CP Sensitivity in Future Long-baseline Experiments*

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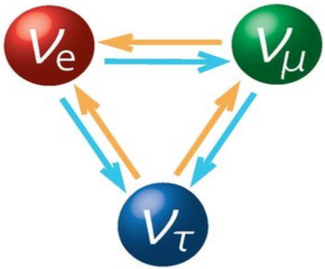
Neutrinos and Open Questions

- Neutrino: Key to New Physics
- To decipher signature(s) of BSM Physics
- Open Questions
  - CP violation in lepton sector ?
  - Majorana or Dirac ?
  - Absolute mass of neutrinos ?
  - Mass ordering: sign of (Δm^2_{13}) ?
  - $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
  - Sterile neutrino(s) ?

Neutrino Oscillations

- Neutrino oscillations provide pathway to Physics beyond the standard model.



- Three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are unitary linear combinations of three neutrinos mass eigenstates (ν_1, ν_2, ν_3) with masses m_1, m_2, m_3 $\rightarrow$ Neutrino mixing
- standard parameterization for PMNS matrix:

$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta_{cp})U_{12}(\theta_{12})$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Controls CP Violation

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- strength of CP violation is parameterized by the Jarlskog invariant:

$$J_{CP}^{PMNS} = \sin\theta_{12}\cos\theta_{12}\sin\theta_{13}\cos^2\theta_{13}\sin\theta_{23}\cos\theta_{23}\sin\delta_{cp}$$

$$\mathrm{J}_{CKM} \approx 3\times 10^{-5}\ \mathrm{(PDG)}$$

[arxiv:0308040 (Lepton Photon 2003) using **Giri-Grossman-Soffer-Zupan** (GGSZ), PRD 68, 054018 2003), $\gamma \approx 70^\circ$]

Using the recent results of nuFit v5.1, in lepton sector:

$$\mathrm{J}_{PMNS} \approx 0.034.\sin\delta_{CP}$$

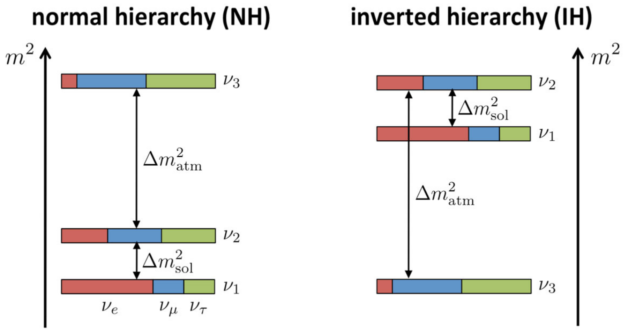
CPV in Lepton Sector

- CPV can be measured in oscillation experiment $P(\nu_\alpha \to \nu_\beta)$
- Comparing neutrino probability with anti-neutrino probability
- So for CP Violation in neutrino mixing matrix

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu_\alpha} \to \bar{\nu_\beta})$$

- In this discussion, we will use $P(\nu_\mu \to \nu_e)$ as oscillation channel.

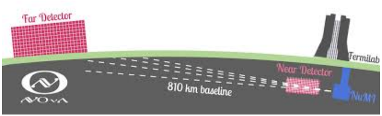
The Mass Ordering?



- mass splitting: $|\Delta m^2_{31}| = 2.517 \times 10^{-3} eV^2$, $\Delta m^2_{21} = 7.42 \times 10^{-5} eV^2$

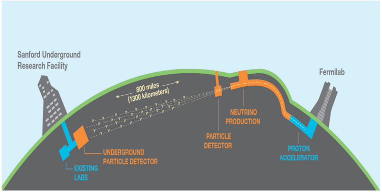
Long Baseline Experiments: NOνA and DUNE

- Detect neutrinos in Fermilab's NuMI beam
- 14 mrad off-axis, E $\approx$ 2 GeV
- Active liquid scintillator calorimeter
- Baseline $\rightarrow$ 810 Km
- Two Detectors:
  - Near detector $\rightarrow$ 0.3 kt
  - Far Detector $\rightarrow$ 14 kt



DUNE

- proposed future superbeam experiment at Fermilab
- Liquid Argon (LAr) detector of mass 40 kt
- Baseline $\rightarrow$ 1300 Km
- Far detector $\rightarrow$ Homestake mine in South Dakota.



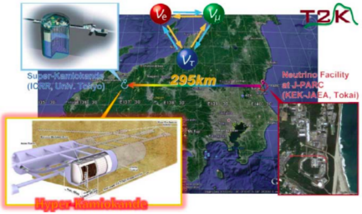
Long Baseline Experiments: T2K and T2HK

T2K

- Detect neutrinos in JPARC beam
- 43 mrad off-axis, E $\approx$ 0.65 GeV
- water Chrenkov Detector
- Baseline $\rightarrow$ 295 Km
- Two Detectors:
  - Near Detector $\rightarrow$ ND280, 280 metres from the target
  - Far Detector $\rightarrow$ (Super K), 295 km from the target in Tokai.

T2HK

- Upgraded version of T2K
- fiducial mass will be increased by about twenty times
- will contain two 187 kt third generation Water Cherenkov detectors
- Baseline $\rightarrow$ 295 Km

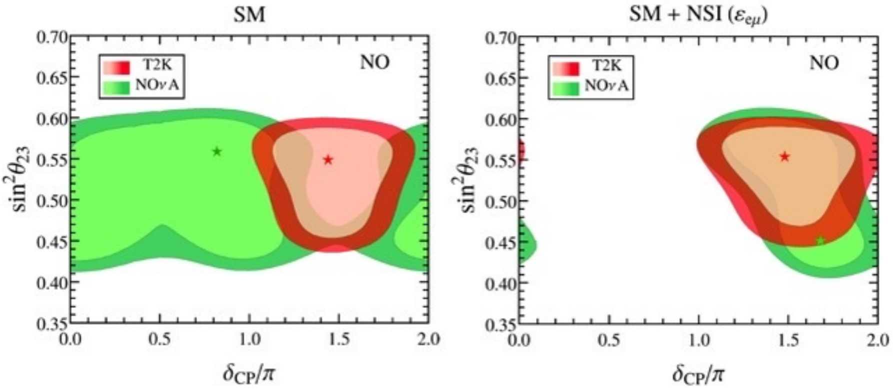


Exploring New Physics

- The main difference between NOνA-T2K as well as DUNE-T2HK is the baseline and matter density, apart from energy.
- Neutrinos at NOνA and DUNE experience stronger matter effects than T2K and T2HK
- New physics signature could probably be inferred from this exercise
- **Non-standard Interactions (NSI)** $\rightarrow$ **LBL CP Sensitivity**

B Brahma, A Giri EPJ C 82, 1145 (2022)

LBL ν-CP Tension!!



S Chatterjee, A Palazzo, PRL,126, 051802 (2021)
P Denton, J Gehrlein, R Pestes, PRL 126, 051801 (2021)

Neutrino Non-Standard Interactions

- NSI can be characterised by dimension-six four-fermion operators of the form:

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} [\overline{\nu_\alpha}\gamma^\mu \nu_\beta][\bar{f}\gamma_\mu f] \tag{1}$$

- The neutrino propagation Hamiltonian in the presence of matter, NSI, can be expressed as

$$H_{Eff} = \frac{1}{2E}\left[U_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{bmatrix} U_{PMNS}^\dagger + V\right] \tag{2}$$

where,

$$V = 2\sqrt{2}G_F N_e E \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{\mu e}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{\tau e}e^{-i\phi_{e\tau}} & \epsilon_{\tau\mu}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{bmatrix}$$

Probability

- In the presence of NSI from $e\mu$ and $e\tau$ sectors, the probability can be expressed as the sum of terms *:

$$P = P_0 + P_1 + P_2 + h.o.$$

where,

$$P_0 = 4s_{13}^2 s_{23}^2 f^2 + 8s_{13}s_{23}s_{12}c_{12}c_{23}rfg\cos(\Delta + \delta_{CP}) + 4r^2 s_{12}^2 c_{12}^2 c_{23}^2 g^2$$

- P_0 denotes the SM probability expression

where,

$$f \equiv \frac{\sin[(1-\hat{A})\Delta]}{1-\hat{A}},\ g \equiv \frac{\sin \hat{A}\Delta}{\hat{A}},\ \hat{A} = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2},\ \Delta = \frac{\Delta m_{31}^2 L}{4E},\ r = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

(*Phys.Rev.D77:013007,2008, JHEP 0903:114,2009, JHEP 0904:033,2009, Phys.Rev.D93,093016(2016))

Probability

$$P_1 = 8\hat{A}\epsilon_{e\mu}[s_{13}s_{23}[s_{23}^2 f^2 \cos(\Psi_{e\mu}) + c_{23}^2 fg \cos(\Delta + \Psi_{e\mu})] + 8 r s_{12} c_{12} c_{23}$$
$$[c_{23}^2 g^2 \cos\Psi_{e\mu} + s_{23}^2 g \cos(\Delta - \phi_{e\mu})]]$$
$$\text{where } \Psi_{e\mu} = \phi_{e\mu} + \delta_{CP}$$

- P_0 along with P_1 denotes the probability expression for SM along with NSI from $e\mu$ sector

$$P_2 = 8\hat{A}\epsilon_{e\tau}[s_{13}c_{23}[s_{23}^2 f^2 \cos(\Psi_{e\tau}) - s_{23}^2 fg \cos(\Delta + \Psi_{e\tau})] - 8 r s_{12} c_{12} s_{23}$$
$$[c_{23}^2 g^2 \cos\Psi_{e\tau} - c_{23}^2 g \cos(\Delta - \phi_{e\tau})]]$$
$$\text{where } \Psi_{e\tau} = \phi_{e\tau} + \delta_{CP}$$

- P_0 along with P_2 denotes the probability expression for SM along with NSI from $e\tau$ sector

Non-standard Interactions

- The flavor changing parameter of NSI:

$$|\epsilon_{e\mu}|e^{i\phi_{e\mu}},\ |\epsilon_{e\tau}|e^{i\phi_{e\tau}},\ |\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$$

- In this work, we consider only the propagation NSI.

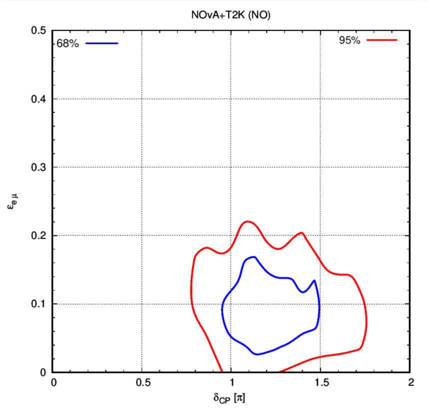
- Will discuss the effect of NSI ranges on sensitivity as well as oscillation probability plots for DUNE and T2HK.

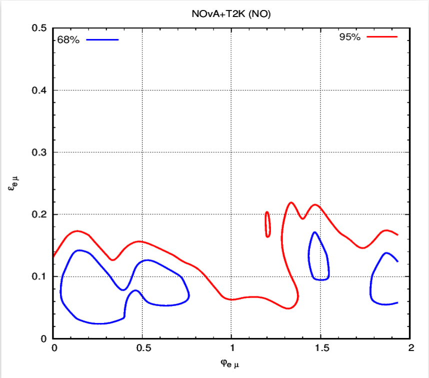
- Use GLoBES and and its additional public tools to deal with non-standard interactions *.

(*Comp.Phys.Comm, 167 (2005) 195; Comp. Phys. Comm, 177 (2007) 432; https://www.mpi-hd.mpg.de/personalhomes/globes/tools/snu-1.0.pdf (2010).)

NSI, $\epsilon_{e\mu}$ Sector

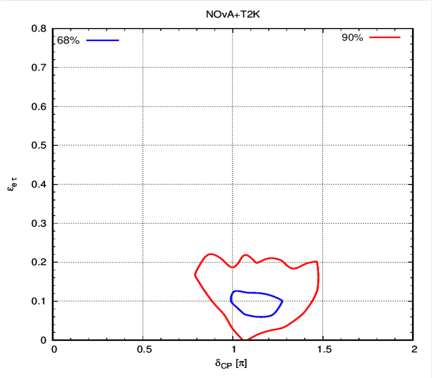
- Allowed regions in the plane spanned by NSI coupling $\epsilon_{e\mu}$ and the standard CP phase (left) and NSI coupling $\epsilon_{e\mu}$ and corresponding phase $\phi_{e\mu}$(right) determined by the combination of T2K and NOνA for NO.
- The allowed regions at the 68% and 95% C.L.

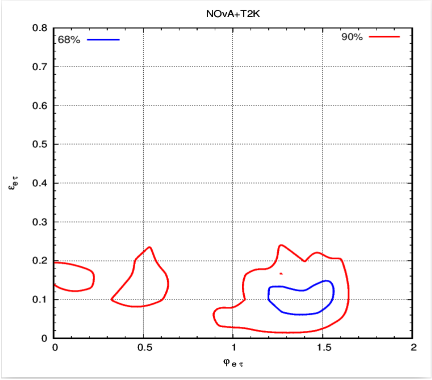




NSI, $\epsilon_{e\tau}$ Sector

- Allowed regions in the plane spanned by NSI coupling $\epsilon_{e\tau}$ and the standard CP phase (left) and NSI coupling $\epsilon_{e\tau}$ and corresponding phase $\phi_{e\tau}$(right) determined by the combination of T2K and NOνA for NO.
- The allowed regions at the 68% and 90% C.L.





NSI Range

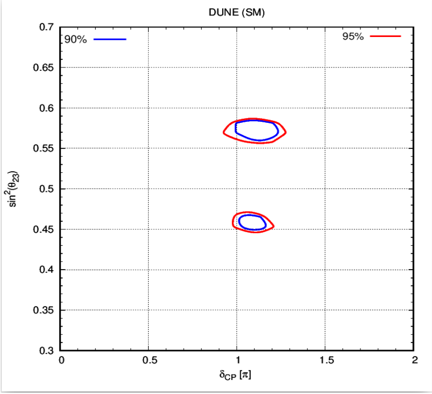
From allowed region plots in the previous slides, the best fit points are:

MO	NSI	$\|\epsilon_{\alpha\beta}\|$	$\phi_{\alpha\beta}/\pi$	χ^2
NO	$\epsilon_{e\mu}$	0.1	0.2	0.518
	$\epsilon_{e\tau}$	0.1	1.47	0.385
IO	$\epsilon_{e\mu}$	0.01	1.67	0.533
	$\epsilon_{e\tau}$	0.13	0.8	1.668

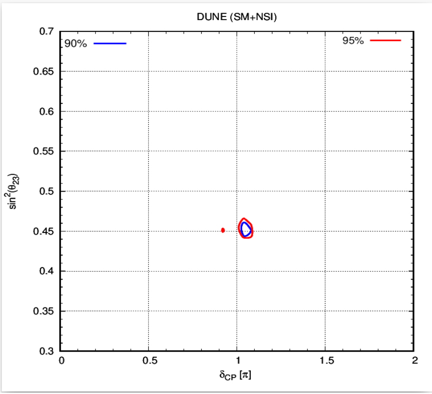
- In SM Plots the standard parameters θ_{13} is marginalized
- In SM+NSI plots, along with θ_{13} the NSI magnitudes $(|\epsilon_{e\mu}|, |\epsilon_{e\tau}|)$ as well as phase $(\phi_{e\mu}, \phi_{e\tau})$ are marginalized
- The plots display the allowed regions at the 68% and 95% level

DUNE Sensitivity with NSI inclusion

SM, NO



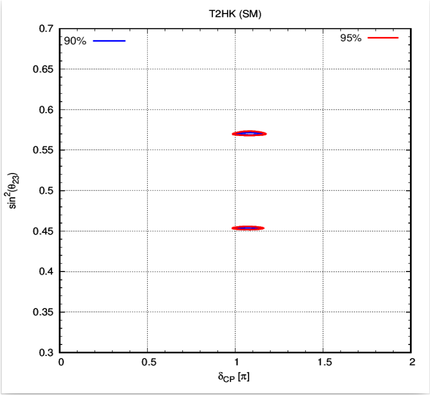
SM+NSI, $\epsilon_{e\mu}$ Sector, NO



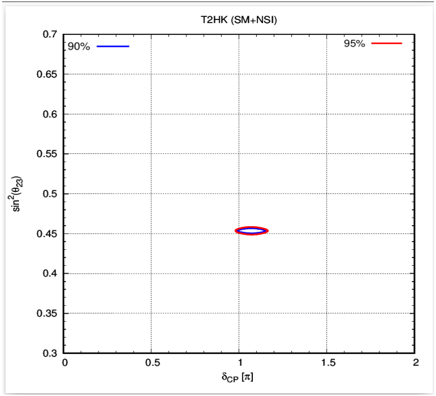
- With inclusion of NSI from $e - \mu$ sector, the allowed region corresponding to the higher octant in DUNE vanishes.

T2HK Sensitivity with NSI inclusion

SM, NO



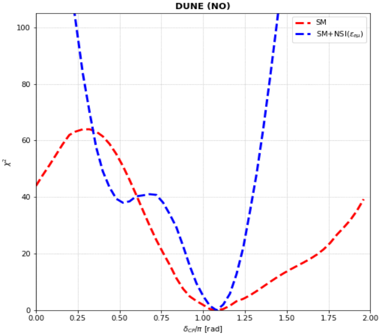
SM+NSI, $\epsilon_{e\mu}$ Sector, NO



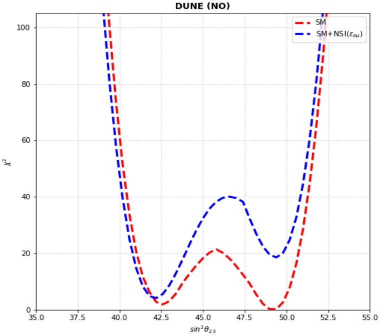
- With inclusion of NSI from $e - \mu$ sector, the allowed region corresponding to the higher octant vanishes.

DUNE 1D Projection

δ_{CP}

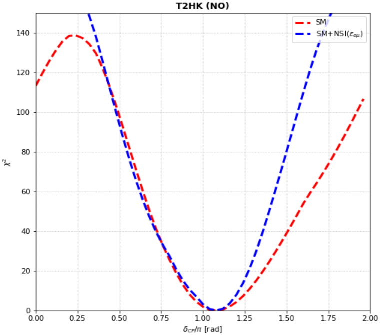


$\sin^2\theta_{23}$

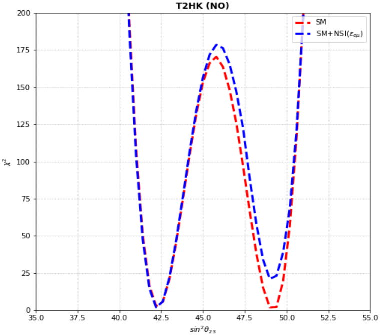


T2HK 1D Projection

δ_{CP}

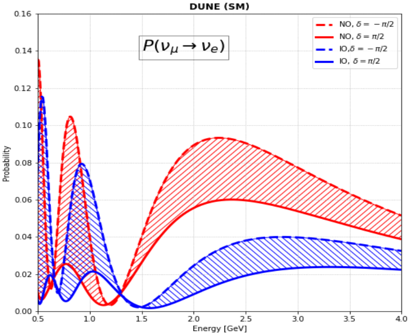


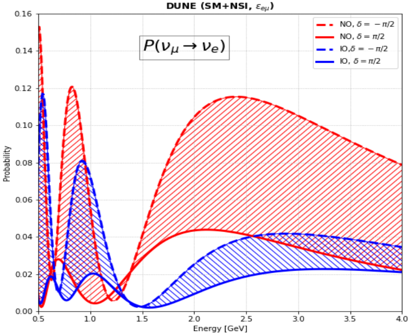
$\sin^2\theta_{23}$



Probability, $P(\nu_\mu \to \nu_e)$ (DUNE)

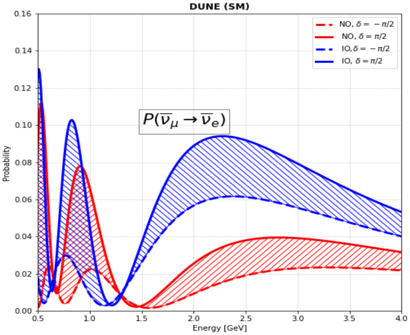
- For SM scenario, we see a good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.
- For SM+NSI scenario from the $e - \mu$ sector, we still have some separation between NO-IO for $\delta_{CP} = 90^\circ$ in mid energy region, and they gradually merges around 4 GeV.

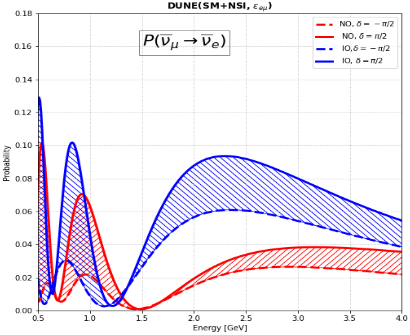




Probability, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ (DUNE)

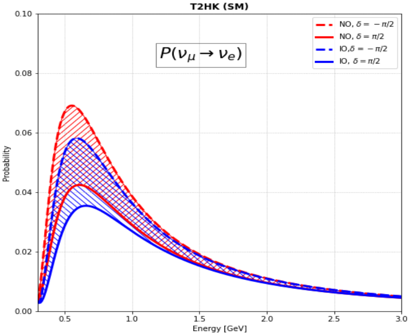
- For SM scenario, we see a good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.
- For SM+NSI scenario, we see a further good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.

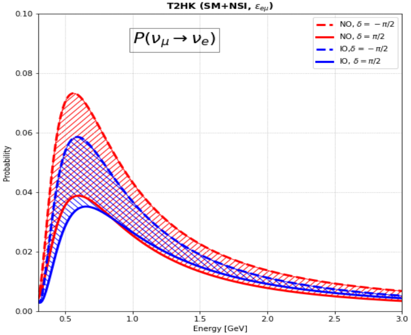




Probability, $P(\nu_\mu \to \nu_e)$ (T2HK)

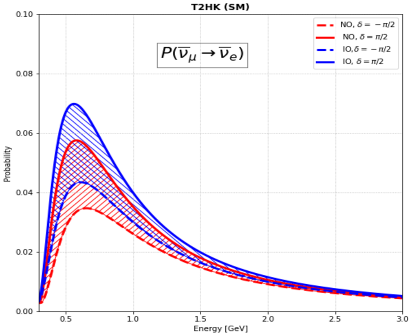
- For SM scenario, we see a perceivable separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$ till 1 GeV.
- For the SM+NSI case from $e - \mu$ sector, we see a better separation between NO-IO for $\delta_{CP} = -90^\circ$. The NO-IO separation continuously decreases for $\delta_{CP} = 90^\circ$ crossing each other around 0.7 GeV.

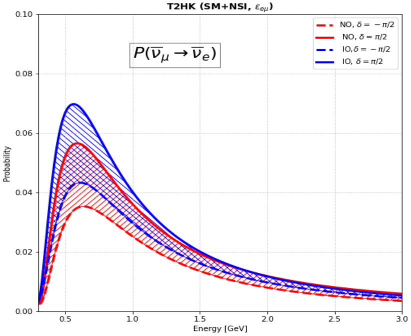




Probability, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ (T2HK)

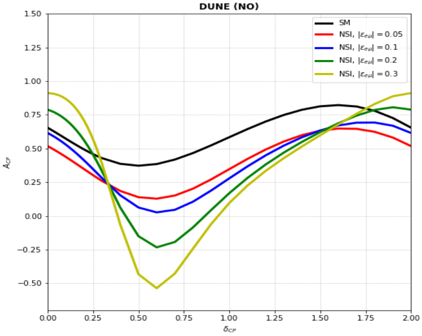
- For SM scenario, we see a perceivable separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$ till 1.3 GeV.
- For SM+NSI case from $e-\mu$ sector, we see a better separation between NO-IO for $\delta_{CP} = -90^\circ$. The NO-IO separation continuously decreases for $\delta_{CP} = 90^\circ$.

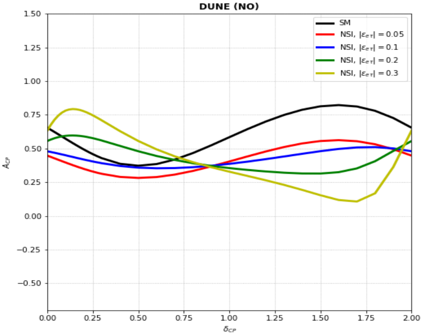




- Baseline = 1300 Km, Energy = 2.6 GeV

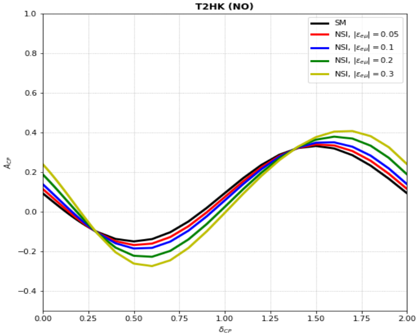
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

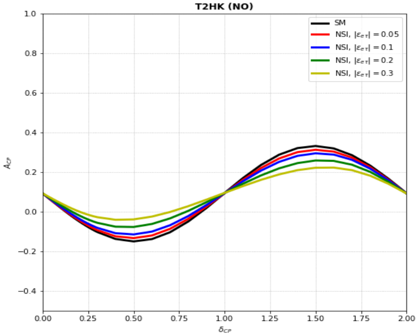




- Baseline = 295 Km, Energy = 0.6 GeV

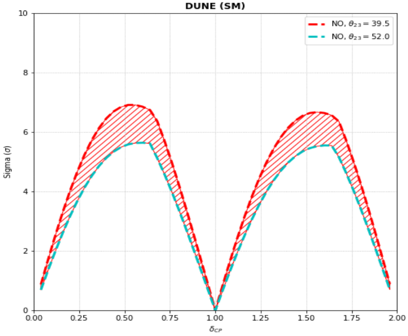
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})}$$

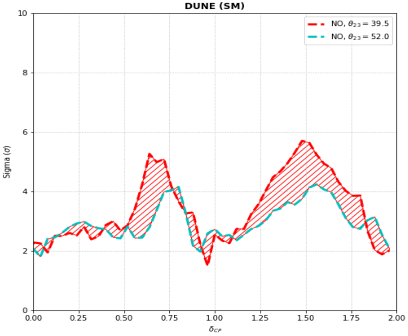




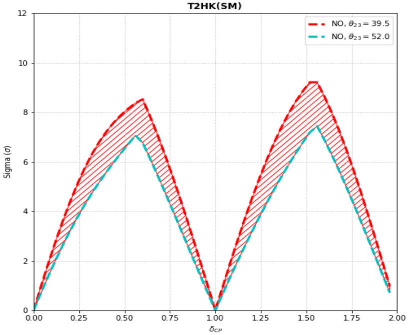
Significance Plots: DUNE

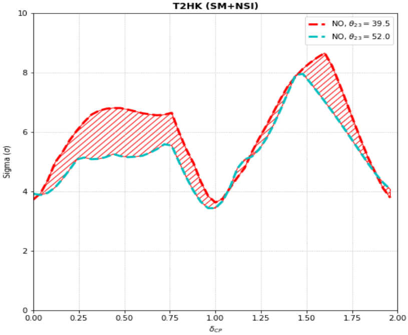
CP discovery potential as a function of the true value of the leptonic CP phase for NO in SM(left) and SM+NSI(right) case





CP discovery potential as a function of the true value of the leptonic CP phase for NO in SM(left) and SM+NSI(right) case





Summary

- NSI included, the allowed region for higher octant disappears for both DUNE and T2HK
- Striking differences in oscillation probabilities for neutrino channel in DUNE and T2HK, may help us to understand the neutrino mass ordering
- Shown the CP discovery potential for both SM and SM+NSI scenarios and NSI reduces the sensitivity, which is prominent in DUNE
- CP asymmetry with NSI show significant differences in LBL experiments

Thank You !!