm eff} \Lambda_H^2 F_\pi^2}{2\Lambda^5} \pi^- \pi^- \bar{e}_L e_R^c + \text{H.c.},$$

Peng, Ramsey-Musolf, Winslow (2015)

QCD corrections and running

Leading order QCD corrections to the **complete set of the short-range** d = 9 0νββ-operators covering the low-energy limits of any possible underlying high-energy scale model



$$
\begin{aligned}
\mathcal{O}_1^{XY} &= 4(\bar{u}P_X d)(\bar{u}P_Y d)\ j, \\
\mathcal{O}_2^{XX} &= 4(\bar{u}\sigma^{\mu\nu}P_X d)(\bar{u}\sigma_{\mu\nu}P_X d)\ j, \\
\mathcal{O}_3^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}\gamma_{\mu}P_Y d)\ j, \\
\mathcal{O}_4^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}\sigma_{\mu\nu}P_Y d)\ j^{\nu}, \\
\mathcal{O}_5^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}P_Y d)\ j_{\mu}
\end{aligned}
$$

$$
\begin{aligned}
\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = {} & G_1 \Big| \beta_1^{XX}\left(C_1^{LL}(\Lambda)+C_1^{RR}(\Lambda)\right)+\beta_1^{LR}\left(C_1^{LR}(\Lambda)+C_1^{RL}(\Lambda)\right)+ \\
& +\beta_2^{XX}\left(C_2^{LL}(\Lambda)+C_2^{RR}(\Lambda)\right)+ \\
& +\beta_3^{XX}\left(C_3^{LL}(\Lambda)+C_3^{RR}(\Lambda)\right)+\beta_3^{LR}\left(C_3^{LR}(\Lambda)+C_3^{RL}(\Lambda)\right)\Big|^2 + \\
+ \ & G_2 \Big| \beta_4^{XX}\left(C_4^{RR}(\Lambda)+C_4^{RR}(\Lambda)\right)+\beta_4^{LR}\left(C_4^{LR}(\Lambda)+C_4^{RL}(\Lambda)\right)+ \\
& +\beta_5^{XX}\left(C_5^{RR}(\Lambda)+C_5^{RR}(\Lambda)\right)+\beta_5^{LR}\left(C_5^{LR}(\Lambda)+C_5^{RL}(\Lambda)\right)\Big|^2 ,
\end{aligned}
$$

e.g.

$$\beta_1^{XX} = \mathcal{M}_1\ U_{(12)11}^{XX} + \mathcal{M}_2 U_{(12)21}^{XX},$$

Gonzalez, Hirsch, Kovalenko (2015)

QCD corrections and running

- QCD corrections can give **sizeable impact** to **short range** contribution

	With QCD		Without QCD	With QCD		Without QCD
^{A}X	$\lvert C_1^{XX}(\Lambda_1)\rvert$	$\lvert C_1^{XX}(\Lambda_2)\rvert$	$\lvert C_1^{XX}\rvert$	$\lvert C_1^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_1^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_1^{LR,RL}\rvert$
^{76}Ge	5.0×10^{-10}	3.8×10^{-10}	$\mathbf{2.6 \times 10^{-7}}$	1.5×10^{-8}	9.1×10^{-9}	$\mathbf{2.6 \times 10^{-7}}$
^{136}Xe	3.4×10^{-10}	2.6×10^{-10}	$\mathbf{1.8 \times 10^{-7}}$	9.7×10^{-9}	6.1×10^{-9}	$\mathbf{1.8 \times 10^{-7}}$
^{A}X	$\lvert C_2^{XX}(\Lambda_1)\rvert$	$\lvert C_2^{XX}(\Lambda_2)\rvert$	$\lvert C_2^{XX}\rvert$	–	–	–
^{76}Ge	3.5×10^{-9}	5.2×10^{-9}	1.4×10^{-9}	–	–	–
^{136}Xe	2.4×10^{-9}	3.5×10^{-9}	9.4×10^{-10}	–	–	–
^{A}X	$\lvert C_3^{XX}(\Lambda_1)\rvert$	$\lvert C_3^{XX}(\Lambda_2)\rvert$	$\lvert C_3^{XX}\rvert$	$\lvert C_3^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_3^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_3^{LR,RL}\rvert$
^{76}Ge	1.5×10^{-8}	1.6×10^{-8}	1.1×10^{-8}	2.0×10^{-8}	2.1×10^{-8}	1.8×10^{-8}
^{136}Xe	9.7×10^{-9}	1.1×10^{-8}	7.4×10^{-9}	1.4×10^{-8}	1.4×10^{-8}	1.2×10^{-8}
^{A}X	$\lvert C_4^{XX}(\Lambda_1)\rvert$	$\lvert C_4^{XX}(\Lambda_2)\rvert$	$\lvert C_4^{XX(0)}\rvert$	$\lvert C_4^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_4^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_4^{LR,RL(0)}\rvert$
^{76}Ge	5.0×10^{-9}	3.9×10^{-9}	$\mathbf{1.2 \times 10^{-8}}$	1.7×10^{-8}	1.9×10^{-8}	1.2×10^{-8}
^{136}Xe	3.4×10^{-9}	2.7×10^{-9}	$\mathbf{7.9 \times 10^{-9}}$	1.2×10^{-8}	1.3×10^{-8}	7.9×10^{-9}
^{A}X	$\lvert C_5^{XX}(\Lambda_1)\rvert$	$\lvert C_5^{XX}(\Lambda_2)\rvert$	$\lvert C_5^{XX}\rvert$	$\lvert C_5^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_5^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_5^{LR,RL}\rvert$
^{76}Ge	2.3×10^{-8}	1.4×10^{-8}	$\mathbf{1.2 \times 10^{-7}}$	3.9×10^{-8}	2.8×10^{-8}	$\mathbf{1.2 \times 10^{-7}}$
^{136}Xe	1.6×10^{-8}	9.5×10^{-9}	$\mathbf{8.2 \times 10^{-8}}$	2.8×10^{-8}	2.0×10^{-8}	$\mathbf{8.2 \times 10^{-8}}$

Gonzalez, Hirsch, Kovalenko (2015)

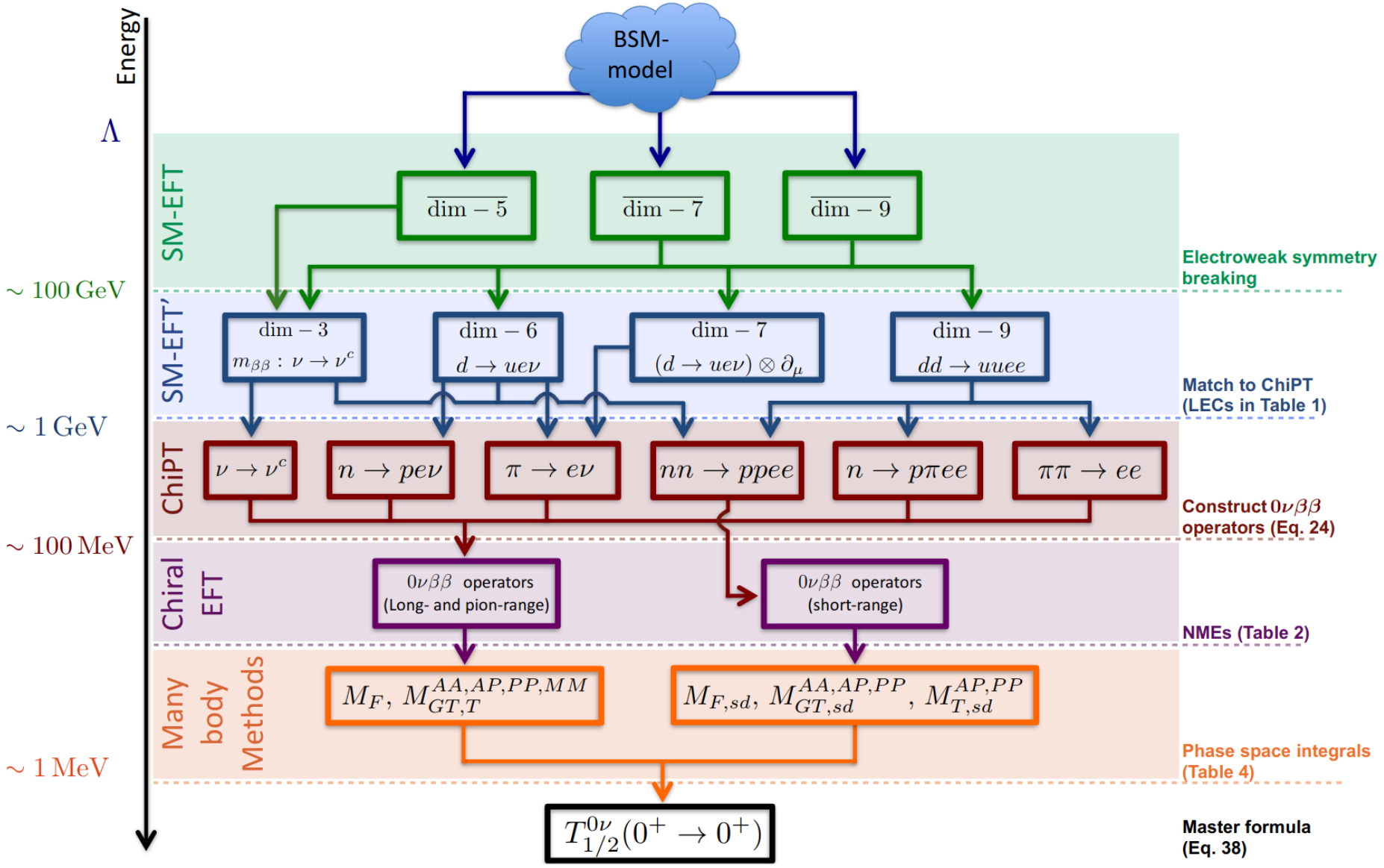
- QCD corrections **sub-dominant** for **long range** contribution (less than 60%)

Arbelaez, Gonzalez, Hirsch, Kovalenko (2016)

- Extrapolation of perturbative results to sub-GeV non-perturbative scales on the basis of **QCD coupling constant "freezing" behavior** using Background Perturbation Theory
  → only **moderate** dependence

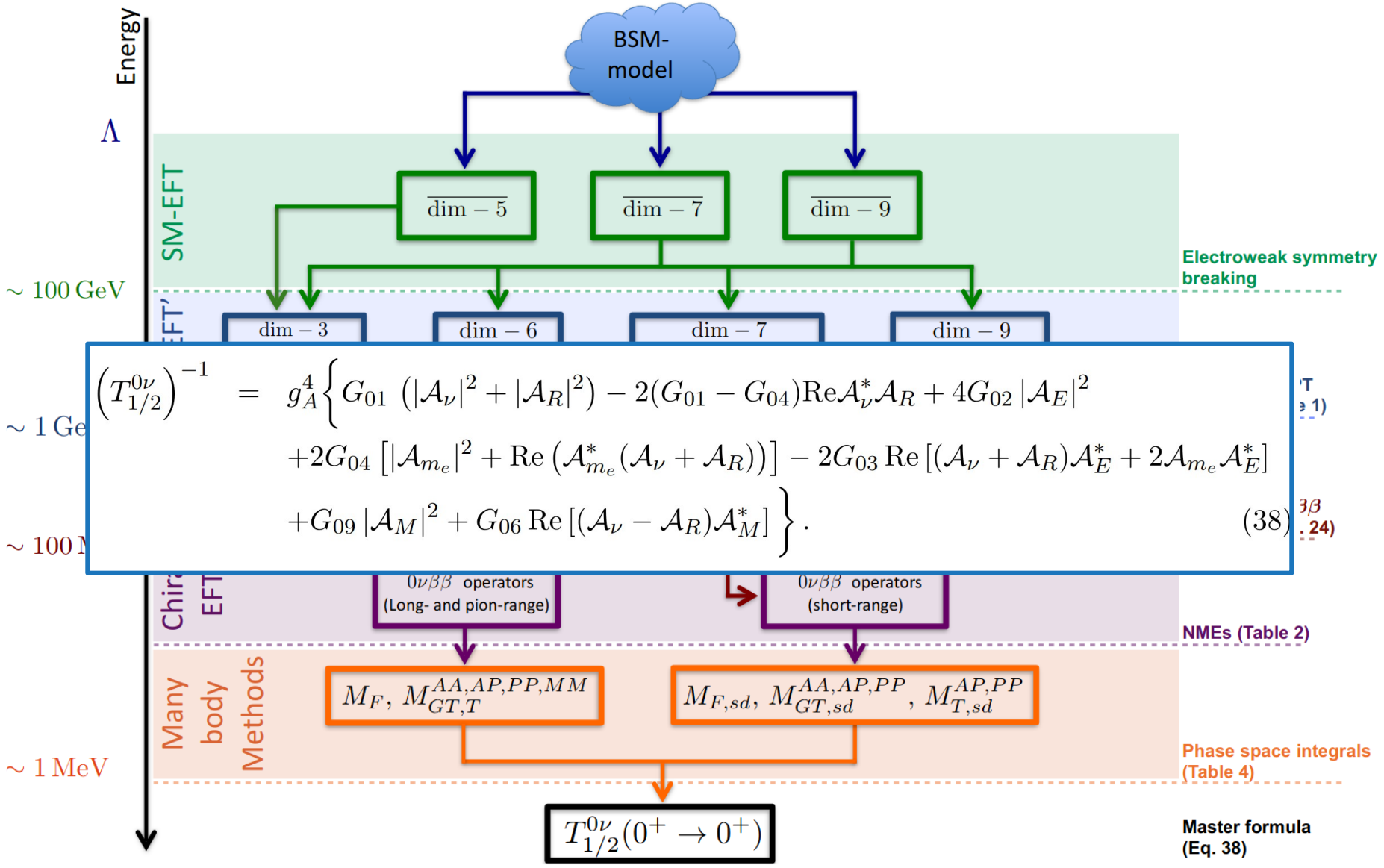
Gonzalez, Hirsch, Kovalenko (2018)

“Master formula”



Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)
Graf, Deppisch, Iachello, Kotila (2018)

“Master formula”



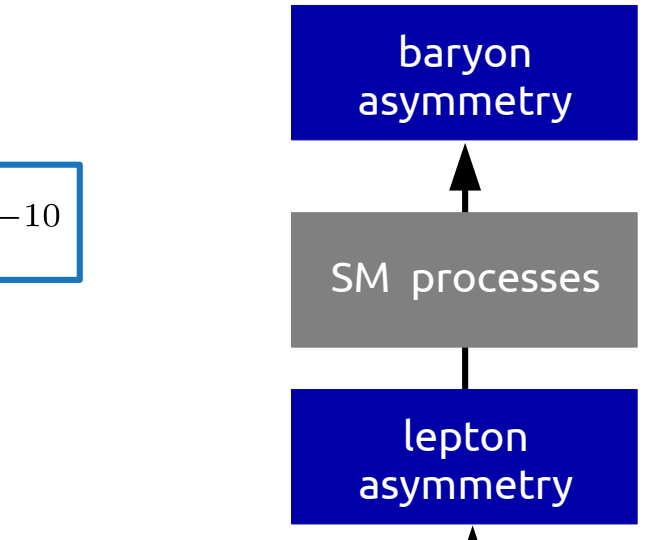
$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \Big\{ G_{01}\ \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2 + 2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu + \mathcal{A}_R)\right)\right] - 2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right] + G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\}. \quad (38)$$

Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)

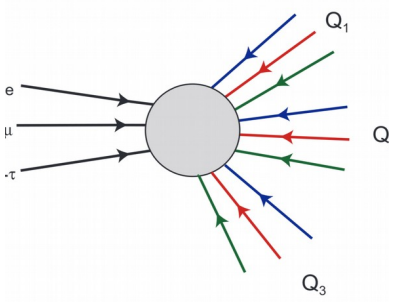
0νββ and Baryogenesis

Observed Baryon asymmetry

$$\eta_B^{\rm obs} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$



$$\Delta B = \Delta L = 3$$



$$\mathcal{O}_{B+L} = \prod_{i=1,2,3} (q_{L_i}, q_{L_i}, q_{L_i}\ell_{L_i})$$

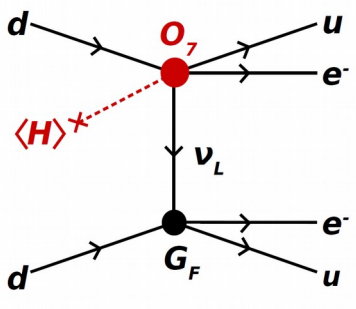
neutrinoless double beta decay

possibly at high scales for LG via decays

Imagine we observe 0νββ, can we make a statement about the washout strength and thus about the validity of a baryogenesis model?

YES!

0νββ and Baryogenesis



$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$

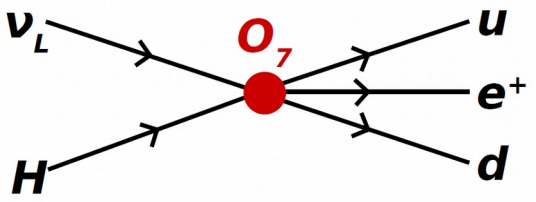
Observation would fix the **effective coupling** for one operator

$\mathcal{O}$	Operator
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$

$$\frac{G_F\epsilon_7}{\sqrt{2}} = \frac{g^3v}{2{\Lambda_7}^3}$$

effective coupling can be related to the **scale of the operator**

$\mathcal{O}_D$	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.1×10^{13}
$\mathcal{O}_7$	2.6×10^4
$\mathcal{O}_9$	2.1×10^3
$\mathcal{O}_{11}$	1.0×10^3



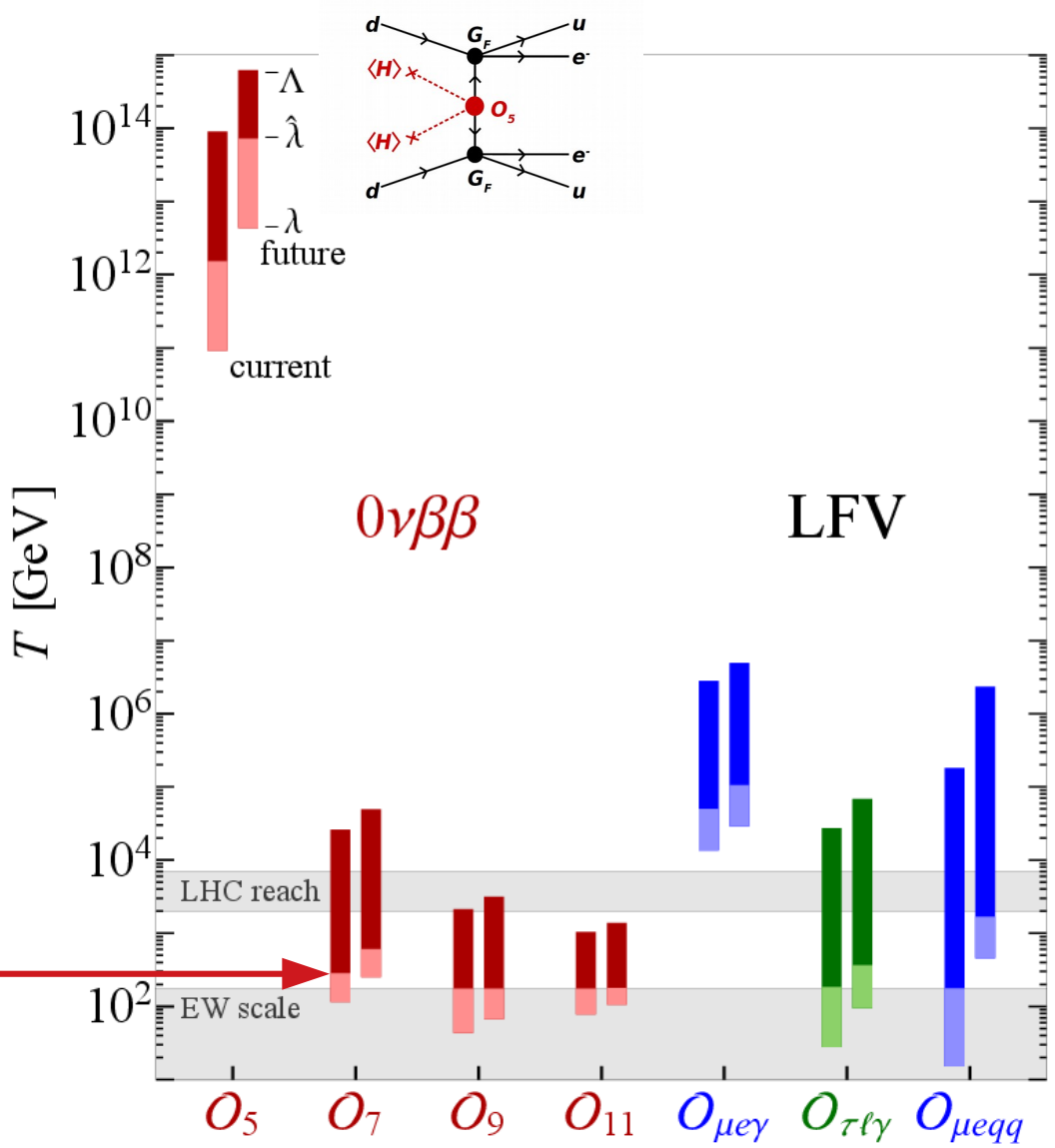
$$\frac{\Gamma_W}{H} > 1$$

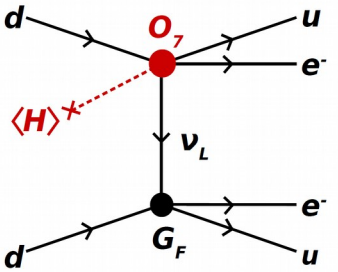
$$\Lambda_7 \left(\frac{\Lambda_7}{c_7'\Lambda_{Pl}}\right)^{\frac{1}{5}} \lambda_7 < T < \Lambda_7$$

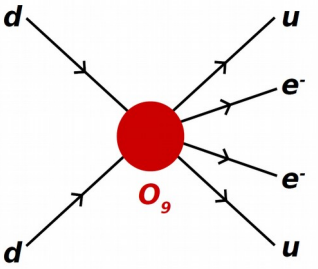
Limit above which the washout is highly effective can be calculated in dependence of the **operator scale**

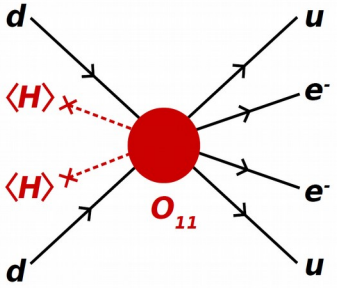
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

0νββ and Baryogenesis









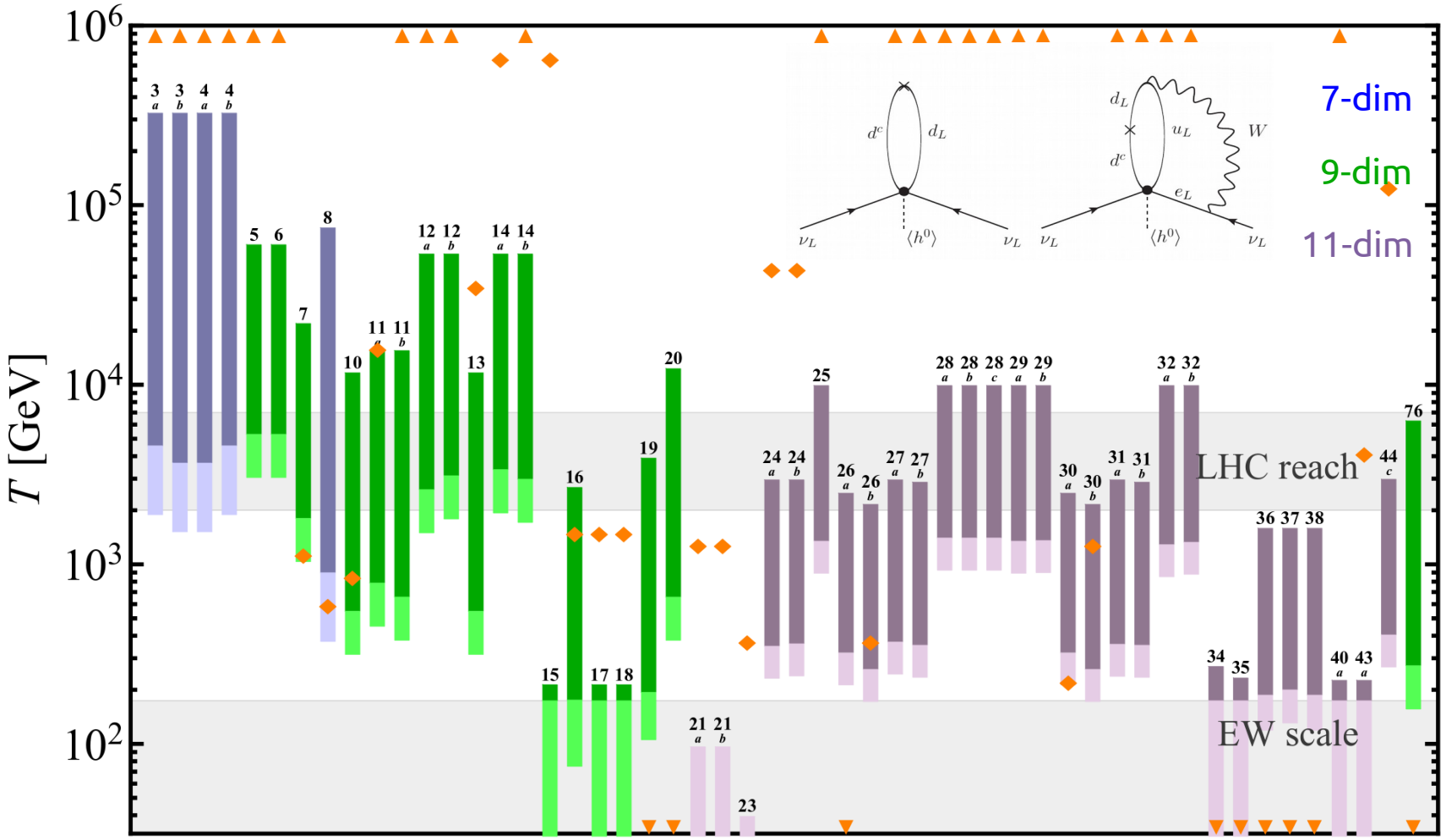
limit above which the washout is highly effective

$$\frac{\Gamma_W}{H} > 1$$

Potential to falsify baryogenesis models!

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

0νββ and Baryogenesis



Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

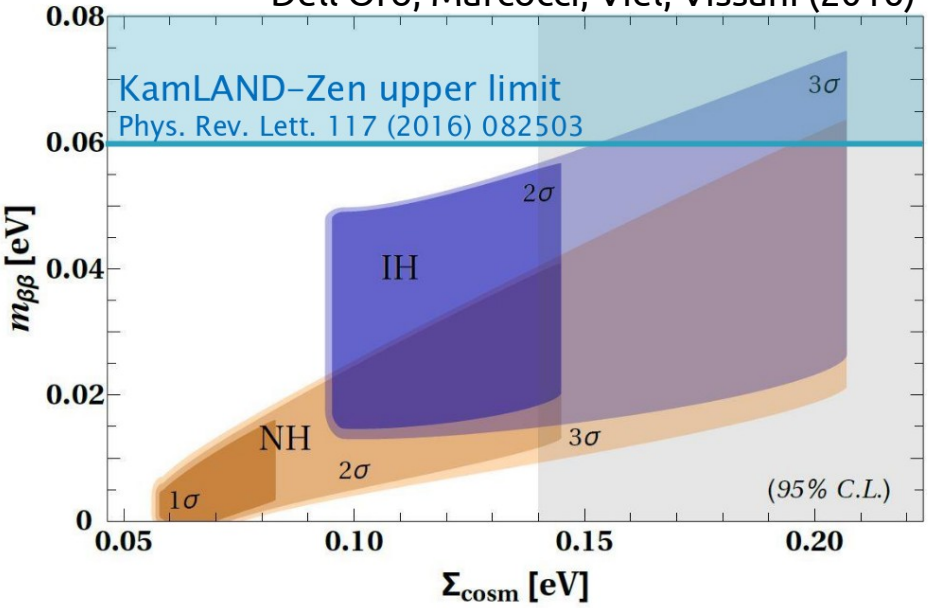
Side remark: **Loop enhanced** rate of neutrinoless double beta decay via **virtuality** of the particle in the loop

Rodejohann, Xu (2019)

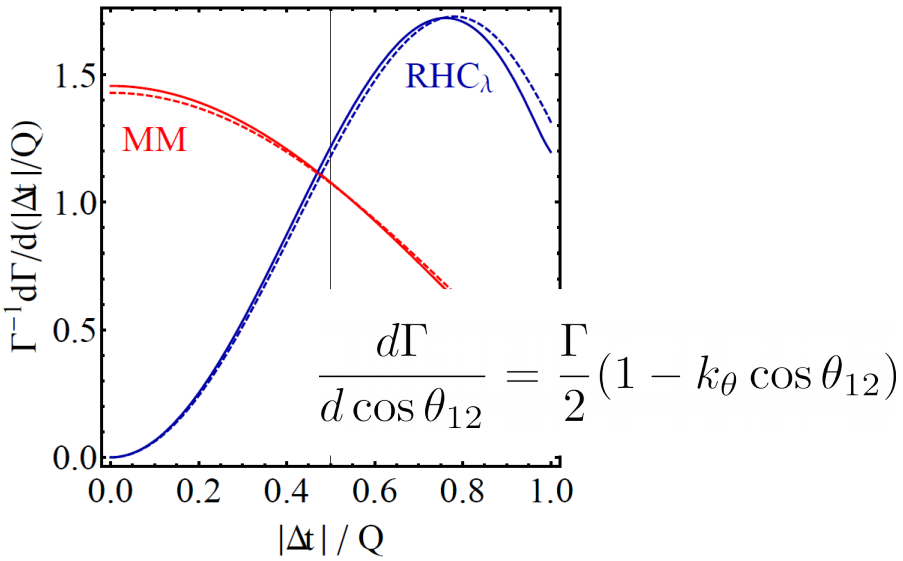
Distinguishing different operators

- **discrepancy** between sum of neutrino masses from **cosmology** and **0νββ half life** measurements could indicate non-standard mechanism

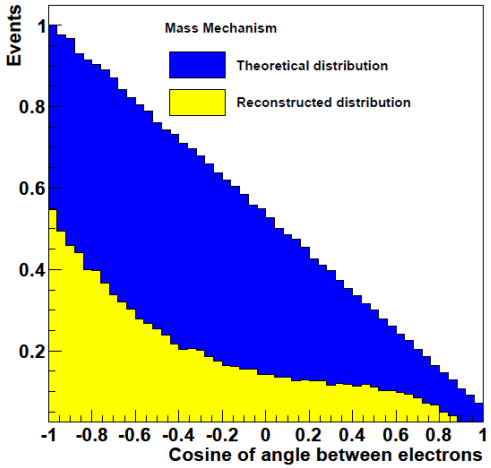
Dell'Oro, Marcocci, Viel, Vissani (2016)

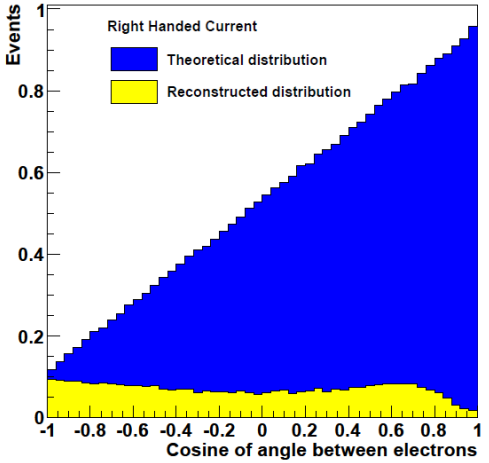


- **Angular distributions** allows to discriminate O_7 from others, due to e^-_R and e^+_L in the final state



$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$





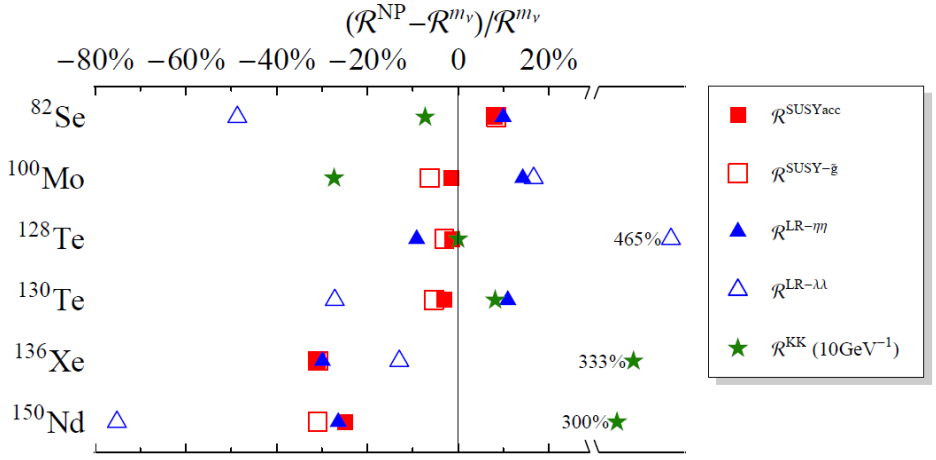
Ali, Borisov, Zhuridov (2006), SuperNemo, Arnold et al. (2010)

Distinguishing different operators

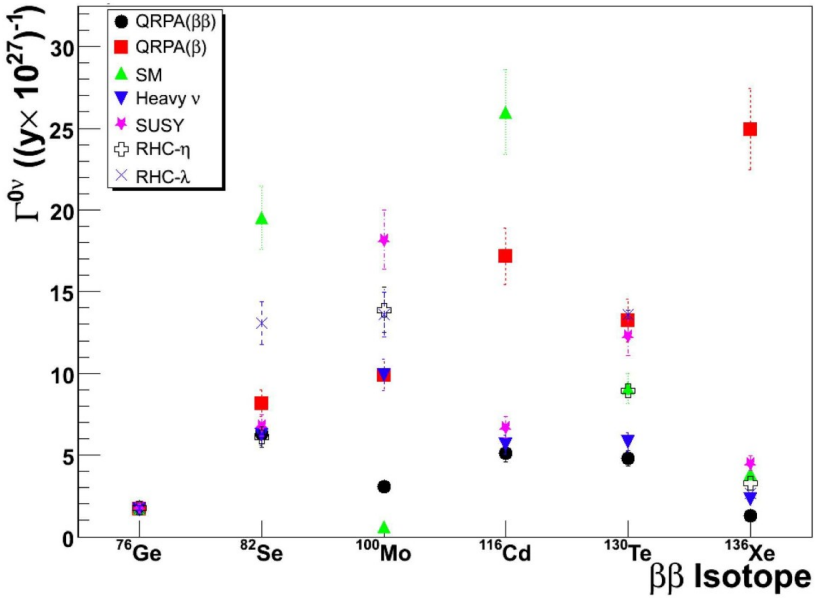
- distinguishing between different mechanisms via **measurements in different isotopes**

$$[T_{1/2}^{NP}]^{-1} = \epsilon_{NP}^2 G^{NP} |\mathcal{M}^{NP}|^2$$

$$\frac{T_{1/2}(^AX)}{T_{1/2}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}(^{76}\mathrm{Ge})|^2 G(^{76}\mathrm{Ge})}{|\mathcal{M}(^AX)|^2 G(^AX)}$$



Deppisch, Päs (2006)



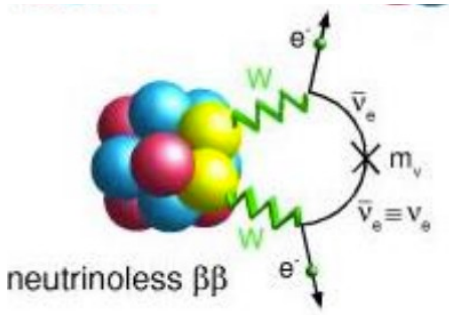
Isotope Ordering	Confidence Level	Number of Isotopes 2	3	4	5	6
Atomic Number	90%	<2%	8%	16%	23%	24%
	68%	<2%	19%	36%	45%	48%
$\Gamma^{0\nu}$ Spread	90%	6%	18%	27%	27%	24%
	68%	13%	29%	41%	42%	47%
Experimental Readiness	90%	3%	11%	24%	24%	24%
	68%	7%	18%	46%	47%	47%
Alternative Ordering	90%	3%	11%	17%	15%	24%
	68%	7%	18%	34%	32%	47%
Experimental Readiness (All 7 models, no ^{116}Cd)	90%	< 2%	6%	14%	16%	
	68%	< 2%	12%	22%	24%	

Gehmann, Elliot (2007)

- observation of 0νββ via O_9 and O_{11} will **imply observation of LNV at LHC**

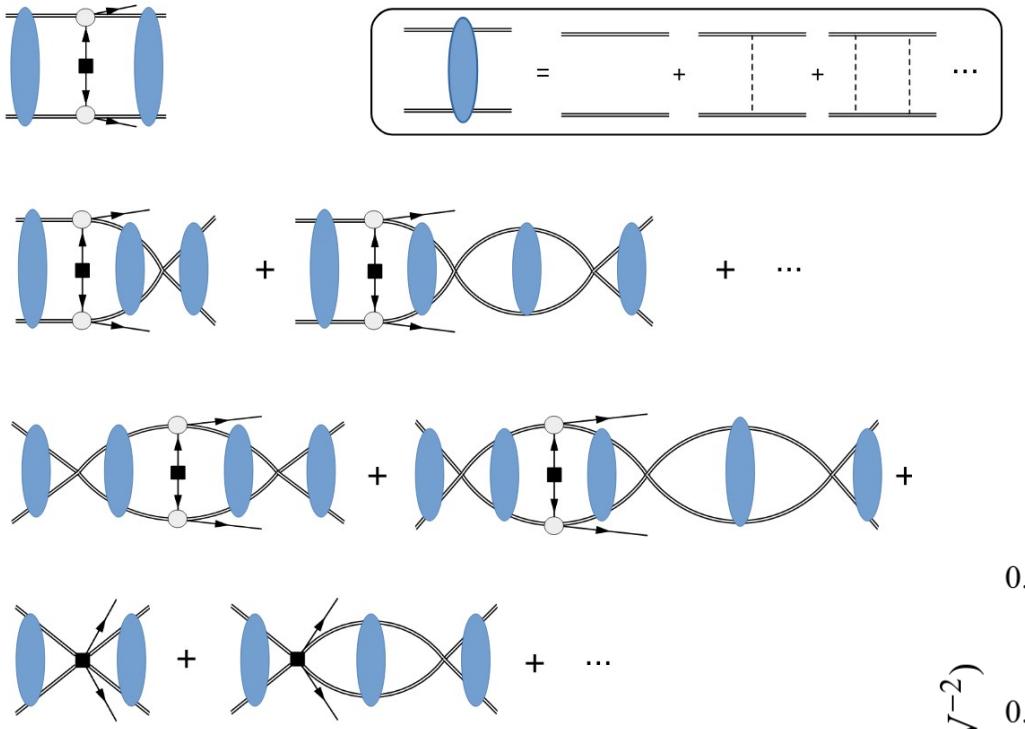
Summary

- 0νββ has huge potential to probe **LNV** and a **Majorana nature** of the neutrino
- Combination with **neutrino oscillations** powerful to constrain specific models
- Many **non-standard contributions** possible, many **topologies** and UV completions
- **0νββ and LHC** compete against better sensitivity
- **QCD running** is important and can affect conclusions → “master formula”
- 0νββ can shed light on **baryogenesis**
- Many ideas to **disentangle different contributions**
- Open questions & uncertainties in **nuclear physics**



Thank you for your attention!

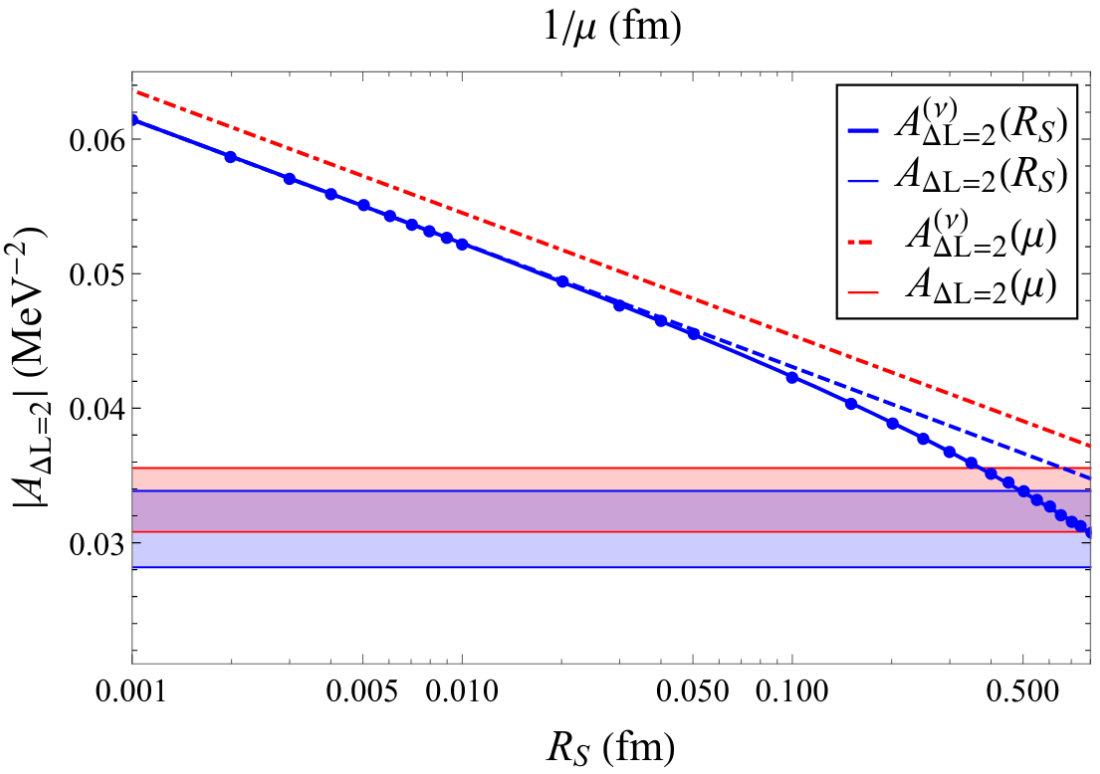
A new leading contribution to 0νββ



$$H_{\rm LNV} = 2G_F^2 V_{ud}^2 \, m_{\beta\beta} \, \bar{e}_L C \bar{e}_L^T \, V_\nu$$

$$V_0(\mathbf{q}) = \tilde{C} + V_\pi(\mathbf{q}) \,, \quad V_\pi(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2} \frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

$$V_{\nu,CT} = -2g_\nu^{NN} \, \tau^{(1)+}\tau^{(2)+}$$



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck (2018)