



北京大学

“Recommended Values for $0\nu\beta\beta$ Decay NME” workshop

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Relativistic Chiral Effective Field Theory for Neutrinoless Double Beta Decay

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Outline

- **Introduction**
- Relativistic chiral EFT for $0\nu\beta\beta$ decay
 - ▶ $nn \rightarrow ppee$ amplitudes
 - ▶ Nuclear matrix elements
- Summary and outlooks

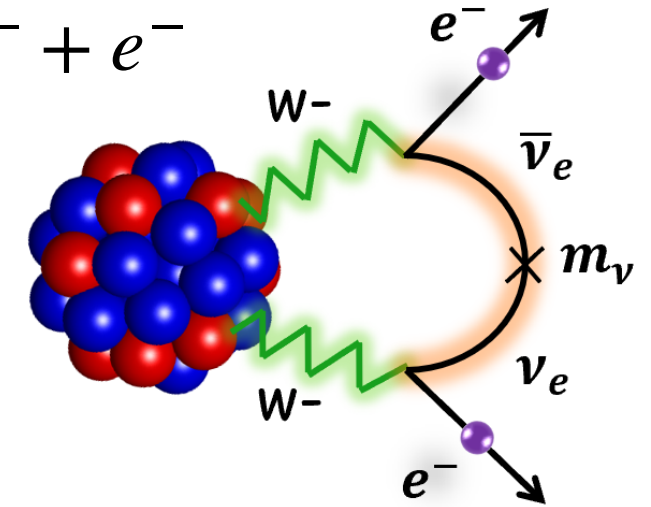
Nuclear matrix elements (NMEs)

- Neutrinoless $\beta\beta$ decay ($0\nu\beta\beta$): $(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$

✓ Lepton number violation

✓ Majorana nature of neutrinos

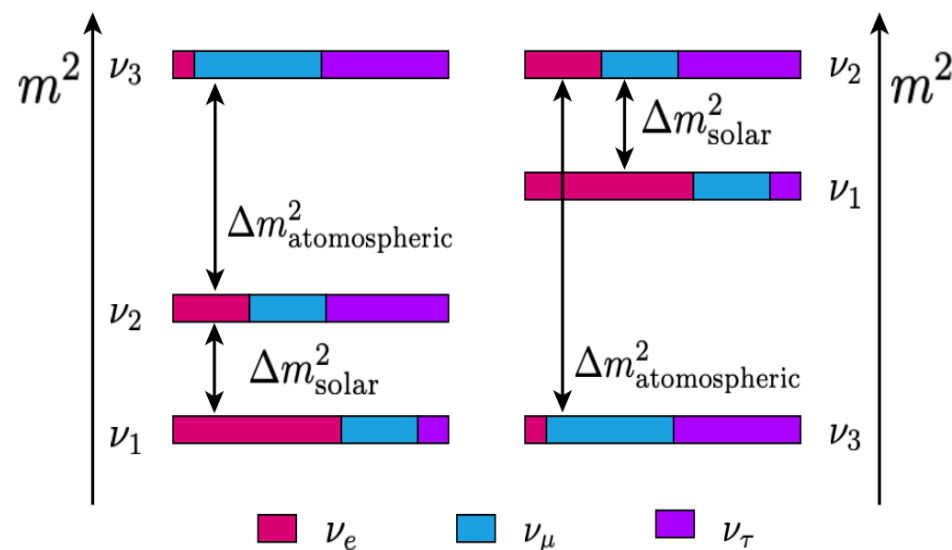
✓ Neutrino mass scale and hierarchy



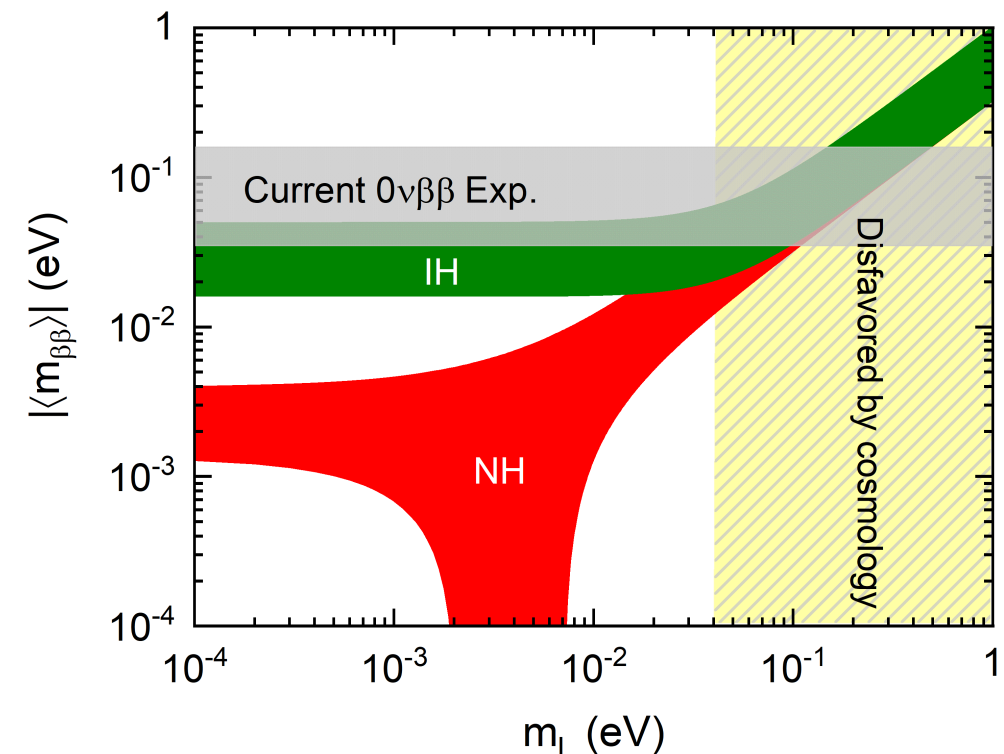
Avignone, Elliott, Engel, Rev. Mod. Phys. 80, 481 (2008)

- Accurate calculation of NMEs is crucial for interpreting the experimental limits

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |m_{\beta\beta}|^2 |M^{0\nu}|^2 + \dots$$



Normal Hierarchy (NH) Inverted Hierarchy (IH)



KamLAND-Zen Collaboration, PRL 130, 051801 (2023)

Hiararchies in $0\nu\beta\beta$

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |m_{\beta\beta}|^2 |M^{0\nu}|^2 \quad M_{0\nu} = \langle \Psi_f | \mathbf{V}_\nu | \Psi_i \rangle$$

Energy Scale

?

$m_{\beta\beta}$

Lepton-number-violating source

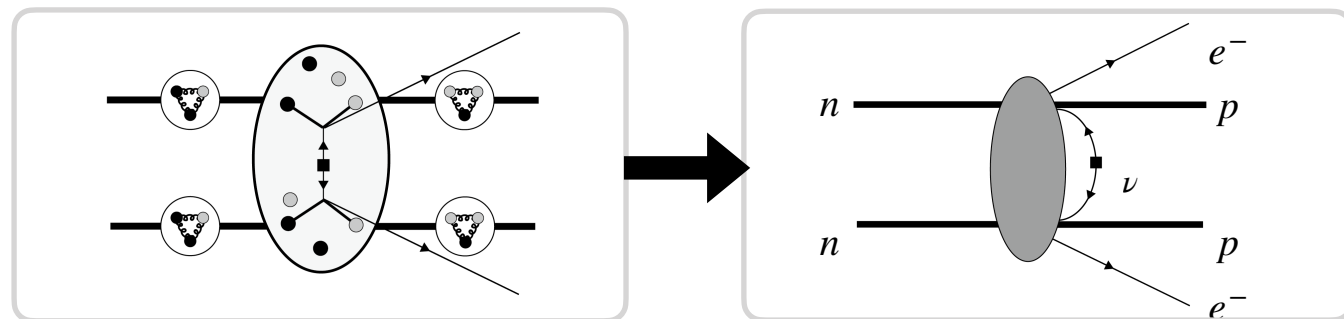
$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_5 + \dots \quad \mathcal{L}_5 \rightarrow -\frac{1}{2} m_{\beta\beta} \nu^T C \nu$$

V_ν

Constructing the $0\nu\beta\beta$ transition operator (neutrino potential V_ν)

Matching quark-level operators to *chiral EFT*

< 1 GeV



100 MeV

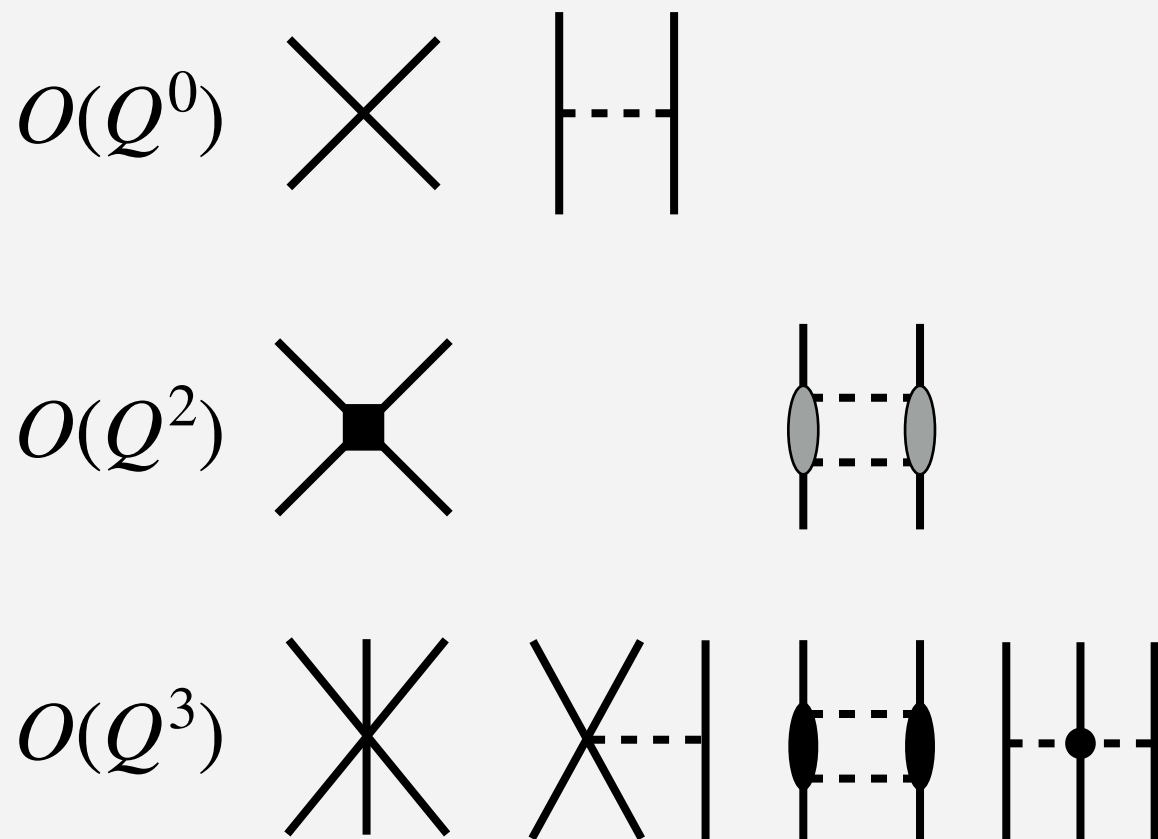
$\Psi_{f,i}$

Nuclear many-body calculations with V_ν as inputs

Neutrino potentials from chiral EFT

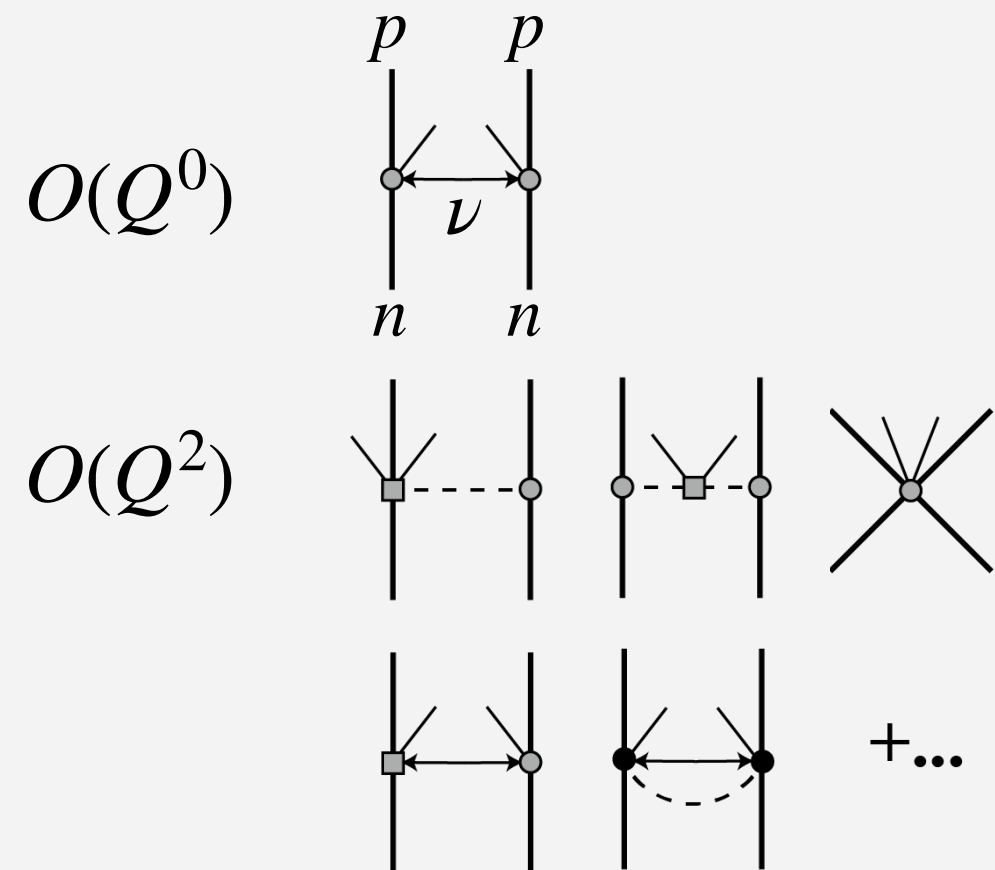
- Chiral EFT provides a way to derive neutrino potentials **consistently** with the nuclear force and **systematically** based on a **power counting**
- Weinberg power counting (Naive dimensional analysis)?

Nuclear force



Epelbaum, Hammer, and Meißner, RMP 81, 1773 (2009)

Neutrino potential



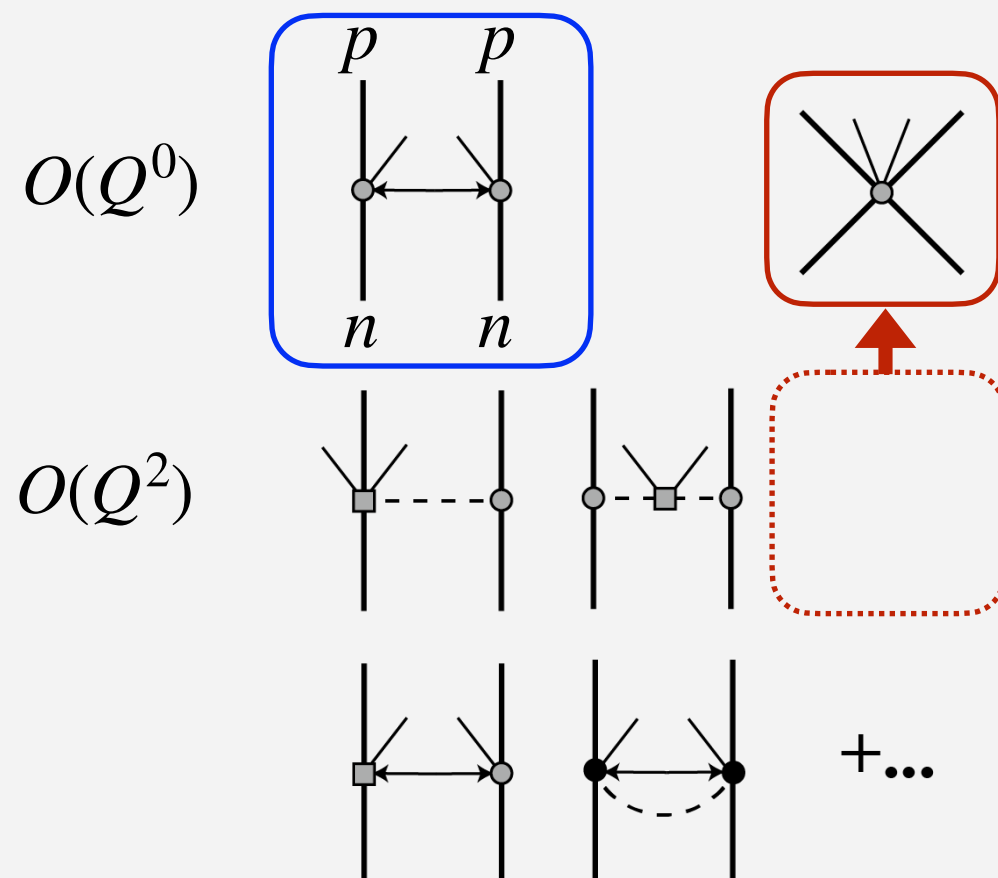
Cirigliano, Dekens, Mereghetti, and Walker-Loud, PRC 97, 065501 (2018)

LO contact term from chiral EFT

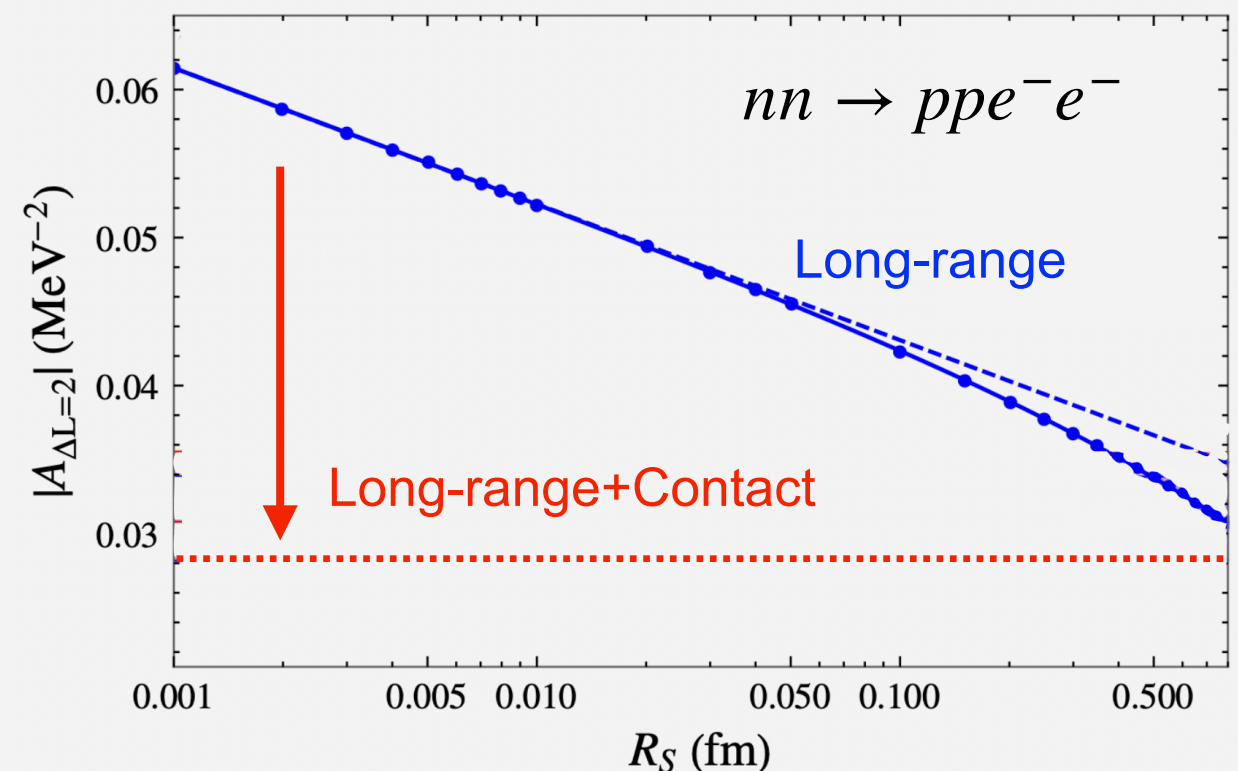
- The LO long-range term does not yield renormalizable amplitudes
- To ensure the renormalizability, a contact term needs to be promoted to LO

$$V_{\text{CT}} = -2g_{\nu}^{\text{NN}}\tau_1^+\tau_2^+$$

Power counting



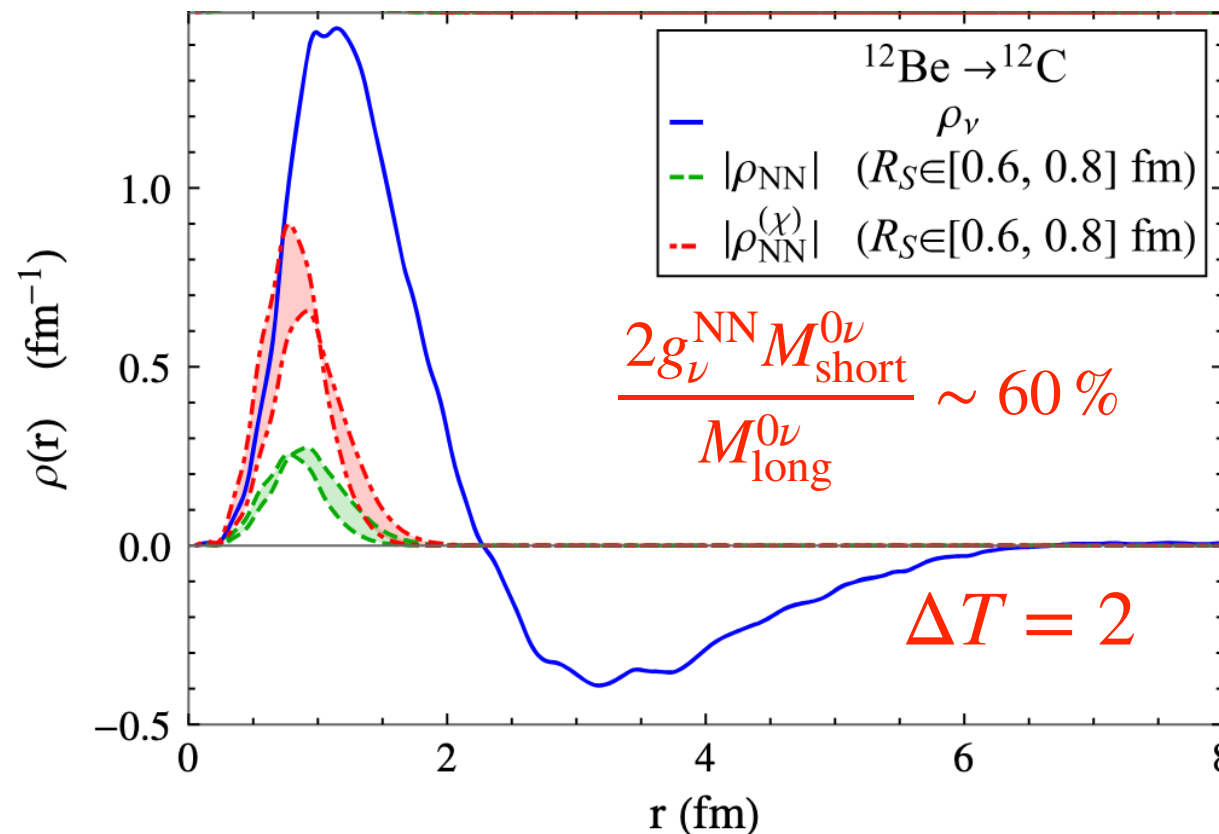
Renormalizability



Impact of LO contact term

- The LO contact term may significantly change the NME values

$$M^{0\nu} = M_{\text{long}}^{0\nu} - 2g_{\nu}^{\text{NN}} M_{\text{short}}^{0\nu}$$



Here, it is assumed that $g_{\nu}^{\text{NN}} = (C_1 + C_2)/2$, i.e., fixed by the CIB LEC in NN potential

Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, and van Kolck, PRL 120, 202001 (2018)

- The LEC g_{ν}^{NN} is unknown and largely uncertain—How to determine g_{ν}^{NN} ?

Generalized Cottingham model

- Matching g_ν^{NN} to a “full-theory” amplitude from a generalized Cottingham model

- ▶ **Model dependence**

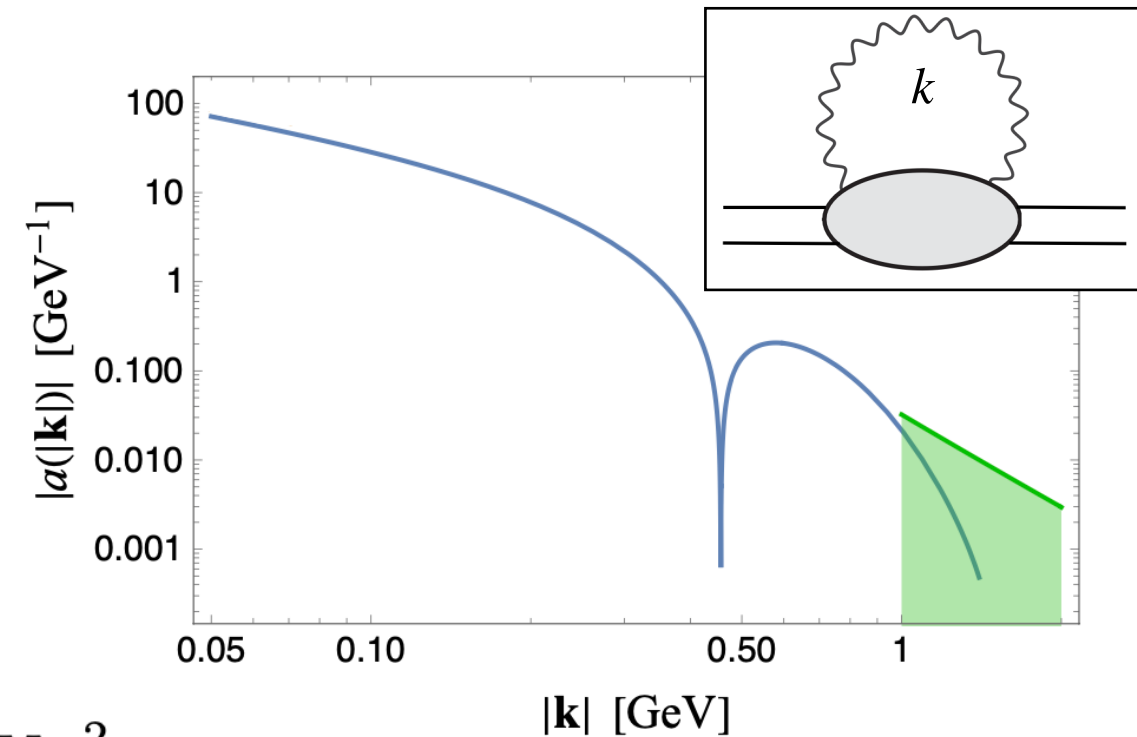
1. Neglect inelastic intermediate states
2. Phenomenological off-shell NN amplitudes
3. Phenomenological weak form factors

...

- ▶ $nn \rightarrow ppee$ amplitude:

$$|\mathcal{A}(p' = 30 \text{ MeV}, p = 25 \text{ MeV})| = 0.0195(5) \text{ MeV}^{-2}$$

Cirigliano et al., PRL 126, 172002 (2021), Cirigliano et al., JHEP 05, 289 (2021)



- Serving as a synthetic datum to constrain g_ν^{NN} in *ab initio* calculations of NMEs

Wirth, Yao, and Hergert, PRL 127, 242502 (2021), ...

How to interpret the enhancement of the LO contact term g_ν^{NN} ?

How to benchmark the estimations of $nn \rightarrow ppee$ amplitude and g_ν^{NN} ?

Relativistic EFT formulation?

- The above analyses are all performed in **nonrelativistic framework**
- Lorentz invariance is a fundamental symmetry, so an EFT formulation should be consistent with **Relativity**
 - ▶ For kinematics, nonrelativistic expansion is a **well controlled approximation**

$$\sqrt{p^2 + m_N^2} = m_N + \frac{p^2}{2m_N} + O(p^4)$$

- ▶ In **renormalization**, relativity could have **significant effect**

$$T = V + \boxed{\int_0^\infty} V G T \quad \text{Virtual excitations up to high momenta}$$

EFT for $0\nu\beta\beta$ decay can be relativistic!

Studying $0\nu\beta\beta$ decay in a relativistic framework provides a different view of the renormalization and, thus, the contact term in chiral EFT

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Modified Weinberg's approach

- Employ the Lorentz invariant Lagrangian and decompose the fermion propagator

Gegelia and Epelbaum, PLB 716, 338 (2012)

$$\frac{\not{p} + m}{p^2 - m^2 + i\epsilon} = \frac{2m P_+ + (\not{p} - m\not{p})}{p^2 - m^2 + i\epsilon} = \underbrace{\frac{2m P_+}{p^2 - m^2 + i\epsilon}}_{\text{include nonperturbatively}} + \underbrace{\dots}_{\text{treat as correction}}$$

Keep the pole $p_0 = +\sqrt{p^2 + m_N^2}$ and **do NOT** perform the nonrelativistic reduction

- Use the **Kadyshevsky equation** to calculate the scattering T -matrix

$$T(\mathbf{p}', \mathbf{p}; E) = V(\mathbf{p}', \mathbf{p}) + \int \frac{d^3\mathbf{k}}{(2\pi)^3} V(\mathbf{p}', \mathbf{k}) \frac{m_N^2}{m_N + k^2} \frac{1}{E - 2\sqrt{k^2 + m_N^2} + i\epsilon} T(\mathbf{k}, \mathbf{p}; E)$$

Reduces to the usual Lippmann-Schwinger equation in $m_N \rightarrow \infty$ Limit

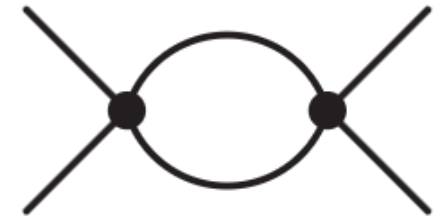
- Apply **Weinberg power counting** to organize the NN potential

$$V^{(0)} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 - \frac{g_A^2}{4f_\pi^2} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q} \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{\mathbf{q}^2 + m_\pi^2} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

UV behavior: relativistic v.s. nonrelativistic

- Renormalizability is closely related to the UV behavior of the loop integrals
- Consider the bubble diagram that enters NN scattering

$$I(p) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \theta(\Lambda - |\vec{k}|) \frac{1}{(k^2 + m_N^2) \left[\sqrt{p^2 + m_N^2} - \sqrt{k^2 + m_N^2} + i\epsilon \right]}$$



- ▶ Calculate the loop and then expand over $1/m_N$

$$I = \frac{1}{4\pi^2} \left[\boxed{-\frac{2i\pi p}{m_N}} - \boxed{2 \ln \frac{\Lambda}{m_N}} - m_N^2 (\pi + \ln 4) + \mathcal{O}\left(\frac{1}{m_N^2}, \frac{1}{\Lambda}\right) \right]$$

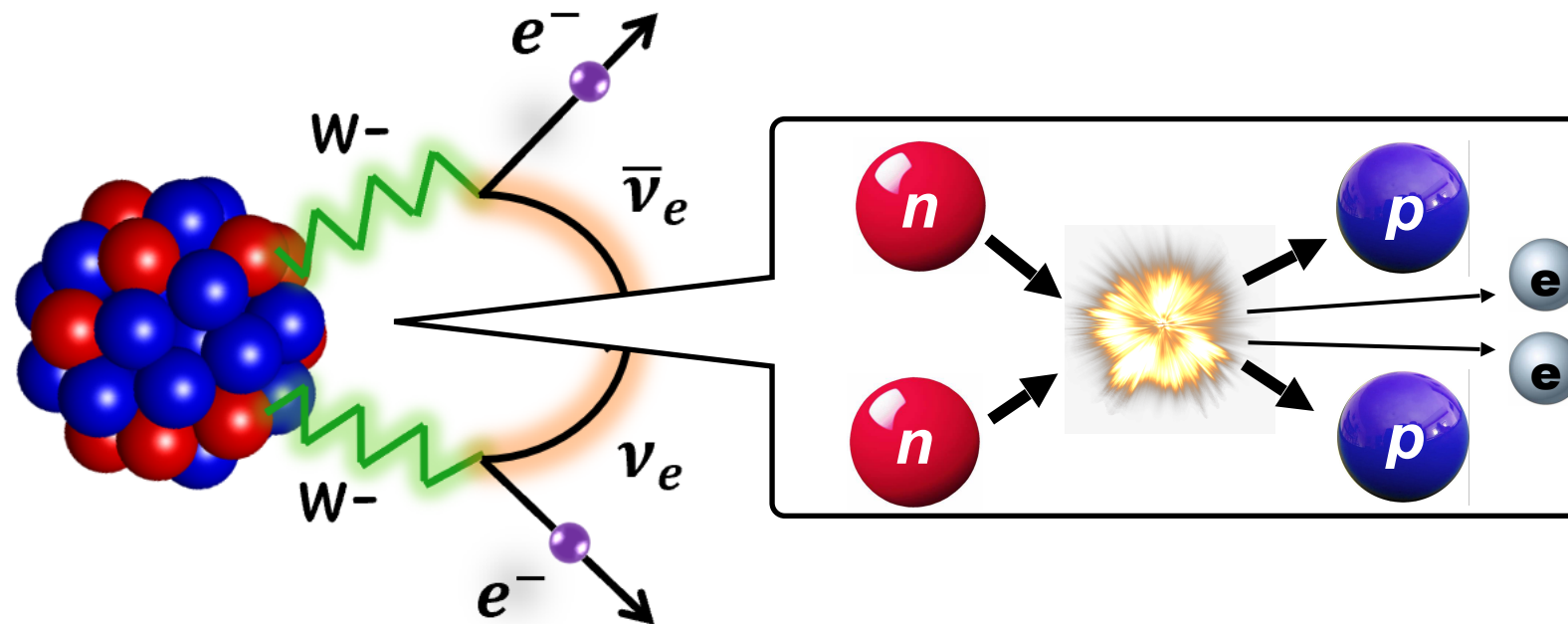
- ▶ Expand over $1/m_N$ (Nonrelativistic EFT) and then calculate the loop

$$I = \frac{1}{4\pi^2} \left[\boxed{-\frac{2i\pi p}{m_N}} - \boxed{\frac{4\Lambda}{m_N}} + \mathcal{O}\left(\frac{1}{m_N^2}, \frac{1}{\Lambda}\right) \right]$$

Gegelia and Epelbaum, PLB 716, 338 (2012)

- Same low-energy physics; different UV divergence absorbed by contact terms
- Both works in NN scattering using $C_S, C_T, \dots$; What about $0\nu\beta\beta$ decay g_ν^{NN} ?

$nn \rightarrow ppee$ process



$$n + n \rightarrow p + p + e^- + e^- \quad A^{0\nu} = \langle nn | V_\nu | pp \rangle$$

- Two-body problem can be solved exactly within EFT
- Benchmarks with first-principle lattice QCD calculations

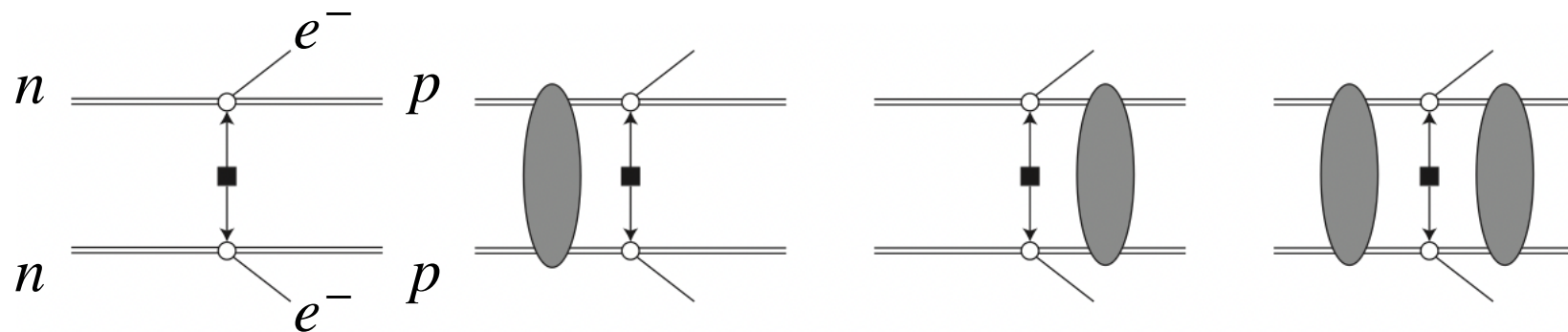
➡ Theoretical laboratory to study and constrain the contact term g_ν^{NN}

$nn \rightarrow ppee$ amplitude at LO

- We focus on $nn \rightarrow ppee$ in 1S_0 wave, as it is the only channel requiring a contact term in the nonrelativistic framework.

Cirigliano et al., PRL 120, 202001 (2018)
Cirigliano et al., PRC 97, 065501 (2018)

- The LO $nn \rightarrow ppee$ decay amplitude



- Standard LO strong and neutrino potentials

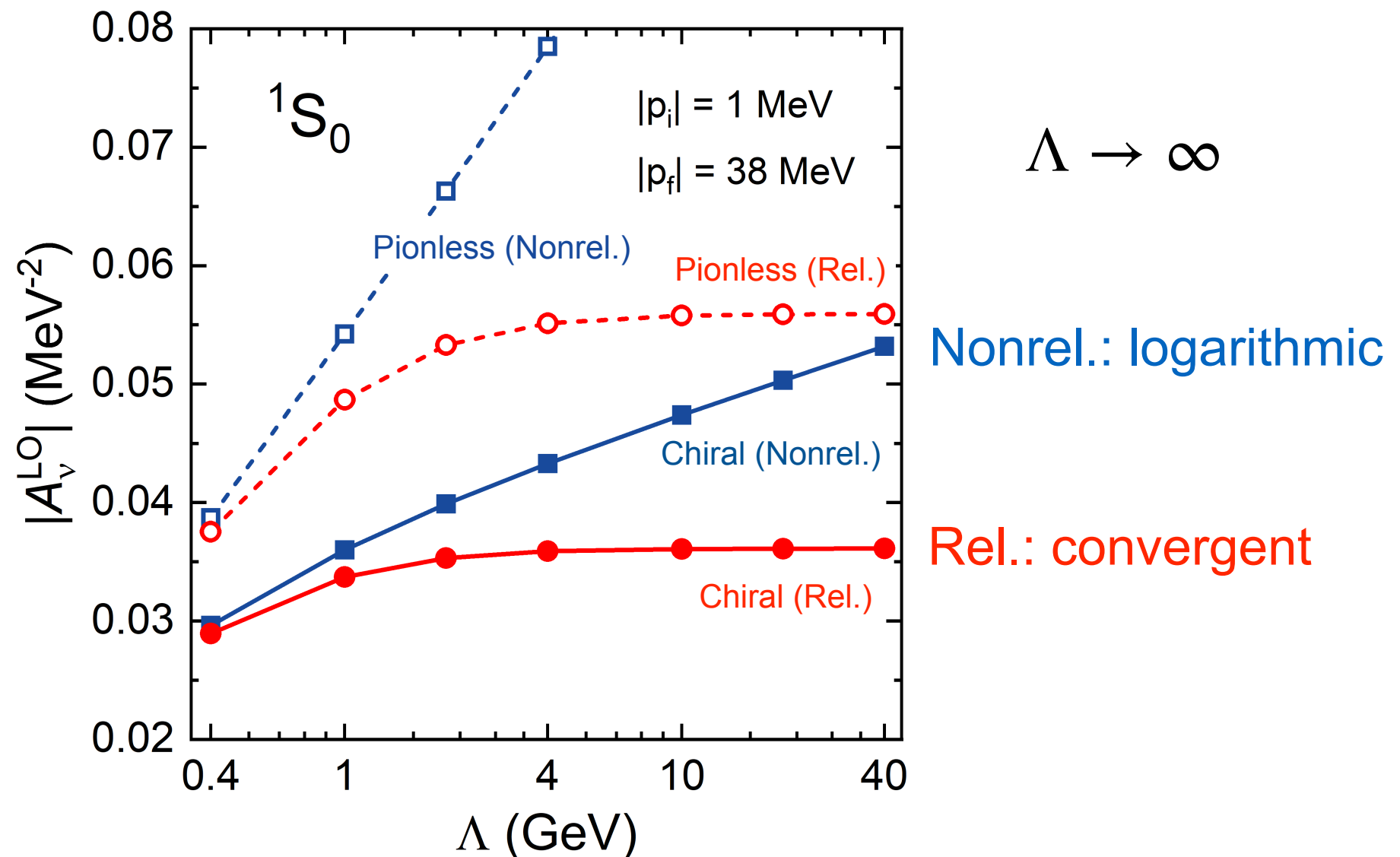
Strong potential: $V_s^{(0)} = \textcolor{red}{C} - \frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{m_\pi^2 + q^2}$ LEC fixed by $\textcolor{red}{a}_{np}(^1S_0) = -23.74(2) \text{ fm}$

Neutrino potential: $V_\nu^{(0)} = \frac{\tau_1^+ \tau_2^+}{q^2} \left\{ 1 + 2g_A^2 \left[1 + \frac{m_\pi^4}{2(q^2 + m_\pi^2)^2} \right] \right\} \quad \mathbf{q} = \mathbf{p}' - \mathbf{p}$

Renormalizability at LO

- In a relativistic formulation, renormalizability is achieved without a LO contact term

YLY and P. W. Zhao, PLB 855, 138782 (2024)



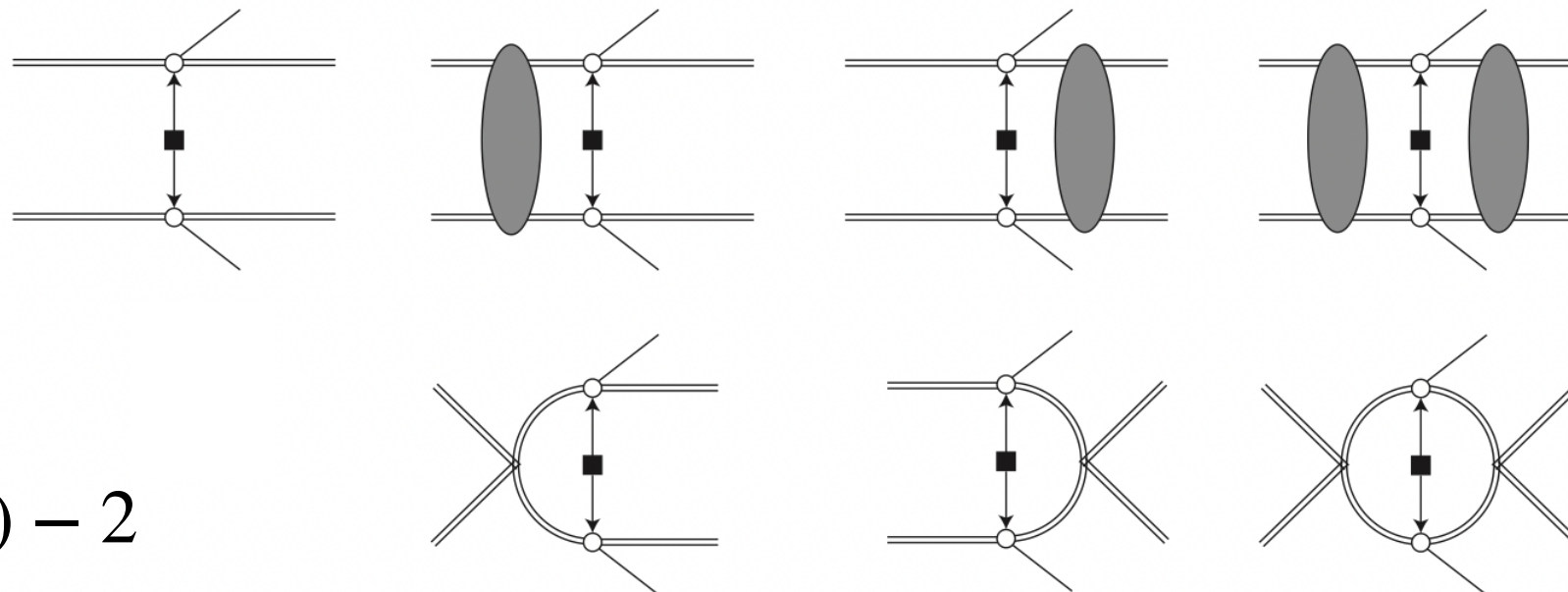
Regularization $V(\mathbf{p}', \mathbf{p}) \rightarrow e^{-p'^4/\Lambda^4} V(\mathbf{p}', \mathbf{p}) e^{-p^4/\Lambda^4}$

Analysis of UV divergence

- Relativistic scattering equation has a milder ultraviolet (UV) behavior

	Relativistic	Nonrelativistic
Propagator:	$\frac{m_N^2}{k^2 + m_N^2} \frac{1}{E - 2\sqrt{k^2 + m_N^2} + i0^+}$	$\frac{1}{E_{\text{kin}} - k^2/m_N + i0^+}$
UV behavior ($k \sim \Lambda$):	$O(\Lambda^{-3})$	$O(\Lambda^{-2})$

- The degree of divergence of $nn \rightarrow ppee$ decay amplitude:



UV behavior:

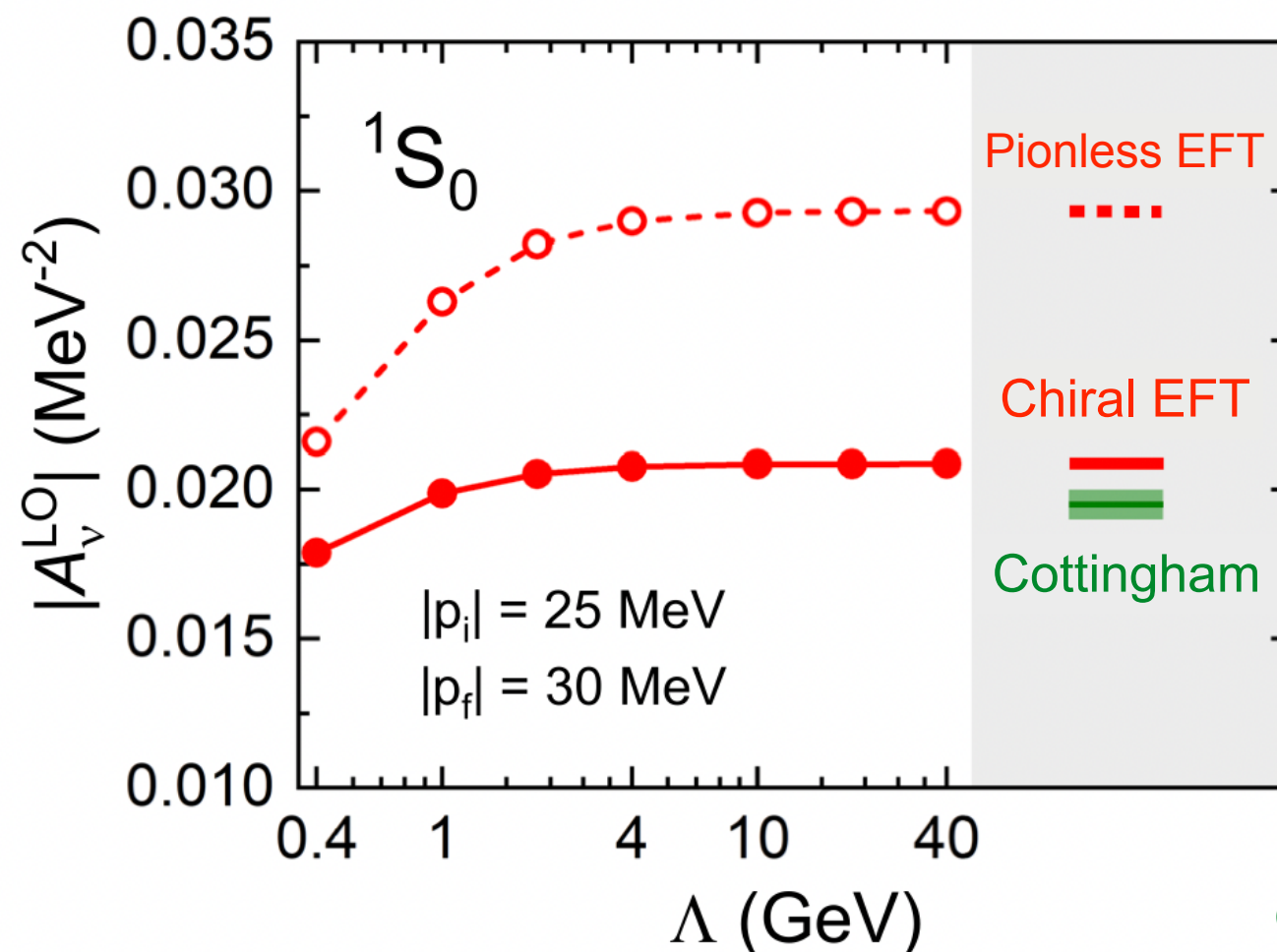
$$D = L(3 + g) - 2$$

Renormalizable?

Relativistic:	—	$O(\Lambda^{-2})$	$O(\Lambda^{-2})$	$O(\Lambda^{-2})$	Yes
Nonrelativistic:	—	$O(\Lambda^{-1})$	$O(\Lambda^{-1})$	$O(\log \Lambda)$	No

LO prediction

- The LO relativistic chiral EFT and the generalized Cottingham model are **consistent at 10% level** YLY and P. W. Zhao, PLB 855, 138782 (2024)
 - ▶ Input of *relativistic EFT*: NN 1S_0 scattering length (*Only one LEC*)
 - ▶ Inputs of generalized Cottingham model: Phenomenological weak form factors, modeling off-shell NN amplitudes, ...



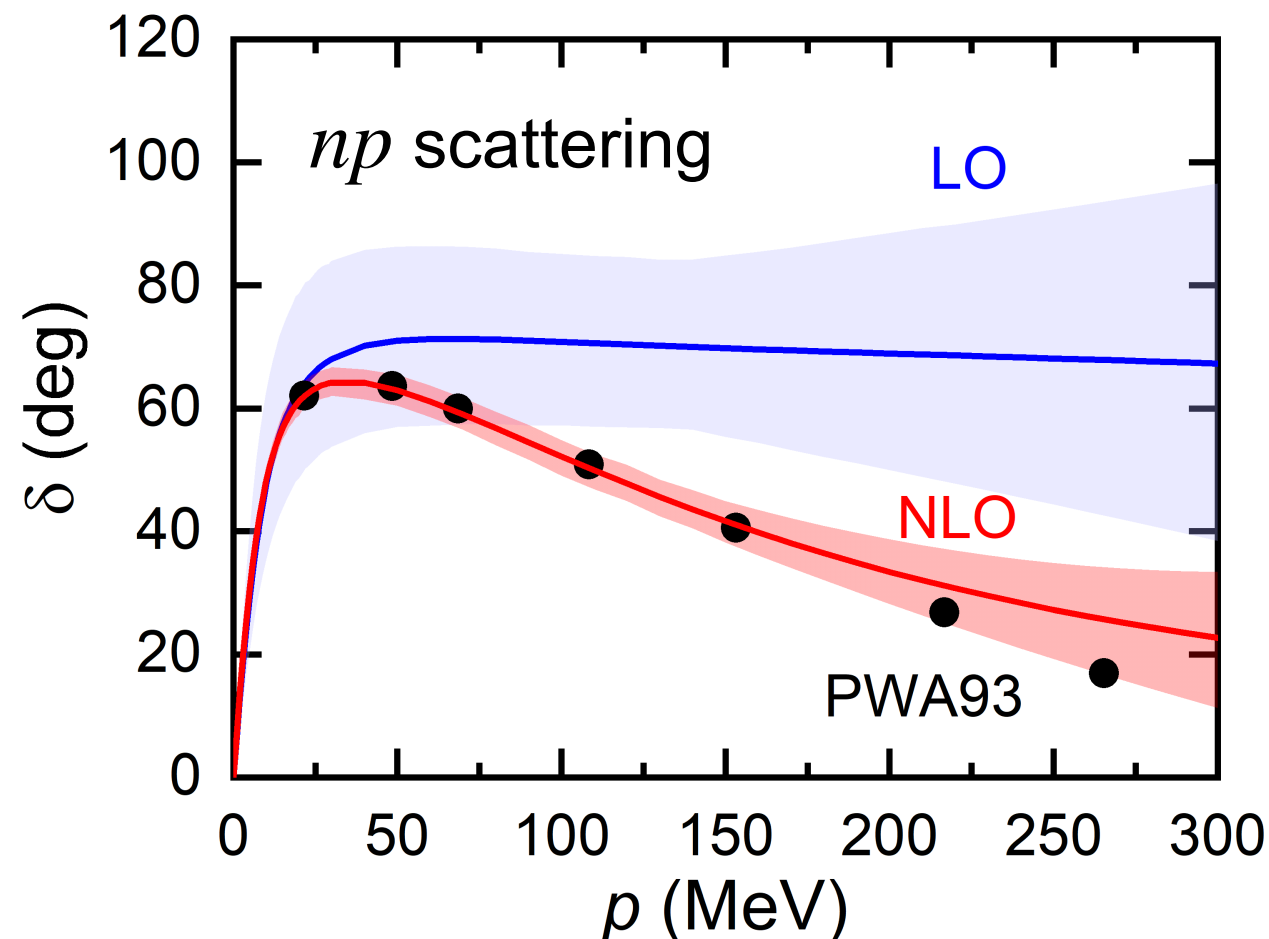
Generalized Cottingham model
Cirigliano et al., PRL 126, 172002 (2021)

Effective range corrections

- Including the effective range corrections in the calculation of the $nn \rightarrow ppee$ amplitude to improve its accuracy, while retaining its renormalizability.

$$V_s = \left(\textcolor{red}{C} - \frac{g_A^2}{4f_\pi^2} \frac{m_\pi^2}{m_\pi^2 + q^2} \right)_{\text{LO}} + \left(\textcolor{red}{D} \frac{p'^2 + p^2}{2} \right)_{\text{NLO}}$$

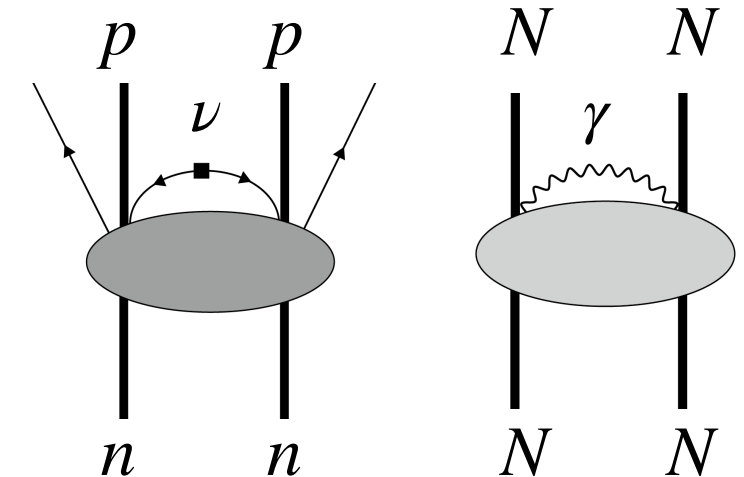
- The two LECs are determined by the np phase shifts with a Bayesian approach



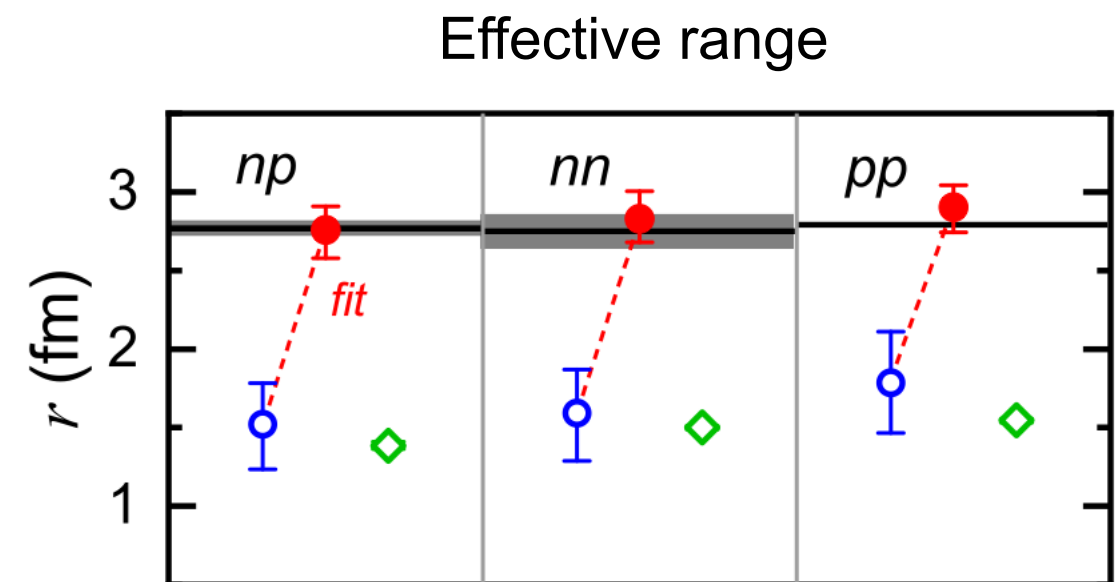
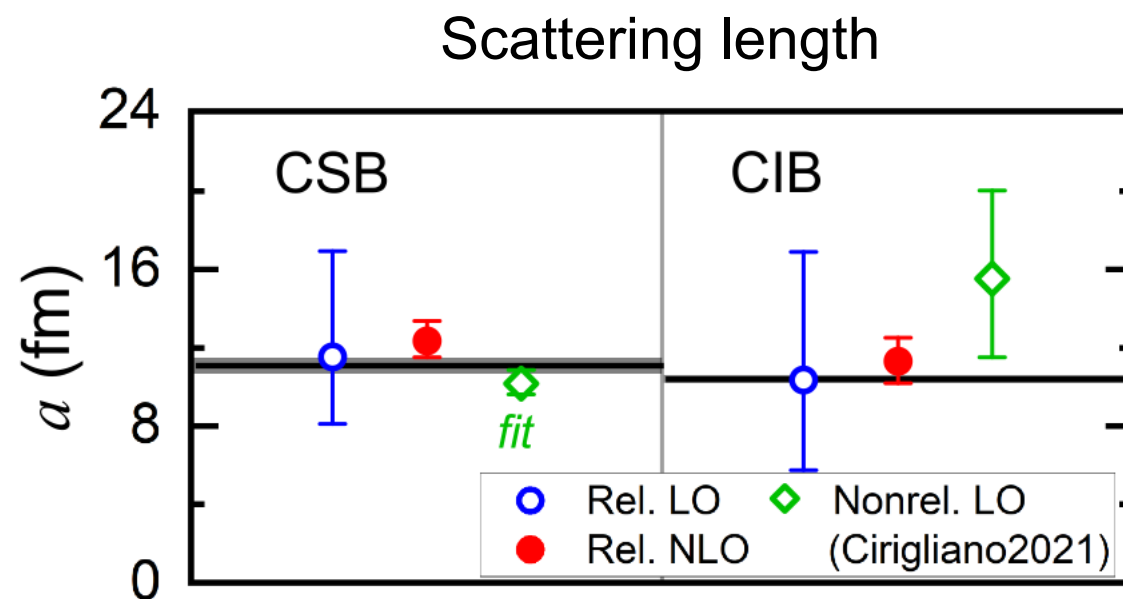
Validation

- We first validate our approach on the CIB and CSB of the NN scattering data at low energies, dominated by the one-photon exchange process

$$V_s^{nn,pp} = \left(C - \frac{g_A^2}{4f_\pi^2} \frac{m_{\pi_0}^2}{m_{\pi_0}^2 + q^2} \right)_{\text{LO}} + \left(D \frac{p'^2 + p^2}{2} \right)_{\text{NLO}} + V_C^{pp}$$



- Predictions agree with experimental data



YLY and P. W. Zhao, PRL 134, 242502 (2025)

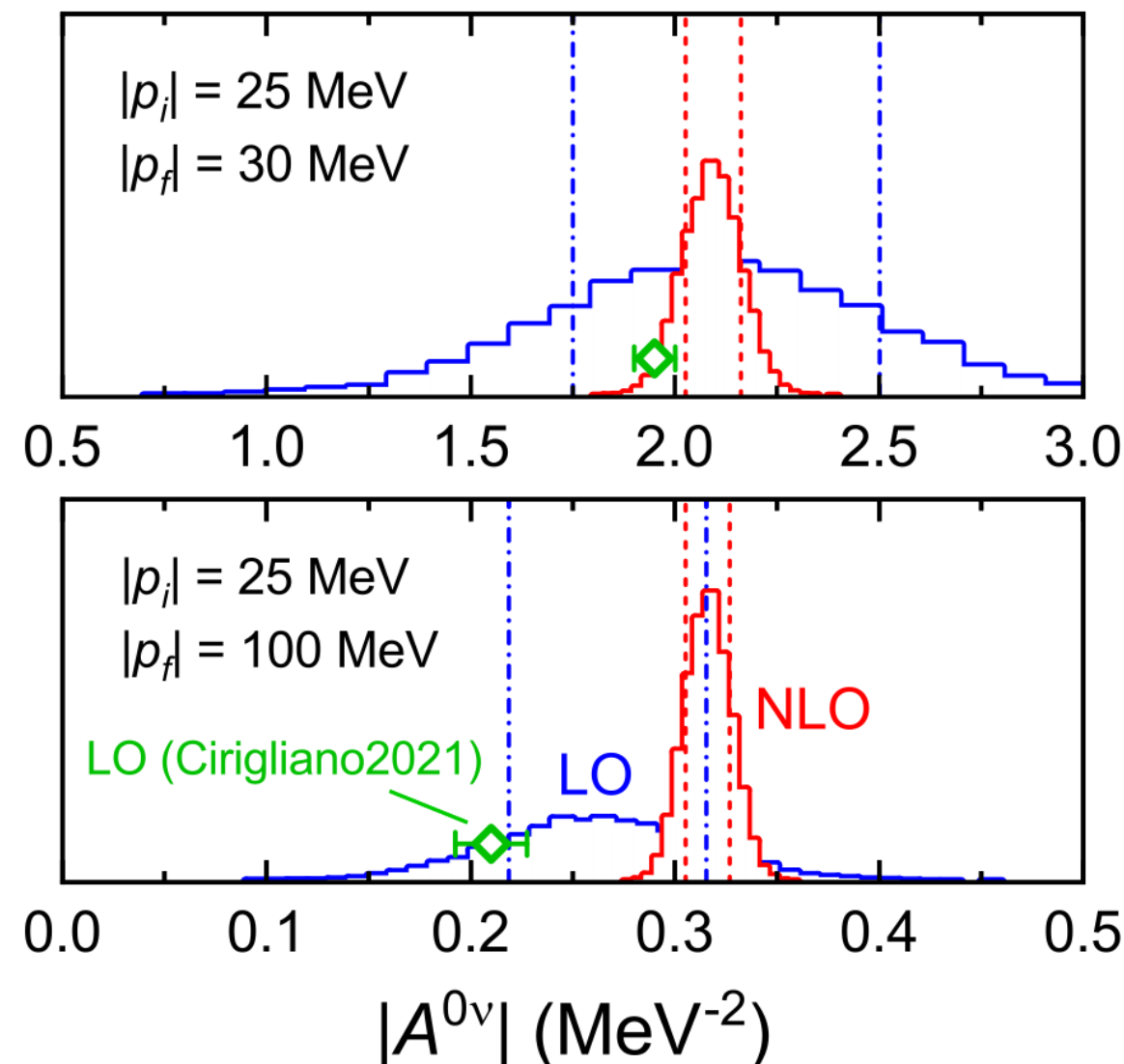
Cirigliano et al., PRL 126, 172002 (2021)

NLO prediction for $nn \rightarrow ppee$

- The NLO corrections significantly reduce the uncertainty of the LO result.
- The NLO prediction is systematically larger than the previous nonrel. LO results.

YLY and P. W. Zhao, PRL 134, 242502 (2025)

$$|\mathcal{A}_{0\nu}| = 0.0209(7) \text{ MeV}^{-2} \quad (p, p') = (25, 30) \text{ MeV}$$



Matching EFTs to LQCD

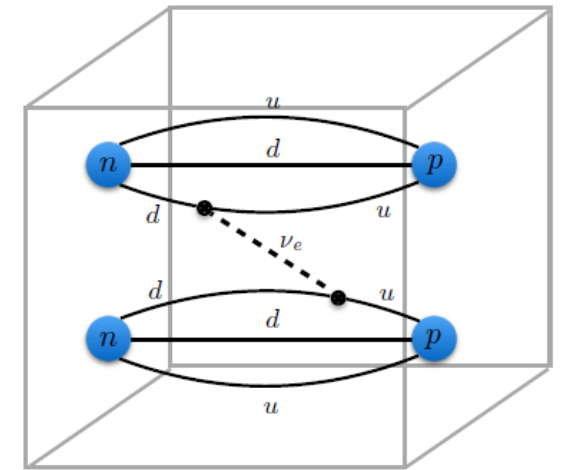
- LQCD can play an important role in constraining g_ν^{NN}

- ✓ Matching procedure from LQCD to g_ν^{NN}

Davoudi and Kadam, PRL 126, 152003 (2021); Phys. Rev. D 105, 094502 (2022)

- ✓ $nn \rightarrow ppee$ matrix elements at $m_\pi = 806$ MeV

Davoudi et al. (NPLQCD), Phys. Rev. D 109, 114514 (2024).



- Matching the LQCD matrix elements in **nonrelativistic** EFT?

$$M_{\text{long}}^{0\nu}(\Lambda) + 2g_\nu^{\text{NN}}(\Lambda)M_{\text{short}}^{0\nu}(\Lambda) = M_{\text{LQCD}}^{0\nu}$$

One can determine g_ν^{NN} at a given cutoff Λ at an m_π value...

- Matching the LQCD matrix elements in **relativistic** EFT?

$$M_{\text{long}}^{0\nu}(\Lambda \rightarrow \infty) \overset{?}{\longleftrightarrow} M_{\text{LQCD}}^{0\nu}$$

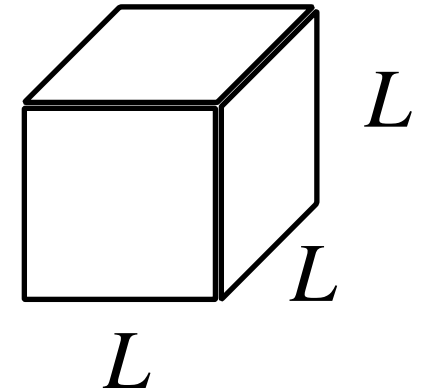
- ✓ Relativistic EFT is renormalizable without g_ν^{NN}

- ✓ Can predict $M^{0\nu}$ at an m_π value and benchmark the EFT prediction with LQCD

Relativistic pionless EFT in finite volume

- Motivated by the large pion mass, we employ a pionless EFT
- In a periodic box with size L , discretize the momentum mode

$$T(\boldsymbol{n}', \boldsymbol{n}) = V(\boldsymbol{n}', \boldsymbol{n}) + \frac{1}{(2\pi)^3} \sum_{\boldsymbol{k}} V(\boldsymbol{n}', \boldsymbol{k}) \frac{M^2}{\omega_k^2} \frac{1}{E - 2\omega_k} T(\boldsymbol{k}, \boldsymbol{n}) \quad \boldsymbol{k} \in \frac{2\pi}{L} \mathbb{Z}^3$$



- Compute the finite-volume matrix element instead of scattering amplitudes

$$\mathcal{T}_L = \int dz_0 \int_L d^3 \boldsymbol{z} \langle E_n | T[\mathcal{J}(z) S_\nu(z) \mathcal{J}(0)] | E_n \rangle$$

- To obtain the wave function $\phi_n(\boldsymbol{k}) = \langle \boldsymbol{k} | E_n \rangle$, we solve the eigen equation consistent with the relativistic scattering equation [Machleidt and Entem, Phys. Rep. 503, 1 \(2011\)](#)

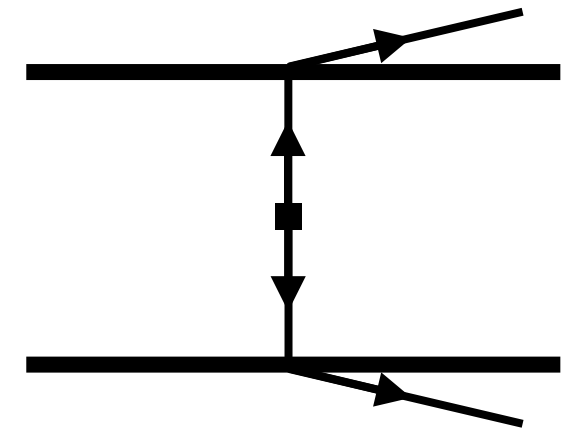
$$\hat{H} \phi_n(\boldsymbol{k}) = E_n \phi_n(\boldsymbol{k}), \quad H(\boldsymbol{k}', \boldsymbol{k}) = 2\omega_k \delta_{\boldsymbol{k}', \boldsymbol{k}} + \frac{1}{(2\pi)^3} \frac{m_N}{\omega_k} \frac{m_N}{\omega_{k'}} V_S(\boldsymbol{k}', \boldsymbol{k})$$

LO neutrino potential in relativistic pionless EFT

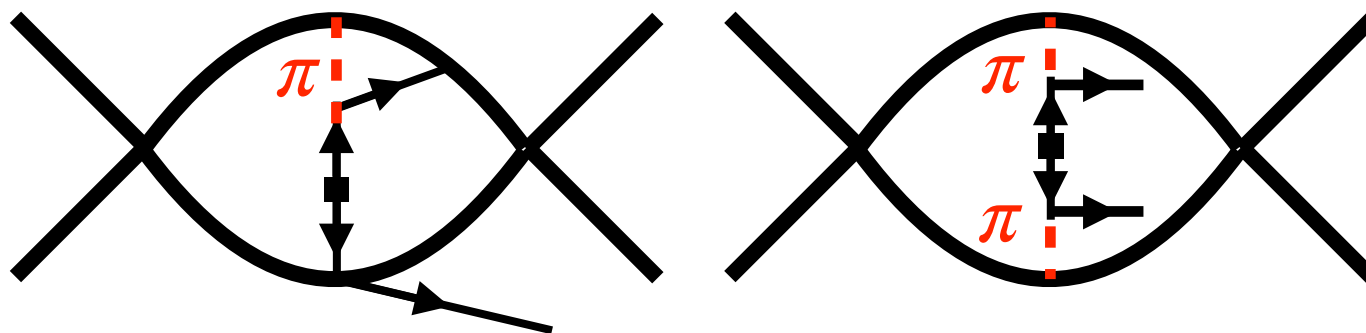
- LO long-range V_ν in pionless EFT

$$V_{\nu L}(\mathbf{p}', \mathbf{p}) = (1 + 3g_A^2) \frac{m_N m_N}{\omega_{p'} \omega_p} \frac{1}{|\mathbf{p}' - \mathbf{p}|^2}$$

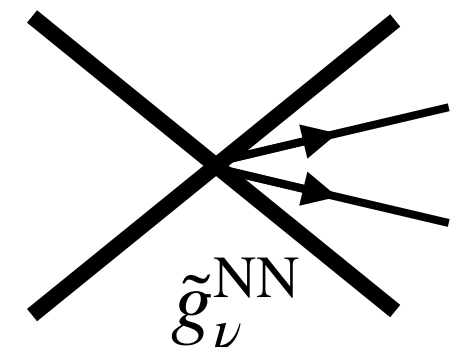
The long-range contribution alone is **renormalizable**



- However, we find a **finite** LO short-range contribution **from integrating out pions**



Chiral EFT



Pionless EFT

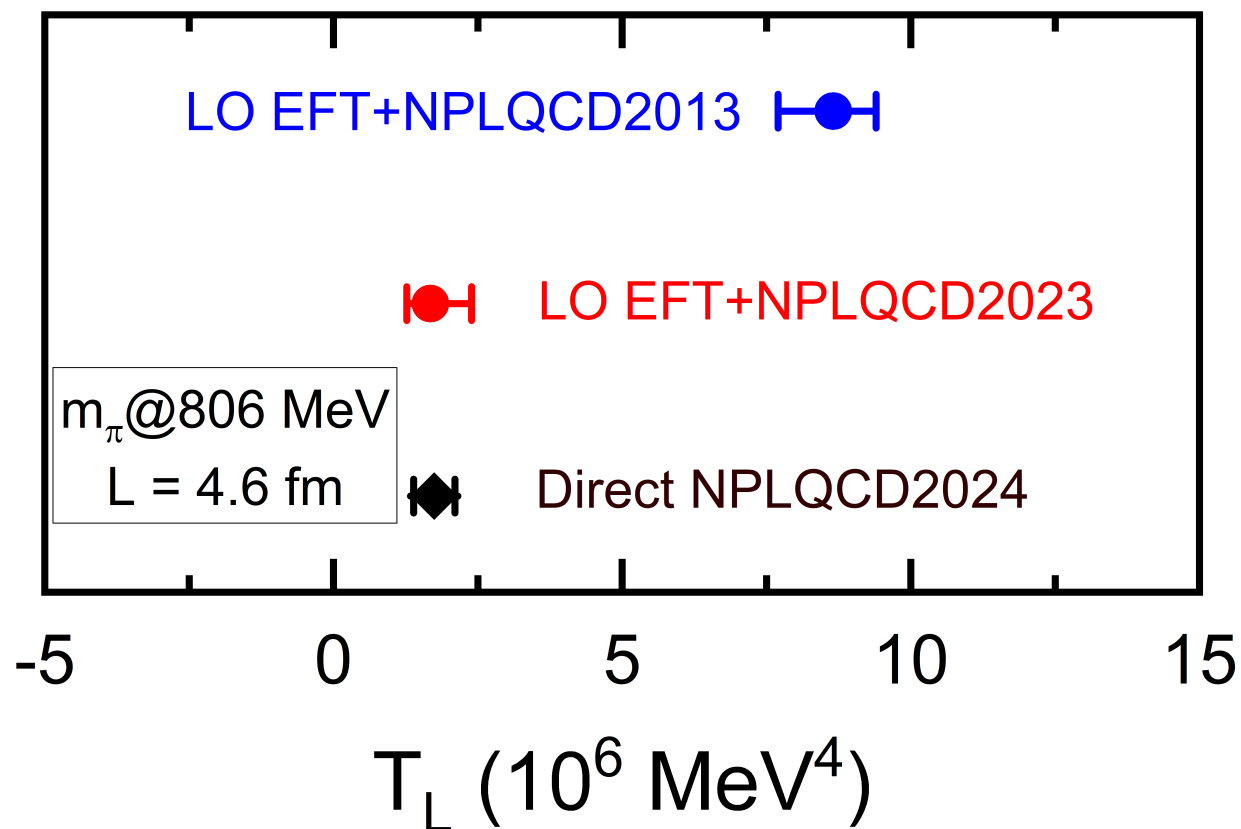
- The size of $\tilde{g}_\nu^{NN}$ is estimated by matching to the pion contributions at threshold

$$\tilde{g}_\nu^{NN} = \frac{(4\pi)^2}{2m_N^2} g_A^2 \delta J^\infty(0, 0)$$

Comparison with LQCD @ $m_\pi = 806$ MeV

- The first benchmark between nuclear EFT and lattice QCD on $0\nu\beta\beta$ decay
- The prediction from LO relativistic pionless EFT is encouraging!

YLY and P. W. Zhao, PRD 111, 014507 (2025)



Inputs of EFT

$$g_A = 1.27$$

$$m_\pi = 0.81 \text{ GeV}$$

$$M_N = 1.64 \text{ GeV}$$

$$E_{nn} = -17(4) \text{ MeV}$$

$$E_{nn} = -3.3(7) \text{ MeV}$$

Beane et al. (NPLQCD), PRD 87, 034506 (2013)
Amarasinghe et al. (NPLQCD), PRD 107, 094508 (2023)
Davoudi et al. (NPLQCD), PRD 109, 114514 (2024)

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Current status

- The short-range contributions to NMEs may be significantly
- Taking ^{76}Ge as an example:

How to fix g_{ν}^{NN}

Many-body method

$M_{\text{short}}/M_{\text{long}}$

CIB coupling

QRPA

32% – 73 %

CIB coupling

Shell model

25% – 40 %

Cottingham model

IM-GCM

23% – 30 %

Jokiniemi et al., PLB 823, 136720 (2021); Weiss et al., PRC 106, 065501 (2022); Belley et al., PRL 132, 182502 (2024)

The aim of our study:

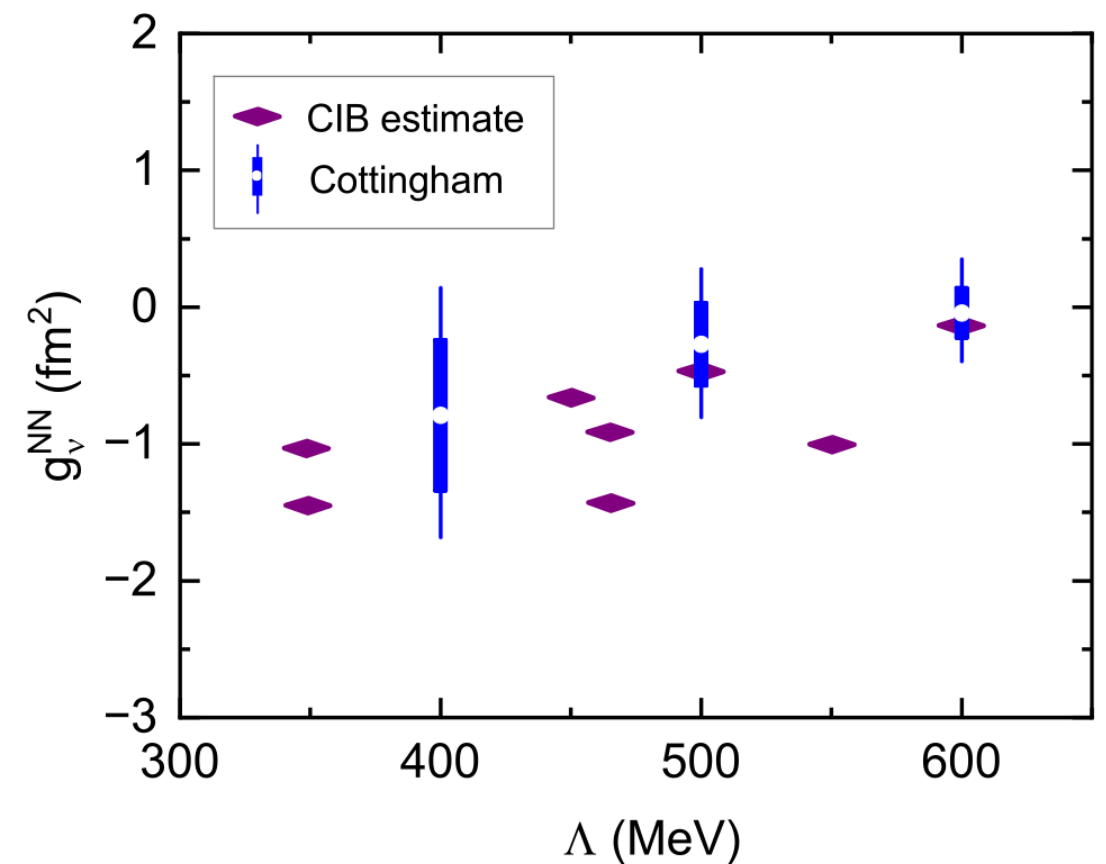
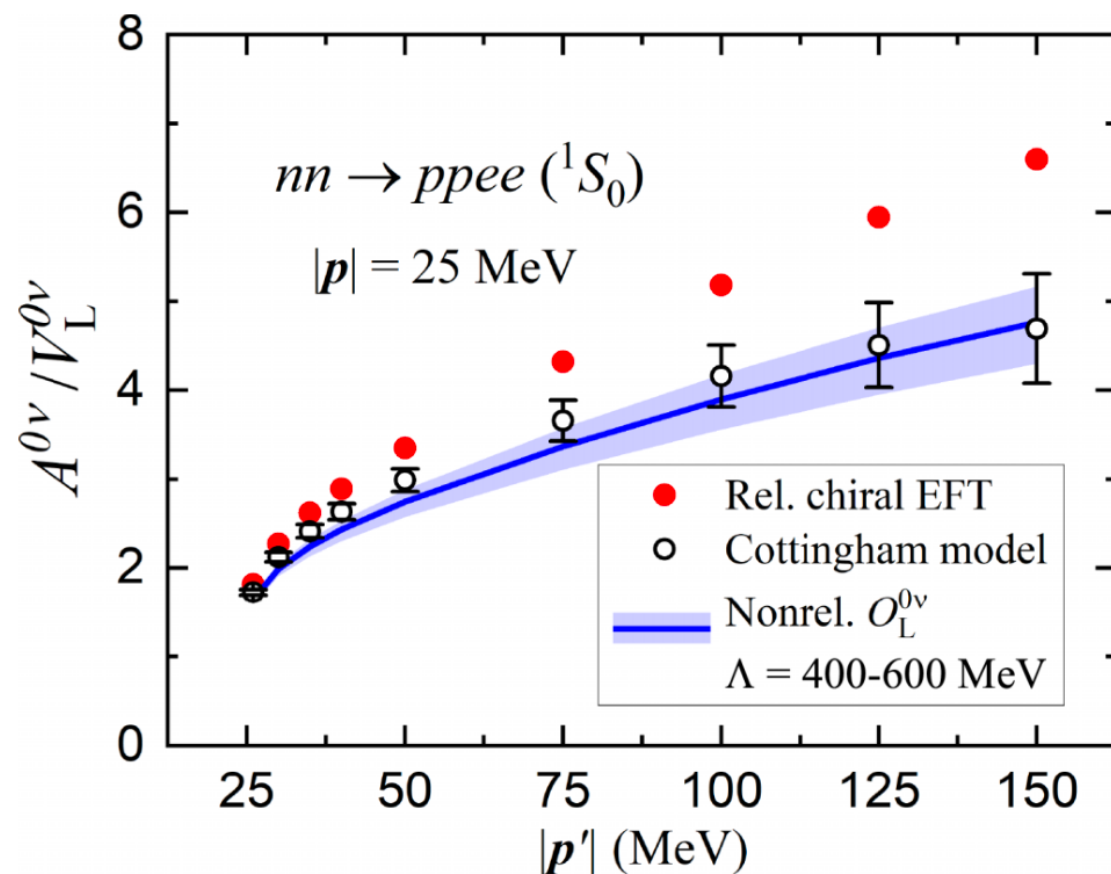
How do the **different schemes of fixing g_{ν}^{NN}** affect NMEs?

Rel. EFT agrees with Nonrel. EFT(+Cottingham model) at NN level—

What about the **Rel. EFT predictions for NMEs?**

Uncertainties induced by the determination of g_{ν}^{NN}

- Variation of momentum cutoffs Λ : usually near/under the breakdown scale Λ_b
- Choice of matching points to the synthetic datum:
 - ▶ Why match at $|\mathbf{p}| = 25$ MeV, $|\mathbf{p}'| = 30$ MeV, but not other kinematics?
 - ▶ Matching points with $p, p' \sim m_{\pi} \sim Q$ are, in principle, equivalent at LO
- Taking both aspects into account, we find that g_{ν}^{NN} can even change its sign

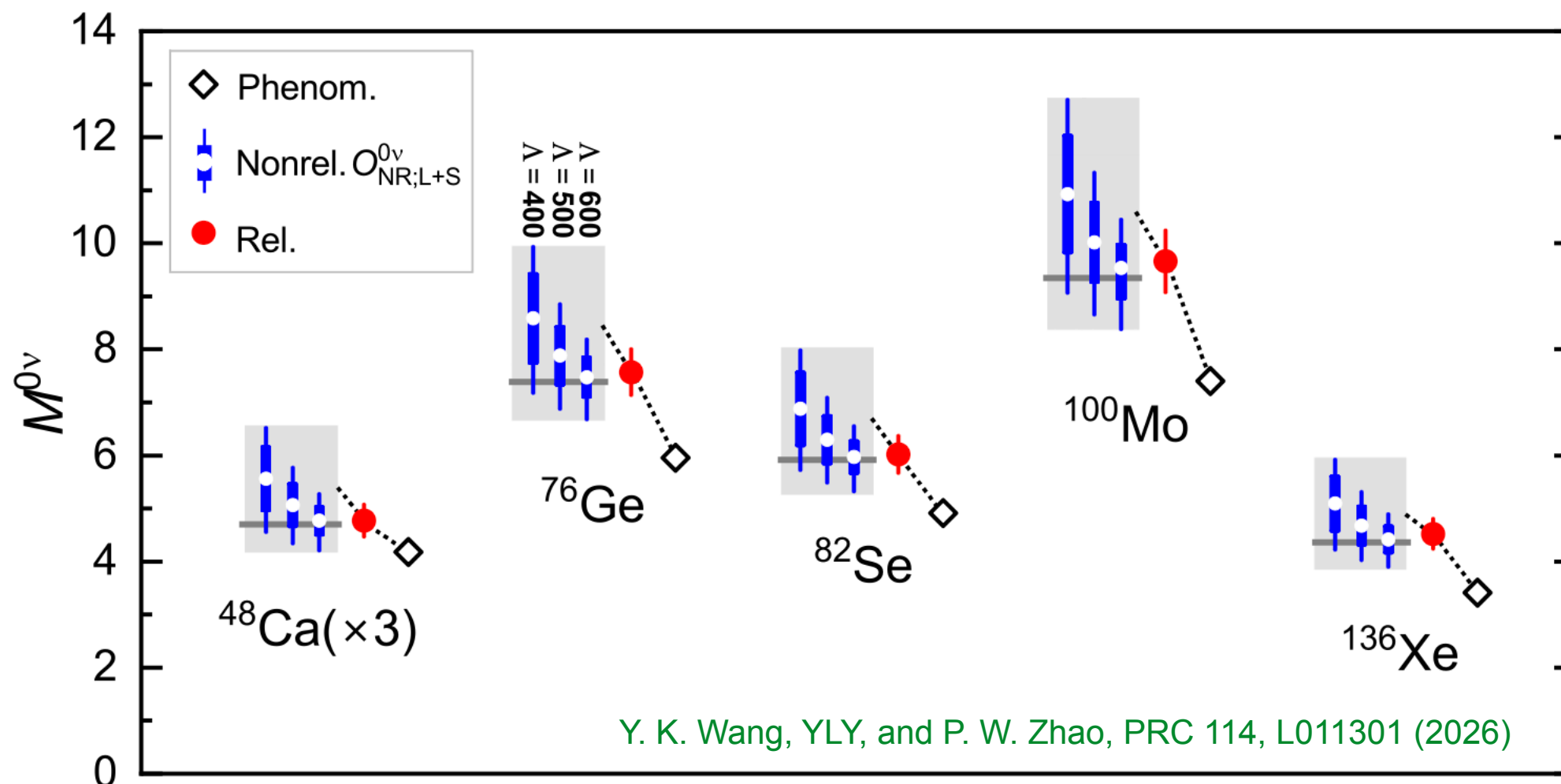


Regulator: $f_{\Lambda}(\mathbf{q}^2) = \exp(-\mathbf{q}^2/\Lambda^2)$

Y. K. Wang, YLY, and P. W. Zhao, PRC 114, L011301 (2026)

Relativistic vs Nonrelativistic operators

- The nuclear many-body wave functions for ^{48}Ca , ^{76}Ge , ^{82}Se , ^{100}Mo , and ^{136}Xe are obtained with **Relativistic Configuration-interaction Density Functional Theory**
- Relativistic $O_{0\nu,L}$ yields consistent NMEs with Nonrelativistic $O_{0\nu,L+S}$, while **circumventing the short-range uncertainties**
- **Caveat: The wave functions are not obtained with chiral nuclear forces; not consistent with the neutrino potential**



Summary

Relativistic chiral EFT is developed for studying $0\nu\beta\beta$ decay

the LO contact term is NOT needed for renormalization YLY and P. W. Zhao, PLB 855, 138782 (2024)

✓ NLO predictions on the $nn \rightarrow ppee$ amplitude YLY and P. W. Zhao, PRL 134, 242502 (2025)

$$|\mathcal{A}_{0\nu}| = 0.0209(7) \text{ MeV}^{-2} \quad (p, p') = (25, 30) \text{ MeV}$$

✓ Validated by reproducing the CSB/CIB contributions in NN scattering and Lattice QCD result at heavy pion mass YLY and P. W. Zhao, PRD 111, 014507 (2025)

✓ NMEs with relativistic configuration-interaction DFT YLY and P. W. Zhao, PRC 114, L011301 (2026)

Outlooks:

Improve the estimated $|\mathcal{A}_{0\nu}|$ by higher-order inelastic corrections

G. Van Goffrier, Phys. Rev. D 111, 055033 (2025)

More benchmarks with future lattice QCD calculations of $0\nu\beta\beta$ decay

In progress with Xu Feng, Ziyu Wang, and Pengwei Zhao

Relativistic ab initio calculations using chiral nuclear forces

Thank you for your attention!

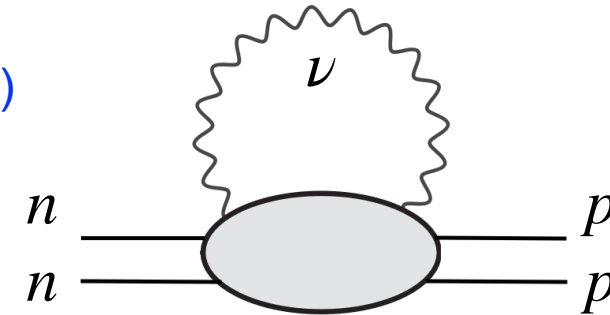
Previous model

- Integral representation

Cirigliano et al., PRL 126, 172002 (2021)

$$\mathcal{A}_\nu \propto \int \frac{d^4 k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \int d^4 x e^{ik \cdot x} \langle pp | T \{ j_w^\alpha(x) j_w^\beta(0) \} | nn \rangle$$

$$= \int_0^\Lambda d|\mathbf{k}| a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}| a_>(|\mathbf{k}|),$$



$$a_<(|\mathbf{k}|) = -\frac{r(|\mathbf{k}|)}{|\mathbf{k}|} \theta(|\mathbf{k}| - 2|\mathbf{p}|) \left[g_V^2(\mathbf{k}^2) + 2g_A^2(\mathbf{k}^2) + \frac{\mathbf{k}^2}{2M} g_M^2(\mathbf{k}^2) \right]$$

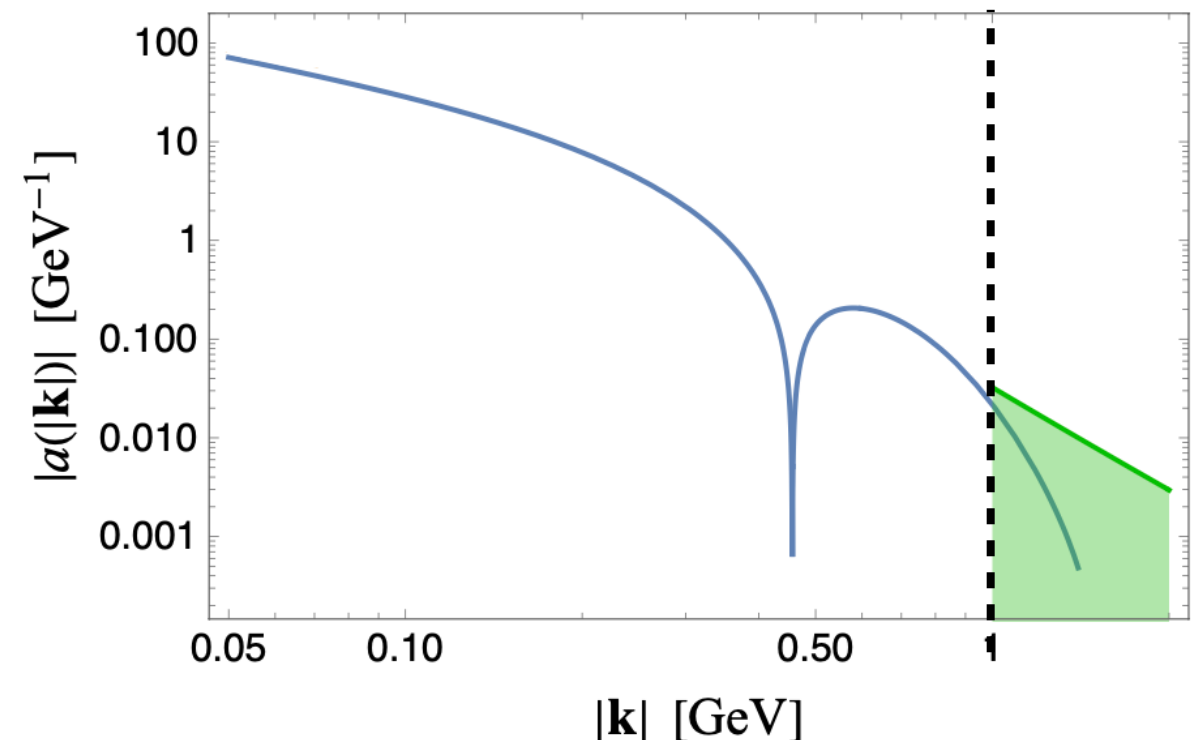
$$a_<(|\mathbf{k}|) = \frac{3\alpha_s(\mu)}{\pi} \bar{g}_1^{NN}(\mu) \frac{f_\pi^2}{|\mathbf{k}|^3}$$

- Model assumptions and inputs:

1. Neglect inelastic intermediate states
2. Phenomenological off-shell NN amplitudes
3. Phenomenological weak form factors
4. Separation of low- and high-energy region
5. Unknown matrix element $\bar{g}_1^{NN}(\mu)$

Low $\leftarrow \Lambda \rightarrow$ High

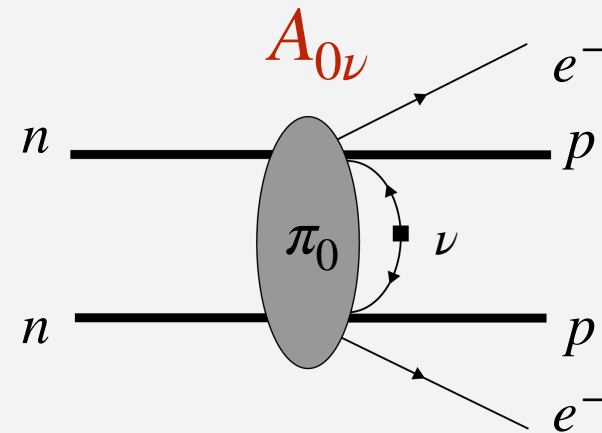
➔ $\tilde{\mathcal{C}}_1(\mu_\chi = M_\pi) \simeq 1.32(50)_{\text{inel}}(20)_{V_S}(5)_{\text{par}}$



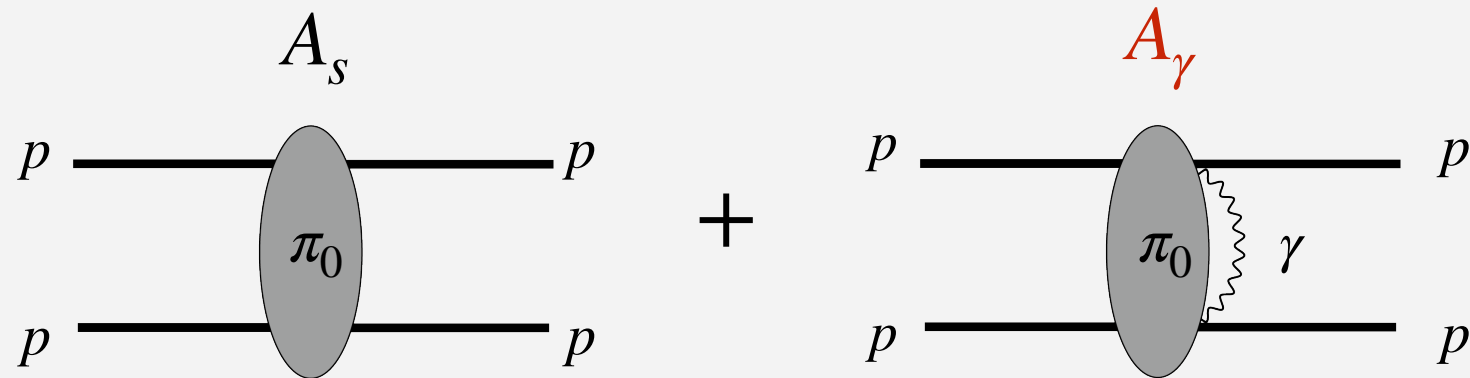
Cirigliano et al., JHEP 05, 289 (2021)

Neutrino and γ exchange

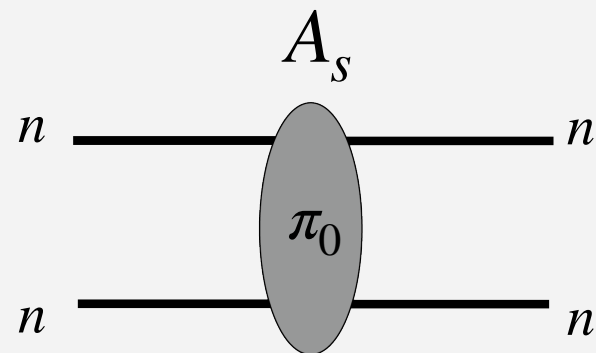
$nn \rightarrow ppee$



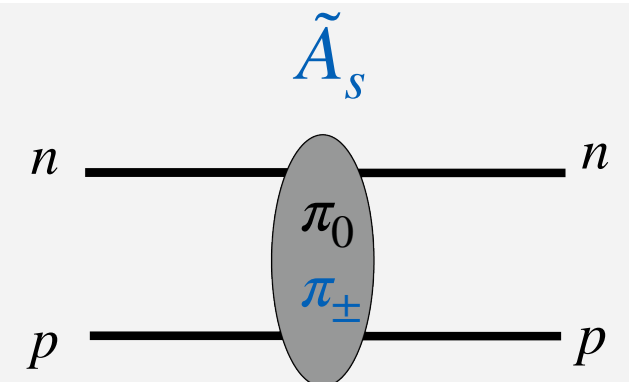
$pp \rightarrow pp$



$nn \rightarrow nn$



$np \rightarrow np$



$$\text{CSB: } A_{nn} - A_{pp} \rightarrow -A_\gamma \quad \text{CIB: } \frac{1}{2}(A_{nn} + A_{pp}) - A_{np} \rightarrow \frac{1}{2}A_\gamma + A_s - \tilde{A}_s$$

1S_0 Phase shifts

