Effects of NSI on neutrino oscillation

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Overview

- Neutrino oscillation provides a very strong evidence for physics BSM.
- In SM, neutrinos are introduced as truly massless fermions. On the contrary, neutrinos oscillate: after being produced, they change their flavours.
- Solar neutrino problem was the first evidence of neutrino oscillation.
- In 1978, Wolfenstein, proposed a possibility of flavor change of the massless neutrinos with non-diagonal neutral current non-standard interactions, during propagation in matter.
- Neutrino oscillation occurs since Flavor eigenstates (of weak interactions) and mass eigenstates (of free particle Hamiltonian) are not aligned for neutrinos.
- Flavor states and mass states are related by mixing matrix called PMNS matrix. (Pontecorvo-Maki-Nakagawa-Sakata matrix). This matrix can be parametrized by 4 parameters (3 angles and at least one phase).

Dimension-6 Non-Standard Interactions (NSIs)

Non-Standard Neutrino Interactions:

- NSIs are described by dimension-6 operators:

$$\mathcal{L}_{\text{NSI}} = -\frac{1}{\Lambda^2} \sum_{f,\alpha,\beta} \epsilon^{fP}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P f\right).$$

- **Components:**
  - Λ: Scale of new physics.
  - $\epsilon^{fP}_{\alpha\beta}$: Dimensionless NSI coefficients.
  - f: SM fermions (e.g., e, u, d).
  - P: Chirality projection (P_L, P_R).
- Modifies neutrino oscillations and scattering processes.

- NSI could play a significant role in modifying neutrino flavor transitions, albeit at a sub-leading level.
- These interactions introduce additional terms in the neutrino propagation Hamiltonian:

$$H_{\text{eff}} = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{NSI}},$$

Implications:

- Affect oscillation probabilities by introducing corrections to matter effects.
- Mimic or obscure standard oscillation parameters, such as CP-violating phases or mass ordering.
- NSIs are testable in high-precision neutrino oscillation experiments, such as DUNE, Hyper-K, and JUNO.

Challenges:

- NSIs must remain consistent with stringent experimental constraints from neutrino scattering and oscillation data.
- Degeneracies between NSI parameters and standard oscillation parameters complicate their identification.

Neutrino Oscillation in Matter

- Neutrino oscillations are affected by matter interactions, which introduce a potential term in the Hamiltonian

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{1}$$

$$\mathcal{H}_{vac} = U_{\mathrm{PMNS}} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^{\dagger}_{\mathrm{PMNS}} \tag{2}$$

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1, 0, 0) \tag{3}$$

- In the two-flavor approximation, the flavor evolution of neutrinos in matter is governed by the Schrödinger-like equation:

$$i \frac{d}{dx} \psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{4}$$

Neutrino Oscillation in Matter

$$\mathcal{H}_F = \begin{bmatrix} -\Delta m^2 \cos 2\theta + A_{CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - A_{CC} \end{bmatrix} \tag{5}$$

where θ is the mixing angle in vacuum and A_{CC} is the charged current potential in matter ($A_{CC} = 2\sqrt{2} G_F N_e E = 2 V_{CC} E$).

- Hamiltonian Diagonalization

$$\mathcal{H}_M = U_M \mathcal{H}_F U_M \tag{6}$$

$$U_M = \begin{bmatrix} \cos 2\theta_M & \sin 2\theta_M \\ -\sin 2\theta_M & \cos 2\theta_M \end{bmatrix} \tag{7}$$

$$\mathcal{H}_M = diag(-\Delta m^2_M, \Delta m^2_M) \tag{8}$$

Neutrino Oscillation in Matter

- The effective parameters are given by:

$$\Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{9}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{10}$$

- In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$, and $U \to U^*$
- In the case of resonance condition $A^{res}_{CC} = \Delta m^2 \sin 2\theta^2$, we have maximal mixing $\theta_M = \pi/4$

- Assuming neutral-current non-standard neutrino interaction

$$\mathcal{L}_{\mathrm{NSI}}^{NC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fC}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f\right)\,, \tag{11}$$

caused flavor change during neutrino propagation in matter

$$H_{mat}^{NSI} = \sqrt{2}G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \tag{12}$$

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^e + (N_d/N_e)\epsilon_{\alpha\beta}^d + (N_u/N_e)\epsilon_{\alpha\beta}^u \tag{13}$$

- Using 2×2 effective Hamiltonian as following

$$H_{\mathrm{vac}}^{\mathrm{eff}} = \frac{\Delta m_{21}^2}{4E_\nu}\begin{pmatrix} \cos 2\theta_{12} & \sin 2\theta_{12} \\ -\sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix}, \tag{14}$$

$$H_{\mathrm{mat}}^{\mathrm{eff}} = \sqrt{2}G_F N_e(r)c_{13}^2\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2}G_F\sum_f N_f(r)\begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

- The coefficients ϵ_D^f and ϵ_N^f are given

$$\epsilon_D^f = -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \tag{15}$$

$$+\mathrm{Re}\left[c_{13}s_{13}e^{i\delta}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right) - \left(1+s_{13}^2\right)c_{23}s_{23}\epsilon_{\mu\tau}^f\right]$$

$$\epsilon_N^f = c_{13}\left(c_{23}\,\epsilon_{e\mu}^f - s_{23}\,\epsilon_{e\tau}^f\right) \tag{16}$$

$$+s_{13}e^{-i\delta}\left[s_{23}^2\,\epsilon_{\mu\tau}^f - c_{23}^2\,\epsilon_{\mu\tau}^{f*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$

$$\tan 2\tilde{\theta}_{12} = \frac{|\sin 2\theta_{12} + 2\hat{A}_E\epsilon_N|}{\cos 2\theta_{12} - \hat{A}_E(c_{13}^2 - 2\epsilon_D)}\,, \tag{17}$$

- P. B and M. Rajaee, "Sensitivities of future solar neutrino observatories to nonstandard neutrino interactions," Phys. Rev. D **102** (2020) no.3, 035024 [arXiv:2003.12984 [hep-ph]].

- P. B. and Y. Farzan, "Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50," JHEP **1407** (2014) 064 [arXiv:1403.0744 [hep-ph]].
- Evolution with H and $-H^*$ leads to the same oscillation probabilities

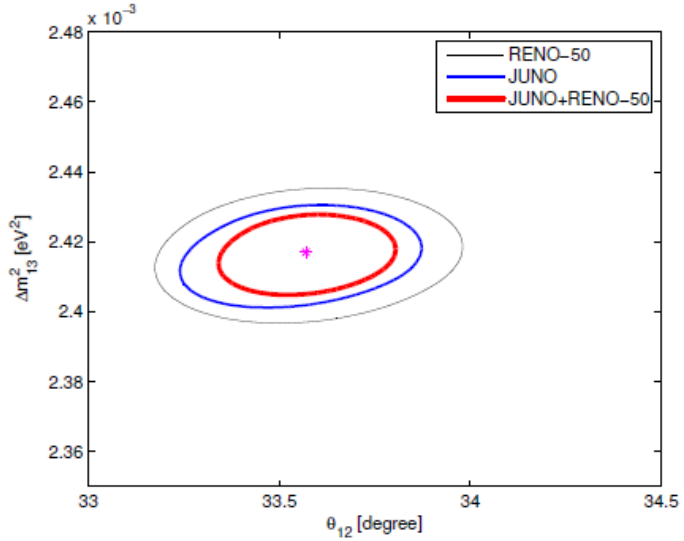
$$\theta_{12} \to \frac{\pi}{2} - \theta_{12}, \;\; \delta \to \pi - \delta, \;\; \Delta_{31} \to -\Delta_{13} + \Delta_{21} \;\; \text{and} \;\; V_{eff} \to -S \cdot V_{eff} \cdot S$$

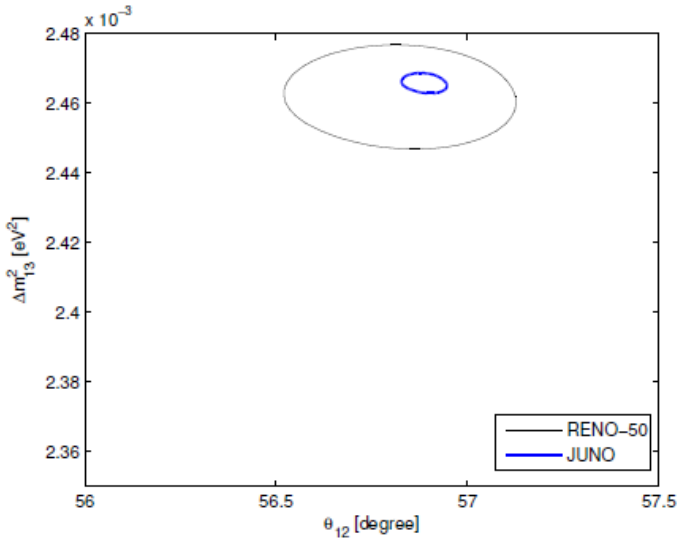
$$S = Diag(-1, 1, 1)$$

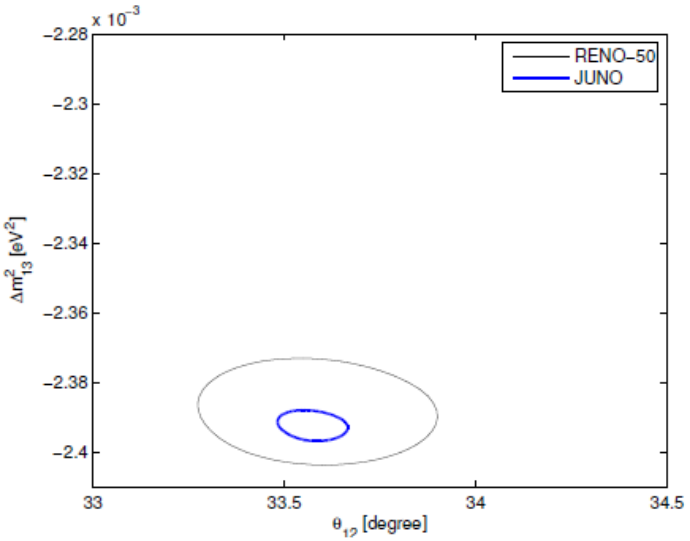
- At the probability level at JUNO

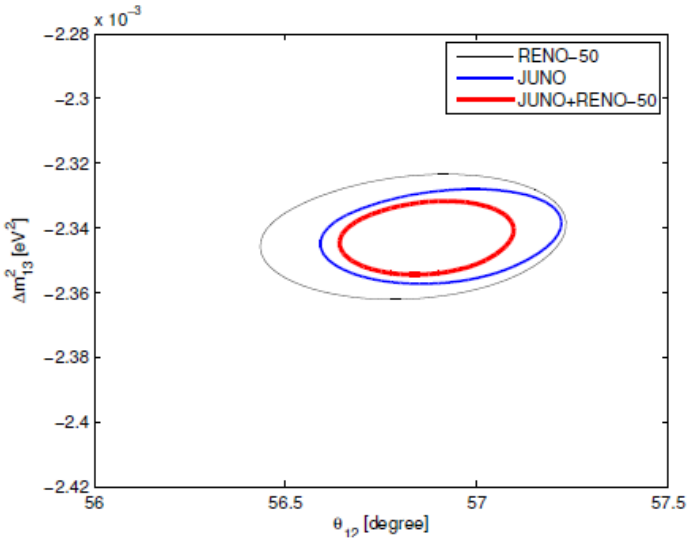
$$P_{\bar{e}\bar{e}} = 1 - \cos^4 2\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \frac{1}{2} \sin^2 2\theta_{13}$$
$$+ \sin^2 2\theta_{13} \left[\cos^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \right]$$

LMA-Dark solution



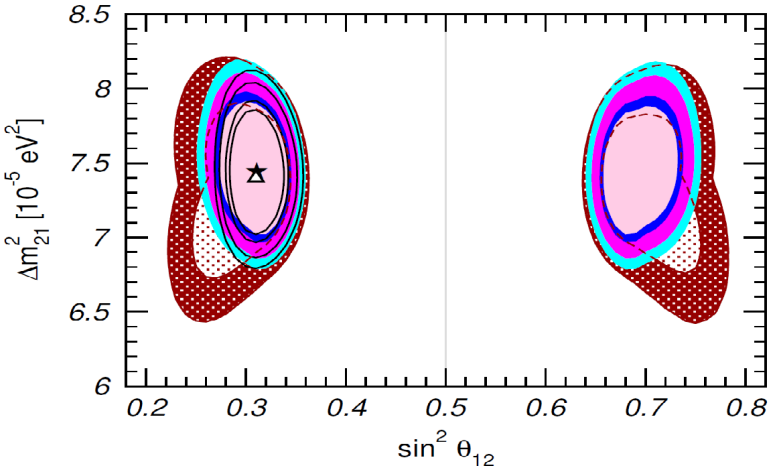




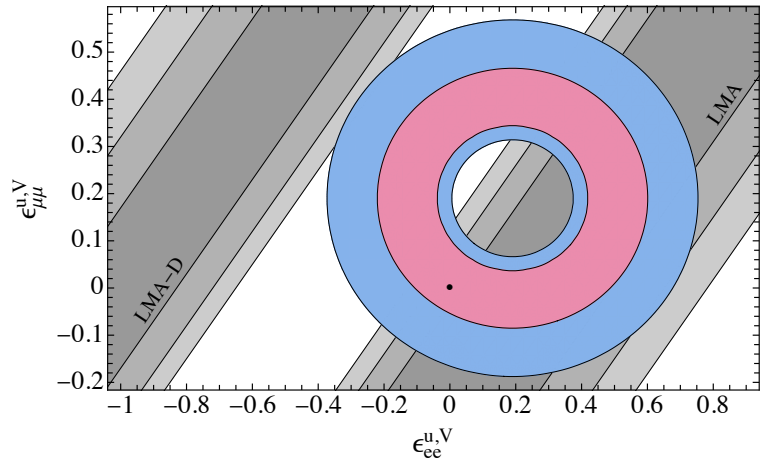


LMA-Dark solution

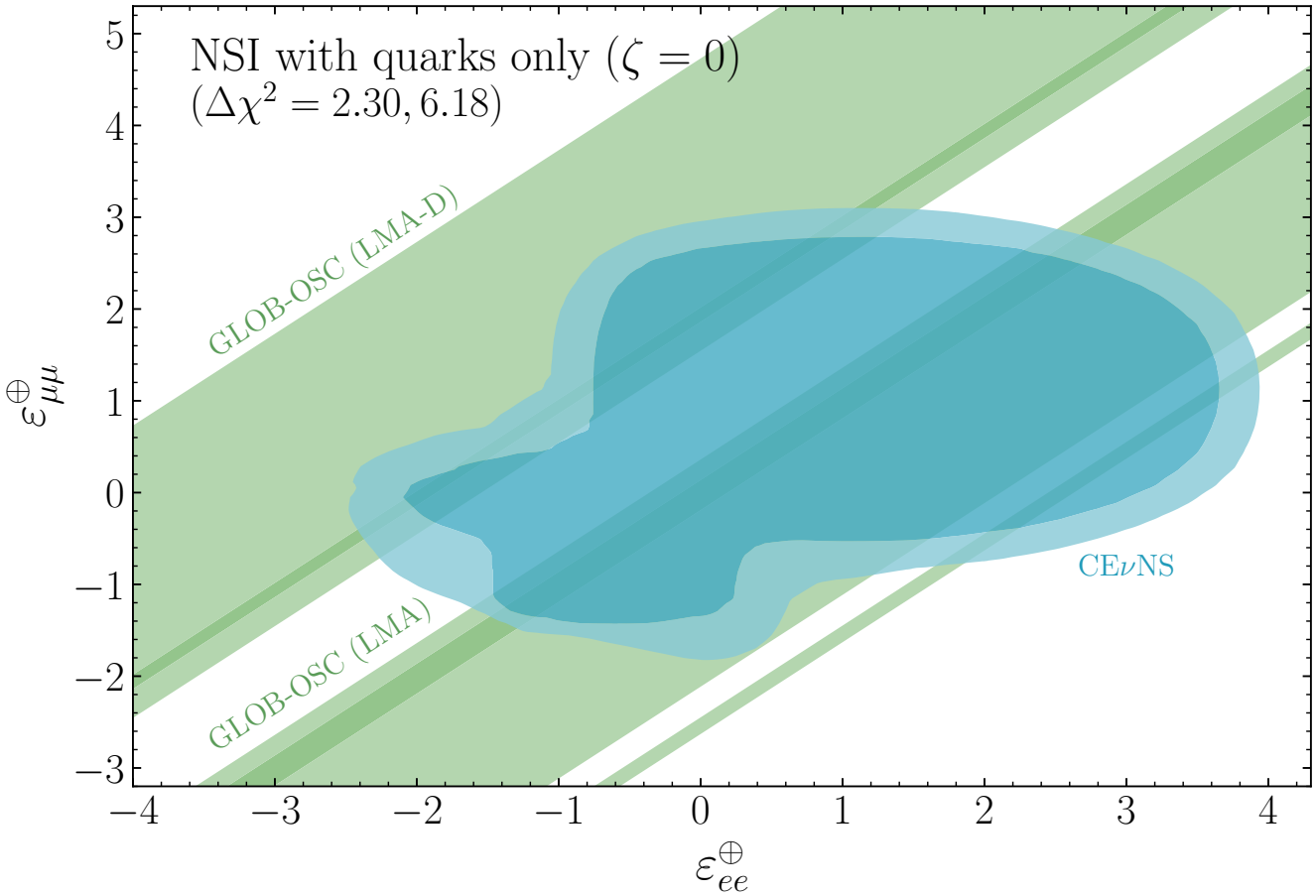
- M. C. Gonzalez-Garcia and M. Maltoni, "Determination of matter potential from global analysis of neutrino oscillation data," JHEP **1309** (2013) 152 [arXiv:1307.3092].



- P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, "A COHERENT enlightenment of the neutrino Dark Side," arXiv:1708.02899 [hep-ph].



LMA-Dark solution



P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, J. P. Pinheiro and S. Urrea, "Global constraints on non-standard neutrino interactions with quarks and electrons," JHEP **08** (2023), 032 [arXiv:2305.07698 [hep-ph]].

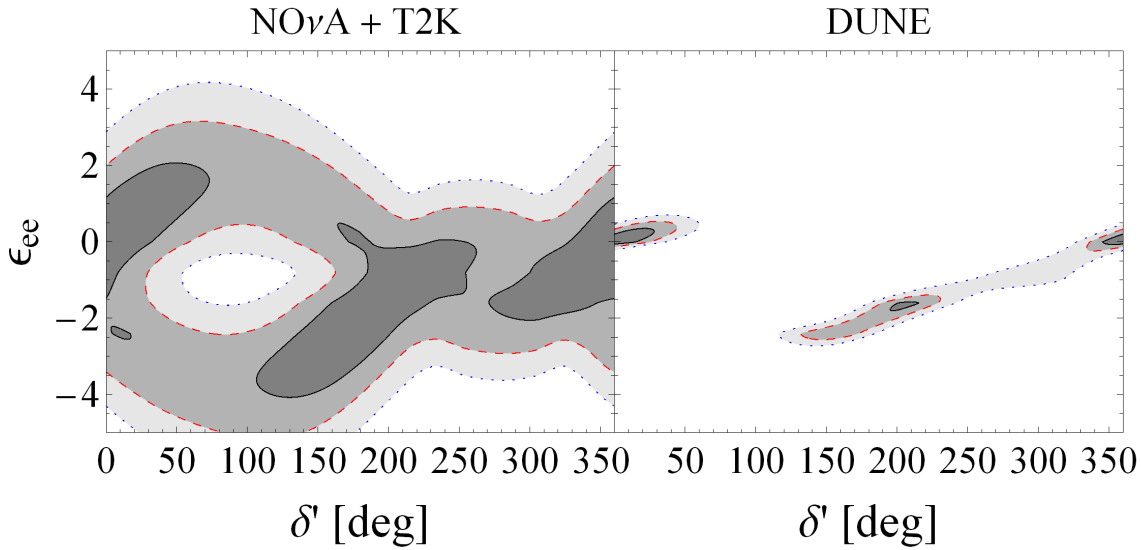
δ_{CP} degeneracies

Considering only non-zero ϵ_{ee}

$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg\cos(\Delta + \delta) + y^2 g^2 + \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3)\,, \quad (18)$$

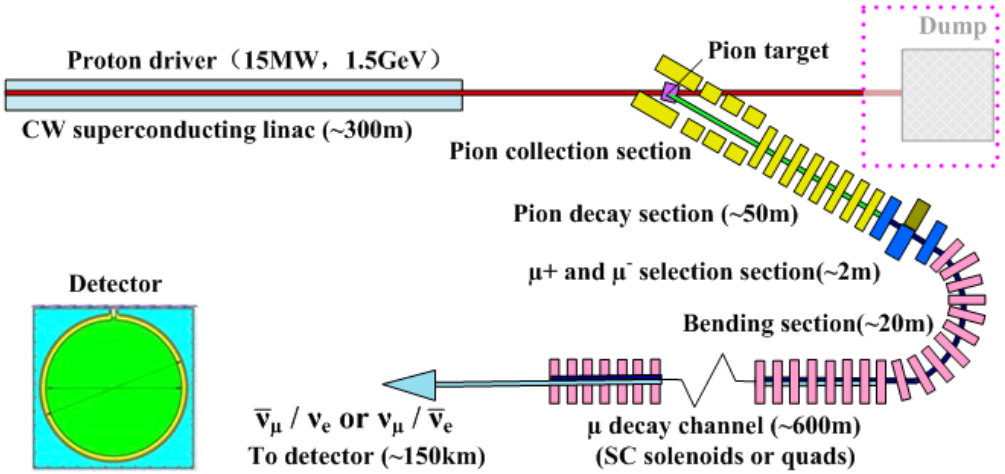
$$x \equiv 2s_{13}s_{23}\,, \quad y \equiv 2rs_{12}c_{12}c_{23}\,, \quad r = |\delta m_{21}^2/\delta m_{31}^2|\,,$$

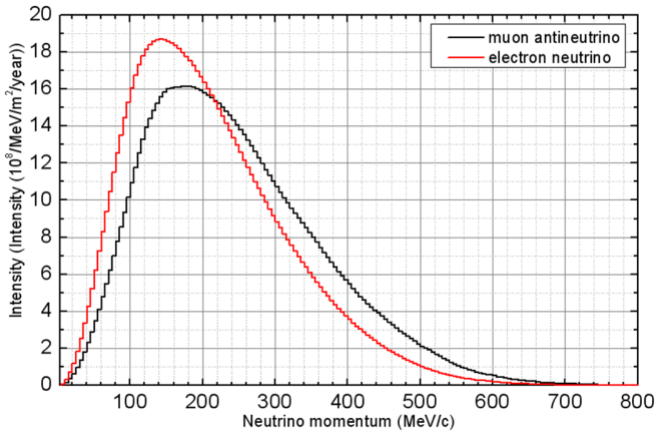
$$\mathrm{f} \equiv \frac{\sin[\Delta(1-\hat{A}(1+\epsilon_{ee}))]}{(1-\hat{A}(1+\epsilon_{ee}))}\,, \; g \equiv \frac{\sin(\hat{A}(1+\epsilon_{ee})\Delta)}{\hat{A}(1+\epsilon_{ee})}\,, \Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|\,, \; \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|\,.$$



J. Liao, D. Marfatia and K. Whisnant, Phys. Rev. D **93** (2016) no.9, 093016 [arXiv:1601.00927 [hep-ph]].

MOMENT





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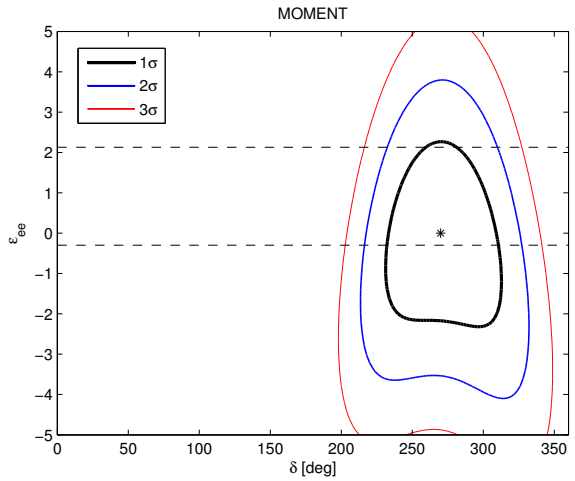
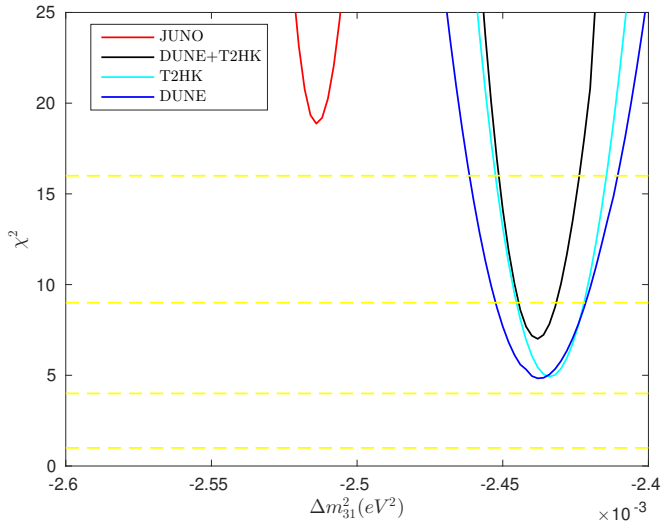
- P. B. and Y. Farzan, "CP-Violation and NSI at the MOMENT," JHEP **1607** (2016) 109 [arXiv:1602.07099 [hep-ph]].

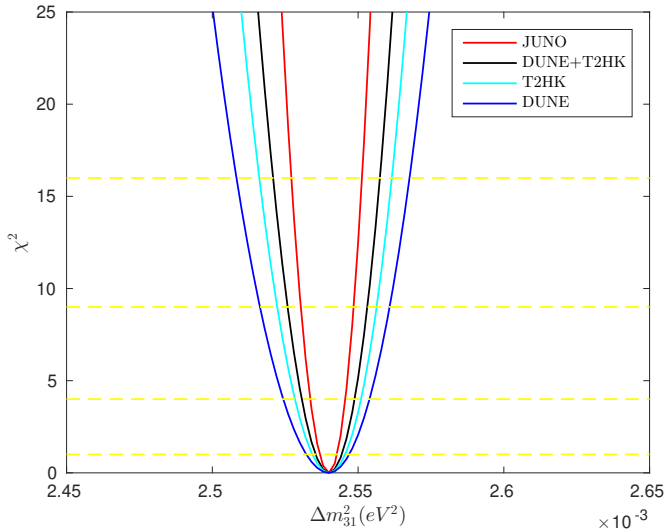


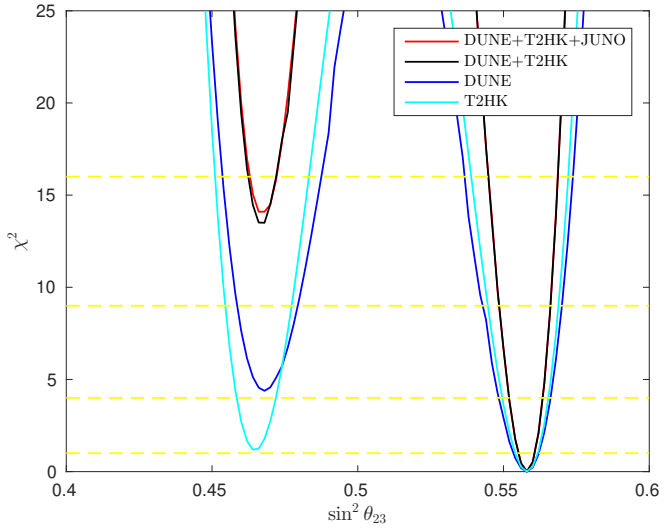
Determination of Mass Ordering in presence of NSI

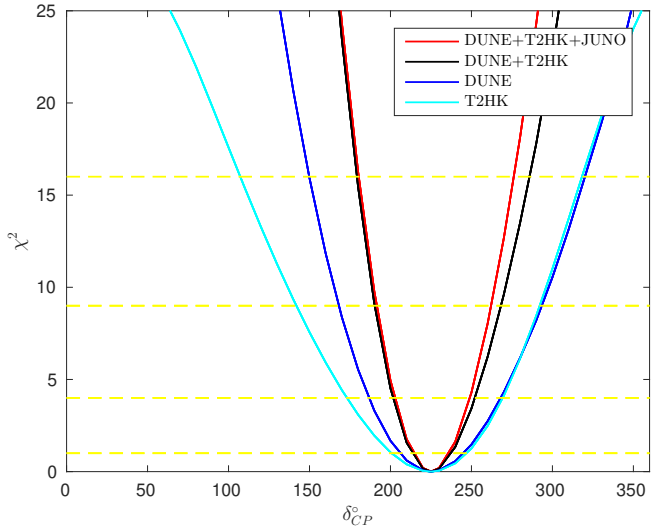
- P. B and M. Rajaee, "Sensitivities of future reactor and long-baseline neutrino experiments to NSI," Phys. Rev. D **103** (2021) no.7, 075003 [arXiv:2010.12849 [hep-ph]].
- Assuming $\epsilon^{u}_{\alpha\beta} = \epsilon^{d}_{\alpha\beta} = \epsilon^{e}_{\alpha\beta}$, LMA-DARK solution is excluded with more than 3σ
- We have considered future experiments DUNE, T2HK and JUNO
- For JUNO since the energy is low ($E_\nu = 2 - 8\ MeV$), matter effect is negligible, so NSI, thus JUNO is sensitve to mass ordering in presence of NSI
- Sensitivity of JUNO to detemine mass ordering in presnce of NSI weeker than no NSI, since oscillation parameters have larger uncertainaty in presence of NSI
- Since DUNE and T2HK have different neutrino energy range, they can break some degenaracies, for determination of θ_{23} octant and δ_{CP}

Mass Ordering, θ_{23} octant and δ_{CP} in presence of NSI



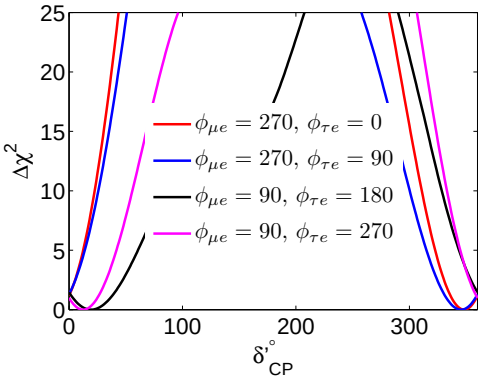






Constraints on CC NSI by near and far detectors of DUNE

$$\mathcal{L}_{\rm NSI}^{CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'L}(\overline{l_\alpha}\gamma_\lambda P_L U_{\beta a}\nu_a)(\bar{f}\gamma^\lambda P_L f')^\dagger \qquad (19)$$



Parameters	F.D.	N.D.	Current C.
$\lvert\epsilon_{ee}\rvert$	0.046	0.003	0.041
$\lvert\epsilon_{\mu\mu}\rvert$	0.015	0.002	0.078
$\lvert\epsilon_{\mu e}\rvert$	0.009	0.006	0.026
$\lvert\epsilon_{\mu\tau}\rvert$	0.074	-	0.013
$\lvert\epsilon_{e\mu}\rvert$	0.049	-	0.026
$\lvert\epsilon_{\tau\mu}\rvert$	0.076	-	0.013
$\lvert\epsilon_{\tau e}\rvert$	0.113	-	0.041

- P. B. , A. N. Khan and W. Wang, "Sensitivities to charged-current nonstandard neutrino interactions at DUNE," J. Phys. G **44** (2017) no.12, 125001

C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0908** (2009) 090 [arXiv:0907.0097 [hep-ph]].

Solar Neutrino Production

- The Sun produces a large number of neutrinos through nuclear fusion reactions in its core, which are emitted into space and can be detected on Earth.
- The primary fusion process in the Sun is the proton-proton (pp) chain, which provides 98.4% of the energy generation. The remaining 1.6% is produced by the CNO cycle.
- The pp chain is a sequence of reactions that converts hydrogen into helium, with the release of energy and the production of neutrinos.
- The first step of the pp chain is the fusion of two protons, which produces a deuteron, a positron, and a neutrino: $p + p \rightarrow d + e^+ + \nu_e$.
- According to the Standard Solar Model (SSM), pp neutrinos make up the majority (about 92%) of the solar neutrino flux.

Future studies of solar neutrinos

- Yemilab (Jinping): 2 kt scintillation detector for ν_e scattering, with high energy resolution (5%) and low-energy threshold (0.1 MeV) to detect low-energy neutrinos with good precision.
- Reactor experiment JUNO will determine Δm^2_{21} and θ_{12} with sub-percent precision, while also detecting ^{8}B, ^{7}Be, and *hep* neutrinos with good energy resolution.
- SNO+: 780 t of liquid scintillator fiducial mass, with an energy threshold of 3 MeV. The upgraded version will have a lower threshold.
- DUNE: 40 kton liquid argon detector with a 10 MeV energy threshold, aiming to study not only solar neutrinos but also neutrinos from supernovae and atmospheric neutrinos.
- Hyper-Kamiokande (KNO): energy threshold of 6.5 MeV, with several 100 kt detectors planned, offering unprecedented sensitivity to solar neutrinos.
- THEIA: water-based liquid scintillator with 1% doping by ^{7}Li, allowing for low-energy threshold and good background rejection.

Day-Night Asymmetry and NSI

P. B and M. Rajaee, Phys. Rev. D **102** (2020) no.3, 035024 [arXiv:2003.12984 [hep-ph]].

$$P_D(E) = \frac{1}{2}c_{13}^4\left[1 + \cos 2\theta_{12}\cos 2\tilde{\theta}_{12}(E)\right] + s_{13}^4 \tag{20}$$

$$N_{D(N)} = A\int dE g_\nu(E^r, E)\sigma(E)f_B(E)P(E)_{D(N)} \tag{21}$$

$$\Delta P(E,\eta) = P_N - P_D = \kappa(E)\left[\int_0^L dx\ V(x)\sin\phi^m(L-x,E) + I_2\right] \tag{22}$$

$$\kappa(E) \equiv -\frac{1}{2}c_{13}^4\cos 2\tilde{\theta}_{12}^s\sin 2\theta_{12}(\sin 2\theta_{12}(c_{13}^2 - 2\epsilon_D^E) + 2\cos 2\theta_{12}\epsilon_N^E) \tag{23}$$

$$\phi^m(L-x,E) \equiv \int_x^L dx\ \Delta_{21}^m(x) \approx \int_x^L dx\Delta_{21}(1 - c_{13}^2\cos 2\theta_{12}a_{CC}^E) \tag{24}$$

Neutral Current NSI Effect on Electron Neutrino Scattering

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1)^2 + (g_2)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2}\right] \quad (25)$$

within the standard model

$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \frac{1}{2} + \sin^2\theta_W = 0.73 \quad (26)$$

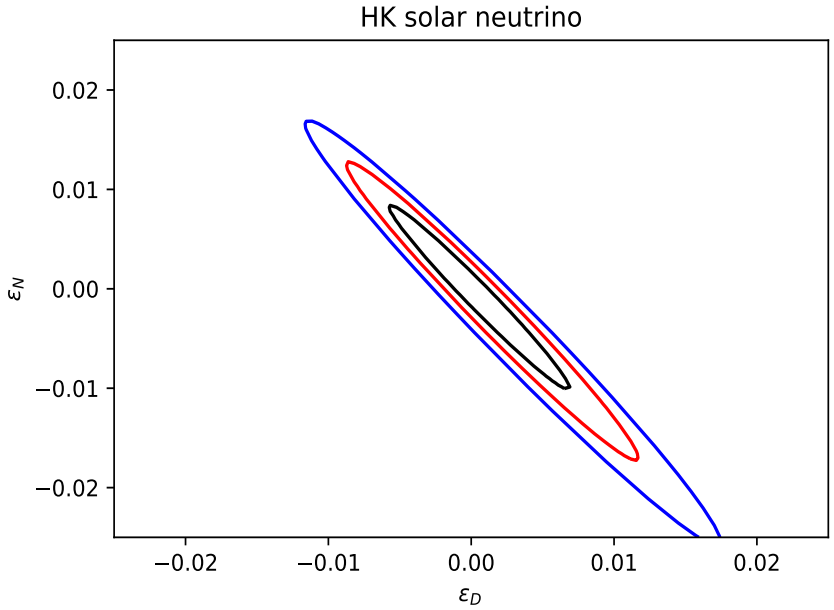
$$g_2^{\nu_e} = g_1^{\bar{\nu}_e} = g_2^{\nu_\mu} = g_1^{\bar{\nu}_\mu} = \sin^2\theta_W = 0.23 \quad (27)$$

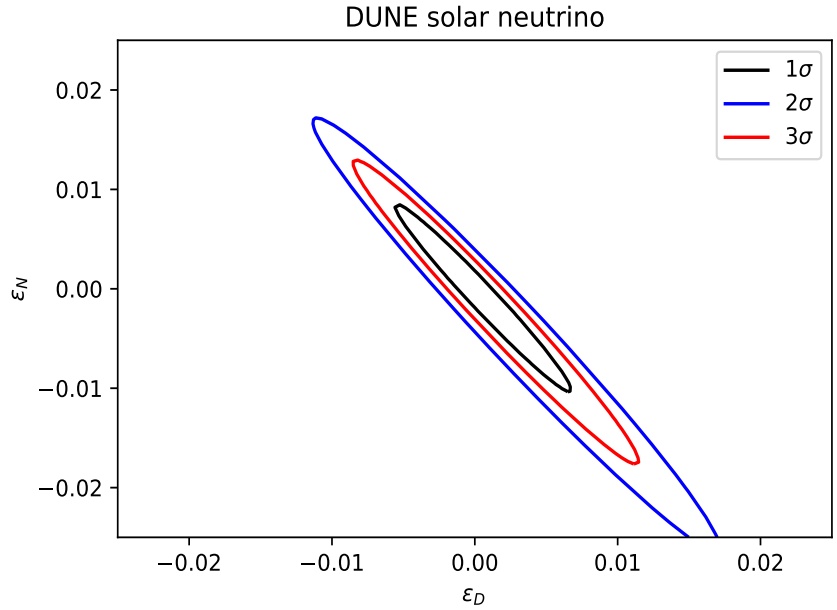
$$g_1^{\nu_\mu} = g_2^{\bar{\nu}_\mu} = -\frac{1}{2} + \sin^2\theta_W = -0.27 \quad (28)$$

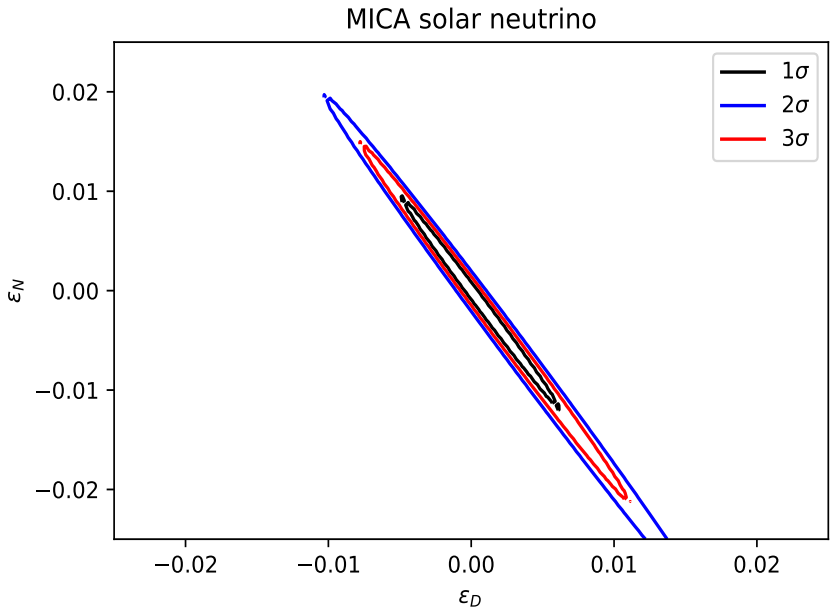
Considering the neutral current NSI

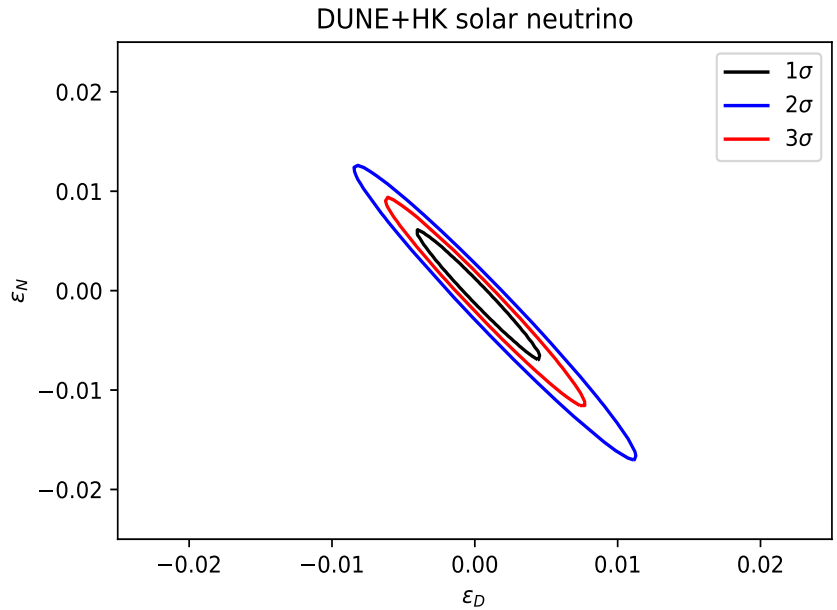
$$g_1^{e\ NSI} = g_1^e + \epsilon_{ee}^{eL} \quad (29)$$

$$g_2^{e\ NSI} = g_2^e + \epsilon_{ee}^{eR} \quad (30)$$

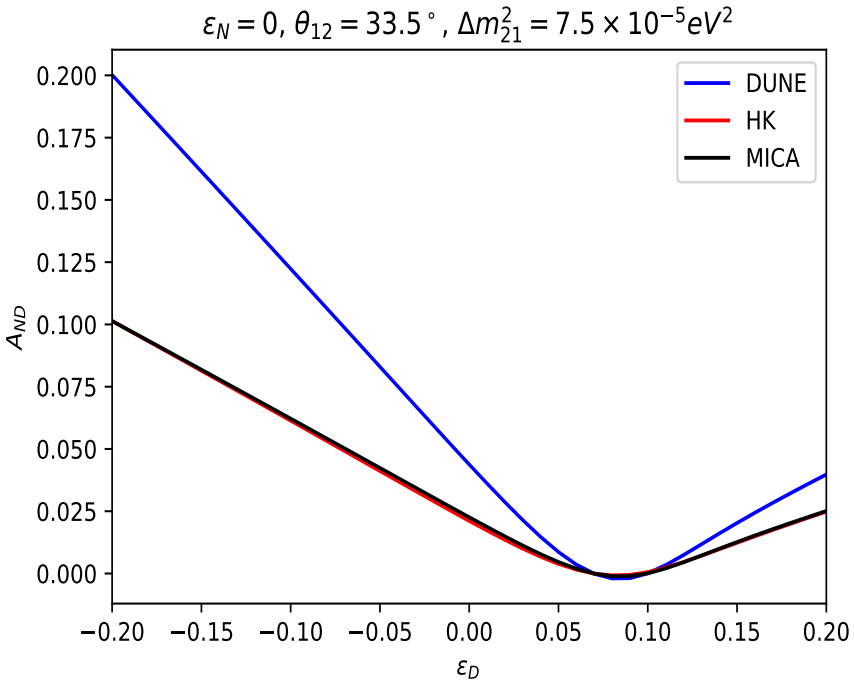

HK solar neutrino
0.02
0.01
0.00
−0.01
−0.02
ε_N
−0.02
−0.01
0.00
0.01
0.02
ε_D

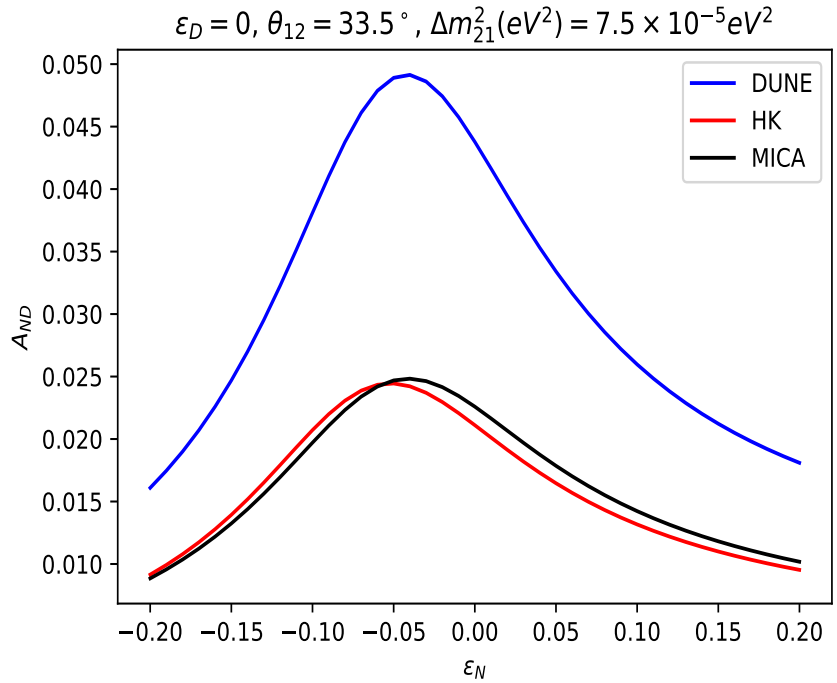

DUNE solar neutrino
1σ
2σ
3σ
0.02
0.01
0.00
−0.01
−0.02
ε_N
−0.02
−0.01
0.00
0.01
0.02
ε_D


MICA solar neutrino
1σ
2σ
3σ
0.02
0.01
0.00
−0.01
−0.02
ε_N
−0.02
−0.01
0.00
0.01
0.02
ε_D

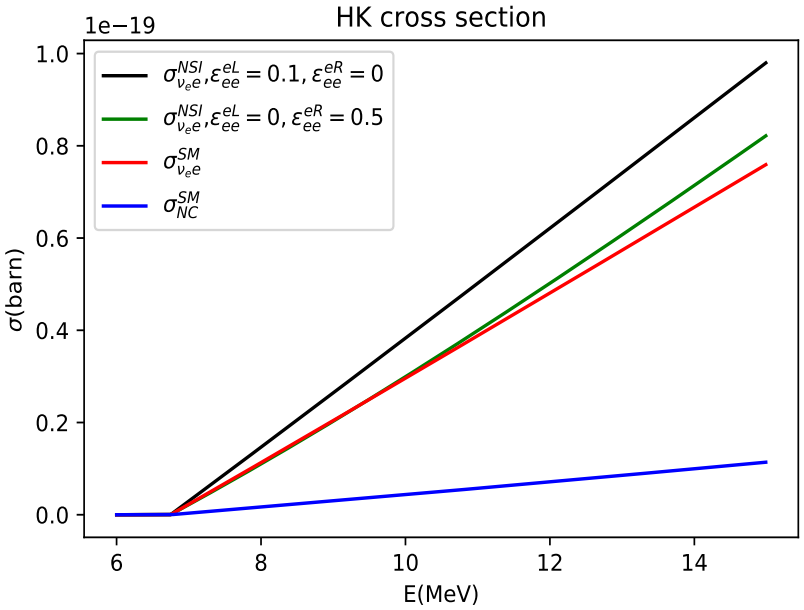

DUNE+HK solar neutrino
1σ
2σ
3σ
0.02
0.01
0.00
−0.01
−0.02
ε_N
−0.02
−0.01
0.00
0.01
0.02
ε_D

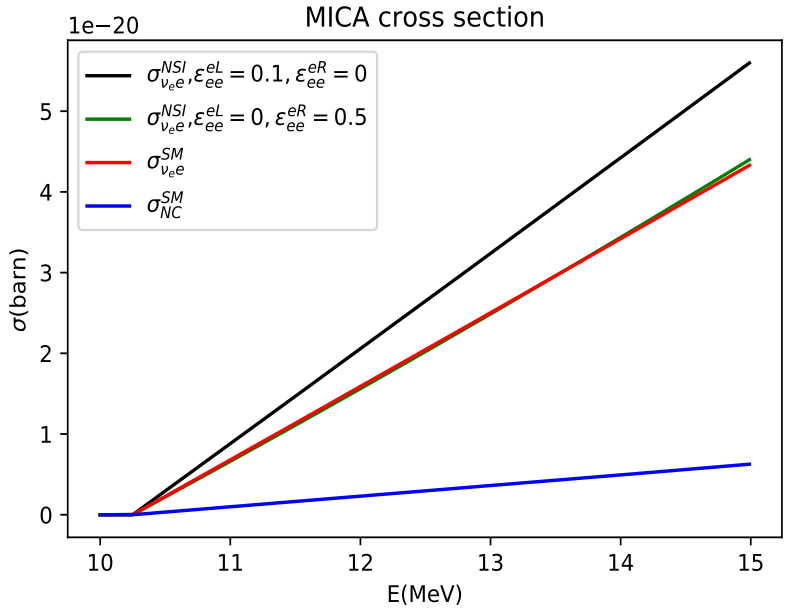
Day-Night Asymmetry

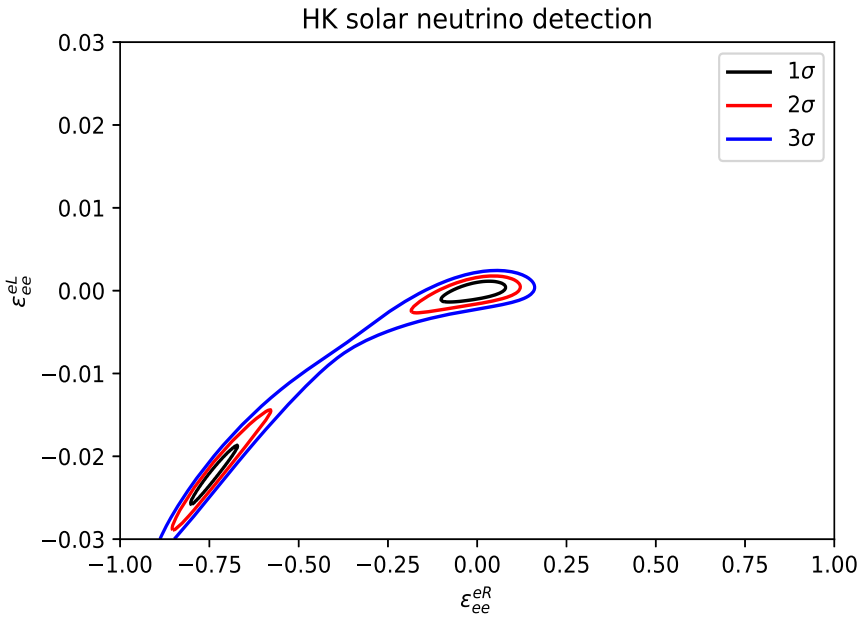


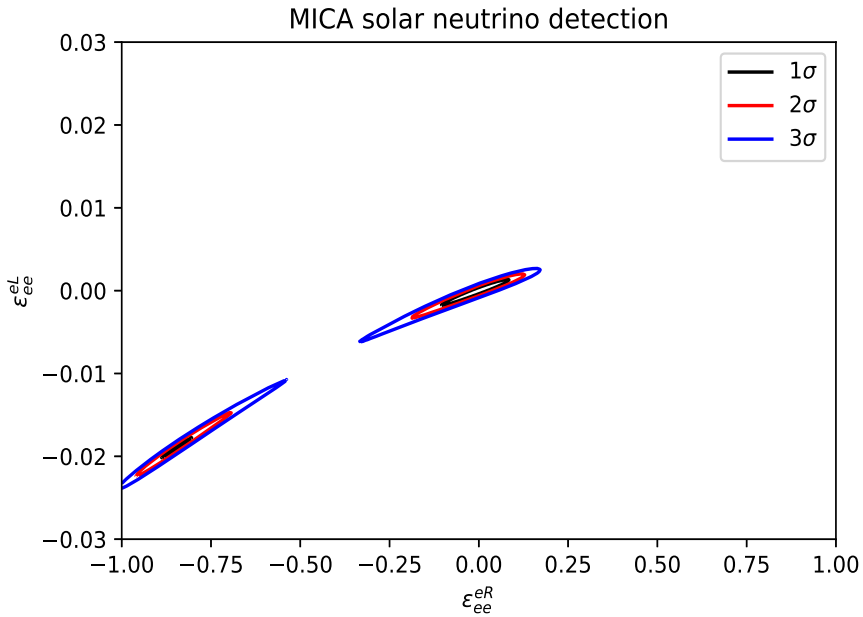


- constraints on ϵ_N will be 0.014, 0.014, and 0.007 respectively by DUNE, HK, and MICA
- constraints on ϵ_D will be 0.004, 0.004, and 0.002 respectively by DUNE, HK, and MICA

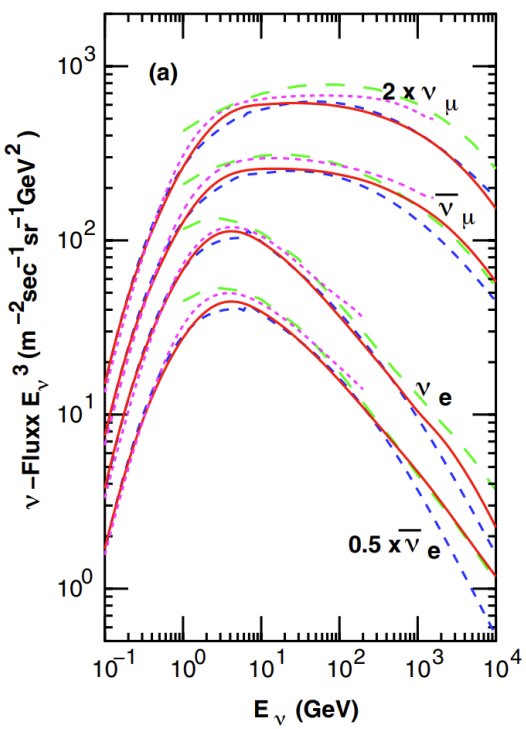

HK cross section
1e−19
$\sigma^{NSI}_{\nu_e e}, \varepsilon^{eL}_{ee} = 0.1, \varepsilon^{eR}_{ee} = 0$
$\sigma^{NSI}_{\nu_e e}, \varepsilon^{eL}_{ee} = 0, \varepsilon^{eR}_{ee} = 0.5$
$\sigma^{SM}_{\nu_e e}$
σ^{SM}_{NC}
σ(barn)
E(MeV)

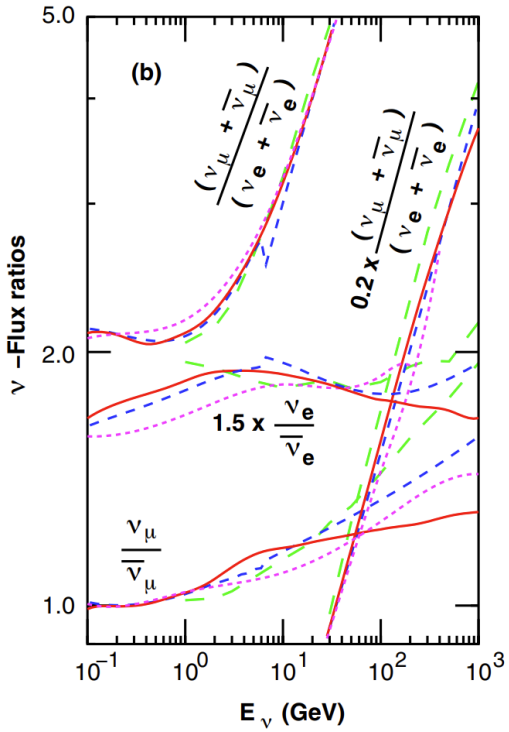

MICA cross section
1e−20
$\sigma^{NSI}_{\nu_e e}, \varepsilon^{eL}_{ee} = 0.1, \varepsilon^{eR}_{ee} = 0$
$\sigma^{NSI}_{\nu_e e}, \varepsilon^{eL}_{ee} = 0, \varepsilon^{eR}_{ee} = 0.5$
$\sigma^{SM}_{\nu_e e}$
σ^{SM}_{NC}
σ(barn)
E(MeV)

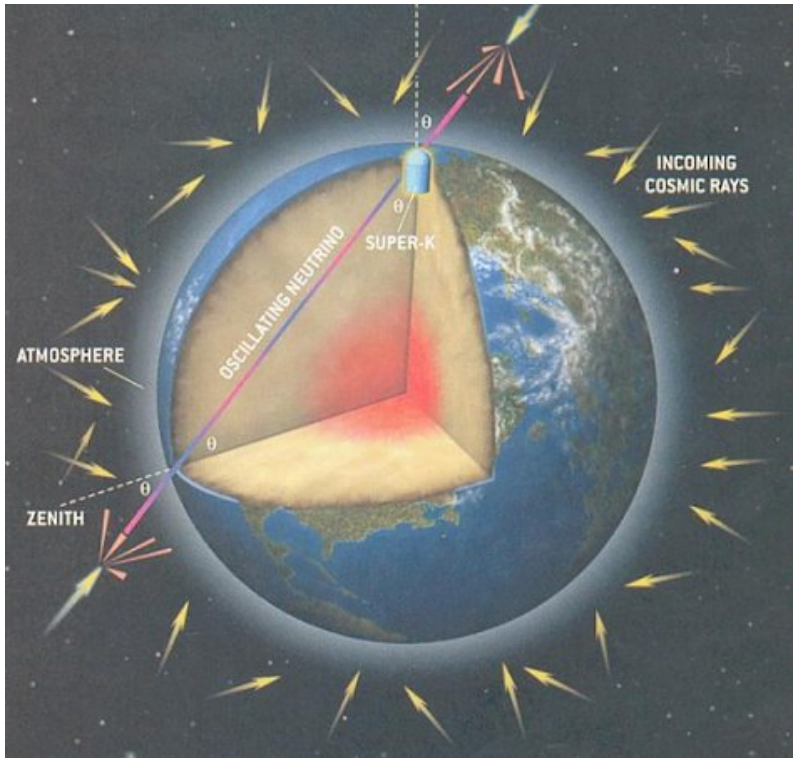

HK solar neutrino detection
1σ
2σ
3σ
ε^{eL}_{ee}
ε^{eR}_{ee}


MICA solar neutrino detection
1σ
2σ
3σ
ε^{eL}_{ee}
ε^{eR}_{ee}

Atmospheric neutrino experiments



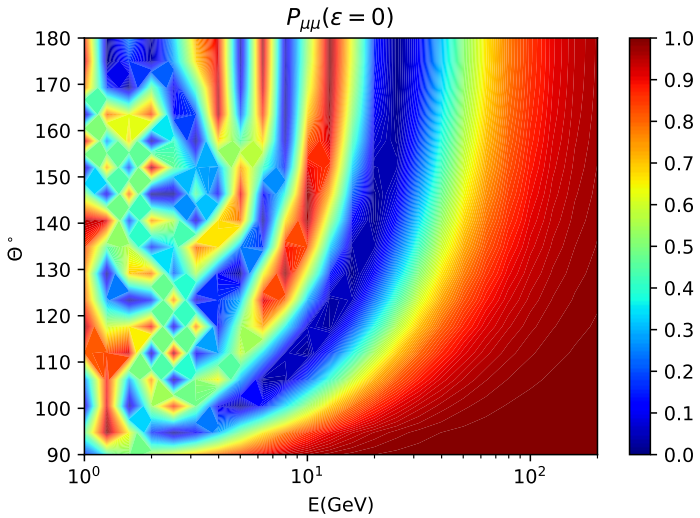


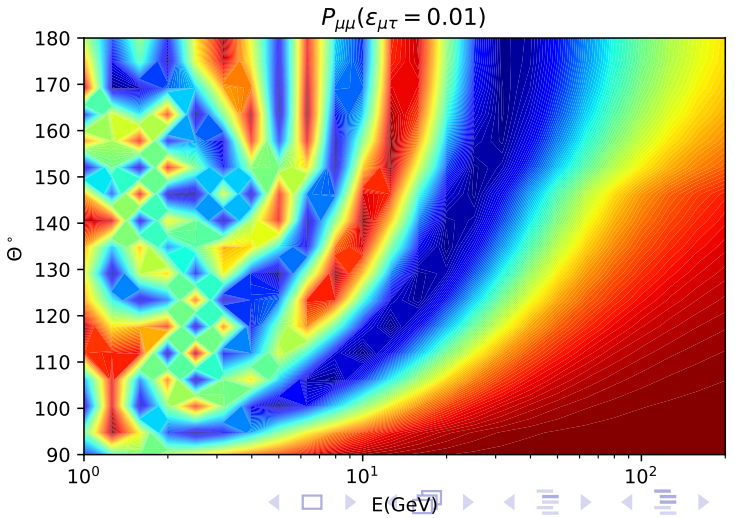


Carlo Giunti, Chung W. Kim - Fundamentals of Neutrino Physics and Astrophysics-Oxford University Press, USA (2007)
https://universe-review.ca/I15-24-neutrino3.jpg

NSI in Atmospheric neutrino experiments

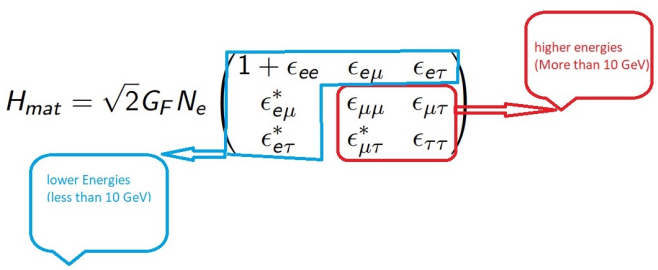
- P. B, M. Rajaee and S. Shin, "Nonstandard interaction of atmospheric neutrino in future experiments," Phys. Rev. D **106** (2022) no.11, 115029 [arXiv:2206.02594 [hep-ph]].
- For energies $E > 10$ GeV, energies much above the θ_{13} resonance, oscillation probabilities obtained for 2 system is a good approximation.
- For energies more than 10 GeV, the only relevant NSI parameters are $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$
- Oscillograms for theprobability $P_{\mu\mu}$ assuming $\delta_{CP} = 0°$.

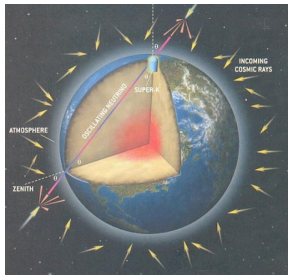




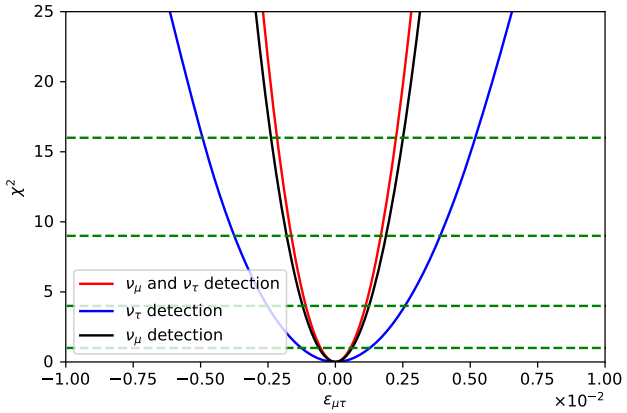
Constraints on NSI using atmospheric neutrinos

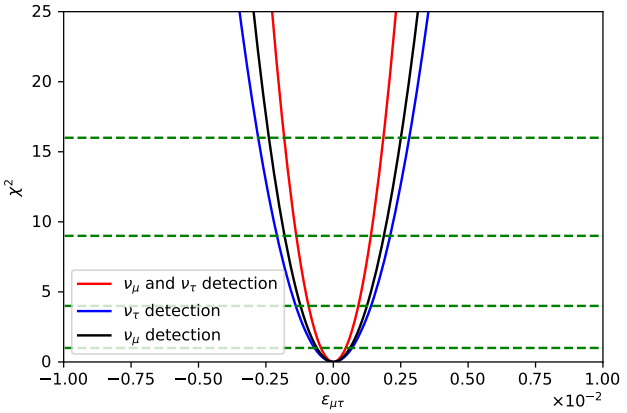
- In the energy range of 1 -10 GeV, the effect of δ_{CP} becomes more significant because of the θ_{13} resonance effect



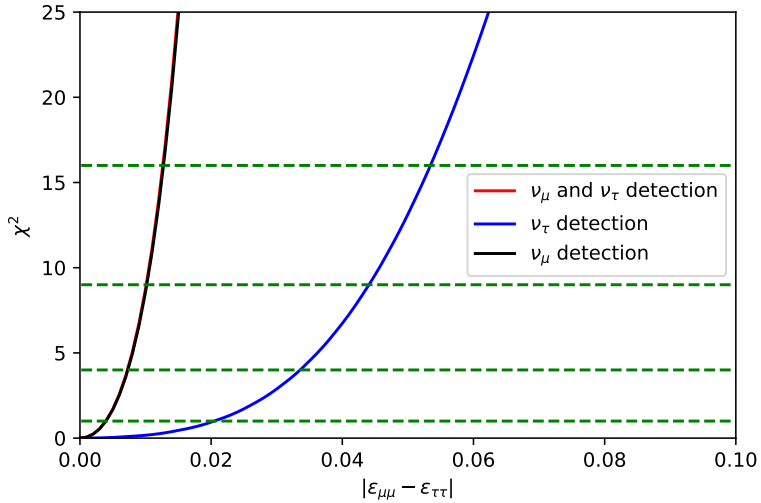


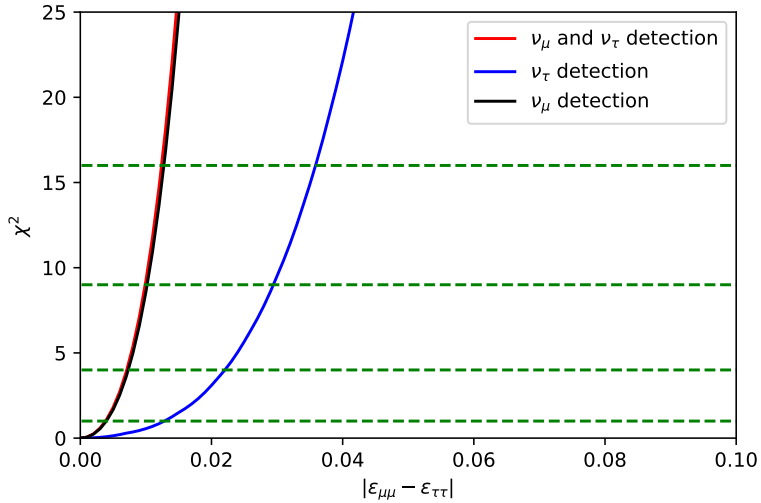
- Tau neutrino detection efficiency of 30% and 100%

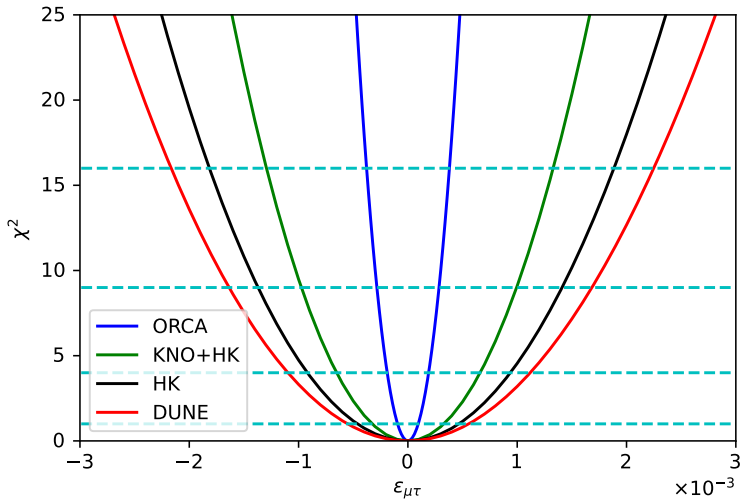


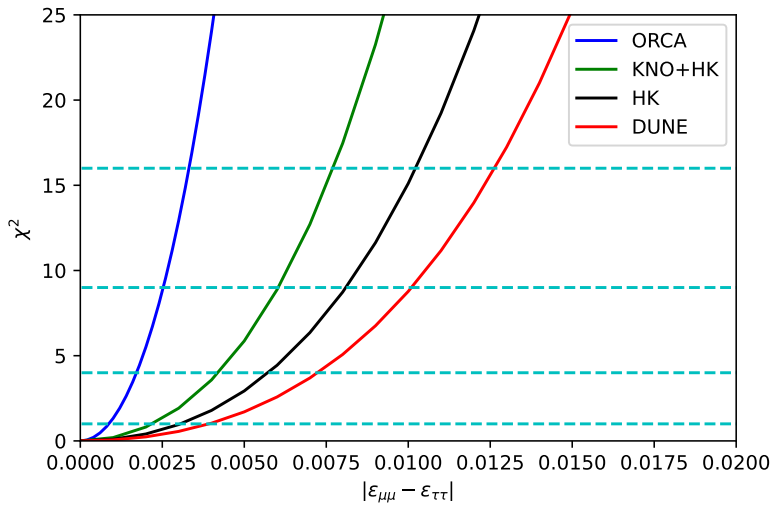


Constraints on $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$

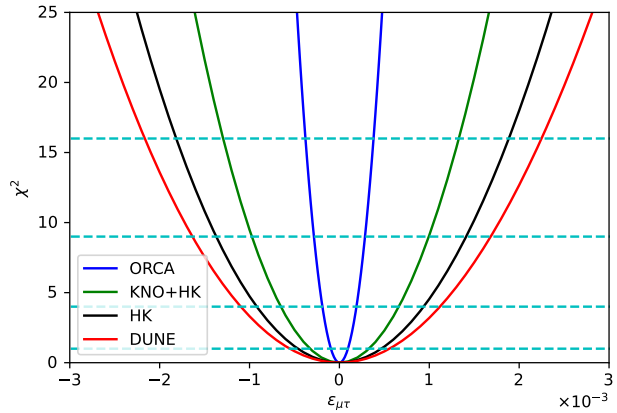


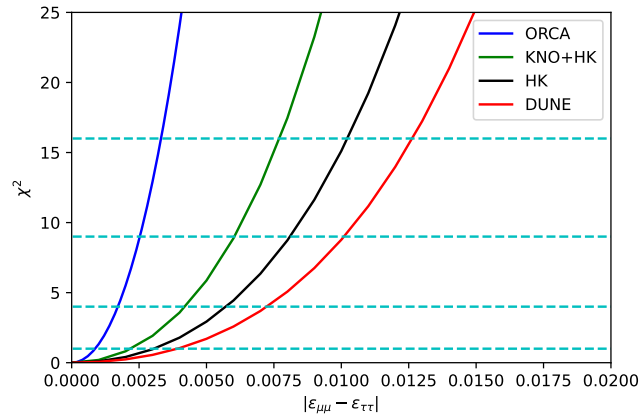




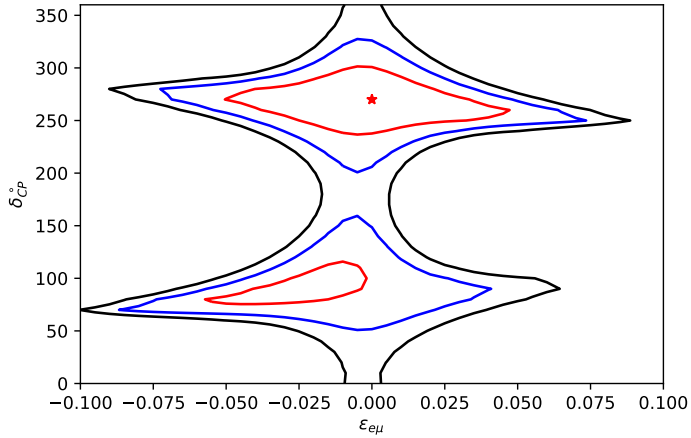


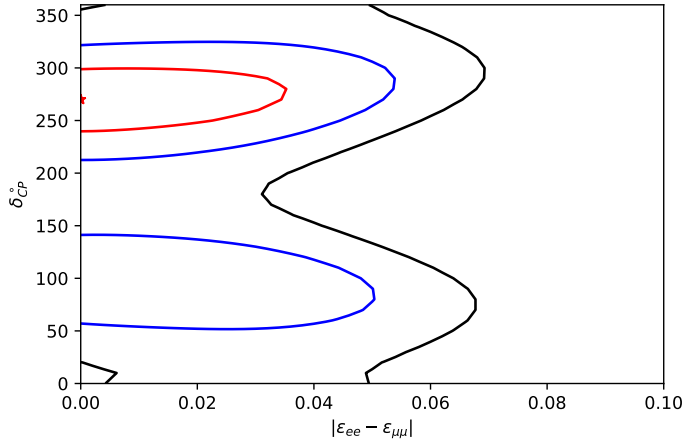
- Constraints of $\epsilon_{e\mu}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$





- Atmospheric neutrinos at HK





NSI at Atmospheric Neutrinos

- We have investigated the impact of the NSI parameters $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$ on the future atmospheric neutrino experiments DUNE, HK, ORCA and KNO using 10 years of simulated data.
- Our analysis shows that ORCA and HK+KNO can improve the current constraints on $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$ by two orders of magnitudes.
- HK+KNO can improve the constraints on $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{ee}|$ by one order of magnitude.
- HK+KNO can determine δ_{CP} in presence of NSI with 3σ C.L.

Summary

- NSI parameters uncertainaty affect the oscillation parameters measurements
- Short-baseline neutrino exeperiments can study both CC NSI and NC NSI and test LMA-Dark solution
- Effect of NC NSI can be studied by combining a low energy and a high energy neutrino experiment
- NSI effcet solar neutrinos for flavour change at the production region, day-night assymetry and detection
- High energy atmospheric neutrinos set the most stringent constraints on $\epsilon_{\mu\tau}$ and $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$
- At low energy (1-10 GeV), θ_{13} resonce condition is important, there are sensitivity to all NSI parameters and there is deneracy between δ_{CP} and NSI

Thank you for your attention.