Exploring NSI effects in LBL neutrino Experiments

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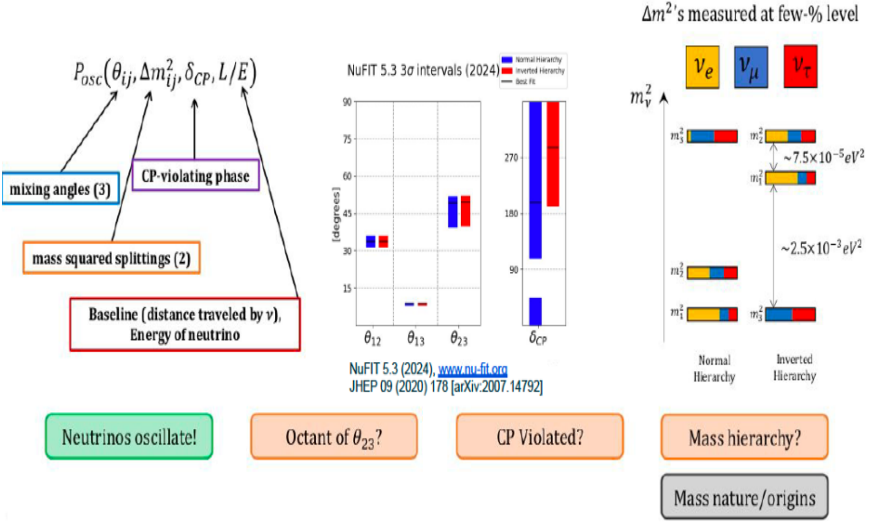
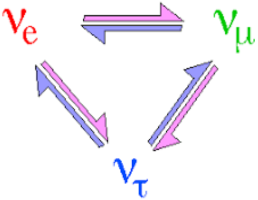


K. Wood - CoSSURF-2024

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:

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

CP Violation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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:

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

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

[arxiv:0308040 (Lepton Photon 2003) using $\gamma \approx 70^\circ$]

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

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

CPV in Lepton Sector

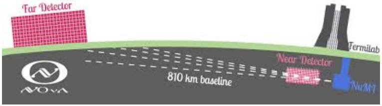
- CPV in lepton sector is essential
- CPV can be measured in oscillation experiment $P(\nu_\alpha \to \nu_\beta)$
- Comparing neutrino probability with anti-neutrino probability
- So for CP Violation in neutrino mixing matrix

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

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

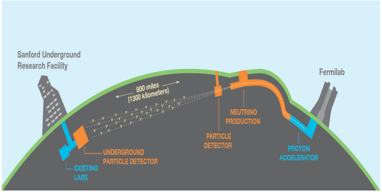
Long Baseline Experiments: NOνA and DUNE

- 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.

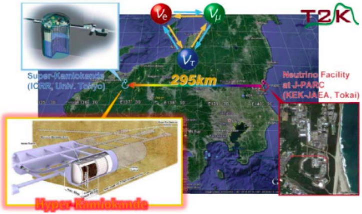


T2K

- 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

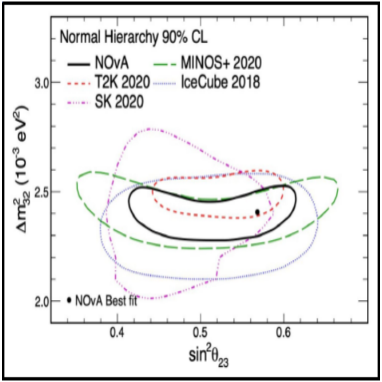
- Upgraded version of T2K
- fiducial mass will be increased by about twenty times
- will contain two 187 kt third generation Water Cherenkov detectors
- Baseline $\rightarrow$ 295 Km

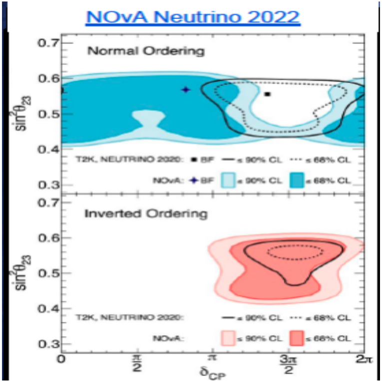


Exploring New Physics

- 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**

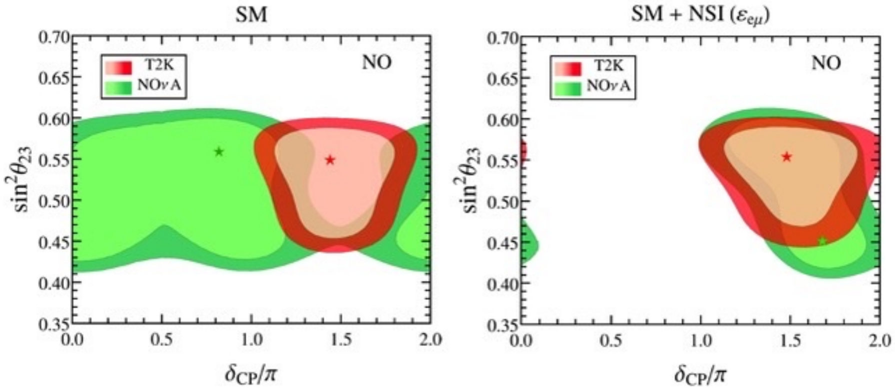
B Brahma, A Giri EPJ C 82, 1145 (2022)
[2302.09592, 2306.05258]





- The best fit value for θ_{23} in the higher octant and different values of δ_{CP} by NOvA for NO and IO.

LBL ν-CP Tension!!



PRL,126, 051802 (2021)
PRL 126, 051801 (2021)

Neutrino Non-Standard Interactions

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

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

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

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

where,

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

where, $\epsilon_{\alpha\beta}e^{(i\phi_{\alpha\beta})} \equiv \sum_{f=e,u,d}(\epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR})\frac{N_f}{N_e}$

Probability

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

$$P_{\mu e} = P_{SM} + P_{\epsilon_{e\mu}} + P_{\epsilon_{e\tau}} + P_{Int} + h.o.$$

where,

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

- 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

$$
\begin{aligned}
P_{\epsilon_{e\mu}} &= 4\hat{A}\epsilon_{e\mu}[xf^2 s_{23}^2 \cos(\Psi_{e\mu}) + xfgc_{23}^2 \cos(\Delta + \Psi_{e\mu}) + yg^2 c_{23}^2 \cos\phi_{e\mu} \\
&+ ygfs_{23}^2 \cos(\Delta - \phi_{e\mu})] + 4\hat{A}^2\epsilon_{e\mu}^2[f^2 s_{23}^4 + g^2 c_{23}^4 + 2fgs_{23}^2 c_{23}^2 \cos\Delta]
\end{aligned}
$$

$$\text{where } \Psi_{e\mu} = \phi_{e\mu} + \delta_{CP}$$

$$
\begin{aligned}
P_{\epsilon_{e\tau}} &= 4\hat{A}\epsilon_{e\tau}[xf^2 s_{23} c_{23} \cos(\Psi_{e\tau}) - xfgs_{23} c_{23} \cos(\Delta + \Psi_{e\tau}) - yg^2 s_{23} c_{23} \cos \\
&+ ygfs_{23} c_{23} f \cos(\Delta - \phi_{e\tau})] + 4\hat{A}^2\epsilon_{e\tau}^2 s_{23}^2 c_{23}^2 [g^2 + f^2 - 2fg \cos\Delta]
\end{aligned}
$$

$$\text{where } \Psi_{e\tau} = \phi_{e\tau} + \delta_{CP}$$

$$
\begin{aligned}
P_{Int} &= 8\hat{A}^2 c_{23} s_{23} \epsilon_{e\mu}\epsilon_{e\tau}[g^2 c_{23}^2 + f^2 s_{23}^2 + 2fgc_{23}^2 \cos(\phi_{e\mu} - \phi_{e\tau}) \cos\Delta \\
&- fg \cos(\Delta - \phi_{e\mu} + \phi_{e\tau})]
\end{aligned}
$$

Non-standard Interactions

- The flavor changing parameter of NSI:

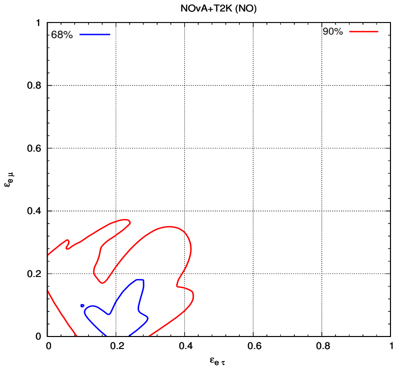
$$|\epsilon_{e\mu}|e^{i\phi_{e\mu}},\ |\epsilon_{e\tau}|e^{i\phi_{e\tau}},\ |\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$$

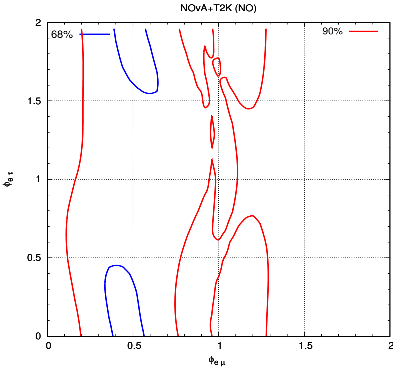
- In this work, we consider only the propagation NSI.
- Will discuss the effect of NSI ranges on sensitivity as well as oscillation probability plots for DUNE and T2HK.
- Use GLoBES and its additional public tools to deal with non-standard interactions *.

(*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).)

Dual NSI, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ Sector

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





NSI Range

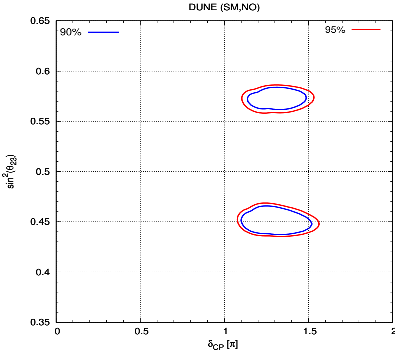
From the allowed region plots in the previous slides, the best-fit points are:

Mass Ordering	$\|\epsilon_{e\mu}\|$	$\|\epsilon_{e\tau}\|$
NO	0.22	0.06
IO	0.04	0.2
Mass ordering	$\phi_{e\mu}/\pi$	$\phi_{e\tau}/\pi$
NO	0.48	1.88
IO	1.24	1.87

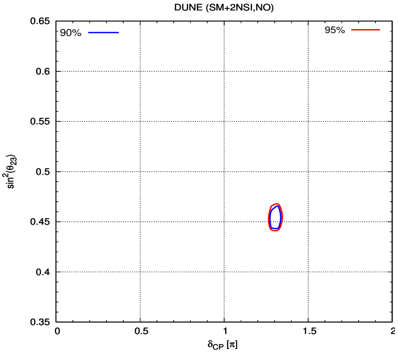
- In SM Plots the standard parameters θ_{13} is marginalized
- In SM+NSI plots, along with θ_{13} the NSI magnitudes ($|\epsilon_{e\mu}|, |\epsilon_{e\tau}|$) as well as phase ($\phi_{e\mu}, \phi_{e\tau}$) are marginalized
- The plots display the allowed regions at the 68% and 95% level

DUNE Sensitivity with dual NSI inclusion

SM, NO



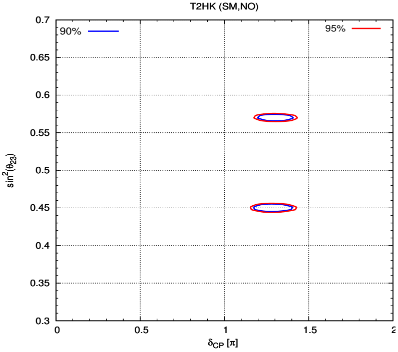
SM+ dual NSI, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ Sector, NO



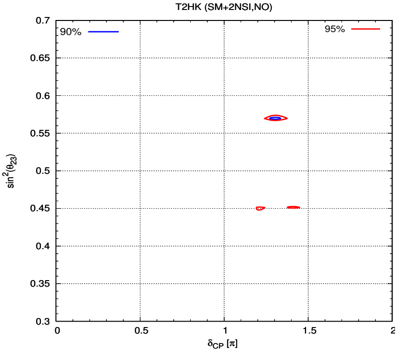
- With the inclusion of dual NSI from $e-\mu$ and $e-\tau$ sector, the allowed region corresponding to the higher octant in DUNE vanishes.

T2HK Sensitivity with dual NSI inclusion

SM, NO



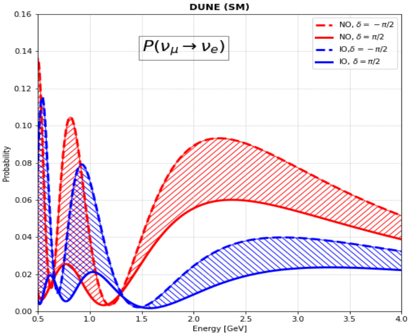
SM+dual NSI, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ Sector, NO

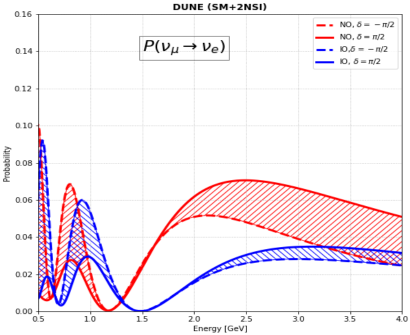


- With the inclusion of dual NSI from $e-\mu$ and $e-\tau$ sector, the allowed region corresponding to both the octants does not vanish completely.

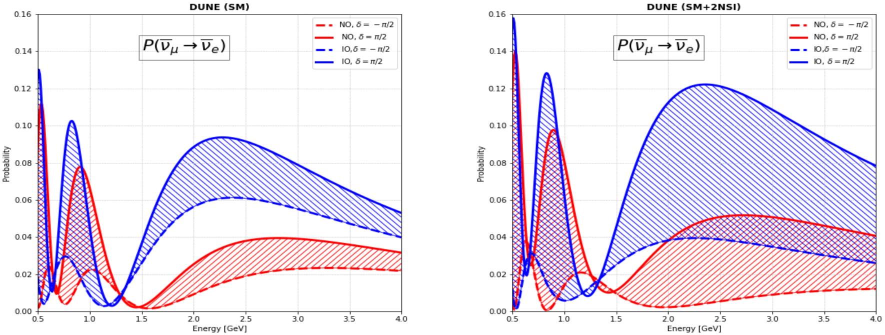
Probability, $P(\nu_\mu \to \nu_e)$ (DUNE)

- For the 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 and dual NSI scenario, we still have some separation between NO-IO for $\delta_{CP} = -90^\circ$ in mid energy region, and they gradually merges around 4 GeV.



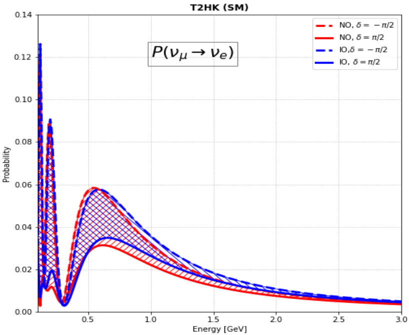


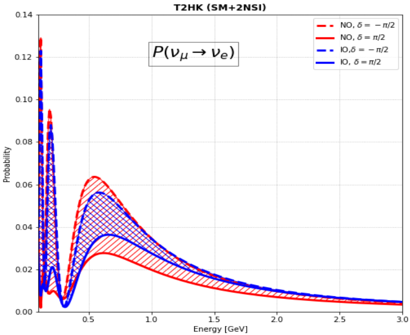
- For the SM scenario, we see a good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.
- For SM and dual NSI scenario, the separation between NO-IO for $\delta_{CP} = 90^\circ$ becomes more than in the SM case. Compared with the SM case, the NO-IO separation decreases for $\delta_{CP} = -90^\circ$.



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

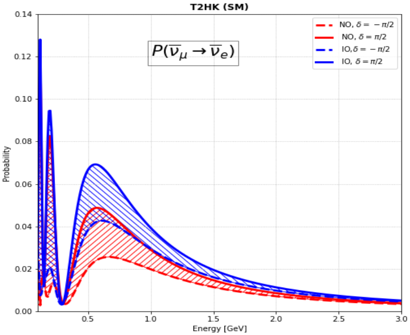
- For the SM scenario, we see a feeble separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$ around 1 GeV.
- For the SM and dual NSI case, we see a better separation between NO-IO for both $\delta_{CP} = -90^\circ$ and $\delta_{CP} = 90^\circ$ around 1 GeV.

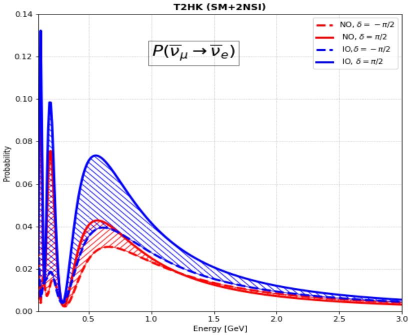




Probability, $P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})$ (T2HK)

- 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 1.5 GeV.
- For SM and dual NSI case, we see a better separation between NO-IO for $\delta_{CP} = 90^\circ$. The NO-IO separation decreases for $\delta_{CP} = -90^\circ$ when compared to the SM case.

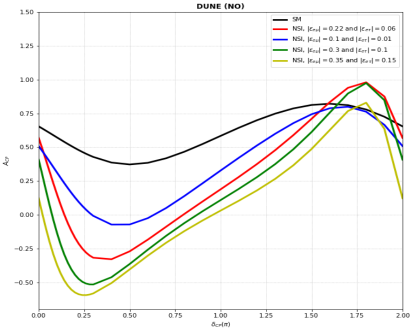


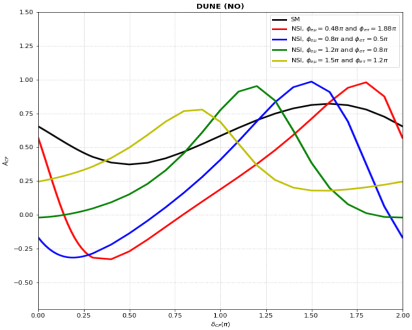


CP Asymmetry:DUNE

- Baseline = 1300 Km, Energy = 2.6 GeV

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

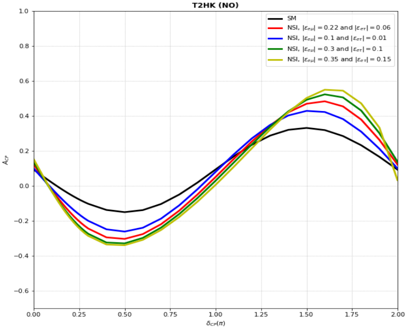


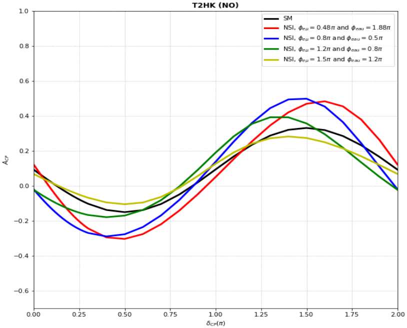


CP Asymmetry:T2HK

- Baseline = 295 Km, Energy = 0.6 GeV

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

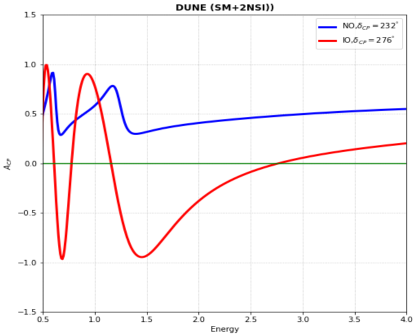


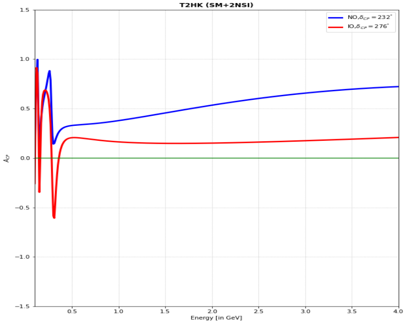


CP Asymmetry versus Energy

- For DUNE: Baseline = 1300 Km, δ_{CP} = 232° (NO) and 272° (IO)
- For T2HK: Baseline = 295 Km, δ_{CP} = 232° (NO) and 272° (IO)

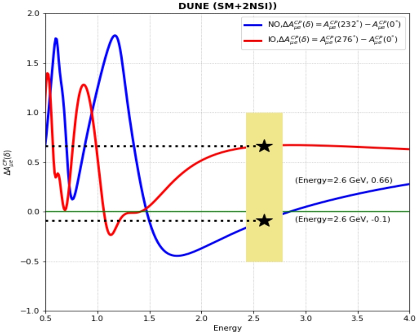
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})}$$

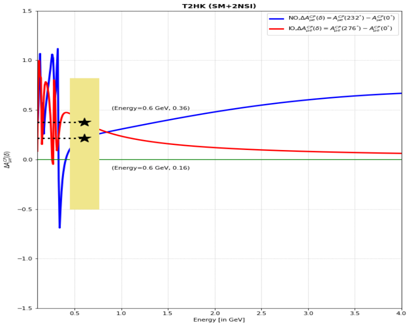




CP Asymmetry versus δ_{CP}

- For DUNE: Baseline = 1300 Km, Energy = 2.6 GeV
- For T2HK: Baseline = 295 Km, Energy = 0.6 GeV
- SM parameter δ_{CP} is varied from 0 to 2π





$$\Delta A^{CP}_{\alpha\beta}(\delta_{CP}) = A_{\alpha\beta}(\delta \neq 0) - A_{\alpha\beta}(\delta = 0)$$

Summary

- With Dual NSI, allowed region for octant θ_{23} for DUNE and T2HK
- Striking differences in oscillation probabilities for ν channel in DUNE and T2HK, consequences for mass ordering
- CP asymmetry with NSI show significant differences in LBL Expts
- CP asymmetry vs. Energy show differences for DUNE and T2HK
- ΔA_{CP} vs. Energy for DUNE and T2HK exhibits sensitive pattern for NO and IO scenarios

Thank You !!

Extra

SM Parameters	bfp ± 1σ NO	bfp ± 1σ IO
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.570^{+0.019}_{-0.016}$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02241^{+0.00074}_{-0.00062}$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	278^{+22}_{-30}
$\frac{\Delta m^2_{21}}{10^{-5}eV^2}$	$7.42^{+0.21}_{-0.20}$	$7.42^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3l}}{10^{-3}eV^2}$	$+2.510^{+0.027}_{-0.027}$	$-2.490^{+0.026}_{-0.028}$