IPM
Institute for Research in Fundamental Sciences

Searching for Axial Neutral Current Non-Standard Interactions of neutrinos by DUNE-like experiments

In collaboration with Y. Farzan, M. Dehpour and S. Safari

JHEP 04 (2024) 038

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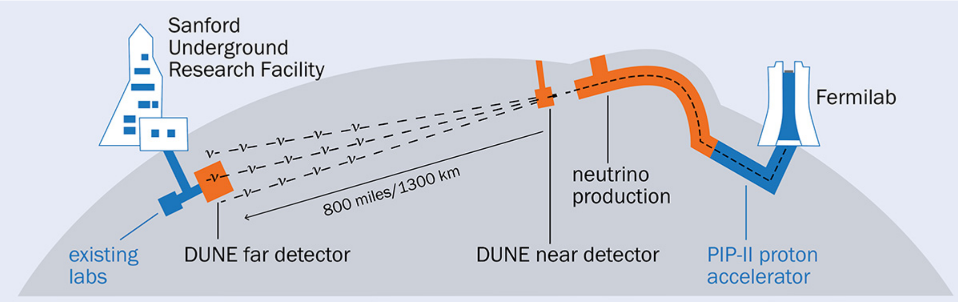
Introduction

- Four-Fermi type Neutrino Non Standard Interaction (NSI)



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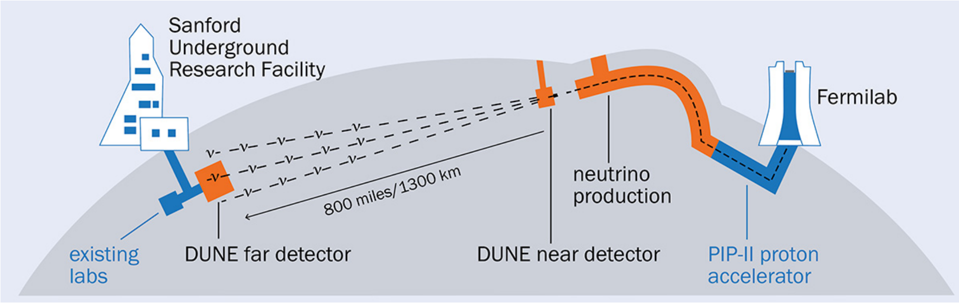

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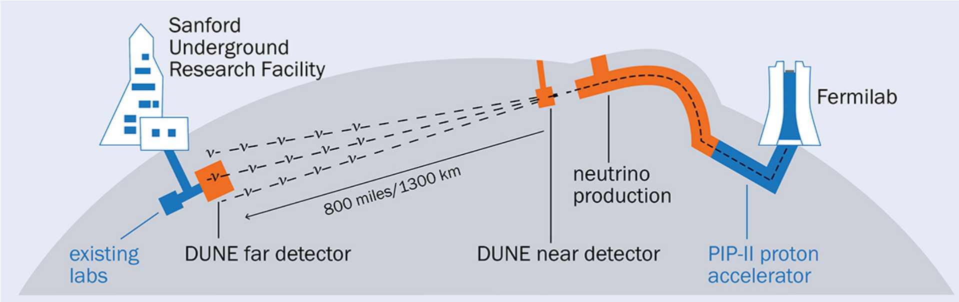
- Neutrino scattering in the presence of neutral current axial NSI



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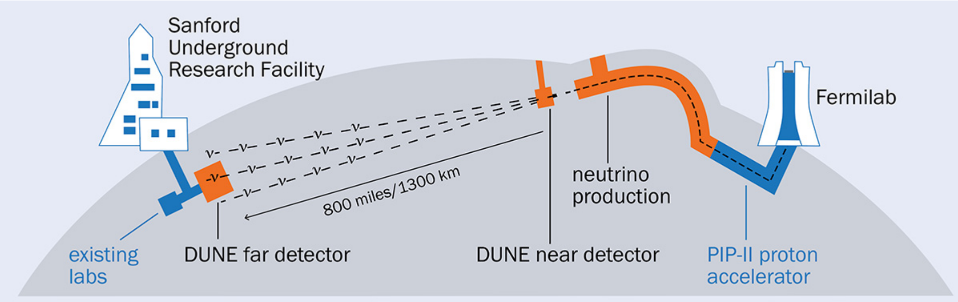
- Four-Fermi type Neutrino Non Standard Interaction (NSI)
- Deep Underground Neutrino Experiment (DUNE)
- Neutrino scattering in the presence of neutral current axial NSI
- Deep Inelastic Scattering (DIS) in the presence of NSI



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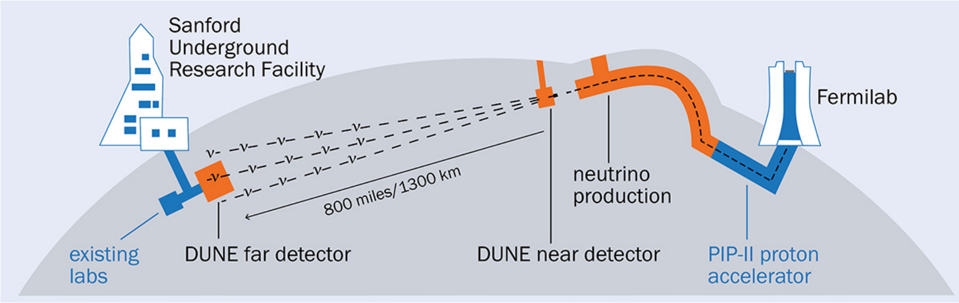
- Deep Underground Neutrino Experiment (DUNE)
- Neutrino scattering in the presence of neutral current axial NSI
- Deep Inelastic Scattering (DIS) in the presence of NSI
- Results



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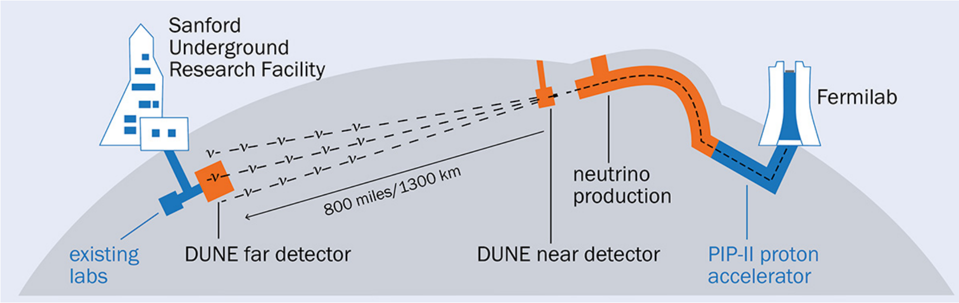
- Future Plan



Four-Fermi type Neutrino Non-Standard Interaction

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

- Charged Current NSI:

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

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

- Neutral Current NSI

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

where $f \in \{e, p, n\}$
Both of these interactions involve the vector and axial parts which are proportional to ϵ^{vf} and ϵ^{Af}, respectively.
In this talk, we will focus on NC NSI, specifically on the axial NSI.

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}.

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]]

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

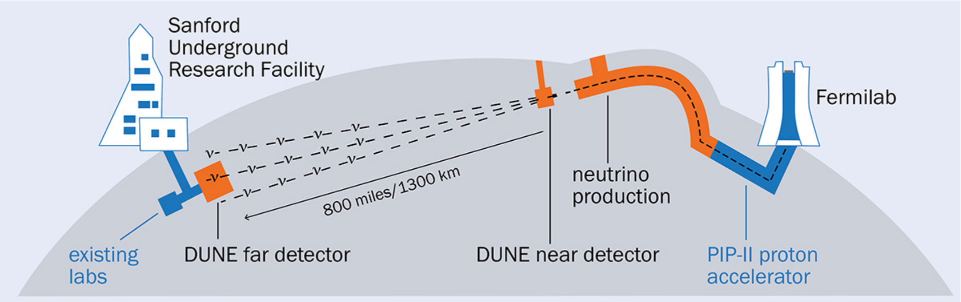
$$1.6 < \epsilon^{Au}_{\mu\tau} - \epsilon^{Ad}_{\mu\tau} < 1.9$$

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

- Because there are no strong bounds on $\epsilon^{Aq}_{\tau\tau}$ and $\epsilon^{As}_{\alpha\beta}$, these parameters require more study.

Deep Underground Neutrino Experiment (DUNE)

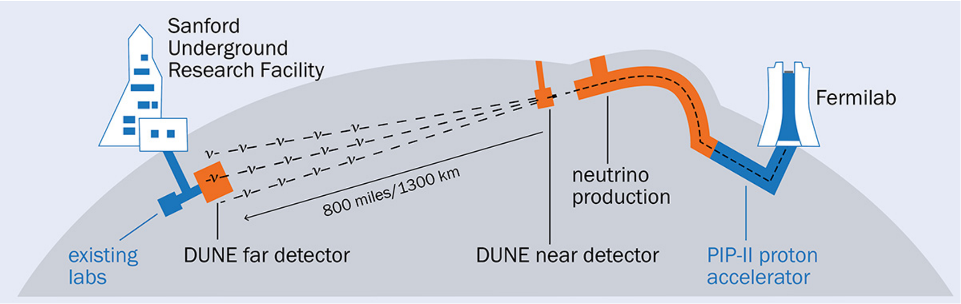
- The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-baseline neutrino oscillation experiment.
- Near Detector, which is located approximately a few hundred meters from the neutrino source and is composed of 67.2 tons of liquid argon (LAr).
  Far Detector (FD) is situated in South Dakota. This detector is composed of 40 kilotons (kt) of liquid argon (LAr).



Neutrinos flux at ND and FD of DUNE

- Flux at ND:

Huge flux of ν_μ or $\bar{\nu}_\mu$ → ND of DUNE → $\epsilon^{Aq}_{\mu,\alpha}$, ϵ^{Aq}_{ee}, $\epsilon^{Aq}_{e\tau}$, $\epsilon^{Aq}_{\tau\tau}$



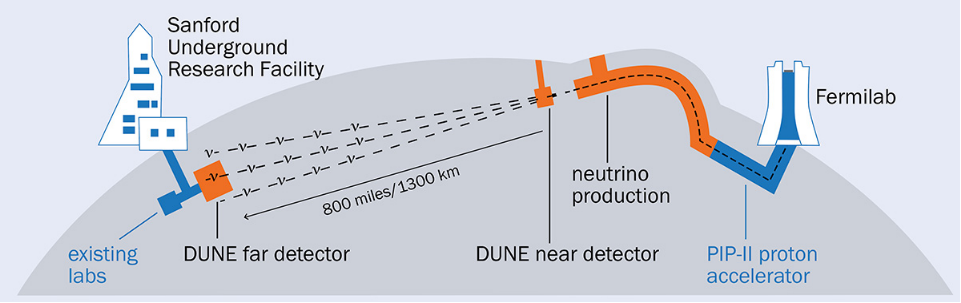
Neutrinos flux at ND and FD of DUNE

- Flux at ND:

Huge flux of ν_μ or $\bar{\nu}_\mu$ → **ND of DUNE** → $\epsilon^{Aq}_{\mu,\alpha}$, ϵ^{Aq}_{ee}, $\epsilon^{Aq}_{e\tau}$, $\epsilon^{Aq}_{\tau\tau}$

- Flux at FD: Due to the neutrino oscillation the flux at FD is coherent combination of flavor eigenstates

Flux included three neutrino flavor → **FD of DUNE** → $\epsilon^{Aq}_{\mu,\alpha}$, ϵ^{Aq}_{ee}, $\epsilon^{Aq}_{e\tau}$, $\epsilon^{Aq}_{\tau\tau}$



Neutrino scattering in the presence of neutral current axial NSI

- At energies of few GeV which is of relevance to a DUNE-like experiment, Deep Inelastic Scattering (DIS) and resonance scattering (RE) can have comparable contributions.

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- In resonance interactions, a nucleon within the target is knocked out and scattered into a resonant baryon (Δ or N^*) which then decays back to a pion and nucleon:

$$\nu + N \to \nu + (\Delta \text{ or } N^*) \to \nu + \pi + N$$

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$$\nu + N \rightarrow \nu + (\Delta \text{ or } N^*) \rightarrow \nu + \pi + N$$

.

- We will only focus on NC DIS .

Standard and Non-Standard Neutral Current neutrino Interaction

- $$\mathcal{L}_{\text{tot}}^{\text{NC}} = -\frac{G_{\text{F}}}{\sqrt{2}} \sum_{\alpha,\beta,q} \left[\overline{\nu}_\alpha \gamma^\mu (1-\gamma_5) \nu_\beta\right] \left[\overline{q} \gamma_\mu \left(f_{\alpha\beta}^{Vq} + f_{\alpha\beta}^{Aq} \gamma_5\right) q\right],$$

Standard and Non-Standard Neutral Current neutrino Interaction

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- $$f_{\alpha\beta}^{Vq} = \epsilon_{\alpha\beta}^{Vq} + g^{Vq}\delta_{\alpha\beta} \quad \text{and} \quad f_{\alpha\beta}^{Aq} = \epsilon_{\alpha\beta}^{Aq} + g^{Aq}\delta_{\alpha\beta}.$$

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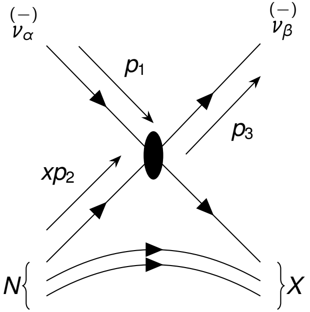
	Up type quarks (u, c, t)	Down type quarks (d, s, b)	Charged leptons (e, μ, τ)	Neutral leptons $(\nu_e, \nu_\mu, \nu_\tau)$
g^L	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	$-\frac{1}{2} + \sin^2\theta_W$	$\frac{1}{2}$
g^R	$-\frac{2}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$	$\sin^2\theta_W$	0
g^V	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2} + 2\sin^2\theta_W$	$\frac{1}{2}$
g^A	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$

Neutrino nucleon Deep Inelastic Scattering (DIS) in the presence of axial NSI

$$\nu_\alpha(p_1)/\bar{\nu}_\alpha(p_1) + N(p_2) \to \nu_\beta(p_3)/\bar{\nu}_\beta(p_1) + X(p') \quad \text{where} \quad N = n, p, \qquad (1)$$

$$p_1^\mu = (p_1^0, \vec{p}_1), \text{ where } |\vec{p}_1| = p_1^0 = E_\nu,$$
$$p_3^\mu = (p_3^0, \vec{p}_3), \text{ where } |\vec{p}_3| = p_3^0 = E'_\nu,$$
$$p_2^\mu = (p_2^0, \vec{p}_2) = (M_N, 0, 0, 0),$$
$$q^\mu = (p_1 - p_3)^\mu,$$
$$x = \frac{-q^2}{2p_2 \cdot q} = \frac{Q^2}{2M_N(E_\nu - E'_\nu)},$$
$$y = 1 - \frac{E'_\nu}{E_\nu}.$$



Neutrino nucleon DIS cross section

$$0 \leq x \leq 1 \quad \text{and} \quad 0 \leq y \leq \frac{1}{1 + M_N x/(2E_\nu)}.$$

$$\frac{d^2\sigma_{\rm NC}(\overset{(-)}{\nu_\alpha} N \to \overset{(-)}{\nu_\beta} + X)}{dxdy} = \frac{G_{\rm F}^2}{\pi}(M_N E_\nu)\Bigg\{\frac{1}{2}\left(xy^2 + 2x - 2xy - \frac{M_N}{E_\nu}x^2 y\right)$$
$$\times \left[\sum_q f_N^q(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right) + \sum_{\bar{q}} f_N^{\bar{q}}(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right)\right]$$
$$\pm 2xy\left(1 - \frac{y}{2}\right)\left[\sum_q f_N^q(x)\Re\left[f_{\alpha\beta}^{Vq}(f_{\alpha\beta}^{Aq})^*\right] - \sum_{\bar{q}} f_N^{\bar{q}}(x)\Re\left[f_{\alpha\beta}^{Vq}(f_{\alpha\beta}^{Aq})^*\right]\right]\Bigg\},$$

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$$\times\left[\sum_q f_N^q(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right) + \sum_{\bar q} f_N^{\bar q}(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right)\right]$$
$$\left.\pm 2xy\left(1 - \frac{y}{2}\right)\left[\sum_q f_N^q(x)\Re\left[f_{\alpha\beta}^{Vq}(f_{\alpha\beta}^{Aq})^*\right] - \sum_{\bar q} f_N^{\bar q}(x)\Re\left[f_{\alpha\beta}^{Vq}(f_{\alpha\beta}^{Aq})^*\right]\right]\right\},$$

Isospin symmetry:

$$f_n^d(x) = f_p^u(x) \equiv u(x), \quad f_n^{\bar d}(x) = f_p^{\bar u}(x) \equiv \bar u(x),$$
$$f_n^u(x) = f_p^d(x) \equiv d(x), \quad f_n^{\bar u}(x) = f_p^{\bar d}(x) \equiv \bar d(x),$$
$$f_n^s(x) = f_p^s(x) \equiv s(x), \quad f_n^{\bar s}(x) = f_p^{\bar s}(x) \equiv \bar s(x).$$

Neutrino nucleon DIS cross section

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

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

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

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

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

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

Integral	u	d	s
$\int_0^1 dx\, x\, [q(x) + \overline{q}(x)]$	0.349 ± 0.007	0.193 ± 0.007	0.033 ± 0.008
$\int_0^1 dx\, x^2\, [q(x) + \overline{q}(x)]$	0.090 ± 0.002	0.037 ± 0.001	0.002 ± 0.0008
$\int_0^1 dx\, x^3\, [q(x) + \overline{q}(x)]$	0.034 ± 0.0009	0.012 ± 0.0007	0.0005 ± 0.0005
$\int_0^1 dx\, x\, [q(x) - \overline{q}(x)]$	0.290 ± 0.008	0.120 ± 0.003	0.0
$\int_0^1 dx\, x^2\, [q(x) - \overline{q}(x)]$	0.084 ± 0.002	0.030 ± 0.001	0.0
$\int_0^1 dx\, x^3\, [q(x) - \overline{q}(x)]$	0.033 ± 0.0009	0.010 ± 0.0007	0.0

Integral of $\int_0^1 dx\, x^n\, [q(x) \pm \overline{q}(x)]$ at $Q = 2,$GeV for quarks of type u, d, and s with $n = 1, 2, 3$. We have computed the quark distribution functions $q(x)$ and $\overline{q}(x)$ using the CT18NNLO PDF.

Cross section at ND and FD

At ND the previous formula can be used to compute the NC DIS rates. However, neutrinos oscillate on their way to the FD:

$$|\nu_{\rm far}(E_\nu)\rangle = \sum_i \sum_\beta e^{im^2_{Mi}L/(2E_\nu)}(U^M_{\mu i})^* U^M_{\beta i}|\nu_\beta\rangle \equiv \sum_\beta \mathcal{A}_\beta|\nu_\beta\rangle \quad (\nu \text{ mode})$$

and

$$|\bar\nu_{\rm far}(E_\nu)\rangle = \sum_i \sum_\beta e^{i\overline{m}^2_{Mi}L/(2E_\nu)}(\overline{U}^M_{\mu i})^* \overline{U}^M_{\beta i}|\bar\nu_\beta\rangle \equiv \sum_\beta \overline{\mathcal{A}}_\beta|\bar\nu_\beta\rangle \quad (\bar\nu \text{ mode})$$

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$$|\nu_{\rm far}(E_\nu)\rangle = \sum_i \sum_\beta e^{im_{Mi}^2 L/(2E_\nu)} (U_{\mu i}^M)^* U_{\beta i}^M |\nu_\beta\rangle \equiv \sum_\beta \mathcal{A}_\beta |\nu_\beta\rangle \quad (\nu \text{ mode})$$

and

$$|\bar\nu_{\rm far}(E_\nu)\rangle = \sum_i \sum_\beta e^{i\overline{m}_{Mi}^2 L/(2E_\nu)} (\overline{U}_{\mu i}^M)^* \overline{U}_{\beta i}^M |\bar\nu_\beta\rangle \equiv \sum_\beta \overline{\mathcal{A}}_\beta |\bar\nu_\beta\rangle \quad (\bar\nu \text{ mode})$$

where, $|\mathcal{A}_\beta|^2 = P(\nu_\mu \to \nu_\beta)$

$$\mathcal{M}(\nu_{\rm far} + q \to \nu_\alpha + q) = \sum_\beta \mathcal{A}_\beta \mathcal{M}(\nu_\beta + q \to \nu_\alpha + q),$$

$$\mathcal{M}(\bar\nu_{\rm far} + q \to \bar\nu_\alpha + q) = \sum_\beta \overline{\mathcal{A}}_\beta \mathcal{M}(\bar\nu_\beta + q \to \bar\nu_\alpha + q).$$

NC NSI events at near and far detectors

$$\mathcal{N}_{\nu}^{\rm ND} = \int \varphi_{\nu}^{\rm ND}(E)\left[(\sigma_n)_{\nu_\mu} N_n^{\rm ND} + (\sigma_p)_{\nu_\mu} N_p^{\rm ND}\right] dE,$$

$$\mathcal{N}_{\bar\nu}^{\rm ND} = \int \varphi_{\bar\nu}^{\rm ND}(E)\left[(\sigma_n)_{\bar\nu_\mu} N_n^{\rm ND} + (\sigma_p)_{\bar\nu_\mu} N_p^{\rm ND}\right] dE,$$

$$\mathcal{N}_{\nu}^{\rm FD} = \int \varphi_{\nu}^{FD}(E)\left[(\sigma_n)_{\nu_{\rm far}} N_n^{\rm FD} + (\sigma_p)_{\nu_{\rm far}} N_p^{\rm FD}\right] dE,$$

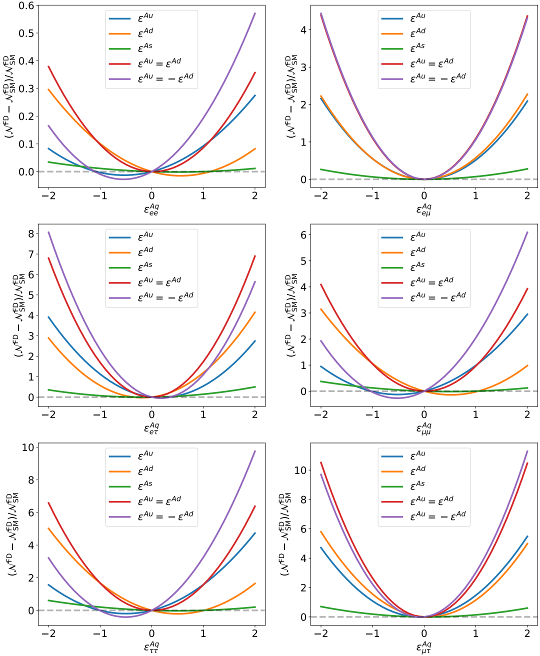
$$\mathcal{N}_{\bar\nu}^{\rm FD} = \int \varphi_{\bar\nu}^{\rm FD}(E)\left[(\sigma_n)_{\bar\nu_{\rm far}} N_n^{\rm FD} + (\sigma_p)_{\bar\nu_{\rm far}} N_p^{\rm FD}\right] dE,$$

where $\varphi_{\nu/\bar\nu}^{\rm FD/ND}$ are the time-integrated fluxes of neutrinos or antineutrinos at ND or FD in the absence of oscillation.

$$N_p^{\rm ND/FD} = \frac{18}{40}\frac{M_{\rm fid}^{\rm ND/FD}}{M_p} \quad \text{and} \quad N_n^{\rm ND/FD} = \frac{22}{40}\frac{M_{\rm fid}^{\rm ND/FD}}{M_p}.$$

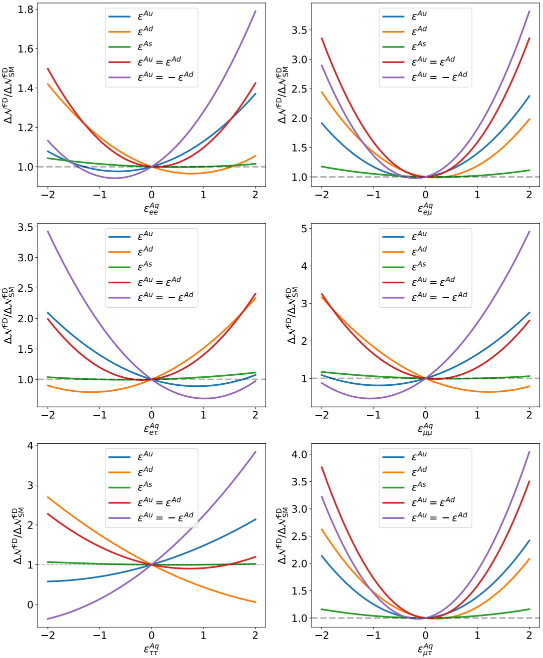
$$\mathcal{N}^{\rm ND}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm ND} + \mathcal{N}_{\bar\nu}^{\rm ND} \quad \text{and} \quad \Delta\mathcal{N}^{\rm ND}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm ND} - \mathcal{N}_{\bar\nu}^{\rm ND},$$

$$\mathcal{N}^{\rm FD}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm FD} + \mathcal{N}_{\bar\nu}^{\rm FD} \quad \text{and} \quad \Delta\mathcal{N}^{\rm FD}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm FD} - \mathcal{N}_{\bar\nu}^{\rm FD}.$$



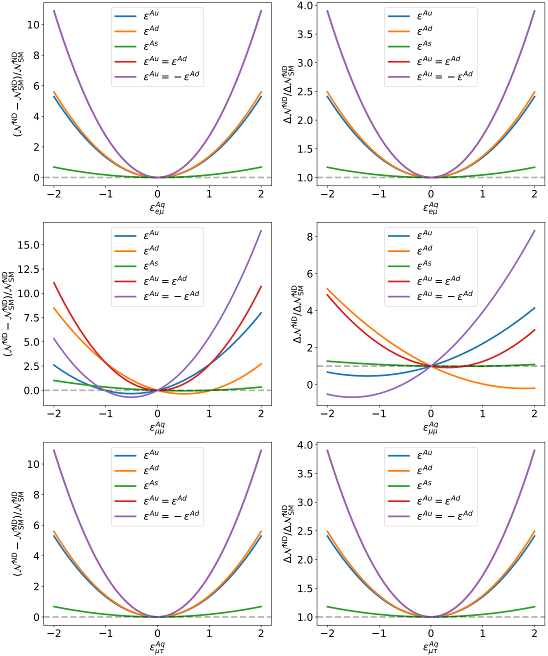
Deviation of the total number of NC DIS neutrino plus antineutrino events from the SM prediction at the far detector versus the NSI parameters,

$$\frac{\mathcal{N}^{\rm FD}(\epsilon^{Aq}_{\alpha\beta}) - \mathcal{N}^{\rm FD}(\epsilon^{Aq}_{\alpha\beta} = 0)}{\mathcal{N}^{\rm FD}(\epsilon^{Aq}_{\alpha\beta} = 0)}$$



Ratio of the difference of the number of NC DIS events in the neutrino and antineutrino modes in the presence of NSI at the far detector to the SM prediction for the same difference versus the NSI parameters,

$$\frac{\Delta\mathcal{N}^{\rm FD}(\epsilon^{Aq}_{\alpha\beta})}{\Delta\mathcal{N}^{\rm FD}(\epsilon^{Aq}_{\alpha\beta}=0)}$$



- **Right column:** Deviation of the total number of NC DIS neutrino plus antineutrino events from the SM prediction at the ND detector versus the NSI parameters,

$$\frac{\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}) - \mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}{\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}.$$

- **Left column:** Ratio of the difference of the number of NC DIS events in the neutrino and antineutrino modes in the presence of NSI at the ND detector to the SM prediction for the same difference versus the NSI parameters,

$$\frac{\Delta\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta})}{\Delta\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}.$$

Forecasting the bounds on axial NSI

The CC events as well as the resonance neutrino interaction events may be misidentified as a signal for DIS NC interactions.

$$\mathcal{B}_{\nu/\bar{\nu}}^{\mathrm{ND/FD}} = \epsilon_{\mathrm{CC}}(\mathcal{N}_{\mathrm{CC}}^{\mathrm{ND/FD}})_{\nu/\bar{\nu}} + \epsilon_{\mathrm{Res}}(\mathcal{N}_{\mathrm{Res}}^{\mathrm{ND/FD}})_{\nu/\bar{\nu}},$$

$$\epsilon_{\mathrm{CC}} \sim 10\%, \qquad \epsilon_{\mathrm{Res}} \sim 10\% \quad (\mathcal{N}_{\mathrm{CC}})_{\nu}^{\mathrm{FD}} = \frac{71}{12}\mathcal{N}_{\nu}^{\mathrm{FD}} \quad \text{and} (\mathcal{N}_{\mathrm{Res}})_{\nu}^{\mathrm{FD}} = \frac{7}{12}\mathcal{N}_{\nu}^{\mathrm{FD}},$$

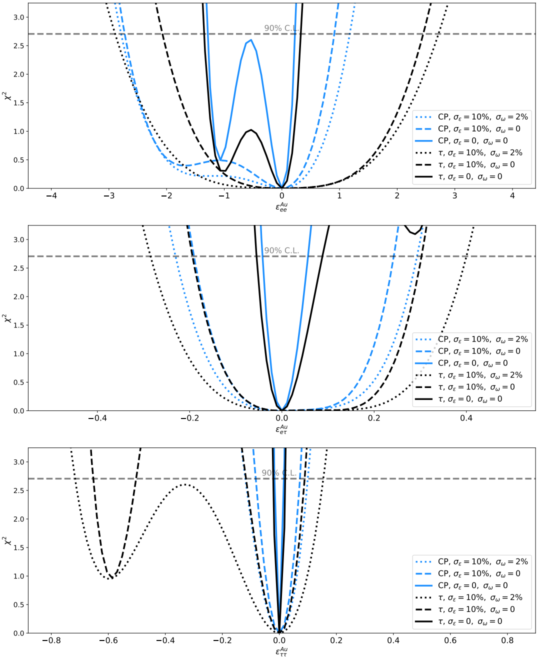
where $\mathcal{N}_{\nu}^{\mathrm{FD}}$ is the number of NC DIS neutrino events at the far detector [B. Abi et al. (DUNE), (2020)]. A similar relation hold for anti neutrino and also for ND.

$$\chi^2 = \left[\sum_{Y=\nu,\bar{\nu}} \left(\frac{\left[\xi \mathcal{N}_Y^{\mathrm{FD}}(\epsilon_{\mathrm{test}}^{Aq}) - \epsilon \mathcal{N}_Y^{\mathrm{FD}}(\epsilon^{Aq}=0) + \omega_Y \mathcal{B}_Y^{\mathrm{FD}}\right]^2}{\epsilon \mathcal{N}_Y^{\mathrm{FD}}(\epsilon^{Aq}=0) + \mathcal{B}_Y^{\mathrm{FD}}} + \frac{\omega_Y^2}{\sigma_\omega^2} \right) + \frac{(\xi-\epsilon)^2}{\sigma_\epsilon^2}\right]_{\min},$$

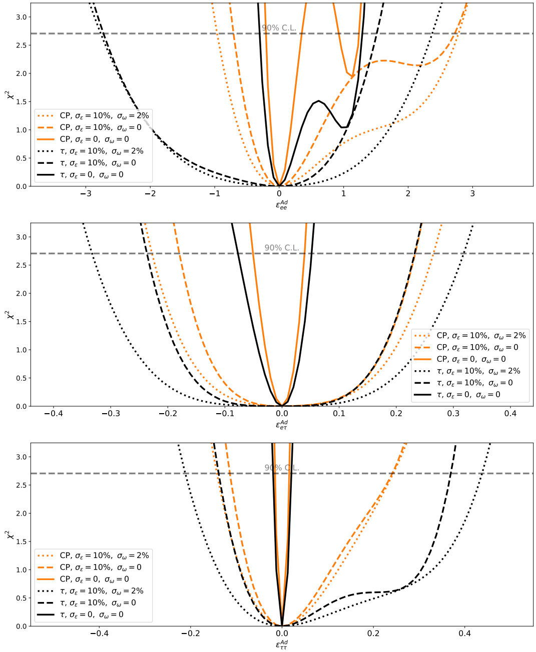
Where $\epsilon = 90\%$ is the efficiency of detecting the signal.
ξ, ω_ν, and $\omega_{\bar{\nu}}$ are pull parameter.

Results

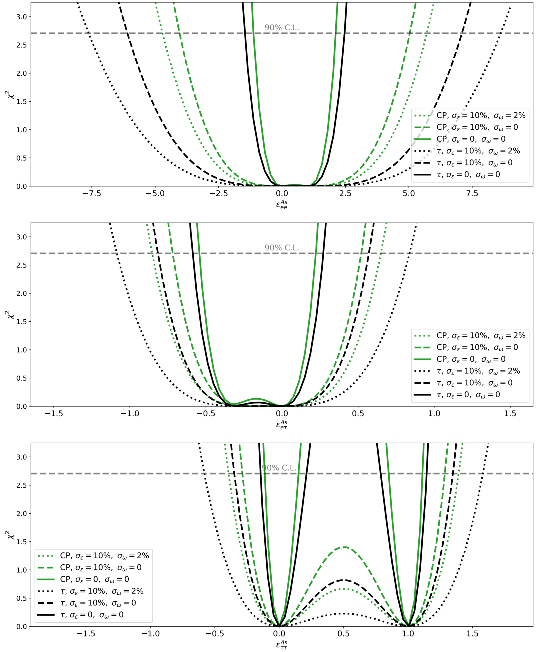
- To compare our forecast with the existing constraints, we consider the cases that only ϵ^{Au} or ϵ^{Ad} is non-zero.
- We also focus on the benchmark point $\epsilon^{Au} = \epsilon^{Ad}$
- We consider the possibility of testing the non-trivial SNO solution ($\epsilon^{Au}_{\tau\tau} - \epsilon^{Ad}_{\tau\tau} \simeq -1.5$).
- We forecast the bounds on ϵ^{As} from the ND and the FD of a DUNE-like experiment.
- We will examine the results for both the “CP-optimized" and “τ-optimized" flux modes.



χ^2 versus ϵ^{Au} for 6.5+6.5 years of data taking at FD.



χ^2 versus ϵ^{Ad} for 6.5+6.5 years of data taking at FD.



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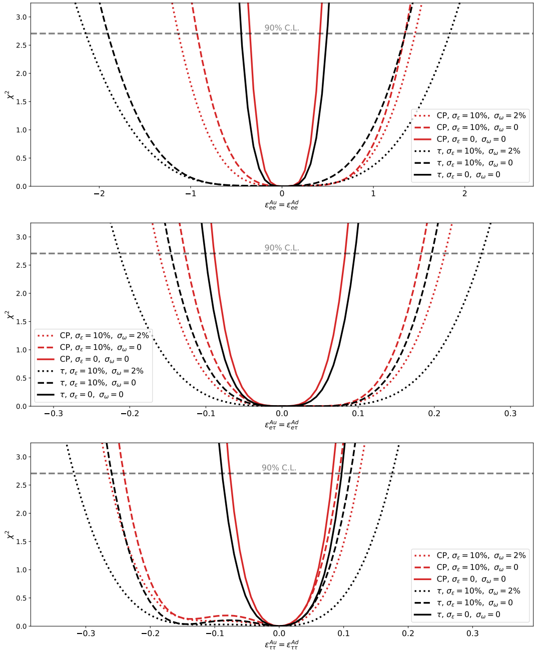
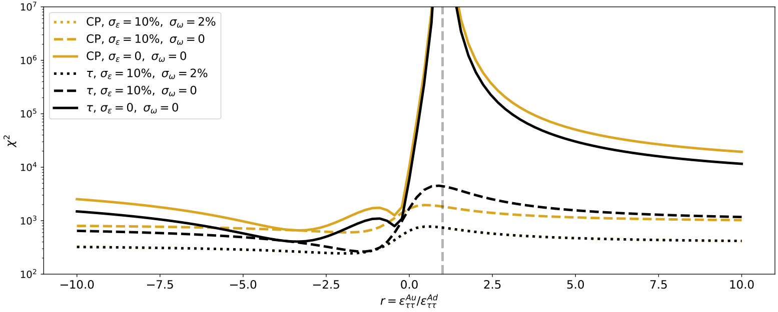
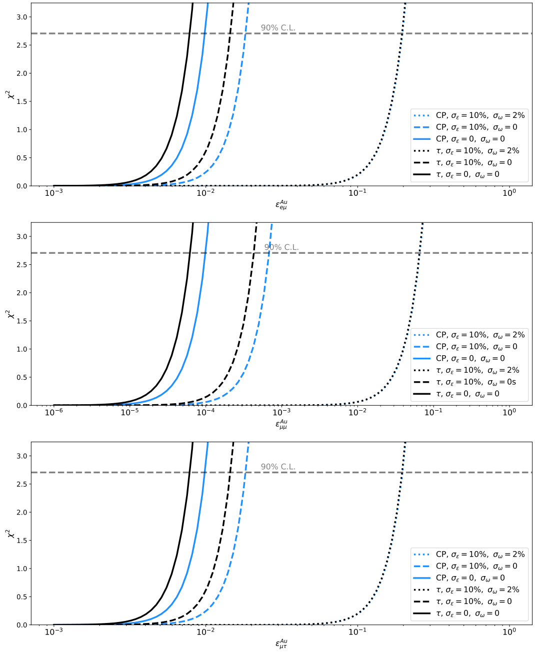


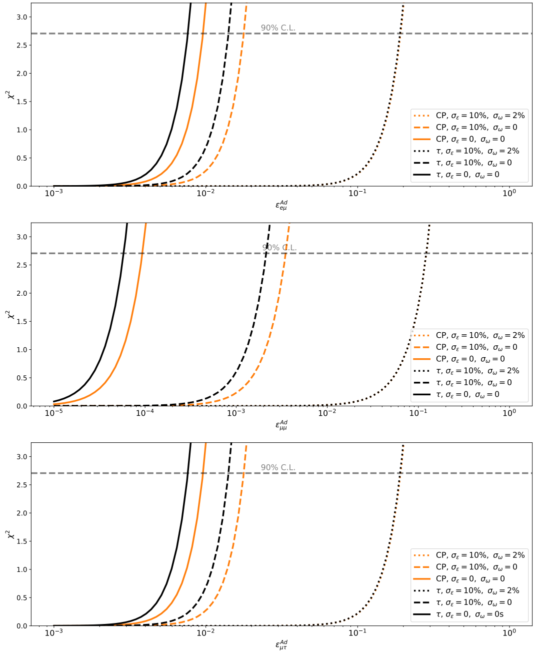
χ^2 versus $\epsilon^{Au} = \epsilon^{Ad}$ for 6.5+6.5 years of data taking at FD.



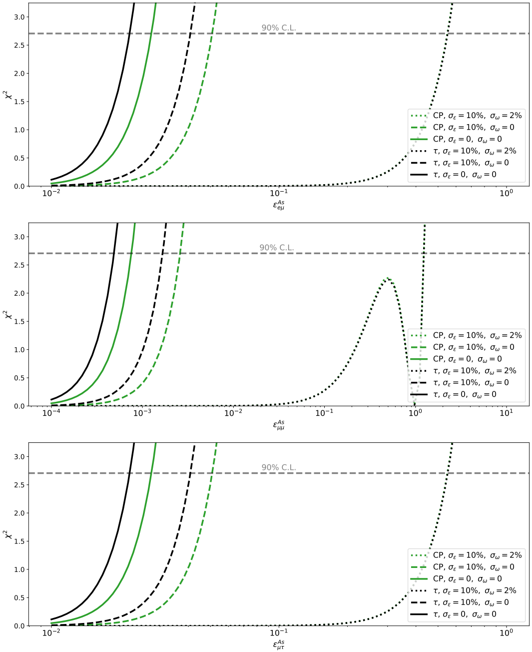
χ^2 versus $r = \epsilon^{Au}_{\tau\tau}/\epsilon^{Ad}_{\tau\tau}$. The difference $\epsilon^{Au}_{\tau\tau} - \epsilon^{Ad}_{\tau\tau}$ is fixed to -1.5 as indicated by the SNO solutions.



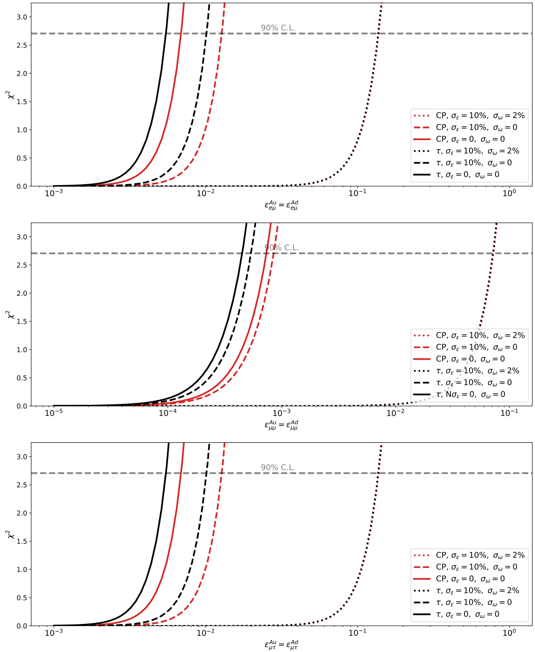
χ^2 versus ϵ^{Au} for 6.5+6.5 years of data taking at ND.



χ^2 versus ϵ^{Ad} for 6.5+6.5 years of data taking at ND.



χ^2 versus ϵ^{As} for 6.5+6.5 years of data taking at FD.



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- We improved the existing bounds obtained from high-energy experiments such as **CHARM** and **FASER**ν.

Beyond the Current Scope: Future Investigations and Goals

- Following the previous study, we have proposed a model that gives rise to axial NSI with large couplings leading to observable deviation from the standard prediction at DUNE. Our new model is based on a U(1) gauge symmetry with a gauge boson of mass $\sim$ 30 GeV, arXiv:2407.13834v1 [hep-ph] .

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- We want to study the NSI through the Resonance neutrino interaction.
- We will also study the NC NSI in other Long Base Line (**LBL**) neutrino experiments like **T2HK**, and **ESSνSB**.

Thanks For Attention

Neutrino Nucleon Scattering

- Charged Current Quasi Elastic Scattering

$$\left.\begin{array}{lcl} \nu_l(k) + n(p) & \longrightarrow & l^-(k') + p(p'), \\ \bar{\nu}_l(k) + p(p) & \longrightarrow & l^+(k') + n(p'), \end{array}\right\} \quad \text{(CC QE)} \qquad (2)$$

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$$\nu_l/\bar{\nu}_l(k) + N(p) \longrightarrow l^-/l^+(k') + N(p') + m\pi(p_\pi) \ \ (\text{CC} \ \ \text{resonance}) \tag{4}$$

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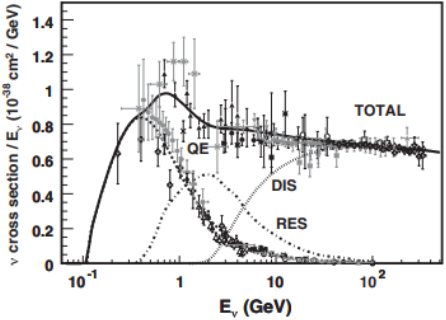
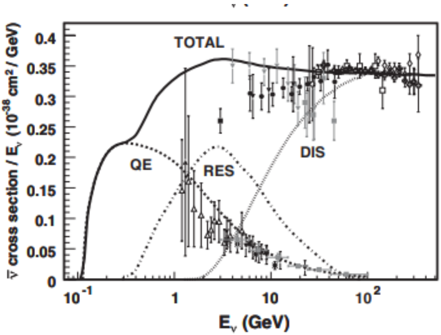
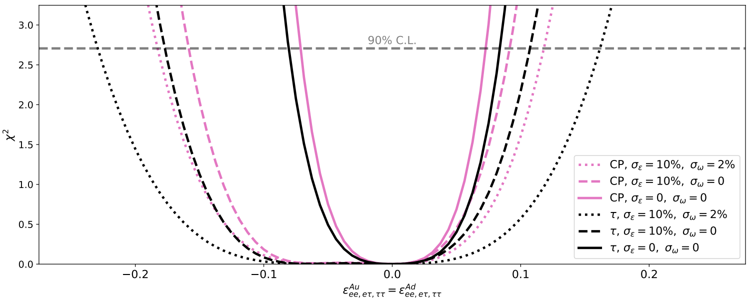
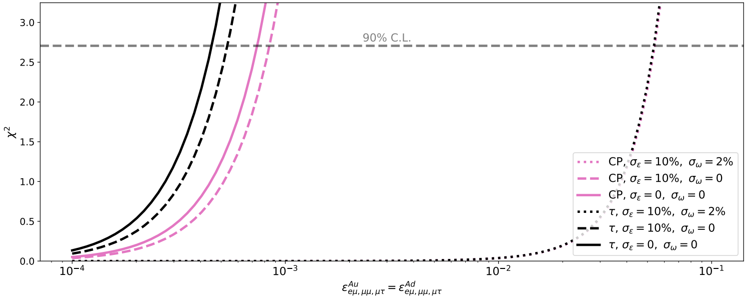
Neutrino (antineutrino)cross section







χ^2 versus $\epsilon^{Au}_{ee,e\tau,\tau\tau} = \epsilon^{Ad}_{ee,e\tau,\tau\tau}$ for 6.5+6.5 years of data taking at FD.



χ^2 versus $\epsilon^{Au}_{e\mu,\mu\mu,\mu\tau} = \epsilon^{Ad}_{e\mu,\mu\mu,\mu\tau}$ for 6.5+6.5 years of data taking at ND.