Non-Standard neutrino Interaction (NSI) and future atmospheric neutrino oscillation experiments

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Reference

- P. Bakhti and M. Rajaee, S. Shin, "Non-Standard Interaction of atmospheric neutrino in future experiments".

Overview

1. Introduction
2. Non-Standard neutrino Interaction (NSI)
3. Atmospheric neutrinos
4. Details of the Experiments
5. Oscillation probabilities
6. Constraints on NSI
7. Summary

- Neutrinos are massive elementary particles which their mass is much less than other massive elementary particles
- Neutrinos are produced via weak interaction in: reactor, sun, supernova, atmosphere, accelarator, ...
- There are three flavours of neutrino (ν_e, ν_μ, ν_τ)
- Flavour of neutrinos are changed during their propagation

Neutrino Oscillation

There is a mixing between mass and flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle\,,\ \alpha = e,\mu,\tau, \quad i = 1,2,3 \tag{1}$$

PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \tag{2}$$

Neutrino oscillation in vacuum

$$P_{\nu_\alpha\to\nu_\beta} = \sum_{k,j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}e^{-i\frac{\Delta m^2_{kj}L}{2E}} \tag{3}$$

Neutrino Oscillation in Vacuum

$$H\left|\nu_k\right\rangle = E_k\left|\nu_k\right\rangle = i\frac{d}{dt}\left|\nu_k(t)\right\rangle \tag{4}$$

$$\left|\nu_k(t)\right\rangle = e^{-iE_k t}\left|\nu_k\right\rangle \tag{5}$$

$$\left|\nu_\alpha(t)\right\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t}\left|\nu_k\right\rangle \tag{6}$$

$$\left|\nu_\alpha(t)\right\rangle = \sum_\beta \sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}\left|\nu_\beta\right\rangle \tag{7}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t} \tag{8}$$

$$E_k \simeq E + \frac{m_k^2}{2E},\ E_k - E_j \simeq \frac{\Delta m^2_{kj}}{2E} \equiv \frac{m_k^2 - m_j^2}{2E}$$

Neutrino Oscillation parameters

NuFIT 2.2 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.56$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.348$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.348$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.440^{+0.023}_{-0.019}$	$0.388 \to 0.630$	$0.584^{+0.018}_{-0.022}$	$0.398 \to 0.634$	$0.388 \to 0.632$
$\theta_{23}/^\circ$	$41.5^{+1.3}_{-1.1}$	$38.6 \to 52.5$	$49.9^{+1.1}_{-1.3}$	$39.1 \to 52.8$	$38.6 \to 52.7$
$\sin^2\theta_{13}$	$0.02163^{+0.00074}_{-0.00074}$	$0.01938 \to 0.02388$	$0.02175^{+0.00075}_{-0.00074}$	$0.01950 \to 0.02403$	$0.01938 \to 0.02396$
$\theta_{13}/^\circ$	$8.46^{+0.14}_{-0.15}$	$8.00 \to 8.89$	$8.48^{+0.15}_{-0.15}$	$8.03 \to 8.92$	$8.00 \to 8.90$
$\delta_{\rm CP}/^\circ$	289^{+38}_{-51}	$0 \to 360$	269^{+39}_{-45}	$146 \to 377$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.526^{+0.039}_{-0.037}$	$+2.413 \to +2.645$	$-2.518^{+0.038}_{-0.037}$	$-2.634 \to -2.406$	$\begin{bmatrix} +2.413 \to +2.645 \\ -2.630 \to -2.409 \end{bmatrix}$

Neutrino Oscillation in Matter

- Forward elastic scattering processes affect neutrino oscillation

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{9}$$

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1,0,0) \tag{10}$$

$$\mathcal{H}_{vac} = U_{PMNS} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^{\dagger}_{PMNS} \tag{11}$$

- Considering 2ν Oscillation

$$i \frac{d}{dx} \psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{12}$$

$$\psi^T = (\psi_{ee}, \psi_{e\mu}) \tag{13}$$

Neutrino Oscillation in Matter

$$\mathcal{H}_F = \begin{bmatrix} -\Delta m^2 \cos 2\theta + A_{CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - A_{CC} \end{bmatrix} \tag{14}$$

$$A_{CC} = 2\sqrt{2} E G_F N_E \tag{15}$$

$$\mathcal{H}_M = U_M \mathcal{H}_F U_M \tag{16}$$

$$U_M = \begin{bmatrix} \cos 2\theta_M & \sin \theta_M \\ -\sin \theta_M & \cos 2\theta_M \end{bmatrix} \tag{17}$$

$$\mathcal{H}_M = diag(-\Delta m_M^2, \Delta m_M^2) \tag{18}$$

Neutrino Oscillation in Matter

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{19}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{20}$$

$$A_{CC}^R = \Delta m^2 \cos 2\theta \tag{21}$$

$$N_e^R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} E G_F} \tag{22}$$

In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$

- NC NSI

$$\mathcal{L}_{\text{NSI}}^{NC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fC}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f\right) \tag{23}$$

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{e} + (N_d/N_e)\epsilon_{\alpha\beta}^{d} + (N_u/N_e)\epsilon_{\alpha\beta}^{u} \tag{24}$$

- CC NSI (pion decay)

$$\mathcal{L}_{\text{NSI}}^{CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{udL}(\overline{l_\alpha}\gamma_\lambda P_L U_{\beta a}\nu_a)(\bar{d}\gamma^\lambda P_L u)^\dagger \tag{25}$$

- CC NSI (muon decay)

$$\mathcal{L}_{\text{NSI}}^{CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{L}(\overline{e}\gamma_\lambda P_L U_{\alpha a}\nu_a)(\overline{\mu}\gamma^\lambda P_L U_{\beta b}\nu_b)^\dagger \tag{26}$$

- Assuming neutral-current non-standard neutrino interaction

$$H_{mat} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \tag{27}$$

- Current constraints on NC NSI parameters (arXiv:1307.3092)

$$\begin{aligned} |\epsilon_{e\mu}| &< 0.16 \\ |\epsilon_{e\tau}| &< 0.26 \\ |\epsilon_{\mu\tau}| &< 0.02 \end{aligned} \tag{28}$$

and

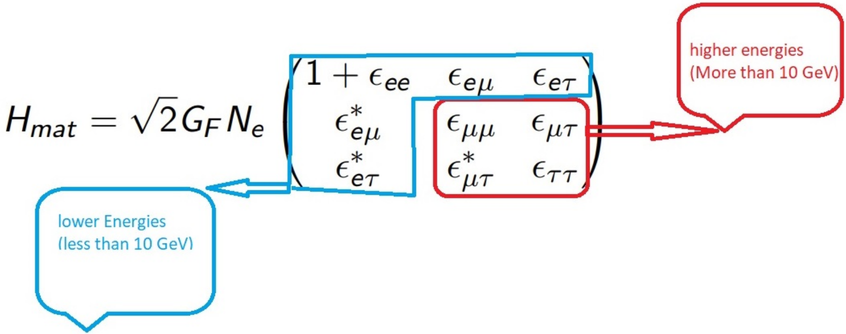
$$\begin{aligned} -0.018 &< \epsilon_{\tau\tau} - \epsilon_{\mu\mu} < 0.054 \\ 0.35 &< \epsilon_{ee} - \epsilon_{\mu\mu} < 0.93. \end{aligned} \tag{29}$$

- NC NSI affect neutrino oscillation during propagation in matter
- CC NSI affect flavour change in neutrino production and detection
- MSW effect of ν and DM interaction, K. Y. Choi, E. J. Chun and J. Kim, "Neutrino Oscillations in Dark Matter, Phys. Dark Univ. **30** (2020), 100606 [arXiv:1909.10478 [hep-ph]].

Constraints on CC NSI by near and far detectors of DUNE

Parameters	Far Detector	Near Detector	Current Constraints
$\lvert\epsilon_{ee}\rvert$	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. Bakhti , A. N. Khan and W. Wang, “Sensitivities to charged-current nonstandard neutrino interactions at DUNE,” J. Phys. G 44 (2017) no.12, 125001 [arXiv:1607.00065 [hep-ph]].



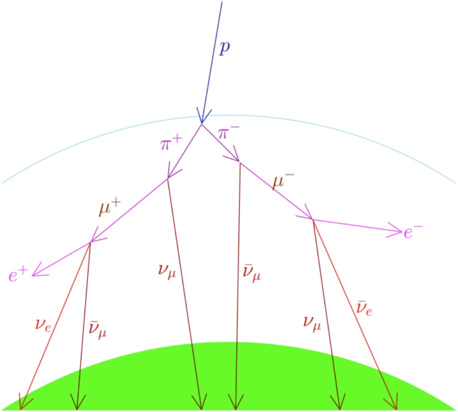
$$H_{mat} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

higher energies
(More than 10 GeV)

lower Energies
(less than 10 GeV)

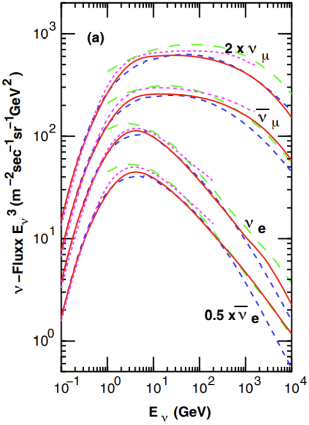
	$E < 10$ GeV	10 GeV$< E < 200$ GeV	$E >$200 GeV
depends on δ_{CP}	Yes	No	No
ν_{atm} Statistics	High	High	Low
ν_{LBL} Statistics	High	Low	Non

Atmospheric neutrino experiments



Carlo Giunti, Chung W. Kim - Fundamentals of Neutrino Physics and Astrophysics-Oxford University Press, USA (2007)

Atmospheric neutrino experiments



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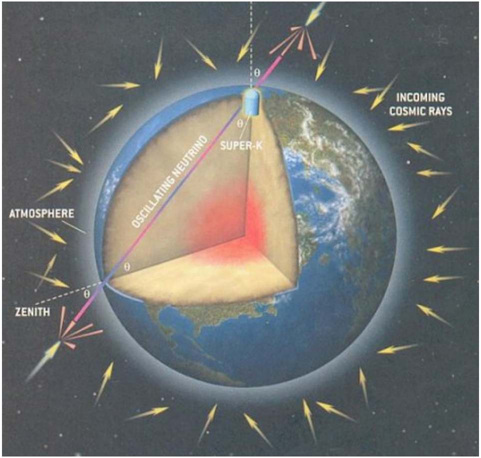
Atmospheric neutrino experiments

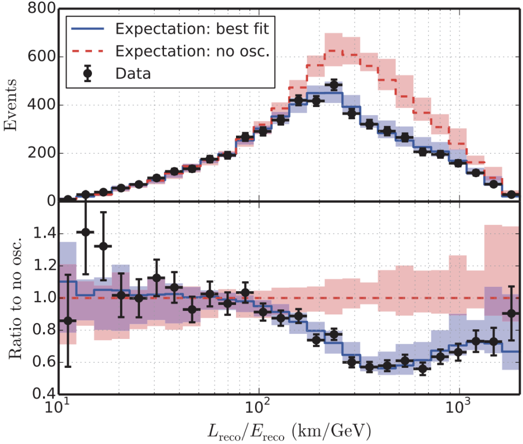


https://universe-review.ca/I15-24-neutrino3.jpg

Oscillation probability of atmospheric neutrinos

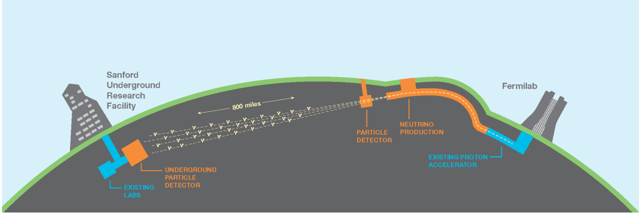
- $P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2(\frac{1.267\Delta m^2(eV^2)L(km)}{E(GeV)})$
- $P_{\mu e} = \sin^2 2\theta_{23} \sin^2 2\theta_{13}^m \sin^2(\frac{1.267\Delta m^2(eV^2)L(km)}{E(GeV)})$
- $\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - \frac{2V_e^{CC}E_\nu}{\Delta_{31}^2})^2 + \sin^2 2\theta_{13}}$
- resonant features are not present for antineutrinos when the mass hierarchy is normal

Atmospheric neutrino oscillation



THE STATE OF THE ART OF NEUTRINO PHYSICS,ISBN 9813226080

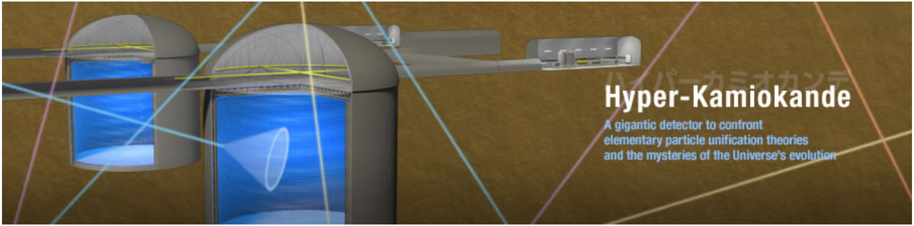
DUNE



http://lbnf.fnal.gov/

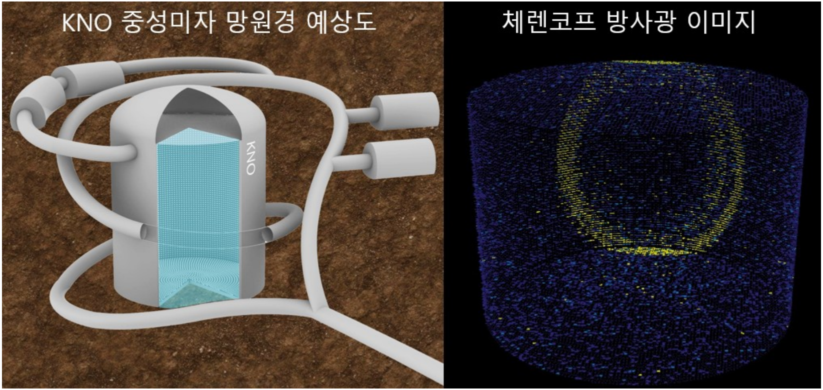
- Deep Underground Neutrino Experiment (DUNE)
- 1300 km baseline and $250MeV < E < 8GeV$ peak around 3 GeV
- Atmosphric neutrino, Solar neutrino and SN neutrino
- Liquid Argon Time-Projection Chamber(LArTPC) with 40 kton fiducial mass

Hyper Kamikande



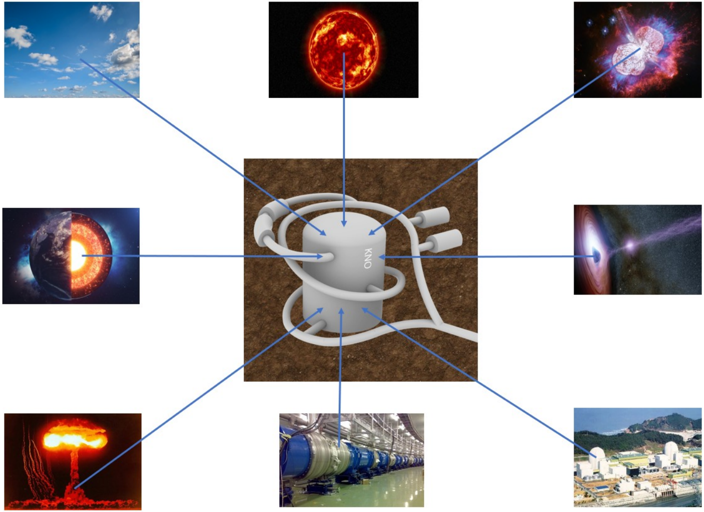
- fiducial mass of HK: 200 kton

Korea Neutrino Observatory (KNO)

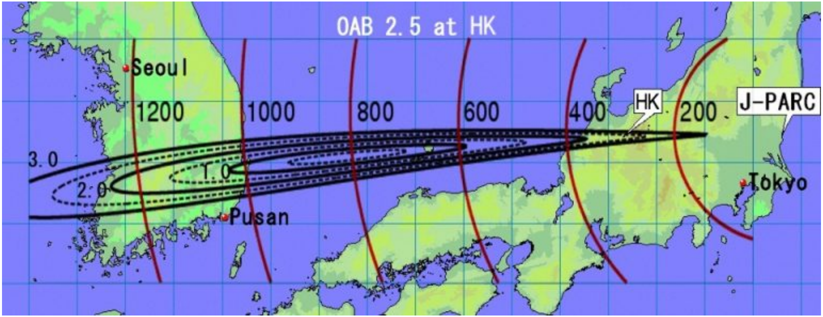


- fiducial mass of KNO: 200 kton

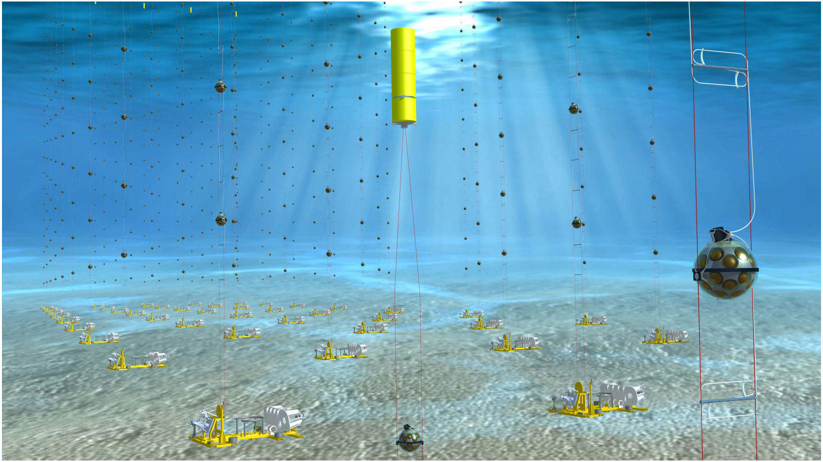
Korea Neutrino Observatory (KNO)



Korea Neutrino Observatory (KNO)



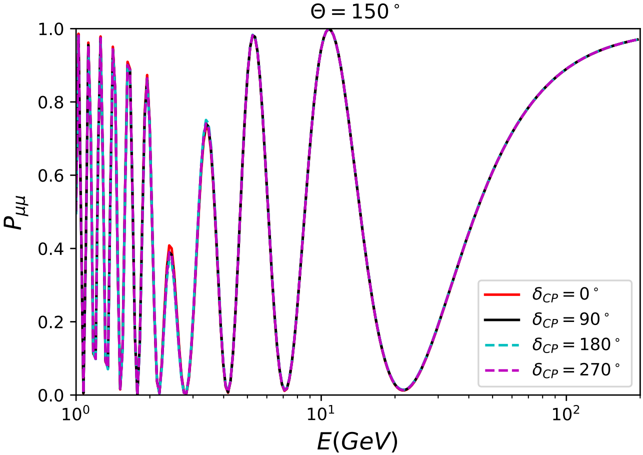
ORCA



- 6 Mton fiducial mass, Energy threshold of 3 GeV, 50% efficiency for ν detection with energies lower than 10 GeV

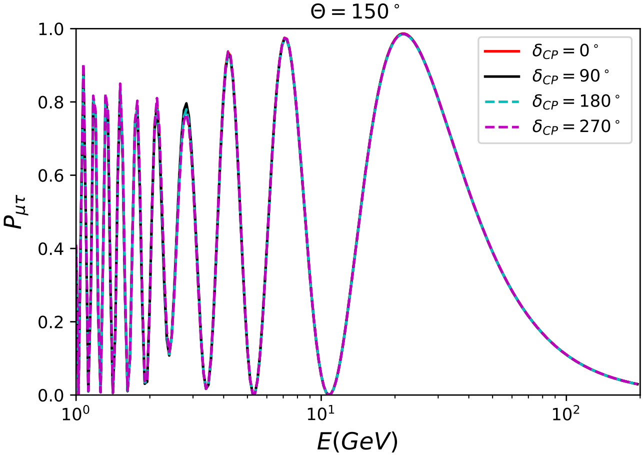
Atmospheric neutrino oscillation probability

For higher energies oscillation probability does not depends on δ_{CP}

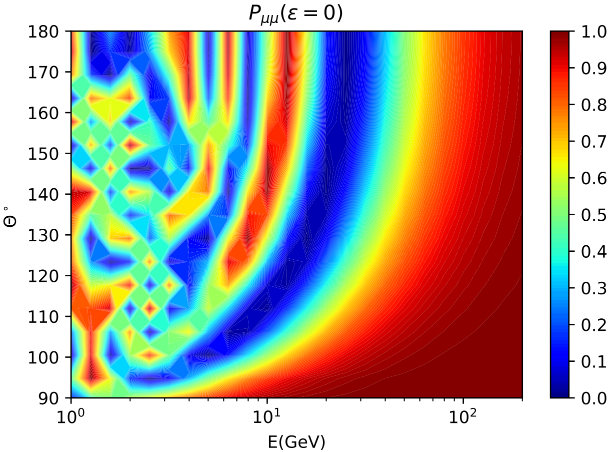


Atmospheric neutrino oscillation probability

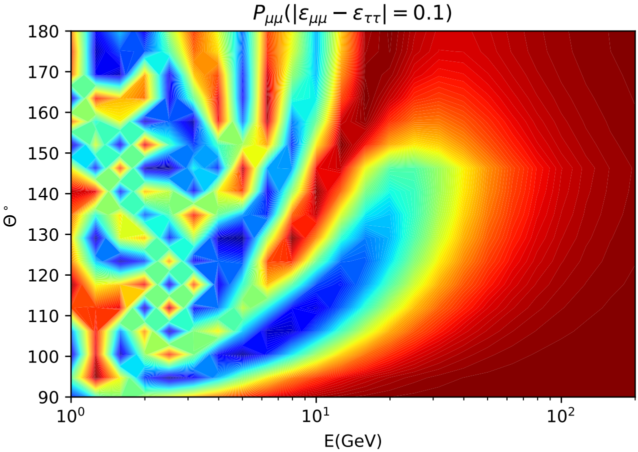
For higher energies oscillation probability does not depends on δ_{CP}



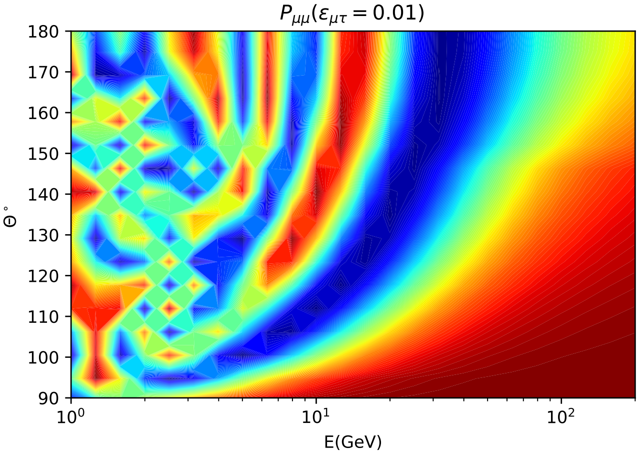
Atmospheric neutrino oscillation probability



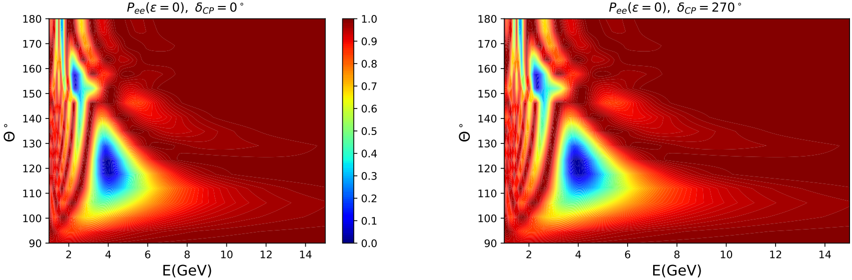
Atmospheric neutrino oscillation probability



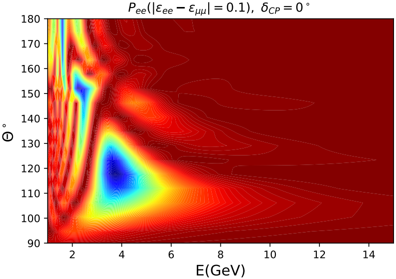
Atmospheric neutrino oscillation probability



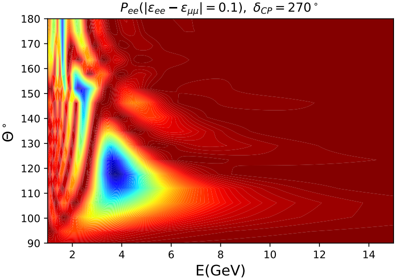
Atmospheric neutrino oscillation probability



Atmospheric neutrino oscillation probability

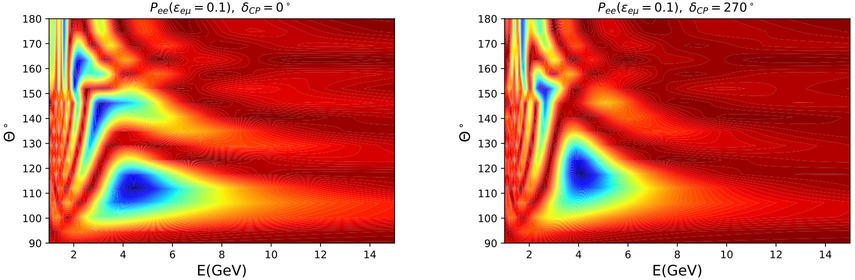


$P_{ee}(|\varepsilon_{ee}-\varepsilon_{\mu\mu}|=0.1),\ \delta_{CP}=0^\circ$



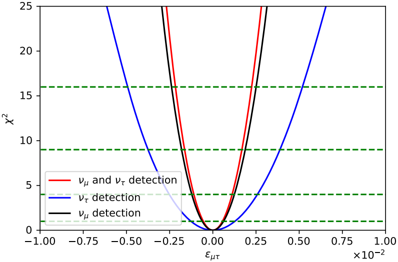
$P_{ee}(|\varepsilon_{ee}-\varepsilon_{\mu\mu}|=0.1),\ \delta_{CP}=270^\circ$

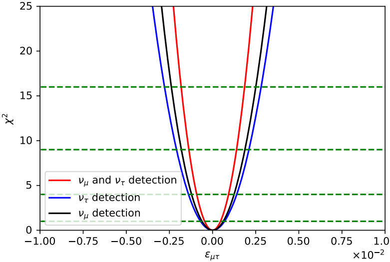
Atmospheric neutrino oscillation probability



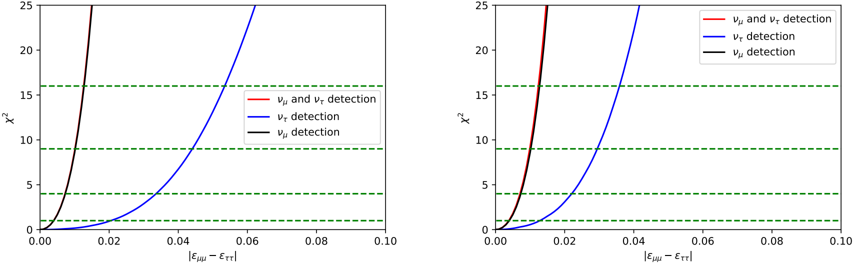
Constraints on $\epsilon_{\mu\tau}$ with DUNE

Tau neutrino detection efficiency of 30% and 100%

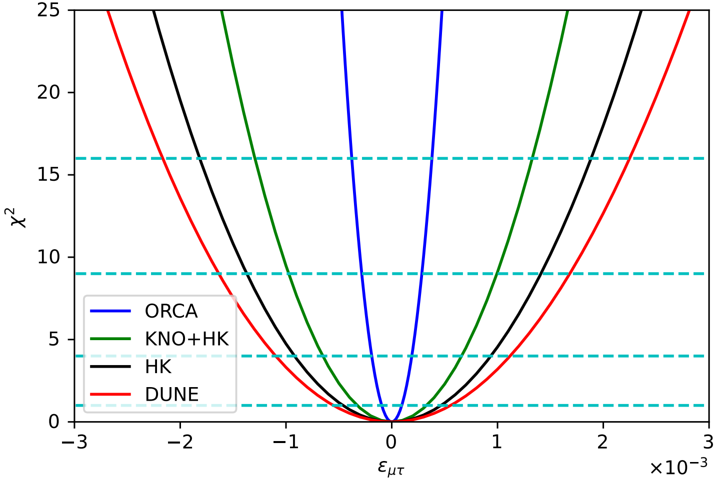




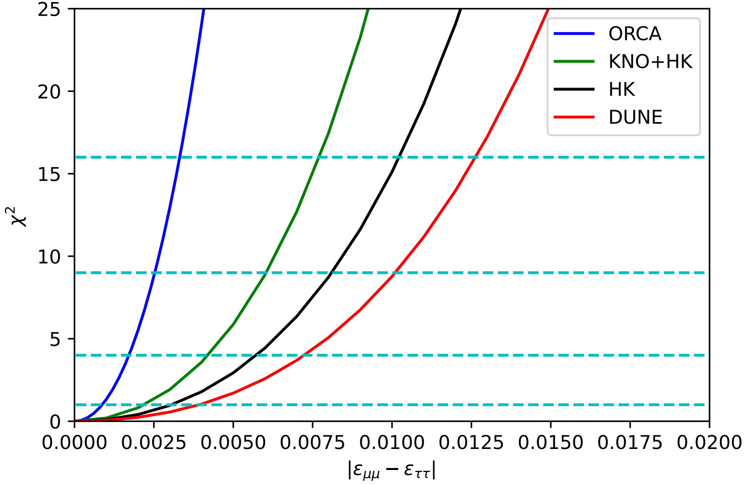
Constraints on $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$ with DUNE



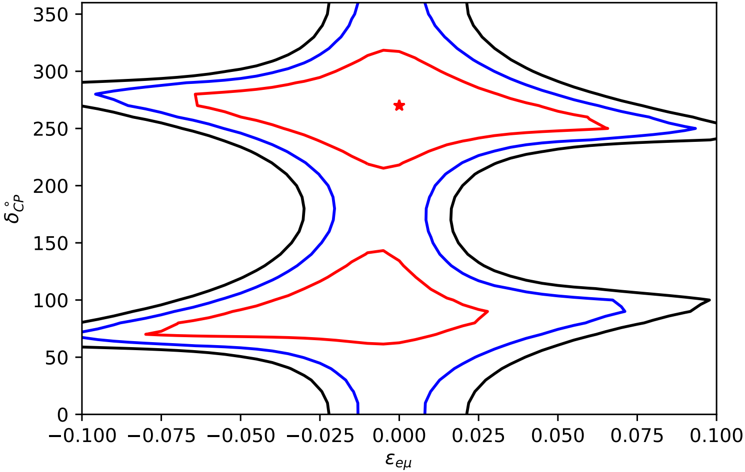
Constraints on $\epsilon_{\mu\tau}$



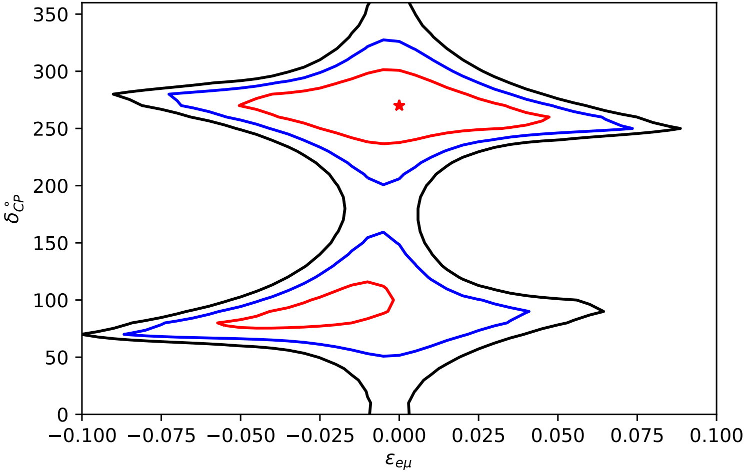
Constraints on $|\epsilon_{\mu\mu} - \epsilon_{\tau\tau}|$



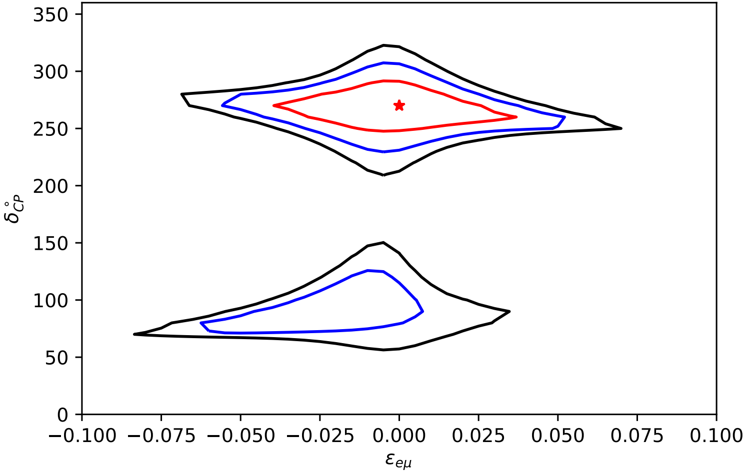
Constraints on δ_{CP} vs. $\epsilon_{e\mu}$ with DUNE



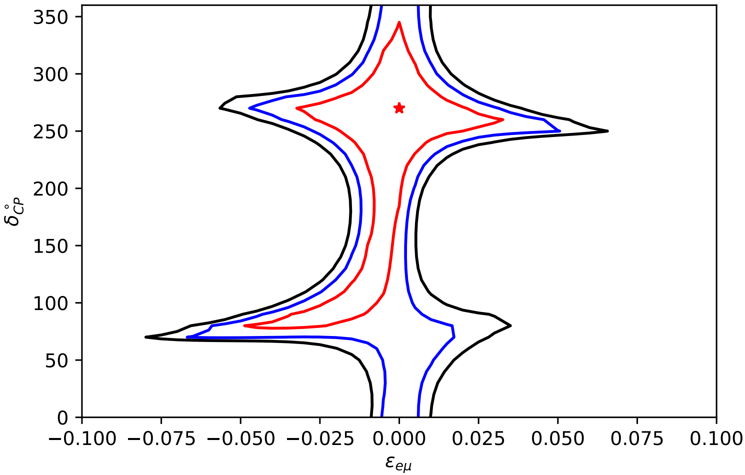
Constraints on δ_{CP} vs. $\epsilon_{e\mu}$ with HK(KNO)



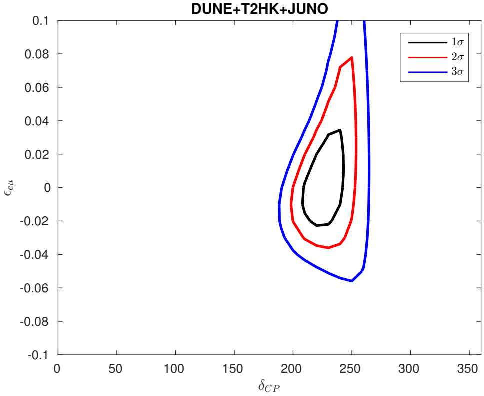
Constraints on δ_{CP} vs. $\epsilon_{e\mu}$ with HK+KNO



Constraints on δ_{CP} vs. $\epsilon_{e\mu}$ with ORCA



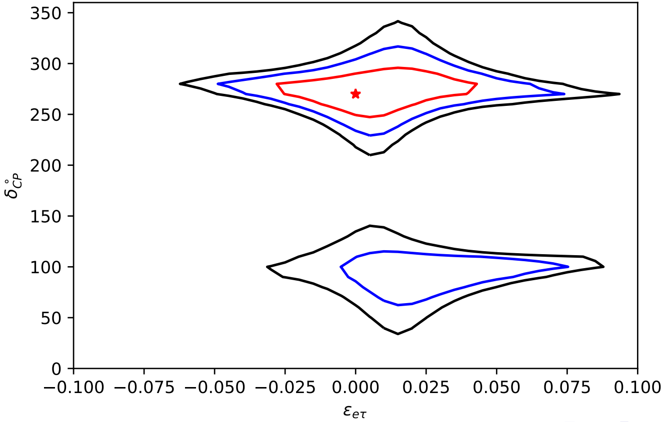
Constraints on δ_{CP} vs. $\epsilon_{e\mu}$ with Long Baseline experiments



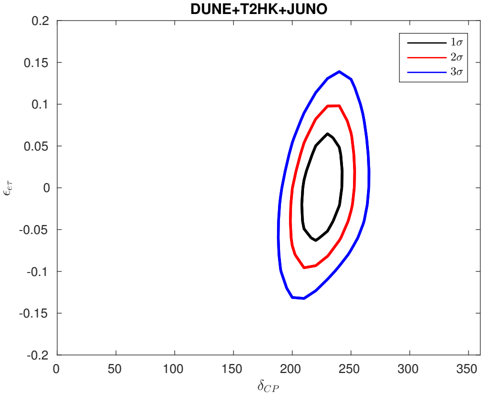
P. Bakhti and M. Rajaee, “Sensitivities of future reactor and long-baseline neutrino experiments to NSI,” Phys. Rev. D **103** (2021) no.7, 075003 [arXiv:2010.12849 [hep-ph]].

Constraints on δ_{CP} vs. $\epsilon_{e\tau}$ with HK+KNO

The results for constraining δ_{CP} vs. $\epsilon_{e\tau}$ is similar to constraints on δ_{CP} vs. $\epsilon_{e\mu}$

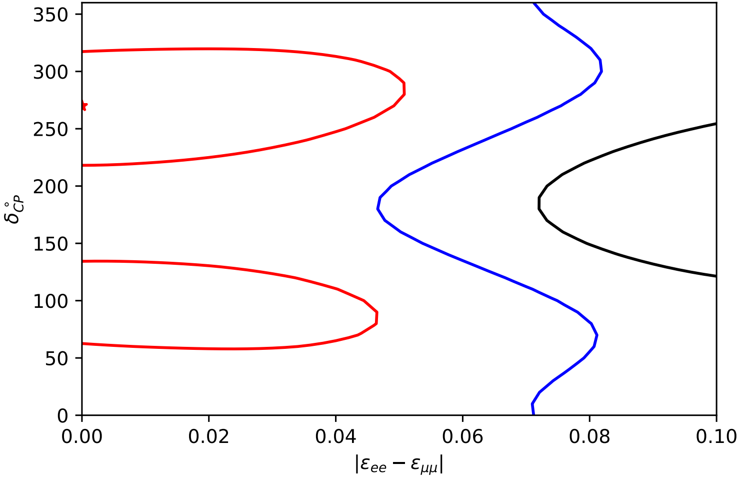


Constraints on δ_{CP} vs. $\epsilon_{e\tau}$ with Long Baseline experiments

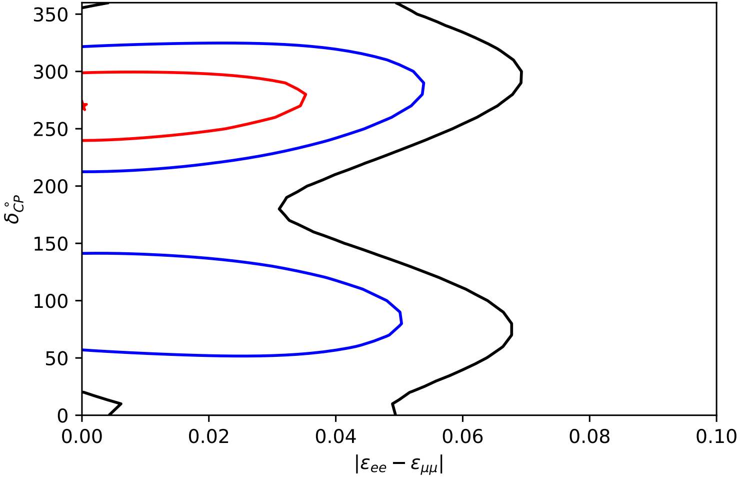


P. Bakhti and M. Rajaee, "Sensitivities of future reactor and long-baseline neutrino experiments to NSI," Phys. Rev. D **103** (2021) no.7, 075003 [arXiv:2010.12849 [hep-ph]].

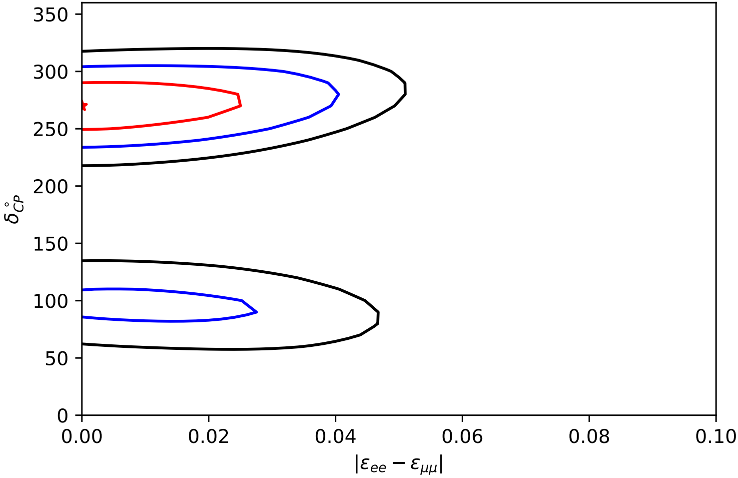
Constraints on δ_{CP} vs. $|\epsilon_{\mu\mu} - \epsilon_{ee}|$ with DUNE



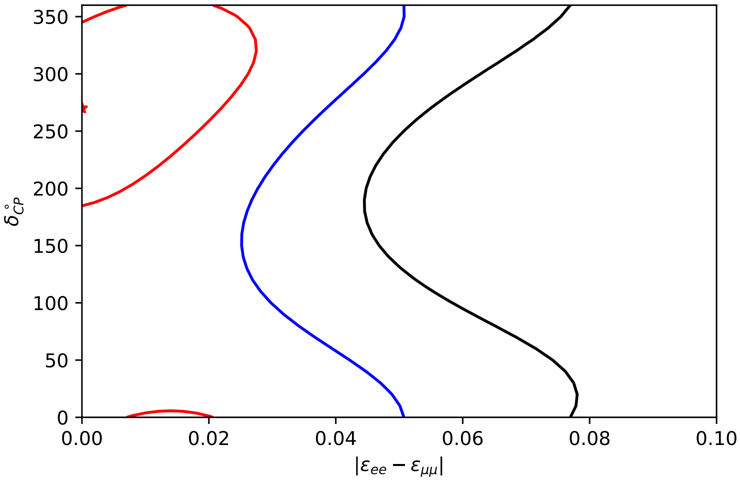
Constraints on δ_{CP} vs. $|\epsilon_{\mu\mu} - \epsilon_{ee}|$ with HK(KNO)



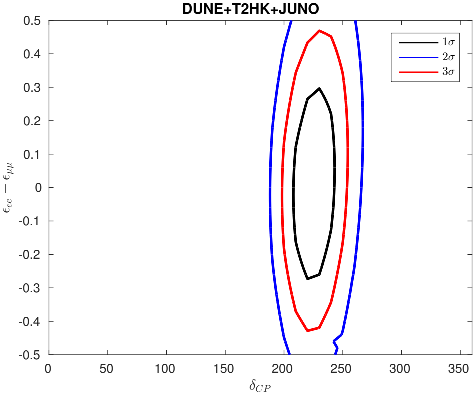
Constraints on δ_{CP} vs. $|\epsilon_{\mu\mu} - \epsilon_{ee}|$ with HK+KNO



Constraints on δ_{CP} vs. $|\epsilon_{\mu\mu} - \epsilon_{ee}|$ with ORCA



Constraints on δ_{CP} vs. $\epsilon_{e\tau}$ with Long Baseline experiments



P. Bakhti 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]].

Summary

- 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.

Thank you for your attention.