Non-standard interactions and parameter degeneracies in DUNE and T2HKK

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The future long baseline experiments such as DUNE and T2HKK have promising prospects to determine the neutrino mass hierarchy and measuring standard CP phase $\delta$. However, presence of possible non-standard interactions of neutrinos with matter may intriccate this picture and is the subject matter of the present work. We have studied the standard parameter degeneracies in presence of non-standard interactions(NSI) with DUNE and T2HKK experiments. We examine the mass hierarchy degeneracy assuming (i) all NSI parameters to be non-zero and (ii) one NSI parameter($e_{\mu\mu}$) and its corresponding CP phase($\delta_{\mu\mu}$) to be non-zero. We find that the later case is more appropriate to resolve mass hierarchy degeneracy with neutrino beam energy range 1 to 4 GeV with DUNE and T2HKK experiments due to relatively small uncertainties emanating from the NSI sector. We have, also, investigated the octant degeneracy with neutrino($\nu_\mu \rightarrow \nu_\tau$) and antineutrino($\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$) mode separately. We find that to resolve this degeneracy the long baseline experiment with combination of neutrino and antineutrino mode is essential. Furthermore, we have considered DUNE in conjunction with T2HKK experiment to study CP phase degeneracy due to standard($\delta$) and non-standard($\delta_{\mu\mu}$) CP phases. We find that CP violation effects from both standard and non-standard CP phases can be disentangled for neutrino beam energy 1.5 to 7 GeV. The DUNE and T2HKK experiments show similar sensitivities to resolve standard parameter degeneracies in presence of non-standard interactions of neutrinos with matter.

I. INTRODUCTION

The discovery of non-zero neutrino masses and lepton flavor mixing by the reactor\textsuperscript{[1]}, accelerator\textsuperscript{2}, atmospheric\textsuperscript{3} and solar\textsuperscript{4} neutrino oscillation experiments have revealed the values of oscillation parameters such as mass squared differences $\Delta m_{21}^2, \Delta m_{31}^2$ and mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$\textsuperscript{3}, to an unprecedented accuracy. At present, there are some unknown quantities in standard three-neutrino framework namely, (i) sign of $\Delta m_{23}^2$, (ii) the octant of $\theta_{23}$, (iii) the CP-phase $\delta$. The difficulty in the determination of these unknowns is the existence of parameter degeneracy. To overcome these degeneracies one of the method is to combine data from different experiments. Recently this procedure has been adopted by various studies\textsuperscript{[6–8]}, where the synergy between different current as well as future experiments has been considered. In principle, future neutrino oscillation experiments have sensitivity reach to perform precision test of three neutrino oscillation paradigm and to probe new physics beyond standard model(SM). In neutrino oscillation experiments, one model-independent way to study new physics(NP) is given by the framework of non-standard interactions(NSI)\textsuperscript{2,10}.

An alternative phenomena to explain neutrino flavor transitions, on the basis of NSI, was first proposed by Wolfenstein\textsuperscript{[11]}. Although, we know that they will show their effect in neutrino oscillation experiments at sub-leading level but, are important, with the emergence of next generation experiments like T2HK\textsuperscript{12}, DUNE\textsuperscript{13}, T2HKK\textsuperscript{14} etc., where such type of interactions can be probed. In general, the NSIs may manifest itself in propagation of neutrino through matter and the processes involved in its creation and detection. The possible manifestations of NSIs have been widely studied in the literature and bounds on NSI parameters have been derived from various experiments\textsuperscript{[9, 10, 15, 16]}. Furthermore, the model-independent bounds on NSI in production and detection regions are an order of magnitude stronger than the matter NSI\textsuperscript{15}. In this work, we focus on matter NSI which can be defined by dimension-six four-fermion operators as\textsuperscript{[17, 18]}

$$\mathcal{L}_{\text{NSI}} = 2\sqrt{2}G_F \epsilon^K_{\alpha\beta} [\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta] \left[ \zeta_{\gamma\rho} F_K \zeta \right] + H.c., \quad (1)$$

where $\alpha, \beta = e, \mu, \tau$, $K = L, R$, $\zeta = u, d, e$ and $\epsilon^K_{\alpha\beta}$ are dimensionless parameters indicating the strength of the new interaction having units of $G_F$. To probe matter NSI long baseline neutrino experiments(LBNE) are ideal because they are more sensitive towards neutral current interactions. The next generation LBNE such as Deep Underground Neutrino Experiment(DUNE)\textsuperscript{13}, Tokai-to-Hyper-Kamiokande(T2HK)\textsuperscript{12} and Tokai-to-Hyper-Kamiokande-and-Korea(T2HKK)\textsuperscript{14} may reach the sensitivity to reveal NSI in neutrino sector.

In the leptonic sector, the CP violation can render leptogenesis mechanism which in turn may shed light on baryogenesis\textsuperscript{[19, 20]}. It is very difficult to measure leptonic CP-violation in presence of NSI as it will is get bewildered by the existence of possible CP-violation generated by NSI itself. Undoubtedly, the existence of NSI have opened an entirely new window to explore NP beyond standard model.

Previously, the authors of ref.\textsuperscript{[6]} have explored the $CP$ violation in the leptonic sector due to standard and non-
standard interactions and studied parameter degeneracies in neutrino oscillations. In ref. [2], the degeneracies in LBNE from non-standard interactions has been studied and in ref. [21], the authors have studied the impact of various parameter degeneracies introduced by non-zero NSI and the CP precision of DUNE. The authors of refs. [22] and [23] have explored the effects of NSI on CP violation sensitivity and hierarchy sensitivity at DUNE, respectively. In ref. [8], the authors have studied the sensitivity to mass hierarchy, the octant of $\theta_{23}$ and CP phase $\delta$ in the future long baseline experiments T2HK and DUNE assuming standard interactions(SI) only.

In the present work, we have focused on (i) resolving the SI degeneracies viz. hierarchy degeneracy and octant degeneracy in presence of discovery potential of NSI and (ii) resolving the degeneracy between standard and non-standard CP-phase, with DUNE and T2HKK experiments.

We organize the paper as follows: in section II, we present the oscillation probability in presence of NSIs. We discuss about the simulation details and long baseline experiments DUNE and T2HKK, in section III. In section IV, we discuss the prospects to resolve parameter degeneracies in LBNEs. We have presented our results and subsequent discussion in section V. Finally, we conclude in section VI.

\section{Oscillation Probabilities}

The Hamiltonian for the neutrino propagation in presence of matter NSI can be written as,

\begin{equation}
H = \frac{1}{2E} [U \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U^\dagger + V],
\end{equation}

where, $U$ is the PMNS mixing matrix having three mixing angles($\theta_{ij}, i < j = 1,2,3$) and one CP phase $\delta$, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$. $V$ is the matter potential due to the neutrino interaction with matter, viz.

\begin{equation}
V = A \begin{pmatrix}
1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\delta_{\mu\mu}} & \epsilon_{e\tau} e^{i\delta_{\tau\tau}} \\
\epsilon_{e\mu} e^{-i\delta_{\mu\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\delta_{\tau\tau}} \\
\epsilon_{e\tau} e^{-i\delta_{\tau\tau}} & \epsilon_{\mu\tau} e^{-i\delta_{\tau\tau}} & \epsilon_{\tau\tau}
\end{pmatrix},
\end{equation}

where, $A \equiv 2\sqrt{2} G_F N_e(r) E$. The unit contribution in the first element of the matrix $V$ is due the matter term contribution from standard charged-current interactions. The diagonal element of $V$ are real i.e, $\delta_{\alpha\beta} = 0$ for $\alpha = \beta$ and $\epsilon_{\alpha\beta} \equiv \sum_{k<K} c_{k,K} N_e$. The oscillation probability for $\mu \to e$ channel can be written as [2].

\begin{equation}
P(\nu_\mu \to \nu_e) = p^2 f^2 + 2pqf g \cos(\Delta + \delta) + q^2 g^2
\end{equation}

\begin{itemize}
\item $+4A^\epsilon_{e\mu} \{p[f \frac{s_{23}^2 f \cos(\delta_{\mu\mu} + \delta) + c_{23}^2 \cos(\Delta + \delta + \delta_{\mu\mu})]} + q^2 g \cos(\Delta - \delta_{\mu\mu})\}$
\item $+4A^\epsilon_{e\tau} s_{23} c_{23} \{f \cos(\delta_{\tau\tau} + \delta) - g \cos(\Delta + \delta + \delta_{\tau\tau})\}$
\item $-qg \{g \cos(\Delta - \delta_{\tau\tau})\} + 4A^2 g^2 \cos(\Delta - \delta_{\tau\tau})$\end{itemize}

\begin{equation}
p \equiv 2s_{13}s_{23}, q \equiv 2r s_{12} c_{13} c_{23}, r = |\Delta m^2_{21}/\Delta m^2_{31}|, (f, \bar{f}) \equiv \frac{\sin(\Delta(1 + A(1 + \epsilon_{ee})))}{(1 + A(1 + \epsilon_{ee}))},
\end{equation}

\begin{equation}
g \equiv \frac{\sin(\Delta A(1 + \epsilon_{ee}))}{A(1 + \epsilon_{ee})}, \Delta \equiv \left|\frac{\Delta m^2_{31}}{4E}\right|, \hat{A} \equiv \frac{A \Delta m^2_{31}}{4E}.
\end{equation}

\section{Experimental Setups}

Considering the sensitivity reach of the present and future long baseline neutrino oscillation experiments(for example, DUNE and T2HKK), It is very important to study the individual and collective effects of NSI parameters on parameter degeneracies. We have used GLoBES
considered in the present work are as follows:

neutrino mixing parameters, as given in [26], to simulate
software [24, 25] with best-fit values and ranges of the
of 1.0 MW, which corresponds to 5.0
sign that utilizes an 80 GeV proton beam with a power
options for beam design and we choose the optimized de-
from Fermilab to the Homestake mine
in South Dakota. We adopted the DUNE CDR [13] with
LAr) detector setting on the axis
sends neutrinos from Fermilab to the Homestake mine
which corresponds to total 2.7
We assume the same neutrino beam as the T2HK exper-
line. For the Korean detector (KD) we consider two op-
the Kamioka mine, and a second in Korea. The Hyper-K
generacy), the octant degeneracy and
In the determination of unknown neutrino mixing pa-
ting in parameter degeneracies. Because of this, the true
solutions can get mimicked by the false solutions making
In case, \( \theta_{23} \) is not maximal, we have two possibilities: ei-
ambiguity creates two solutions (\( \theta_{23}, \delta \)) and (90° - \( \theta_{23}, \delta' \)). The resolution of
impact is important
\( \nu_{\mu} \rightarrow \nu_{e} \) channel to study various parameter degen-
effects such as DUNE and T2HKK. In left(right) panel of Fig.(1), we have shown the mass hierarchy degeneracy assuming all(\( \epsilon_{e\mu}, \delta_{e\mu} \)) NSI parameters, along with corresponding CP phases, to be non-zero for DUNE and
The oscillation probabilities for disappearance chan-
In presence of new physics there may appear additional
In this work we have investigated the prospects for disentanglement of standard(\( \delta \)) and non-standard CP phases with DUNE+T2HKK using CP fractions. \( F(\delta) \) and \( F(\delta_{e\mu}) \) are the CP fractions corresponding to standard and non-standard CP phases, respectively [27].

A. DUNE

The DUNE experiment [13] with baseline 1300 km
The T2HKK experiment [14] with two detectors one in
The Hyper-K detector (HK) is located in same place as the T2HKK [12] experiment, with a 2.5° off-axis-angle and a 295 km base-
We assume the same neutrino beam as the T2HK exper-
With respect to the beam direction. There are various
35 kton liquid argon (LAr) detector setting on the axis
in general, the different set of oscillation parameter
gives the same value of the oscillation probability result-
in parameter degeneracies. Because of this, the true
solutions can get mimicked by the false solutions making it difficult to uniquely determine the parameters. In this
section, we focus on parameter degeneracy which involve
We explore the mass hierarchy degeneracy (sign de-
the \( CP \) phase degeneracy (SI and NSI \( CP \)-phase degeneracy) with future long
line experiments DUNE and T2HKK.

B. T2HKK

The T2HKK experiment [14] with two detectors one in
off-axis-angle with respect to the beam direction. There are various
options for beam design and we choose the optimized de-
that utilizes an 80 GeV proton beam with a power
of 1.0 MW, which corresponds to 5.0 \( \times \) 10\(^{20} \) protons on
target per year. We assume 5 + 5 years of run time in
antineutrino modes, respectively. The total exposure comes is around 350 kt.MW.years.

Thus, we study the prospects to resolve this degeneracy with two future long baseline experiments DUNE and T2HKK in-
volving NSIs. Throughout this work we have considered the \( \nu_{\mu} \rightarrow \nu_{e} \) channel to study various parameter degen-
eracies. We have obtained plots for DUNE and T2HKK for the two cases assuming (i) all NSI parameters non-zero, and (ii) only \( \epsilon_{e\mu}, \delta_{e\mu} \) are non-zero.

C. \( CP \) phase degeneracy

In presence of new physics there may appear additional
sources of \( CP \) violation other than due to Dirac-type \( CP \) phase \( \delta \). The \( CP \) effects will, in general, include
contributions from both standard and non-standard \( CP \) phases. In this work we have investigated the prospects for disentanglement of standard(\( \delta \)) and non-standard \( CP \) phases with DUNE+T2HKK using CP fractions. \( F(\delta) \) and \( F(\delta_{e\mu}) \) are the CP fractions corresponding to standard and non-standard \( CP \) phases, respectively [27].
FIG. 1. The appearance probability $P(\nu_\mu \rightarrow \nu_e)$ with neutrino beam energy $E$ in GeV for DUNE(first row) and T2HKK(second row). The left(right) panel describes mass hierarchy assuming all($\epsilon_{e\mu}, \delta_{e\mu}$) NSI parameters non-zero.

DUNE and T2HKK for energy range 1 to 4 GeV assuming only $\epsilon_{e\mu}$ and corresponding phase to be non-zero(right panel). Furthermore, the future long baseline experiments such as DUNE and T2HKK with higher statistics and better energy resolution focusing on neutrino beam energy 1 to 4 GeV may provide better opportunity to resolve mass hierarchy degeneracy. However, for the same energy range DUNE have brighter prospects to resolve the mass degeneracy than T2HKK.

In Fig.(2), we have shown the status octant degeneracies in DUNE and T2HKK. It is evident from Fig.(2) that octant degeneracy can be resolved with DUNE and T2HKK experiments using combination of neutrino and antineutrino oscillation modes. In Fig.(2), the region between solid and dashed lines($-\pi/2 \leq \delta \leq \pi/2$) represents the lower octant(LO) and the region between dash-dotted and dotted lines($-\pi/2 \leq \delta \leq \pi/2$) represents the higher octant(HO). The left(right) panel in Fig.(2) represents neutrino(antineutrino) mode of DUNE and T2HKK experiments. For LO($\theta_{23} < 45^\circ$), with $\delta = \pi/2$ and for HO($\theta_{23} > 45^\circ$) with $\delta = -\pi/2$, both DUNE and T2HKK can resolve the octant degeneracies with neutrino mode only. Moreover, for LO with $\delta = -\pi/2$ and HO with $\delta = \pi/2$, octant degeneracies can be resolved with both DUNE and T2HKK with antineutrino mode only. Thus, in general, the neutrino and antineutrino modes are exigent to resolve octant degeneracy in DUNE and T2HKK experiments.

The current and future neutrino oscillation experiments are diligently aiming at measuring neutrino mass hierarchy and $CP$ violating phase $\delta$. In presence of NSI (for example, assuming $\epsilon_{e\mu}$ and $\delta_{e\mu}$ non-zero) the situation becomes more complicated due to presence of additional sources of $CP$ violation. The nature may intrum $CP$ violation for wide range of $\delta(\delta_{e\mu})$. In the present work, instead of focusing on measurement of $CP$ phases($\delta, \delta_{e\mu}$) we have obtained all possible $\delta(true)$ and $\delta_{e\mu}(true)$ values which are different from $CP$ conserving values of $\delta$ and $\delta_{e\mu}$ at certain confidence level obtained from neutrino oscillation experiments. It is advantageous to use $CP$ fraction formalism [27] to study $CP$ violation and to disentangle the standard and non-standard $CP$ violation effects in neutrino oscillation experiments. The $CP$ fraction corresponding to $\delta(\delta_{e\mu})$ may be defined as the fraction $F(\delta(F(\delta_{e\mu}))$ of total allowed range ($0$ to $2\pi$) over which $CP$ violation can
FIG. 2. The appearance probability for neutrino(antineutrino) mode with neutrino beam energy $E$ in GeV for DUNE(first row) and T2HKK(second row). The Octant degeneracy is represented for neutrino mode(left panel) and for antineutrino mode(right panel).

FIG. 3. The $CP$ asymmetry with neutrino beam energy $E$ in GeV for DUNE+T2HKK(left panel) for both standard and non-standard $CP$ phases. The $CP$ fraction corresponding to both $\delta_{CP}$ and $\delta_{e\mu}$ (right panel).
be discovered for $\delta(\text{true})/\delta_{\text{true}}$. We have fixed absolute values of NSI parameters to their true values and $\delta_{\text{true}}$ to their CP conserving values $(\delta, \delta_{\text{true}}) \in \{(0,0), (0, \pi), (\pi,0), (\pi, \pi)\}$ taking into account both mass hierarchies in test values. To disentangle the CP violation effects from standard and non-standard CP phases using CP fractions we have shown the effect of the real NSI parameter ($\epsilon_{\mu\nu}$) on the CP violation discovery reach for DUNE+T2HKK experiments.

In Fig. (3a), we have shown CP asymmetry with neutrino beam energy for both $\delta$ and $\delta_{\text{true}}$ for DUNE+T2HKK. In Fig. (3a), the solid (dashed) line represents $\delta = 0, \delta_{\text{true}} = \pi/2, \delta = \pi/2, \delta_{\text{true}} = 0$ case whereas, in Fig. (3b)), the solid (dashed) line represents the CP fraction corresponding to the $\delta_{\text{true}}(\delta)$. The contribution to CP asymmetry from non-standard CP phase $\delta_{\text{true}}$ is more than the standard CP phase for neutrino beam energy 1.5 to 7 GeV which is, also, evident from Fig. (3b)). The CP degeneracy between standard and non standard CP phases can be resolved in DUNE+T2HKK as the CP fraction for $\delta(F(\delta) \approx 0.57)$ is smaller than that of $\delta_{\text{true}}(F(\delta_{\text{true}}) \approx 0.76)$.

VI. CONCLUSIONS

In conclusion, we have investigated the sensitivities of DUNE and T2HKK experiments to resolve mass hierarchy and octant degeneracies in presence of matter NSI. We have, also, studied the CP phase degeneracy due to standard and non-standard CP phases for DUNE+T2HKK. We find that the mass hierarchy degeneracy cannot be resolved in presence of all NSI parameters due to their large experimental uncertainties (Figs.1(a) and 1(c)). However, it can be resolved for neutrino beam energy range 1 to 4 GeV in case of one non-zero NSI parameter $\epsilon_{\mu\nu}$ and corresponding NSI CP phase $\delta_{\text{true}}$ for DUNE and T2HKK experiments (Figs.1(b) and 1(d)). Furthermore, for LO($\theta_{23} < 45^\circ$), with $\delta = \pi/2$ and for HO($\theta_{23} > 45^\circ$) with $\delta = -\pi/2$, both DUNE and T2HKK can resolve the octant degeneracies with neutrino mode only. Moreover, for LO with $\delta = -\pi/2$ and HO with $\delta = \pi/2$, both DUNE and T2HKK can resolve with both DUNE and T2HKK with antineutrino mode only. Thus, combination of neutrino and antineutrino mode of DUNE and T2HKK can resolve the octant degeneracy. The contribution to CP asymmetry from non-standard CP phase $\delta_{\text{true}}$ is more than the standard CP phase $\delta$ for neutrino beam energy 1.5 to 7 GeV (Fig. 3(a)) which is, also, evident from Fig. (3b)). The CP fraction corresponding to NSI phase $\delta_{\text{true}}$ is found to be larger than that of SI phase $\delta(\pi/2)$ in combined analysis of DUNE+T2HKK. Thus, the combination of DUNE and T2HKK experiments can, in principle, disentangle the standard and non-standard CP phase degeneracy.

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