Studies of neutrino interactions at low energies

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Neutrino Scattering: Theory, Experiment, Phenomenology

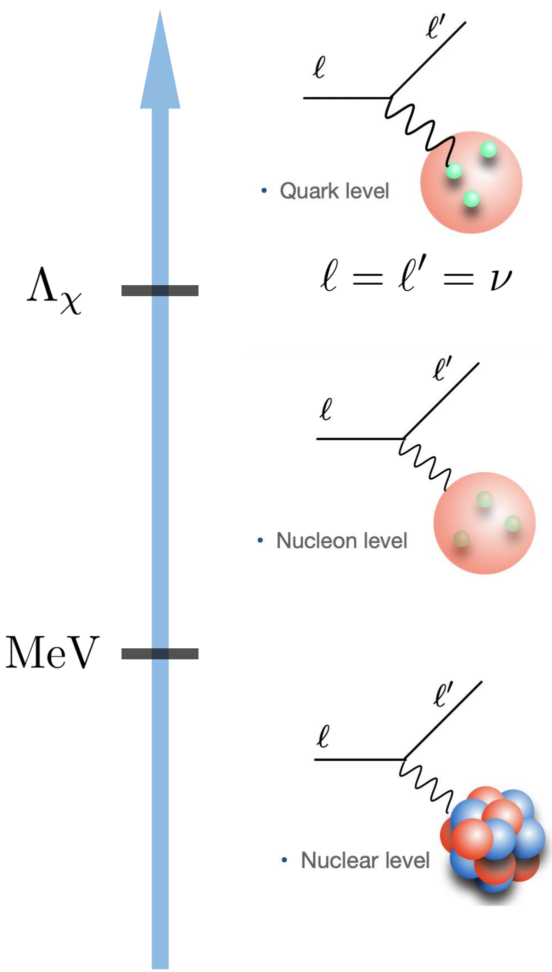
Beijing, October 25, 2025

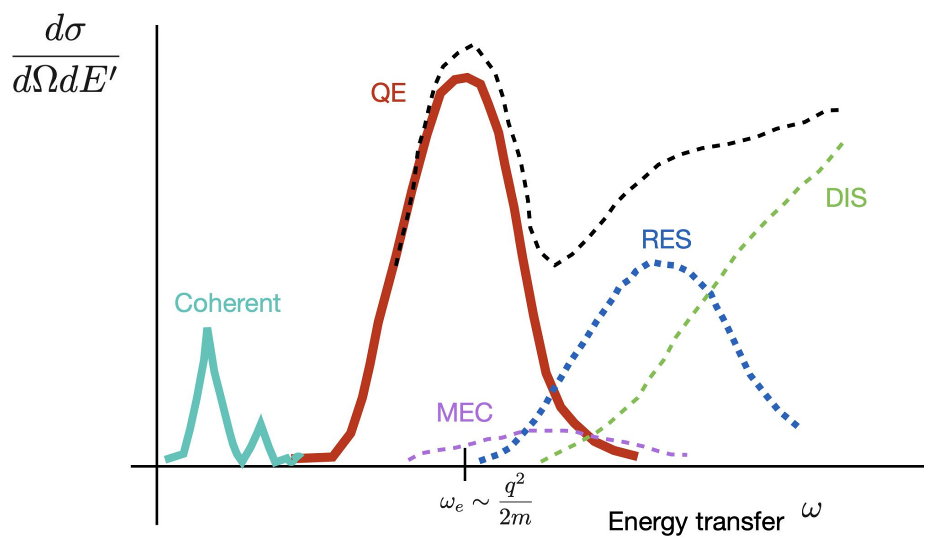
Outline

- Coherent elastic neutrino-nucleus scattering
- LEFT operators for CEvNS
- Chiral operators for CEvNS
- Nuclear response and cross section
- Experimental constraints
- Summary

Neutrino interactions with matter

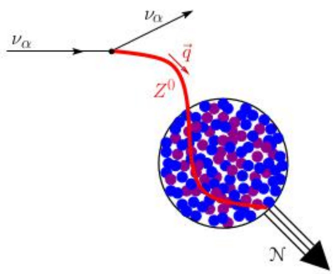
Neutrino interactions at low energies:

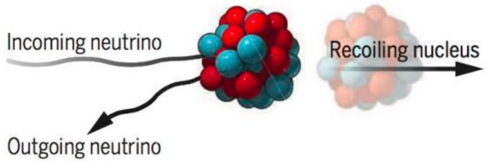




CEvNS

Coherent elastic neutrino-nucleus scattering





nuclear response

- The nucleus recoils as a whole; coherent up to $E_\nu \sim 100\ \mathrm{MeV}$
- The SM cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{G_F^2 m_A}{4\pi}\left(1 - \frac{m_A T}{2E_\nu^2}\right) Q_{\mathrm{w}}^2 \left[F_{\mathrm{w}}\left(q^2\right)\right]^2 \boxed{\propto N^2 \quad \text{coherent enhancement}}$$

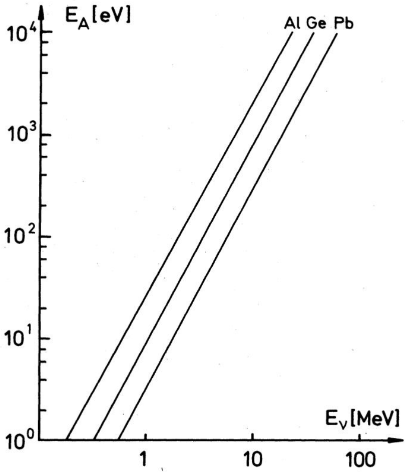
weak charge: $Q_{\mathrm{w}} = Z\left(1 - 4\sin^2\theta_W\right) - N$

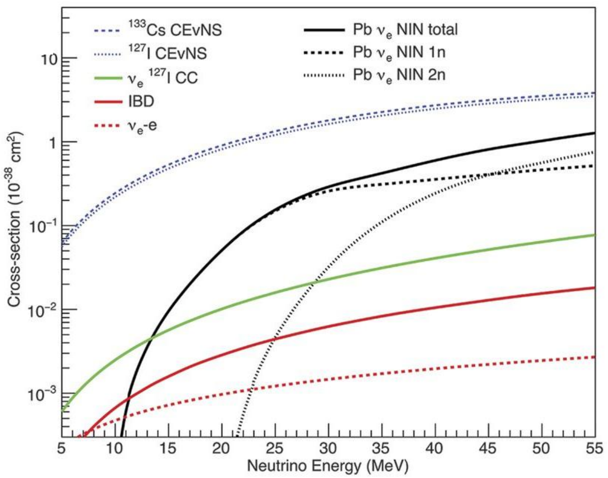
D. Z. Freedman, Phys.Rev.D 9 (1974) 1389

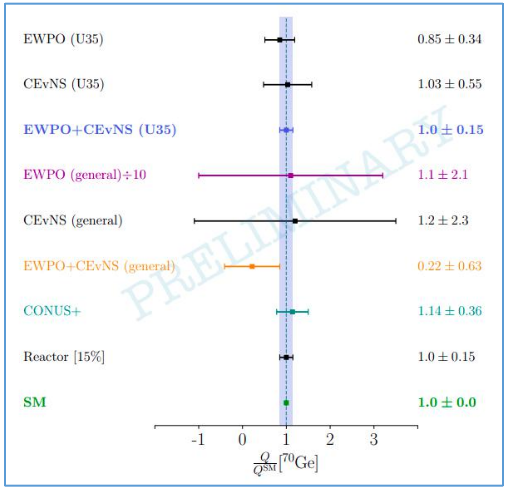
$F_{\mathrm{w}}(q^2)$: nuclear form factor

CEvNS

Coherent elastic neutrino-nucleus scattering







$$E_A = \frac{2}{3A}(E_\nu/1\ \mathrm{MeV})^2\ \mathrm{keV}$$

Drukier, Stodolsky, Phys.Rev.D 30 (1984) 2295

COHERENT, Science 357 (2017) 6356, 1123

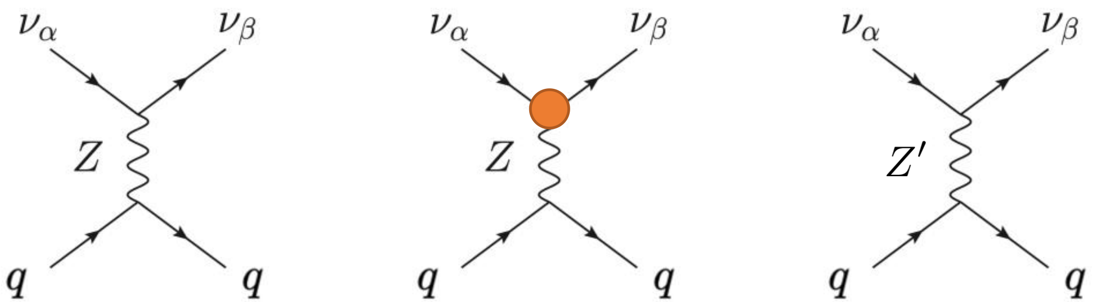
CONUS+, Nature 643 (2025) 8074, 1229

Yong Du, "Dark Matter and Neutrino Focus Week"@TDLI, 2025

see Jiajun Liao's talk

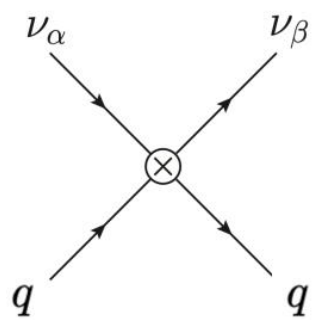
CEvNS

Neutrino non-standard interactions (NSIs)



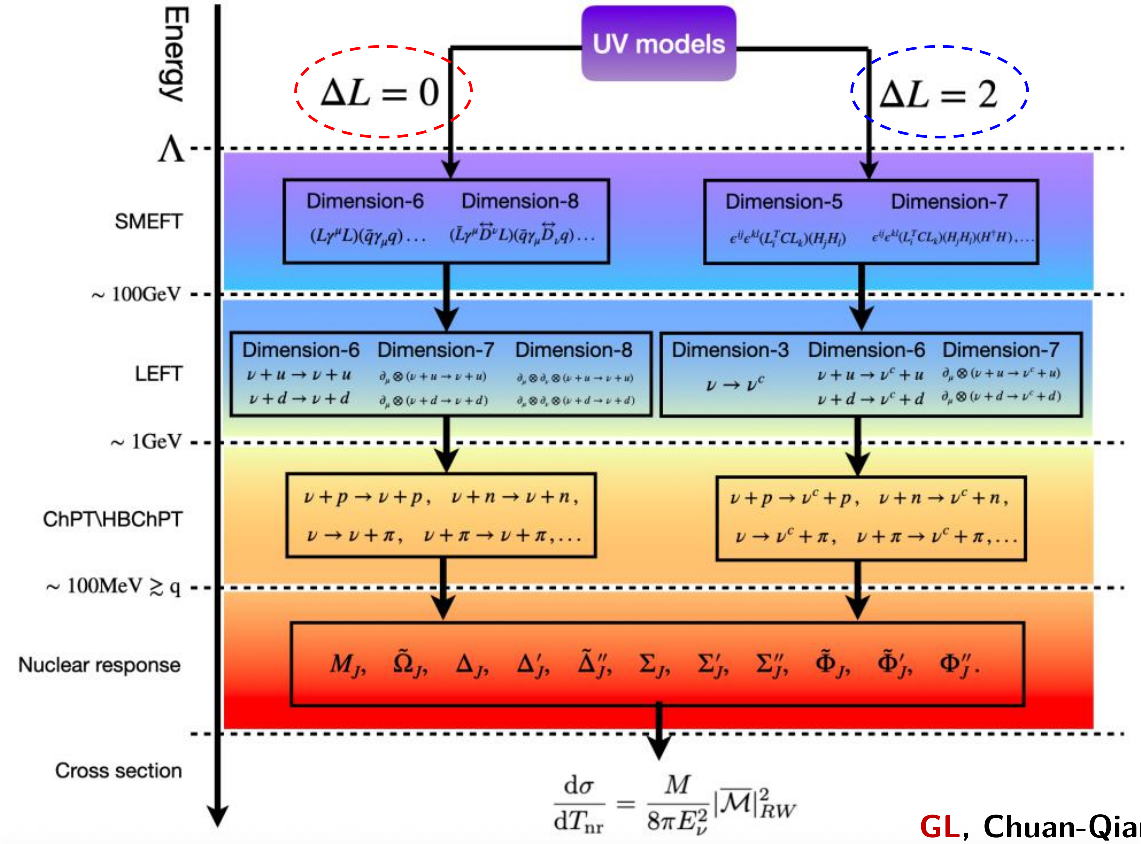
$+$ other BSM particles

$\mu < M_Z$



CEvNS

Effective field theory framework



GL, Chuan-Qiang Song, Feng-Jie Tang, Jiang-Hao Yu, in preparation

LEFT operators

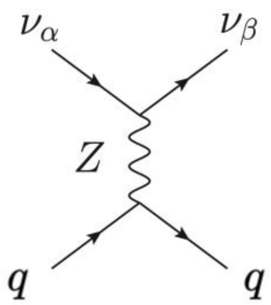
Below the electroweak scale ($\sim$ 100 GeV)

$$\mathcal{L}_{\mathrm{LEFT}} = \sum_{d,a} \hat{\mathcal{C}}_a^d \mathcal{O}_a^d, \quad \hat{\mathcal{C}}_a^d = \frac{\mathcal{C}_a^d}{\Lambda_{\mathrm{EW}}^{d-4}}$$

$\Delta L = 0$: vector/axial-vector operators

$$\mathcal{O}_1^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\left(\bar{q}\gamma_\mu \tau^{p/n} q\right), \quad \mathcal{O}_2^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\left(\bar{q}\gamma^5\gamma_\mu \tau^{p/n} q\right)$$

In the SM:



$$\hat{\mathcal{C}}_1^{6p/n}\Big|_{\mathrm{SM}} = \mp \frac{G_F}{\sqrt{2}}\left(1 - \frac{8(4)}{3}\sin^2\theta_W\right)\delta_{\alpha\beta}$$

$$\hat{\mathcal{C}}_2^{6p/n}\Big|_{\mathrm{SM}} = \pm \frac{G_F}{\sqrt{2}}\delta_{\alpha\beta}$$

LEFT operators

Below the electroweak scale ($\sim$ 100 GeV)

$$\mathcal{L}_{\mathrm{LEFT}} = \sum_{d,a} \hat{\mathcal{C}}_a^d \mathcal{O}_a^d, \quad \hat{\mathcal{C}}_a^d = \frac{\mathcal{C}_a^d}{\Lambda_{\mathrm{EW}}^{d-4}}$$

$\Delta L = 0$: derivative operators

$$\mathcal{O}_1^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\overleftrightarrow{\partial}_\mu \tau^{p/n} q)\,, \qquad \mathcal{O}_2^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\overleftrightarrow{\partial}_\mu \tau^{p/n} q)\,,$$

$$\mathcal{O}_1^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\partial^2(\bar{q}\gamma_\mu \tau^{p/n} q)\,, \qquad \mathcal{O}_2^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\partial^2(\bar{q}\gamma^5\gamma_\mu \tau^{p/n} q)\,.$$

$$\mathcal{O}_3^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})(\bar{q}\gamma_\mu \overleftrightarrow{\partial}_\nu \tau^{p/n} q)\,, \qquad \mathcal{O}_4^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu \overleftrightarrow{\partial}_\nu \tau^{p/n} q)\,,$$

$$\mathcal{O}_5^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{p/n} q)G^A_{\mu\nu}\,, \qquad \mathcal{O}_6^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{p/n} q)G^A_{\mu\nu}\,,$$

$$\mathcal{O}_7^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{p/n} q)\tilde{G}^A_{\mu\nu}\,, \qquad \mathcal{O}_8^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{p/n} q)\tilde{G}^A_{\mu\nu}\,,$$

$$\mathcal{O}_9^{8} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})G^A_{\mu\rho}G^{A\rho}_{\nu}\,,$$

$\Delta L = 2$: scalar/pseudo-scalar/tensor/photon operators

$$\mathcal{O}_1^{5} = (\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})F_{\mu\nu}\,, \qquad \mathcal{O}_3^{6p/n} = (\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})(\bar{q}\sigma_{\mu\nu}\tau^{p/n} q)\,,$$

$$\mathcal{O}_4^{6p/n} = (\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\tau^{p/n} q)\,, \qquad \mathcal{O}_5^{6p/n} = (\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\gamma^5\tau^{p/n} q)\,,$$

Chiral operators

Below the chiral symmetry breaking scale ($\sim$ 1 GeV)

- Meson sector

$$
\begin{aligned}
\mathcal{L}_\pi =\ & \frac{\Lambda_\chi^2}{\Lambda_{\rm EW}^2}\mathcal{C}_{1,2}^{6p/n}(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})\langle Q_\mp u_\mu\rangle + \frac{\Lambda_\chi^2}{\Lambda_{\rm EW}^2}2B_0\mathcal{C}_{4,5}^{6p/n}(\nu_{L\alpha}^T C\nu_{L\beta})\langle\Sigma_\pm\rangle \\
& + \frac{\Lambda_\chi}{\Lambda_{\rm EW}^2}\mathcal{C}_3^{6p/n}(\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})\Big\{\Lambda_1\langle\Sigma_+[u_\mu,u_\nu]\rangle + \Lambda_2\langle\Sigma_-[u_\mu,u_\nu]\rangle\Big\} \\
& + \frac{\Lambda_\chi}{\Lambda_{\rm EW}^3}\mathcal{C}_{1,2}^{7p/n}(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_1^\pi\langle\Sigma_\pm[\nabla^\nu u_\mu,u_\nu]\rangle + g_2^\pi\langle\nabla^\nu\Sigma_\pm[u_\mu,u_\nu]\rangle \\
& \quad + g_3^\pi\langle\Sigma_\pm[u_\mu,\chi_-]\rangle + g_4^\pi\langle\Sigma_\mp[u_\mu,\chi_+]\rangle + \varepsilon_{\mu\nu\rho\lambda}\langle u^\nu u^\rho\nabla^\lambda\Sigma_\mp\rangle\Big\} \\
& + \frac{\Lambda_\chi^4}{\Lambda_{\rm EW}^4}\mathcal{C}_{5,6}^{8p/n}g_5^\pi(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})\langle Q_\mp u_\mu\rangle \\
& + \frac{\Lambda_\chi^2}{\Lambda_{\rm EW}^4}\mathcal{C}_{7,8}^{8p/n}(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_6^\pi\langle u^\nu u_\nu[u_\mu,Q_\pm]\rangle + g_7^\pi\langle\chi_+[u_\mu,Q_\pm]\rangle\Big\} \\
& + \frac{\Lambda_\chi^2}{\Lambda_{\rm EW}^4}\mathcal{C}_9^{8p/n}g_8^\pi(\bar\nu_L\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_L)\langle u^\rho u_\rho\rangle\langle u_\mu u_\nu\rangle + \dots .
\end{aligned}
$$

GL, Chuan-Qiang Song, Jiang-Hao Yu, 2507.02538

see Chuan-Qiang Song's talk

Chiral operators

Below the chiral symmetry breaking scale ($\sim$ 1 GeV)

- Nucleon sector

$$
\begin{aligned}
\mathcal{L}_{\pi N} = & \frac{(4\pi)^2}{\Lambda_{\rm EW}^2}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}_{1,2}^{6p/n}\left[(\bar{N}_v v_\mu Q_\pm N_v) + g_A(\bar{N}_v S_\mu Q_\mp N_v)\right]\right\} \\
& \frac{(4\pi)^2\Lambda_\chi^2}{\Lambda_{\rm EW}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}_{5,6}^{8p/n}[(\bar{N}_v v_\mu Q_\pm N_v) + g_A^1(\bar{N}_v S_\mu Q_\mp N_v)]\right\} \\
& \frac{(4\pi)^2\Lambda_\chi^2}{\Lambda_{\rm EW}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}_{7}^{8p/n}(\bar{N}_v[u_\mu, Q_+]N_v) + \mathcal{C}_{8}^{8p/n}(\bar{N}_v[u_\mu, Q_-]N_v)\right\} \\
& + \frac{(4\pi)^2}{\Lambda_{\rm EW}^2}(\nu_{L\alpha}^T C\nu_{L\beta})\left\{\mathcal{C}_{4,5}^{6p/n}\left[(\bar{N}_v\Sigma_\pm N_v) + (\bar{N}_v N_v)\langle\Sigma_\pm\rangle\right]\right\} \\
& + \frac{(4\pi)^2}{\Lambda_{\rm EW}^2}(\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})\left\{\mathcal{C}_{3}^{6p/n}\left[\varepsilon_{\mu\nu\rho\lambda}(\bar{N}_v v^\rho S^\lambda\Sigma_+ N_v) + (\bar{N}_v[v_\mu, S_\nu]\Sigma_- N)\right]\right\} \\
& + \frac{(4\pi)^2\Lambda_\chi}{\Lambda_{\rm EW}^3}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}_{1,2}^{7p/n}\left[(\bar{N}_v v^\mu\Sigma_\pm N_v) + (\bar{N}_v v^\mu N_v)\langle\Sigma_\pm\rangle\right]\right\} \\
& + \frac{\Lambda_\chi(4\pi)^2}{\Lambda_{\rm EW}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\overset{\leftrightarrow}{\partial}^\nu\nu_{L\beta})\left\{\mathcal{C}_{3,4}^{8p/n}\left[(\bar{N}_v Q_\pm v_\mu v_\nu N_v) + (\bar{N}_v Q_\mp S_\mu v_\nu N_v)\right]\right\} + \ldots,
\end{aligned}
$$

see Chuan-Qiang Song's talk

Power counting

Naive dimensional analysis (NDA)

- In the ChPT, the operators are normalized as

$$f^2\Lambda_\chi^2 \left[\frac{\partial}{\Lambda_\chi}\right]^{N_p} \left[\frac{\psi}{f\sqrt{\Lambda_\chi}}\right]^{N_\psi} \left[\frac{F}{\Lambda_\chi f}\right]^{N_A} \qquad 4\pi f \sim \Lambda_\chi$$

Manohar, Georgi, NPB 234 (1984) 189

- In the LEFT, the operators are normalized as

$$\frac{\Lambda_{\mathrm{EW}}^4}{16\pi^2} \left[\frac{\partial}{\Lambda_{\mathrm{EW}}}\right]^{N_p} \left[\frac{4\pi F}{\Lambda_{\mathrm{EW}}^2}\right]^{N_F} \left[\frac{4\pi\psi}{\Lambda_{\mathrm{EW}}^{3/2}}\right]^{N_\psi}$$

Gavela, Jenkins, Manohar, Merlo, 1601.07551 (EPJC)

$$\sim \left[\frac{\Lambda_\chi}{\Lambda_{\mathrm{EW}}}\right]^{\mathcal{D}} \left(f^2\Lambda_\chi^2 \left[\frac{\partial}{\Lambda_\chi}\right]^{N_p} \left[\frac{\psi}{f\sqrt{\Lambda_\chi}}\right]^{N_\psi} \left[\frac{F}{\Lambda_\chi f}\right]^{N_A}\right)$$

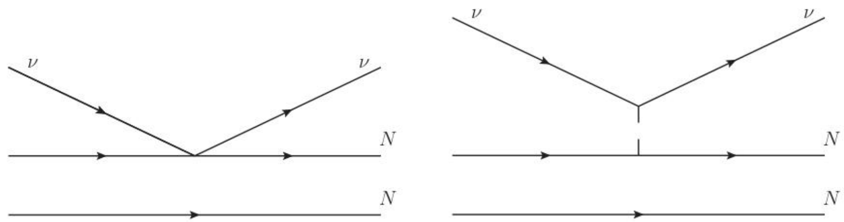
Chuan-Qiang Song, Hao Sun, Jiang-Hao Yu, 2501.09787

$$\mathcal{D} = N_p + 2N_F + \frac{3}{2}N_\psi - 4$$

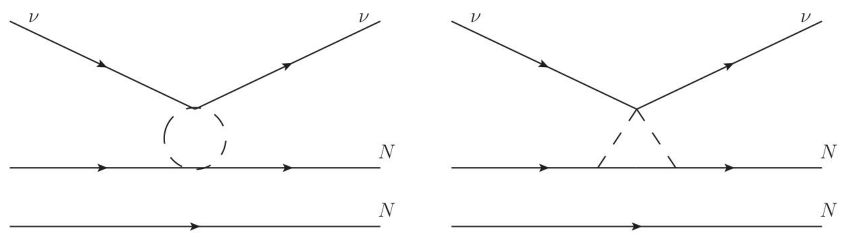
ψ: all fermions

Power counting

One-body current:

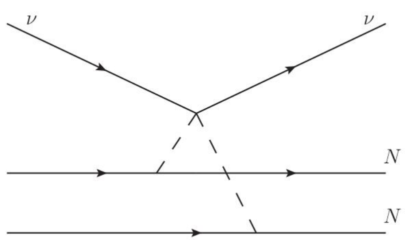


$$\sim \left(\frac{\Lambda_\chi}{\Lambda_{\rm EW}}\right)^2 \left(\frac{1}{2f}\right)^2$$



$$\sim \left(\frac{\Lambda_\chi}{\Lambda_{\rm EW}}\right)^2 \left(\frac{1}{2f}\right)^2 \boxed{\left(\frac{q}{2f}\right)^2 \frac{1}{16\pi^2}}$$

Two-body current:



$$\sim \left(\frac{\Lambda_\chi}{\Lambda_{\rm EW}}\right)^2 \left(\frac{1}{2f}\right)^2 \boxed{\left(\frac{q}{2f}\right)^2 \frac{1}{16\pi^2}}$$

Nucleon level

One-body current:

- Non-relativistic chiral Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm NR}^{\Delta L=0} =& \bar\nu_L l_0^D \bar\nu_L \cdot 1_N + \bar\nu_L l_{0,A}^D \bar\nu_L \cdot \left(\frac{\mathbf{K}\cdot\mathbf{S}_N}{m_N}\right) + \bar\nu_L \mathbf{l}_5^D \bar\nu_L \cdot (2\mathbf{S}_N) \\ &+ \bar\nu_L \mathbf{l}_M^D \bar\nu_L \cdot \left(\frac{\mathbf{K}_N}{2m_N}\right) + \bar\nu_L \mathbf{l}_E^D \bar\nu_L \cdot \left(-i\frac{\mathbf{K}\times\mathbf{S}_N}{m_N}\right)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm NR}^{\Delta L=2} =& \nu_L^T C l_0^M \bar\nu_L \cdot 1_N + \nu_L^T C l_{0,A}^M \bar\nu_L \cdot \left(\frac{\mathbf{K}\cdot\mathbf{S}_N}{m_N}\right) + \nu_L^T C \mathbf{l}_5^M \bar\nu_L \cdot (2\mathbf{S}_N) \\ &+ \nu_L^T C \mathbf{l}_M^M \bar\nu_L \cdot \left(\frac{\mathbf{K}_N}{2m_N}\right) + \nu_L^T C \mathbf{l}_E^M \bar\nu_L \cdot \left(-i\frac{\mathbf{K}\times\mathbf{S}_N}{m_N}\right)\end{aligned}$$

$$1_N \equiv \bar N N, \quad \mathbf{S}_N \equiv \bar N \mathbf{S} N$$
$$\mathbf{K}_N \equiv \bar N \mathbf{K} N$$

- NR operators:

$$\left\{1_N,\ \frac{\mathbf{K}\cdot\mathbf{S}_N}{m_N},\ \mathbf{S}_N,\ \frac{\mathbf{K}_N}{m_N},\ \frac{\mathbf{K}\times\mathbf{S}_N}{m_N}\right\}$$

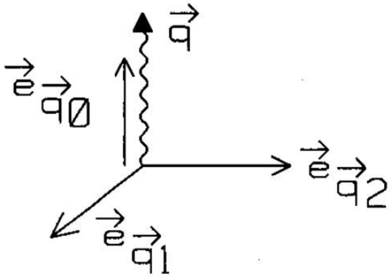
Nucleon level

One-body current:

$$\langle f|\mathcal{O}^d|i\rangle \to \langle \nu'|\mathcal{O}^d_\nu|\nu\rangle \int d\mathbf{x} e^{-i\mathbf{qx}} \boxed{\langle N'|\mathcal{O}^d_N(\mathbf{x})|N\rangle}$$

Multipole expansion

$$\left\langle f\middle|\hat{H}_{\mathrm{W}}\middle|i\right\rangle = -\frac{G}{\sqrt{2}} l_\mu \int d^3x e^{-i\mathbf{q}\cdot\mathbf{x}} \left\langle f\middle|\hat{\mathcal{J}}_\mu(\mathbf{x})\middle|i\right\rangle$$
$$= -\frac{G}{\sqrt{2}} \int d^3x e^{-i\mathbf{q}\cdot\mathbf{x}} [\mathbf{1}\cdot\mathcal{J}(\mathbf{x})_{\mathrm{fi}} - l_0\mathcal{J}_0(\mathbf{x})_{\mathrm{fi}}]$$



$$\left\langle f\middle|j^{\mathrm{lept}}_\mu(\mathbf{x})\middle|i\right\rangle = l_\mu e^{-i\mathbf{q}\cdot\mathbf{x}}$$

- expand the plane wave in the spherical vector basis

$$\mathbf{e}_{\mathbf{q}\lambda} e^{i\mathbf{q}\cdot\mathbf{x}} = -\sum_{J\geq 1}^{\infty} \sqrt{2\pi(2J+1)}\, i^J \left\{\lambda j_J(qx)\boldsymbol{Y}^\lambda_{JJ1} + \frac{1}{q}\nabla\times\left[j_J(qx)\mathcal{Y}^\lambda_{JJ1}\right]\right\}$$

- operators with definite angular momenta and projection

Eugenio Del Nobile, Lect. Notes Phys. 996 (2022)

Nucleon level

Multipole operators:

$$\hat{\mathcal{M}}_{JM_J;TM_T} \equiv \int d\mathbf{x} M_{JM}(|\mathbf{q}|\mathbf{x})\hat{\mathcal{J}}_0(\mathbf{x})_{TM_T}$$

$$\hat{\mathcal{L}}_{JM_J;TM_T} \equiv \frac{i}{|\mathbf{q}|}\int d\mathbf{x}\,[\nabla M_{JM}(|\mathbf{q}|\mathbf{x})]\cdot\hat{\vec{\mathcal{J}}}(\mathbf{x})_{TM_T}$$

$$\hat{\mathcal{T}}^{el}_{JM_J;TM_T} \equiv \frac{1}{|\mathbf{q}|}\int d\mathbf{x}\left[\nabla\times\mathbf{M}^M_{JJ}(|\mathbf{q}|\mathbf{x})\right]\cdot\hat{\vec{\mathcal{J}}}(\mathbf{x})_{TM_T}$$

$$\hat{\mathcal{T}}^{mag}_{JM_J;TM_T} \equiv \int d\mathbf{x}\mathbf{M}^M_{JJ}(|\mathbf{q}|\mathbf{x})\cdot\hat{\vec{\mathcal{J}}}(\mathbf{x})_{TM_T}$$

$$M_{JM}(|\mathbf{q}|\mathbf{x}) \equiv j_J(|\mathbf{q}|x)Y_{JM}(\Omega_x)$$

$$\mathbf{M}^M_{JL}(|\mathbf{q}|\mathbf{x}) \equiv j_L(|\mathbf{q}|x)\mathbf{Y}_{JLM}$$

Connell, Donnelly, Walecka, Phys. Rev. C 6 (1972) 719

In the NR limit, multiple operators can be expressed in terms of the 11 independent single-particle operators:

$$M_J, \tilde{\Omega}_J, \Delta_J, \Delta'_J, \tilde{\Delta}''_J, \Sigma_J, \Sigma'_J, \Sigma''_J, \tilde{\Phi}_J, \tilde{\Phi}'_J, \Phi''_J$$

Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542 (JCAP)

Earlier applications: electron, neutrino (CC), dark matter scattering

Nucleon level

Restrict nuclear ground state to have good parity and CP symmetry, only 6 single-particle operators are relevant:

$$O_J \in \{M_J, \Delta_J, \Sigma'_J, \Sigma''_J, \tilde{\Phi}'_J, \Phi''_J\}$$

$$\Delta_{JM}(|\mathbf{q}|\mathbf{x}) \equiv \mathbf{M}_{JJ}^{M}(|\mathbf{q}|\mathbf{x}) \cdot \frac{1}{|\mathbf{q}|}\nabla$$

$$\Sigma'_{JM}(|\mathbf{q}|\mathbf{x}) \equiv -i\left\{\frac{1}{|\mathbf{q}|}\nabla \times \mathbf{M}_{JJ}^{M}(|\mathbf{q}|\mathbf{x})\right\} \cdot \sigma$$

$$\Sigma''_{JM}(|\mathbf{q}|\mathbf{x}) \equiv \left\{\frac{1}{|\mathbf{q}|}\nabla M_{JM}(|\mathbf{q}|\mathbf{x})\right\} \cdot \sigma$$

$$\tilde{\Phi}'_{JM}(|\mathbf{q}|\mathbf{x}) \equiv \left(\frac{1}{|\mathbf{q}|}\nabla \times \mathbf{M}_{JJ}^{M}(|\mathbf{q}|\mathbf{x})\right) \cdot \left(\sigma \times \frac{1}{|\mathbf{q}|}\nabla\right) + \frac{1}{2}\mathbf{M}_{JJ}^{M}(|\mathbf{q}|\mathbf{x}) \cdot \sigma$$

$$\Phi''_{JM}(|\mathbf{q}|\mathbf{x}) \equiv i\left(\frac{1}{|\mathbf{q}|}\nabla M_{JM}(|\mathbf{q}|\mathbf{x})\right) \cdot \left(\sigma \times \frac{1}{|\mathbf{q}|}\nabla\right)$$

Anand, Fitzpatrick, Haxton, 1308.6288 (PRC)

Nuclear level

Nuclear matrix elements:

$$\langle j_N; TM_T || O_{J;\tau;i} || j_N; TM_T \rangle = (-1)^{T-M_T} \begin{pmatrix} T & \tau & T \\ -M_T & 0 & M_T \end{pmatrix} \sum_{|\alpha|,|\beta|,i} \Psi^{J;\tau}_{|\alpha|,|\beta|} \langle |\alpha| \vdots\vdots O_{J;\tau;i} \vdots\vdots |\beta| \rangle$$

$\Psi^{J;\tau}_{|\alpha|,|\beta|}$ one-body density matrix, calculated in shell model

Hoferichter, Menéndez, Schwenk, 2007.08529 (PRD)

$\langle |\alpha| \vdots\vdots O_{J;\tau;i} \vdots\vdots |\beta| \rangle$ single particle matrix element, calculated in the harmonic oscillator model

Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit $q \to 0$	Response Type
$\sum_{J=0,2,\ldots}^{\infty} \lvert\langle J_i \|\| M_{JM} \|\| J_i \rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}} 1(i)$	M_{JM} : Charge
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \|\| \Sigma''_{JM} \|\| J_i \rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}} \sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,\ldots}^{\infty} \lvert\langle J_i \|\| \Sigma'_{JM} \|\| J_i \rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}} \sigma_{1M}(i)$	T^{el5}_{JM} : Axial Transverse Electric

Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542 (JCAP)

Nuclear level

Response enhancement:

LEFT operators	Chiral operators	Response enhance
$\mathcal{O}_1^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar{q}\gamma_\mu\tau^{p/n}q)$	$\frac{(4\pi)^2}{\Lambda_{\rm EW}^2}\mathcal{C}_1^{6p/n}\,(\bar{\nu}\gamma^\mu\nu)\,(\bar{N}_v v_\mu Q_+ N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-2})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_2^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu\tau^{p/n}q)$	$\frac{(4\pi)^2}{\Lambda_{\rm EW}^2}\mathcal{C}_2^{6p/n}\,(\bar{\nu}\gamma^\mu\nu)\,(\,g_A\,\bar{N}_v S_\mu Q_+ N_v\,)$	$\mathcal{O}(\Lambda_{\rm EW}^{-2})\cdot\mathcal{O}(q^2)\cdot 1$
$\mathcal{O}_4^{6p/n} = (\nu_{L\alpha}^T C\nu_{L\beta})(\bar{q}\tau^{p/n}q)$	$\frac{(4\pi)^2}{\Lambda_{\rm EW}^2}\,\mathcal{C}_4^{6p/n}\,(\nu^T C\nu)\,(\bar{N}_v\Sigma_+ N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-2})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_5^{6p/n} = (\nu_{L\alpha}^T C\nu_{L\beta})(\bar{q}\gamma^5\tau^{p/n}q)$	$\frac{(4\pi)^2}{\Lambda_{\rm EW}^2}\,\mathcal{C}_4^{6p/n}\,(\nu^T C\nu)\,(\bar{N}_v N_v)\langle\Sigma_+\rangle$	$\mathcal{O}(\Lambda_{\rm EW}^{-2})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_3^{6p/n} = (\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})(\bar{q}\sigma_{\mu\nu}\tau^{p/n}q)$	$\frac{(4\pi)^2}{\Lambda_{\rm EW}^2}\,\mathcal{C}_3^{6p/n}\,(\nu^T C\sigma^{\mu\nu}\nu)\,\varepsilon_{\mu\nu\rho\lambda}\,(\bar{N}_v v^\rho S^\lambda\Sigma_+ N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-2})\cdot\mathcal{O}(q^2)\cdot 1$
$\mathcal{O}_1^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar{q}\overleftrightarrow{\partial}_\mu\tau^{p/n}q)$	$\frac{(4\pi)^2\,\Lambda_\chi}{\Lambda_{\rm EW}^3}\,\mathcal{C}_1^{7p/n}\,(\bar{\nu}\gamma^\mu\nu)\,(\bar{N}_v v^\mu\Sigma_+ N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-3})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_2^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar{q}\gamma^5\overleftrightarrow{\partial}_\mu\tau^{p/n}q)$	$\frac{(4\pi)^2\,\Lambda_\chi}{\Lambda_{\rm EW}^3}\,\mathcal{C}_1^{7p/n}\,(\bar{\nu}\gamma^\mu\nu)\,(\bar{N}_v v^\mu N_v)\langle\Sigma_+\rangle$	$\mathcal{O}(\Lambda_{\rm EW}^{-3})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_3^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})(\bar{q}\gamma_\mu\overleftrightarrow{\partial}_\nu\tau^{p/n}q)$	$\frac{\Lambda_\chi\,(4\pi)^2}{\Lambda_{\rm EW}^4}\,\mathcal{C}_3^{8p/n}\,(\bar{\nu}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu)\,(\bar{N}_v Q_+\,v_\mu v_\nu N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-4})\cdot\mathcal{O}(q^2)\cdot A$
$\mathcal{O}_4^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu\overleftrightarrow{\partial}_\nu\tau^{p/n}q)$	$\frac{\Lambda_\chi\,(4\pi)^2}{\Lambda_{\rm EW}^4}\,\mathcal{C}_4^{8p/n}\,(\bar{\nu}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu)\,(\bar{N}_v Q_+\,S_\mu v_\nu N_v)$	$\mathcal{O}(\Lambda_{\rm EW}^{-4})\cdot\mathcal{O}(q^2)\cdot 1$

For the response enhancement at the NLO for tensor operators, see

Jiajun Liao, Jian Tang, Bing-Long Zhang, 2502.10702 (PRD)

Nuclear level

- Nuclear response functions:

$$W_{O_J O'_J} = \sum_J \langle j_N \| O_J \| j_N \rangle \langle j_N \| O'_J \| j_N \rangle$$

- Kinematic factors (neutrino part)

$$R^{\tau\tau'}_{MM} = \langle l_0^\tau \rangle \left\langle l_0^{\tau'} \right\rangle^\dagger$$

$$R^{\tau\tau'}_{\Sigma''\Sigma''} = \hat{q} \cdot \langle \mathbf{l}_5^\tau \rangle \, \hat{q} \cdot \left\langle \mathbf{l}_5^{\tau'} \right\rangle^\dagger$$

$$R^{\tau\tau'}_{\Sigma'\Sigma'} = \frac{1}{2} \left(\langle \mathbf{l}_5^\tau \rangle \cdot \left\langle \mathbf{l}_5^{\tau'} \right\rangle^\dagger - \hat{q} \cdot \langle \mathbf{l}_5^\tau \rangle \, \hat{q} \cdot \left\langle \mathbf{l}_5^{\tau'} \right\rangle^\dagger \right)$$

$$R^{\tau\tau'}_{\Phi''\Phi''} = \hat{q} \cdot \langle \mathbf{l}_E^\tau \rangle \, \hat{q} \cdot \left\langle \mathbf{l}_E^{\tau'} \right\rangle^\dagger$$

$$R^{\tau\tau'}_{\Phi'\Phi'} = \frac{1}{2} \left(\langle \mathbf{l}_E^\tau \rangle \cdot \left\langle \mathbf{l}_E^{\tau'} \right\rangle^\dagger - \hat{q} \cdot \langle \mathbf{l}_E^\tau \rangle \, \hat{q} \cdot \left\langle \mathbf{l}_E^{\tau'} \right\rangle^\dagger \right)$$

$$R^{\tau\tau'}_{\Delta\Delta} = \frac{1}{2} \left(\langle \mathbf{l}_M^\tau \rangle \cdot \left\langle \mathbf{l}_M^{\tau'} \right\rangle^\dagger - \hat{q} \cdot \langle \mathbf{l}_M^\tau \rangle \, \hat{q} \cdot \left\langle \mathbf{l}_M^{\tau'} \right\rangle^\dagger \right)$$

$$R^{\tau\tau'}_{\Phi''M} = \hat{q} \cdot \mathrm{Re} \left[\langle \mathbf{l}_E^\tau \rangle \left\langle l_0^{\tau'} \right\rangle^\dagger \right]$$

$$R^{\tau\tau'}_{\Delta\Sigma'} = 2\hat{q} \cdot \mathrm{Re} \left[i \, \langle \mathbf{l}_M^\tau \rangle \times \left\langle \mathbf{l}_5^{\tau'} \right\rangle^\dagger \right]$$

$$\langle l \rangle \equiv \langle \nu' | \, l | \nu \rangle \qquad \tau, \tau' = 0, 1$$

W. Altmannshofer, M. Tammaro, J. Zupan, 1812.02778 (JHEP)

CEvNS cross section

One-body contributions only:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{1}{32\pi m_A E_\nu^2} \left|\mathcal{M}_{1C}\right|^2$$

$$\begin{aligned}
\left|\mathcal{M}_{1C}\right|^2 = \frac{4\pi}{2J_A+1} \sum_{\tau,\tau'} \Bigg\{ &\left[R_{MM}^{\tau\tau'} W_{MM}^{\tau\tau'}(y) + R_{\Sigma''\Sigma''}^{\tau\tau'} W_{\Sigma''\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'\Sigma'}^{\tau\tau'} W_{\Sigma'\Sigma'}^{\tau\tau'}(y) \right] \\
&+ \frac{|\mathbf{q}|^2}{m_N^2} \left[R_{\Phi''\Phi''}^{\tau\tau'} W_{\Phi''\Phi''}^{\tau\tau'}(y) + R_{\Phi'\Phi'}^{\tau\tau'} W_{\Phi'\Phi'}^{\tau\tau'}(y) + R_{\Delta\Delta}^{\tau\tau'} W_{\Delta\Delta}^{\tau\tau'}(y) \right] \\
&- \frac{2|\mathbf{q}|}{m_N} \left[R_{\Phi''}^{\tau\tau'} W_{\Phi'' M}^{\tau\tau'}(y) + R_{\Delta\Sigma'}^{\tau\tau'} W_{\Delta\Sigma'}^{\tau\tau'}(y) \right] \Bigg\} \qquad y = (|\mathbf{q}|b/2)^2
\end{aligned}$$

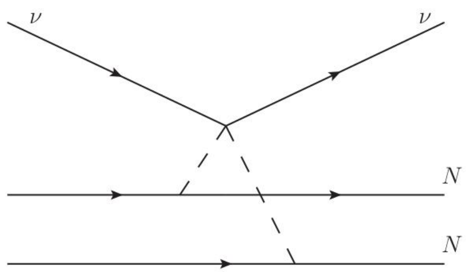
In the SM,

$$\begin{aligned}
\left|\mathcal{M}_{1C}\right|^2 = 8 m_A^2 G_F^2 E_\nu^2 \Bigg[&\boxed{4 \left((F_1^q g_V^q)_{NN'}^2 \widetilde{W}_M^{NN'} + (F_A^q g_A^q)_{NN'}^2 \widetilde{W}_{\Sigma'}^{NN'} \right)} \approx \left[-2\left(Z g_V^p + N g_V^n\right)\right]^2 \\
&- 4 \frac{\boldsymbol{q}^2}{4E_\nu^2} \left((F_1^q g_V^q)_{NN'}^2 \widetilde{W}_M^{NN'} - (F_A^q g_A^q)_{NN'}^2 \widetilde{W}_{\Sigma'}^{NN'} \right) \\
&+ \frac{\boldsymbol{q}^2}{m_A^2} \left(1 - \frac{\vec{q}^2}{4E_\nu^2} \right) (F_A^q g_A^q)_{NN'}^2 \left(\widetilde{W}_{\Sigma''}^{NN'} - \widetilde{W}_{\Sigma'}^{NN'} \right) \Bigg]
\end{aligned}$$

CEvNS cross section

Two-body contributions included:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{1}{32\pi m_A E_\nu^2}\left(|\mathcal{M}_{1C} + \mathcal{M}_{2C}|^2\right)$$



- cannot be expressed as multipole operators

$$\langle f|\mathcal{O}^d|i\rangle \to \langle \nu'|\,\mathcal{O}_\nu^d|\nu\rangle \int d\mathbf{x}e^{-i\mathbf{q}\mathbf{x}}\, \boxed{\langle N'N'|\,\mathcal{O}_N^d(\mathbf{x})|NN\rangle}$$

- nuclear form factor obtained with the fit function:

$$F_\pi(y) = e^{-y/2}\sum_{i=0}^{m} c_i y^i$$

Hoferichter, Klos, Menéndez, Schwenk, 1812.05617 (PRD)
Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542 (JCAP)

Experimental constraints

From COHERENT:

- Number of PEs in i-th bin

$$N^i_{\nu_\alpha} = n_N \sum_{x=\mathrm{Cs,I}} \eta_x \langle \varepsilon_T \rangle_{\nu_\alpha} \int_{n^i_{\mathrm{PE}}}^{n^{i+1}_{\mathrm{PE}}} \mathrm{d}n_{\mathrm{PE}} \varepsilon(n_{\mathrm{PE}}) \times \int_{T_{\mathrm{nr,min}}}^{T_{\mathrm{nr,max}}} \mathrm{d}T_{\mathrm{nr}} P(n_{\mathrm{PE}}) \frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}}|_x$$

number of target nuclei: n_N

fraction of $\mathrm{Cs/I}$: η_x

average time efficiency: $\langle \varepsilon_T \rangle_{\nu_\alpha}$

detector efficiency: $\varepsilon(n_{\mathrm{PE}})$

detector energy resolution: $P(n_{\mathrm{PE}})$

- Differential event rate

$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}} = \int_{E_{\nu,\mathrm{min}}}^{E_{\nu,\mathrm{max}}} dE_\nu \Phi_{\nu_\alpha}(E_\nu) \frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathrm{nr}}}$$

total neutrino flux

$$\Phi_{\nu_e}(E_\nu) = \mathcal{N} \frac{192 E_\nu^2}{m_\mu^3} \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right)$$

$$\Phi_{\bar{\nu}_\mu}(E_\nu) = \mathcal{N} \frac{64 E_\nu^2}{m_\mu^3} \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right)$$

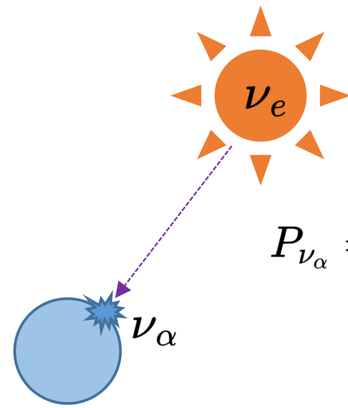
$$\Phi_{\nu_\mu}(E_\nu) = \mathcal{N} \delta \left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2 m_\pi} \right)$$

Experimental constraints

From PandaX-4T and XENONnT:

- Number of signal events

$$N_{\nu_\alpha} = n_N \int_{T_{\mathrm{nr,min}}}^{T_{\mathrm{nr,\,max}}} \mathrm{d}T_{\mathrm{nr}}\, \varepsilon\left(T_{\mathrm{nr}}\right) \frac{\mathrm{d}R_\alpha}{\mathrm{d}T_{\mathrm{nr}}}$$



$$P_{\nu_\alpha} = \left|\langle \nu_e(t_0) | \nu_\alpha(t_E)\rangle\right|^2$$

- Differential event rate:

$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}} = \int_{E_{\nu,\mathrm{min}}}^{E_{\nu,\,\mathrm{max}}} dE_\nu \boxed{\Phi_{\nu_\alpha}\left(E_\nu\right)} \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathrm{nr}}}}$$

exposure

$$\Phi_{\nu_\alpha}\left(E_\nu\right) = \frac{\mathcal{E}}{M_{\mathrm{det}}} \boxed{\langle P_{\nu_\alpha}\rangle} \phi\left({}^8\,\mathrm{B}\right)$$

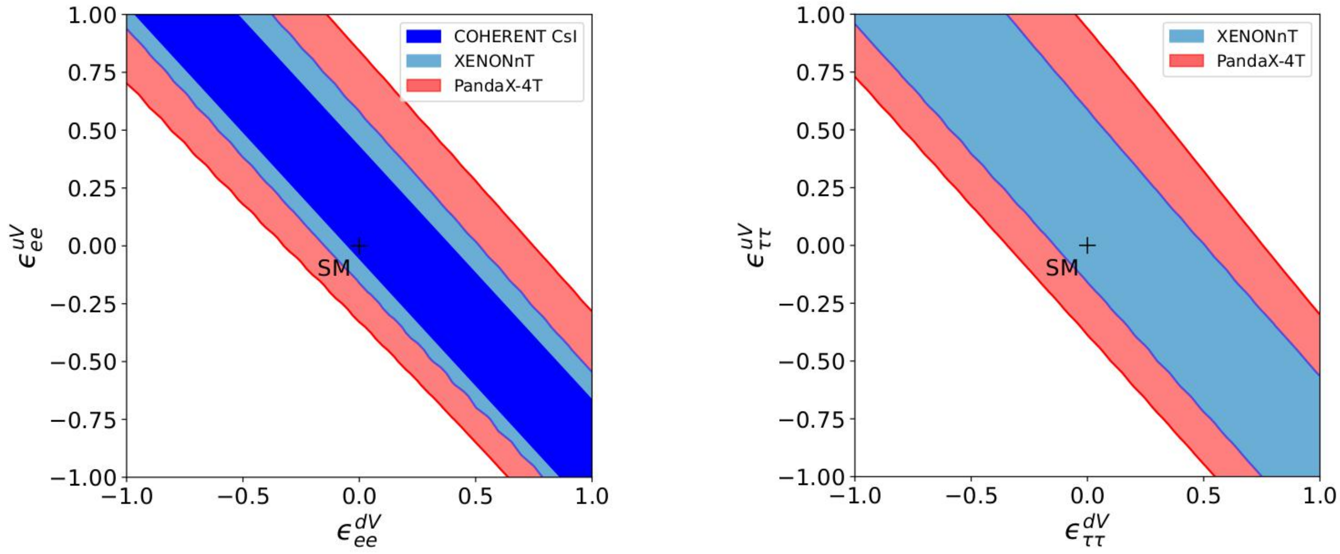
$$i\frac{d}{dr}|\nu\rangle = \left[\frac{1}{2E_\nu} U H_{\mathrm{vac}} U^\dagger + H_{\mathrm{mat}}\right]|\nu\rangle$$

$$\underline{\Delta H_{\mathrm{mat}}} = \sqrt{2} G_F n_q \begin{pmatrix} \epsilon_{ee}^{qV} & \epsilon_{e\mu}^{qV} & \epsilon_{e\tau}^{qV} \\ \epsilon_{e\mu}^{qV*} & \epsilon_{\mu\mu}^{qV} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^{qV*} & \epsilon_{\mu\tau}^{qV*} & \epsilon_{\tau\tau}^{qV} \end{pmatrix}$$

Experimental constraints

Combined results:

$$\mathcal{L}_{\mathrm{NC}} \supset -2\sqrt{2}G_F\left[\epsilon^{qL}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{q}\gamma_\mu P_L q\right)+\epsilon^{qR}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{q}\gamma_\mu P_R q\right)\right] \qquad \boxed{\epsilon^{qV}_{\alpha\beta}=\epsilon^{qL}_{\alpha\beta}+\epsilon^{qR}_{\alpha\beta}}$$



GL, Chuan-Qiang Song, Feng-Jie Tang, Jiang-Hao Yu, 2409.04703 (PRD)

Summary

- We study neutrino interactions at low energies via the CEvNS
- We propose a general formalism from the quark to nucleus levels
- LEFT operators up to dimension-8 are considered
- Contributions up to order of p^2 at nucleon level are included
- Outlook: full calculation and automatic code will be continued

Thank you