Neutrinoless double beta decay of hyperons in covariant chiral perturbation theory

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arXiv:2602.08453

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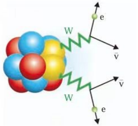
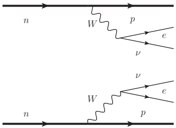
Nuclear double beta decays

- $2\nu 2\beta$-decay

  [M.G.Mayer,Phys.Rev.48,512(1935)]





$$T_{\frac{1}{2}} \sim 10^{18-24}\text{yr}$$

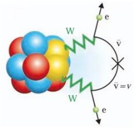
✓Experimentally Observed

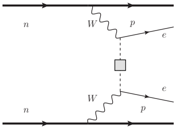
[A.s.Barabash,Phys.Rev.C81,035501(2010)]

$$^{A}_{Z}X \rightarrow {}_{Z+2}^{A}Y + 2e^{-} + 2\bar{\nu}_e$$

- $0\nu 2\beta$-decay

  [Furry,Phys,Rev.56,1184(1939)]





$$T_{\frac{1}{2}} > 3.8 \times 10^{26}\text{yr}$$

✓Lepton number violation
✓Majorana nature of neutrinos
✓Neutrino mass scale and hierarchy

[KamLAND-Zen Collaboration,arXiv:2406.11438 [hep-ex] (2024)]

$$^{A}_{Z}X \rightarrow {}_{Z+2}^{A}Y + 2e^{-}$$

Theoretical

Due to the lepton number violation(LNV) in the neutrinoless double beta decay process, there must be new physics to the process that goes beyond the Standard Model.

- Top-down approach: Study signals in explicit BSM
- Bottom-up approach: Work with effective field theories(EFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)} + \sum_k \frac{C_k^{(7)}}{\Lambda^3}\mathcal{O}_k^{(7)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \sum_j \frac{C_j^{(9)}}{\Lambda^5}\mathcal{O}_j^{(9)} + \cdots$$

$$\mathcal{O}^{(5)} = \epsilon_{kl}\epsilon_{mn}(L_k^T \mathcal{C}^{(5)} C L_m) H_l H_n$$

[Phys. Rev. Lett. 43 (1979) 1566]
[JHEP 11(2016)043]

$$\psi^2 H^4: \quad \epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$$

$$\psi^2 H^2 D^2: \quad \epsilon_{ij}\epsilon_{mn}(L_i^T C D_\mu L_j) H_m (D^\mu H)_n$$

$$\epsilon_{im}\epsilon_{jn}(L_i^T C D_\mu L_j) H_m (D^\mu H)_n$$

$$\psi^2 H^3 D: \quad \epsilon_{ij}\epsilon_{mn}(L_i^T C \gamma^\mu e) H_m (D_\mu H)_n$$

$$\psi^2 H^2 X: \quad \epsilon_{ij}\epsilon_{mn} g' (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n B_{\mu\nu}$$

$$\epsilon_{ij}(\epsilon\tau^I)_{mn} g (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n W^I_{\mu\nu}$$

$$\psi^4 D: \quad \epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C D^\mu L_j)$$

$$\psi^4 H: \quad \epsilon_{ij}\epsilon_{mn}(\bar{e} L_i)(L_j^T C L_m) H_n$$

$$\epsilon_{ij}\epsilon_{mn}(\bar{d}_L Q_i^T C L_m) H_n$$

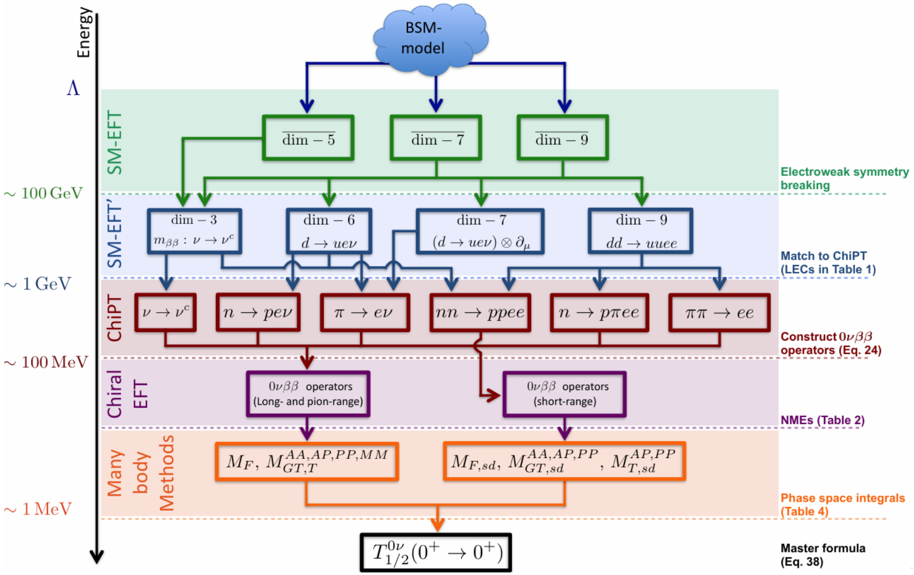
$$\epsilon_{ij}\epsilon_{mn}(\bar{d}_L Q_j^T C L_m) H_n$$

$$\epsilon_{ij}(\bar{u}_L Q_m^T C L_i) H_j$$

$$\epsilon_{ij}(\bar{e}\bar{d}_R)(Q_j^T C u_R) H_i$$

EFT at various energy scales

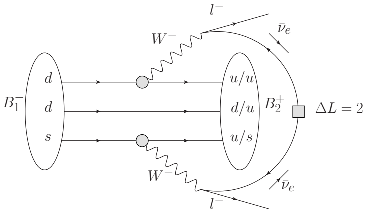
[Cirigliano,et al.JHEP12(2018)]



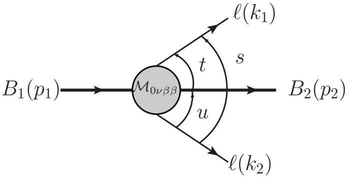
Hyperon $0\nu 2\beta$ decay in BChPT

BChPT is an effective field theory of QCD at low energy based on chiral symmetry at hadronic level.

A first glance: from quarks to hadrons



Quark level



Hadron level

- $\Delta S = 0$: $\Sigma^-[dds] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 1$: $\Sigma^-[dds] \to p[duu]\ell^-\ell^-$,$\Xi^-[dss] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 2$: $\Xi^-[dss] \to p[duu]\ell^-\ell^-$.

Chiral effective Lagrangian

The chiral effective Lagrangian relevant to the decay process:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{M}^{(2)} + \mathcal{L}_{\Delta L=2} + \mathcal{L}^{C}$$

- The LO baryon-meson interaction Lagrangian is given by

$$\mathcal{L}_{\text{MB}}^{(1)} = \text{Tr}\left[\bar{B}\left(i\not{D} - m\right)B\right] - \frac{D}{2}\left\langle \bar{B}\gamma^{\mu}\gamma_5\left\{u_{\mu}, B\right\}\right\rangle - \frac{F}{2}\left\langle \bar{B}\gamma^{\mu}\gamma_5\left[u_{\mu}, B\right]\right\rangle$$

- The LO chiral Lagrangian for purely mesonic interaction reads

$$\mathcal{L}_{M}^{(2)} = \frac{F_0^2}{4}\text{Tr}[(D_{\mu}U)^{\dagger}D^{\mu}U] + \frac{F_0^2}{4}\text{Tr}[U^{\dagger}\chi + U\chi^{\dagger}]$$

- Low-energy dimension-5 operator for the $\Delta L{=}2$ Lagrangian

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2}(m_{\ell\ell})_{ij}(\nu_{L,i}^{T}C\nu_{L,j} + \bar{\nu}_{L,i}C^{\dagger}\bar{\nu}_{L,j}^{T})$$

Counterterm Lagrangian

Under the chiral $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R}$ group

$$B \to KBK^\dagger \qquad \bar{B} \to K\bar{B}K^\dagger$$
$$u \to LuK^\dagger = KuR^\dagger \qquad T^+ \to LT^+L^\dagger$$

Chiral- and Lorentz-invariant counterterm Lagrangian:

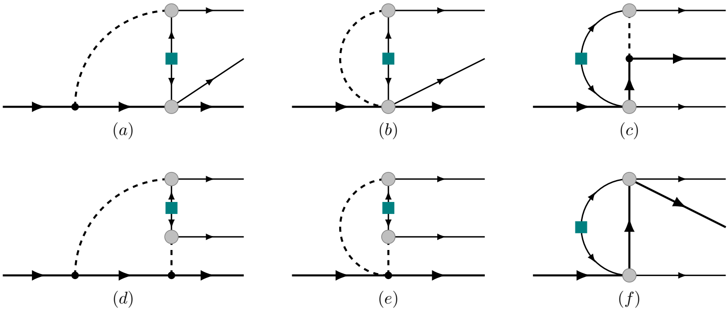
$$\mathcal{L}_1^C = 4m_{\ell\ell}G_F^2\,\mathrm{Tr}[\bar{B}u^\dagger T^+ u]g_{\mu\nu}(g_1 + g_1'\gamma_5)\mathrm{Tr}[u^\dagger T^+ uB]\bar{\ell}_L\gamma^\mu\gamma^\nu C\bar{\ell}_L^T + \text{h.c.}$$
$$\mathcal{L}_2^C = 4im_{\ell\ell}G_F^2\,\mathrm{Tr}[\bar{B}u^\dagger T^+ u]\gamma_\mu\gamma_\nu\gamma_\rho(g_2 + g_2'\gamma_5)\mathrm{Tr}[u^\dagger T^+ uB]\bar{\ell}_L\gamma^\mu\gamma^\nu C(\partial_\rho\bar{\ell}_L^T) + \text{h.c.}$$
$$\mathcal{L}_3^C = 4im_{\ell\ell}G_F^2\,\mathrm{Tr}[\bar{B}u^\dagger T^+ u]\gamma_\mu(g_3 + g_3'\gamma_5)\mathrm{Tr}[u^\dagger T^+ uB]\bar{\ell}_L\gamma^\mu\gamma^\nu C(\partial_\nu\bar{\ell}_L^T) + \text{h.c.}$$

Counterterm Lagrangian can be expressed as

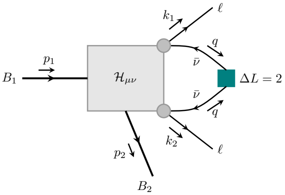
$$\mathcal{L}^C = \mathcal{L}_1^C + \mathcal{L}_2^C + \mathcal{L}_3^C$$

Hyperon $0\nu 2\beta$ decay in BChPT

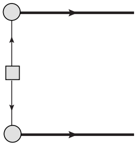
Description of $0\nu 2\beta$ decay of hyperons at one-loop level in ChPT



Amplitude structure



Mass mechanism



Leptonic part

$$\mathcal{M} = L^{\mu\nu} H_{\mu\nu} = \underbrace{T_{\text{lept}}[\bar{u}_{\ell L}(k_1)\gamma^\mu\gamma^\nu C\bar{u}^T_{\ell L}(k_2)]}_{\text{leptonic}} \underbrace{H_{\mu\nu}}_{\text{hadronic}}$$

	$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
Process	$\Sigma^- \to \Sigma^+ e^- e^-$	$\Sigma^- \to p\ell^-\ell^-$	$\Xi^- \to p\ell^-\ell^-$
		$\Xi^- \to \Sigma^+ e^- e^-$	
T_{lept}	$4m_{\ell\ell}G_F^2 V_{ud}^2$	$4m_{\ell\ell}G_F^2 V_{ud}V_{us}$	$4m_{\ell\ell}G_F^2 V_{us}^2$

Lorentz decomposition of hadronic tensor

$$H_{\mu\nu} = \bar{u}(p_2)\left\{\sum_{i=1}^{34}(V_i(s,u)\mathcal{O}^i_{V,\mu\nu} + A_i(s,u)\mathcal{O}^i_{A,\mu\nu})\right\}u(p_1)$$

$\mathcal{O}^1_{V,\mu\nu} = g_{\mu\nu}$	$\mathcal{O}^{13}_{V,\mu\nu} = p_{1\nu}k_{2\mu}$	$\mathcal{O}^{24}_{V,\mu\nu} = p_{1\nu}\gamma_\mu$
$\mathcal{O}^2_{V,\mu\nu} = \not{k}_1 g_{\mu\nu}$	$\mathcal{O}^{14}_{V,\mu\nu} = k_{1\mu}k_{2\nu}\not{k}_1$	$\mathcal{O}^{25}_{V,\mu\nu} = k_{1\mu}\gamma_\nu$
$\mathcal{O}^3_{V,\mu\nu} = \gamma_\mu\gamma_\nu\not{k}_1$	$\mathcal{O}^{15}_{V,\mu\nu} = k_{1\nu}k_{2\mu}\not{k}_1$	$\mathcal{O}^{26}_{V,\mu\nu} = k_{2\mu}\gamma_\nu$
$\mathcal{O}^4_{V,\mu\nu} = \gamma_\mu\gamma_\nu$	$\mathcal{O}^{16}_{V,\mu\nu} = k_{1\mu}k_{1\nu}\not{k}_1$	$\mathcal{O}^{27}_{V,\mu\nu} = k_{1\nu}\gamma_\mu$
$\mathcal{O}^5_{V,\mu\nu} = k_{1\mu}k_{2\nu}$	$\mathcal{O}^{17}_{V,\mu\nu} = k_{2\mu}k_{2\nu}\not{k}_1$	$\mathcal{O}^{28}_{V,\mu\nu} = k_{2\nu}\gamma_\mu$
$\mathcal{O}^6_{V,\mu\nu} = k_{1\nu}k_{2\mu}$	$\mathcal{O}^{18}_{V,\mu\nu} = p_{1\mu}p_{1\nu}\not{k}_1$	$\mathcal{O}^{29}_{V,\mu\nu} = p_{1\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^7_{V,\mu\nu} = k_{1\mu}k_{1\nu}$	$\mathcal{O}^{19}_{V,\mu\nu} = k_{1\nu}p_{1\mu}\not{k}_1$	$\mathcal{O}^{30}_{V,\mu\nu} = p_{1\nu}\gamma_\mu\not{k}_1$
$\mathcal{O}^8_{V,\mu\nu} = k_{2\mu}k_{2\nu}$	$\mathcal{O}^{20}_{V,\mu\nu} = p_{1\mu}k_{2\nu}\not{k}_1$	$\mathcal{O}^{31}_{V,\mu\nu} = k_{1\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^9_{V,\mu\nu} = p_{1\mu}k_{2\nu}$	$\mathcal{O}^{21}_{V,\mu\nu} = k_{1\mu}p_{1\nu}\not{k}_1$	$\mathcal{O}^{32}_{V,\mu\nu} = k_{2\nu}\gamma_\mu\not{k}_1$
$\mathcal{O}^{10}_{V,\mu\nu} = k_{1\nu}p_{1\mu}$	$\mathcal{O}^{22}_{V,\mu\nu} = p_{1\nu}k_{2\mu}\not{k}_1$	$\mathcal{O}^{33}_{V,\mu\nu} = k_{2\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^{11}_{V,\mu\nu} = p_{1\mu}k_{2\nu}$	$\mathcal{O}^{23}_{V,\mu\nu} = p_{1\mu}\gamma_\nu$	$\mathcal{O}^{34}_{V,\mu\nu} = k_{1\nu}\gamma_\mu\not{k}_1$
$\mathcal{O}^{12}_{V,\mu\nu} = k_{1\mu}p_{1\nu}$		

$$\mathcal{O}^i_{A,\mu\nu} = \mathcal{O}^i_{V,\mu\nu}\gamma_5 \qquad i = 1, \cdots, 34$$

Renormalization

Loop Caculation

- Dimensional regularization (DR) in d dimensions
- $\overline{\text{MS}} - 1$ subtraction: $R = \frac{2}{d-4} + \gamma_E - 1 - \ln(4\pi)$

Divergences

- UV divergences: $H^{\text{UV}}_{\mu\nu} \propto R$
- Split couplings: $g_i^{(\prime)} = g_i^{(\prime)r} + \frac{\beta_{g_i^{(\prime)}}}{16\pi^2} R$

Extended-on-mass-shell scheme

- Remove PCB terms via finite shift: $g_i^{(\prime)r} = \tilde{g}_i^{(\prime)} + \frac{\tilde{\beta}_{g_i^{(\prime)}}}{16\pi^2}$
- Consistent power counting:

$$g_1 \sim \mathcal{O}(p^2) \qquad g_1', g_i', \tilde{g}_i^{(\prime)} \sim \mathcal{O}(p^3)$$

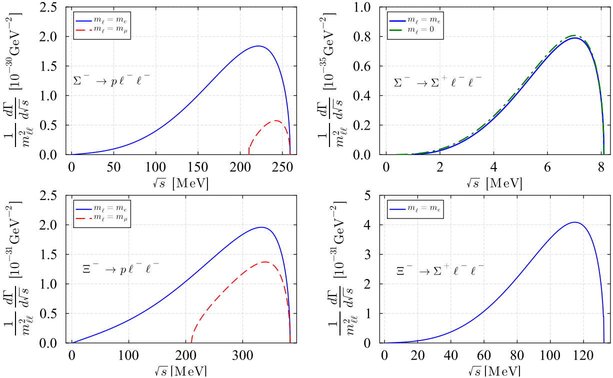
Differential Decay Rate

Differential decay rate formula:

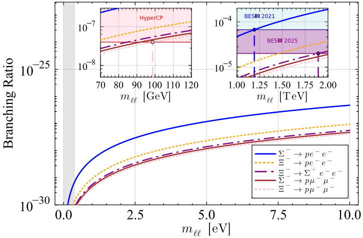
$$\frac{\mathrm{d}\,\Gamma}{\mathrm{d}\sqrt{s}} = \frac{1}{(2\pi)^3}\frac{|C_{\text{Lept}}|^2}{64 m_1^3\sqrt{s}}\int_{u_-}^{u_+}\overline{|\mathcal{M}_{0\nu\beta\beta}|^2}\,\mathrm{d}u$$

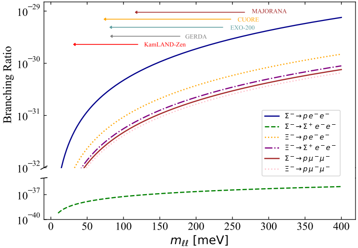
where $\overline{|\mathcal{M}_{0\nu\beta\beta}|^2}$ is obtained from Casimir's trick:

$$\overline{|\mathcal{M}_{0\nu\beta\beta}|^2} = \frac{1}{4}|C_{\text{Lept}}|^2\mathrm{Tr}[\gamma^\mu\gamma^\nu \not{k}_1\gamma^\beta\gamma^\alpha\not{k}_2 P_R]\mathrm{Tr}[\Gamma^3_{\mu\nu}(\not{p}_1+m_1)\bar{\Gamma}^4_{\alpha\beta}(\not{p}_2+m_2)]$$



Branching Ratios





Process	$\frac{\Gamma_{0\nu}}{m_{\ell\ell}^2}$ [sec^{-1}/MeV^2]	$\mathcal{B}(B_1 \to B_2 \ell^- \ell^-)$	
		This work	Experiments
$\Sigma^- \to p\, e^- e^-$	3.194×10^{-7}	4.7×10^{-31}	$< 6.7 \times 10^{-5}$
$\Sigma^- \to \Sigma^+ e^- e^-$	3.925×10^{-14}	5.8×10^{-38}	-
$\Sigma^- \to p\, \mu^- \mu^-$	3.202×10^{-8}	4.7×10^{-28}	-
$\Xi^- \to \Sigma^+ e^- e^-$	3.404×10^{-8}	5.6×10^{-32}	$< 2.0 \times 10^{-5}$
$\Xi^- \to p\, e^- e^-$	5.706×10^{-8}	9.4×10^{-32}	-
$\Xi^- \to p\, \mu^- \mu^-$	2.509×10^{-8}	4.1×10^{-28}	$< 4.0 \times 10^{-8}$

Electron-mode branching ratios use $m_{ee}^2 = (100\text{meV})^2$, while muon-mode branching ratios use $m_{\mu\mu}^2 = (10\text{eV})^2$.

Transition Form Factors

The lepton tensor can be decomposed as

$$L^{\mu\nu} = \underbrace{\bar{u}_{\ell\, L}(k_1) g^{\mu\nu} C \bar{u}^T_{\ell\, L}(k_2)}_{L_S^{\mu\nu}} - \underbrace{i \bar{u}_{\ell\, L}(k_1) \sigma^{\mu\nu} C \bar{u}^T_{\ell\, L}(k_2)}_{L_A^{\mu\nu}}$$

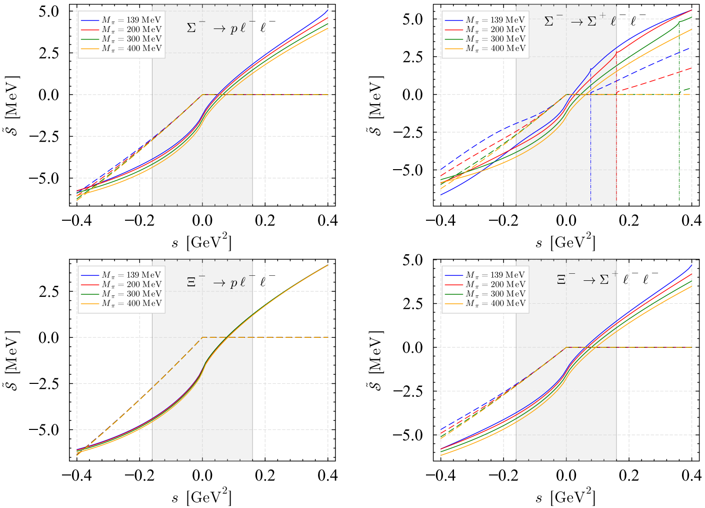
For identical final-state lepton four-momenta $k_1 = k_2 = k$, we define transition form factors(TFFs) $\mathcal{S}(s)$ and $\mathcal{P}(s)$

$$\begin{aligned}\mathcal{M}_{0\nu\beta\beta} &= C_{\text{Lept}}\, H_{\mu\nu}\, L_S^{\mu\nu} \\ &= C_{\text{Lept}} \left\{ \bar{u}(p_2) \left[\mathcal{S}(s) + \gamma_5 \mathcal{P}(s) \right] u(p_1) \right\} \left\{ \bar{u}_{\ell L}(k) C \bar{u}^T_{\ell L}(k) \right\}\end{aligned}$$

In the chiral limit, the contributions from the γ_5 terms vanish. We just need to consider $\mathcal{S}(s)$

$$\mathcal{S}(s) = 8\tilde{g}_1 + \widetilde{\mathcal{S}}(s)^{\text{loop}}$$

Transition Form Factors



Recommended Lattice QCD Fit Range: $0 \leq s \leq s_{\text{th}} = (2M_\pi)^2$

Summary and Outlook

Summary

- The amplitude of $0\nu\beta\beta$ decay involving spin-1/2 hyperons is computed within BChPT, with counterterms constructed and renormalization carried out in the EOMS scheme.
- TFFs are defined, their dependence on s and m_π is analyzed, and the branching ratios of hyperon decays are predicted.

Outlook

- Extend the study to the SU(3) particles with spin-$\frac{3}{2}$ using BChPT.
- We are currently using a dimension-5 operator for $\Delta L = 2$, and as the next step will calculate the decay width in the presence of dimension-7 operators

Thank you very much for your patience!