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

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

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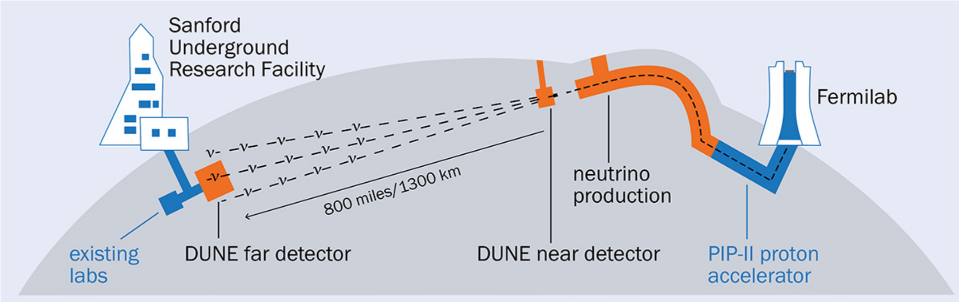
Introduction

- Neutrino Non Standard Interaction (NSI)



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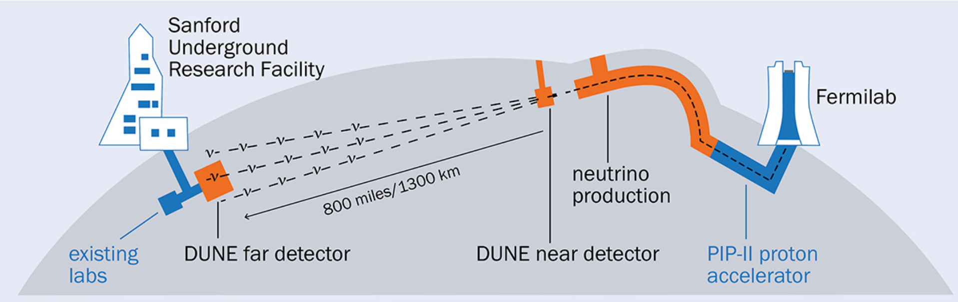
- Deep Underground Neutrino Experiment (DUNE)



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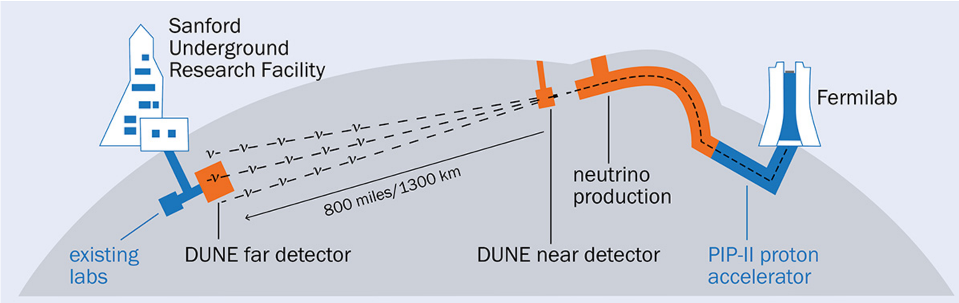
- Deep Underground Neutrino Experiment (DUNE)
- Standard and Non-Standard Neutral Current neutrino Interaction



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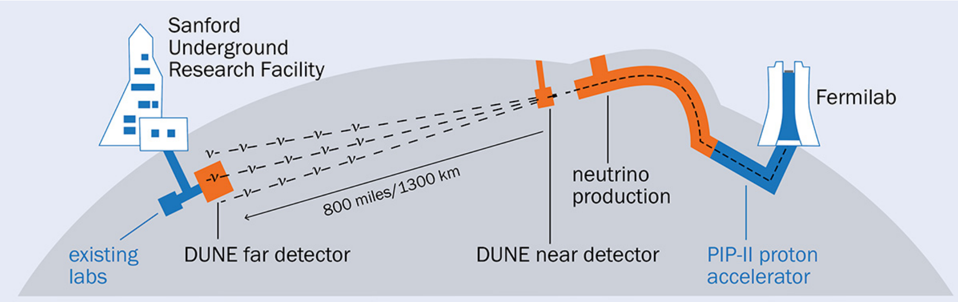

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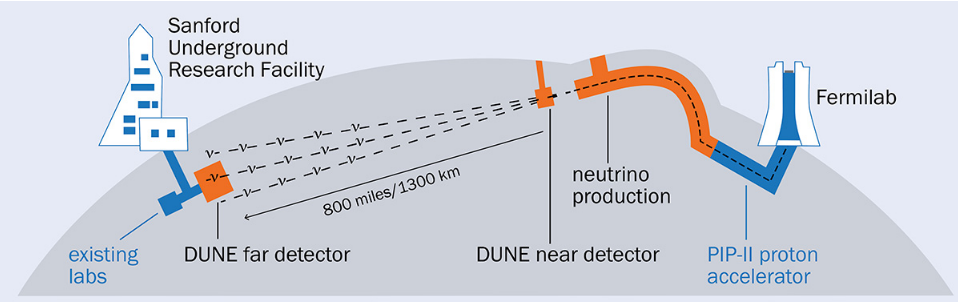
- Deep Inelastic Scattering (DIS) in the presence of NSI
- Results



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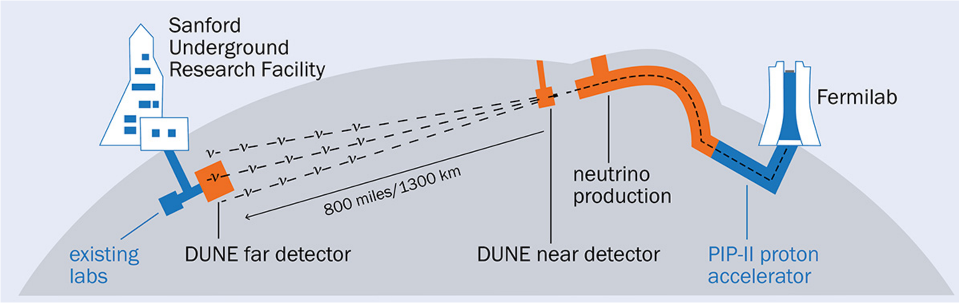
- Deep Inelastic Scattering (DIS) in the presence of NSI
- Results
- Future Plan



Neutrino Non-Standard Interaction

- Charged Curent NSI

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

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- Neutral Current NSI

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

Neutrino Non-Standard Interaction

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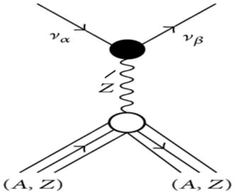

Axial NSI

- NuTeV neutrino nucleus scattering experiment $\rightarrow \epsilon^{Au}_{\mu\alpha}$, $\epsilon^{Ad}_{\mu\alpha}$

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

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- CHARM Experiment $\rightarrow \epsilon^{Au}_{e\alpha}, \epsilon^{Ad}_{e\alpha}$

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

Axial NSI

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

- SNO experiment $\rightarrow \epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}$

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

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

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

Axial NSI

- NuTeV neutrino nucleus scattering experiment $\to \epsilon^{Au}_{\mu\alpha}, \epsilon^{Ad}_{\mu\alpha}$

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

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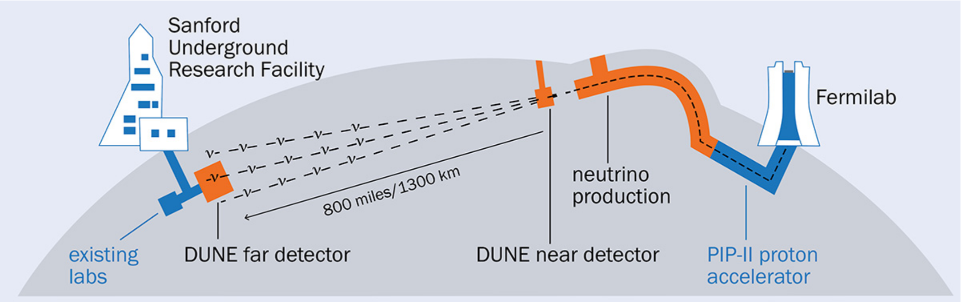
$\epsilon^{Aq}_{\tau\tau}$?

$\epsilon^{As}_{\alpha\beta}$?

Deep Underground Neutrino Experiment (DUNE)

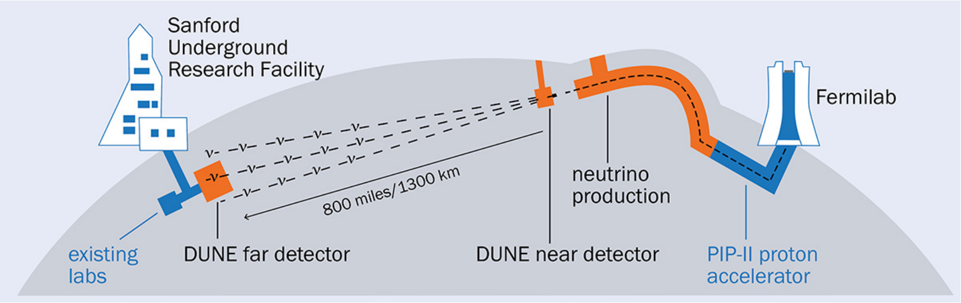
- DUNE is a long-baseline next-generation on-axis experiment situated in Fermilab
- Neutrno beam consists mostly of muon neutrinos of energy around 2.5 GeV
- The experiment consists of a Near Detector (ND) system located a few hundred meters from the neutrino source at Fermilab and a Far Detector (FD) system composed of 40 kt 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}, $\epsilon^{Aq}_{e\tau}$, $\epsilon^{Aq}_{\tau\tau}$



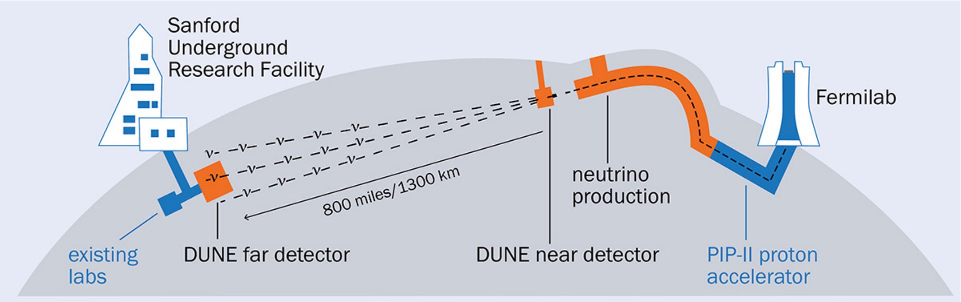
Neutrinos flux at ND and FD of DUNE

- 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 included three neutrino flavor

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



Standard and Non-Standard Neutral Current neutrino Interaction

- $$\mathcal{L}_{\text{SM}}^{\text{NC}} = -\frac{G_{\text{F}}}{\sqrt{2}} \sum_{\alpha,\beta,f} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma_5) \nu_\beta\right] \left[\bar{f} \gamma_\mu \left(g^{V,f} + g^{A,f}\gamma_5\right) f\right]$$

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- $$\mathcal{L}_{\rm NSI}^{\rm NC} = -\sum_{\alpha,\beta,f} \frac{G_{\rm F}}{\sqrt{2}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma_5)\nu_\beta\right] \left[\bar{f}\gamma_\mu \left(\epsilon^{Vf}_{\alpha\beta} + \epsilon^{Af}_{\alpha\beta}\gamma_5\right) f\right] \quad \text{where} \quad f \in \{e,u,d,s\}$$

Standard and Non-Standard Neutral Current neutrino Interaction

- $$\mathcal{L}_{\text{SM}}^{\text{NC}} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta,f} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma_5) \nu_\beta\right] \left[\bar{f} \gamma_\mu \left(g^{V,f} + g^{A,f} \gamma_5\right) f\right]$$

- $$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -\sum_{\alpha,\beta,f} \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma_5) \nu_\beta\right] \left[\bar{f} \gamma_\mu \left(\epsilon_{\alpha\beta}^{Vf} + \epsilon_{\alpha\beta}^{Af} \gamma_5\right) f\right] \quad \text{where} \quad f \in \{e, u, d, s\}$$

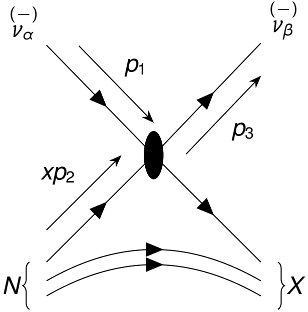
	Up type quarks (u, c, t)	Down type quarks (d, s, b)	Charged leptons (e, μ, τ)	Neutral leptons $(\nu_e, \nu_\mu, \nu_\tau)$
g^L	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	$-\frac{1}{2} + \sin^2\theta_W$	$\frac{1}{2}$
g^R	$-\frac{2}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$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

Deep Inelastic Scattering (DIS) in the presence of NS

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

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

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



Neutrino nucleon DIS cross section

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

$$\frac{d^2\sigma_{\rm NC}(\overset{(-)}{\nu_\alpha} N \to \overset{(-)}{\nu_\beta} + X)}{dxdy} = \frac{G_{\rm F}^2}{\pi}(M_N E_\nu)\Bigg\{\frac{1}{2}\left(xy^2 + 2x - 2xy - \frac{M_N}{E_\nu}x^2 y\right)$$

$$\times \left[\sum_q f_N^q(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right) + \sum_{\bar q} f_N^{\bar q}(x)\left(\left|f_{\alpha\beta}^{Vq}\right|^2 + \left|f_{\alpha\beta}^{Aq}\right|^2\right)\right]$$

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

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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

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

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

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

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

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

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.

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

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

$$\sum_\alpha |\mathcal{A}_\alpha|^2 = 1 \quad \text{and} \quad \sum_\alpha |\overline{\mathcal{A}}_\alpha|^2 = 1.$$

Neutrinos oscillate on their way to the FD

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

and

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

$$\sum_\alpha |\mathcal{A}_\alpha|^2 = 1 \quad \text{and} \quad \sum_\alpha |\bar{\mathcal{A}}_\alpha|^2 = 1.$$

Thus,

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

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

Neutrinos oscillate on their way to the FD

$$\langle \nu_\perp | \nu_{\rm far} \rangle = \langle \nu_\perp | \nu_T \rangle = \langle \nu_T | \nu_{\rm far} \rangle = 0.$$

Without loss of generality, we can choose

$$\begin{bmatrix} \nu_{\rm far} \\ \nu_\perp \\ \nu_T \end{bmatrix} = \begin{bmatrix} \mathcal{A}_e & \mathcal{A}_\mu & \mathcal{A}_\tau \\ 0 & -\mathcal{A}_\tau^*/\mathcal{A} & \mathcal{A}_\mu^*/\mathcal{A} \\ \frac{\mathcal{A}\mathcal{A}_e}{|\mathcal{A}_e|} & -\frac{\mathcal{A}_\mu |\mathcal{A}_e|}{\mathcal{A}} & -\frac{\mathcal{A}_\tau |\mathcal{A}_e|}{\mathcal{A}} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \cdot \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}, \tag{1}$$

where $\mathcal{A} = \sqrt{|\mathcal{A}_\tau|^2 + |\mathcal{A}_\mu|^2}$. Similarly, we can define the basis $(\bar{\nu}_{\rm far}, \bar{\nu}_\perp, \bar{\nu}_T)$ replacing $U \to \overline{U}$ in which $\mathcal{A}_\alpha \to \overline{\mathcal{A}}_\alpha$. In the new basis, we can write the couplings as

$$f_{\alpha\beta}^{Vq} \to \tilde{f}_{\alpha\beta}^{Vq} = (U \cdot f^{Vq} \cdot U^\dagger)_{\alpha\beta} = f_{\alpha\beta}^{Vq} \quad \text{and} \quad f_{\alpha\beta}^{Aq} \to \tilde{f}_{\alpha\beta}^{Aq} = (U \cdot f^{Aq} \cdot U^\dagger)_{\alpha\beta} \neq f_{\alpha\beta}^{Aq}.$$

$$(\sigma_{n/p})_{\nu_{\rm far}} = \sum_{\alpha \in \{{\rm far}, \perp, T\}} \sigma_{n/p}(\nu_{\rm far} + N \to \nu_\alpha + X),$$

in the neutrino mode and

$$(\sigma_{n/p})_{\bar{\nu}_{\rm far}} = \sum_{\alpha \in \{{\rm far}, \perp, T\}} \sigma_{n/p}(\bar{\nu}_{\rm far} + N \to \bar{\nu}_\alpha + X),$$

in the antineutrino mode.

NC NSI events at near and far detectors

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

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

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

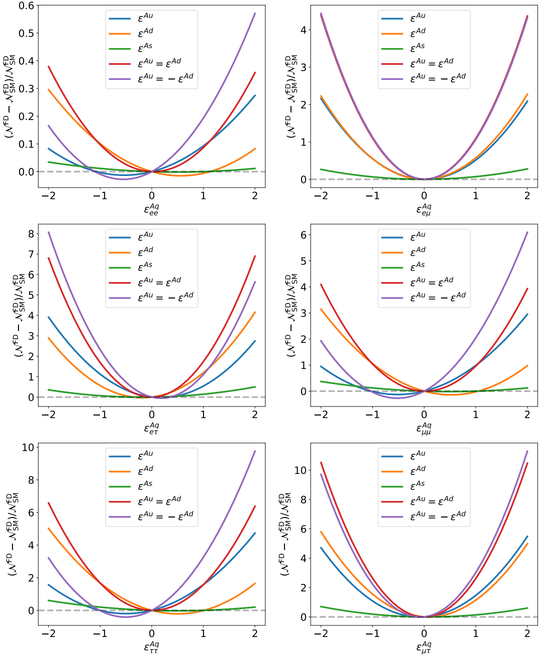
$$\mathcal{N}_{\bar\nu}^{\rm FD} = \int \varphi_{\bar\nu}^{\rm FD}(E) \left[(\sigma_n)_{\bar\nu_{\rm far}} N_n^{\rm FD} + (\sigma_p)_{\bar\nu_{\rm far}} N_p^{\rm FD}\right] dE,$$

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.

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

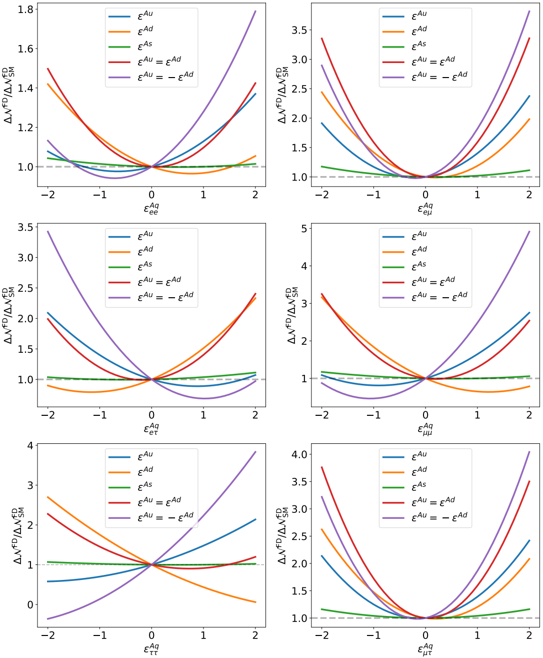
$$\mathcal{N}^{\rm ND}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm ND} + \mathcal{N}_{\bar\nu}^{\rm ND} \quad \text{and} \quad \Delta\mathcal{N}^{\rm ND}(\epsilon_{\alpha\beta}^{Aq}) \equiv \mathcal{N}_{\nu}^{\rm ND} - \mathcal{N}_{\bar\nu}^{\rm ND},$$

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



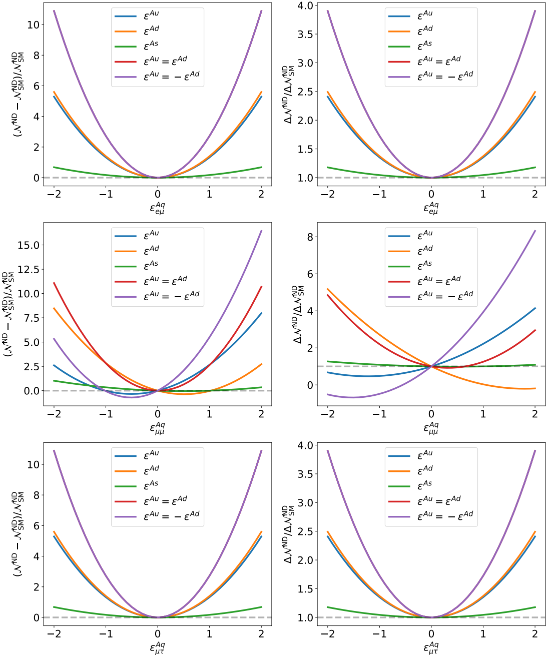
Deviation of the total number of NC DIS neutrino plus antineutrino events from the SM prediction at the far detector versus the NSI parameters,

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



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,

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



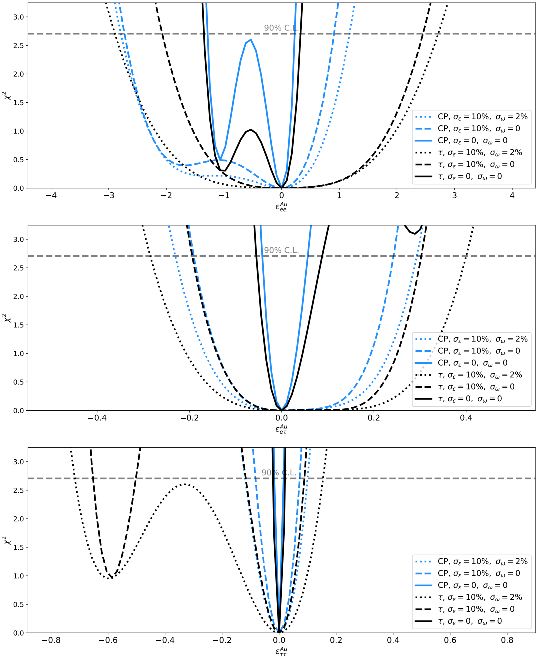
- Right column: Deviation of the total number of NC DIS neutrino plus antineutrino events from the SM prediction at the ND detector versus the NSI parameters,
$$\frac{\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}) - \mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}{\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}.$$
- 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,
$$\frac{\Delta\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta})}{\Delta\mathcal{N}^{\rm ND}(\epsilon^{Aq}_{\alpha\beta}=0)}.$$

THE BOUNDS ON AXIAL NSI

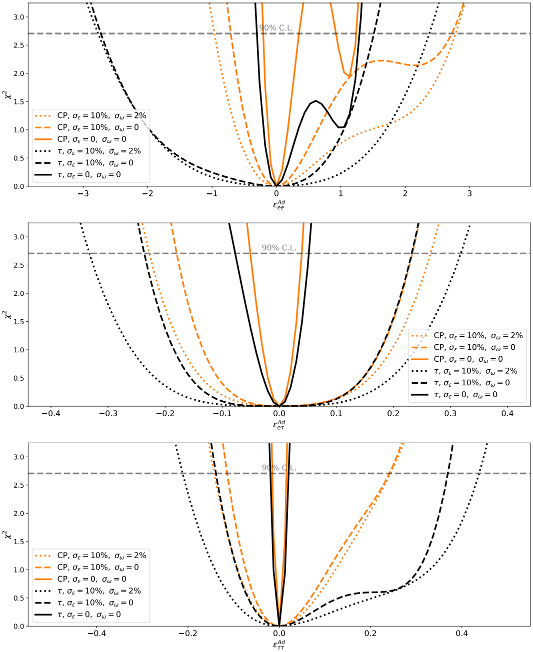
$$\mathcal{B}^{\mathrm{ND/FD}}_{\nu/\bar{\nu}} = \epsilon_{\mathrm{CC}}(\mathcal{N}^{\mathrm{ND/FD}}_{\mathrm{CC}})_{\nu/\bar{\nu}} + \epsilon_{\mathrm{Res}}(\mathcal{N}^{\mathrm{ND/FD}}_{\mathrm{Res}})_{\nu/\bar{\nu}},$$

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

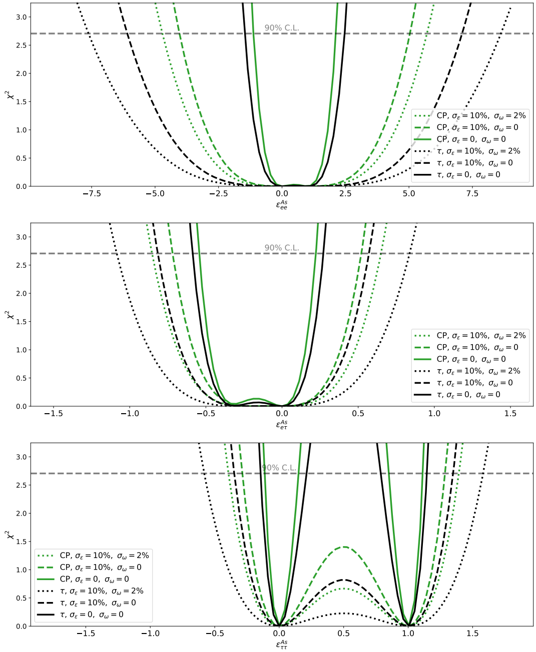
Where $\epsilon = 90\%$ is the efficiency of detecting the signal.



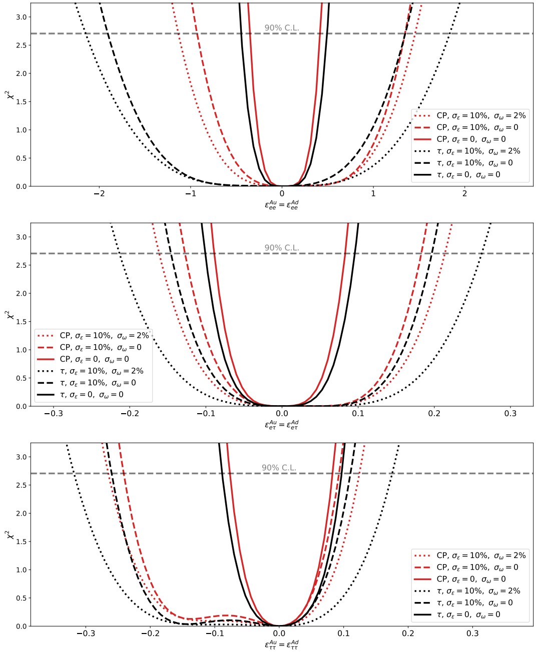
χ^2 versus ϵ^{Au} for 6.5+6.5 years of data taking at FD.



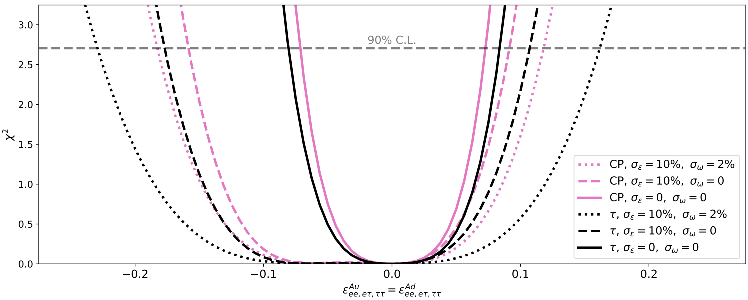
χ^2 versus ϵ^{Ad} for 6.5+6.5 years of data taking at FD.



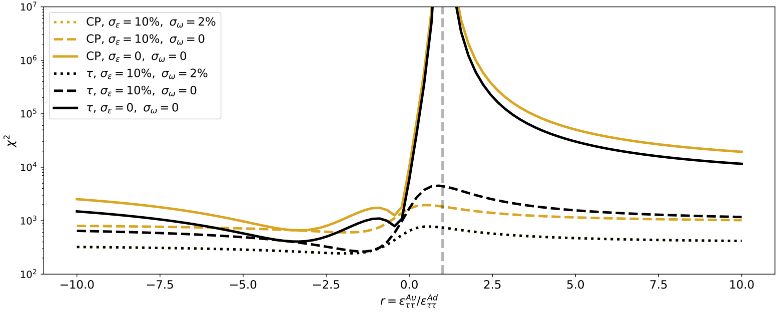
χ^2 versus ϵ^{As} for 6.5+6.5 years of data taking at FD.



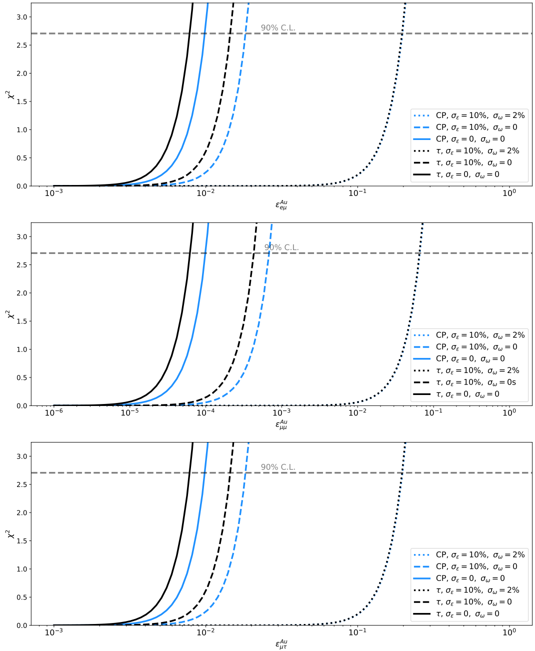
χ^2 versus $\epsilon^{Au} = \epsilon^{Ad}$ for 6.5+6.5 years of data taking at FD.



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



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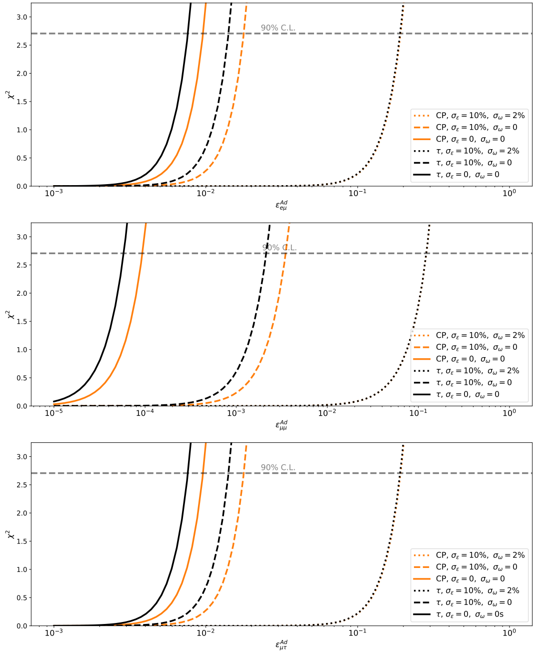

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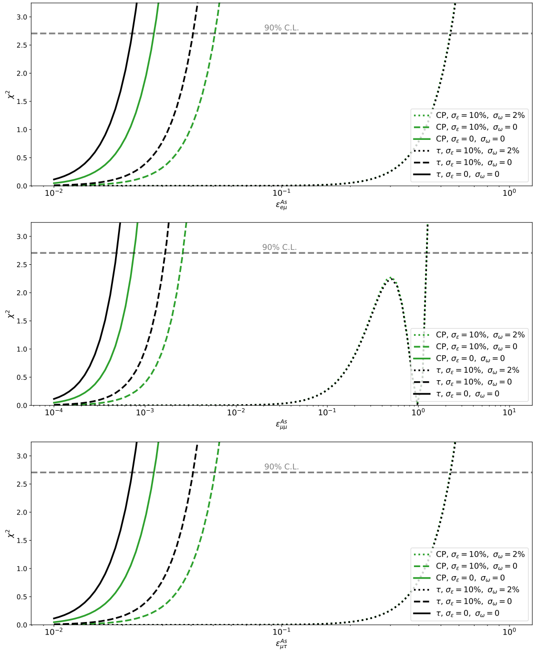

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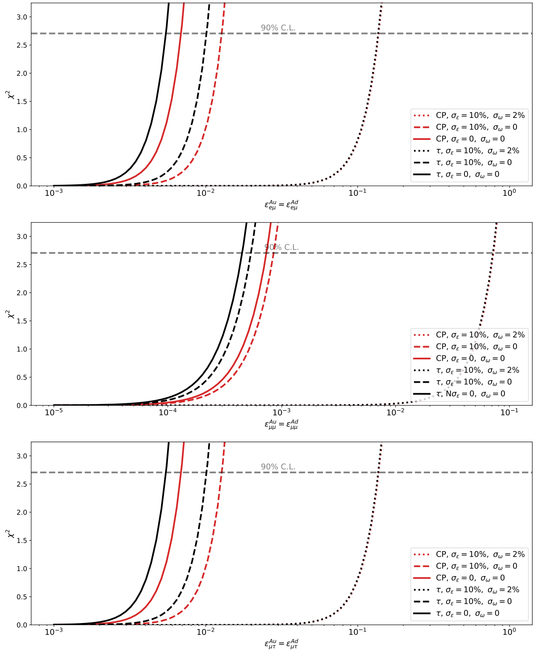

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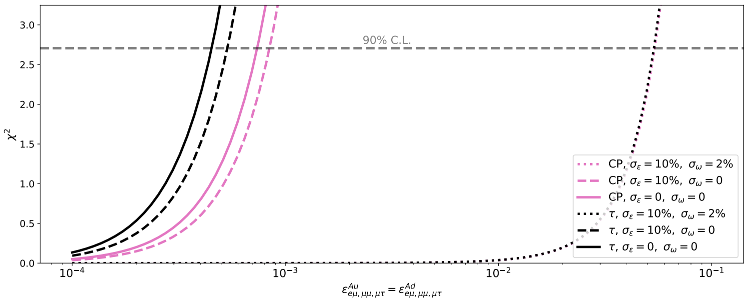

χ^2 versus $\epsilon^{Au}_{e\mu,\mu\mu,\mu\tau} = \epsilon^{Ad}_{e\mu,\mu\mu,\mu\tau}$ for 6.5+6.5 years of data taking at ND.

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- We improved the **CHARM** and **FASER**ν bounds on **NSI** parameter.

Future Plans

- Considering the energy spectrum of neutrinos in **DUNE-like** experiments, which is in the range of $1 - 10$ GeV, the effect of neutrino-nucleon resonance interaction also becomes important in the energy range of $1 - 2GV$. In the following, we will consider the neutrino resonance interaction.

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- We will utilize the chi-squared test for binned data in energy spectra to evaluate the model's goodness of fit to experimental data.

Future Plans

- 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

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

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Neutrino (antineutrino)cross section