Institute for Research in Fundamental Sciences

Neutrino nucleus Quasi-Elastic and resonant Neutral Current scatterings with Non-Standard Interactions

In collaboration with Y. Farzan, M. Dehpour and S. Safari
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- Effects of NSI on neutrino and antineutrino cross sections with an argon nucleus, including nuclear scattering effects.
- Results.

Four-Fermi type Neutrino NSI

Neutrino non-standard interactions mediated by heavy particles can be described using an effective four-Fermi interaction, [Wolfenstein - 1978]

- Charged Current NSI:

$$\mathcal{L}_{\rm CC} = -\sqrt{2}G_{\rm F} \sum_{f,f',\alpha,\beta} \left[\bar{\nu_\alpha}\gamma_\mu \left(1-\gamma^5\right) l_\beta\right] \left(\epsilon^{V,f}_{\alpha\beta}\bar{f}\gamma^\mu f' + \epsilon^{A,f}_{\alpha\beta}\bar{f}\gamma^\mu\gamma^5 f'\right),$$

  where $f \neq f'$ and $f, f' \in \{e, p, n\}$

- Neutral Current NSI

$$\mathcal{L}_{\rm NC} = -\sqrt{2}G_{\rm F} \sum_{f,\alpha,\beta} \left[\bar{\nu_\alpha}\gamma_\mu \left(1-\gamma^5\right) \nu_\beta\right] \left(\epsilon^{V,f}_{\alpha\beta}\bar{f}\gamma^\mu f + \epsilon^{A,f}_{\alpha\beta}\bar{f}\gamma^\mu\gamma^5 f\right)$$

  where $f \in \{e, p, n\}$. Both of these interactions involve the vector and axial parts which are proportional to $\epsilon^{\rm vf}$ and $\epsilon^{\rm Af}$, respectively.
  The vector part of the Lagrangian can affect the pattern of neutrino oscillation in matter as well as the Coherent Elastic ν Nucleus Scattering (CEνNS). As a result, there are strong bonds on the values of $\epsilon^{Vq}_{\alpha\beta}$.
  By comparison, the axial couplings $\epsilon^{Aq}_{\alpha\beta}$ are less constrained because these couplings cannot affect the neutrino oscillation pattern or CEνNS.

The Hadronic Currents in the Presence Of NSI

- The total (SM+NSI) four-Fermi neutrino quark NC interactions can be written as the product of the leptonic and hadronic currents:

$$\frac{G_{\mathrm{F}}}{\sqrt{2}}\left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma_5)\nu_\beta\right](J^\mu_{\mathrm{had}})_{\alpha\beta}.$$

- The hadronic NC current can be decomposed into vector and axial components:

$$(J^\mu_{\mathrm{had}})_{\alpha\beta} = (V^\mu_{\mathrm{NC}})_{\alpha\beta} + (A^\mu_{\mathrm{NC}})_{\alpha\beta}\ .$$

- Each of these currents can be expressed as the sum of SM and NSI contributions:

$$V^\mu_{\mathrm{NC}} = V^\mu_{\mathrm{SM}} + V^\mu_{\mathrm{NSI}} \quad \text{and} \quad A^\mu_{\mathrm{NC}} = A^\mu_{\mathrm{SM}} + A^\mu_{\mathrm{NSI}}$$

The Hadronic Currents in the Presence of NSI

- Where

$$(V^{\mu}_{\rm SM})_{\alpha\beta} = \left[(1-2\sin^2\theta_W)\overline{Q}\gamma^{\mu}\frac{\tau^3}{2}Q - \frac{\sin^2\theta_W}{3}\overline{Q}\gamma^{\mu}Q + (\frac{2}{3}\sin^2\theta_W - \frac{1}{2})\bar{s}\gamma^{\mu}s\right]\delta_{\alpha\beta}$$

and

$$(A^{\mu}_{\rm SM})_{\alpha\beta} = \left[-\overline{Q}\gamma^{\mu}\gamma^5\frac{\tau^3}{2}Q + \frac{1}{2}\bar{s}\gamma^{\mu}\gamma^5 s\right]\delta_{\alpha\beta}$$

in which $Q = (u\ d)^T$ and $\tau^3 = \mathrm{diag}(1,-1)$ is a Pauli matrix.

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- The NSI currents can be written as

$$(V^{\mu}_{\mathrm{NSI}})_{\alpha\beta} = \frac{\epsilon^{Vu}_{\alpha\beta} + \epsilon^{Vd}_{\alpha\beta}}{2}\overline{Q}\gamma^{\mu}Q + \frac{\epsilon^{Vu}_{\alpha\beta} - \epsilon^{Vd}_{\alpha\beta}}{2}\overline{Q}\gamma^{\mu}\tau^3 Q + \epsilon^{Vs}_{\alpha\beta}\bar{s}\gamma^{\mu}s \qquad (1)$$

and

$$(A^{\mu}_{\mathrm{NSI}})_{\alpha\beta} = \frac{\epsilon^{Au}_{\alpha\beta} + \epsilon^{Ad}_{\alpha\beta}}{2}\overline{Q}\gamma^{\mu}\gamma^{5}Q + \frac{\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}}{2}\overline{Q}\gamma^{\mu}\gamma^{5}\tau^3 Q + \epsilon^{As}_{\alpha\beta}\bar{s}\gamma^{\mu}\gamma^{5}s.$$

Existing bounds on NSI couplings

- *Neutrino oscillation experiments:* Neutrino oscillation pattern in matter is sensitive to $\epsilon_{\alpha\beta}^{Vq}\Big|_{\alpha\neq\beta}$ and to $\epsilon_{\alpha\alpha}^{Vq} - \epsilon_{\beta\beta}^{Vq}$. As a result, solar, atmospheric, and long baseline neutrino oscillation experiments can probe these combinations of NSI.

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- *High energy neutrino beam scattering experiments:* The DIS of neutrinos is sensitive to the following chiral couplings:

$$\epsilon^{Rq} = \left(\epsilon^{Vq} + \epsilon^{Aq}\right)/2 \quad \text{and} \quad \epsilon^{Lq} = \left(\epsilon^{Vq} - \epsilon^{Aq}\right)/2.$$

The CHARM experiment, utilizing ν_e and $\bar{\nu}_e$ beams, was a DIS experiment and was therefore sensitive to the combinations:

$$(g^u_L + \epsilon^{Lu}_{ee})^2 + \sum_{\alpha\neq e} |\epsilon^{Lu}_{\alpha e}|^2 + (g^d_L + \epsilon^{Ld}_{ee})^2 + \sum_{\alpha\neq e} |\epsilon^{Ld}_{\alpha e}|^2,$$

$$(g^u_R + \epsilon^{Ru}_{ee})^2 + \sum_{\alpha\neq e} |\epsilon^{Ru}_{\alpha e}|^2 + (g^d_R + \epsilon^{Rd}_{ee})^2 + \sum_{\alpha\neq e} |\epsilon^{Rd}_{\alpha e}|^2,$$

$$g^u_L = \frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W},\ g^d_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W},\ g^u_R = -\frac{2}{3}\sin^2\theta_{\rm W} \text{ and } g^d_R = \frac{1}{3}\sin^2\theta_{\rm W}.$$

We observe a $2^4 = 16$ fold degeneracy between the SM solution $\epsilon^{Lu}_{ee} = \epsilon^{Ru}_{ee} = \epsilon^{Ld}_{ee} = \epsilon^{Rd}_{ee} = 0$ and the non-trivial cases where one or several of the following relations are satisfied:

$$\epsilon^{Lu}_{ee} = -1 + \frac{4}{3}\sin^2\theta_W,\ \epsilon^{Ru}_{ee} = \frac{4}{3}\sin^2\theta_W,\ \epsilon^{Ld}_{ee} = 1 - \frac{2}{3}\sin^2\theta_W,\ \text{and } \epsilon^{Rd}_{ee} = -\frac{2}{3}\sin^2\theta_W.$$

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$$[Zg_p^V + (A-Z)g_n^V + (Z+A)\epsilon_{\alpha\alpha}^{Vu} + (2A-Z)\epsilon_{\alpha\alpha}^{Vd}]^2 + \sum_{\alpha\neq\beta}[(Z+A)\epsilon_{\alpha\beta}^{Vu} + (2A-Z)\epsilon_{\alpha\beta}^{Vd}]^2$$

in which $g_n^V = -1/2$ and $g_p^V = 1/2 - 2\sin^2\theta_{\rm W}$.
The CEνNS results for arbitrary A and Z is degenerate with the SM provided that

$$\epsilon_{\alpha\alpha}^{Vd} = 1 - \frac{4}{3}\sin^2\theta_W \quad \text{and} \quad \epsilon_{\alpha\alpha}^{Vu} = -1 + \frac{8}{3}\sin^2\theta_W.$$

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- *The SNO experiment:* The Deuteron dissociation at SNO was sensitive to $\epsilon_{\alpha\beta}^{Au} - \epsilon_{\alpha\beta}^{Ad}$. The SNO NC measurement, along with the solution $\epsilon_{\alpha\beta}^{Au} \simeq \epsilon_{\alpha\beta}^{Ad}$, has non-trivial solutions such as $\epsilon_{ee}^{Au} - \epsilon_{ee}^{Ad} \simeq +2$ and/or $\epsilon_{\mu\mu}^{Au} - \epsilon_{\mu\mu}^{Ad} = +2$ and/or $\epsilon_{\tau\tau}^{Au} - \epsilon_{\tau\tau}^{Ad} = +2$.

Existing bounds on NSI couplings

- Taking $\epsilon_{\alpha\beta}^{A/Vq} \propto \delta_{\alpha\beta}$ (or equivalently $\epsilon_{\alpha\beta}^{L/Rq} \propto \delta_{\alpha\beta}$), we find that satisfying the relations $\epsilon_{\alpha\alpha}^{L/R,q} = -2g_{L/R}^{q}$ automatically ensures:
$\epsilon_{\alpha\alpha}^{Vd} = 1 - \frac{4}{3}\sin^2\theta_W \quad \text{and} \quad \epsilon_{\alpha\alpha}^{Vu} = -1 + \frac{8}{3}\sin^2\theta_W.$

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- In the following, we will focus on the impact of axial NSI on QE and resonance interactions, which is the subject of our recent study arXiv:2412.13349v2.
- In our previous work, we discussed how the study of NC DIS at DUNE can improve the bounds on $\epsilon^{Aq}_{\alpha\beta}$. In particular, we demonstrated that the far detector of DUNE can probe $\epsilon^{Aq}_{\tau\tau}$ at values well below current bounds [arXiv:2312.12420 [hep-ph]].

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- In our previous work, we discussed how the study of NC DIS at DUNE can improve the bounds on $\epsilon_{\alpha\beta}^{Aq}$. In particular, we demonstrated that the far detector of DUNE can probe $\epsilon_{\tau\tau}^{Aq}$ at values well below current bounds [arXiv:2312.12420 [hep-ph]].
- Following that, we proposed a toy model leading to $\epsilon_{\tau\tau}^{Au} = \epsilon_{\tau\tau}^{Ad} \sim 1$ with a dark matter candidate as a bonus to be tested by the spin-dependent direct dark matter search experiments, [arXiv:2407.13834 [hep-ph]].

Quasi-Elastic scattering in the presence of NC axial NSI

- The cross section of the QE scattering is given by

$$\frac{d\sigma^{\rm QE}_{\rm NC}(\overset{(-)}{\nu}_\alpha + N \to \overset{(-)}{\nu}_\beta + N)}{dQ^2} =$$
$$\frac{G_F^2 Q^2}{2\pi E_\nu^2}\left[A^N(Q^2) \pm B^N(Q^2)\left(\frac{4E_\nu}{M_N} - \frac{Q^2}{M_N^2}\right) + C^N(Q^2)\left(\frac{4E_\nu}{M_N} - \frac{Q^2}{M_N^2}\right)^2\right],$$

The functions $A(Q^2)$, $B(Q^2)$, and $C(Q^2)$ are defined as follows:

$$A^N(Q^2) =$$
$$\frac{1}{4}\left[\left(\tilde{F}_A^N\right)^2\left(1+\frac{Q^2}{4M_N^2}\right) - \left(\left(\tilde{F}_1^N\right)^2 - \frac{Q^2}{4M_N^2}\left(\tilde{F}_2^N\right)^2\right)\left(1-\frac{Q^2}{4M_N^2}\right) + \left(\frac{Q^2}{M_N^2}\right)\tilde{F}_1^N\tilde{F}_2^N\right],$$
$$B^N(Q^2) = -\frac{1}{4}\tilde{F}_A^N\left(\tilde{F}_1^N + \tilde{F}_2^N\right),$$
$$C^N(Q^2) = \frac{M_N^2}{16Q^2}\left[\left(\tilde{F}_A^N\right)^2 + \left(\tilde{F}_1^N\right)^2 + \left(\frac{Q^2}{4M_N^2}\right)\left(\tilde{F}_2^N\right)^2\right].$$

$$(\tilde{F}_i^p)_{\alpha\beta} = \left(\frac{\delta_{\alpha\beta}}{2} - 2\delta_{\alpha\beta}\sin^2\theta_W + 2\epsilon_{\alpha\beta}^{Vu} + \epsilon_{\alpha\beta}^{Vd}\right) F_i^p + \left(-\frac{\delta_{\alpha\beta}}{2} + \epsilon_{\alpha\beta}^{Vu} + 2\epsilon_{\alpha\beta}^{Vd}\right) F_i^n$$

$$+ \left(-\frac{\delta_{\alpha\beta}}{2} + \epsilon_{\alpha\beta}^{Vu} + \epsilon_{\alpha\beta}^{Vd} + \epsilon_{\alpha\beta}^{Vs}\right) F_i^s,$$

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$$(\tilde{F}_A^p)_{\alpha\beta} = \left(-\frac{\delta_{\alpha\beta}}{2} + \frac{\epsilon_{\alpha\beta}^{Au} - \epsilon_{\alpha\beta}^{Ad}}{2}\right) F_A + \frac{3}{2}(\epsilon_{\alpha\beta}^{Au} + \epsilon_{\alpha\beta}^{Ad})F_A^{(8)} + \left(\frac{\delta_{\alpha\beta}}{2} + \epsilon_{\alpha\beta}^{Au} + \epsilon_{\alpha\beta}^{Ad} + \epsilon_{\alpha\beta}^{As}\right) F_A^s,$$

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Vector Form factors

- *$\tilde{F}_i^N$ and vector NSI:* The form factors F_1^N and F_2^N are directly related to the electric charge and magnetic dipole of the nucleon, N. F_1^p and F_2^p have been extracted as a function of Q^2 with a remarkable precision from the electron proton scattering experiments:

$$F_1^N(Q^2) = \frac{1}{1+\frac{Q^2}{4M_N^2}}\left[\left(\frac{Q^2}{4M_N^2}\right)G_M^N(Q^2) + G_E^N(Q^2)\right],$$

$$F_2^N(Q^2) = \frac{1}{1+\frac{Q^2}{4M_N^2}}\left[G_M^N(Q^2) - G_E^N(Q^2)\right],$$

- $\tilde{F}_i^N$ can also be derived from studying the scattering of neutrino and antineutrino beams.
- Within the SM, the knowledge of $\tilde{F}_i^N$ and F_i^N can yield F_i^s.
- The ν_μ scattering data from MiniBooNE: $-0.09 < F_1^s(Q^2) < 0.1$ for $Q^2 < 1$ GeV^2.
- The lattice QCD predicted: $F_1^s(0) = 0$, $F_1^s(Q^2) < 0.004$ and $F_2^s(0) = -0.017$.
- F_i^s from global analysis of parity violating electron-proton scattering experiments is consistent with the lattice QCD results.
  While two former methods are not affected by NSI of neutrinos, the derivation of F_i^s from the ν_μ scattering off protons in the presence of NSI should be interpreted as $(2\epsilon_{\mu\mu}^{Vu} + \epsilon_{\mu\mu}^{Vd})F_i^p + (\epsilon_{\mu\mu}^{Vu} + 2\epsilon_{\mu\mu}^{Vd})F_i^n + (-1/2 + \epsilon_{\mu\mu}^{Vs})F_i^s$.
- If future measurements establish $F_1^s(Q^2) \sim 0.01$, it should be interpreted as nonzero $\epsilon_{\mu\mu}^{Vu}$ and/or $\epsilon_{\mu\mu}^{Vd}$.

Axial Form factors

- F_A is related to $\langle N|\overline{Q}\gamma^{\mu}\gamma^{5}\tau^{3}Q|N\rangle$. At low Q^2, $F_A(Q^2)$ is usually parametrized as a dipole:

$$F_A(Q^2) = g_A \left[1 + Q^2/M_A^2\right]^{-2}, \qquad (2)$$

where $g_A = F_A(0) = 1.27641(55)$, is called weak axial vector coupling constant and M_A is the axial mass.

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- $F_A^s(Q^2)$: Similarly to the case of $F_A(Q^2)$, for low Q^2, $F_A^s(Q^2)$ can be parameterized as a dipole form:

$$F_A^s = g_A^s \left[1 + Q^2/(M_A^s)^2\right]^{-2} . \tag{3}$$

In principle, M_A^s can be different from M_A but within the present experimental uncertainties, we can set $M_A^s = M_A$.
There are four main ways to determine g_A^s: lattice QCD calculations, parity-violating electron scattering experiments, neutrino-nucleus scattering data, and hyperon beta decays.

Axial Form factors

- F_A is related to $\langle N|\overline{Q}\gamma^\mu\gamma^5\tau^3 Q|N\rangle$. At low Q^2, $F_A(Q^2)$ is usually parametrized as a dipole:

$$F_A(Q^2) = g_A \left[1 + Q^2/M_A^2\right]^{-2}, \tag{2}$$

where $g_A = F_A(0) = 1.27641(55)$, is called weak axial vector coupling constant and M_A is the axial mass.

- $F_A^s(Q^2)$: Similarly to the case of $F_A(Q^2)$, for low Q^2, $F_A^s(Q^2)$ can be parameterized as a dipole form:

$$F_A^s = g_A^s \left[1 + Q^2/(M_A^s)^2\right]^{-2} . \tag{3}$$

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- $F_A^{(8)}(Q^2)$: This form factor is not relevant for the NC interaction within the SM; however, for $\epsilon_{\alpha\beta}^{Au} + \epsilon_{\alpha\beta}^{Ad} \neq 0$, the NC cross section depends on this form factor. $F_A^{(8)}$ from the lattice QCD:

$$F_A^{(8)}(Q^2) = g_A^{(8)} \left[1 + Q^2/(M_A^{(8)})^2\right]^{-2},$$

where $g_A^{(8)} = 0.53 \pm 0.022$ and $M_A^{(8)} = 1.154(101)$.

Axial Form Factors

- $\tilde{F}_A^N$ can be derived by studying the energy dependence of the neutrino scattering cross section. Within SM, this measurement combined with F_A from beta decay can determine F_A^s. This is the idea behind measuring F_A^s using atmospheric neutrinos at KamLAND. However, in the presence of NSI, such a derivation should be revisited.
- Another tool to investigate NSI is flavor. While F_A^s is a property of nucleon and is independent of the flavor of neutrinos that scatter off the nucleon, $\epsilon_{\alpha\beta}^{Aq}$ depends on the flavor. Therefore, by comparing the derivation of $\tilde{F}_A^N$ at the far and near detectors of long baseline experiments, one can obtain information on $\epsilon_{\alpha\beta}^{Aq}$ and its flavor structure.
- Another approach to utilize different flavors is studying the energy dependence of the NC event rates at the far detector as $P(\nu_\alpha \to \nu_\beta)$ depends on the energy of the neutrino.
- The upcoming more accurate experiments such as JUNO combined with the prediction of F_A^s from lattice QCD can help to set significant bounds on $\epsilon_{\tau\tau}^{Au} + \epsilon_{\tau\tau}^{Ad}$.

Resonance

For energy range $1\ \mathrm{GeV} < E_\nu < 4\ \mathrm{GeV}$, the resonance cross section dominates both over QE and DIS. Within the SM, the dominant NC resonance is $\nu + N \to \nu + \Delta(1232)$.

$$\mathcal{L}^{\mathrm{NC}}_{\mathrm{tot}} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \left[\bar{\nu}_\alpha \gamma_\mu (1-\gamma_5) \nu_\beta\right] J^\mu_\Delta,$$

The hadronic current for the reaction is given by

$$\begin{aligned} J^\mu_\Delta &=< \Delta^+ | J^\mu_\Delta(0) | p >=< \Delta^0 | J^\mu_\Delta(0) | n > \\ &= \bar{\psi}_\delta(p') \Gamma^{\delta\mu}_{3/2\pm} u(p). \end{aligned}$$

Here $\psi_\delta(p')$ is the Rarita-Schwinger spinor for the Δ, and $u(p)$ is the Dirac spinor for the nucleon.

$$\Gamma^{\delta\mu}_{3/2+} = \left[\mathcal{V}^{\delta\mu}_{3/2} - \mathcal{A}^{\delta\mu}_{3/2}\right] \gamma_5,$$

In terms of form factors, the vector and and the axial parts are given by

$$\mathcal{V}^{\delta\mu}_{3/2} = \frac{\mathcal{C}^V_3}{M_N}(g^{\delta\mu} \not{q} - q^\delta \gamma^\mu) + \frac{\mathcal{C}^V_4}{M_N^2}(g^{\delta\mu} q\cdot p' - q^{\delta\mu}) + \frac{\mathcal{C}^V_5}{M_N^2}(g^{\delta\mu} q\cdot p - q^\delta p^\mu) + g^{\delta\mu}\mathcal{C}^V_6,$$

$$-\mathcal{A}^{\delta\mu}_{3/2} = \left[\frac{\mathcal{C}^A_3}{M_N}(g^{\delta\mu} \not{q} - q^\delta \gamma^\mu) + \frac{\mathcal{C}^A_4}{M_N^2}(g^{\delta\mu} q\cdot p' - q^\delta p'^\mu) + \mathcal{C}^A_5 g^{\delta\mu} + \frac{\mathcal{C}^A_6}{M_N^2} q^\delta q^\mu\right] \gamma_5$$

Resonance

- The resonances with isospin different from $1/2$ cannot receive any contribution from the isospin invariant operators so the Δ resonance will not be sensitive to $\epsilon^{Au}+\epsilon^{Ad}$, $\epsilon^{Vu}+\epsilon^{Vd}$, ϵ^{Vs} or ϵ^{As}. The effects of $\epsilon^{Au}-\epsilon^{Ad}$ and $\epsilon^{Vu}-\epsilon^{Vd}$ on the cross section of the process $\nu+N\rightarrow\nu+\Delta$ can be treated by the following replacements

$$\tilde{C}_i^A\delta_{\alpha\beta}\rightarrow\tilde{C}_i^A(\delta_{\alpha\beta}-\epsilon^{Au}_{\alpha\beta}+\epsilon^{Ad}_{\alpha\beta})$$

$$\tilde{C}_i^V\delta_{\alpha\beta}=-(1-2\sin^2\theta_W)C_i^N\delta_{\alpha\beta}\rightarrow-\left[(1-2\sin^2\theta_W)\delta_{\alpha\beta}+\epsilon^{Vu}_{\alpha\beta}-\epsilon^{Vd}_{\alpha\beta}\right]C_i^N.$$

-

$$C_3^V(Q^2)=C_3^V(0)\frac{1}{(1+Q^2/M_V^2)^2}\frac{1}{(1+Q^2/4M_V^2)}$$

$$C_4^V(Q^2)=-C_3^V(Q^2)\frac{M_N}{W},$$

$$C_5^V(Q^2)=C_3^A(Q^2)=0,$$

$$C_4^A(Q^2)=-\frac{C_5^A(Q^2)}{4},$$

$$C_5^A(Q^2)=C_A^5(0)\frac{1}{(1+Q^2/M_A^2)^2}\frac{1}{(1+Q^2/3M_A^2)},$$

$$C_6^A(Q^2)=C_5^A(Q^2)\frac{M_N^2}{Q^2+m_\pi^2}$$

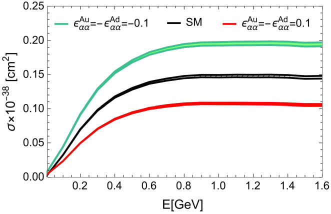
where $W^2=M_\Delta^2$ and $m_\pi=135MeV$ is the pion mass.

Results

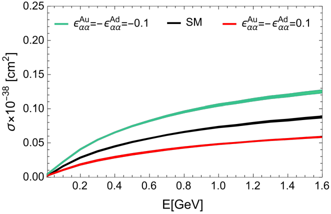
- To compute the cross sections, we use GiBBU 2023 as an event generator that accounts for nuclear effects implementing the necessary changes to take into account the NC NSI effects. With the off-diagonal NSI, the scattering can be lepton flavor violating: $\overset{(-)}{\nu}_\alpha + N \to \overset{(-)}{\nu}_\beta + N$ and $\overset{(-)}{\nu}_\alpha + N \to \overset{(-)}{\nu}_\beta + \Delta$ with $\alpha \neq \beta$. Since the detectors do not determine the flavor of the final neutrino at NC scattering, we sum over the flavor of the final neutrino when computing the NC scattering.

Parameter	Value	Method
M_V	$0.843\ \mathrm{GeV}$	$\nu - N$ CC QE scattering
$M_A^{(8)}$	$1.154 \pm 0.101\ \mathrm{GeV}$	lattice QCD
M_A	$0.999 \pm 0.011\ \mathrm{GeV}$	$\nu - N$ CC QE scattering
g_A	1.2695	β-decay
$g_A^{(8)}$	0.530 ± 0.022	lattice QCD
g_A^s	-0.15 ± 0.09	Mominal

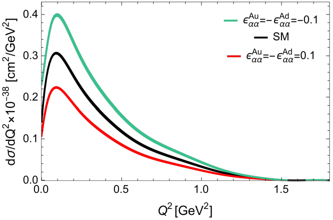
ν QE cross section



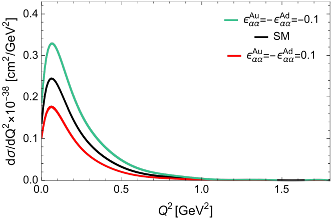
$\bar{\nu}$ QE cross section

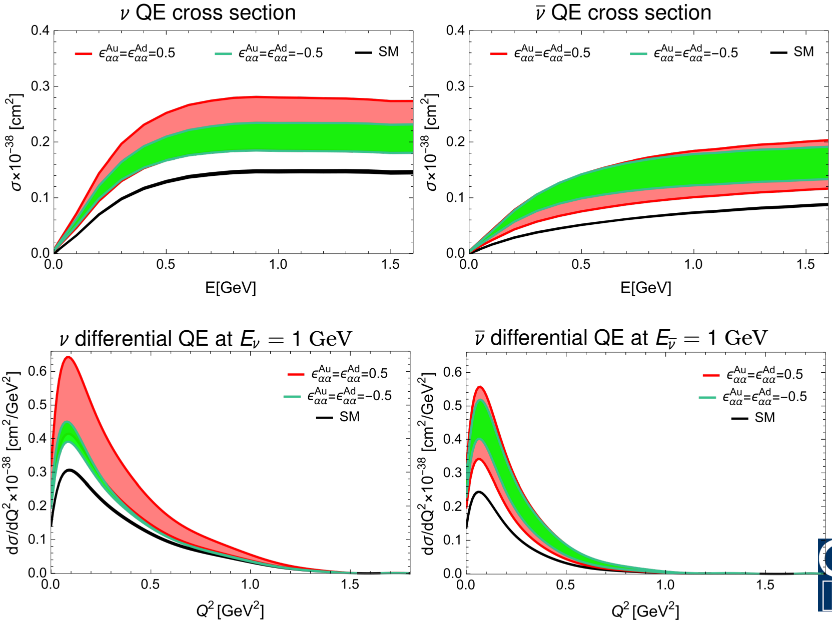


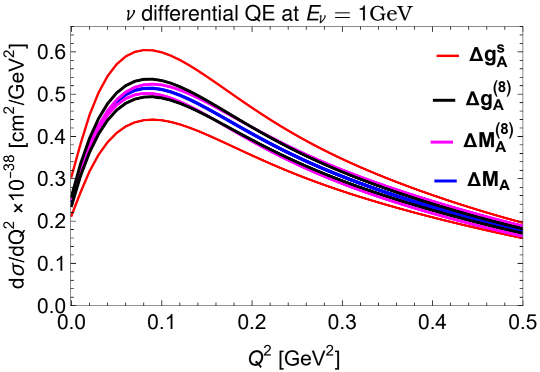
ν differential QE at $E_\nu = 1$ GeV



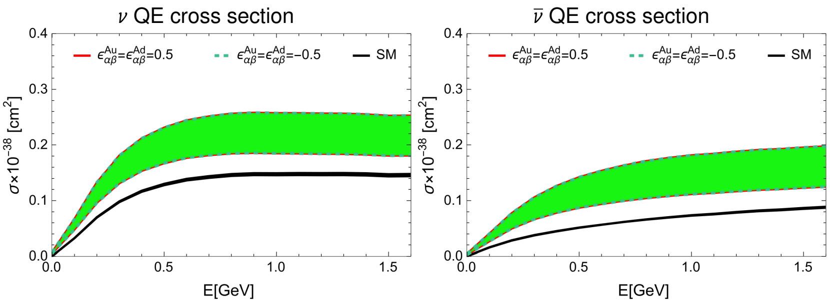
$\bar{\nu}$- differential QE at $E_{\bar{\nu}} = 1$ GeV



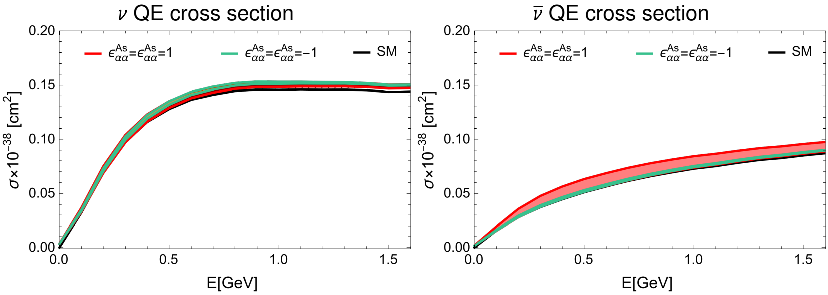

ν QE cross section
ν̄ QE cross section
$\epsilon_{\alpha\alpha}^{Au}=\epsilon_{\alpha\alpha}^{Ad}$=0.5
$\epsilon_{\alpha\alpha}^{Au}=\epsilon_{\alpha\alpha}^{Ad}$=−0.5
SM
σ×10^−38 [cm^2]
E[GeV]
ν differential QE at $E_\nu = 1$ GeV
ν̄ differential QE at $E_{\bar{\nu}} = 1$ GeV
dσ/dQ^2×10^−38 [cm^2/GeV^2]
Q^2 [GeV^2]



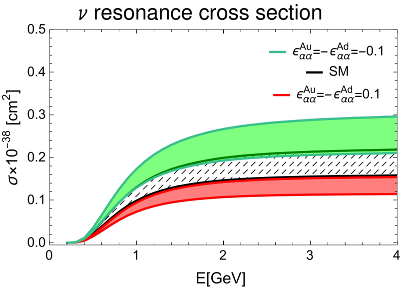
The differential cross sections per nucleon for QE NC scattering off Argon at an energy of $E_\nu = 1$ GeV, taking $\epsilon^{Au}_{\alpha\alpha} = \epsilon^{Ad}_{\alpha\alpha} = 0.5$. It disentangles the uncertainty induced by each form factor parameter, in which each pair of curves show the uncertainty induced by a single form factor parameter, setting the rest of the parameters equal to their central values. Unlike the case of the isovector NSI, the uncertainty induced by g_A^s is significant. This is because at $\epsilon^{Au}_{\alpha\alpha} = \epsilon^{Ad}_{\alpha\alpha} = \pm 0.5$, the central values of $\tilde{F}_A^p$ and $\tilde{F}_A^n$ are not opposite to each other and cancellations between the variations of the proton and neutron contribution do not take place.

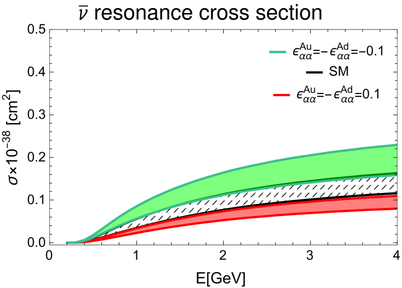


This figure shows how the QE scattering cross section changes in the presence of lepton flavor violating NSI. The green/red curves show the sum of the cross sections of $\nu_\alpha + N \to \nu_\alpha + N$ (from the SM) and of $\nu_\alpha + N \to \nu_\beta + N$ (from the lepton flavor violating NSI). The latter is proportional to $|\epsilon^{Au}_{\alpha\beta}|^2$ and is therefore always positive and independent of the sign of $\epsilon^{Au}_{\alpha\beta} = \epsilon^{Ad}_{\alpha\beta}$. As a result, the red and green curves have complete overlap.



This Figure shows the impact of $\epsilon^{As}_{\alpha\alpha} = \pm 1$ on the cross section. As seen from the figure, the sensitivity to $\epsilon^{As}_{\alpha\alpha}$ is too small to be resolvable. There are two reasons for the suppressed sensitivity: (1) The effect is suppressed by the coefficient $F^s_A(0) \simeq -0.15$; (2) The variations due to ϵ^{As} in the cross sections of neutron and proton are in opposite directions.





Parameter	m_V^Δ	m_A^Δ	$C_3^V(0)$	$C_4^V(0)$	$C_5^V(0)$	$C_5^A(0)$
Value	0.84 GeV	0.94 ± 0.03 GeV	2.13	-1.51	0.48	1.19 ± 0.08

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- We have then discussed how these degeneracies can be solved by employing extra information on the value of the form factors from the lattice QCD prediction or from the scattering of charged leptons off nuclei.
- We have found that an isoscalar axial NSI, $\epsilon^{Au} = \epsilon^{Ad}$ leads to only an excess in the QE NC cross section relative to the SM prediction, but the lepton flavor conserving isovector axial NSI, $\epsilon_{\alpha\alpha}^{Au} = -\epsilon_{\alpha\alpha}^{Aa}$ can lead to both excess or deficit depending on its sign.

Conclusion:

- Considering the bounds on $\epsilon^{Au} - \epsilon^{Ad}$, we have shown that the deviation for the isovector case cannot be larger than 30 %. Therefore, an excess of more than 30 % can be interpreted as axial isoscalar NSI but not isovector NSI.

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- The measurement of Δ resonance cross section can be used as a discriminant between isovector and isoscalar NSI.
- Finally, we have studied the impact of ϵ^{As} on the QE cross sections. Even with $\mathcal{O}(1)$ values, its effects on the cross section of neutrinos or antineutrinos off Argon will be buried in the form factor uncertainties because
  (1) its effects are suppressed by F_A^s;
  (2) the effects on neutron and protons cancel each other.

Thanks For Attention

Vector and axial Non-Standard Interaction

- Because the neutrino propagation in matter as well as Coherent Elastic neutrino Nucleus Scattering (CEνNS) are sensitive to ϵ^{vf}, the vector NSI couplings have been extensively studied and there are strong bounds on this coupling.
  arXiv:1805.04530 [hep-ph], arXiv:hep-ph/0508299
- Since ϵ^{Af} couplings do not affect the neutrino oscillation patterns or CEνNS, obtaining information on the axial NSI is more challenging.
- The high-energy neutrino scattering, such as deep inelastic scattering, is sensitive to both vector and axial NSI coupling.
- In the following, we will concentrate on the ϵ^{Af}.

Neutrino Nucleon Scattering

- Charged Current Quasi Elastic Scattering

$$\left.\begin{array}{lcl} \nu_l(k) + n(p) & \longrightarrow & l^-(k') + p(p'), \\ \bar{\nu}_l(k) + p(p) & \longrightarrow & l^+(k') + n(p'), \end{array}\right\} \text{(CC QE)} \tag{4}$$

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- Neutral Current Elastic Scattering

$$\nu_l/\bar{\nu}_l(k) + N(p) \longrightarrow \nu_l/\bar{\nu}_l(k') + N(p') \quad (\text{NC} \quad \text{elastic}) \tag{5}$$

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- Charged Current Resonance Scattering

$$\nu_l/\bar{\nu}_l(k) + N(p) \quad \longrightarrow \quad l^-/l^+(k') + N(p') + m\pi(p_\pi) \;\; (\text{CC} \;\; \text{resonance}) \tag{6}$$

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- Charged Current Depp Inelastic Scattering

$$\nu_l/\bar{\nu}_l(k) + N(p) \longrightarrow l^-/l^+(k') + X(p') \quad (\mathrm{CC\ DIS}) \tag{8}$$

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Axial NSI

- High-energy neutrino experiments, such as the NuTeV and CHARM experiments, have provided information on $\mu\alpha$ and $e\alpha$ elements of ϵ^{Af}:
- From NuTeV neutrino nucleus scattering experiment [arXiv:hep-ex/0110059]

$$|\epsilon^{Au}_{\mu\mu}| < 0.006, \quad |\epsilon^{Ad}_{\mu\mu}| < 0.018, \quad |\epsilon^{Au}_{\mu\tau}|, |\epsilon^{Ad}_{\mu\tau}| < 0.01,$$

- From CHARM Experiment [Phys. Lett. B 335, 246 (1994)].

$$|\epsilon^{Au}_{ee}| < 1, \quad |\epsilon^{Ad}_{ee}| < 0.9, \quad |\epsilon^{Au}_{e\tau}|, |\epsilon^{Ad}_{e\tau}| < 0.5.$$

- From SNO experiment date and neutrino-deuterium NC interaction [arXiv:2305.07698 [hep-ph]], the combination $\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}$ is constrained

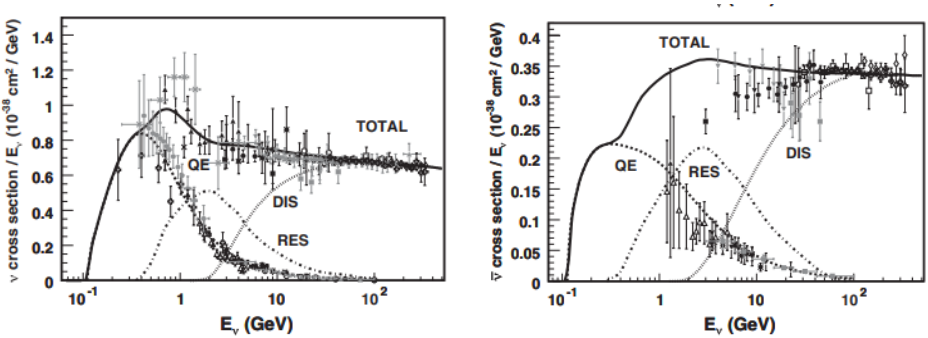
$$-2.1 < \epsilon^{Au}_{ee} - \epsilon^{Ad}_{ee} < -1.8$$

$$1.6 < \epsilon^{Au}_{\mu\tau} - \epsilon^{Ad}_{\mu\tau} < 1.9$$

$$-1.6 < \epsilon^{Au}_{\tau\tau} - \epsilon^{Ad}_{\tau\tau} < -1.4.$$

- However, the bounds on $\epsilon^{Aq}_{\tau\tau}$ and $\epsilon^{Aq}_{e\tau}$ are still very weak and these parameters require more study.

Neutrino (antineutrino)cross section



Neutrino nucleon DIS cross section

$$\sigma_p(\overset{(-)}{\nu}_\alpha + p \to \overset{(-)}{\nu}_\beta + X) \simeq \frac{G_F^2}{\pi}(M_N E_\nu)\int_0^1 dx$$

$$\times\left\{\frac{2}{3}\left[1-\frac{3}{2}\frac{M_p x}{2E_\nu}+\frac{9}{4}\left(\frac{M_p x}{2E_\nu}\right)^2\right] x\left[[u(x)+\overline{u}(x)]\left(|f^{Vu}_{\alpha\beta}|^2+|f^{Au}_{\alpha\beta}|^2\right)\right.\right.$$

$$\left.+\left[d(x)+\overline{d}(x)\right]\left(|f^{Vd}_{\alpha\beta}|^2+|f^{Ad}_{\alpha\beta}|^2\right)+[s(x)+\overline{s}(x)]\left(|f^{Vs}_{\alpha\beta}|^2+|f^{As}_{\alpha\beta}|^2\right)\right]$$

$$\pm\frac{2}{3}\left[1-\frac{3}{2}\frac{M_p x}{2E_\nu}+\frac{3}{2}\left(\frac{M_p x}{2E_\nu}\right)^2\right] x\left[[u(x)-\overline{u}(x)]\,\Re\left[f^{Vu}_{\alpha\beta}(f^{Au}_{\alpha\beta})^*\right]\right.$$

$$\left.\left.+\left[d(x)-\overline{d}(x)\right]\Re\left[f^{Vd}_{\alpha\beta}(f^{Ad}_{\alpha\beta})^*\right]+[s(x)-\overline{s}(x)]\Re\left[f^{Vs}_{\alpha\beta}(f^{As}_{\alpha\beta})^*\right]\right]\right\}$$

Using the isospin symmetry, the cross section of scattering off the neutron, σ_n is obtained with $u(x) \leftrightarrow d(x)$.