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Particle Physics of Non-Standard Neutrinoless Double Beta Decay

Lukas Graf

Max-Planck-Institut für Kernphysik

1711.10432, 1806.06058 + follow-up - to appear soon

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Outline

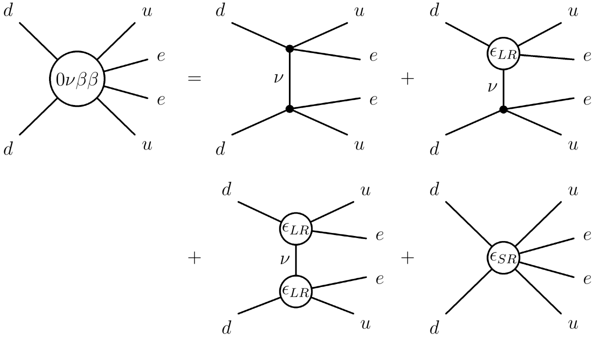
- introduction and motivation
- neutrinoless double beta decay ($0\nu\beta\beta$) approached effectively
- microscopic description of $0\nu\beta\beta$ (Jenni's talk on Tue)
  $\rightarrow$ half-life, angular correlation
- constraints on Physics beyond the SM
- low-energy $0\nu\beta\beta$ decay description $\leftrightarrow$ $\Delta L = 2$ SM effective operators
- baryogenesis and leptogenesis - lepton number washout
- conclusions

Introduction and Motivation

- neutrinos - neutral, left-handed, massive, light ...
- $\implies$ problem, neutrinos massless in the Standard Model
- Dirac or Majorana nature?
- Majorana masses $\iff$ LNV $\iff$ $0\nu\beta\beta$ decay
- massive right-handed neutrinos (seesaw mechanism) or something else?
- LNV at high energies - leptogenesis

$0\nu\beta\beta$ Decay Mechanisms

- $\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{LR} + \mathcal{L}_{SR}$, general Lagrangian in terms of effective couplings ϵ corresponding to the pointlike vertices at the Fermi scale



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

General Lagrangian for $0\nu\beta\beta$ Decay

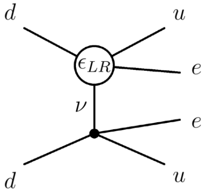
- long-range part: $\mathcal{L}_{LR} = \frac{G_F}{\sqrt{2}}\left[J^{\dagger}_{V-A\,\mu} j^{\mu}_{V-A} + \tilde{\sum}_{\alpha,\beta} \epsilon^{\beta}_{\alpha} J^{\dagger}_{\alpha} j_{\beta}\right]$,

  where $J^{\dagger}_{\alpha} = \bar{u} O_{\alpha} d$, $j_{\beta} = \bar{e}\mathcal{O}_{\beta}\nu$

  and $\mathcal{O}_{V\pm A} = \gamma^{\mu}(1 \pm \gamma_5)$,

  $\mathcal{O}_{S\pm P} = (1 \pm \gamma_5)$,

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



- short range part:

$$\mathcal{L}_{SR} = \frac{G_F^2}{2m_p}\left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}\right],$$

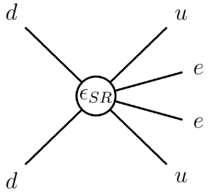
with $J = \bar{u}(1 \pm \gamma_5) d$,

$J^{\mu} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5) d$,

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

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

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



H. Päs et. al.: Phys.Lett. B453 (1999) 194-198 and B498 (2001) 35-39

General Lagrangian for $0\nu\beta\beta$

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- connection to the experimental half-life - if only a single ϵ is considered to be non-zero at a time: $T_{1/2}^{-1} = |\epsilon|^2 G_i |M_i|^2$
- $\implies 0\nu\beta\beta$ half-life sets constraints on effective couplings
- accurate calculation of nuclear matrix elements (NMEs) and phase-space factors (PSFs) is crucial for this estimation (content of Jenni Kotila's talk on Tue)
- main focus here: short-range $0\nu\beta\beta$ decay mechanisms & their interference with the standard mechanism

Short-Range Mechanisms Revisited

- $\mathcal{L}_{SR} = \frac{G_F^2}{2m_p}\left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\mu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right]$
- first: Is this formula complete?
- combination of left- and right-handed tensor currents = 0
- total number of independent low-energy $0\nu\beta\beta$ effective operators of dim. 9?
- Hilbert Series! - a powerful approach to construction of bases of effective operators using a specified particle content respecting given symmetries

  L. Lehman, A. Martin: 1503.07537, B. Henning, X. Lu, T. Melia, and H. Murayama: 1512.03433
- $\Longrightarrow$ 24 independent effective operators, in agreement with other literature (e.g. M. L. Graesser: 1606.04549)
- these are covered by the above short-range Lagrangian

Short-Range Mechanisms Revisited

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- $F_{PS}(q^2) = \frac{g_{PS}}{\left(1+q^2/m_{PS}^2\right)^2} \frac{1}{1+q^2/m_\pi^2}$

  $g_{PS} = 349$

  M. Gonzalez-Alonso, O. Naviliat-Cuncic and N. Severijns, Prog. Part. Nucl. Phys. 104, 165 (2019), [1803.08732].

- $F_P(q^2) = \frac{g_A}{\left(1+q^2/m_A^2\right)^2} \frac{1}{1+q^2/m_\pi^2} \times \frac{4m_p^2}{m_\pi^2}\left(1 - \frac{m_\pi^2}{m_A^2}\right)$

  $g_P = 233$

  V. Bernard, L. Elouadrhiri, U.-G. Meissner, J. Phys. G28, R1 (2002), [hep-ph/0107088]

- enhanced values of pseudoscalar form factors $\Longrightarrow$ additional NMEs taken into account

$$
\begin{aligned}
\mathcal{M}_1 =\; & g_S^2 \mathcal{M}_F \\
& (+\;+\;-)\; \frac{g_{PS}^2}{12}\left(\mathcal{M}'^{PP}_{GT} - \mathcal{M}'^{PP}_{T}\right), \\
\mathcal{M}_2 =\; & -2g_{T_1}^2 \mathcal{M}_{GT}, \\
\mathcal{M}_3 =\; & g_V^2 \mathcal{M}_F \\
& (-\;-\;+)\; g_A^2 \mathcal{M}^{AA}_{GT} \\
& (+\;+\;-)\; \frac{g_A g_P}{6}\left(\mathcal{M}'^{AP}_{GT} - \mathcal{M}'^{AP}_{T}\right) \\
& + \frac{(g_V + g_W)^2}{12}\left(\mathcal{M}'_{GT} + \frac{1}{2}\mathcal{M}'_{T}\right) \\
& (-\;-\;+)\; \frac{g_P^2}{48}\left(\mathcal{M}''^{PP}_{GT} - \mathcal{M}''^{PP}_{T}\right), \\
\mathcal{M}_4^\mu =\; & (-\;-\;+\,+)\; i g^{\mu 0} g_A g_{T_1} \mathcal{M}^{A}_{GT} \\
& (+\;+\;-\,-)\; i g^{\mu 0} \frac{g_P g_{T_1}}{12}\left(\mathcal{M}'^{P}_{GT} - \mathcal{M}'^{P}_{T}\right), \\
\mathcal{M}_5^\mu =\; & g^{\mu 0} g_S g_V \mathcal{M}_F \\
& (+\;+\;-\,-)\; g^{\mu 0} \frac{g_A g_{PS}}{12}\left(\tilde{\mathcal{M}}^{AP}_{GT} - \tilde{\mathcal{M}}^{AP}_{T}\right) \\
& (-\;-\;+\,+)\; g^{\mu 0} \frac{g_P g_{PS}}{24}\left(\mathcal{M}'^{q_0 PP}_{GT} - \mathcal{M}'^{q_0 PP}_{T}\right).
\end{aligned}
$$

General Half-Life Formula

- let's consider $\mathcal{L}_{SR} + \frac{G_F}{\sqrt{2}} J^{\dagger}_{V-A\mu} j^{\mu}_{V-A}$
- $\implies$ general formula for half-life of $0\nu\beta\beta$ decay induced by the short-range mechanisms + the standard mechanism and their mutual interference:

$$
\begin{aligned}
T_{1/2}^{-1} = G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right|^2 + G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right|^2 \\
+ G_{11-}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right)^* \right] \\
+ G_{66}^{(0)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2 + G_{16}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right] \\
- G_{16}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right]
\end{aligned}
$$

- additional NMEs, enhanced form factors, exact (non-approximated) numerical PSFs

Limits on Couplings

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- new NMEs + new PSFs + current exp. bounds on $T_{1/2}^{0\nu\beta\beta}$ $\Longrightarrow$ new limits on effective neutrino mass $\langle m_\nu \rangle$ and new-physics couplings ϵ_I

$\langle m_\nu \rangle = \sum U_{ei}^2 m_{\nu_i}$

	$T_{1/2}^{\text{exp}}$ [y]	$\langle m_\nu \rangle$ [eV]
^{76}Ge	8×10^{25}	0.093
^{82}Se	2.4×10^{24}	0.32
^{96}Zr	9.2×10^{21}	4.2
^{100}Mo	1.1×10^{24}	0.34
^{116}Cd	2.2×10^{23}	1.3
^{130}Te	1.5×10^{24}	1.9
^{130}Te	1.5×10^{25}	0.13
^{136}Xe	1.07×10^{26}	0.059
^{150}Nd	2.0×10^{22}	1.9

$\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu$

	$T_{1/2}^{\text{exp}}$ [y]	$\lvert\epsilon_1^{XX}\rvert$	$\lvert\epsilon_1^{LR}\rvert$	$\lvert\epsilon_2^{XX}\rvert$	$\lvert\epsilon_3^{XX}\rvert$	$\lvert\epsilon_3^{LR}\rvert$	$\lvert\epsilon_4^{XX,LR}\rvert$	$\lvert\epsilon_5^{XX}\rvert$	$\lvert\epsilon_5^{RL,LR}\rvert$
^{76}Ge	8×10^{25}	1.88	1.86	93.8	56.2	88.8	126	39.3	33.3
^{82}Se	2.4×10^{24}	6.24	6.17	315	188	299	435	131	111
^{96}Zr	9.2×10^{21}	90.7	89.5	3990	2370	3660	5220	2520	2000
^{100}Mo	1.1×10^{24}	6.32	6.24	283	169	263	371	174	139
^{116}Cd	2.2×10^{23}	22.0	21.7	1010	606	961	1330	619	493
^{130}Te	1.5×10^{24}	36.1	35.6	1780	1040	1720	2250	696	581
^{130}Te	1.5×10^{25}	2.54	2.51	126	73.6	121	172	53.0	44.3
^{136}Xe	1.07×10^{26}	1.20	1.18	59.0	34.7	57.2	80.3	25.4	21.2
^{150}Nd	2.0×10^{22}	41.9	41.4	1930	1140	1820	2580	1060	856

PRELIMINARY

- restricting the scale: $\frac{1}{\Lambda_{\text{NP}}^5} = \frac{G_F^2}{2m_p}\epsilon_I$

Limits on Couplings

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- above: effective couplings at $\Lambda_{\text{QCD}} \approx 1$ GeV
- more correctly: new-physics scale $\Lambda_{\text{NP}} \approx 1$ TeV
- $\implies$ QCD running taken into account

M. González, M. Hirsch and S. G. Kovalenko, Phys. Rev. D93, 013017 (2016), [1511.03945]

$$c_1 JJj + c_2 J^{\mu\nu} J_{\mu\nu} j + c_3 J^{\mu} J_{\mu} j + c_4 J^{\mu} J_{\mu\nu} j^{\nu} + c_5 J^{\mu} J j_{\mu}$$

	$T_{1/2}^{\text{exp}}$ [y]	$\lvert c_1^{XX}\rvert$	$\lvert c_1^{LR}\rvert$	$\lvert c_2^{XX}\rvert$	$\lvert c_3^{XX}\rvert$	$\lvert c_3^{LR}\rvert$	$\lvert c_4^{XX}\rvert$	$\lvert c_4^{LR}\rvert$	$\lvert c_5^{XX}\rvert$	$\lvert c_5^{RL,LR}\rvert$
^{76}Ge	8×10^{25}	0.762	0.445	145	80.2	106	315	203	16.3	8.07
^{82}Se	2.4×10^{24}	2.53	1.48	478	268	356	1080	702	54.4	26.9
^{96}Zr	9.2×10^{21}	36.6	21.4	7530	3380	4360	14000	8410	1030	485
^{100}Mo	1.1×10^{24}	2.55	1.49	518	242	313	995	598	71.5	33.6
^{116}Cd	2.2×10^{23}	8.88	5.19	1770	866	1140	3570	2150	255	119
^{130}Te	1.5×10^{24}	14.6	8.53	2800	1490	2050	5620	3620	289	141
^{130}Te	1.5×10^{25}	1.03	0.602	197	105	144	429	277	22.0	10.7
^{136}Xe	1.07×10^{26}	0.485	0.283	93.0	49.5	68.1	202	129	10.5	5.12
^{150}Nd	2.0×10^{22}	17.0	9.91	3380	1630	2170	6810	4170	437	207

PRELIMINARY

Interference with Mass Mechanism

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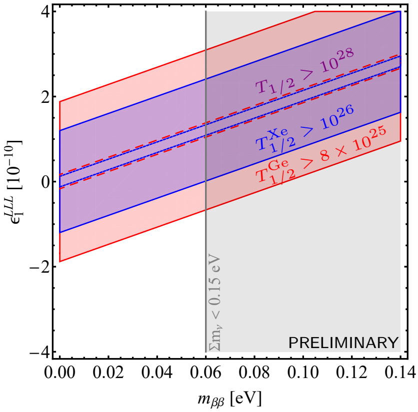
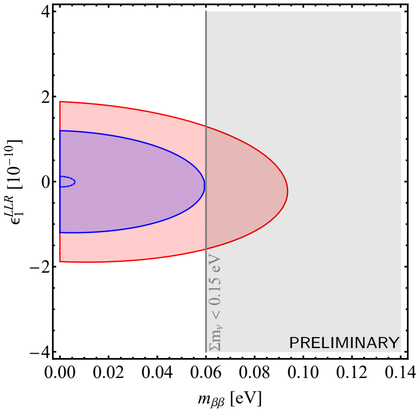
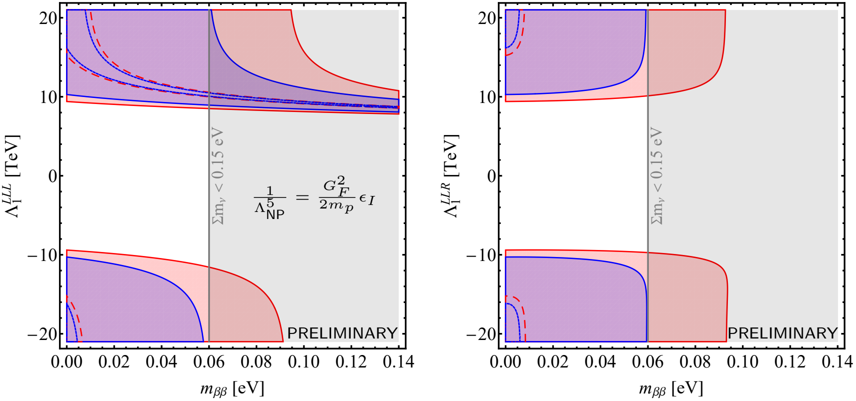




$$T_{1/2}^{-1} = G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right|^2$$

$$T_{1/2}^{-1} = G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right|^2 + G_{66}^{(0)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2 - G_{16}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right]$$

Interference with Mass Mechanism



$$T_{1/2}^{-1} = G_{11+}^{(0)} \left|\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu\right|^2$$

$$T_{1/2}^{-1} = G_{11+}^{(0)} \left|\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I\right|^2 + G_{66}^{(0)} \left|\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I\right|^2 - G_{16}^{(0)} 2\mathrm{Re}\left[\left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I\right)\left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I\right)^*\right]$$

LNV at high energies?

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The best theory we have is the Standard Model, where lepton number is conserved.

Physics beyond the SM (at higher energy scales) can be effectively described by SMEFT.

SM Effective Operators with $\Delta L = 2$

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- now SM effective interactions
- unbroken phase: $0\nu\beta\beta$ can be described using SM-invariant effective operators with $\Delta L = 2$

  K. S. Babu, C. N. Leung: Nucl.Phys. B619 (2001) 667-689

  A. de Gouvea, J. Jenkins: Phys. Rev. D77 (2008), 013008

- always operators of odd dimensions: $5, 7, 9, 11, \dots$

  A. Kobach: Phys.Lett. B758 (2016) 455-457

$\mathcal{O}$	Operator	$m_{\alpha\beta}$	Λ_ν (TeV)	Best Probed	Disfavored
4_a	$L^iL^j\overline{Q}_i\bar{u^c}H^k\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	4×10^9	$\beta\beta0\nu$	U
4_b	$L^iL^j\overline{Q}_k\bar{u^c}H^k\epsilon_{ij}$	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^6	$\beta\beta0\nu$	U
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$	U
6	$L^iL^j\overline{Q}_k\bar{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$	U
7	$L^iQ^j\bar{e^c}\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$y_{\ell_\beta}\frac{g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^2	mix	C
8	$L^i\bar{e^c}\bar{u^c}d^cH^j\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	mix	C
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	3×10^3	$\beta\beta0\nu$	U
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	$\beta\beta0\nu$	U
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2 g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	30	$\beta\beta0\nu$	U
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^4	$\beta\beta0\nu$	U
12_a	$L^iL^j\overline{Q}_i\bar{u^c}\overline{Q}_j\bar{u^c}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$	U
12_b	$L^iL^j\overline{Q}_k\bar{u^c}\overline{Q}_l\bar{u^c}\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2 g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$	U
13	$L^iL^j\overline{Q}_i\bar{u^c}L^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$	U
14_a	$L^iL^j\overline{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_d y_u g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$	U

$\Delta L = 2$ SM Effective Operators

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- dimension 5 - unique Weinberg operator $L^i L^j H^k H^l \varepsilon_{ik} \varepsilon_{jl}$
- dimension 7 - 7 operators, 4 of them contributing to the long-range mechanisms at tree level
- dimension 9 - 30 operators, at tree level 3 contribute to the long-range mechanisms and 5 to the short-range mechanisms
  - additional (although trivial!) operator $\bar{e^c}\bar{e^c}d^c d^c \bar{u^c}\bar{u^c}$ found when checking with Hilbert Series
- dimension 11 - selection of operators, 15 tree-level contributions to the short-range mechanisms

Eff. Operators and $\mathcal{L}_{0\nu\beta\beta}$ Correspondence

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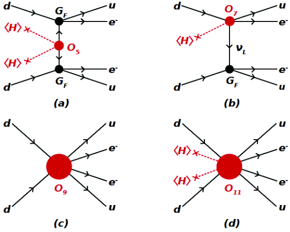
- contributions to $0\nu\beta\beta$ decay generated by the $\Delta L = 2$ SM effective operators in terms of effective vertices, point-like at the nuclear Fermi level scale



- for example:

$$\left.\begin{array}{l}\mathcal{O}_{3a}:\dfrac{\lambda^3_{BSM}v}{\Lambda^3_{3a}}\\[2ex] \mathcal{O}_{3b}:\dfrac{\lambda^3_{BSM}v}{\Lambda^3_{3b}}\\[2ex] \mathcal{O}_{5}:\dfrac{\lambda^3_{BSM}v^3}{\Lambda^5_{5}}\end{array}\right\} = \frac{G_F\epsilon^{S+P}_{S+P}}{\sqrt{2}},$$

$$\left.\begin{array}{l}\mathcal{O}_{11b},\mathcal{O}_{12a},\mathcal{O}_{14b}:\dfrac{\lambda^4_{BSM}}{\Lambda^5_i}\\[2ex] \left.\begin{array}{r}\mathcal{O}_{24a},\mathcal{O}_{28a},\\ \mathcal{O}_{28c},\mathcal{O}_{32a},\\ \mathcal{O}_{36},\mathcal{O}_{37},\mathcal{O}_{38}\end{array}\right\}:\dfrac{\lambda^6_{BSM}v^2}{\Lambda^7_i}\end{array}\right\} = \frac{G_F^2\epsilon_1}{2m_p},$$

$$\mathcal{O}_7:\frac{\lambda^3_{BSM}v^3}{\Lambda^5_7} = 2\frac{G_F\epsilon^{V+A}_{V-A}}{\sqrt{2}}.$$

Other $\Delta L = 2$ Effective Operators?

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- so far: operators contributing to $0\nu\beta\beta$ decay directly at tree level (employing certain type of mechanism)
- all the $\Delta L = 2$ SM effective operators can be related by SM Feynman rules
- $\implies$ all of them contribute to $0\nu\beta\beta$ decay in various possible ways
- if we know the relations, we can determine the dominant contribution of every operator to $0\nu\beta\beta$ decay via each possible channel

Example of Reduction

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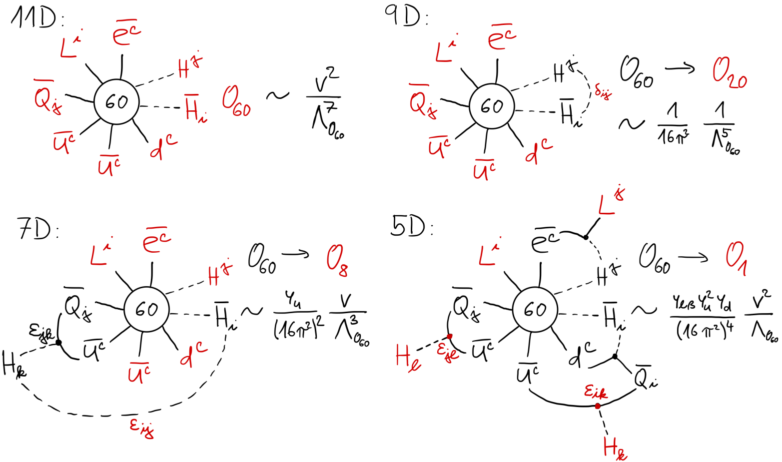
- let's consider operator $\mathcal{O}_{60} = L^i d^c \bar{Q}_j \bar{u^c} \bar{e^c} \bar{u^c} H^j \bar{H}_i$ (dim 11)



$\Delta L = 2$ SM Effective Operators & $0\nu\beta\beta$

- similar reduction can be done for each LNV effective operator
- every operator can be reduced to various operators trigerring $0\nu\beta\beta$ decay at tree level
- automation needed to obtain all possible contributions, for some operators - quite a demanding computation
- resulting contributions $\rightarrow$ relations among operators' scales and epsilons from $\mathcal{L}_{0\nu\beta\beta}$ for every operator $\rightarrow$ the typical scales Λ of the SM effective operators can be contrained

Algorithmic Approach

- $SU(2)_L$ decomposition of all the operators

- reduction of every component of every operator to the tree-level-contributing $0\nu\beta\beta$ decay operators (their component) of equal or lower dimension using a loop-closing algorithm

- identify the dominant contributions for the long-range and short-range mechanisms

- by their comparison with corresponding effective couplings ϵ we can calculate the scale of the operator

Algorithmic Approach - Output

- processed output: all the contributions for all the $\Delta L = 2$ SM effective operators

```
"Operator 1"    vev^2*Λ*No[1]*PartOp[4]    (aLOOP*vev^2*ye^2*No[1]*PartOp[2])/Λ    (aLOOP*vev^2*ye^2*No[1]*PartOp[3])/Λ
"Operator 2"    (aLOOP*vev^2*ye*No[1]*PartOp[2])/Λ    (aLOOP*vev^2*ye*No[1]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*ye*No[3]*PartOp[2])/Λ    (aLOOP^2*g^2*vev^2*ye*N
(aLOOP^2*g^2*vev^2*ye*No[3]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*ye*No[5]*PartOp[4])/Λ    (aLOOP^2*vev^2*ye^3*No[9]*PartOp[2])/Λ    (aLOOP^2*vev^2*ye^3*No[11]*Par
Λ    (aLOOP^2*vev^2*ye^3*No[11]*PartOp[4])/Λ    (aLOOP^2*vev^2*ye^3*No[1]*PartOp[2])/Λ    (aLOOP^2*vev^2*ye^3*No[9]*PartOp[2])/Λ    (aLOOP^2*vev^2*ye^3*No[1]*PartOp[4])/Λ
(aLOOP*vev^4*ye^3*No[1]*PartOp[2])/Λ^3    (aLOOP*vev^4*ye^3*No[1]*PartOp[4])/Λ^3
"Operator 3 version 1"    (aLOOP^2*g^2*vev^2*yd*No[13]*PartOp[2])/Λ    (aLOOP^2*g^2*vev^2*yd*No[13]*PartOp[4])/Λ    (aLOOP^3*g^4*vev^2*yd*No[9]*PartOp[2])/Λ
(aLOOP^3*g^2*vev^2*yd^3*No[21]*PartOp[2])/Λ    (aLOOP^3*g^2*vev^2*yd^3*No[23]*PartOp[2])/Λ    (aLOOP^3*g^2*vev^2*yd^3*No[21]*PartOp[4])/Λ    (aLOOP^3*g^2*vev^2*yd^
(aLOOP^3*g^2*vev^2*yd^3*No[11]*PartOp[2])/Λ    (aLOOP^3*g^2*vev^2*yd^3*No[11]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^4*yd^3*No[17]*PartOp[2])/Λ^3    (aLOOP^2*g^2*vev^4*yd^
(aLOOP^3*vev^2*yd*ye^2*yu^2*No[3]*PartOp[1])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[7]*PartOp[1])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[5]*PartOp[2])/Λ    (aLOOP^3*vev^2*yd*ye^2
(aLOOP^3*vev^2*yd*ye^2*yu^2*No[3]*PartOp[3])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[7]*PartOp[3])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[5]*PartOp[4])/Λ    (aLOOP^3*vev^2*yd*ye^2
(aLOOP^2*vev^4*yd*ye^2*yu^2*No[1]*PartOp[2])/Λ^3    (aLOOP^2*vev^4*yd*ye^2*yu^2*No[1]*PartOp[4])/Λ^3    (aLOOP^3*g^2*vev^4*yd*ye^2*yu^2*No[1]*PartOp[2])/Λ^3
(aLOOP^3*g^2*vev^4*yd*ye^2*yu^2*No[1]*PartOp[4])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[5]*PartOp[1])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[9]*PartOp[1])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[13]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[15]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[5]*PartOp[3])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[9]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[13]*PartOp[4])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[15]*PartOp[4])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[3]*PartOp[1])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[7]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[3]*PartOp[3])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[7]*PartOp[4])/Λ^3    (aLOOP^2*vev^6*yd^3*ye^2*yu^2*No[9]*PartOp[2])/Λ^5    (aLOOP^2*vev^6*yd^3*ye^2*yu^2*No[9]*PartOp[4])/Λ^5
(aLOOP^3*vev^4*yd*ye^2*yu^4*No[15]*PartOp[1])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[19]*PartOp[1])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[5]*PartOp[2])/Λ^3
Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[15]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[19]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[5]*PartOp[4])/Λ
(aLOOP^3*vev^4*yd*ye^2*yu^4*No[7]*PartOp[4])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[1]*PartOp[1])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[3]*PartOp[2])/Λ^3
Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[3]*PartOp[4])/Λ^3    (aLOOP^2*vev^6*yd*ye^2*yu^4*No[1]*PartOp[2])/Λ^5    (aLOOP^2*vev^6*yd*ye^2*yu^4*No[1]*PartOp[4])/Λ
"Operator 3 version 2"    (aLOOP*vev^2*yd*No[1]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*yd*No[1]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*yd*No[13]*PartOp[2])/Λ    (aLOOP
(aLOOP^2*vev^2*yd^3*No[5]*PartOp[4])/Λ    (aLOOP^2*vev^2*yd^3*No[7]*PartOp[4])/Λ    (aLOOP^2*vev^2*yd^3*No[5]*PartOp[4])/Λ    (aLOOP*vev^4*yd^3*No[1]*PartOp[4])/Λ^3    (aLOOP
(aLOOP^3*g^2*vev^2*yd^3*No[23]*PartOp[2])/Λ    (aLOOP^3*g^2*vev^2*yd^3*No[11]*PartOp[2])/Λ    (aLOOP^2*g^2*vev^4*yd^3*No[17]*PartOp[2])/Λ^3    (aLOOP^3*vev^2*yd*ye^2
(aLOOP^3*vev^2*yd*ye^2*yu^2*No[7]*PartOp[2])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[3]*PartOp[3])/Λ    (aLOOP^3*vev^2*yd*ye^2*yu^2*No[7]*PartOp[3])/Λ    (aLOOP^2*vev^4*yd*ye^2
(aLOOP^4*g^2*vev^2*yd*ye^2*yu^2*No[13]*PartOp[1])/Λ    (aLOOP^4*g^2*vev^2*yd*ye^2*yu^2*No[17]*PartOp[1])/Λ    (aLOOP^3*g^2*vev^4*yd*ye^2*yu^2*No[1]*PartOp[2])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[13]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[15]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[5]*PartOp[3])/Λ^3
(aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[9]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[7]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^3*ye^2*yu^2*No[3]*PartOp[3])/Λ^3
(aLOOP^2*vev^6*yd^3*ye^2*yu^2*No[9]*PartOp[2])/Λ^5    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[5]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[7]*PartOp[2])/Λ^3
(aLOOP^3*vev^4*yd*ye^2*yu^4*No[15]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[19]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd*ye^2*yu^4*No[3]*PartOp[2])/Λ^3
Λ^3    (aLOOP^2*vev^6*yd*ye^2*yu^4*No[1]*PartOp[2])/Λ^5    (aLOOP^4*g^2*vev^4*yd^3*ye^2*yu^2*No[29]*PartOp[1])/Λ^3    (aLOOP^4*g^2*vev^4*yd^3*ye^2*yu^2*No[33]*PartO
(aLOOP^4*g^2*vev^4*yd^3*ye^2*yu^2*No[13]*PartOp[1])/Λ^3    (aLOOP^4*g^2*vev^4*yd*ye^2*yu^4*No[35]*PartOp[1])/Λ^3    (aLOOP^4*g^2*vev^4*yd*ye^2*yu^4*No[39]*PartOp[1])/Λ^3
(aLOOP^4*g^2*vev^4*yd*ye^2*yu^4*No[15]*PartOp[1])/Λ^3    (aLOOP^4*vev^4*yd*ye^4*yu^4*No[3]*PartOp[1])/Λ^3    (aLOOP^4*vev^4*yd*ye^4*yu^4*No[7]*PartOp[1])/Λ^3
(aLOOP^4*vev^6*yd^3*ye^4*yu^4*No[5]*PartOp[1])/Λ^5    (aLOOP^4*vev^6*yd^3*ye^4*yu^4*No[9]*PartOp[1])/Λ^5    (aLOOP^4*vev^6*yd^3*ye^4*yu^4*No[1]*PartOp[1])/Λ^5
(aLOOP^4*vev^6*yd*ye^4*yu^6*No[11]*PartOp[1])/Λ^5    (aLOOP^4*vev^6*yd*ye^4*yu^6*No[15]*PartOp[1])/Λ^5    (aLOOP^4*vev^6*yd*ye^4*yu^6*No[3]*PartOp[1])/Λ^5
"Operator 4 version 1"    (aLOOP*vev^2*yu*No[1]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*yu*No[1]*PartOp[4])/Λ    (aLOOP^2*g^2*vev^2*yu*No[13]*PartOp[2])/Λ    (aLOOP
(aLOOP^2*vev^2*yu^3*No[5]*PartOp[4])/Λ    (aLOOP^2*vev^2*yu^3*No[7]*PartOp[4])/Λ    (aLOOP^2*vev^2*yu^3*No[5]*PartOp[4])/Λ    (aLOOP*vev^4*yu^3*No[1]*PartOp[4])/Λ^3    (aLOOP
(aLOOP^3*g^2*vev^2*yu^3*No[23]*PartOp[2])/Λ    (aLOOP^3*g^2*vev^2*yu^3*No[11]*PartOp[2])/Λ    (aLOOP^2*g^2*vev^4*yu^3*No[17]*PartOp[2])/Λ^3    (aLOOP^3*vev^2*yd^2*ye
(aLOOP^3*vev^2*yd^2*ye^2*yu*No[7]*PartOp[2])/Λ    (aLOOP^3*vev^2*yd^2*ye^2*yu*No[3]*PartOp[3])/Λ    (aLOOP^3*vev^2*yd^2*ye^2*yu*No[7]*PartOp[3])/Λ    (aLOOP^2*vev^4*yd^2*ye
(aLOOP^4*g^2*vev^2*yd^2*ye^2*yu*No[13]*PartOp[1])/Λ    (aLOOP^4*g^2*vev^2*yd^2*ye^2*yu*No[17]*PartOp[1])/Λ    (aLOOP^3*g^2*vev^4*yd^2*ye^2*yu*No[1]*PartOp[2])/Λ^3
Λ^3    (aLOOP^3*vev^4*yd^4*ye^2*yu*No[7]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^4*ye^2*yu*No[15]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd^4*ye^2*yu*No[19]*PartOp[3])/Λ
(aLOOP^3*vev^4*yd^4*ye^2*yu*No[3]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^4*ye^2*yu*No[1]*PartOp[3])/Λ^3    (aLOOP^2*vev^6*yd^4*ye^2*yu*No[1]*PartOp[2])/Λ^5
(aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[13]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[15]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[5]*PartOp[3])/Λ^3
(aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[9]*PartOp[3])/Λ^3    (aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[7]*PartOp[2])/Λ^3    (aLOOP^3*vev^4*yd^2*ye^2*yu^3*No[3]*PartOp[3])/Λ^3
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Resulting Contributions to $0\nu\beta\beta$

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- result of our code: dominant contributions of $\Delta L = 2$ SM effective operators to mass, long-range and and short-range mechanisms of $0\nu\beta\beta$ decay
- e.g. 11D $\Delta L = 2$ SM effective operators:

$\mathcal{O}$	Operator	m_ν	LR	$\epsilon_{\rm LR}$	SR	$\epsilon_{\rm SR}$
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_e y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e y_e^{\rm ex} y_u^{\rm ex}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon_{V-A}^{V+A}$	–	–
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_e y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e y_e^{\rm ex} y_u^{\rm ex}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon_{V-A}^{V+A}$	–	–
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_e y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_{d\|(e)}^{\rm ex} y_d^{\rm ex} y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon_{S-P}^{S+P}\|\epsilon_{V+A}^{V+A}$	–	–
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S+P}^{S+P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S+P}^{S+P}	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ_{S+P}^{S+P}	$\frac{y_u^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
26_a	$L^iL^jQ^kd^c\overline{L}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_e y_d}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S+P}^{S+P}	–	–
26_b	$L^iL^jQ^kd^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_e y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ_{S+P}^{S+P}	–	–
27_a	$L^iL^jQ^kd^c\overline{Q}_i\bar{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S+P}^{S+P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
27_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ_{S+P}^{S+P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
28_a	$L^iL^jQ^kd^c\overline{Q}_j\bar{u^c}H^l\overline{H}_i\epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S+P}^{S+P}	$\frac{v^2}{\Lambda^7}$	ϵ_1
28_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{u^c}H^l\overline{H}_i\epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_{u\|d}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon_{S\pm P}^{S+P}$	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
28_c	$L^iL^jQ^kd^c\overline{Q}_l\bar{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S-P}^{S+P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
29_a	$L^iL^jQ^ku^c\overline{Q}_k\bar{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ_{S-P}^{S+P}	$\frac{y_d^{\rm ex} y_u^{\rm ex}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
29_b	$L^iL^jQ^ku^c\overline{Q}_l\bar{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S-P}^{S+P}	$\frac{y_d^{\rm ex} y_u^{\rm ex}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
30_a	$L^iL^j\overline{L}_i\overline{e^c}\overline{Q}_k\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_e y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S-P}^{S+P}	–	–
30_b	$L^iL^j\overline{L}_m\overline{e^c}\overline{Q}_n\bar{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_e y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ_{S-P}^{S+P}	–	–
31_a	$L^iL^j\overline{Q}_i\bar{d^c}\overline{Q}_k\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ_{S-P}^{S+P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
31_b	$L^iL^j\overline{Q}$ [illegible] $\bar{d^c}\overline{Q}$ [illegible] $\bar{u^c}H^kH^l\epsilon$ [illegible] ϵ^{mn}	$y_d y_u$ [illegible] v^2 [illegible] $f($ [illegible]	y_d [illegible] v [illegible]	ϵ^{S+P} [illegible]	$y_d^{\rm ex2}$ [illegible] 1 [illegible]	ϵ_1

Implications for Baryon Asymmetry?

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Suppose we have LNV processes triggered by one of the above operators.

What does it imply for mechanisms of baryogenesis?

Baryon Asymmetry

- observed baryon asymmetry $\rightarrow$ asymmetry in primordial matter and antimatter
- $\eta_b^{\text{obs}} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$
- BSM mechanism of baryogenesis needed, 3 Sakharov conditions

- popular theory: leptogenesis - the asymmetry produced at a high scale in the lepton sector can be converted into a baryon asymmetry via sphaleron processes

Leptogenesis

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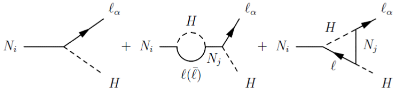
- heavy neutrino N decays out of equilibrium to leptons and antileptons unevenly M. Fukugita, T. Yanagida: Phys. Lett. B **174** (1986), p. 45

$$\varepsilon_{1CP} = \frac{\sum_\alpha \left(\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell_\alpha} H^*)\right)}{\sum_\alpha \left(\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell_\alpha} H^*)\right)}$$

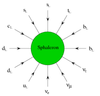
- contributing processes:

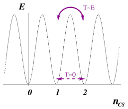


- the asymmetry in the lepton sector can be converted into baryon asymmetry via sphaleron processes

F. R. Klinkhamer, N. S. Manton: Phys. Rev. D **30** (1984), p. 2212–2220

- tunnelling between different vacua, $100 \lesssim T \lesssim 10^{12}$ GeV
- occurs at the boundary between broken and unbroken phase (between different vacuum states)





Leptogenesis: Washout Effects

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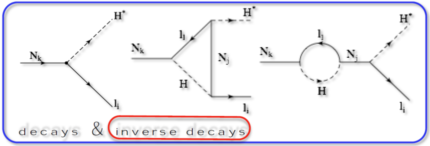
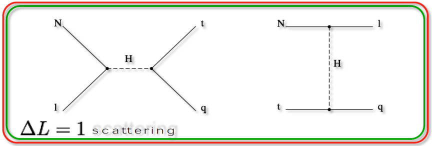
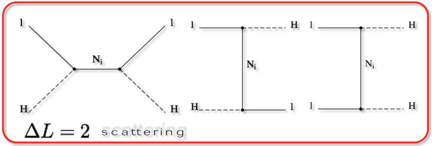
- evolution of lepton number density described by Boltzmann equations

- $$Hz\frac{\mathrm{N}_{\mathrm{N}_1}}{\mathrm{d}z} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{eq}),$$
  $$Hz\frac{\mathrm{N}_{\mathrm{N}_\mathrm{L}}}{\mathrm{d}z} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{eq}) - \Gamma_W N_L$$
  and $z = \frac{M_{N_1}}{T}$







- competition between generation of lepton asymmetry and LNV washout processes

- but what about LNV at some lower scale described by one of the above presented $\Delta L = 2$ SM effective operators?

Washout Effects: Example

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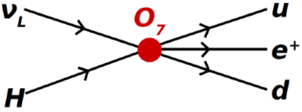
- for 7D operator $\frac{1}{\Lambda^3}\left(L^i d^c\right)\left(\bar{e^c}\bar{u^c}H^j\epsilon_{ij}\right)$



$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -\left[L_e\bar{e^c} \leftrightarrow u^c\bar{d^c}\bar{H}\right] + (\text{other permutations})$$

$$= -\left(\frac{n_{L_e}n_{\bar{e^c}}}{n^{\text{eq}}_{L_e}n^{\text{eq}}_{\bar{e^c}}} - \frac{n_{u^c}n_{\bar{d^c}}n_{\bar{H}}}{n^{\text{eq}}_{u^c}n^{\text{eq}}_{\bar{d^c}}n^{\text{eq}}_{\bar{H}}}\right)\gamma^{\text{eq}}(L_e\bar{e^c} \to u^c\bar{d^c}\bar{H}) + \cdots$$

- relate chemical potentials:

$$\mu_H = \tfrac{4}{21}\textstyle\sum_\ell \mu_{L_\ell},\ \mu_{\bar{u^c}} = \tfrac{5}{63}\sum_\ell \mu_{L_\ell},\ \mu_{\bar{e^c_\ell}} = \mu_{L_\ell} - \tfrac{4}{21}\sum_\ell \mu_{L_\ell},\ \mu_{\bar{d^c}} = -\tfrac{19}{63}\sum_\ell \mu_{L_\ell}$$

- $\implies n_\gamma HT\frac{\mathrm{d}\eta_L}{\mathrm{d}T} = c_7\frac{T^{10}}{\Lambda_7^6}\eta_L$, where $c_7 \equiv \frac{11\sqrt{195}}{7\pi^7}$

- LNV processes that equilibrate species $\iff$ 3rd Sakharov condition (needed for leptogenesis) violated

Washout Effects

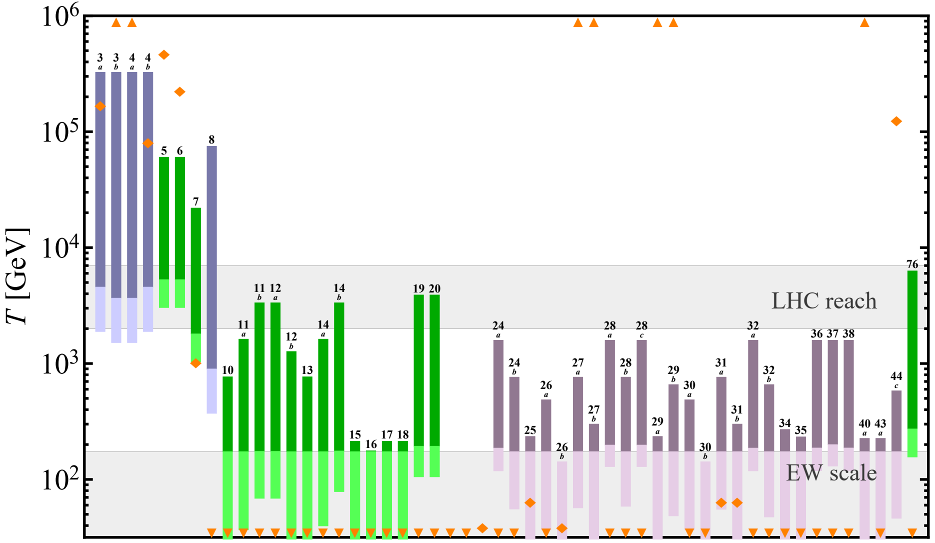
- for dimension-D operator: $n_\gamma H T \frac{\mathrm{d}\eta_L}{\mathrm{d}T} = c_D \frac{T^{2D-4}}{\Lambda_D^{2D-8}} \eta_L$

- washout is effective if: $\frac{\Gamma_W}{H} = c'_D \frac{\Lambda_{Pl}}{\Lambda_D} \left(\frac{T}{\Lambda_D} \right)^{2D-9} \gtrsim 1$

- if $0\nu\beta\beta$ is observed $\implies$ lepton number asymmetry washed out in temperature interval:

$$\Lambda_D \left(\frac{\Lambda_D}{c'_D \Lambda_{Pl}} \right)^{\frac{1}{2D-9}} \equiv \lambda_D \lesssim T \lesssim \Lambda_D$$

Results - Washout Intervals



Discrimination of $0\nu\beta\beta$ Decay Mechanism

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- analysis of angular correlation between the emitted electrons

- in certain cases the operators correspond to a final state of opposite electron chiralities (e.g. $\mathcal{O}_8$) $\implies$ can be distinguished by SuperNEMO from the purely left-handed current interaction via the measurement of the decay distribution

  R. Arnold et al. (NEMO-3): Phys. Rev. D98 (2007), 232501

- some operators can be probed at the LHC

- another way: comparing ratios of half life measurements for different isotopes

  F. Deppisch, H. Päs: Phys. Rev. Lett. 89 (2014), 111101

Conclusions

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- a number of different non-standard mechanisms can contribute to $0\nu\beta\beta$ decay
- improved description of the short-range scenarios
  $\implies$ new limits on BSM physics from experimental bounds on $0\nu\beta\beta$ decay half-life and nuclear (and atomic) calculations
- $\Delta L = 2$ SM effective operators - can be correlated with the low-energy effective description of $0\nu\beta\beta$ decay
- observation of $0\nu\beta\beta$ decay $\rightarrow$ possible implications for baryon asymmetry and neutrino mass origin

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Thank You for attention!