SEARCHING FOR AXIAL NEUTRAL CURRENT NON-STANDARD INTERACTIONS OF NEUTRINOS BY DUNE-LIKE EXPERIMENTS

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AsYmmetry
Essential Asymmetries of Nature

Outline of my talk

- Part 1: Introduction and present bound
- Part 2: Search for axial NSI by DUNE
- Part 3: Bounds from MINOS and MINOS+

Neutral current
Non-Standard Interaction (NSI)

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

Neutrino propagation in matter: Oscillation pattern

Coherent Elastic neutrino Nucleus Scattering $CE\nu NS$

Neutral current
Non-Standard Interaction (NSI)

$$\frac{G_{\mathrm{F}}}{\sqrt{2}}\left[\overline{\nu}_{\alpha}\gamma^{\mu}\left(1-\gamma_{5}\right)\nu_{\beta}\right]\left[\overline{f}\gamma_{\mu}\left(\epsilon_{\alpha\beta}^{Vf}+\epsilon_{\alpha\beta}^{Af}\gamma_{5}\right)f\right] \quad \text{where} \quad f\in\{e,u,d,s\},$$

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High energy scattering experiments such as CHARM and NuTeV

Bounds from scattering experiments

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

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

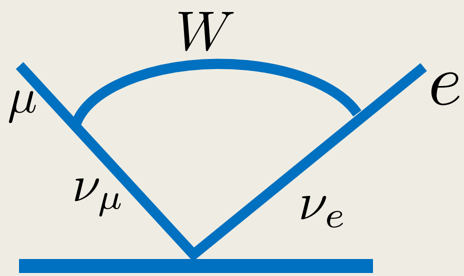
S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria,
JHEP 03, 011 (2003), arXiv:hep-ph/0302093.

Bounds from scattering experiments

$$\text{From NuTeV}: \quad |\epsilon_{\mu\mu}^{Au}| < 0.006, \quad |\epsilon_{\mu\mu}^{Ad}| < 0.018, \quad |\epsilon_{\mu\tau}^{Au}|, |\epsilon_{\mu\tau}^{Ad}| < 0.01,$$

$$\text{From CHARM}: \quad |\epsilon_{ee}^{Au}| < 1, \quad |\epsilon_{ee}^{Ad}| < 0.9, \quad |\epsilon_{e\tau}^{Au}|, |\epsilon_{e\tau}^{Ad}| < 0.5.$$

Heavy mediator

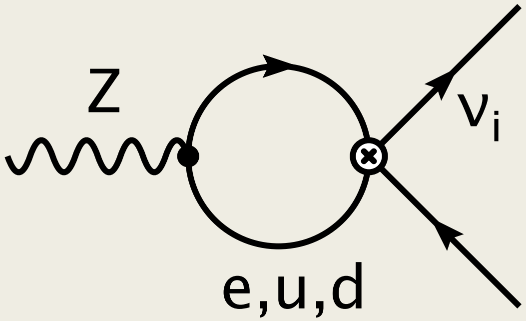


$$R_{\mu e} \equiv \frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to \text{capture})} < 4.3 \times 10^{-12} \,,$$

S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria,
JHEP 03, 011 (2003), arXiv:hep-ph/0302093.

$$|\epsilon^{qR}_{e\mu}|, |\epsilon^{qL}_{e\mu}| < 7.7 \times 10^{-4} \,, \qquad q \in \{u, d\}.$$

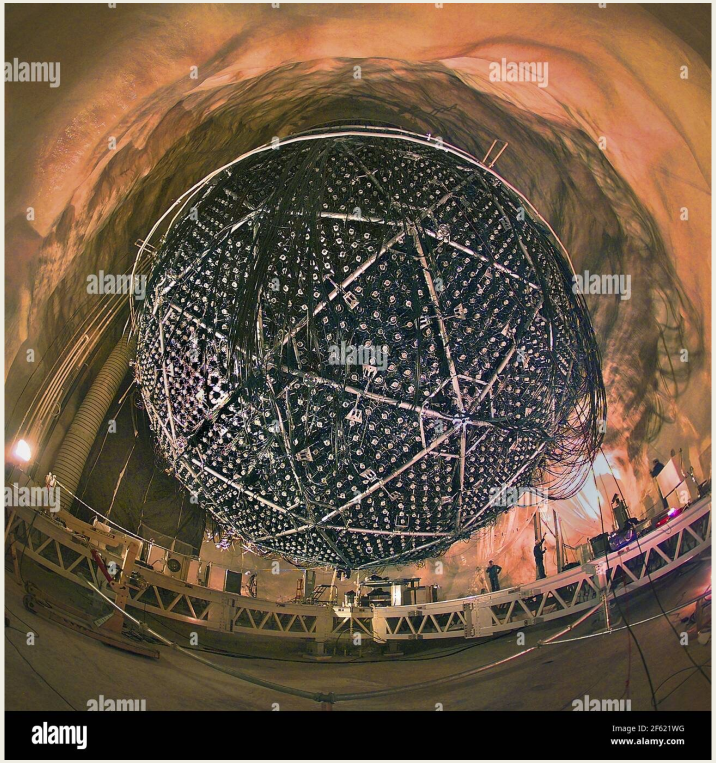
Invisible decay mode of Z bosons

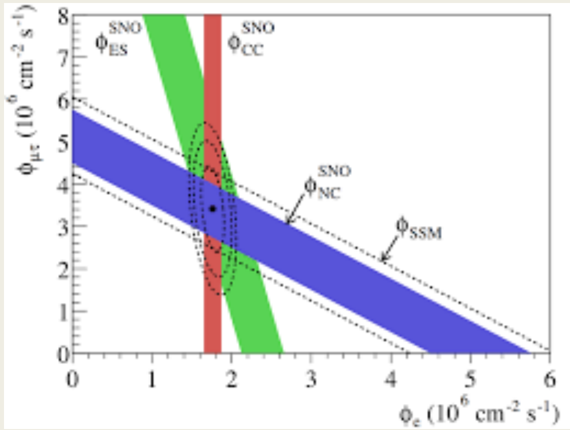


S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria,
JHEP 03, 011 (2003), arXiv:hep-ph/0302093.

$$|\epsilon_{\tau\tau}^{qA}| < \mathcal{O}(1)\ , \qquad q \in \{u, d\}.$$

New solution found in SNO data





2019-2006

D_2O

$$\mathrm{D} + \nu \rightarrow n + p + \nu$$

Deuterium dissociation

$$\frac{G_F}{\sqrt{2}} \left[\overline{\nu}_\alpha \gamma^\mu \left(1-\gamma_5\right) \nu_\beta\right] \left[\overline{f} \gamma_\mu \left(\epsilon^{Vf}_{\alpha\beta} + \epsilon^{Af}_{\alpha\beta}\gamma_5\right) f\right]$$

$$\frac{G_F}{\sqrt{2}} \left[\overline{\nu}_\alpha \gamma^\mu \left(1-\gamma_5\right) \nu_\beta\right] \left(\epsilon^{An}_{\alpha\beta}\, \overline{n}\gamma^\mu\gamma_5 n + \epsilon^{Ap}_{\alpha\beta}\, \overline{p}\gamma^\mu\gamma_5 p\right),$$

$$\epsilon^{Ap}_{\alpha\beta} = \Delta_u \epsilon^{Au}_{\alpha\beta} + \Delta_d \epsilon^{Ad}_{\alpha\beta},$$

$$\epsilon^{An}_{\alpha\beta} = \Delta_u \epsilon^{Ad}_{\alpha\beta} + \Delta_d \epsilon^{Au}_{\alpha\beta}.$$

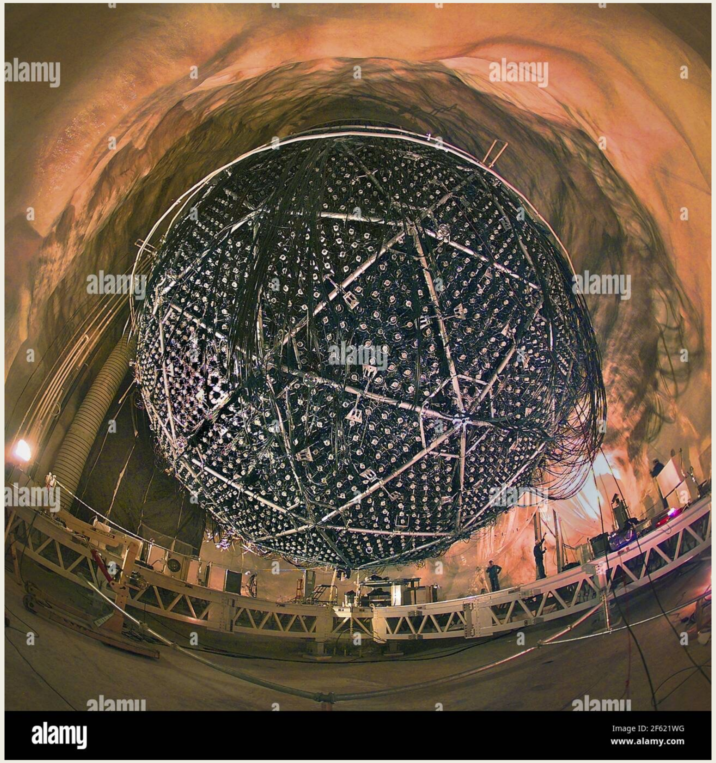
$$\Delta_d = -0.43$$

$$\Delta_u = 0.84$$

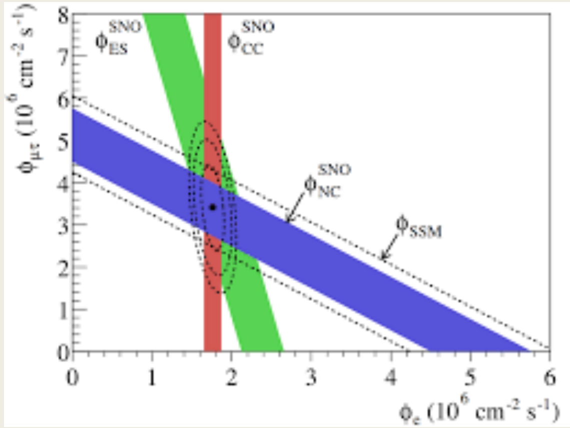
M. Cirelli, E. Del Nobile, and P. Panci, JCAP 10, 019 (2013),

$$\epsilon^{An}_{\alpha\beta} - \epsilon^{Ap}_{\alpha\beta} = \left(\Delta_u - \Delta_d\right)\left(\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}\right) = 1.27\left(\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}\right).$$

New solution found in SNO data



$$-2.1 < \epsilon_{\tau\tau}^{Au} - \epsilon_{\tau\tau}^{Ad} < -1.8$$



P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni,
J. a. P. Pinheiro, and S. Urrea, JHEP 08, 032 (2023)

	Allowed ranges at 90% CL (1-parameter)	
	GLOB-OSC	
$\varepsilon_{ee}^{u,A}$	$[-2.1, -1.8] \oplus [-0.19, +0.13]$	$-\varepsilon_{ee}^{d,A}$
$\varepsilon_{\mu\mu}^{u,A}$	$[-2.2, -1.7] \oplus [-0.26, +0.18]$	$-\varepsilon_{\mu\mu}^{d,A}$
$\varepsilon_{\tau\tau}^{u,A}$	$[-2.1, -1.8] \oplus [-0.20, +0.15]$	$-\varepsilon_{\tau\tau}^{d,A}$
$\varepsilon_{e\mu}^{u,A}$	$[-1.5, -1.2] \oplus [-0.16, +0.12] \oplus [+1.4, +1.7]$	$-\varepsilon_{e\mu}^{d,A}$
$\varepsilon_{e\tau}^{u,A}$	$[-1.5, -1.3] \oplus [-0.13, +0.10] \oplus [+1.4, +1.7]$	$-\varepsilon_{e\tau}^{d,A}$
$\varepsilon_{\mu\tau}^{u,A}$	$[-0.085, +0.11] \oplus [+1.6, +1.9]$	$-\varepsilon_{\mu\tau}^{d,A}$

P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni,
J. a. P. Pinheiro, and S. Urrea, JHEP 08, 032 (2023)

A model for Axial NSI

- S. Abbaslu and Y. F.,
- "A model for Axial Non-Standard Interactions of neutrinos with quarks,''
- arXiv:2407.13834
- *Nucl.Phys.B* 1018 (2025) 117070

Model building

New U(1) gauge symmetry

$$Q_1 = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \to \exp^{i\alpha} Q_1 \ , \quad Q_2 = \begin{pmatrix} c_L \\ s_L \end{pmatrix} \to \exp^{i\alpha} Q_2 \ , \quad \text{and} \quad Q_3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \to \exp^{i\alpha} Q_3 \ .$$

$$u_R \to \exp^{-i\alpha} u_R \quad \text{and} \quad d_R \to \exp^{-i\alpha} d_R \ .$$

Axial coupling to first generation quarks

$$g_Z Z'_\mu(\bar{u}\gamma^\mu \frac{1-\gamma_5}{2} u + \bar{d}\gamma^\mu \frac{1-\gamma_5}{2} d - \bar{u}\gamma^\mu \frac{1+\gamma_5}{2} u - \bar{d}\gamma^\mu \frac{1+\gamma_5}{2}) = -g_Z Z'_\mu(\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d) \ .$$

To cancel the $U(1)-SU(2)-SU(2)$ anomaly,

$$L_\tau = \begin{pmatrix} \nu_\tau \\ \tau_L \end{pmatrix} \to e^{-9i\alpha} L_\tau \quad \text{under } U(1)$$

$$\boxed{\epsilon_{\tau\tau}^{Au} = \epsilon_{\tau\tau}^{Ad} = \frac{9\sqrt{2} g_{Z'}^2}{m_{Z'}^2 G_F}.}$$

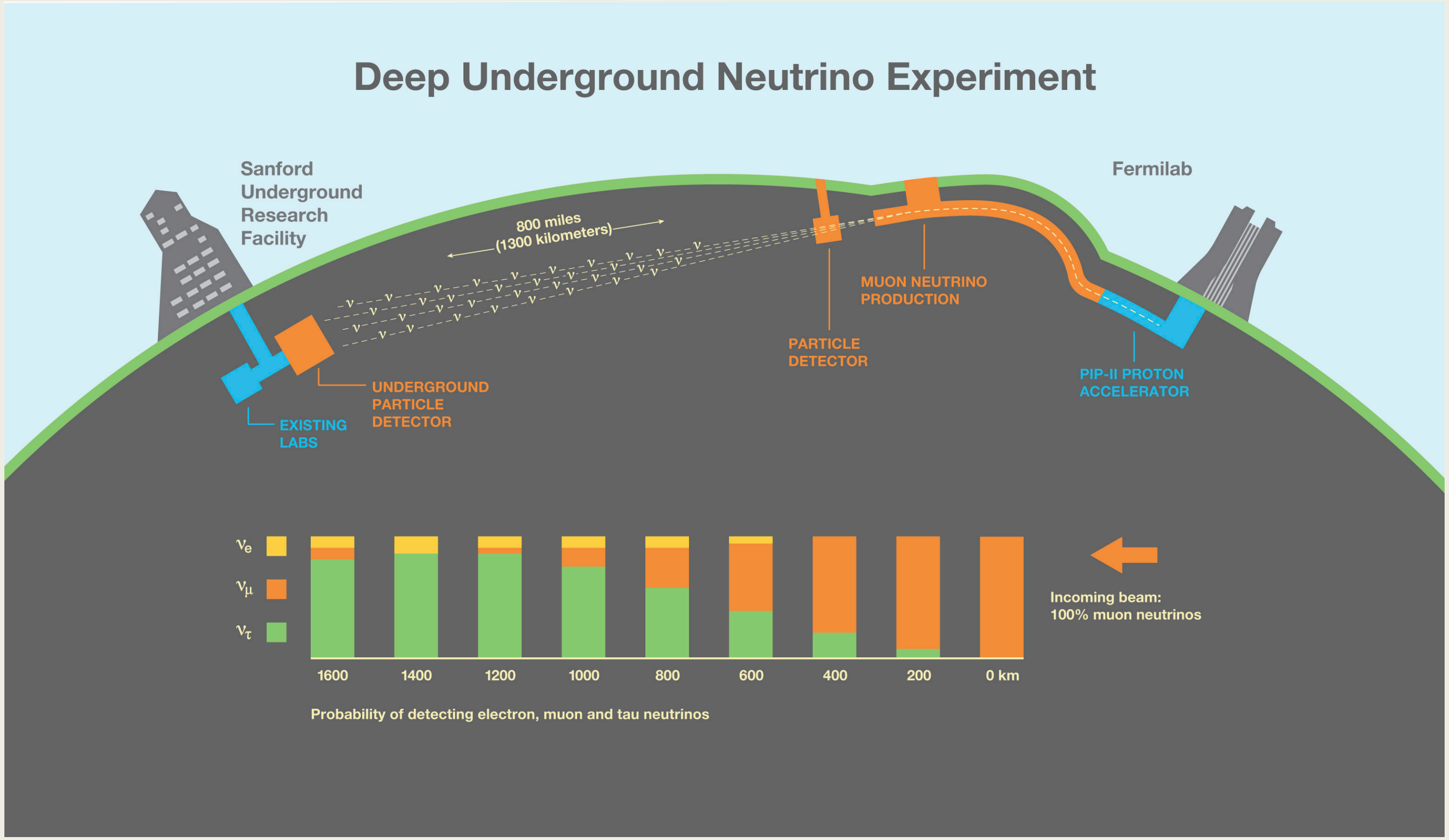
■Part Two

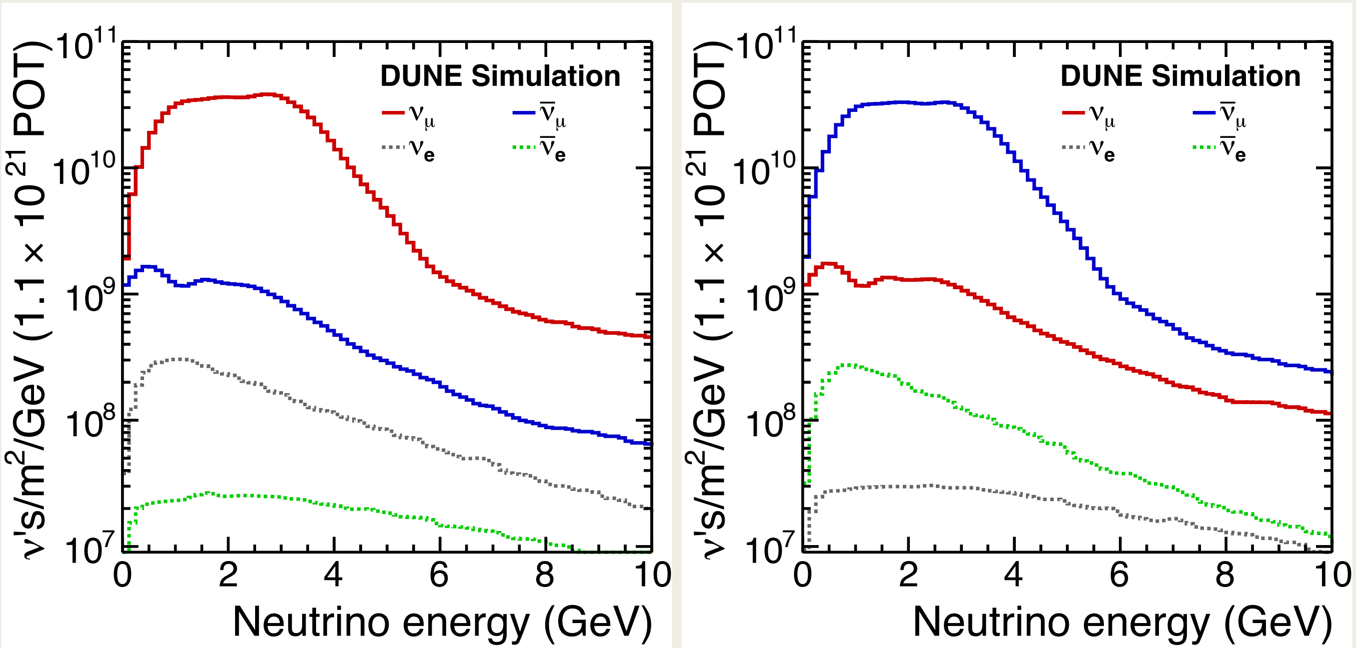
Based on

Searching for axial neutral current non-standard interactions of neutrinos by DUNE-like experiments

Saeed Abbaslu, Mehran Dehpour, YF., Sahar Safari

JHEP 04 (2024) 038


Deep Underground Neutrino Experiment
Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
MUON NEUTRINO PRODUCTION
PARTICLE DETECTOR
PIP-II PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
νe
νμ
ντ
1600
1400
1200
1000
800
600
400
200
0 km
Incoming beam: 100% muon neutrinos
Probability of detecting electron, muon and tau neutrinos



DUNE TDR, arXiv:2103.04797

Deep Inelastic Scattering (DIS) in the presence of NSI

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

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

$$\epsilon_{\alpha\beta}^{V/Aq} = \epsilon_{\alpha\beta}^{Lq} \pm \epsilon_{\alpha\beta}^{Rq} \text{ and } g_{\alpha\beta}^{V/Aq} = g^{Lq} \pm g^{Rq}.$$

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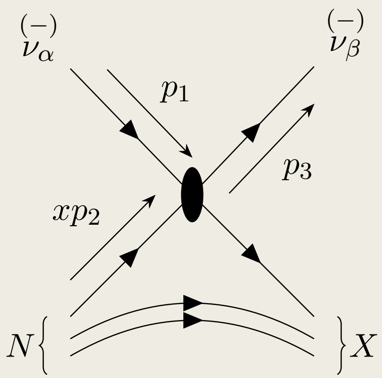
	Up type quarks (u, c, t)	Down type quarks (d, s, b)	Charged leptons (e, μ, τ)	Neutral leptons $(\nu_e, \nu_\mu, \nu_\tau)$
g^L	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\text{W}}$	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\text{W}}$	$-\frac{1}{2} + \sin^2\theta_{\text{W}}$	$\frac{1}{2}$
g^R	$-\frac{2}{3}\sin^2\theta_{\text{W}}$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

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

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



$$p_1^\mu = (p_1^0, \vec{p}_1), \text{ where } |\vec{p}_1| = p_1^0 = E_\nu,$$

$$p_3^\mu = (p_3^0, \vec{p}_3), \text{ where } |\vec{p}_3| = p_3^0 = E'_\nu,$$

$$p_2^\mu = (p_2^0, \vec{p}_2) = (M_N, 0, 0, 0).$$

$$q^\mu = (p_1 - p_3)^\mu$$

$$x = \frac{-q^2}{2p_2 \cdot q} = \frac{Q^2}{2M_N(E_\nu - E'_\nu)}, \qquad y = 1 - \frac{E'_\nu}{E_\nu},$$

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

$$\frac{d^2\sigma_{\rm NC}(\overset{(-)}{\nu}_\alpha\, N \to \overset{(-)}{\nu}_\beta + X)}{dxdy} = \sigma^0_{\rm NC}\Bigg\{\frac{1}{2}\left(xy^2 + 2x - 2xy - \frac{M_N}{E_\nu}x^2 y\right)$$

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

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

$$\sigma^0_{\rm NC} = \frac{G_{\rm F}^2}{\pi}\left(M_N E_\nu\right).$$

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

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

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

$$\sigma_p(\overset{(-)}{\nu}_\alpha + p \to \overset{(-)}{\nu}_\beta + X) \simeq \sigma^0_{\rm NC} \int_0^1 dx$$

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

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

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

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

- CT18 next-to-next to-leading order (CT18NNLO)

T.-J. Hou et al., Phys. Rev. D 103, 014013 (2021)

The CT18 PDF set is obtained by the CTEQ-TEA collaboration implementing a comprehensive range of high-precision Large Hadron Collider (LHC) data, plus the combined HERA I+II Deep Inelastic Scattering (DIS) data, along with the CT14 global QCD analysis.

Q=2 GeV

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

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

and

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

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

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

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

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

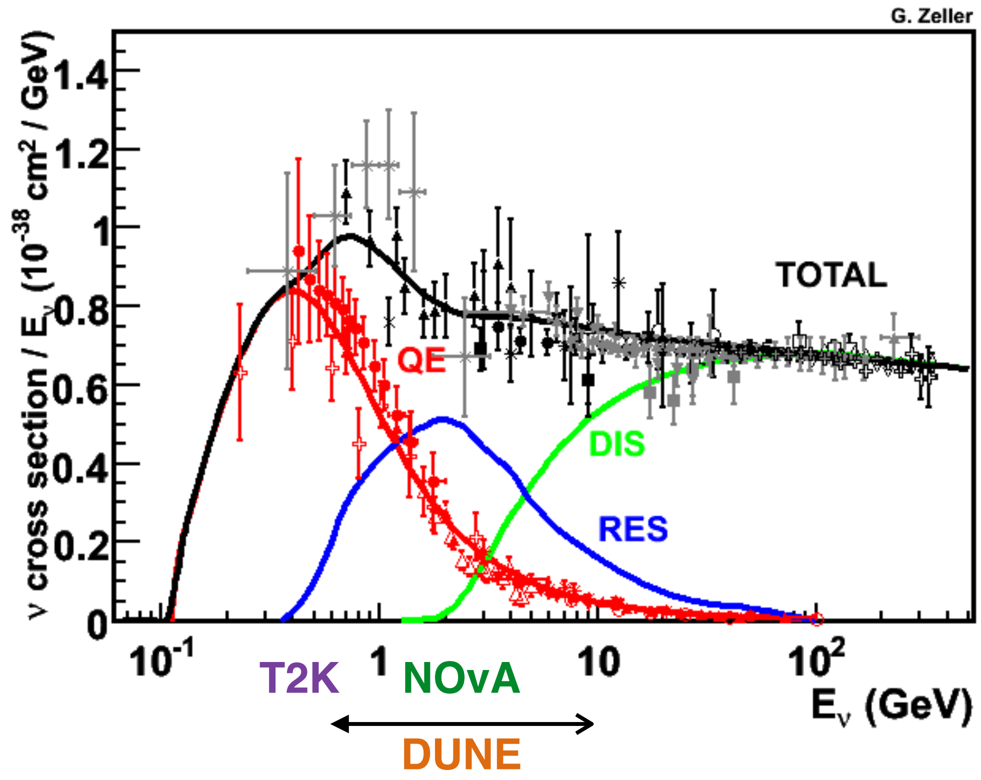
Change of basis

$$\alpha \in \{\text{far}, \perp, T\}$$

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

$$\mathcal{A} = \sqrt{|\mathcal{A}_\tau|^2 + |\mathcal{A}_\mu|^2}.$$

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



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

$$\text{DIS} : \nu + N \rightarrow \nu + X$$

$$\text{RES} : \nu + N \rightarrow \nu + \Delta \rightarrow \nu + N + \pi$$

$$\text{DIS}: \nu + N \rightarrow \nu + X$$

$$\text{RES}: \nu + N \rightarrow \nu + \Delta \rightarrow \nu + N + \pi$$

J. Tingey et al.
"Neutrino characterisation
using convolutional neural networks in CHIPS water Cherenkov detectors,"
JINST **18** (2023) no.06, P06032

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

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

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

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

6.5 years for running in each neutrino and antineutrino mode

1.1×10^{21} POT/year

https://glaucus.crc.nd.edu/DUNEFluxes/.

“CP-optimized”

“τ-optimized”

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

$M_{\rm fid}^{\rm ND} = 67.2$ ton and $M_{\rm fid}^{\rm FD} = 40$ kton

B. Abi, R. Acciarri, et al., arXiv:2103.04797 [hep-ex].

: LAr detector at the near site

Including the GAr detector and SAND would yield slightly more statistics and therefore better results.

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

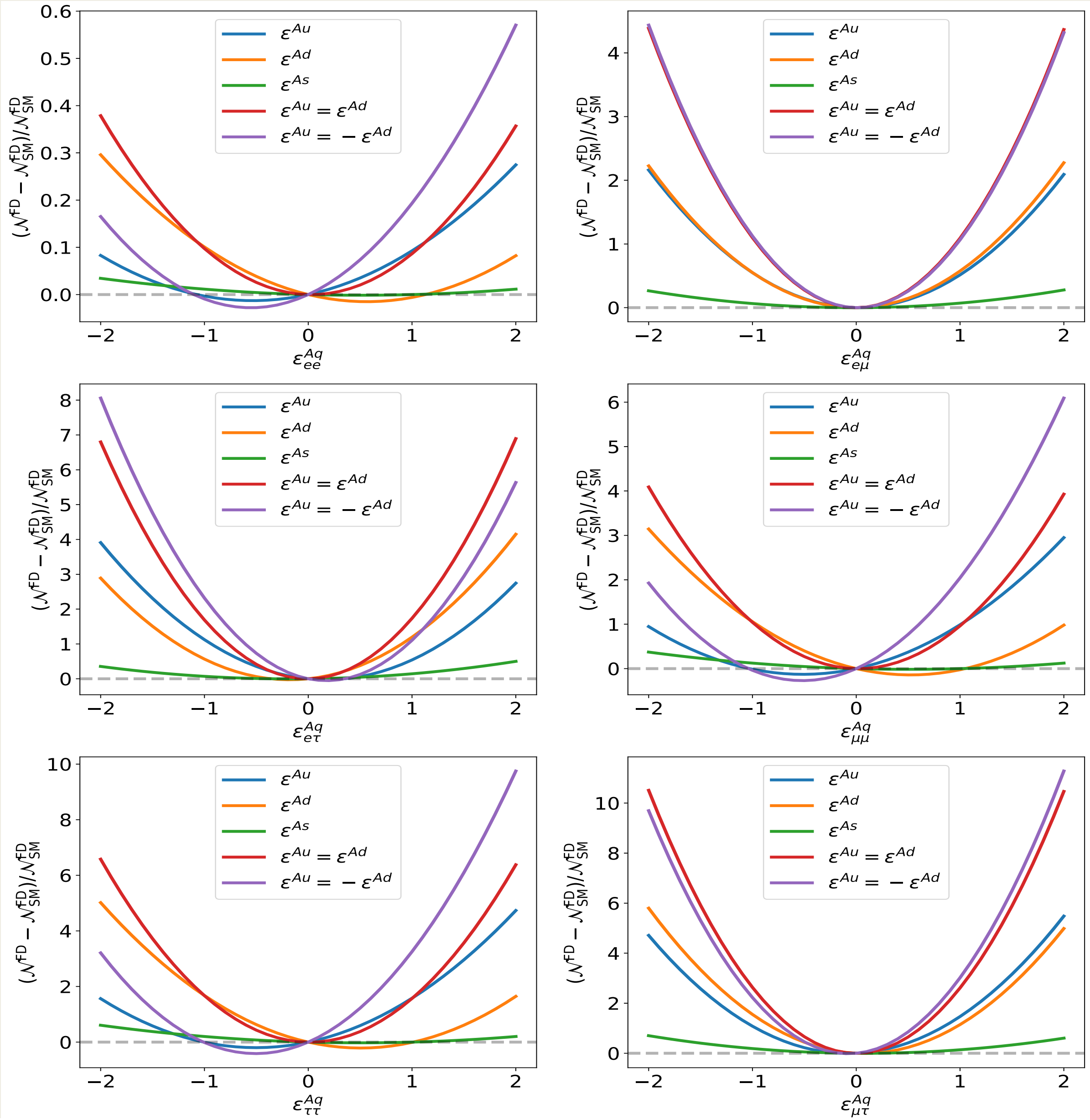
Total number of NC DIS events at ND and FD

6.5+6.5 years

$$\mathcal{N}^{\rm ND} \equiv \mathcal{N}_{\nu}^{\rm ND} + \mathcal{N}_{\overline{\nu}}^{\rm ND}$$

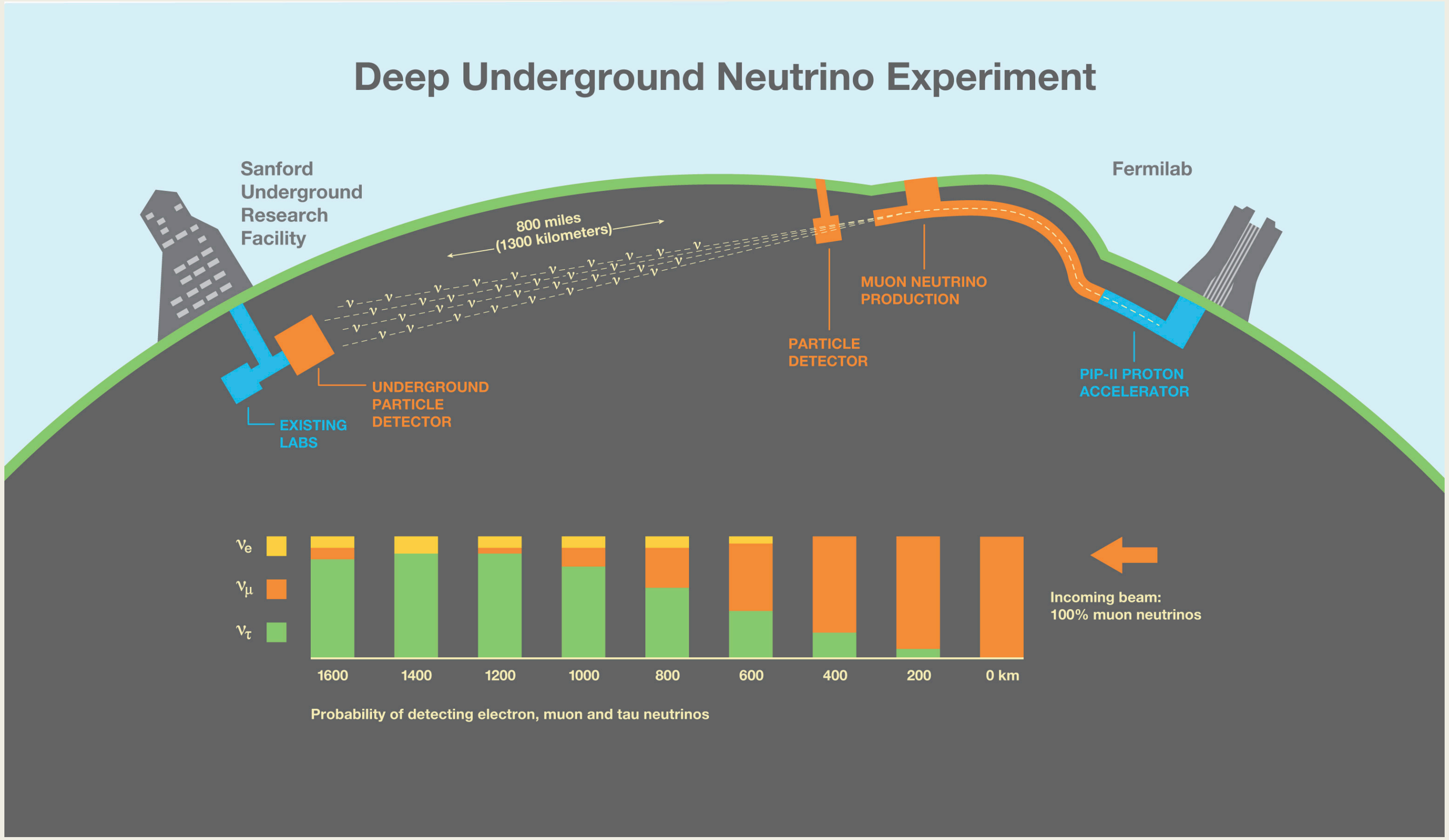
$$\mathcal{N}^{\rm FD} \equiv \mathcal{N}_{\nu}^{\rm FD} + \mathcal{N}_{\overline{\nu}}^{\rm FD}$$

$$\mathcal{N}_{\rm SM}^{\rm ND,FD} \equiv \mathcal{N}^{\rm ND,FD}(\epsilon_{\alpha\beta}^{Aq} = 0)$$



$$\int_0^1 dx\, x s(x) / \int_0^1 dx\, x u(x) \sim 0.1$$

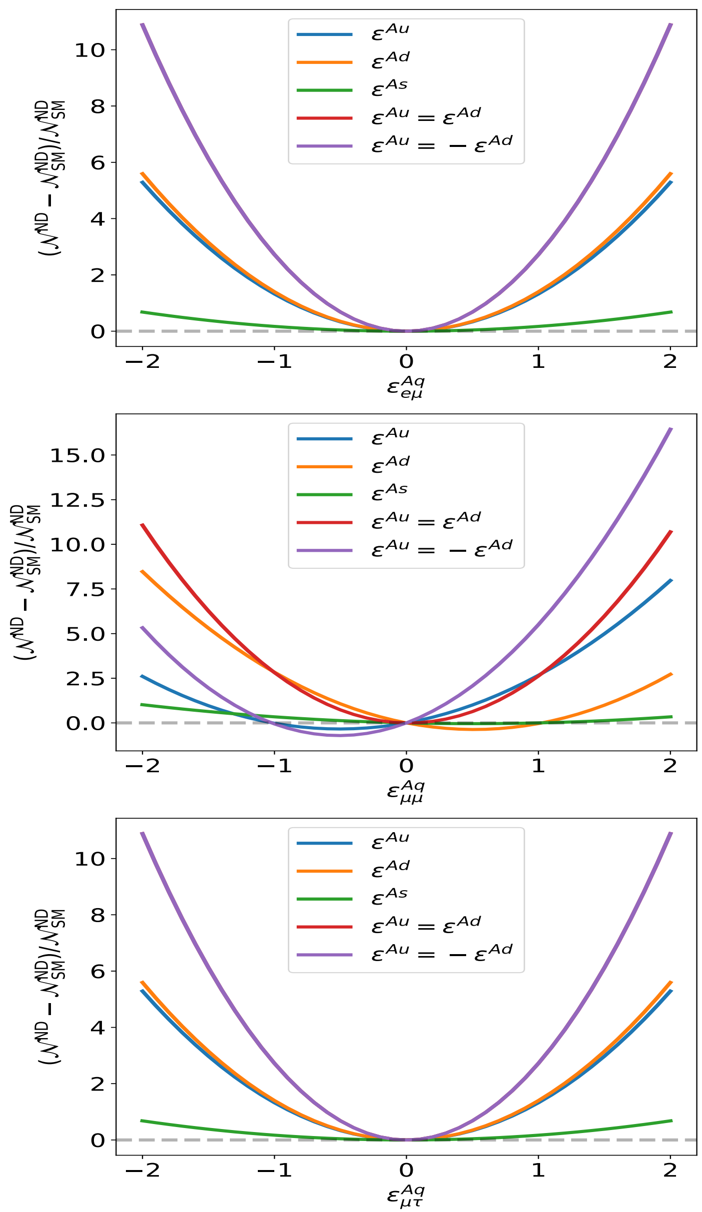
$$|\langle \nu_e | \nu_{far} \rangle|^2 \ll |\langle \nu_\mu | \nu_{far} \rangle|^2 \sim |\langle \nu_\tau | \nu_{far} \rangle|^2$$



Deep Underground Neutrino Experiment
Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
MUON NEUTRINO PRODUCTION
PARTICLE DETECTOR
PIP-II PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
ν_e
ν_μ
ν_τ
1600
1400
1200
1000
800
600
400
200
0 km
Incoming beam: 100% muon neutrinos
Probability of detecting electron, muon and tau neutrinos

Near detector

No sendiditivity to ϵ_{ee}^{Aq}, $\epsilon_{e\tau}^{Aq}$ and $\epsilon_{\tau\tau}^{Aq}$



Forecasting bounds from DUNE

Benchmarks:

$$\epsilon^{Au} \neq 0 \ , \ \epsilon^{Ad} = 0 \ , \epsilon^{As} = 0$$

$$\epsilon^{Au} = 0 \ , \ \epsilon^{Ad} \neq 0 \ , \epsilon^{As} = 0$$

$$\epsilon^{Au} = 0 \ , \ \epsilon^{Ad} = 0 \ , \epsilon^{As} \neq 0$$

$$\epsilon^{Au} = \epsilon^{Ad} \neq 0 \ , \epsilon^{As} = 0$$

Isospin symmetric benchmark

$$\epsilon^{Au} = \epsilon^{Ad} \neq 0 \;, \epsilon^{As} = 0$$

This benchmark is unconstrained by SNO;

$$\epsilon^{An}_{\alpha\beta} - \epsilon^{Ap}_{\alpha\beta} = (\Delta_u - \Delta_d)\left(\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}\right) = 1.27\left(\epsilon^{Au}_{\alpha\beta} - \epsilon^{Ad}_{\alpha\beta}\right) .$$

Background

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

$\epsilon_{\mathrm{CC}} \sim 10\%.$

P. Coloma, D. V. Forero, and S. J. Parke, JHEP 07, 079 (2018)

$\epsilon_{\mathrm{Res}} \sim 10\%.$

J. Tingey et al., JINST 18, P06032 (2023)

Mode	Flux	$\mathcal{N}^{\mathrm{ND}}$	$\mathcal{B}^{\mathrm{ND}}$	$\mathcal{N}^{\mathrm{FD}}$	$\mathcal{B}^{\mathrm{FD}}$
ν	CP	198334815	128917629	18835	12242
	τ	528621779	343604156	46059	29938
$\overline{\nu}$	CP	88543625	57553356	8244	5358
	τ	209747742	136336032	18145	11794

6.5+6.5 years

Background

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

$\epsilon_{\mathrm{CC}} \sim 10\%.$

P. Coloma, D. V. Forero, and S. J. Parke, JHEP 07, 079 (2018)

$\epsilon_{\mathrm{Res}} \sim 10\%.$

J. Tingey et al., JINST 18, P06032 (2023)

6.5+6.5 years

$\mathcal{N}^{ND} \sim \mathcal{B}^{ND} \sim O(10^8)$

$\mathcal{N}^{FD} \sim \mathcal{B}^{FD} \sim O(10^4)$

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

$$\epsilon = 90\%$$

Coloma, D. V. Forero, and S. J. Parke, JHEP 07, 079 (2018),

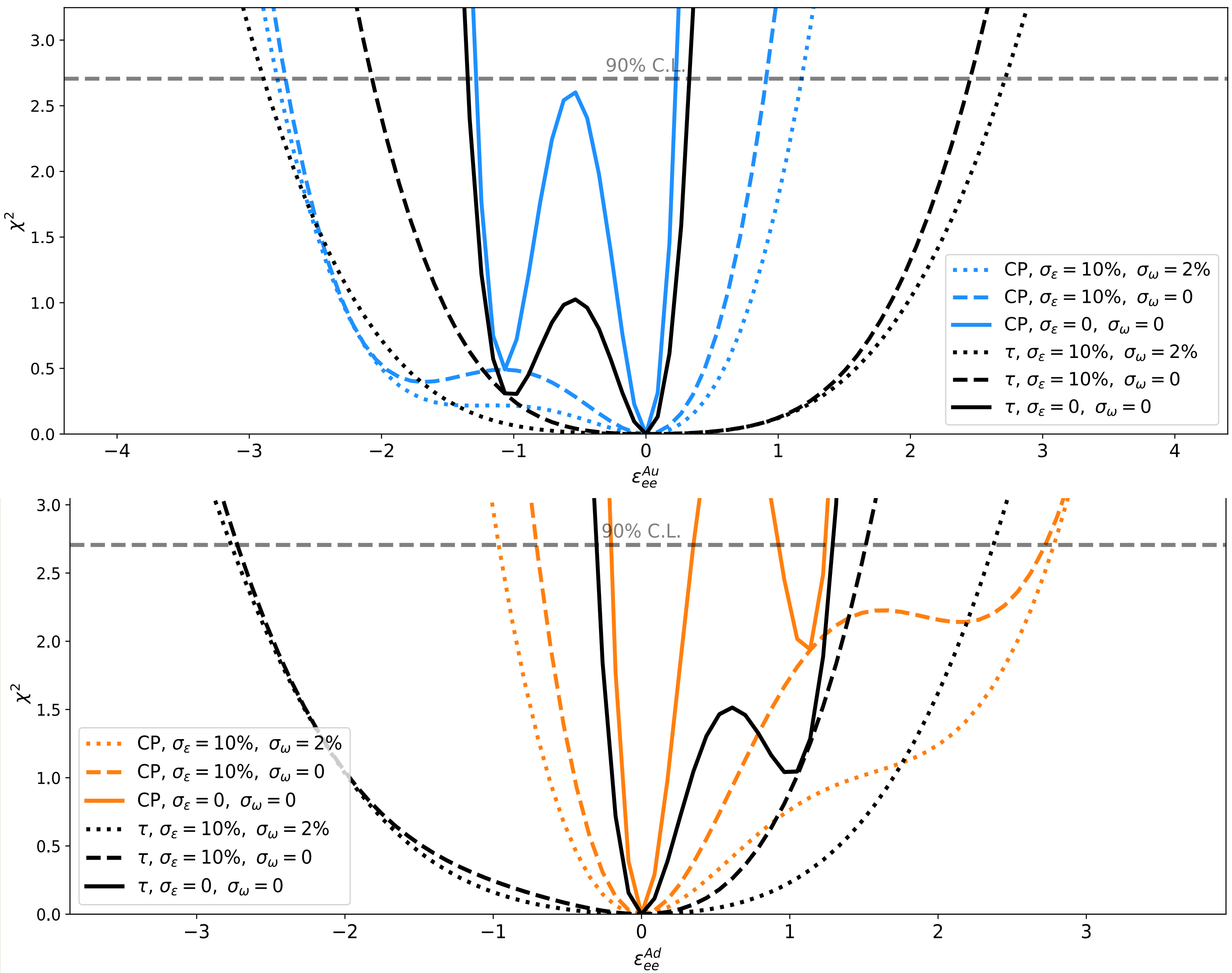
$$\chi^2 = \left[\sum_{Y=\nu,\overline{\nu}} \left(\frac{\left[\xi \mathcal{N}_Y^{\rm FD}(\epsilon_{\rm test}^{Aq}) - \epsilon \mathcal{N}_Y^{\rm FD}(\epsilon^{Aq}=0) + \omega_Y \mathcal{B}_Y^{\rm FD}\right]^2}{\epsilon \mathcal{N}_Y^{\rm FD}(\epsilon^{Aq}=0) + \mathcal{B}_Y^{\rm FD}} + \frac{\omega_Y^2}{\sigma_\omega^2}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

No energy binning

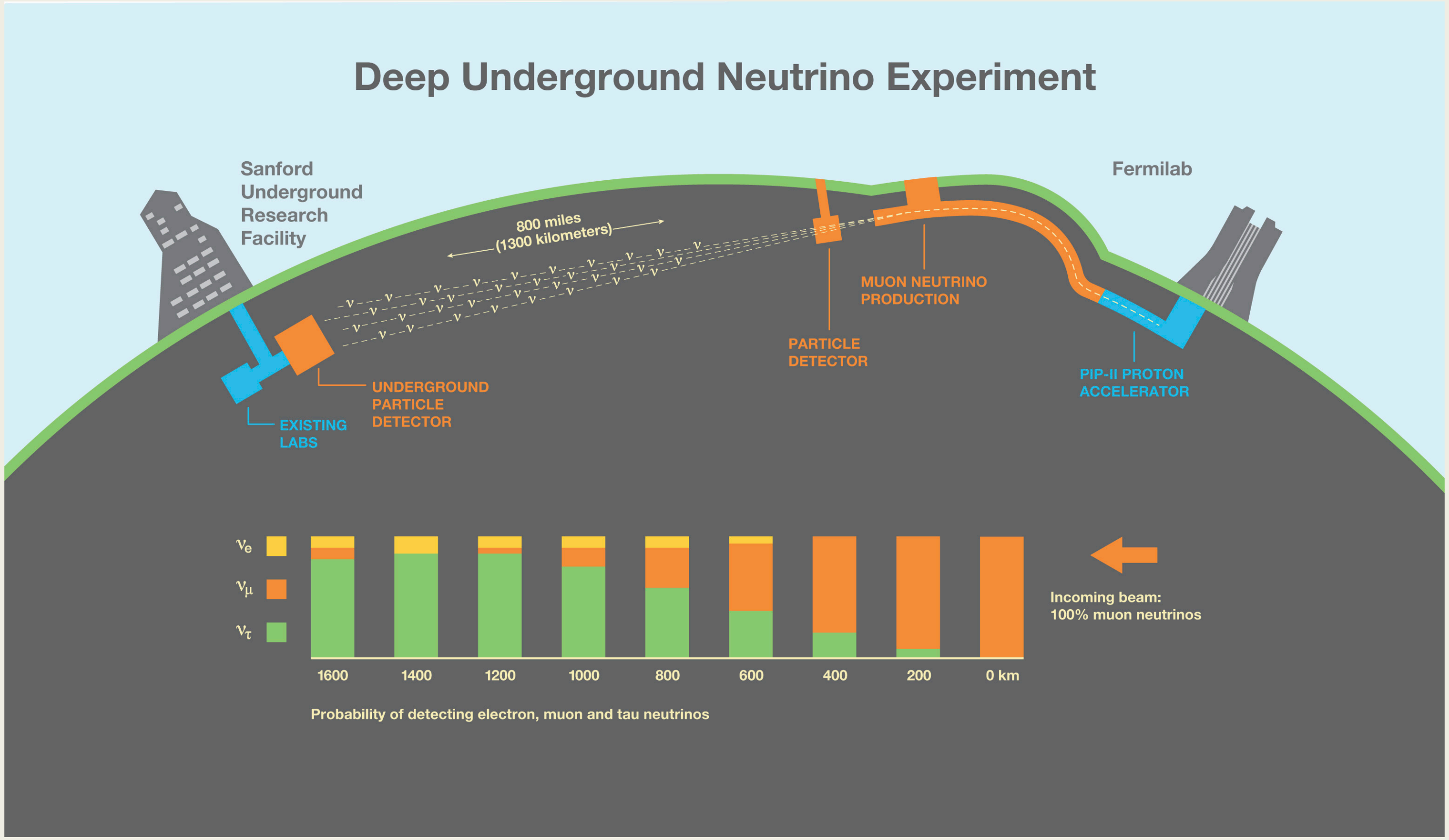
Missing energy in NC

Migration matrices?

Far detector



$$|\epsilon_{ee}^{Au}| < 1, \quad |\epsilon_{ee}^{Ad}| < 0.9,$$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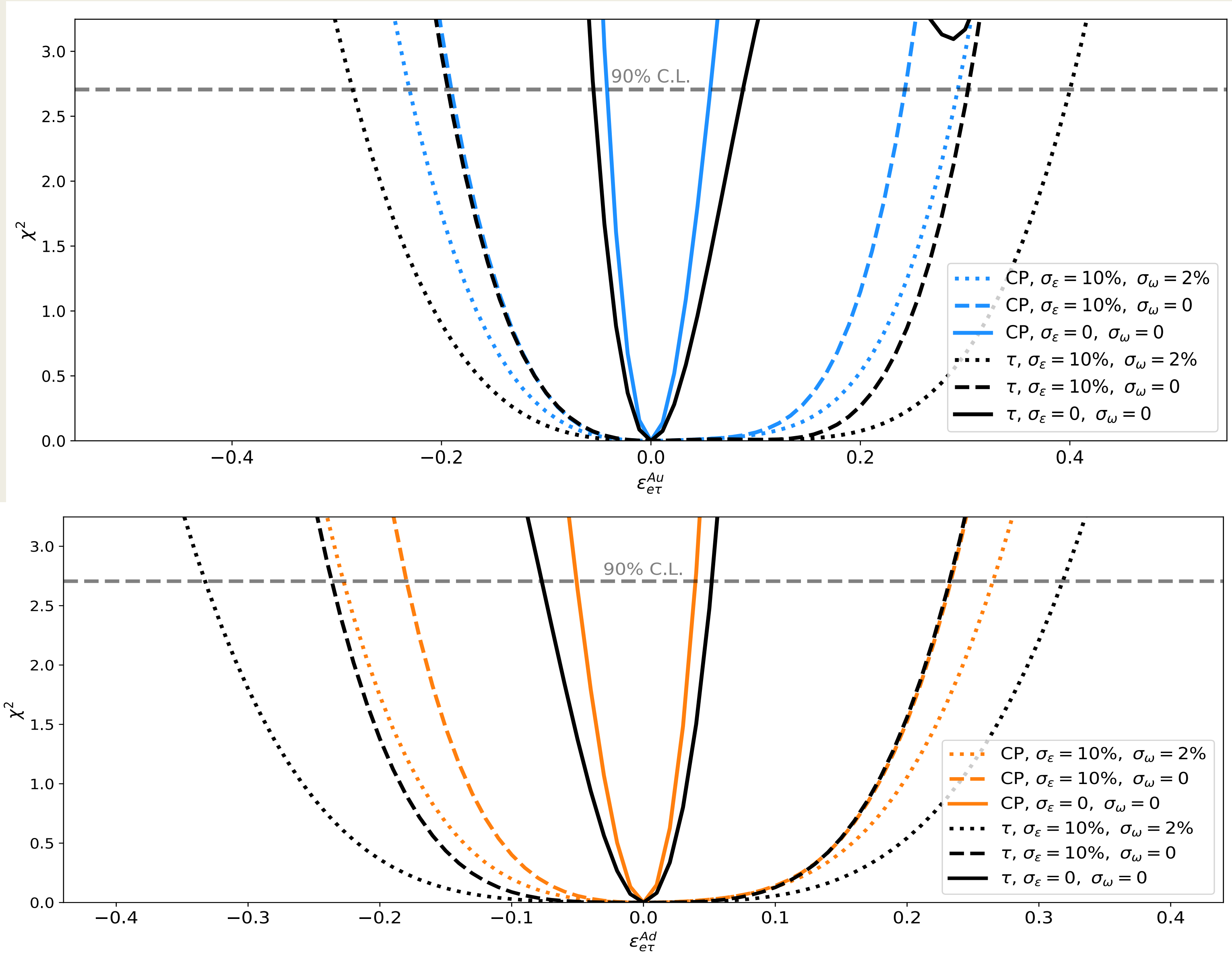
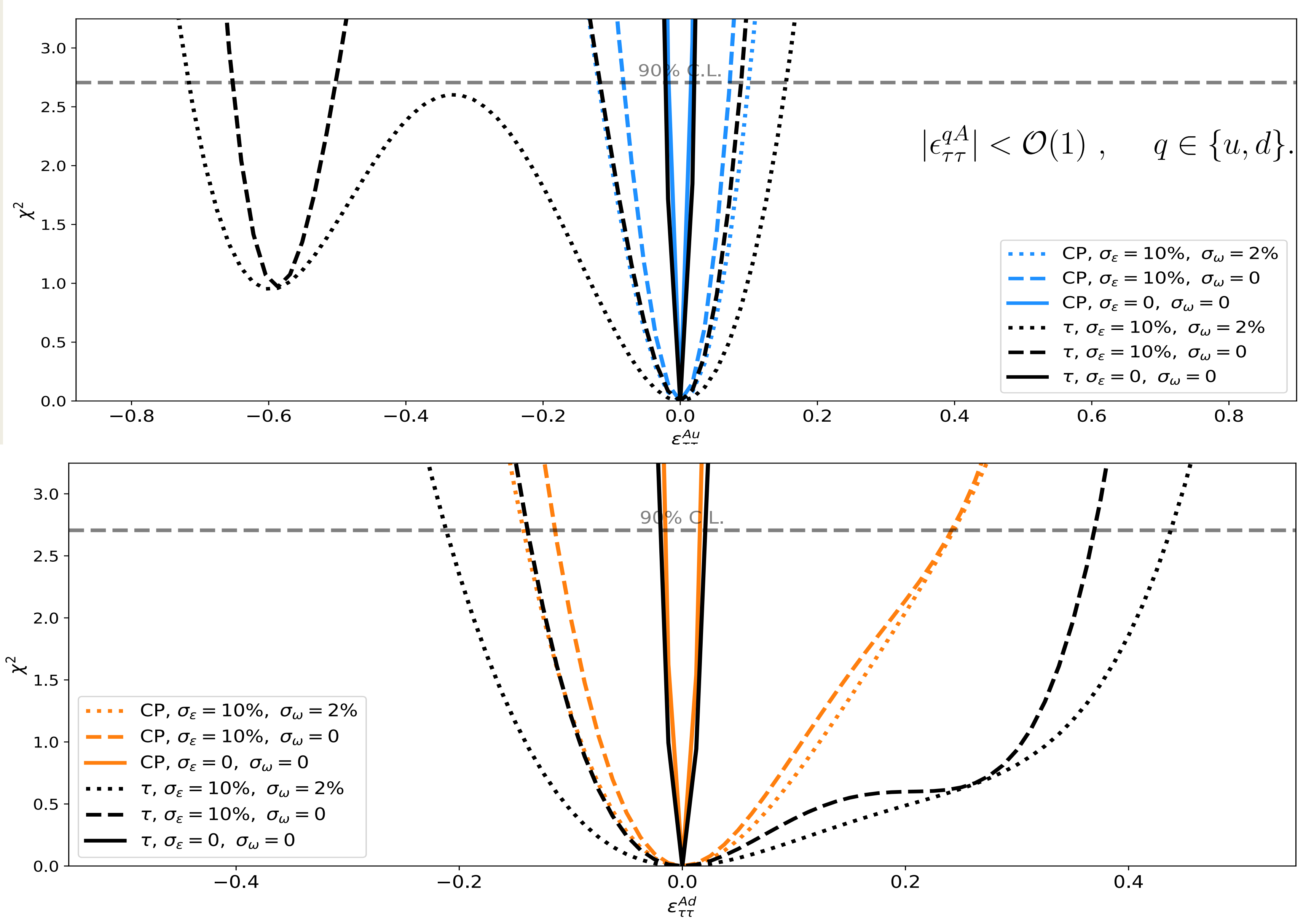
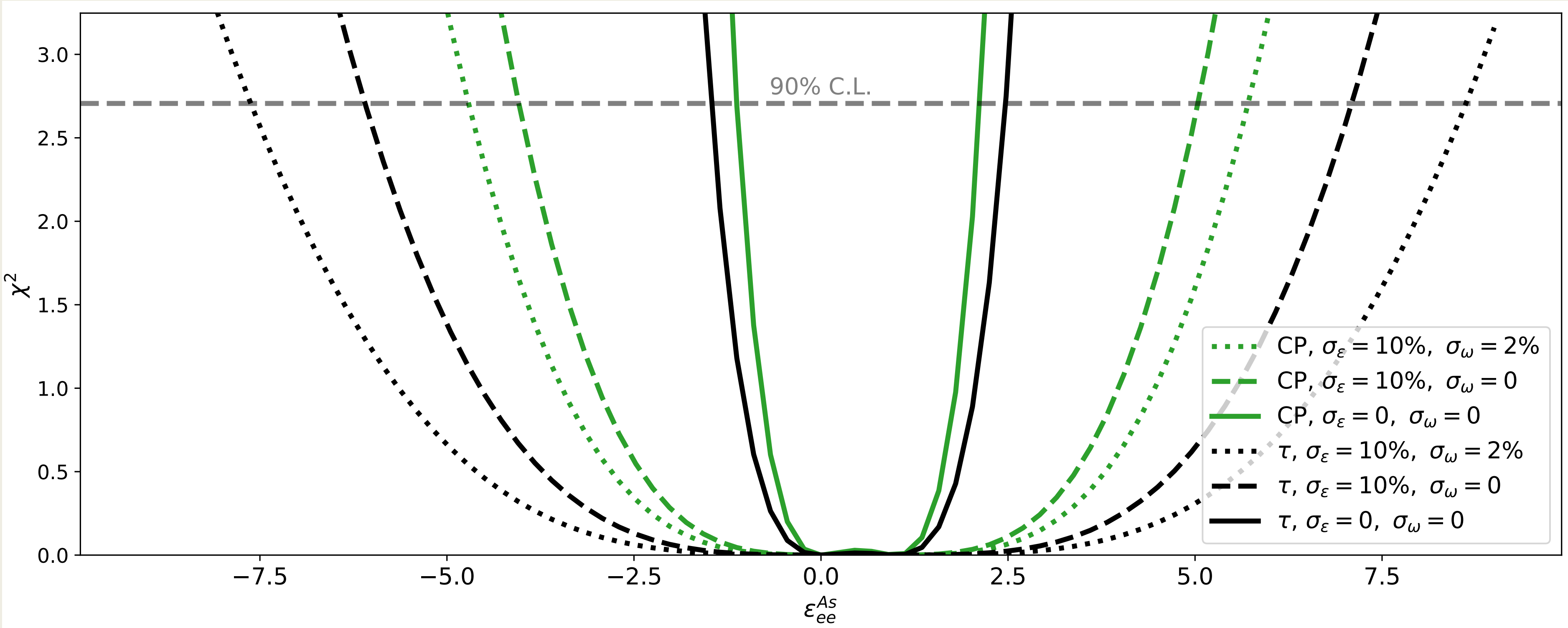


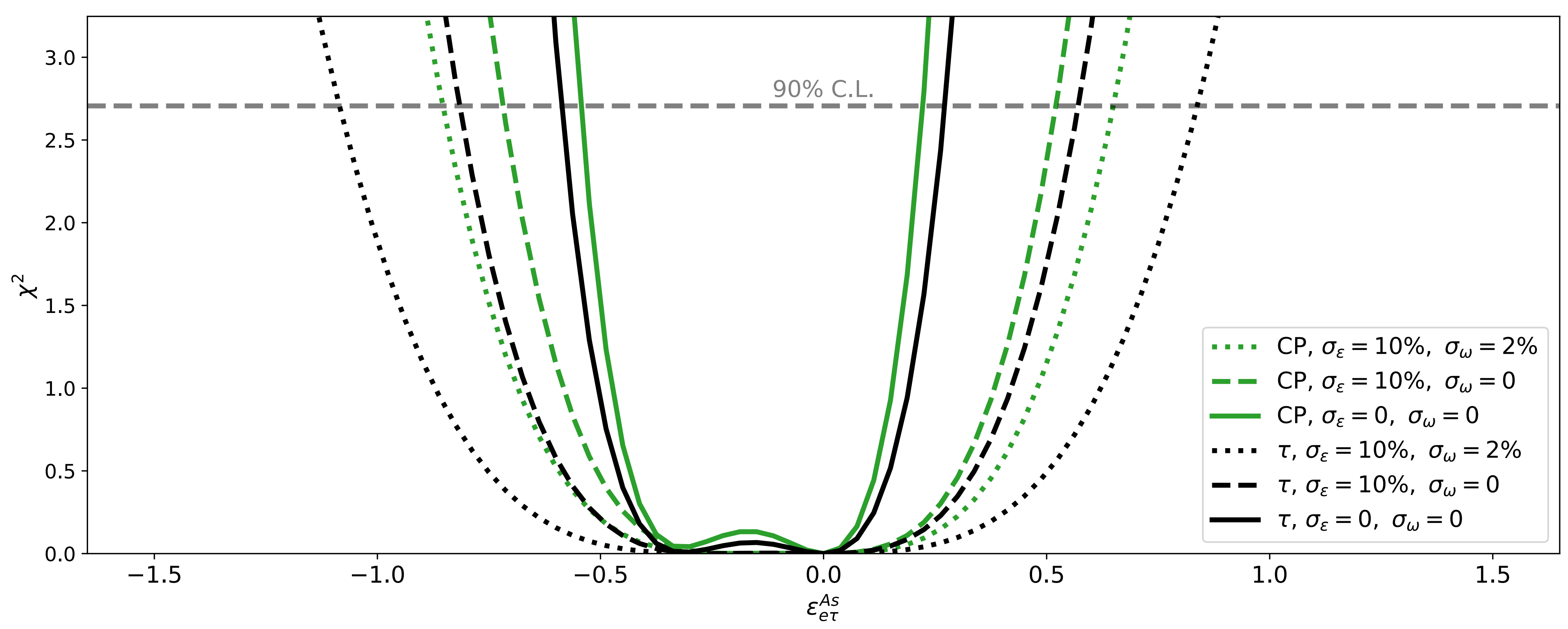
$$|\epsilon_{e\tau}^{Au}|, |\epsilon_{e\tau}^{Ad}| < 0.5.$$



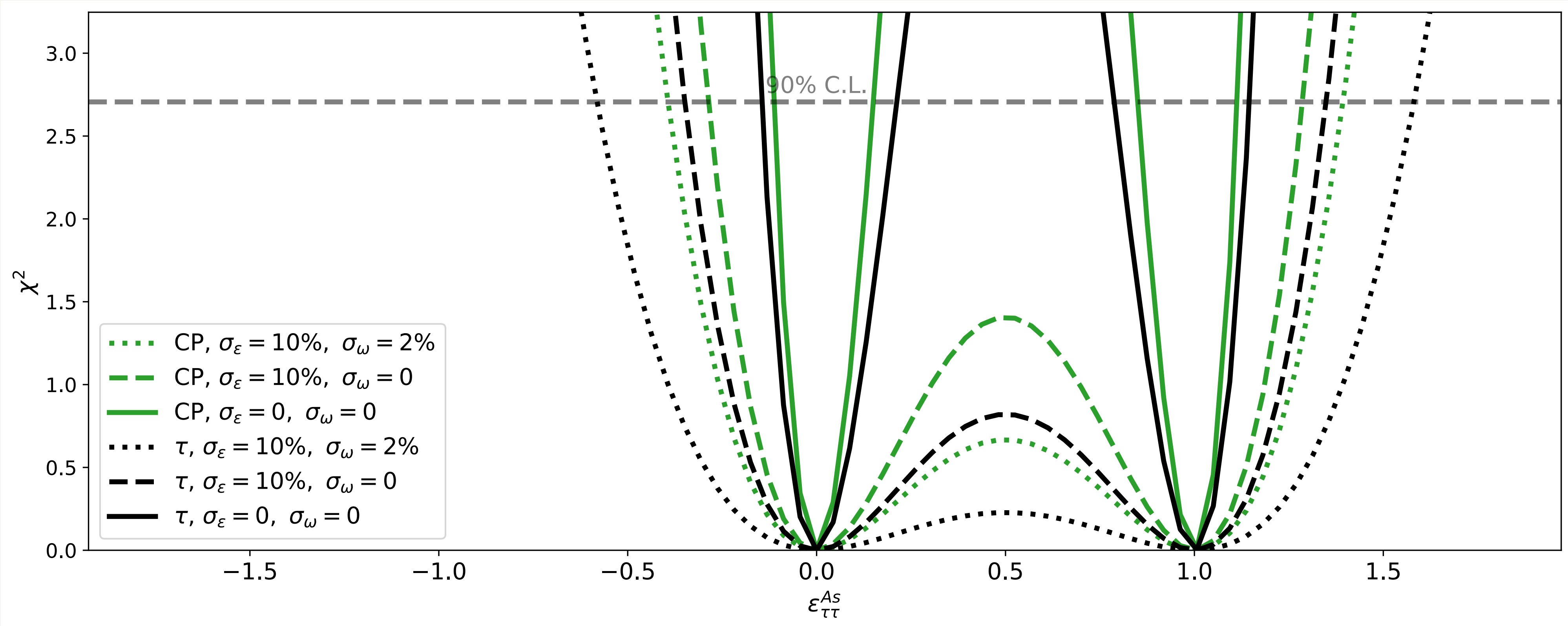
90% C.L.
$|\epsilon^{qA}_{\tau\tau}| < \mathcal{O}(1)\ , \qquad q \in \{u, d\}.$
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
χ^2
$\varepsilon^{Au}_{\tau\tau}$
90% C.L.
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
χ^2
$\varepsilon^{Ad}_{\tau\tau}$



90% C.L.
χ^2
ε_{ee}^{As}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$

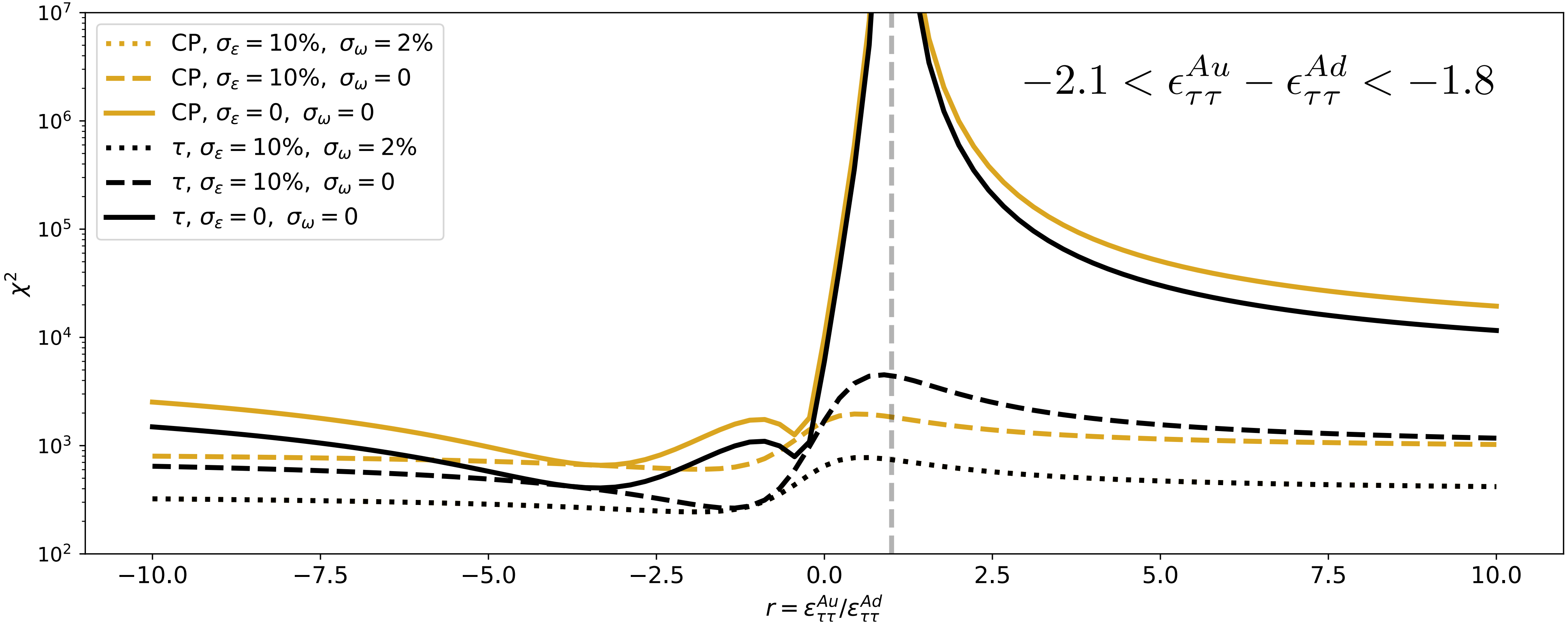


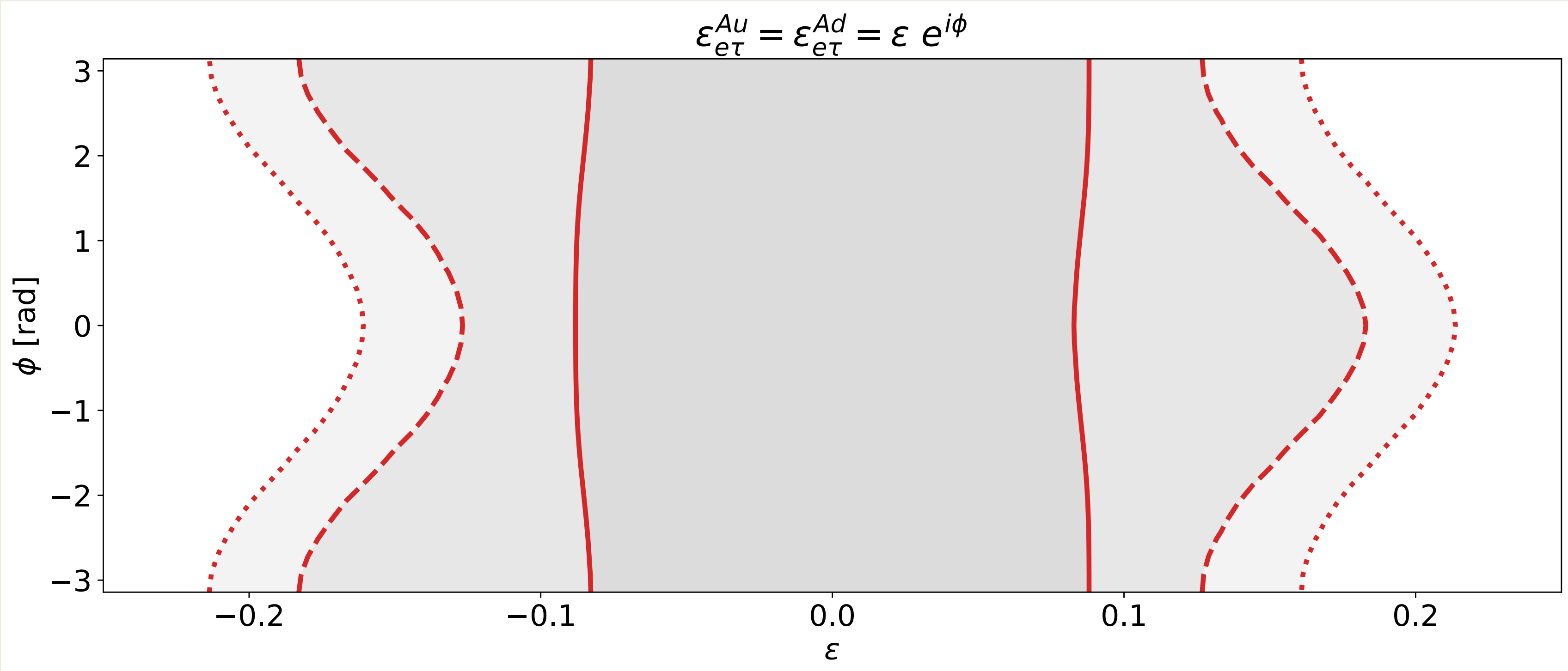
90% C.L.
χ^2
$\varepsilon_{e\tau}^{As}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
CP, $\sigma_\varepsilon = 10\%, \ \sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%, \ \sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0, \ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%, \ \sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%, \ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0, \ \sigma_\omega = 0$



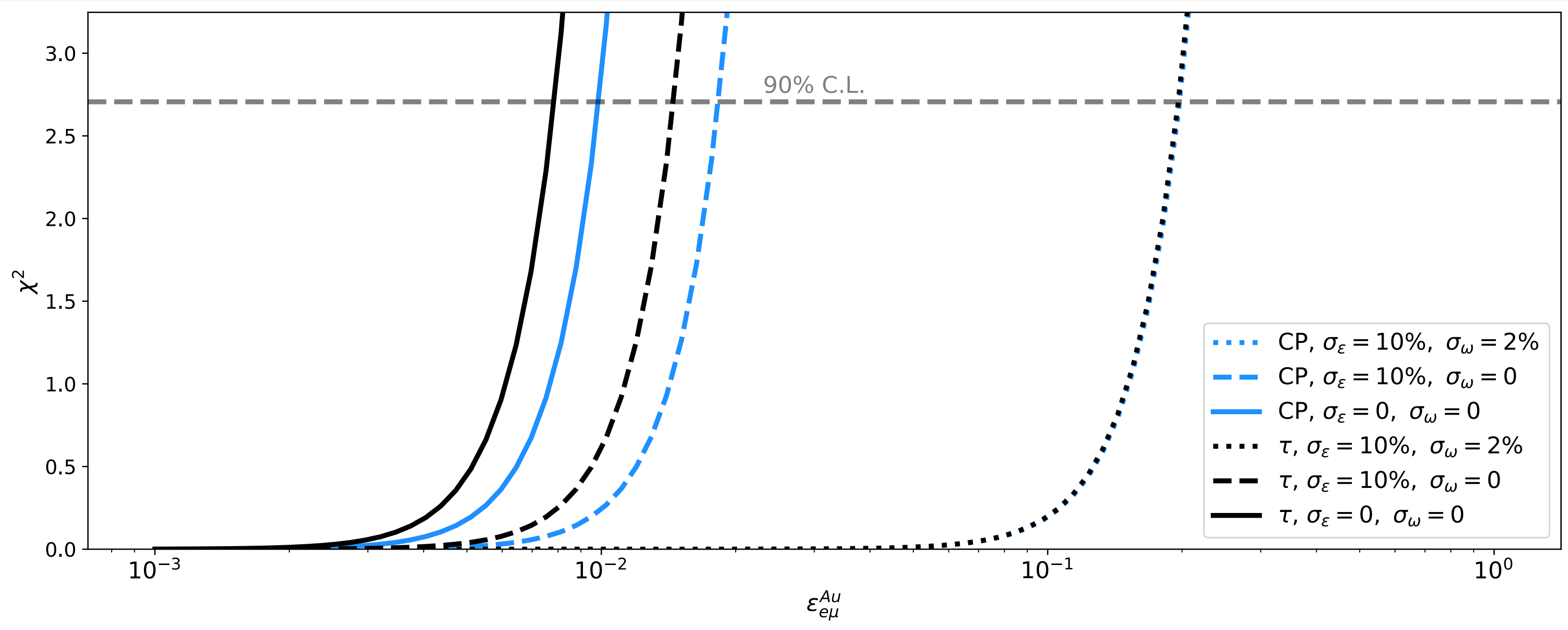
90% C.L.
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%,\ \sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0,\ \sigma_\omega = 0$
χ^2
$\varepsilon_{\tau\tau}^{As}$

Non-trivial solution of SNO

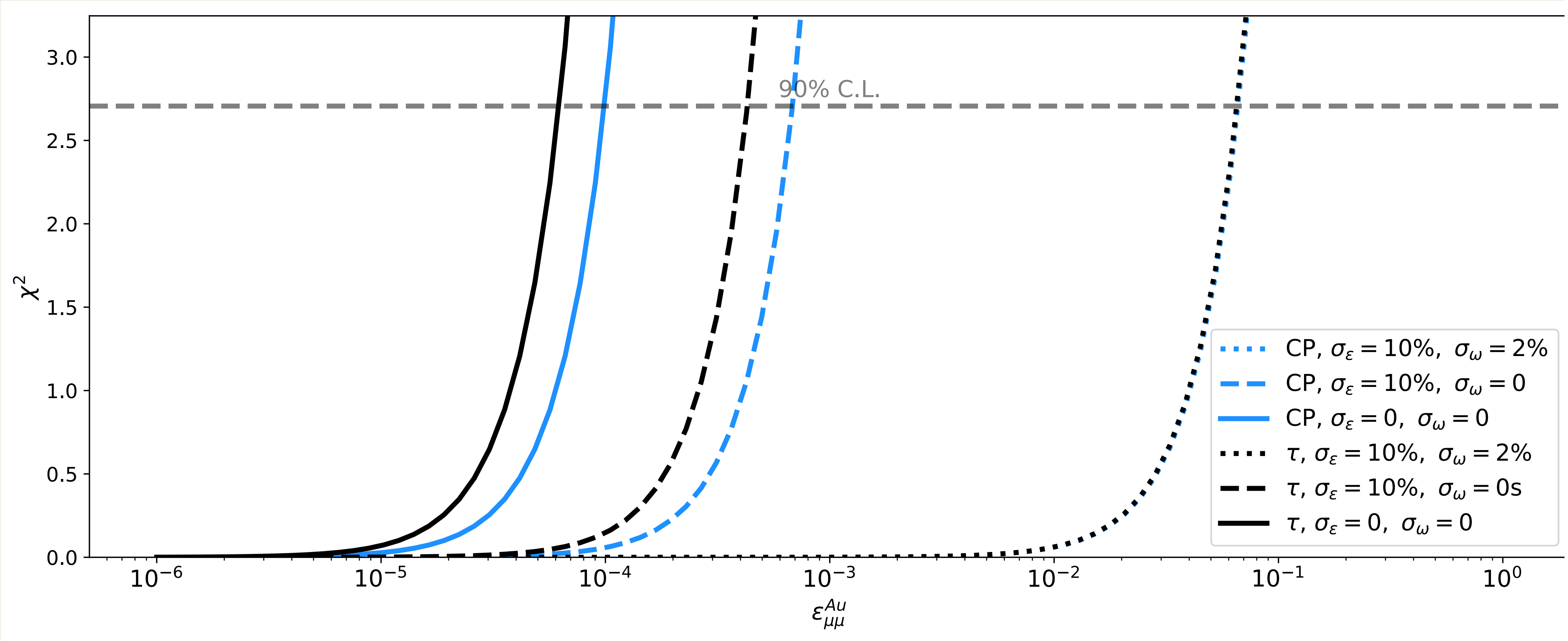



$\varepsilon_{e\tau}^{Au} = \varepsilon_{e\tau}^{Ad} = \varepsilon\ e^{i\phi}$
ϕ [rad]
3
2
1
0
−1
−2
−3
−0.2
−0.1
0.0
0.1
0.2
ε

Near Detector



$$\mathrm{Ti} + \mu \to \mathrm{Ti} + e \qquad |\epsilon_{e\mu}^{qR}|, |\epsilon_{e\mu}^{qL}| < 7.7 \times 10^{-4} , \quad q \in \{u, d\}.$$



$$|\epsilon_{\mu\mu}^{Au}| < 0.006, \quad |\epsilon_{\mu\mu}^{Ad}| < 0.018,$$

S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria,
JHEP 03, 011 (2003),

$$\text{From NuTeV}: \quad |\epsilon_{\mu\mu}^{Au}| < 0.006, \quad |\epsilon_{\mu\mu}^{Ad}| < 0.018,$$

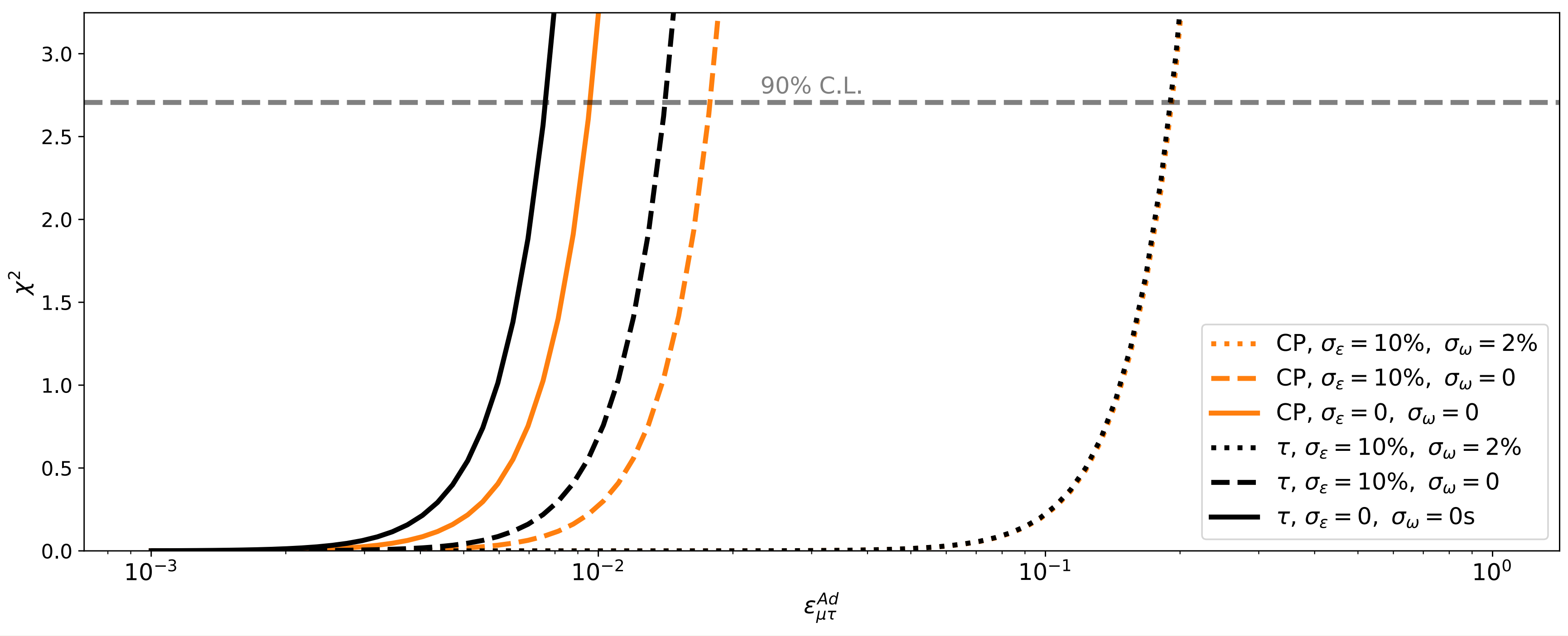
Ratio of NC/CC

For an isospin symmetric target is independent of PDFs

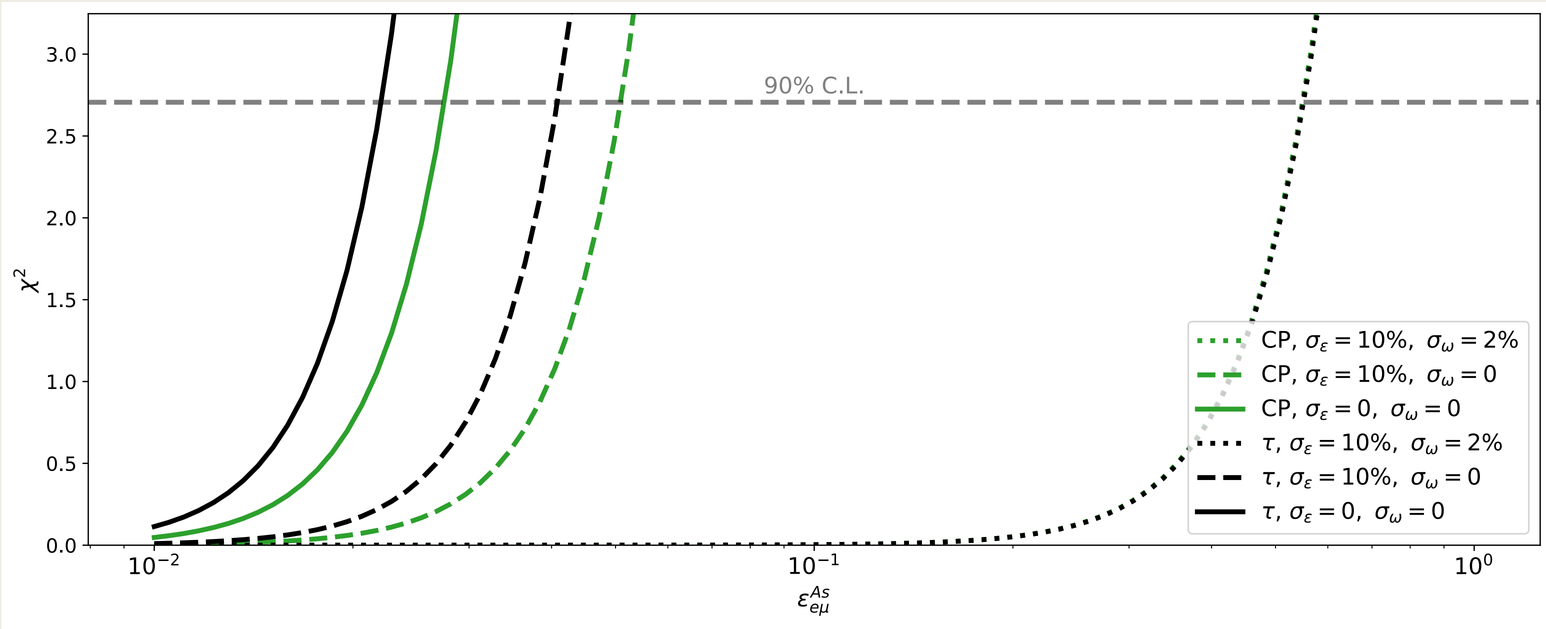
How accurate is this symmetry?

cannot be better than 3 %.

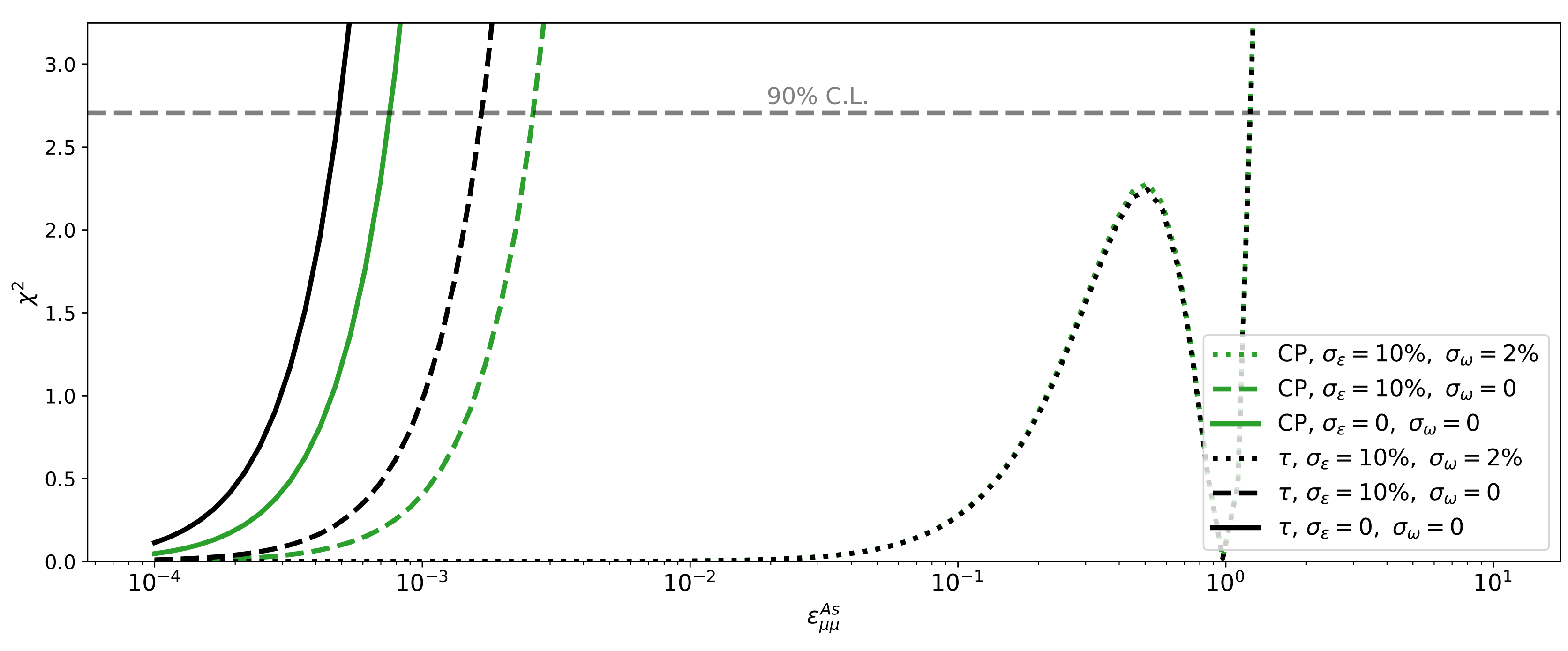
$\mathcal{O}(15\%)$



$$|\epsilon_{\mu\tau}^{Au}|, |\epsilon_{\mu\tau}^{Ad}| < 0.01,$$



3.0
2.5
2.0
1.5
1.0
0.5
0.0
χ^2
90% C.L.
10^{-2}
10^{-1}
10^{0}
$\varepsilon_{e\mu}^{As}$
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$

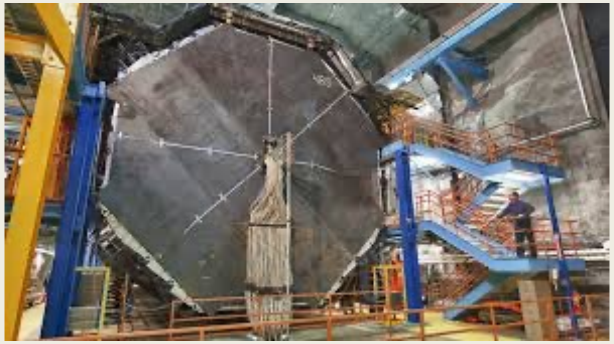


90% C.L.
χ^2
$\varepsilon_{\mu\mu}^{As}$
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
CP, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
CP, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 2\%$
τ, $\sigma_\varepsilon = 10\%$, $\sigma_\omega = 0$
τ, $\sigma_\varepsilon = 0$, $\sigma_\omega = 0$

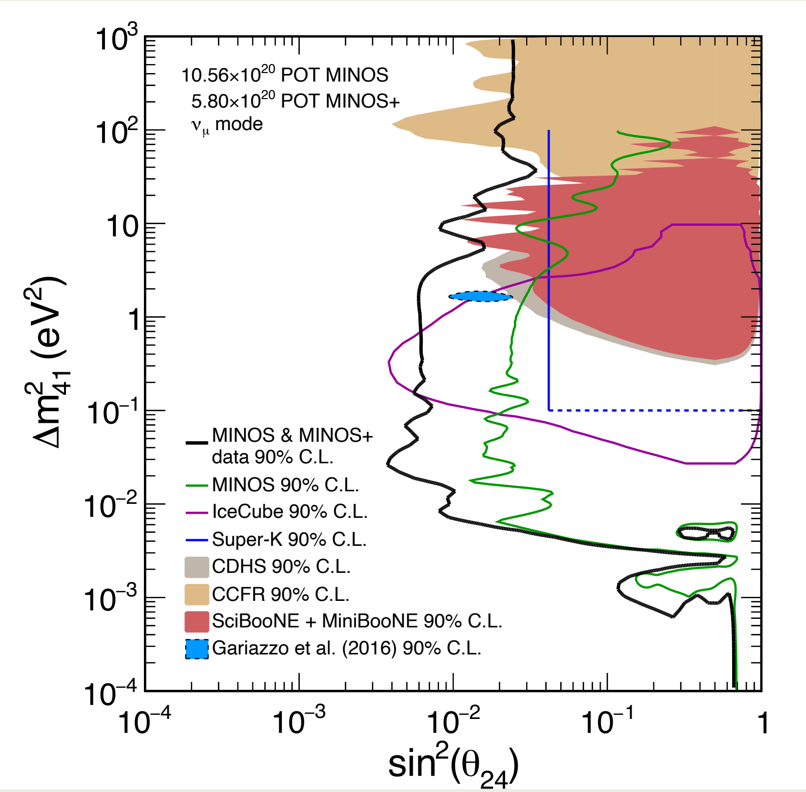
Summary of part 2

- The bound on Axial NSI can be improved by neutral current measurements at DUNE.
- The amount of improvements depends on how much the systematic errors are under control.
- While the tau mode is better for probing the mu components at near detector, the CP mode is more efficient in probing ee, e tau and tau tau components at the far detector.

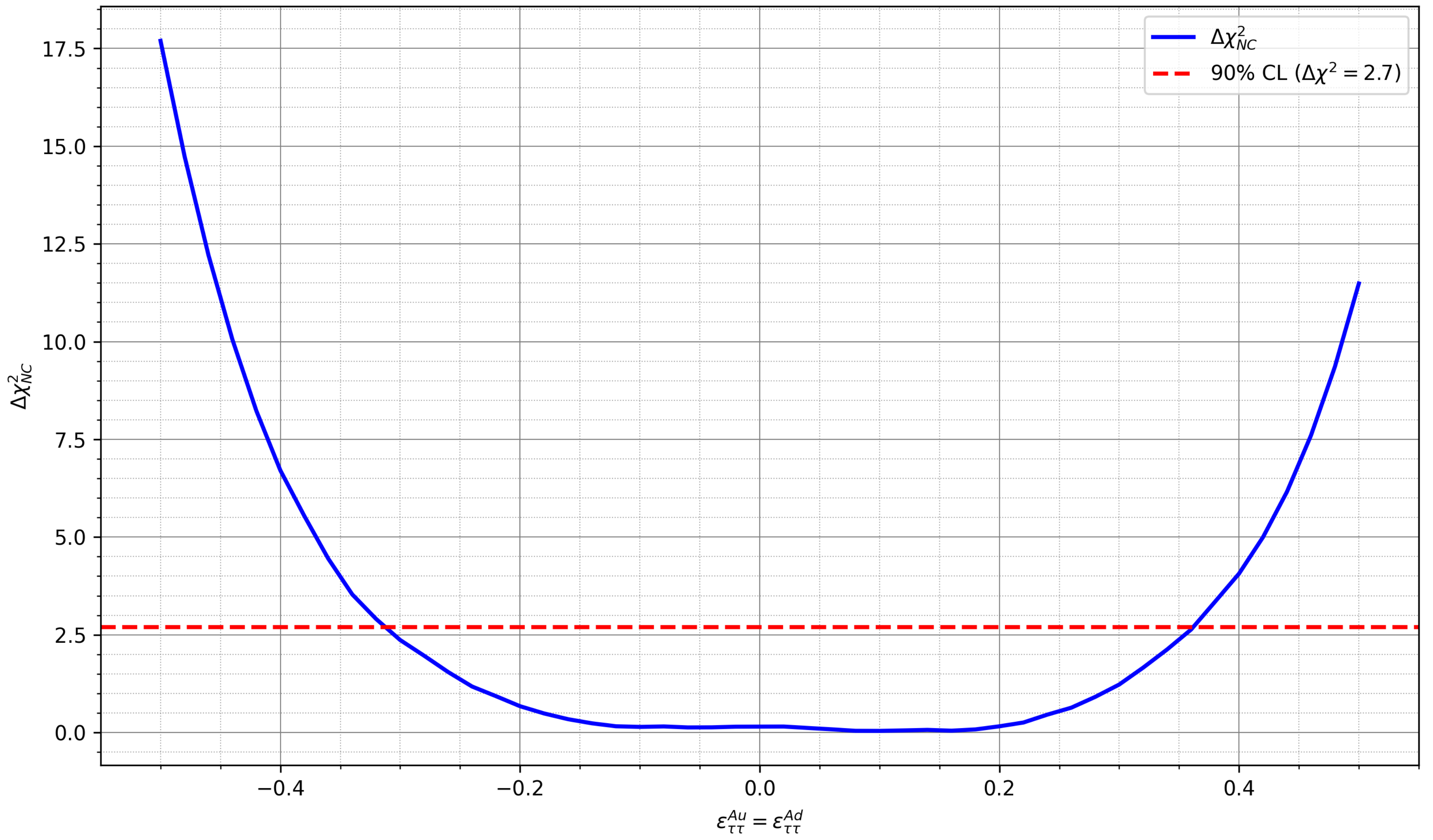
MINOS and MINOS+



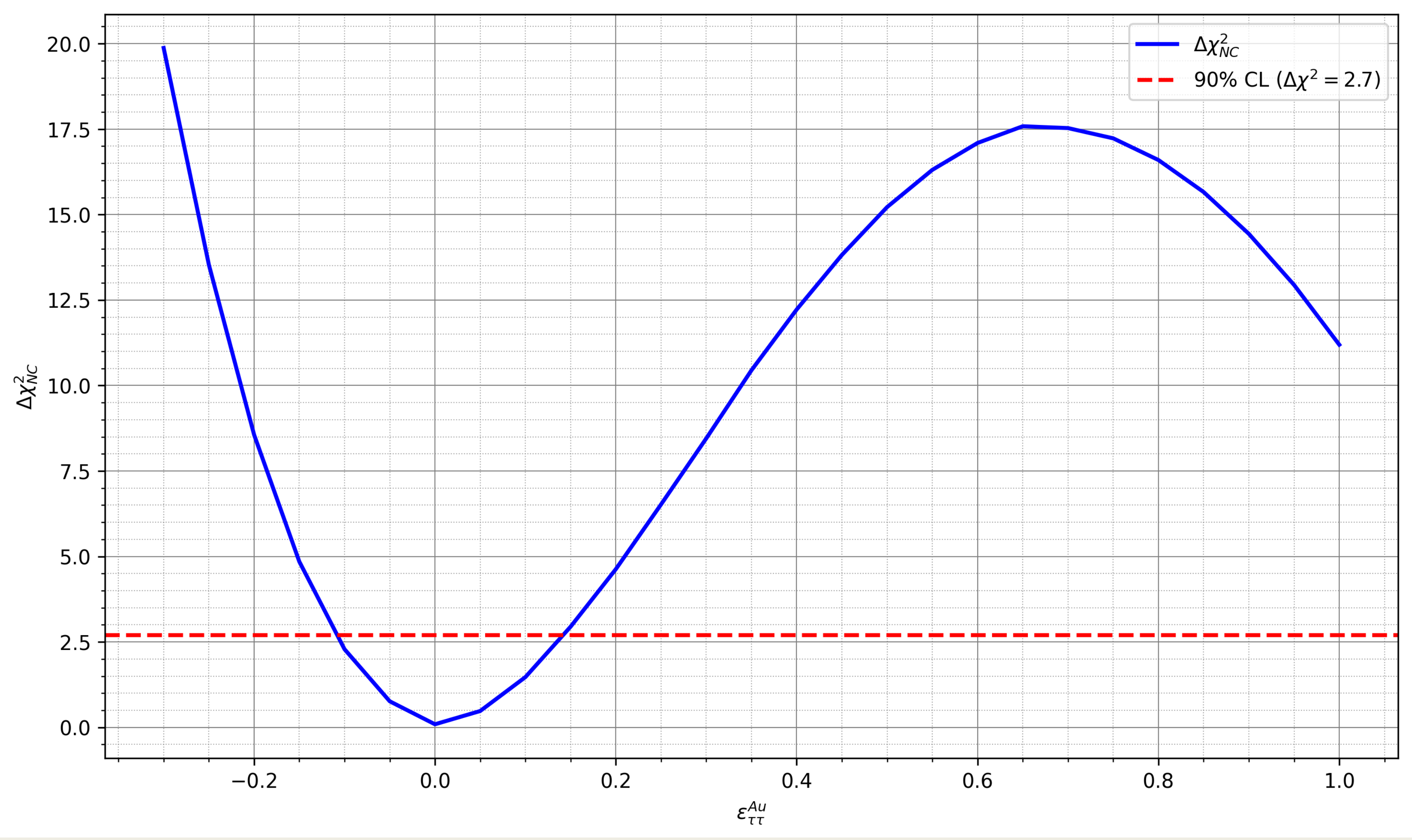
NC events of MINOS and MINOS+



MINOS+ collaboration,
Phys.Rev.Lett. 122 (2019) 9, 091803



Saeed Abbaslu and YF, work in progress



Saeed Abbaslu and YF, work in progress

Summary of part 3

- Stay tuned!
- Bounds from existing the MINOS and MINOS+ data on

$$|\epsilon_{\tau\tau}^{Aq}| \text{ and } |\epsilon_{e\tau}^{Aq}| < 0.2 - 0.3$$