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Exploring NSI Sensitivities for T2HK and DUNE

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Neutrino oscillations in matter offer a novel path to investigate new physics. One of the main goals of neutrino experiments is to determine the CP phase and the presence of new physics can alter the scenario. We assume that the observed difference, if any, in the CP phase is due to the possible non-standard interactions. We derive the relevant coupling strengths using the simulated data sets of NOνA and T2K and study their effects in the next generation long-baseline experiments: T2HK and DUNE. Our analysis show significant impact on the sensitivity of atmospheric mixing angle θ_{23} in the normal as well as inverted orderings and also exhibits appreciable difference in probabilities for both the experiments with inclusion of non-standard interaction arising from $e-\mu$ as well as $e-\tau$ sectors.

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1. Introduction

Neutrinos, the most intriguing particle, can change flavour as they travel from one location to another. Neutrinos get influenced by the matter potential. This is known as Wolfenstein matter effect [1]. In order to probe new physics [2, 3], Wolfenstein introduced non-standard interaction (NSI), besides the neutrino mass matrix. NSI affects neutrino propagation in matter through the neutral-current and charged-current interactions.

The recent results from NOνA prefer CP phase close to $\delta_{CP} \approx 0.8\pi$ [4] whereas T2K identifies a value of $\delta_{CP} \approx 1.5\pi$ [5] in the case of normal ordering (NO) and no disagreement appears in the case of inverted ordering (IO). Once the NSI from $e-\mu$ sector is taken into account the tension concerning the δ_{CP} parameter for NOνA and T2K becomes placid but a difference is observed for θ_{23} . NOνA prefers lower octant whereas T2K prefers higher octant [6, 7]. In our analysis, we observe that once the NSI ($e-\mu$) effect is included, a clear shift in the preference of CP phase to a higher value is observed in case of NOνA. Moreover, in standard oscillation with no NSI, IO is preferred over NO, whereas with the inclusion of NSI, NO is preferred over IO (as also shown in [6]). In this work, we utilise data from both NOνA and T2K experiments to find the constraints on NSI contributions. Thereafter, we use the same coefficients to see if we can get any discernible result in the future long-baseline (LBL) neutrino experiments: DUNE and T2HK.

The main aim here is to see whether the degeneracy for the standard model parameter θ_{23} still exists in presence of NSI arising from both $e-\mu$ and $e-\tau$ sectors for DUNE and T2HK or not.

2. Formalism

The NSI can be characterised by the six-dimensional four-fermion (ff) operators of the form [1]:

$$\mathcal{L}_{NSI} = 2\sqrt{2}G_F \epsilon^{fC}_{\alpha\beta}[\overline{\nu_\alpha}\gamma^\rho P_L \nu_\beta][\overline{f}\gamma_\rho P_C f] + h.c. \tag{1}$$

where $\alpha, \beta = e, \mu, \tau$ indicate the neutrino flavor, superscript $C = L, R$ refers to the chirality of ff current, $f = u, d, e$ denotes the matter fermions and $\epsilon^{fC}_{\alpha\beta}$ are dimensionless parameters that measure the new interaction's strength in relation to the SM. The neutrino propagation Hamiltonian in the presence of matter, NSI, can be expressed as

$$H_{Eff} = \frac{1}{2E}\left[U_{PMNS}\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{bmatrix}U^\dagger_{PMNS} + V\right]$$

where U_{PMNS} is the unitary Potecorvo-Maki-Nakagawa-Sakata mixing matrix, E is the neutrino energy and $\Delta m^2_{21} \equiv m^2_2 - m^2_1$, $\Delta m^2_{31} \equiv m^2_3 - m^2_1$. m_1, m_2 and m_3 are the different mass eigenstates. V is written as:

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

N_e is the number density of electrons and for neutrino propagation in the Earth, G_F is Fermi coupling constant, $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C}\epsilon^{fC}_{\alpha\beta}\frac{N_f}{N_e} \equiv \sum_{f=e,u,d}(\epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta})\frac{N_f}{N_e}$, N_f being the number

PoS(ICHEP2022)622

density of f fermion. The $\epsilon_{\alpha\beta}$ are real and $\phi_{\alpha\beta} = 0$ for $\alpha = \beta$. We concentrate on flavour non-diagonal NSI ($\epsilon_{\alpha\beta}$'s with $\alpha \neq \beta$). Here, we consider single NSI parameter $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$ (one at a time) to examine the conversion probability of $\nu_\mu \to \nu_e$ for the LBL studies which can be stated as the sum of three (plus higher order; cubic and beyond) terms in the presence of NSI:

$$P_{\mu e} = P_0 + P_1 + P_2 + h.o. \tag{2}$$

the above Eq.(2), similar to [8] takes the following form:

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

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

and,

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

where, $f \equiv \frac{\sin[(1-\hat{A})\Delta]}{1-\hat{A}}$; $g \equiv \frac{\sin\hat{A}\Delta}{\hat{A}}$;$\hat{A} = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$; $\Delta = \frac{\Delta m_{31}^2 L}{4E}$; $r = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$. Furthermore, here we used: $\Psi_{e\mu} = \phi_{e\mu} + \delta_{CP}$; $\Psi_{e\tau} = \phi_{e\tau} + \delta_{CP}$.

3. Analysis details and results

In our analysis, we used the software GLoBES [9] and its additional public tool [10]. The best fit values of the standard model parameters are taken from nuFIT v5.0 [11] and PDG [12]. For example, the parameter values taken (for normal ordering) are: $\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}$; $\sin^2\theta_{23} = 0.573^{+0.016}_{-0.020}$; $\sin^2\theta_{13} = 0.02219^{+0.00062}_{-0.00063}$; $\delta_{CP} = 197^{+27}_{-24}$; $\frac{\Delta m_{21}^2}{10^{-5}eV^2} = 7.42^{+0.21}_{-0.20}$; and $\frac{\Delta m_{3l}^2}{10^{-3}eV^2} = +2.517^{+0.026}_{-0.028}$. We considered combined T2K and NOνA data for NO and IO scenarios to obtain the NSI parameters. For NOνA we considered running for 3 years in ν and 3 years in $\bar{\nu}$ mode and for T2K 2 years in ν and 6 years in $\bar{\nu}$ mode. We used GLoBES [13] for simulating experiments like NOνA, T2K, T2HK and DUNE. DUNE and T2HK were considered to be running for 3.5 years and 3 years in ν mode and similarly 3.5 years and 4 years in $\bar{\nu}$ mode, respectively. DUNE will have a 40 kiloton liquid argon detector that will use a 1.2 MW proton beam to generate neutrino and antineutrino beams from in-flight pion decays. The proton beam will originate 1300 kilometres upstream at Fermilab. Whereas, T2HK will have a 225 kt water Cherenkov detector. It will use an upgraded 30 GeV J-PARC beam with a power of 1.3 MW and its detector will be located 295 km away from the source.

In Fig. 1, the results of the analysis for the combination of T2K and NOνA are displayed for $e-\mu$ NO sector. The left panel shows the allowed region in the plane spanned by $\epsilon_{e\mu}$ and the CP-phase δ_{CP}, whereas the right panel displays the allowed region for $\epsilon_{e\mu}$ and the NSI phase $\phi_{e\mu}$. The corresponding best fit points for $e-\mu$ IO sector, $e-\tau$ NO as well as IO sector are reported in Table 1.

In Fig. 2, we display the allowed regions in the plane spanned by the standard CP-phase δ_{CP} and the atmospheric mixing angle θ_{23} in the NO case for DUNE (top panel) and T2HK (bottom panel) . The left panel refers to the SM case, while the middle and right panels concern the SM+NSI scenario with NSI arising from the $e-\mu$ and $e-\tau$ sectors, respectively. The mixing angle θ_{13}

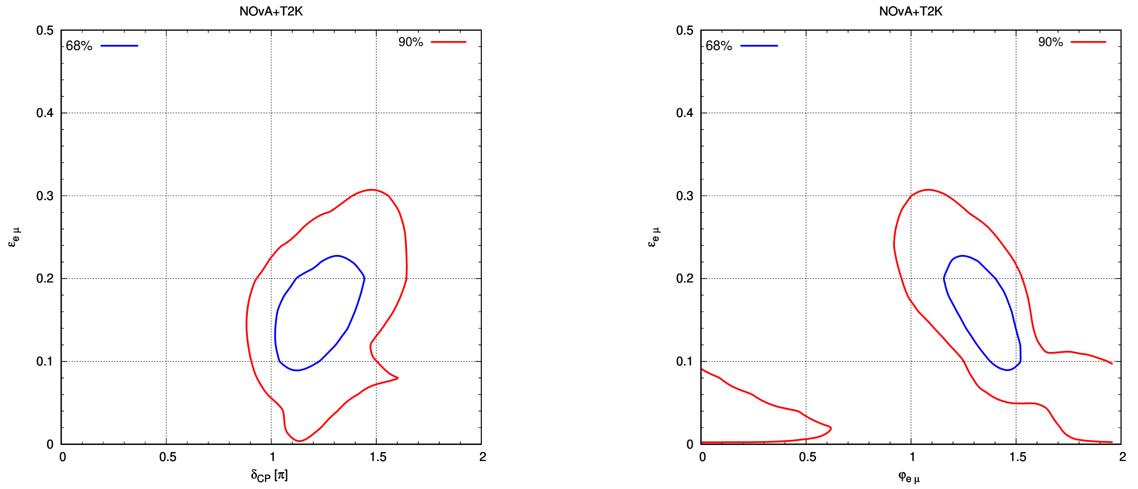

Figure 1: Allowed regions for $\epsilon_{e\mu}$ and the CP phase (left); $\epsilon_{e\mu}$ and phase $\phi_{e\mu}$(right) determined by the combination of T2K and NOνA for NO. The contours are drawn at the 68% and 90% C.L. for 1 d.o.f.

Table 1: From allowed region plots, the best fit points are listed here

Mass ordering	NSI	$\|\epsilon_{\alpha\beta}\|$	$\phi_{\alpha\beta}/\pi$	χ^2
NO	$\epsilon_{e\mu}$	0.14	1.40	2.966
	$\epsilon_{e\tau}$	0.26	1.64	0.252
IO	$\epsilon_{e\mu}$	0.01	1.00	0.147
	$\epsilon_{e\tau}$	0.16	1.64	0.093

is marginalized away in the SM case whereas relevant NSI couplings ($\epsilon_{e\mu}$,$\epsilon_{e\tau}$) and non-standard CP-phases ($\phi_{e\mu}$,$\phi_{e\tau}$) are marginalized away in SM+NSI case. In the middle and right panels we have taken the NSI parameters with their best fit values from the combined analysis of NOνA and T2K. More specifically, $|\epsilon_{e\mu}| = 0.14$, $\phi_{e\mu} = 1.40\pi$ (middle panel) and $|\epsilon_{e\tau}|= 0.26$, $\phi_{e\tau} = 1.64$ (right panel).

Comparing the SM scenario with that of SM+NSI arising from $e-\mu$ sector, we found distinct parameter space in the determination of θ_{23} for both DUNE and T2HK. Also, there is a clear preference for higher octant in $e-\mu$ sector for DUNE as $\Delta\chi^2 = 0.041$ and similarly for T2HK, $\Delta\chi^2 = 1.77$, where $\Delta\chi^2 = \chi^2_{SM} - \chi^2_{SM+NSI}$. Similar exercise for IO is also carried out and the conclusions follow similar pattern like the NO results.

4. Effect of NSI Parameters on Oscillation Probability

In order to understand clearly the effect of NSI on LBL experiment DUNE, we discuss the corresponding probability plots for neutrino mode. In Fig. 3, we present the oscillation probability plots for DUNE in neutrino mode in the SM (left panel), SM+NSI arising from $e-\mu$ sector (middle panel) and SM+NSI arising from $e-\tau$ sector (right panel). For the SM scenario, we

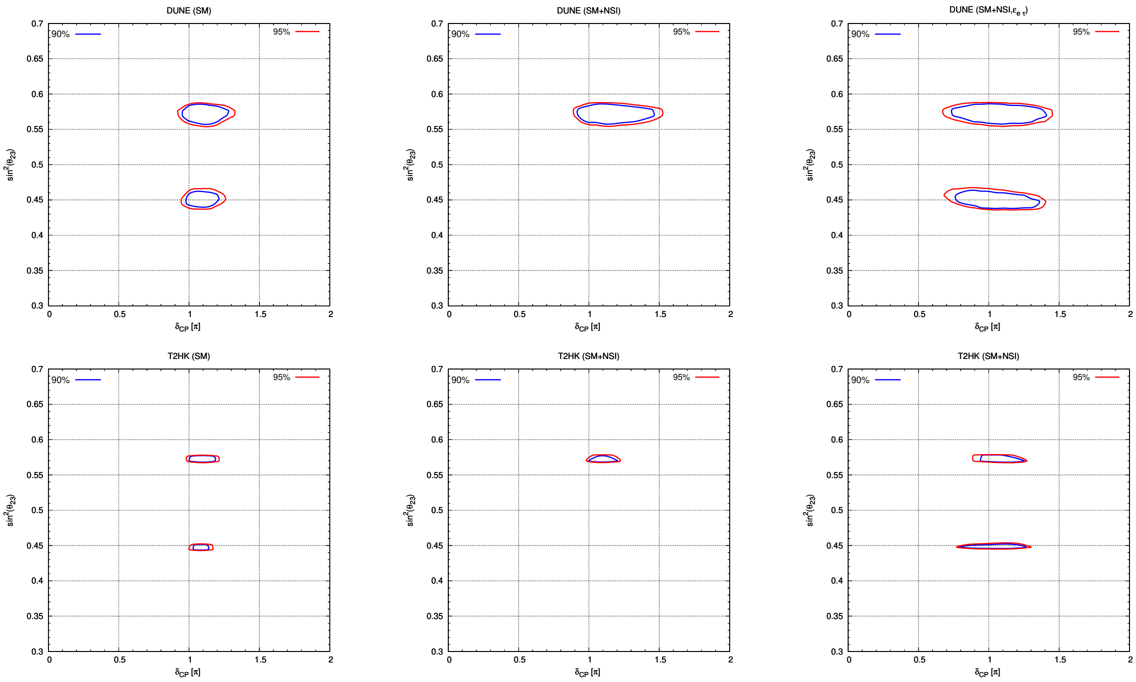

Figure 2: Allowed regions for DUNE (top panel) and T2HK (bottom panel) in SM (left), SM+NSI arising from $e-\mu$ sector (middle) and SM+NSI arising from $e-\tau$ sector (right) for NO. The contours are drawn at the 90% and 95% C.L. for 2 d.o.f.

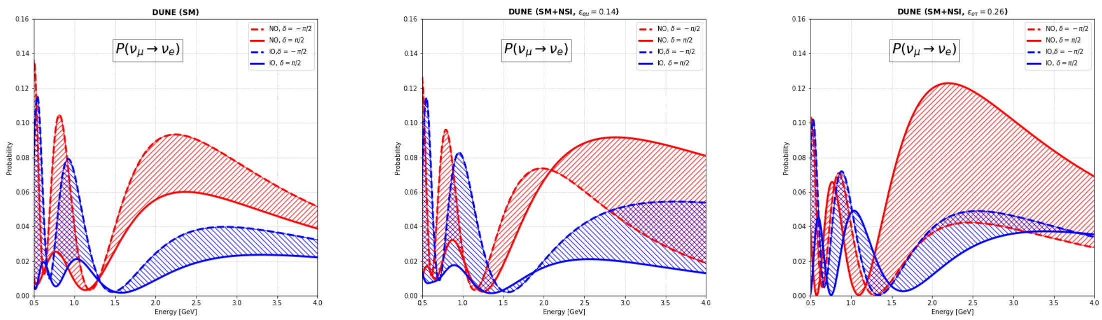

Figure 3: Probability Plots for DUNE in SM (left) and SM+NSI scenario with NSI arising from $e-\mu$ sector (middle) and $e-\tau$ sector (right) for ν mode

see a good separation between NO-IO for both $\delta_{CP} = 90°$ as well as $\delta_{CP} = -90°$. For SM+NSI scenario arising from $e-\mu$ sector, we see a further good separation between NO-IO for $\delta_{CP} = 90°$ whereas the separation continuously decreases for $\delta_{CP} = -90°$ and crosses each other at 2.75 GeV. For SM+NSI scenario arising from $e-\tau$ sector, we see a huge separation between NO-IO for $\delta_{CP} = 90°$ whereas there is no separation for $\delta_{CP} = -90°$ till 1.8 GeV and for the remaining energy we visualise a feeble separation. Similar pattern follows for T2HK.

5. Conclusions

In this article, we assumed that new physics occurs in the form of NSI and hence the minor discrepancy observed in T2K and NOνA CP phase results could be resolved. Thereafter, we obtained the constraints on NSI parameters, considering the effect of one coefficient at a time. We used the derived constraints (we have shown here mostly the case for NO but checked that similar results also follow in the case of IO) from both NOνA and T2K and have shown that for θ_{23} when we use NSI arising from $e-\mu$ sector, both DUNE and T2HK prefer higher octant, whereas inclusion of NSI arising from $e-\tau$ sector brings back the degeneracy of both the lower and higher octants. Moreover, using the same set of constraints, we see striking differences in oscillation probabilities for neutrino channel in DUNE. Future data from NOνA and T2K will decide the fate of existing tension in δ_{CP} and clear the picture. If the tension persists, as we have shown in this analysis, it could probably signal the existence of new physics. Nonetheless, future studies may enable us to disentangle the NSI effects for cleaner extraction of the neutrino parameters.

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