Chiral EFT for neutrinoless double beta decay

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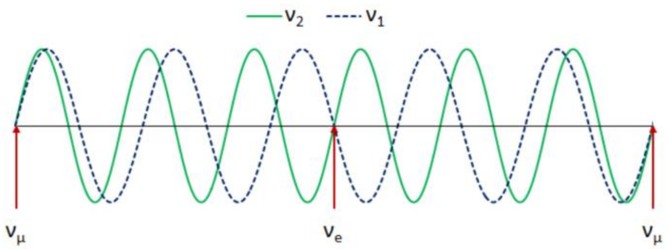
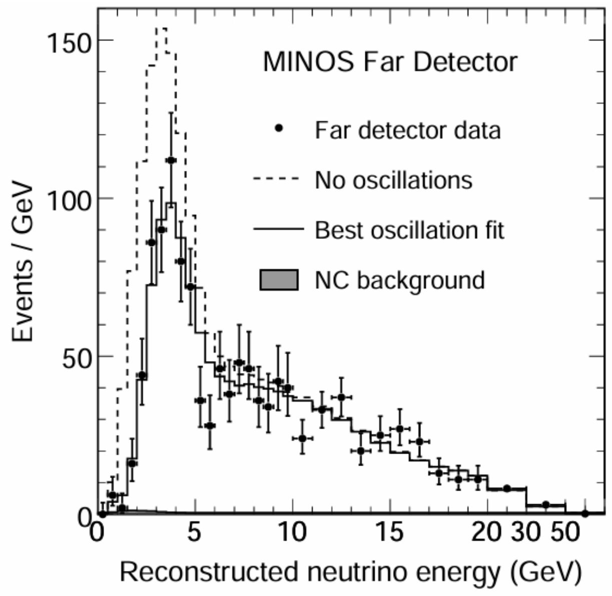
Outline

- Introduction
- $n + n \to p + p + e + e$ under the standard mechanism
- Discussion and outlook
- Summary

Neutrino oscillation



The neutrino is massive, becoming a portal to new physics



[MINOS, 2008]

The solution with the lowest cost:

1937, $\psi^c = \psi$

Insert gauge-singlet right-handed neutrino N_R:

$$\mathcal{L} = -\bar{l}_L Y_\nu \tilde{H} N_R \quad \longrightarrow \quad \mathcal{L} = -\bar{l}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\overline{N_R^c} M_R N_R$$

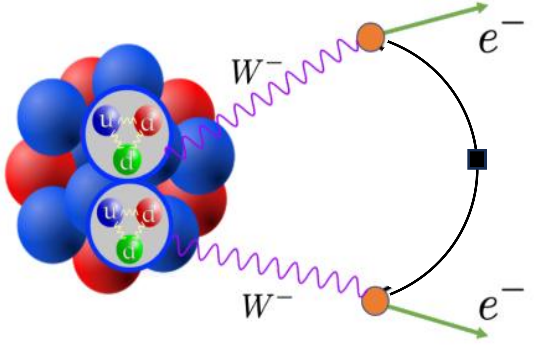
Dirac mass term:

↳ $m_\nu \sim Y_\nu v \sim 10^{-12} * 200$ GeV

Majorana mass term

Gains: seesaw mechanism $\rightarrow m_\nu \sim Y_\nu \dfrac{v^2}{M_R} Y_\nu^T$ + Lepton-number-violating decay $+\cdots$

Neutrinoless double beta (0νββ) decay: A promising process for searching LNV signal



Effective Majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \frac{\left|\langle m_{\beta\beta}\rangle\right|^2}{m_e^2}$$

Phase space factor

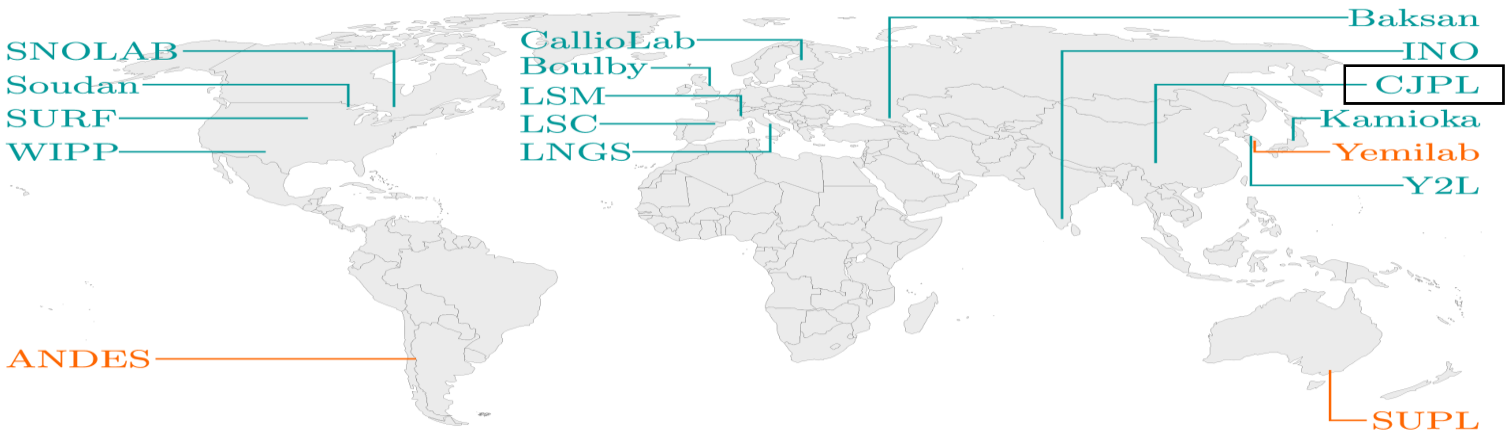
Nuclear Matrix Elements (NMEs)

- Dirac or Majorana;
- Origin of neutrino masses;

…

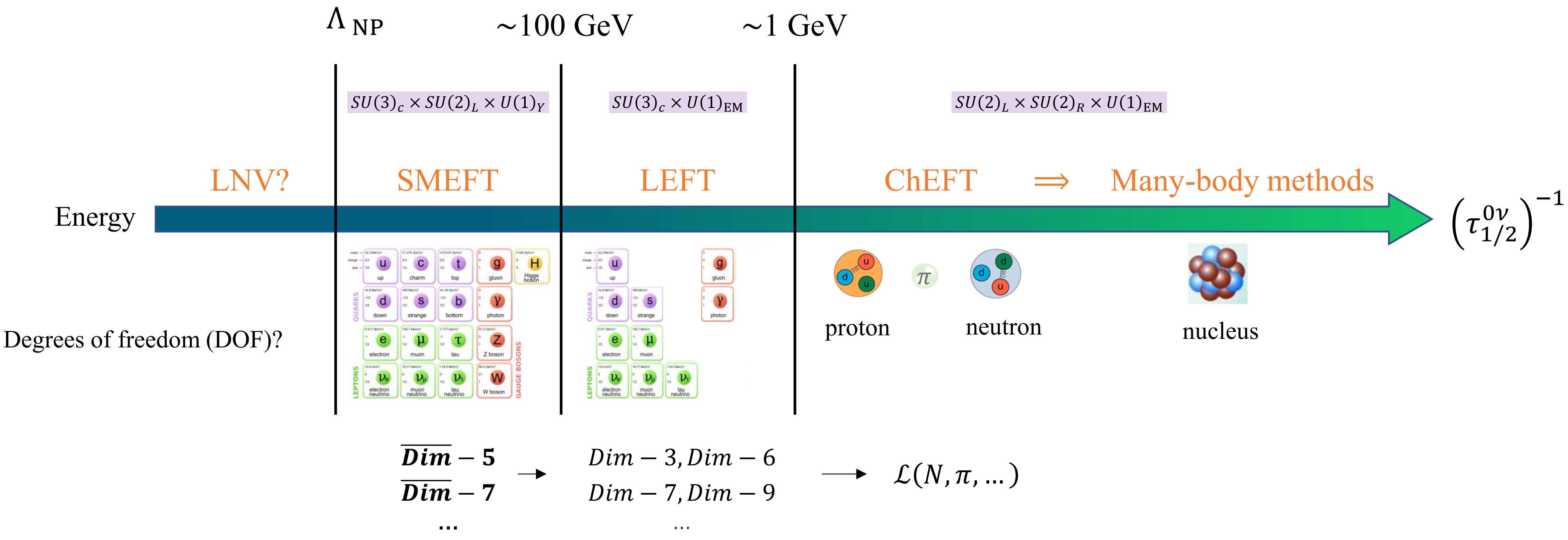
- Over 20 experimental groups in the world are hunting for this decay;
- One of the state-of-the-art limit: $T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) > 1.8 \times 10^{26}$ yr;
- The next-generation detector will improve the lower limit to 10^{28} yr ;

The deep underground laboratories in the world



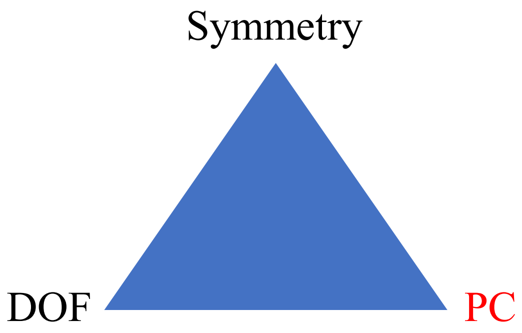
[Agostini, et al.,2023]

EFT perspective on LNV decay



Why EFT:

- Independence on the details of UV physics;
- Quantifiable uncertainties, utilizing power counting (PC);
- Distinguishing various BSM physics;



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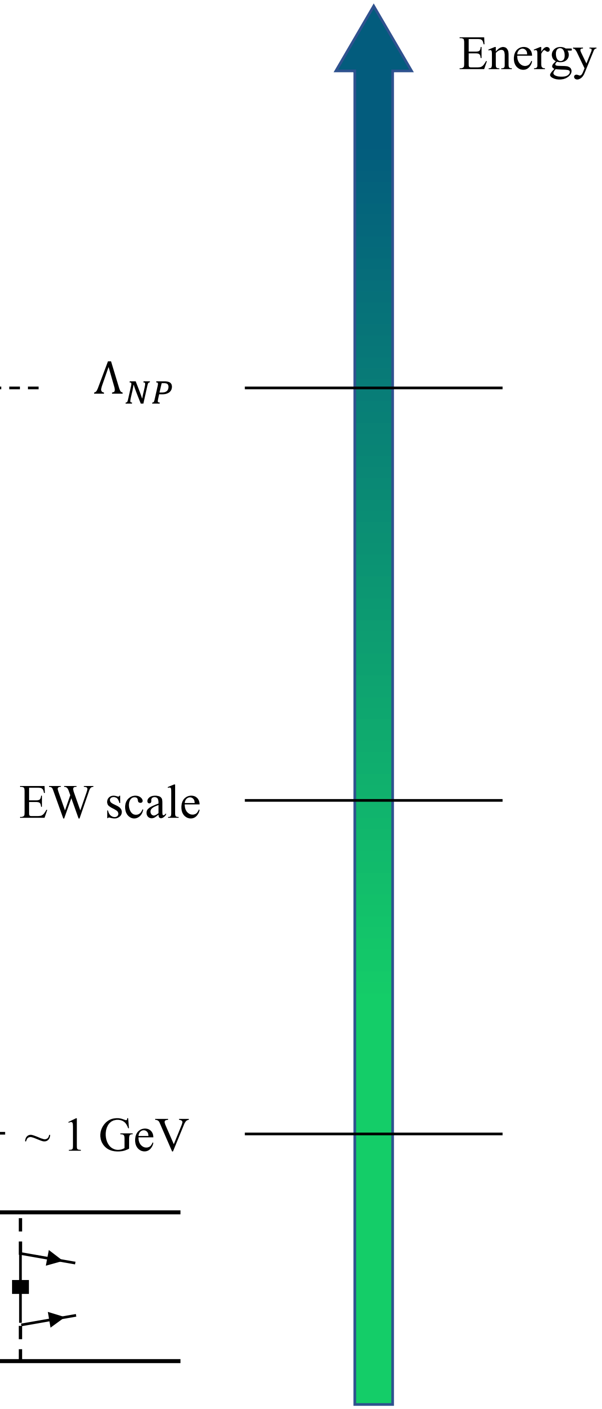
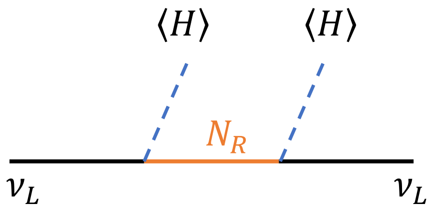
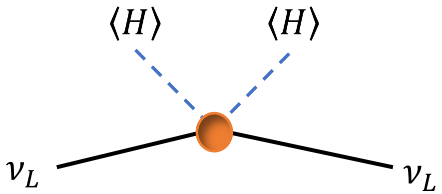
The standard mechanism (light Majorana neutrino exchange)





Integrating out the heavy DOFs

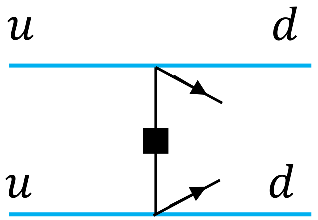


[Weinberg, 1979]

$$\mathcal{L}_5 = \frac{c_5}{\Lambda}\left(L^T \widetilde{H}\right)\left(\widetilde{H}^T L\right)$$

The Majorana mass

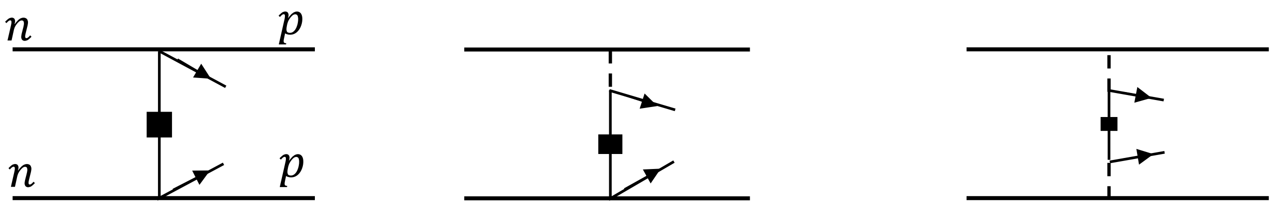
Integrating out the heavy DOFs



$$\mathcal{L}_m = \nu^T C \nu$$

$$\mathcal{L}_{CC} = -2\sqrt{2} G_F V_{ud} \overline{u_L} \gamma^\mu d_L \overline{e_L} \gamma_\mu \nu_L$$

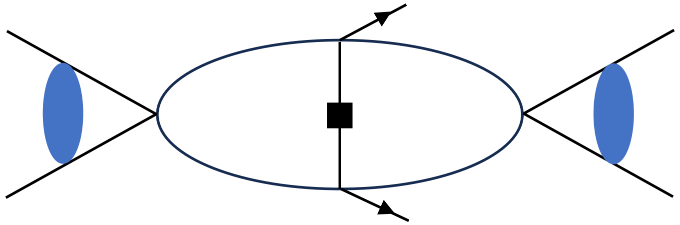
The neutrino potential V_ν



The fundamental 0νββ decay: $n + n \to p + p + e + e$

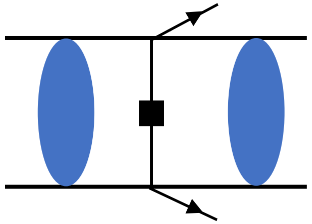
$V_{NN} = V_\pi + C$

The transition amplitude $A_\nu = \langle pp|V_\nu|nn\rangle$ is given by

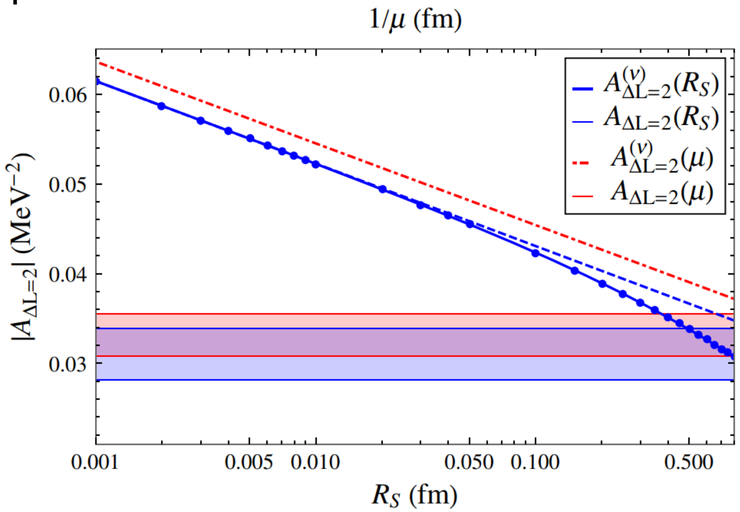


$$\propto \quad m_N^2 \int \frac{d^3q_1}{(2\pi)^3} \int \frac{d^3q_2}{(2\pi)^3} \frac{1}{k^2 - q_1^2 + i\varepsilon} \frac{g_a^2}{q_2^2 + m_\nu^2} \frac{1}{k^2 - (\boldsymbol{q}_1 + \boldsymbol{q}_2)^2 + i\varepsilon}$$

$$= -\frac{m_N^2 g_a^2}{64\pi^2}\left[R - 2\ln\frac{\mu^2}{-k^2 + i\epsilon} + \text{const}\right]$$

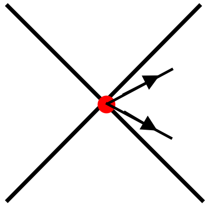
$+$  $+$ …

⟵ finite



[Cirigliano, 2018]

◆ **Renormalization requires a LO contact term**



Scheme 1

Another renormalization scheme (a relativistic description for 0νββ decay)

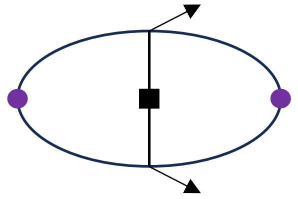
Scheme 2

[Yang and Zhao, 2023]

The relativistic scattering equation:

$$T(\boldsymbol{p}',\boldsymbol{p}) = V(\boldsymbol{p}',\boldsymbol{p}) + \int \frac{d^3q}{(2\pi)^2} V(\boldsymbol{p}',\boldsymbol{q}) \frac{m_N^2}{\boldsymbol{q}^2+m_N^2} \frac{1}{E_{\text{total}} - 2E_{\boldsymbol{q}} + i\epsilon} T(\boldsymbol{q},\boldsymbol{p})$$

$\tilde{G}$: the relativistic two-nucleon propagator



- At LO, the (strong and neutrino) potentials take their nonrelativistic forms, such that $V \sim \mathcal{O}(\Lambda^{-2})$ for momentum $\sim \Lambda$
- $\tilde{G} \sim \mathcal{O}(\Lambda^{-3})$ in the UV region, while the nonrelativistic propagator $G \sim \mathcal{O}(\Lambda^{-2})$.

⇒

- Nonrelativistic case: $\mathcal{O}(\Lambda^{0})$, logarithmic divergence
- Relativistic case: $\mathcal{O}(\Lambda^{-2})$, convergence

Another renormalization scheme (a relativistic description for 0νββ decay)

Scheme 2

[Yang and Zhao, 2023]

The relativistic scattering equation:

$$T(\boldsymbol{p}',\boldsymbol{p}) = V(\boldsymbol{p}',\boldsymbol{p}) + \int \frac{d^3q}{(2\pi)^2} V(\boldsymbol{p}',\boldsymbol{q}) \boxed{\frac{m_N^2}{\boldsymbol{q}^2 + m_N^2} \frac{1}{E_{\text{total}} - 2E_{\boldsymbol{q}} + i\epsilon}} T(\boldsymbol{q},\boldsymbol{p})$$

$\tilde{G}$: the relativistic two-nucleon propagator

- At LO, the (strong and neutrino) potentials take their nonrelativistic forms, such that $V \sim \mathcal{O}(\Lambda^{-2})$ for momentum ~ Λ
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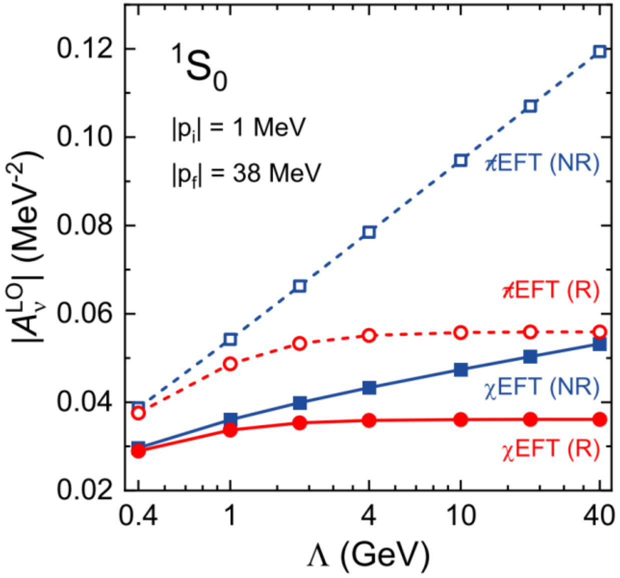
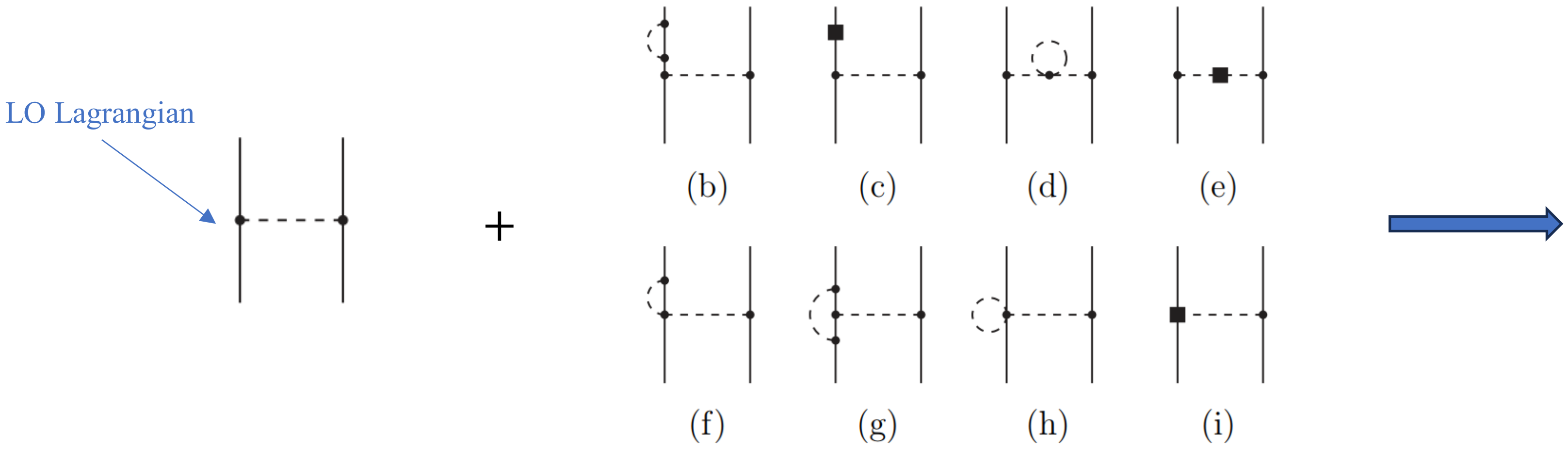


Another way to view this scheme:

Resum all relativistic corrections to the two-nucleon propagator.

- Incorporating specific higher-order corrections into the LO one-pion-exchange potential

[Machleidt, 2011]



$$V_{\text{OPE}} = -\frac{g_A^2}{4f_\pi^2}\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \frac{(\vec{\sigma_1} \cdot \vec{q})(\vec{\sigma_2} \cdot \vec{q})}{q^2 + m_\pi^2}$$

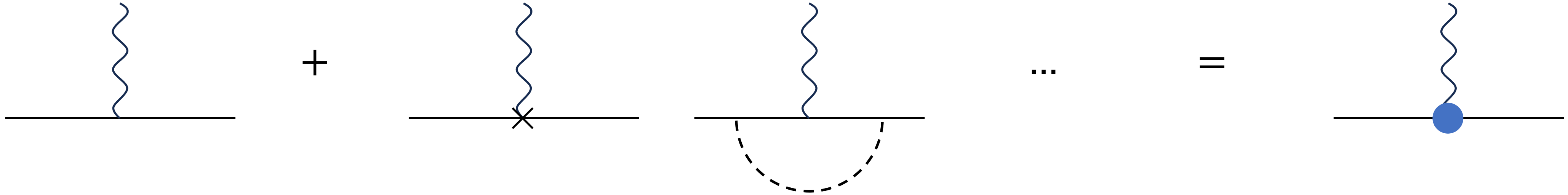
as the LO long-range force

We use $g_A = 1.290$ (instead of $g_A = 1.276$ [130]) to account for the Goldberger-Treiman discrepancy. Via the Goldberger-Treiman relation, $g_{\pi NN} = g_A M_N / f_\pi$, our value for g_A together with $f_\pi = 92.4$ MeV and $M_N = 938.918$ MeV implies $g_{\pi NN}^2/4\pi = 13.67$ which is consistent with the empirical value $g_{\pi NN}^2/4\pi = 13.65 \pm 0.08$ obtained from πN and NN data analysis [131, 132]. The renormalizations of f_π, m_π, and M_N are taken care of by working with their physical vales.

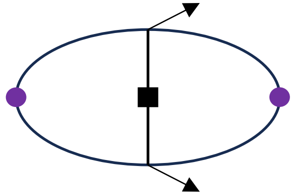
The renormalization scheme with the effects of nucleon finite size

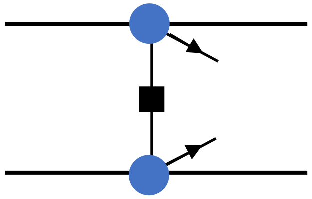
Scheme 3

- Incorporating the higher-order corrections to single nucleon currents into the LO neutrino potential



- The neutrino potential with the effects of nucleon finite size:





$$V_\nu(\boldsymbol{p}',\boldsymbol{p}) = \tau_1^+\tau_2^+ \frac{1}{\boldsymbol{q}^2}\left[G_V^2(\boldsymbol{q}^2) - G_A^2(\boldsymbol{q}^2)\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + G_A^2(\boldsymbol{q}^2)\,\boldsymbol{\sigma}_1\cdot\boldsymbol{q}\,\boldsymbol{\sigma}_2\cdot\boldsymbol{q}\,\frac{2m_\pi^2+\boldsymbol{q}^2}{(\boldsymbol{q}^2+m_\pi^2)^2}\right]$$

$G_\alpha \sim \mathcal{O}(\Lambda^{-4})$, for $\boldsymbol{q} \to \Lambda$

- Nonrelativistic case: $\mathcal{O}(\Lambda^{0})$, logarithmic divergence
- Relativistic case: $\mathcal{O}(\Lambda^{-2})$, convergence
- This work: $\mathcal{O}(\Lambda^{-8})$, convergence

The renormalization scheme with the effects of nucleon finite size

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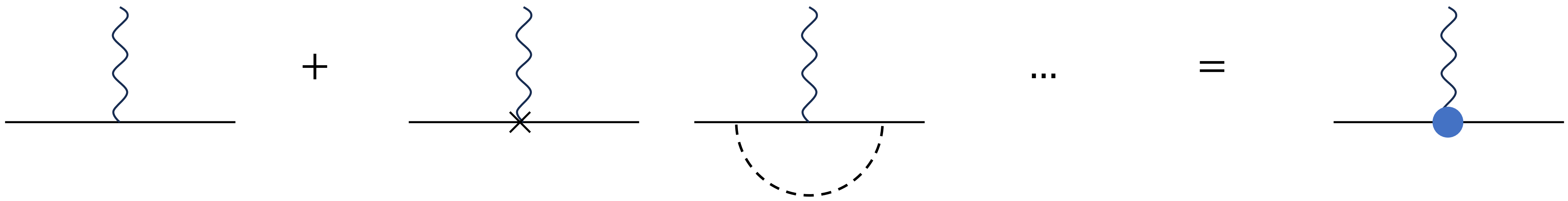
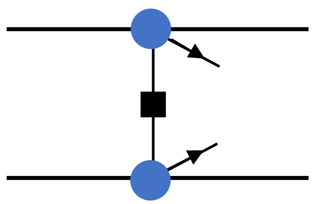
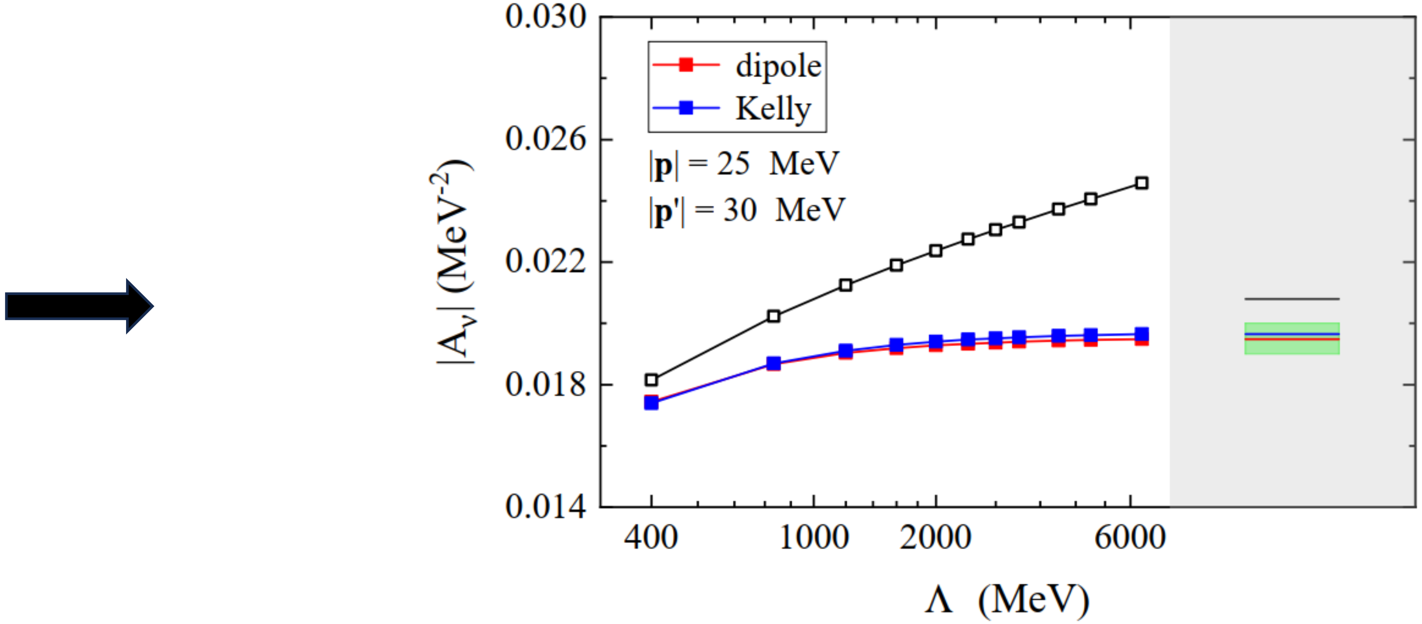


- The neutrino potential with the effects of nucleon finite size:



$$V_\nu(\boldsymbol{p}',\boldsymbol{p}) = \tau_1^+\tau_2^+ \frac{1}{\boldsymbol{q}^2}\left[G_V^2\left(\boldsymbol{q}^2\right) - G_A^2\left(\boldsymbol{q}^2\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + G_A^2\left(\boldsymbol{q}^2\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{q}\,\boldsymbol{\sigma}_2\cdot\boldsymbol{q}\frac{2m_\pi^2+\boldsymbol{q}^2}{\left(\boldsymbol{q}^2+m_\pi^2\right)^2}\right]$$



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The comparison of two renormalization schemes

Scheme 1 (V. Cirigliano):

$$V_\nu = \frac{\tau_1^+\tau_2^+}{\boldsymbol{q}^2}\left[1 + 2g_A^2 + \frac{g_A^2 m_\pi^4}{(\boldsymbol{q}^2+m_\pi^2)^2}\right] + \tau_1^+\tau_2^+ g_\nu^{NN}$$

Scheme 3 (this work):

$$V_\nu = \frac{\tau_1^+\tau_2^+}{\boldsymbol{q}^2}\left[G_V^2(\boldsymbol{q}^2) + 2G_A^2(\boldsymbol{q}^2) + G_A^2(\boldsymbol{q}^2)\frac{m_\pi^4}{(\boldsymbol{q}^2+m_\pi^2)^2}\right]$$

Impact on the many-body calculations

- Adhere to the precondition of the renormalization scheme
- In contrast, one may encounter the double-counting problem if the calculation employes the following potential

$$V_\nu = \frac{\tau_1^+\tau_2^+}{\boldsymbol{q}^2}\left[G_V^2(\boldsymbol{q}^2) + 2G_A^2(\boldsymbol{q}^2) + G_A^2(\boldsymbol{q}^2)\frac{m_\pi^4}{(\boldsymbol{q}^2+m_\pi^2)^2}\right] + \tau_1^+\tau_2^+ g_\nu^{NN}$$

Following the Ref. *Phys.Lett.B* 823 (2021) 136720 (Menendez) , choosing $\Lambda = 450$ and $f(q,\Lambda) = e^{-q^2/\Lambda^2}$, we obtain using pnQRPA

Nucleus	Scheme 1: $\tilde{V}_L + \tilde{V}_S$			Scheme 3: V_L
^{76}Ge	$\tilde{M}_L^{0\nu}$	$\tilde{M}_S^{0\nu}$	Total	$M_L^{0\nu}$
	5.667	-0.920	4.747	4.679

~1% difference

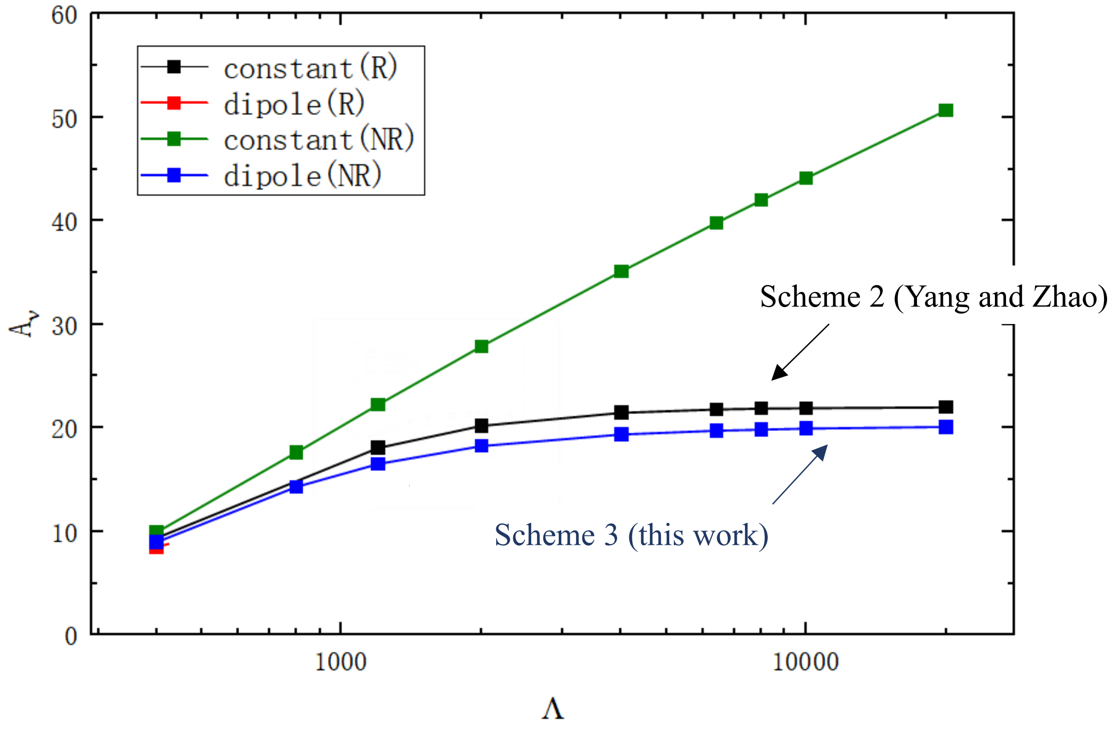
The future works:

- The further validation from the ab initio calculation is lacking.
- Can Scheme 3 capture the short-range effects predicted by the Cottingham approach?
- For other mechanisms of 0νββ decay, is Scheme 3 still valid?

➢ For other mechanisms of 0νββ decay, is the Scheme 3 still validation?

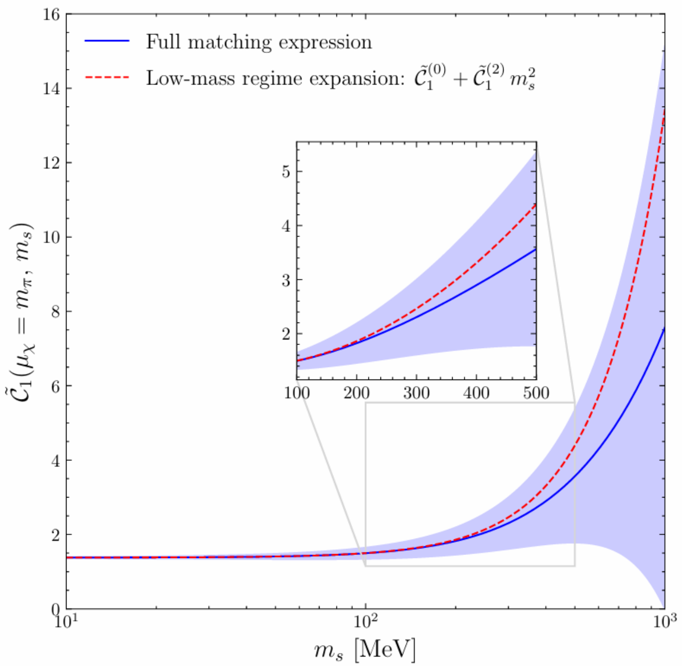
- The scalar and pseudoscalar currents

$$\mathcal{L}_{\mathrm{SP}}^{(6)}:\quad V_\nu^{{}^1S_0}(p',p) = 2\pi \int_{-1}^{1} dz\, g_A \frac{m_\pi^2 \boldsymbol{q}^2}{(\boldsymbol{q}^2+m_\pi^2)^2}$$



- The neutrino-extended standard model (νSM)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \left[\overline{\psi_L}\widetilde{H}Y_D N_R + \frac{1}{2}\bar{N}_R^c M_R N_R + h.c\right]$$



The mass-dependent LEC

[Cirigliano, 2025]

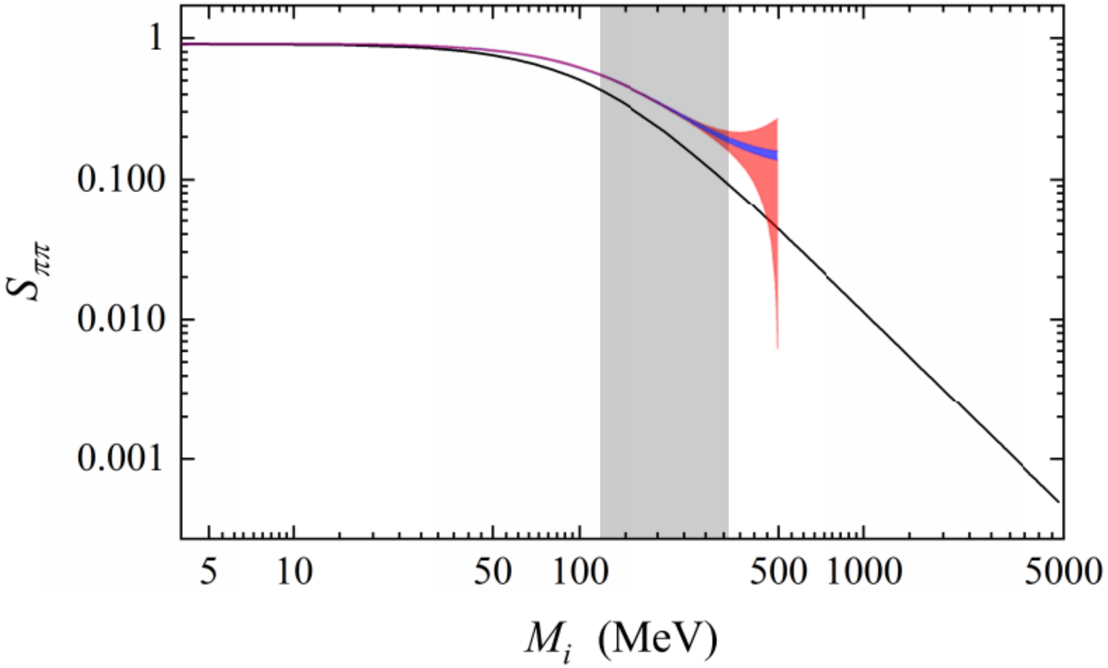
We may also anchor the mass dependence of $\tilde{C}$ using Scheme 3

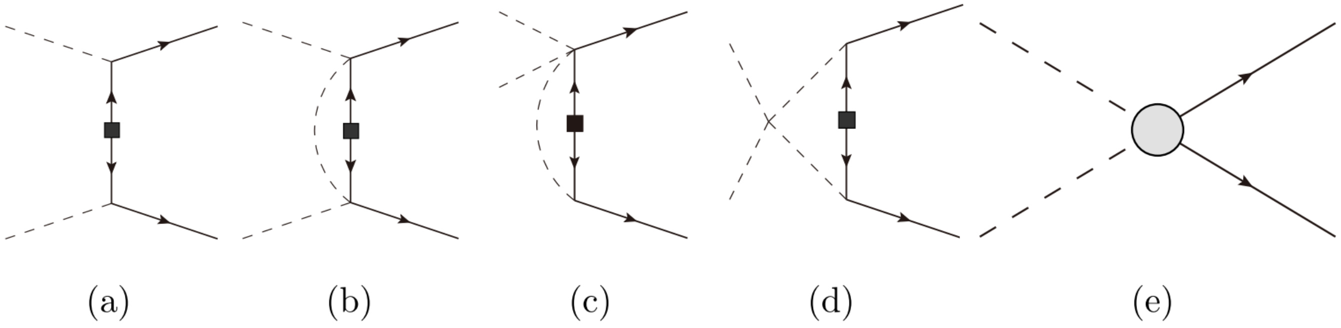
A challenge in νSM

- ► Currently, there are no stringent constraints on the mass of sterile neutrinos. Therefore, for the neutrino with mass $\sim \Lambda_\chi$, ChEFT will be invalid.

$$\pi^- + \pi^- \to e^- + e^-$$

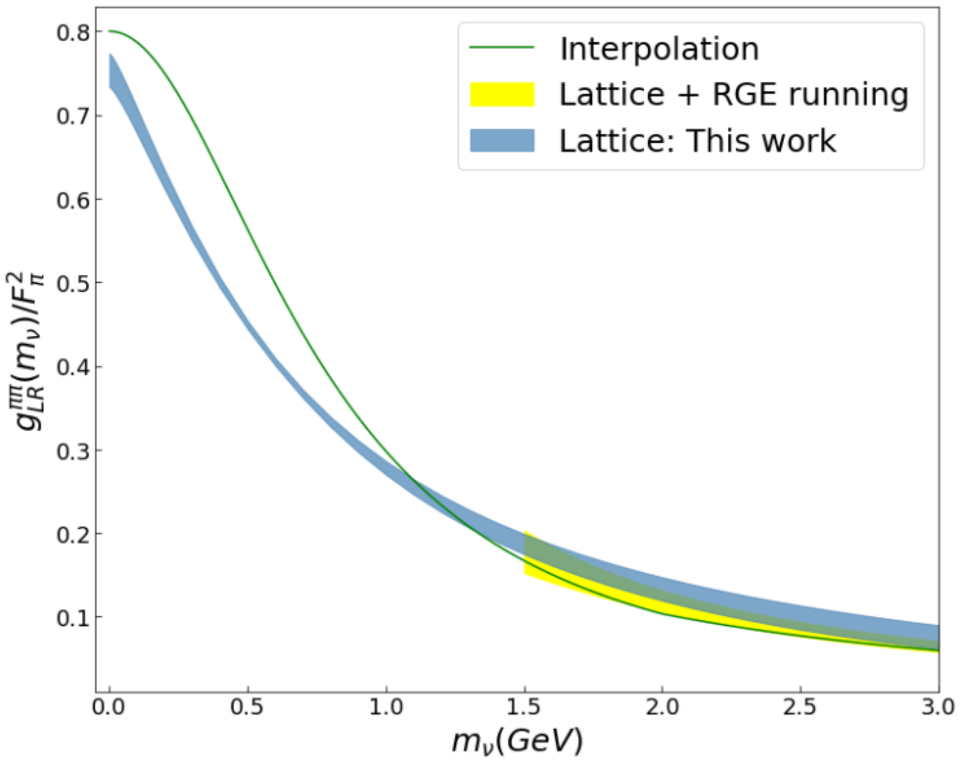
$$S_{\pi\pi}^{\text{fit}}(M_i) = S_{\pi\pi}(0)\frac{1}{1+(M_i/m_a)^2}$$





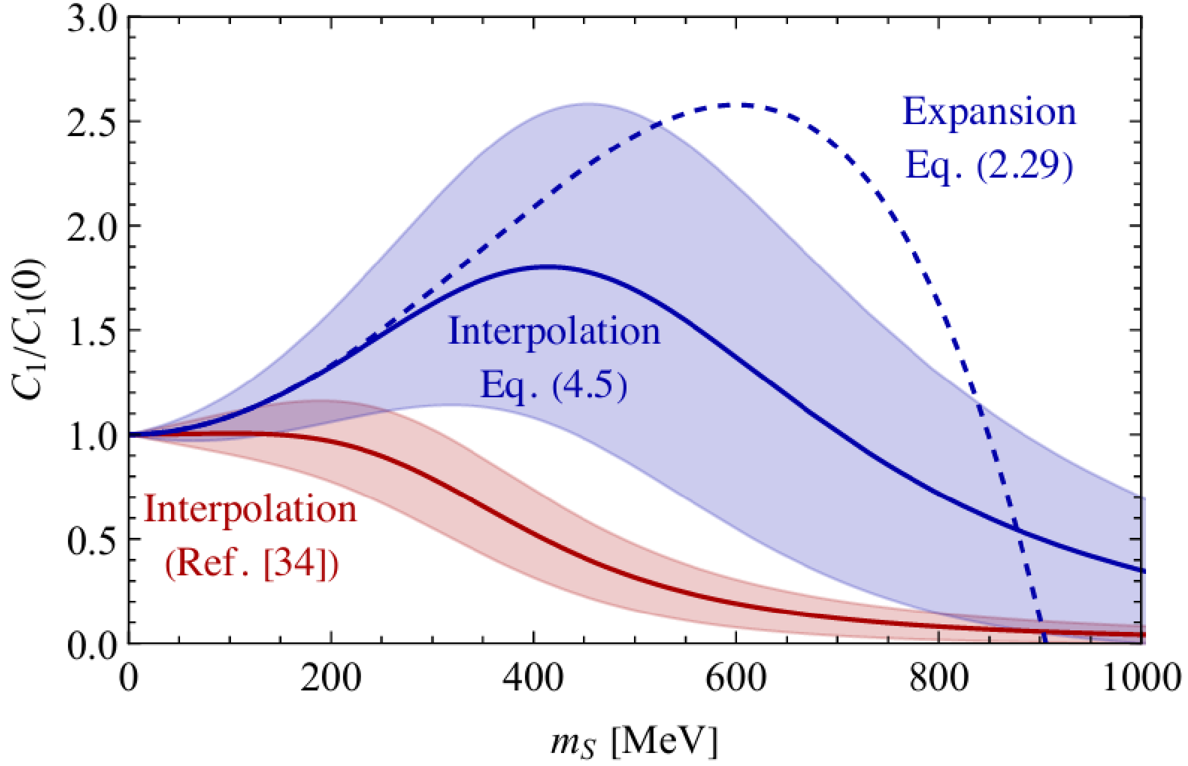
A challenge in νSM

$\pi^- + \pi^- \to e^- + e^-$



[Tuo, et. al, 2022]

$n + n \to p + p + e^- + e^-$



[Cirigliano, 2025]

The discrepancy is large, over 10% at LO

The inspiration from Scheme 2

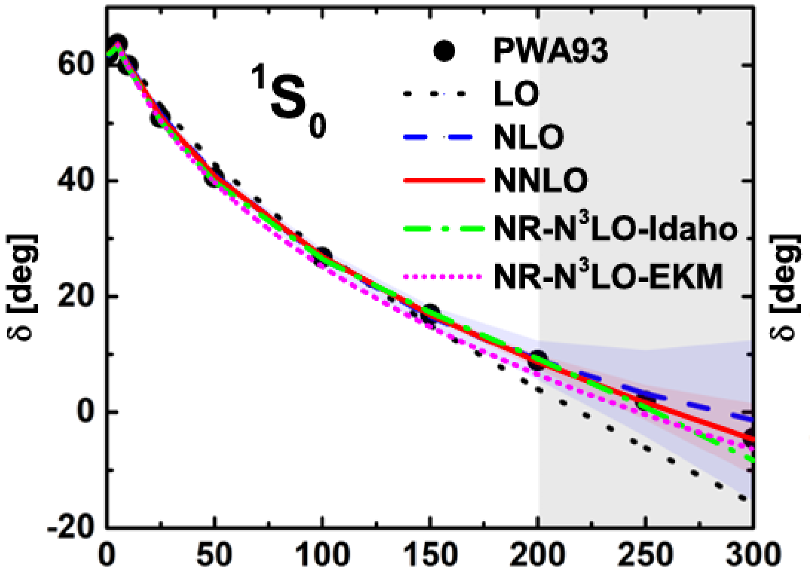
the nonrelativistic potential + the relativistic two-nucleon propagator

The manifestly Lorentz-invariant chiral framework

the relativistic potential + the relativistic two-nucleon propagator

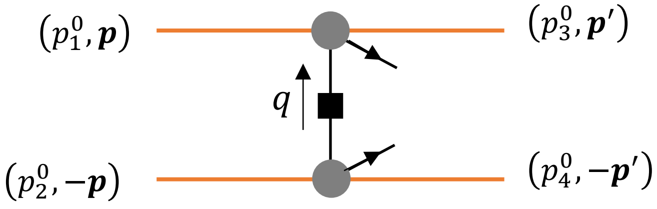
The covariant chiral framework

The relativistic chiral force



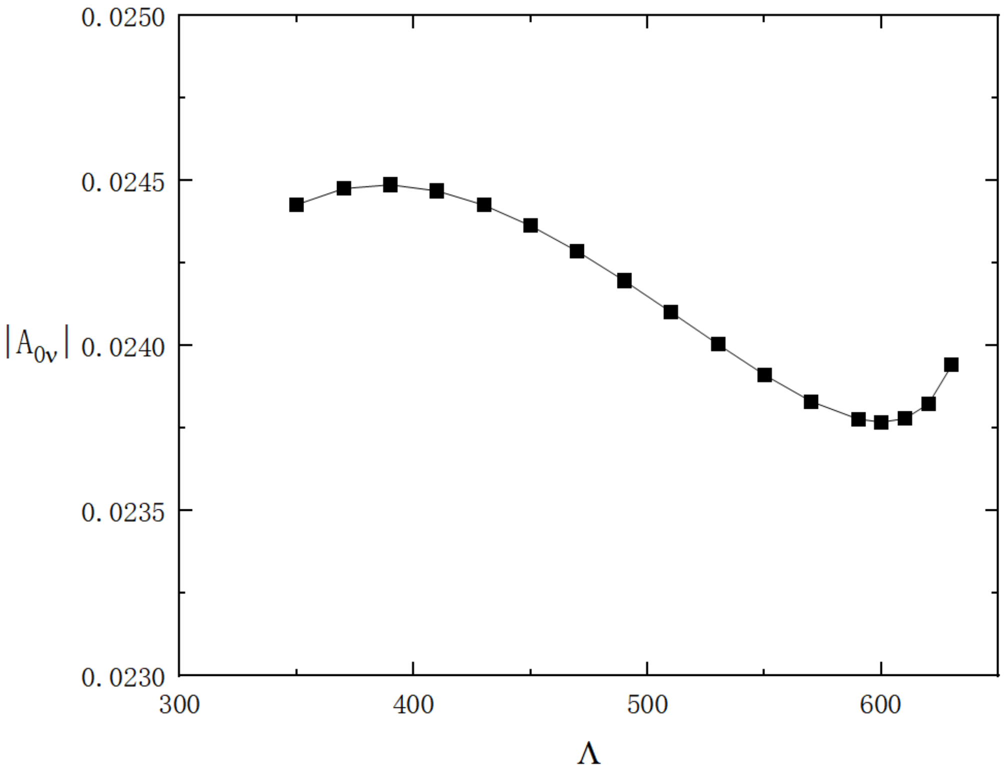
[Lu, et. al, 2022]

The LO relativistic neutrino potential:



$$V(\boldsymbol{p}', \boldsymbol{p}; P) = \tau_1^+ \tau_2^+ (4G_F^2 V_{ud}^2)[\bar{u}(k_1) P_R C \bar{u}^T(k_2)] \frac{m_{\beta\beta}}{\boldsymbol{q}^2} [\bar{u}(p_3, s_1') J_V^\mu(q) u(p_1, s_1) \bar{u}(p_4, s_2') J_{V\mu}(q) u(p_2, s_2)]$$
$$[+\bar{u}(p_3, s_1') J_A^\mu(q) u(p_1, s_1) \bar{u}(p_4, s_2') J_{A\mu}(q) u(p_2, s_2)]$$

We can investigate the 0νββ decay using the covariant ChEFT



The transition amplitude based on the covariant ChEFT

- The LO contact term seems to be required.
- How to determine the size of this LO operator?
- The description of the covariant ChEFT for other mechanisms
- How about the renormalization?

…

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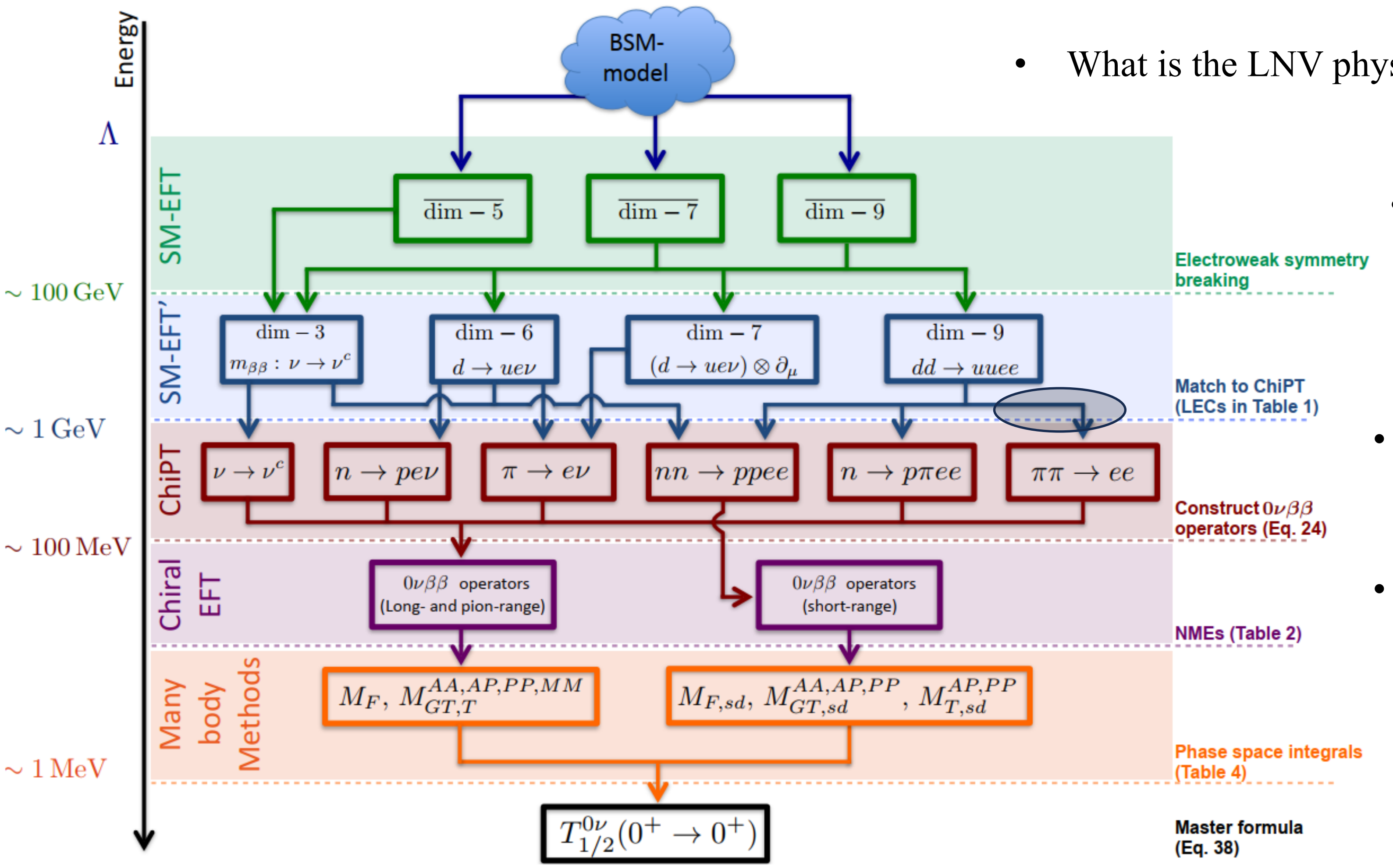
- EFT plays a key role in mapping UV physics to the low-energy scale.



[Cirigliano, et al.,2018]

- What is the LNV physics
- How to constraint NP with data
- How to describe the region where EFT is invalid
- Renormalization in ChEFT