vSTEP 2024

EFT STUDIES OF NEUTRINOLESS DOUBLE BETA DECAY IN LR SYMMETRIC MODEL

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Outline

- Matching to EFT
- Derivation of reaction matrix
- Many-body calculations
- Conclusion and perspective

LR symmetric model

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Neutrino masses and mixings in gauge models with spontaneous parity violation

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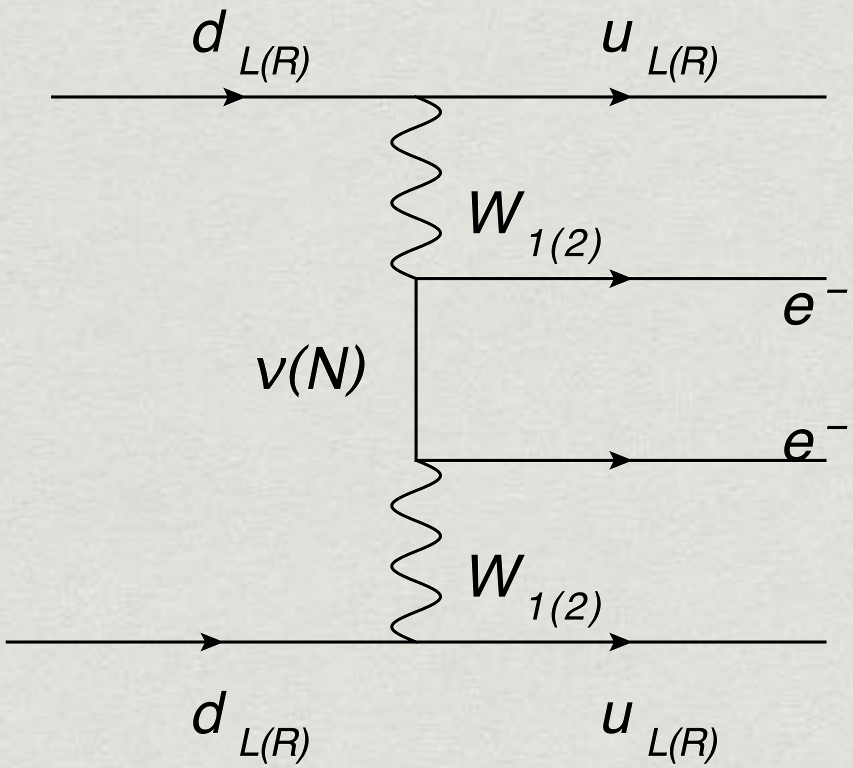
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 8 August 1980)

- The LR symmetric SM is proposed by Mohapatra and Senjanovic
- One introduces the right-handed copies of neutrinos, gauge bosons as well as Higgs boson
- Besides a triplet Higgs boson has been introduced which gives rise of Majorana mass term of neutrino

Neutrinoless double beta decay

Doi et al. PTPS83,1(1985)



- Neutrinoless double beta decay related terms
  - Mass terms:

$$\nu_{eL} = \sum_{j=1}^{3}(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C),$$
$$\nu_{eR} = \sum_{j=1}^{3}(T_{ej}^*(\nu_{jL})^C + V_{ej}^* N_{jR}).$$

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$

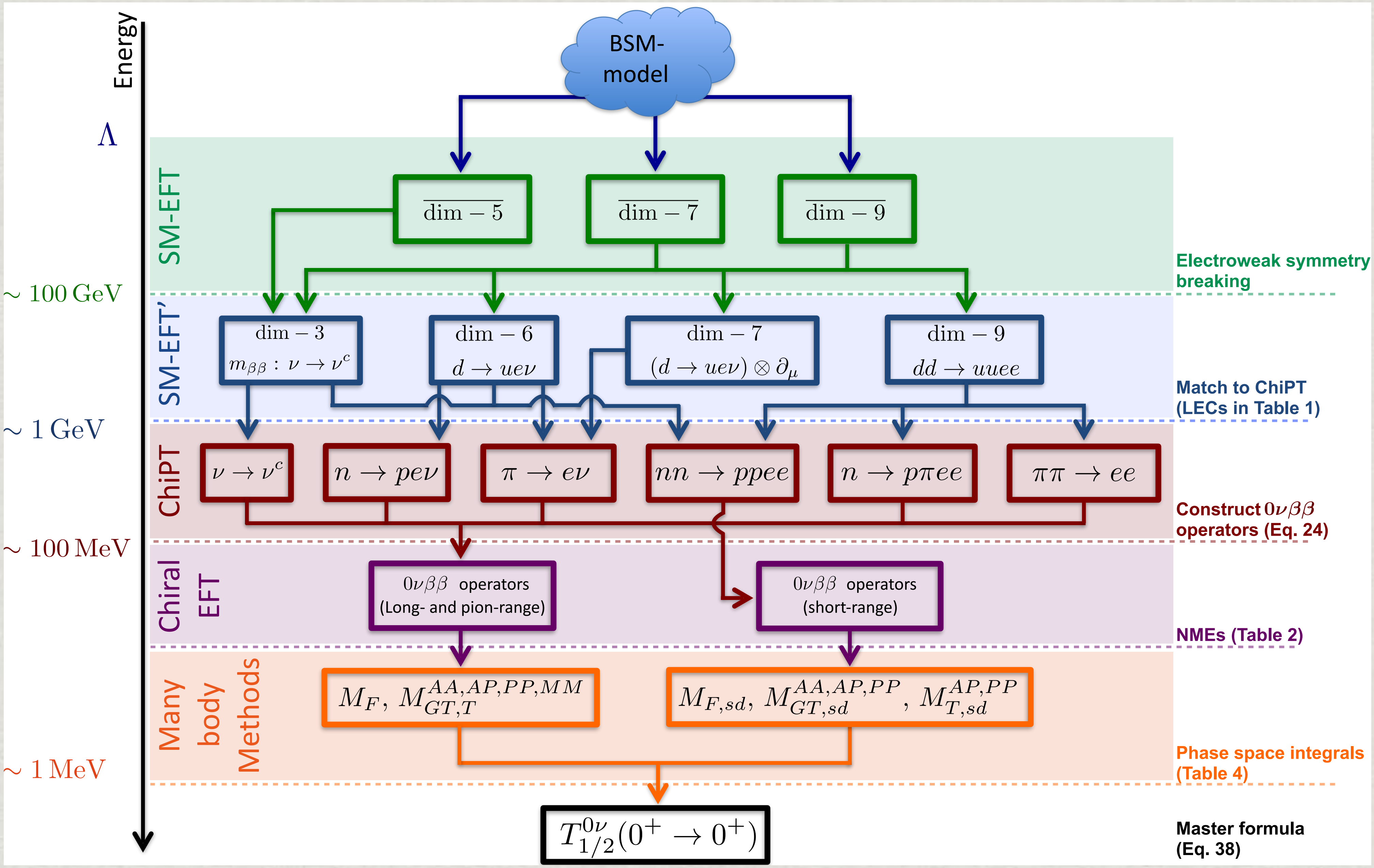
  - Weak current:

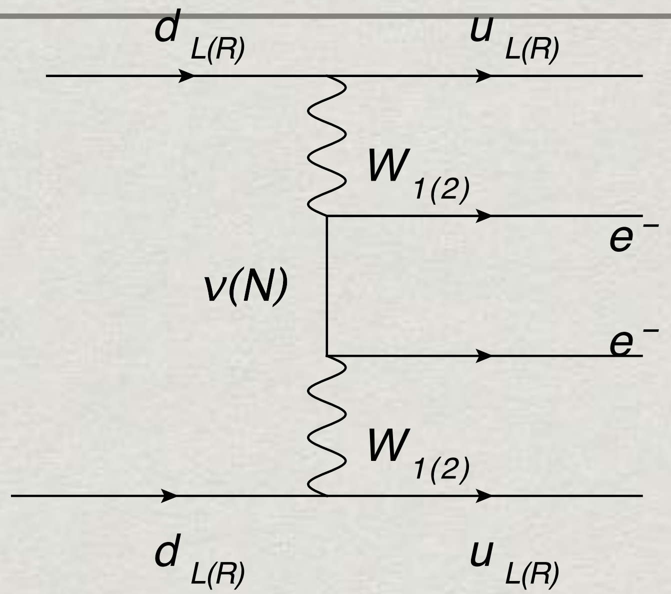
$$H^\beta = \frac{G_\beta}{\sqrt{2}}[j_L^\rho J_{L\rho}^\dagger + \chi j_L^\rho J_{R\rho}^\dagger + \eta j_R^\rho J_{L\rho}^\dagger + \lambda j_R^\rho J_{R\rho}^\dagger + \mathrm{H.c.}]$$

$$\eta \simeq -\tan\zeta \quad \lambda \simeq (M_{W_1}/M_{W_2})^2$$

Matching

Cirigliano et al. JHEP12,097(2018)





SMEFT

Cirigliano et al. JHEP12,097(2018)

- Matching to SMEFT
  - Dim-5: $\mathscr{C}^{(5)}\epsilon_{kl}\epsilon_{mn}(L_k^T C L_m)H_l H_n$
  - Dim-7: $\mathscr{C}^{(7)}_{LHDe}\epsilon_{ij}\epsilon_{mn}(L_i^T C\gamma_\nu e)H_j H_m(D^\mu H_n)$

    $\mathscr{C}^{(7)}_{Leu\bar{d}H}\epsilon_{ij}(L_i^T C\gamma_\mu e)(\bar{d}\gamma^\mu u)H_j$
  - Dim-9: $\mathscr{C}^{(9)}_{eeud}\bar{e}Ce\bar{u}\gamma_\mu d\bar{u}\gamma^\mu d$

    $\mathscr{C}^{(9)}_{eeHud}\bar{e}Ce\bar{u}\gamma_\mu d((iD^\mu H)^\dagger\tilde{H})$

    $\mathscr{C}^{(9)}_{eeHD}\bar{e}Ce((iD^\mu H)^\dagger\tilde{H})^2$

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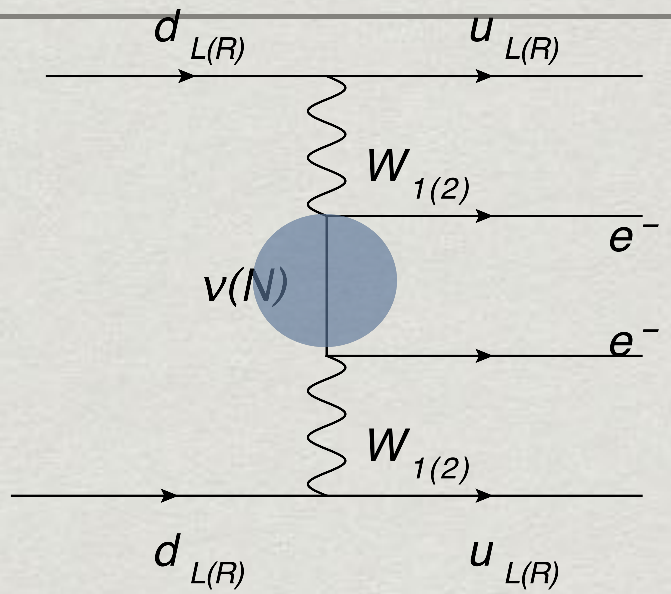

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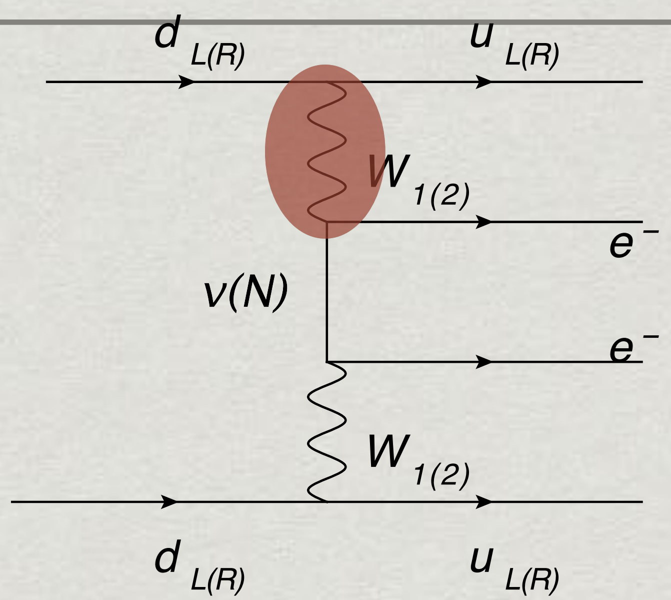

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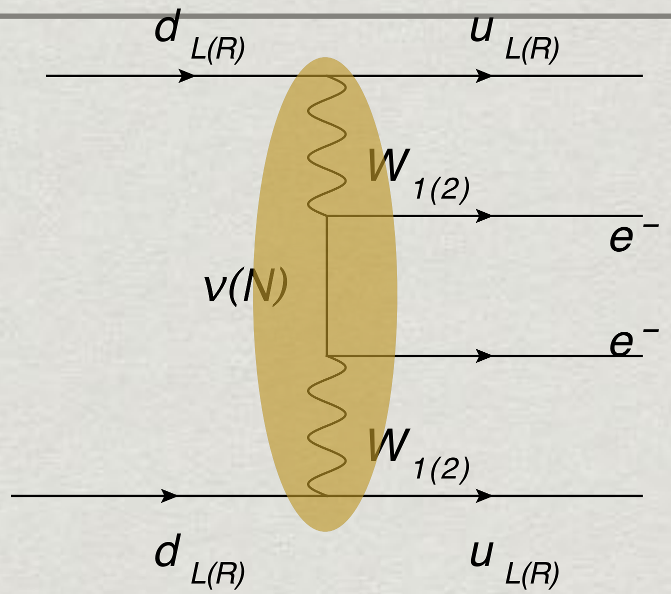

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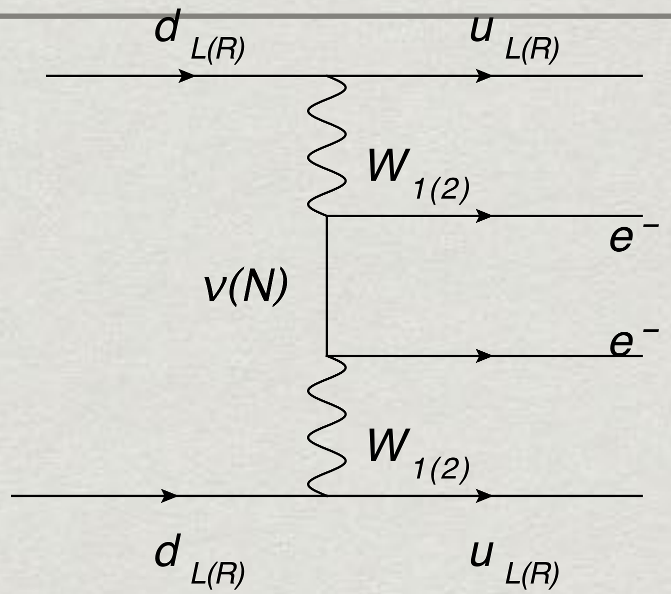

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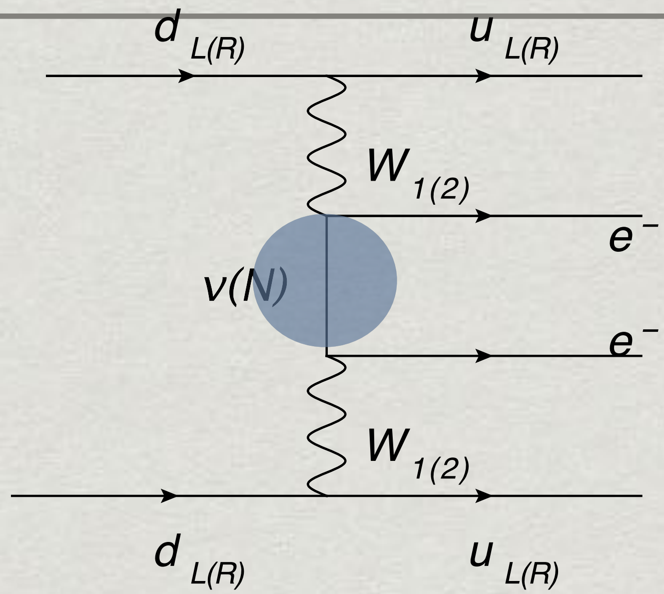

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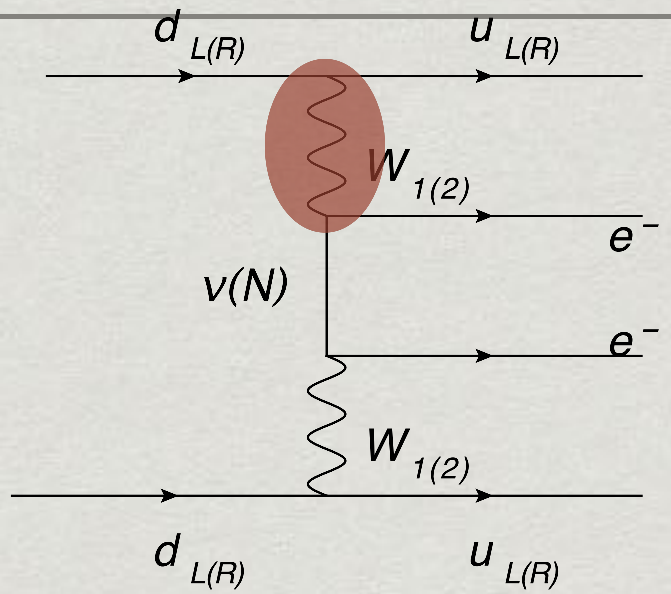

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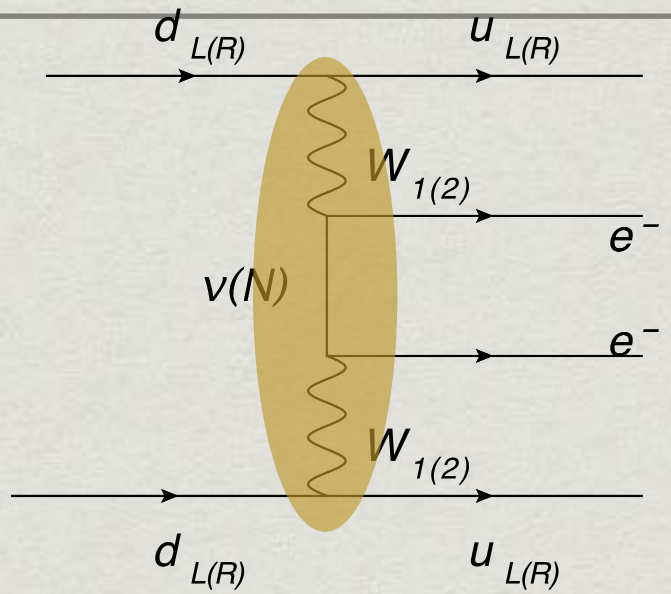

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LEFT

Cirigliano et al. JHEP12,097(2018)

- Matching operators after EWSB, we focus on long-range mechanism with light neutrinos:
- Dim-3:

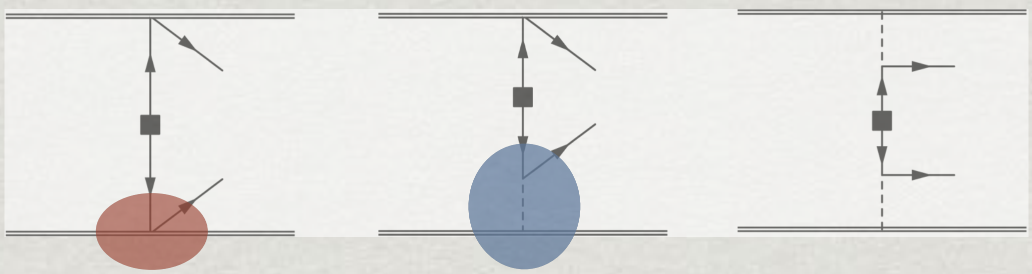
$$m_{\beta\beta}\nu_{eL}^{T}C\nu_{eL} \qquad m_{\beta\beta} = -\,v^2(\mathscr{C}^{(5)})_{ee}$$

- Dim-6:

$$C_{VL}^{(6)}\bar{u}_L\gamma^\mu d_L\bar{e}_R\gamma_\mu C\bar{\nu}_L^T \qquad C_{VL}^{(6)} = -\,iV_L^{ud}\frac{v^3}{\sqrt{2}}(\mathscr{C}_{LHDe})^*$$

$$C_{VR}^{(6)}\bar{u}_R\gamma^\mu d_R\bar{e}_R\gamma_\mu C\bar{\nu}_L^T \qquad C_{VR}^{(6)} = \frac{v^3}{\sqrt{2}}(\mathscr{C}_{LeudH}^{(7)})^*$$

Chiral EFT



- The mesonic chiral Lagrangian at LO

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

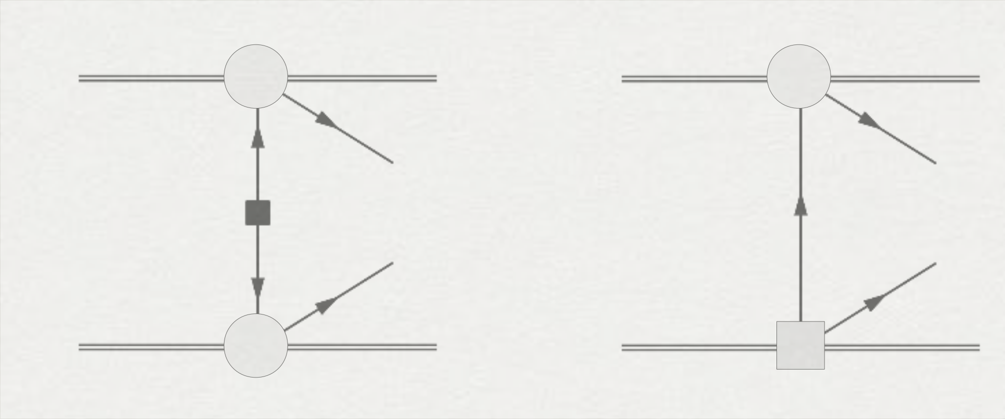
- The baryonic chiral Lagrangian at LO

$$\mathscr{L}_{\pi N}^{(1)} = i\bar{N} v \cdot DN + g_A \bar{N} S \cdot uN + c_5 \bar{N} \hat{\chi}_+ N + \ldots$$

- NLO

$$\mathscr{L}_{\pi N}^{(2)} = \frac{1}{2m_N}(v^\mu v^\nu - g^{\mu\nu})(\bar{N} D_\mu D_\nu N) - \frac{g_M}{4m_N} \epsilon^{\mu\nu\alpha\beta} v_\alpha \bar{N} S_\beta f_{\mu\nu}^+ N \ldots$$

Chiral EFT



- χEFT Lagrangian for these weak decay vertices is

$$\mathcal{A}^{n\to pe^-\nu} = \bar{N}\tau^+\left[\frac{l_\mu + r_\mu}{2}J_V^\mu + \frac{l_\mu - r_\mu}{2}J_A^\mu\right]N$$

- the lepton currents are introduced as external fields

$$l_\mu = \frac{2G_F}{\sqrt{2}v}(\tau^+)\left[-2vV_{ud}\bar{e}_L\gamma_\mu\nu_L + v\,C^{(6)}_{\rm VL}\,\bar{e}_R\gamma_\mu C\bar{\nu}_L^T\right] + \text{h.c.}$$
$$r_\mu = \frac{2G_F}{\sqrt{2}v}(\tau^+)\left[v\,C^{(6)}_{\rm VR}\,\bar{e}_R\gamma_\mu C\bar{\nu}_L^T\right] + \text{h.c.}$$

- And corresponding nuclear current

$$J_V^\mu = g_V(\mathbf{q}^2)\left(v^\mu + \frac{p^\mu + p'^\mu}{2m_N}\right) + \frac{ig_M(\mathbf{q}^2)}{m_N}\varepsilon^{\mu\nu\alpha\beta}v_\alpha S_\beta q_\nu\,,$$
$$J_A^\mu = -g_A(\mathbf{q}^2)\left(2S^\mu - \frac{v^\mu}{2m_N}2S\cdot(p+p')\right) + \frac{g_P(\mathbf{q}^2)}{2m_N}2q^\mu\,S\cdot q\,,$$

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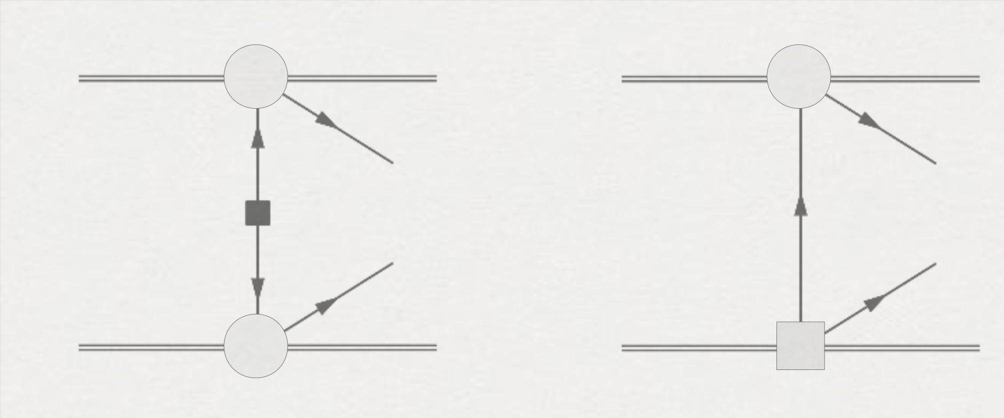

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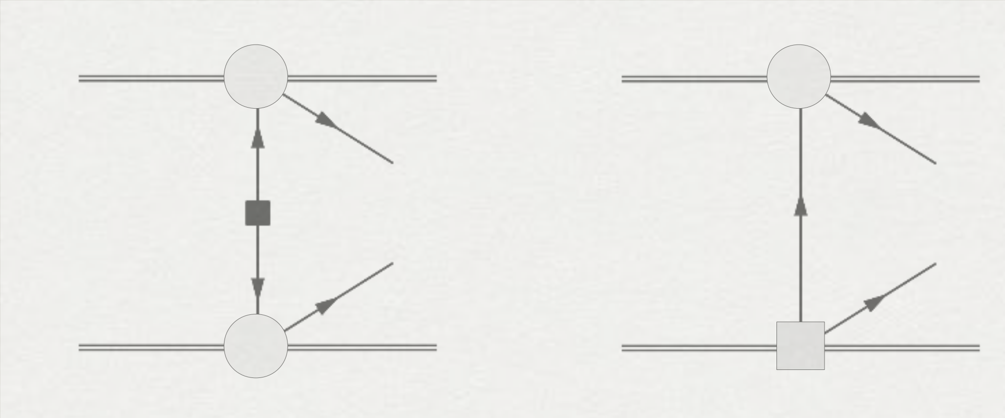

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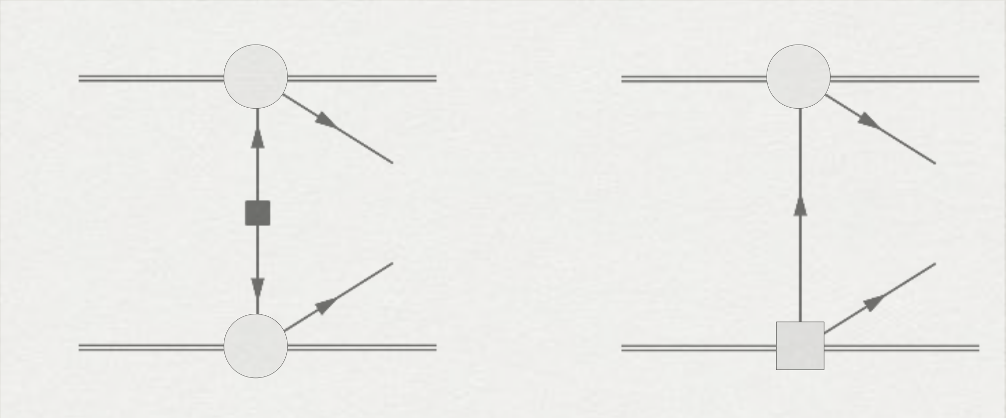

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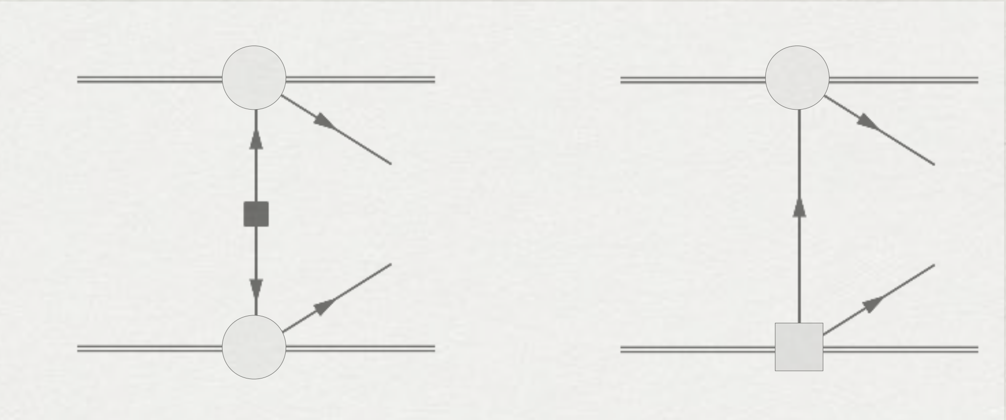
Decay width



Doi et al. PTPS83,1(1985)

- The decay width can be obtained from S-matrix theory

$$d\Gamma_{0\nu} = 2\pi \sum_{\text{spin}} |R_{0\nu}|^2 \delta(\varepsilon_1 + \varepsilon_2 + E_f - M_i)\, d\Omega_{e_1} d\Omega_{e_2}$$

- The reaction matrix element can be expressed as

$$R_{0\nu} = \frac{1}{\sqrt{2}} \int dx \int dy \langle p_1 p_2; f \,|\, T\{ e^{iH_0(x_0 - y_0)} H_{int}(\vec{x}) H_{int}(\vec{y}) \} \,|\, i \rangle$$

- This is a typical second order process

Decay width

- After tedious derivation, we come to

$$\Gamma^{0\nu} = \frac{|m_{\beta\beta}|^2}{m_e^2}\mathscr{C}_{mm} + |\frac{C_{VL}^{(6)}}{2V_{ud}}|^2\mathscr{C}_{\eta\eta} + |\frac{C_{VR}^{(6)}}{2V_{ud}}|^2\mathscr{C}_{\lambda\lambda}$$

$$+Re(\frac{m_{\beta\beta}C_{VR}^{(6)}}{2m_eV^{ud}})\mathscr{C}_{m\lambda} - Re(\frac{m_{\beta\beta}C_{VL}^{(6)}}{2m_eV^{ud}})\mathscr{C}_{m\eta} - Re(\frac{C_{VL}^{(6)}C_{VR}^{(6)}}{4|V^{ud}|^2})\mathscr{C}_{\lambda\eta}$$

- This agrees with earlier calculations based on LR symmetric model

Decay width

$$
\begin{aligned}
\mathcal{C}_{mm} &= \mathcal{G}_{01}|M_m^{0\nu}|^2 \\
\mathcal{C}_{m\lambda} &= -\mathcal{G}_{03}M_m^{0\nu}M_{\omega-}^{0\nu} + \mathcal{G}_{04}M_m^{0\nu}M_{q+}^{0\nu} \\
\mathcal{C}_{m\eta} &= \mathcal{G}_{03}M_m^{0\nu}M_{\omega+}^{0\nu} - \mathcal{G}_{04}M_m^{0\nu}M_{q-}^{0\nu} - \mathcal{G}_{05}M_m^{0\nu}M_P^{0\nu} \\
&+ \mathcal{G}_{06}M_m^{0\nu}M_R^{0\nu} \\
\mathcal{C}_{\lambda\lambda} &= \mathcal{G}_{02}|M_{\omega-}^{0\nu}|^2 + \mathcal{G}_{011}|M_{q+}^{0\nu}|^2 \\
\mathcal{C}_{\eta\eta} &= \mathcal{G}_{02}|M_{\omega+}^{0\nu}|^2 + \mathcal{G}_{011}|M_{q-}^{0\nu}|^2 + \mathcal{G}_{08}|M_P^{0\nu}|^2 \\
&+ \mathcal{G}_{09}|M_R^{0\nu}|^2 - \mathcal{G}_{07}M_P^{0\nu}M_R^{0\nu} \\
\mathcal{C}_{\lambda\eta} &= -2\mathcal{G}_{02}M_{\omega-}^{0\nu}M_{\omega+}^{0\nu} - \mathcal{G}_{010}(M_{q+}^{0\nu}M_{\omega+}^{0\nu} + M_{q-}^{0\nu}M_{\omega-}^{0\nu}) \\
&\quad - 2\mathcal{G}_{011}M_{q+}^{0\nu}M_{q-}^{0\nu}
\end{aligned}
$$

- Here G's are phase space factors and M's the matrix elements

NME

$$M^{0\nu}_{m} = -M_F + M_{GT} + M_T$$

$$M^{0\nu}_{\omega\pm} = M_{\omega GT\pm} + M_{\omega T\pm} \pm M_{\omega F}$$

$$M^{0\nu}_{q\pm} = \frac{1}{3m_e R}(M_{qGT\pm} - 6M_{qT\pm} \pm 3M_{qF})$$

$$M^{0\nu}_{R} = \frac{1}{m_e R}(M_{RGT} + M_{RT})$$

$$M^{0\nu}_{P} = \frac{1}{m_e R}M_P$$

$$M_{iGT} = M^{AA}_{iGT} + M^{AP}_{iGT} + M^{PP}_{iGT} + M^{MM}_{iGT}$$

$$M_{iT} = M^{AA}_{iT} + M^{AP}_{iT} + M^{PP}_{iT} + M^{MM}_{iT}$$

$$i = m, \omega, q$$

- Detailed expressions for NMEs

Nuclear many-body methods

- For double beta decay calculations, various many-body approaches have been adopted:
  - Nuclear Shell Model
  - Quasi-particle Random phase approximation (QRPA)
  - Generator coordinator method (GCM)
  - Interacting Boson model (IBM-2)
  - ……

Results

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NME			^{76}Ge→^{76}Se		^{82}Se→^{82}Kr		^{130}Te→^{130}Xe		^{136}Xe→^{136}Ba	
			jun45	jj44b	jun45	jj44b	jj55a	GCN50:82	jj55a	GCN50:82
M_m	F		-0.665	-0.601	-0.624	-0.523	-0.668	-0.701	-0.574	-0.567
	GT	AA	3.584	3.278	3.360	2.860	3.147	3.180	2.648	2.549
		AP	-1.090	-0.960	-1.021	-0.834	-0.979	-1.034	-0.820	-0.829
		PP	0.344	0.300	0.321	0.261	0.313	0.335	0.260	0.268
		MM	0.247	0.215	0.229	0.188	0.227	0.244	0.188	0.194
		total	3.085	2.833	2.889	2.474	2.708	2.724	2.277	2.183
	T	AP	-0.013	-0.004	-0.014	-0.012	0.008	0.015	0.002	0.014
		PP	0.002	-0.001	0.003	0.003	-0.006	-0.007	-0.003	-0.006
		MM	-0.001	-0.000	-0.001	-0.002	0.003	0.003	0.001	0.002
		total	-0.012	-0.004	-0.013	-0.010	0.004	0.010	-0.000	0.010
$M_{\omega\pm}$	F		-0.637	-0.575	-0.597	-0.500	-0.637	-0.669	-0.545	-0.540
	GT	AA	3.276	2.980	3.073	2.596	2.883	2.931	2.427	2.351
		AP	-1.044	-0.919	-0.978	-0.798	-0.939	-0.993	-0.786	-0.795
		PP	0.333	0.290	0.310	0.252	0.303	0.324	0.252	0.259
		MM	0.239	0.208	0.221	0.181	0.220	0.236	0.182	0.188
		GT_+total	2.803	2.558	2.626	2.231	2.466	2.498	2.075	2.002
		GT_-total	2.325	2.172	2.184	1.789	2.026	2.026	2.711	2.626
	T	AP	-0.012	-0.003	-0.013	-0.011	0.009	0.015	0.003	0.014
		PP	0.002	-0.001	0.003	0.003	-0.006	-0.007	-0.003	-0.006
		MM	-0.001	-0.000	-0.001	-0.002	0.003	0.003	0.001	0.002
		T_+total	-0.011	-0.004	-0.012	-0.010	0.005	0.010	0.000	0.010
		T_-total	-0.0013	-0.004	-0.014	-0.014	-0.001	0.004	-0.001	0.006

- Mass term and ω term are basically the same

Results

NME			^{76}Ge→^{76}Se		^{82}Se→^{82}Kr		^{130}Te→^{130}Xe		^{136}Xe→^{136}Ba	
			jun45	jj44b	jun45	jj44b	jj55a	GCN50:82	jj55a	GCN50:82
	F		-0.379	-0.351	-0.359	-0.304	-0.408	-0.417	-0.358	-0.342
$M_{q\pm}$	GT	AA	3.210	2.981	3.016	2.605	2.781	2.751	2.348	2.209
		AP	4.842	4.317	4.571	3.741	4.267	4.425	3.607	3.563
		PP	-1.943	-1.706	-1.829	-1.479	-1.731	-1.827	-1.454	-1.468
		MM	-1.874	-1.636	-1.745	-1.426	-1.708	-1.825	-1.419	-1.456
		GT_+total	7.983	7.228	7.502	6.293	7.026	7.173	5.920	5.760
		GT_-total	4.235	3.956	4.012	3.441	3.610	3.523	3.082	2.848
	T	AA	-0.056	-0.033	-0.055	-0.042	-0.031	-0.009	-0.031	0.002
		AP	0.004	-0.001	0.006	0.008	-0.018	-0.018	-0.007	-0.015
		PP	0.000	0.001	-0.001	-0.003	0.007	0.005	0.002	0.003
		MM	0.000	-0.000	-0.000	-0.001	0.001	0.001	0.000	0.001
		T_+total	-0.051	-0.034	-0.050	-0.035	-0.043	-0.023	-0.036	-0.012
		T_-total	-0.051	-0.034	-0.050	-0.037	-0.041	-0.021	-0.036	-0.009
M_R	GT		4.256	3.713	4.037	3.314	4.686	5.048	3.948	4.080
	T		0.014	0.004	0.018	0.028	-0.056	-0.056	-0.014	-0.042
M_P			-0.431	-0.279	-0.428	-0.152	-0.498	-0.425	-0.289	-0.255

- MM becomes LO for q term
- Larger R term than expected

Results

		rough estimation			^{76}Ge			^{82}Se			^{130}Te			^{136}Xe		
		lepton	nuclear	$\mathcal{R}$	$G_{0\nu}$	$M_{0\nu}$		$G_{0\nu}$	$M_{0\nu}$		$G_{0\nu}$	$M_{0\nu}$		$G_{0\nu}$	$M_{0\nu}$	
$\mu_{\beta\beta}$		$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	0.24	5.62 5.16		1.02	5.26 4.50		1.43	5.04 5.11		1.46	4.25 4.10	
					r_e	r_N	r_R	r_e	r_N	r_R	r_e	r_N	r_R	r_e	r_N	r_R
$C_{VL}^{(6)}$	M_ω	$\mathcal{O}(\epsilon_{12}/m_e)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	1.25	0.78 0.78	0.98 0.98	1.85	0.78 0.78	1.45 1.44	1.61	0.78 0.77	1.25 1.24	1.57	0.78 0.77	1.22 1.21
	M_q	$\mathcal{O}(\omega R)$	$\mathcal{O}(q/m_e)$	$\mathcal{O}(1)$	0.010	55.1 53.6	0.53 0.51	0.012	54.0 52.6	0.65 0.63	0.013	44.2 43.7	0.59 0.58	0.013	43.4 42.5	0.58 0.57
$C_{VR}^{(6)}$	M_ω	$\mathcal{O}(\epsilon_{12}/m_e)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	1.25	0.69 0.69	0.86 0.86	1.85	0.69 0.69	1.27 1.27	1.61	0.66 0.66	1.07 1.06	1.57	0.66 0.66	1.04 1.04
	M_q	$\mathcal{O}(\omega R)$	$\mathcal{O}(q/m_e)$	$\mathcal{O}(1)$	0.010	38.1 38.1	0.36 0.36	0.012	37.7 37.4	0.45 0.45	0.013	31.3 29.6	0.41 0.39	0.013	31.4 29.0	0.42 0.39
	M_R	$\mathcal{O}(1)$	$\mathcal{O}(q^2/(M_N m_e))$	$\mathcal{O}(\varepsilon^{-1})$	3.02	64.6 63.7	195.3 192.4	2.96	63.5 66.4	187.8 196.4	2.97	65.5 71.8	194.7 213.4	2.97	67.8 73.4	201.6 218.2
	M_P	$\mathcal{O}(\alpha Z)$	$\mathcal{O}(q/m_e)$	$\mathcal{O}(\varepsilon^{-1})$	0.34	7.40 5.21	2.49 1.75	0.33	7.65 3.18	2.50 1.04	0.27	7.97 6.71	2.19 1.84	0.25	5.41 4.94	1.37 1.25

- Dominance of R term in C_{VR} and coexistence of ω and q terms in C_{VL}

LO contact term

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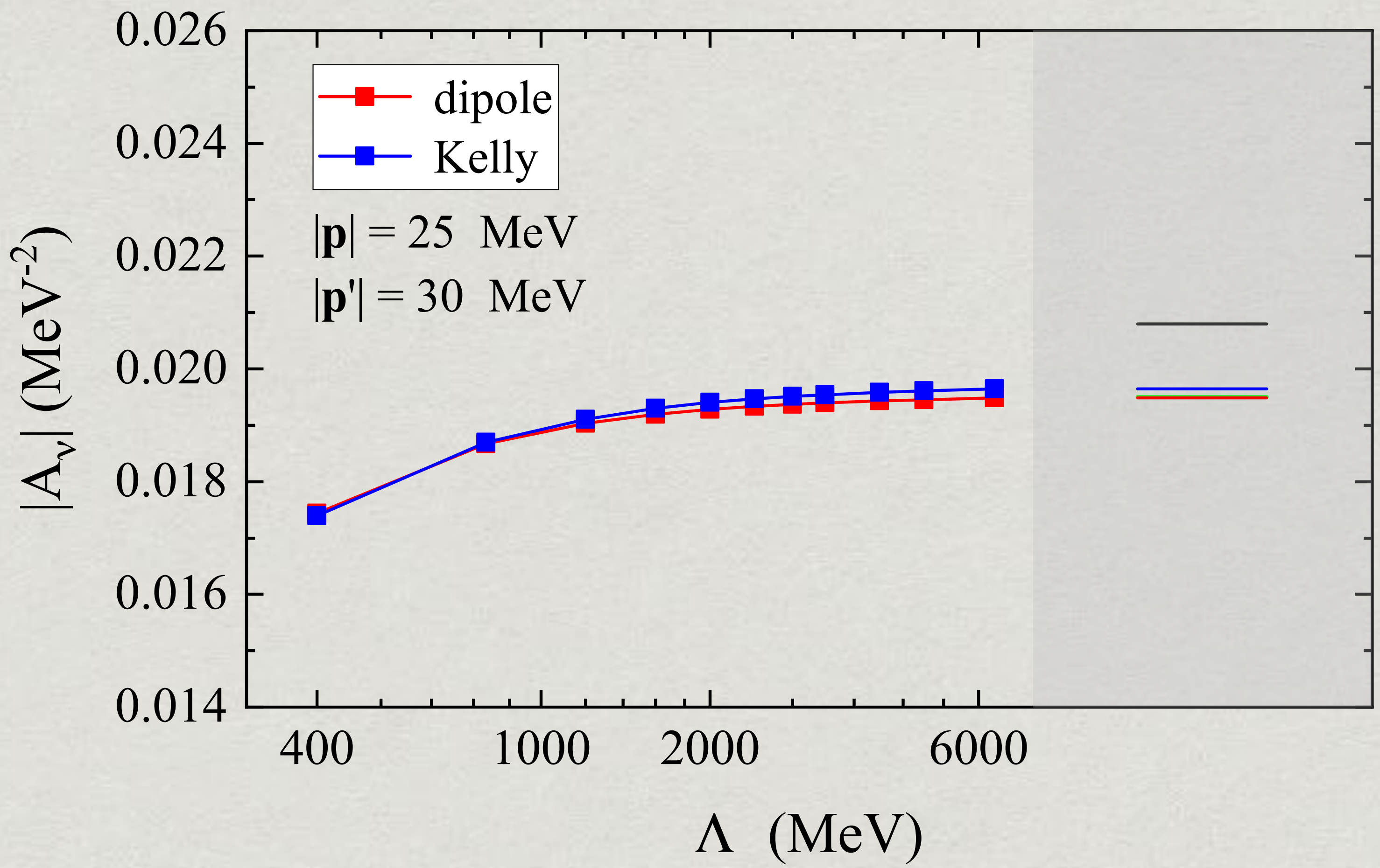
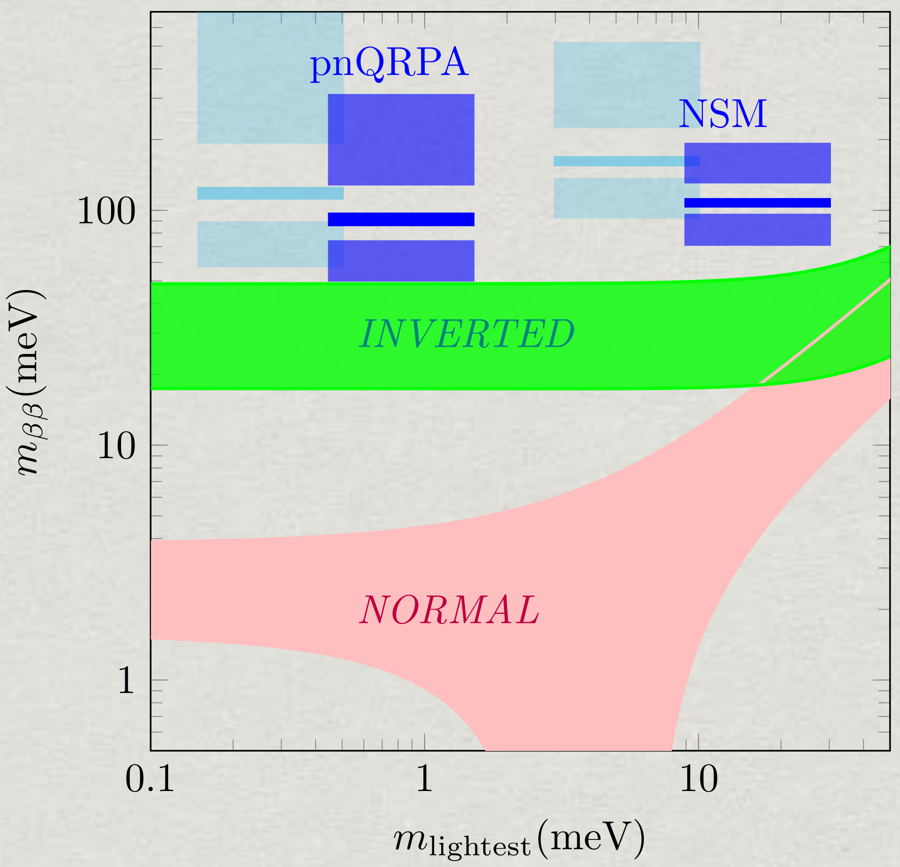


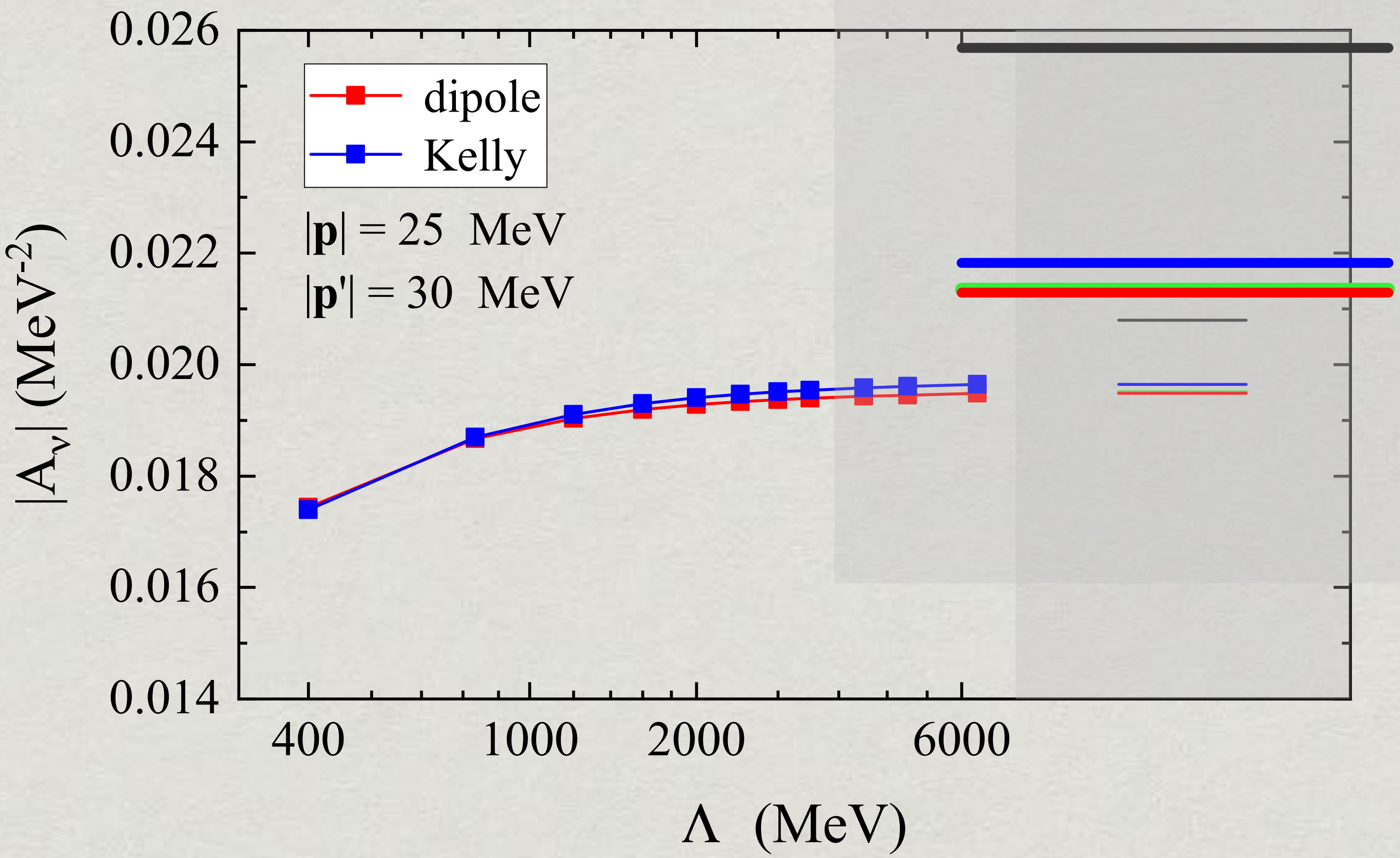
Jokiniemi et al. PLB823,136720(2021)



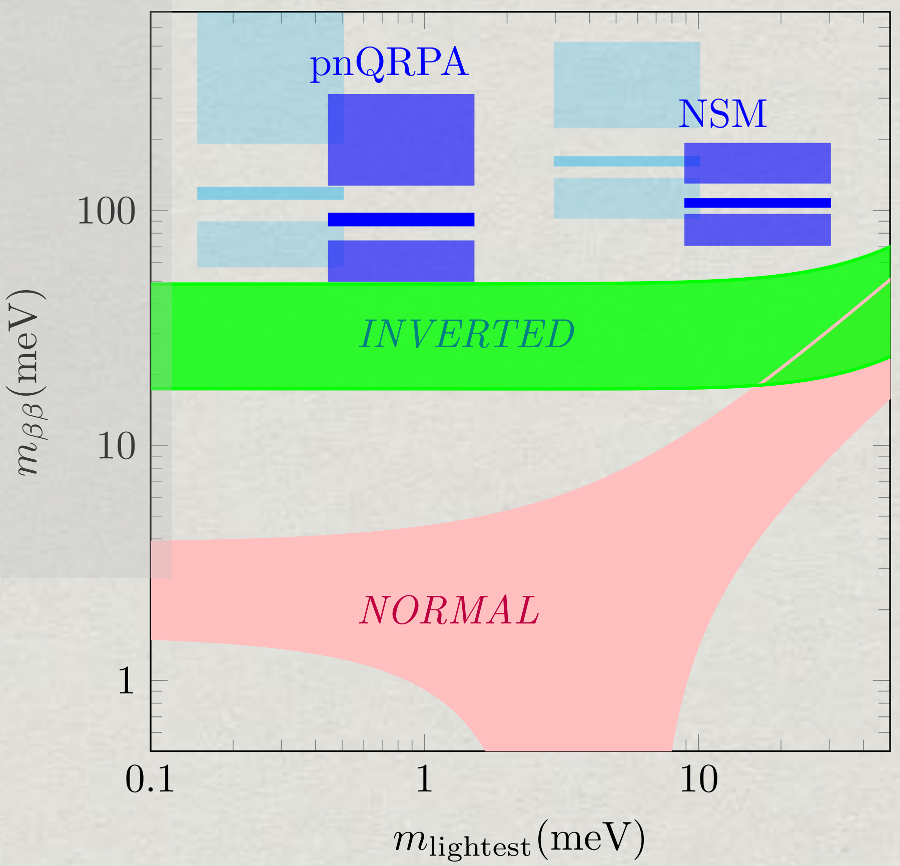
- In conventional many-body calculations, this new contribution has already been considered

LO contact term

Liu et al. in preparation



Jokiniemi et al. PLB823,136720(2021)



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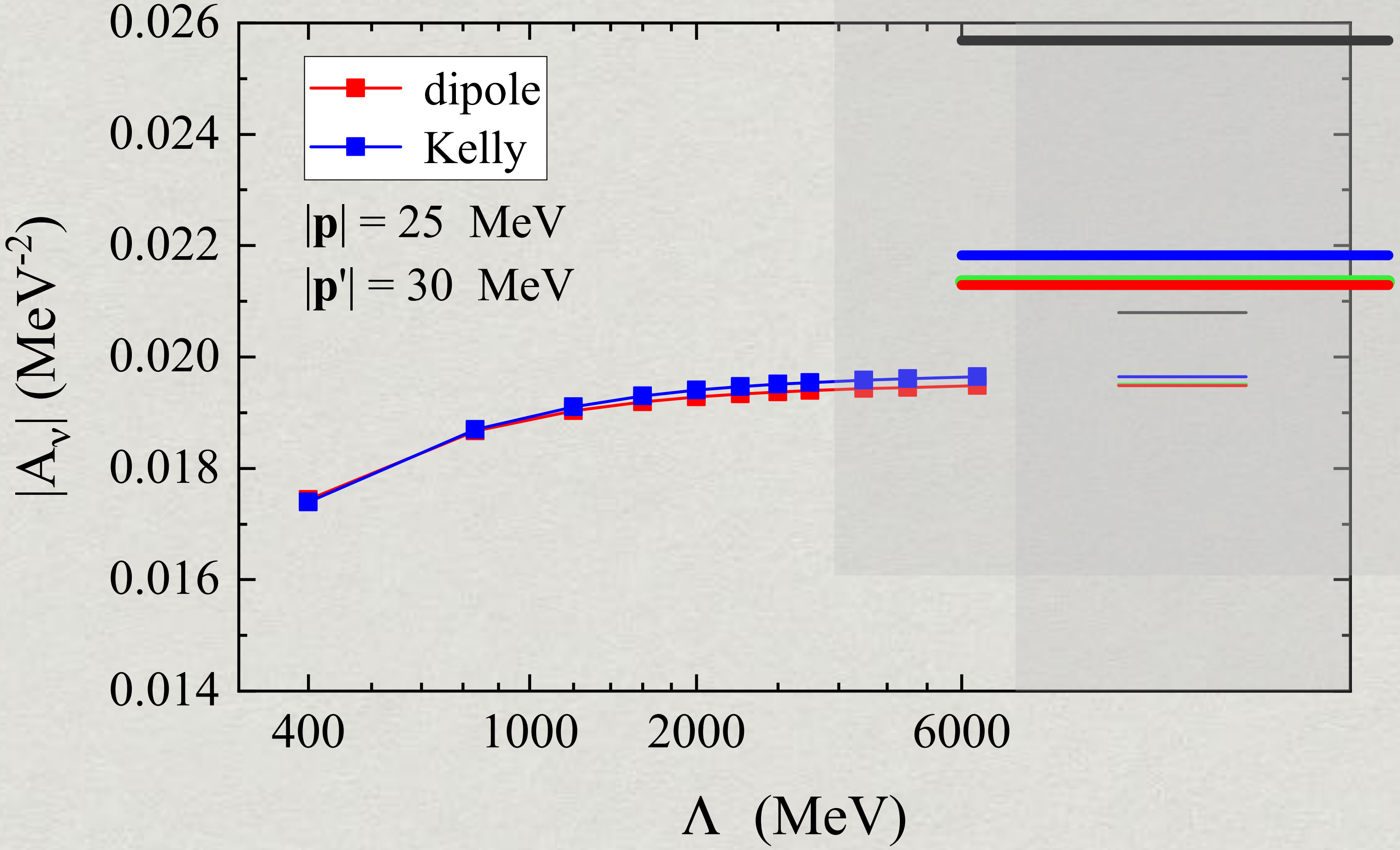

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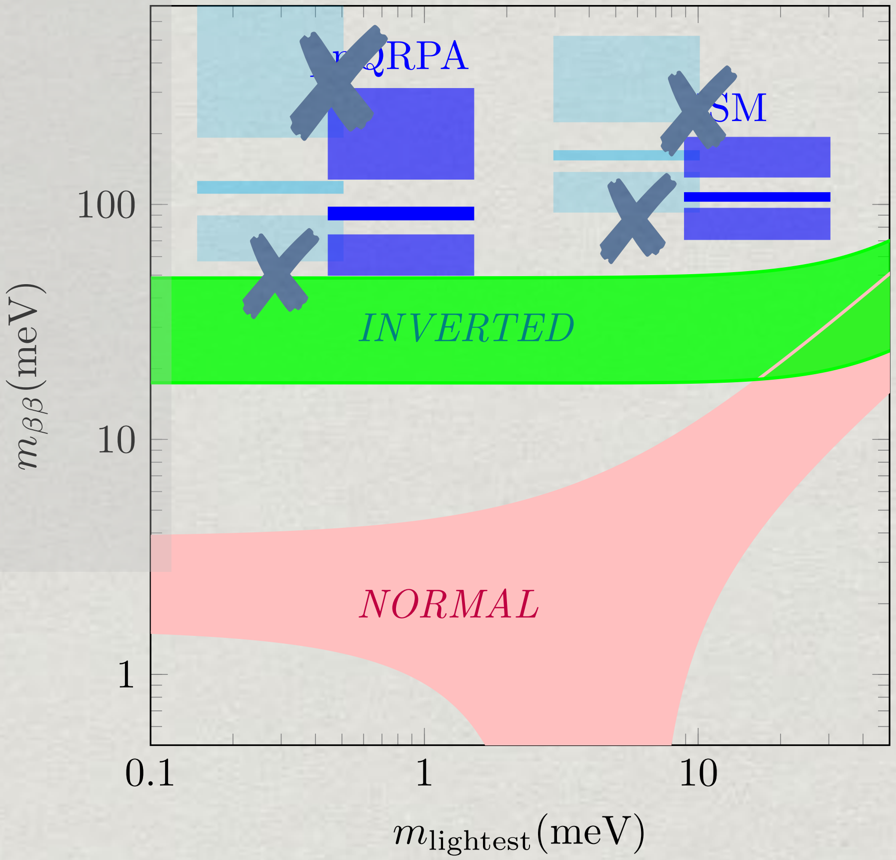

- In conventional many-body calculations, this new contribution has already been considered

Conclusions

- EFT studies of neutrinoless double beta decay agrees well with previous model studies
- We give related NMEs with shell model calculations and compare the relative magnitude of each term
- The mater formula offers very good approximations
- Two frames are equally efficient for double beta decay studies
- Constraints on Wilson coefficients by neutrinoless double beta decay is on going

谢谢