Non-Standard Mechanisms of Neutrinoless Double Beta Decay, Their Probes and Implications

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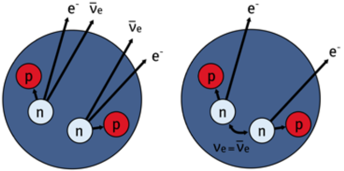
Introduction and Motivation

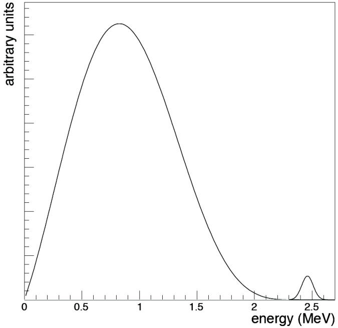
- neutrinos - neutral, left-handed, massive, light ...
- $\Longrightarrow$ problem of the Standard Model (SM)
- Dirac or Majorana nature?
- Majorana masses $\Longleftrightarrow$ LNV $\Longleftrightarrow$ neutrinoless double beta decay ($0\nu\beta\beta$)
- massive right-handed neutrinos (seesaw mechanism) $\Longrightarrow$ leptogenesis

Neutrinoless Double Beta Decay

- current limit: $T_{1/2}^{^{76}Ge} > 2.1 \times 10^{25}$ y (GERDA)

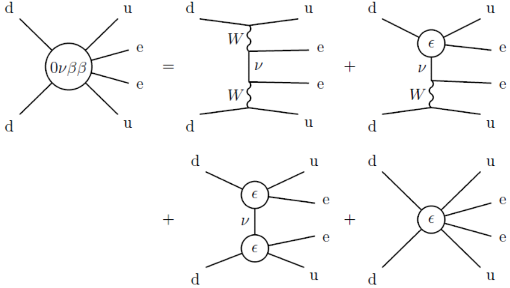
  $T_{1/2}^{^{136}Xe} > 1.07 \times 10^{26}$ y (KamLAND-Zen)
- future experimental sensitivity: $T_{1/2} \sim 6.6 \times 10^{27}$ y (nEXO)





Neutrinoless Double Beta Decay

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



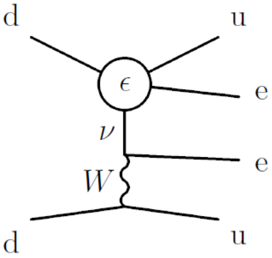
- F. F. Deppisch, M. Hirsch, H. Päs: *Neutrinoless Double Beta Decay and Physics Beyond the Standard Model*, J. Phys. G **39** (2012), 124007

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

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

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

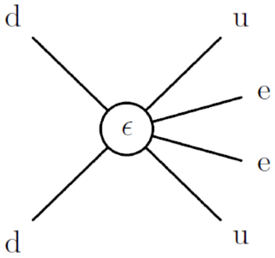


General Lagrangian for $0\nu\beta\beta$

- short range part:

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

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



- connection to the experimental half-life: $T_{1/2}^{-1} = |\epsilon_{\alpha}^{\beta}|^2 G_i |M_i|^2$
- $\implies$ $0\nu\beta\beta$ half-life sets constraints on effective couplings

Isotope	$\lvert\epsilon_{V-A}^{V+A}\rvert$	ϵ_{V+A}^{V+A}	ϵ_{S-P}^{S+P}	ϵ_{S+P}^{S+P}	ϵ_{TL}^{TR}	ϵ_{TR}^{TR}
^{76}Ge	3.3×10^{-9}	5.9×10^{-7}	1.0×10^{-8}	1.0×10^{-8}	6.4×10^{-10}	1.0×10^{-9}

Isotope	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz(RRz)}\rvert$	$\epsilon_3^{LRz(RLz)}$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
^{76}Ge	3.0×10^{-7}	1.7×10^{-9}	2.1×10^{-8}	1.3×10^{-8}	1.4×10^{-8}	1.4×10^{-7}

- accurate calculation of nuclear matrix elements (NMEs) and phase-space factors (PSFs) is crucial for this estimation

Nuclear Matrix Elements and Phase-Space Factors for $0\nu\beta\beta$ Decay

- goal: a thorough theoretical description of non-standard $0\nu\beta\beta$ decay mechanisms - involves NMEs and PSFs $\rightarrow$ a very complex, interdisciplinary project
- collaboration with prof. Francesco Iachello from Yale University started
- understanding the nuclear and atomic parts of the process
- nuclear description - Interacting Boson Model (IBM)

Nuclear Matrix Elements and Phase-Space Factors for $0\nu\beta\beta$ Decay

- older literature may cause a confusion (notations, mistakes, lack of explanation), but long-range part recently rigorously covered (checked)
- $\implies$ similar analysis of the short-range part $\implies$ complete, consistent and cross-checked description of all contributions
- application of the nuclear physics model (IBM2, maybe more), numerical calculation of NMEs
- numerical computation of relevant PSFs

- complicated calculation - a number of approximations used (nucleon current approximation, non-relativistic approximation, closure approximation)
- considering nucleon isodoublet $\mathcal{N} = \binom{P}{N}$, the nucleon matrix elements of the quark currents are

$$\begin{aligned}
\langle P(p)|\, \bar{u}(1 \pm \gamma_5) d \left| N(p') \right\rangle &= \bar{\mathcal{N}}(p)\tau^+ \left[F_S^{(3)}(q^2) \pm F_P^{(3)}(q^2)\gamma_5 \right] \mathcal{N}(n), \\
\langle P(p)|\, \bar{u}\gamma^\mu(1 \pm \gamma_5) d \left| N(p') \right\rangle &= \bar{\mathcal{N}}(p)\tau^+ \left[F_V^{(3)}(q^2)\gamma^\mu - iF_W^{(3)}(q^2)\sigma^{\mu\nu}q_\nu \right] \mathcal{N}(n) \\
&\quad \pm \bar{\mathcal{N}}(p)\tau^+ \left[F_A^{(3)}(q^2)\gamma^\mu\gamma_5 - F_P^{(3)}(q^2)\gamma_5 q^\mu \right] \mathcal{N}(n), \\
\langle P(p)|\, \bar{u}\sigma^{\mu\nu}(1 \pm \gamma_5) d \left| N(p') \right\rangle &= \bar{\mathcal{N}}(p)\tau^+ \left[J^{\mu\nu} \pm \frac{i}{2}\varepsilon^{\mu\nu\rho\sigma} J_{\rho\sigma} \right] \mathcal{N}(n),
\end{aligned}$$

where we have defined:

$$J^{\mu\nu} = T_q^{(3)}(q^2)\sigma^{\mu\nu} + T_2^{(3)}(q^2)\frac{i}{m_p}(\gamma^\mu q^\nu - \gamma^\nu q^\mu) + T_3^{(3)}(q^2)\frac{1}{m_p^2}(\sigma^{\mu\rho}q_\rho q^\nu - \sigma^{\nu\rho}q_\rho q^\mu).$$

- non-relativistic limit then gives the resulting approximated nuclear bilinears

$$
\begin{aligned}
J_{S\pm P} &= \sum_a \tau_+^a \delta(\mathbf{x}-\mathbf{r}_a)\left(F_S^{(3)} \pm F_P^{(3)}\frac{1}{2m_p}(\boldsymbol{\sigma}_a\cdot\boldsymbol{q})\right),\\
J^\mu_{V\pm A} &= \sum_a \tau_+^a \delta(\mathbf{x}-\mathbf{r}_a)\left\{g^{\mu 0}\left[F_V(q^2)I_a \pm \frac{F_A(q^2)}{2m_p}\left(\boldsymbol{\sigma}_a\cdot\boldsymbol{Q} - \frac{F_P(q^2)}{F_A(q^2)}q^0\mathbf{Q}\cdot\boldsymbol{\sigma}_a\right)\right]\right.\\
&\quad \left. + g^{\mu i}\left[\mp F_A(q^2)(\boldsymbol{\sigma}_a)_i - \frac{F_V(q^2)}{2m_p}\left(\mathbf{Q}I_a - \left(1 - 2m_p\frac{F_W(q^2)}{F_V(q^2)}\right)i\boldsymbol{\sigma}\times\mathbf{q}\right)_i\right]\right\},\\
J^{\mu\nu}_{T\pm T_5} &= \sum_a \tau_+^a \delta(\mathbf{x}-\mathbf{r}_a)\,T_1^{(3)}\Big[(g^{\mu i}g^{\nu 0} - g^{\mu 0}g^{\nu i})T_a^i + g^{\mu j}g^{\nu k}\varepsilon^{ijk}\sigma^{ai}\\
&\quad \pm\frac{i}{2}\varepsilon^{\mu\nu\rho\sigma}(g_{\mu i}g_{\nu 0} - g_{\mu 0}g_{\nu i})T_{ai} + g_{\mu m}g_{\nu n}\varepsilon_{mni}\sigma_{ai}\Big],
\end{aligned}
$$

where we have defined:

$$
T_a^i = \frac{i}{2m_p}\left[\left(1 - 2\frac{T_2^{(3)}}{T_1^{(3)}}\right)q^i I_a + (\boldsymbol{\sigma}_a\times\mathbf{Q})^i\right].
$$

Nuclear Matrix Elements and Phase-Space Factors for $0\nu\beta\beta$ Decay

- reaction matrix element

$$\mathcal{R}_{0\nu}^{SR} = \left(\frac{G\cos\theta_C}{\sqrt{2}}\right)^2 \sum_{i=1}^{2n} \int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y} \left[\bar{\psi}_e^{\mathbf{p}_2 s_2'}(\mathbf{y}) O_l 2P_c \psi_e^{\mathbf{p}_1 s_1'}(\mathbf{x})\right] \times \int \frac{\mathrm{d}\mathbf{k}}{(2\pi)^3} \langle F| J_{c_1 i}^{l_1}(\mathbf{y}) J_{c_2 i}^{l_2}(\mathbf{x}) |I\rangle e^{i\mathbf{k}\cdot(\mathbf{y}-\mathbf{x})},$$

- $\Longrightarrow$ a bunch of matrix elements to be computed

$$M_{GT} = \langle H(r_{12})(\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2})\rangle$$

$$\chi_F = (M_{GT})^{-1} \frac{g_V^2}{g_A^2} \langle H(r_{12})\rangle$$

$$\tilde{\chi}_{GT} = (M_{GT})^{-1} \langle \tilde{H}(r_{12})(\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2})\rangle$$

$$\tilde{\chi}_F = (M_{GT})^{-1} \frac{g_V^2}{g_A^2} \langle \tilde{H}(r_{12})\rangle$$

$$\chi'_{GT} = (M_{GT})^{-1} \langle -r_{12} H'(r_{12})(\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2})\rangle$$

$$\chi'_F = (M_{GT})^{-1} \frac{g_V^2}{g_A^2} \langle -r_{12} H'(r_{12})\rangle$$

$$\chi'_T = (M_{GT})^{-1} \langle -r_{12} H'(r_{12}) \left[(\boldsymbol{\sigma_1}\cdot\widehat{\boldsymbol{r}}_{\boldsymbol{12}})(\boldsymbol{\sigma_2}\cdot\widehat{\boldsymbol{r}}_{\boldsymbol{12}}) - \tfrac{1}{3}(\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2})\right]\rangle$$

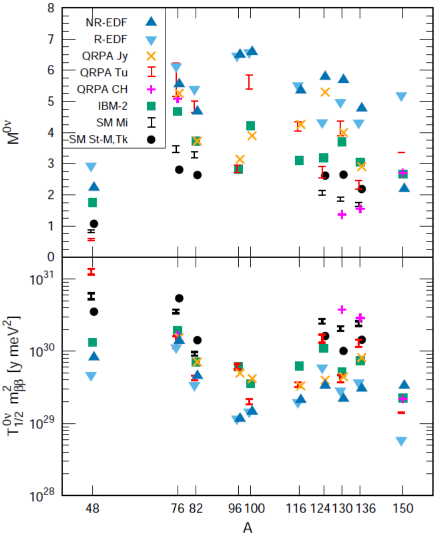
$$\chi'_R = (M_{GT})^{-1} \frac{g_V}{\ldots} \langle -\frac{1}{\ldots} r_{+12} H'(r_{12}) i(\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot(\widehat{\boldsymbol{r}}_{\boldsymbol{12}}\times\widehat{\boldsymbol{r}}_{\boldsymbol{+12}})\rangle$$

Nuclear Matrix Elements for $0\nu\beta\beta$ Decay

- different nuclear physics models ... so far, quite different results ...

- J. Engel, J. Menéndez: *Status and Future of Nuclear Matrix Elements for Neutrinoless Double-Beta Decay: A Review*,

  arXiv: 1610.06548



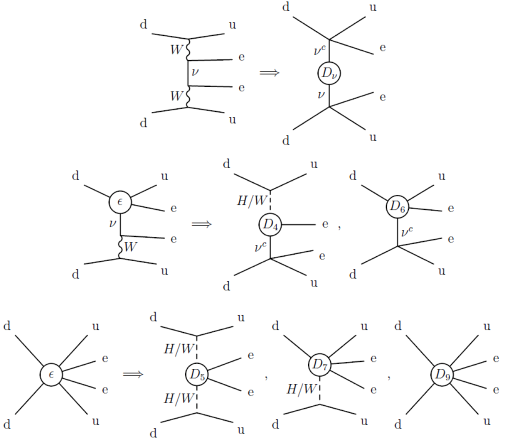
LNV Effective Operators

- alternatively: $0\nu\beta\beta$ can be described using SM effective field theories with $\Delta L = 2$
- a long list of eff. operators, odd dimensions: $5, 7, 9, 11, \ldots$
  - A. de Gouvea, J. Jenkins: *A Survey of Lepton Number Violation Via Effective Operators*, Phys. Rev. D **77** (2008), 013008

$\mathcal{O}$	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
14_b	$L^iL^j\overline{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$	U
15	$L^iL^jL^kd^c\overline{L}_i\bar{u^c}\epsilon_{jk}$	$\frac{y_d y_u g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$	U
16	$L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC	U

LNV Effective Operators and $\mathcal{L}_{0\nu\beta\beta}$

- correspondence between general $0\nu\beta\beta$ decay Lagrangian and the set of $\Delta L = 2$ LNV effective operators



LNV Effective Operators & $0\nu\beta\beta$ decay

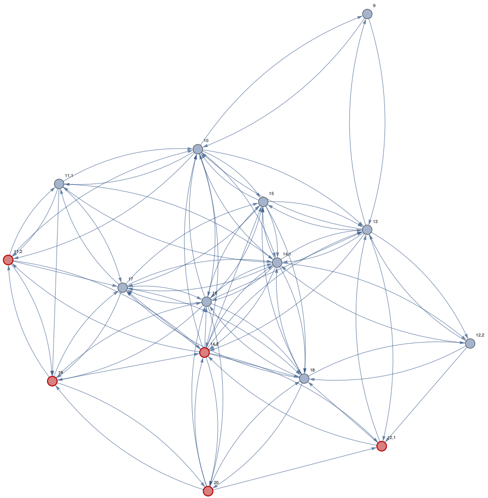
- there is a variety of operators of different dimensions contributing (directly) to $0\nu\beta\beta$ decay (employing certain type of mechanism)

- all the $\Delta L = 2$ LNV effective operators can be related by SM Feynman rules

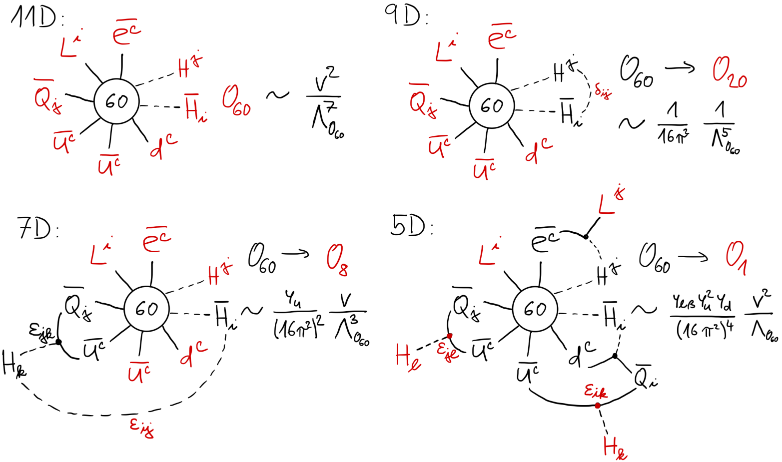
- $\Longrightarrow$ all of them contribute to $0\nu\beta\beta$ decay in all possible ways

- 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: a “web” of LNV effective operators of dimension 9



- 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)



LNV Effective Operators & $0\nu\beta\beta$

- similar reduction can be done for each LNV effective operator
- every operator can be related to all possible $0\nu\beta\beta$-decay-trigerring operators $\rightarrow$ more than just 4 loop-closing calculations need to be done
- automation - loop-closing algorithm, all possible contributions obtained, for some operators - quite a demanding computation
- at the moment we are cross-checking the results, selecting the dominant ones, final results soon
- resulting prefactors - relations among operators' scales and epsilons from $\mathcal{L}_{0\nu\beta\beta}$ $\rightarrow$ use for further calculations

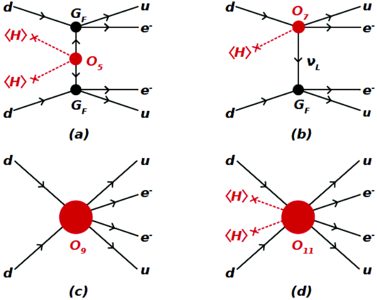
LNV Operators and $0\nu\beta\beta$ - Illustration

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

- if $0\nu\beta\beta$ is observed, the scale of the underlying operator can be determined

- $m_e \epsilon_{\mathcal{O}_5} = \frac{v^2}{\Lambda_5}, \; \frac{G_F \epsilon_{\mathcal{O}_7}}{\sqrt{2}} = \frac{v}{2\Lambda_7^3}$

- $\frac{G_F^2 \epsilon_{\{\mathcal{O}_9, \mathcal{O}_{11}\}}}{2m_p} = \left\{ \frac{1}{\Lambda_9^5}, \frac{v^2}{\Lambda_{11}^7} \right\}$



$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl},$$
$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c} \bar{u^c}) H^j \epsilon_{ij},$$
$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

Washout Effects

- LNV processes that equilibrate species $\iff$ 3rd Sakharov condition (needed for leptogenesis) violated
- washout is effective if: $\dfrac{\Gamma_W}{H} = c'_D \dfrac{\Lambda_{Pl}}{\Lambda_D} \left(\dfrac{T}{\Lambda_D}\right)^{2D-9} \gtrsim 1$
- if $0\nu\beta\beta$ is observed $\implies$ lepton number asymmetry washed out in temperature interval:

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

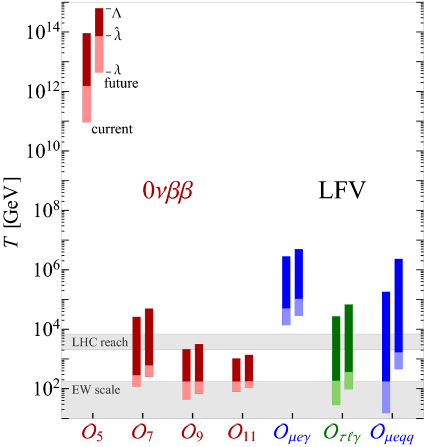
- solving the Boltzmann equation $\implies$ scale $\hat{\lambda}_D$, above which a maximal lepton asymmetry of 1 is washed out to η_b^{obs} or less

$$\hat{\lambda}_D \approx \left[(2D-9)\ln\left(\frac{10^{-2}}{\eta_b^{\mathrm{obs}}}\right)\lambda_D^{2D-9} + v^{2D-9}\right]^{\frac{1}{(2D-9)}}$$

Results

- big gap between Weinberg op. $\mathcal{O}_5 \approx 10^{14}$ GeV and other LNV operators $\approx 10^{3-4}$ GeV

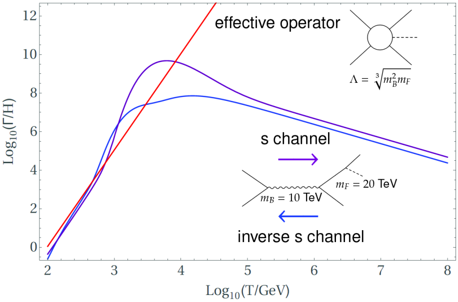
- observation of a non-standard $0\nu\beta\beta$ mechanism would imply that highscale baryogenesis is generally excluded $\rightarrow$ it is likely to occur at a low scale, under the electroweak scale



- if high scale baryogenesis $\implies$ the only manifestation of LNV at low scales is $0\nu\beta\beta$ through the standard mass mechanism + origin of neutrino mass lies very probably at a high scale

Effective Approach v. UV-completed Model

- we also look at UV-completed models causing the effective LNV at low energies
- demonstration of the relevancy of the general effective approach, estimation of possible uncertainties
- figure: comparison of washout calculated using the effective LNV operator $\mathcal{O}_7$ and the corresponding UV-completion
- even when considering just the s-channel contribution, the washout rate of the completed model is higher



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

- analysis of angular correlation between the emitted electrons
- in certain cases the operators correspond to a final state of opposite electron chiralities (e.g. $\mathcal{O}_7$) $\implies$ 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): *Search for Neutrinoless Double-Beta Decay of 100Mo with the NEMO-3 Detector*, Phys.Rev. D **98** (2007), 232501
- some operators can be probed at the LHC (this is the case of $\mathcal{O}_9$ and $\mathcal{O}_{11}$)
- another way: comparing ratios of half life measurements for different isotopes
    - F. Deppisch, H. Päs: *Pinning down the mechanism of neutrinoless double beta decay with measurements in different nuclei*, Phys. Rev. Lett. **89** (2014), 111101

Conclusions

- $0\nu\beta\beta$ decay can be trigerred by a number of different mechanisms
- nuclear physics description of $0\nu\beta\beta$ decay - a complex problem; important hints for experiments and for discrimination of the underlying mechanism; nontrivial to get reliable numerical results
- LNV effective operators - a convenient model-independent description of (not only) non-standard $0\nu\beta\beta$ decay mechanisms; operators' scales constrained by half-life and nuclear predictions
- observation of $0\nu\beta\beta$ decay $\rightarrow$ possible implications for baryon asymmetry and neutrino mass origin

Thank You for attention