Implications of lepton flavour violation on long baseline neutrino oscillation experiments

Soumya C. and R. Mohanta

School of Physics, University of Hyderabad, Hyderabad - 500 046, India

Abstract

Non-standard neutrino interactions (NSIs), the sub-leading effects in the flavour transitions of neutrinos, play a crucial role in the determination of the various unknowns in neutrino oscillations, such as neutrino mass hierarchy, Dirac CP violating phase and the octant of atmospheric mixing angle. In this work, we focus on the possible implications of lepton flavour violating (LFV) NSIs, which generally affect the neutrino propagation, on the determination of the these unknown oscillation parameters. We study the effect of these NSIs on the physics potential of the currently running and upcoming long-baseline experiments, i.e., T2K, NOνA and DUNE. We also check the allowed oscillation parameter space in presence of LFV NSIs.

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I. INTRODUCTION

Neutrino oscillation [1–7], the phenomenon of flavour transition of neutrinos, provides strong evidences for neutrino mass and mixing. Further, the three flavour neutrino oscillation model has become a very successful theoretical framework, which could accommodate almost all neutrino oscillation experimental data except some results in very short baseline experiments. However, some of the oscillation parameters [8, 9] (Dirac CP violating phase, neutrino mass hierarchy and the octant of atmospheric mixing angle) in the standard paradigm are still not known. Recently, Daya Bay [10, 11], RENO [12] and Double CHOOZ [13] experiments have observed that the value of reactor mixing angle is significantly large (close to its upper bound), which improves the sensitivities to determine these unknowns by enhancing the matter effect. Therefore, a well understanding of sub-leading contributions to neutrino oscillation, coming from various new physics scenarios, may lead to the enhancement of physics potentials of long-baseline neutrino oscillation experiments.

Non-standard neutrino interactions (NSIs) [14, 15] can be considered as sub-leading effects in the neutrino oscillations, which arise from various new physics scenarios beyond the standard model. The NSIs, which come from Neutral Current (NC) interactions can affect the propagation of neutrino, whereas NSIs coming from the Charged Current (CC) interactions of neutrinos with quarks and leptons can affect the production and detection processes of neutrinos. However, in this work, we consider only the NSIs which affect the propagation of neutrinos. The Lagrangian corresponds to NSIs during the propagation is given by [16],

\[
\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \varepsilon^{fC}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_C f),
\]

where \(G_F\) is the Fermi coupling constant, \(\varepsilon^{fC}_{\alpha\beta}\) are the new coupling constants, so called NSI parameters, \(f\) is fermion and \(P_C = (1 \pm \gamma_5)/2\) are the right (\(C = R\)) and left (\(C = L\)) chiral projection operators. The NSI contributions which are relevant as neutrino propagate through the earth are those coming from the interaction of neutrino with \(e, u\) and \(d\) because the earth matter is made up of these fermions only. Therefore, the effective NSI parameter is given by

\[
\varepsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{n_f}{n_e} \varepsilon^{f}_{\alpha\beta},
\]

where \(\varepsilon^{f}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}\), \(n_f\) is the number density of the fermion \(f\) and \(n_e\) the number density.
of electrons in earth. For earth matter, we can assume that the number densities of electrons, protons and neutrons are equal, i.e, \( n_n \approx n_p \approx n_e \), which implies that \( n_u \approx n_d = 3n_e \).

NSIs and their consequences have been studied quite extensively in the literature both in model dependent (mass models) and independent ways. Furthermore, there are studies, which have been done to investigate the effect of NSIs on atmospheric neutrinos [17–19], solar neutrinos [20–24], accelerator neutrinos [25–35] and supernova neutrinos [36–38]. However, it is very crucial to understand the implications of new physics effects at the long baseline experiments like T2K, NO\( \nu \)A and DUNE. In this regard, there are many recent works which have been discussed the various aspects of NSIs at long baseline experiments [39–41], for instance in [42], the authors have obtained the constrain on NSI parameters using long baseline experiments and in [43] authors have discussed the degeneracies among the oscillation parameters in presence of NSIs. However, in this paper, we focus on the effect of the lepton flavour violating NSIs on the determination of various unknowns at long baseline experiments.

We have discussed the physics potential of long baseline experiments in our previous papers [44, 45]. As neutrino oscillation physics already entered into its precision era, one should take care of various sub-leading effects such as NSIs in the oscillation physics. In this regard, we would like to study the effect of the lepton flavor violating NSIs on the determination of oscillation parameters. This paper is organized as follows. In section II, we discuss the basic formalism of neutrino oscillation including NSI effects. In section III, we study the effect of NSI parameters on \( \nu_e \) appearance oscillation probability. The effect of LFV NSI on Physics potential of long baseline experiments are discussed in section IV. In section V, we discuss the parameter degeneracies among the oscillation parameters in presence of NSIs. Section VI contains the summary and conclusions.

II. NEUTRINO OSCILLATION WITH NSIS

In the standard oscillation (SO) paradigm, the propagation of neutrino through matter is described by the Hamiltonian

\[
H_{SO} = H_0 + H_{\text{matter}} \\
= \frac{1}{2E} U \cdot \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger + \text{diag}(V_{CC}, 0, 0),
\]

(3)
where the $H_0$ is the Hamiltonian in vacuum, $\Delta m^2_{ji} = m^2_j - m^2_i$ is neutrino mass squared difference, $H_{\text{matter}}$ is the Hamiltonian responsible for matter effect, $V_{CC} = \sqrt{2}G_F n_e$ is the matter potential and $U$ is the PMNS mixing matrix which is described by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and one phase ($\delta_{CP}$) and is given by

$$U_{\text{PMNS}} = \begin{pmatrix}
  c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
  -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\
  s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23}
\end{pmatrix},$$

(4)

with $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The NSI Hamiltonian, which is coming from the interactions of neutrinos as they propagate through matter is given by

$$H_{\text{NSI}} = V_{CC} \begin{pmatrix}
  \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\
  \varepsilon^{*}_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\
  \varepsilon^{*}_{e\tau} & \varepsilon^{*}_{\mu\tau} & \varepsilon_{\tau\tau}
\end{pmatrix},$$

(5)

where $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$ are the complex NSI parameters, which give the coupling strength of non-standard interactions. The off-diagonal elements of the NSI Hamiltonian ($\varepsilon_{e\mu}, \varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$) are the lepton flavor violating NSI parameters, which are our subject of interest.

Almost all current neutrino oscillation data are consistent with the standard oscillation paradigm. Therefore, the effect of NSI on the oscillation phenomena is expected to be very small. Moreover, some neutrino mass models for instance, triplet seesaw model [46], Zee Babu model [47] predict the value of NSI parameters of the order of $10^{-4} - 10^{-3}$, which depend on the scale of new physics and the neutrino mass ordering. The strong constraints on NSI parameters make them very difficult to be observed in the long baseline experiments. Therefore, we use phenomenological way to study the effect of NSIs on the physics potential of such experiments. The model independent current upper bounds of NSI parameters at 90 % C.L. are given as [48, 49]

$$|\varepsilon_{\alpha\beta}| < \begin{pmatrix}
  4.2 & 0.3 & 0.5 \\
  0.3 & 0.068 & 0.04 \\
  0.5 & 0.04 & 0.15
\end{pmatrix}.$$
III. LFV-NSI EFFECT ON $\nu_e$ APPEARANCE PROBABILITY

In general, the measurement of branching ratios (BRs) and the CP violation parameters can be used to probe the New Physics effects or non-standard interactions in the flavor sector. If any inconsistency found between the experimental observed values and the corresponding SM predictions in these observables, it would imply the presence of new physics. However, in the case of neutrinos one can not use branching ratio measurements to study the new physics effects, since the mass difference between neutrinos is really small and also experiments detect neutrinos as flavour states (mixed state of mass eigenstates). The various issues regarding the BR measurement of neutrinos are discussed in [50]. Therefore, in the case of neutrinos, new physics effect can be studied by using the oscillation probabilities. The super-beam experiments like T2K, NO$\nu$A and DUNE use muon neutrino beams as neutrino source. Therefore, in this section, we discuss the consequences of LFV-NSI parameters on neutrino appearance ($\nu_\mu \rightarrow \nu_e$) probability.

| Expt. setup | T2K | NO$\nu$A | DUNE |
|-------------|-----|---------|------|
| Detector    | Water Cherenkov | Scintillator | Liquid Argon |
| Beam Power(MW) | 0.75 | 0.77 | 0.7 |
| Fiducial mass(kt) | 22.5 | 14 | 35 |
| Baseline length(km) | 295 | 810 | 1300 |
| Running time (yrs) | 5 ($3\nu+2\bar{\nu}$) | 6 ($3\nu+3\bar{\nu}$) | 10 ($5\nu+5\bar{\nu}$) |

TABLE I: The experimental specifications.

We use GLoBES package [51, 52] along with snu plugin [53, 54] for our analysis to study the implications of LFV-NSI on the propagation of neutrinos. The experimental details of T2K, NO$\nu$A and DUNE that we consider in this analysis are given in Table I. The values of standard oscillation parameters that we use in the analysis are given in the Table II.
FIG. 1: Neutrino appearance probability for the $\nu_\mu \rightarrow \nu_e$ without NSI (light shaded region) and with NSI (dark shaded green, red and blue regions are correspond to $\varepsilon_{e\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{e\tau}$ parameters contribution respectively) for T2K (top panel), NO$\nu$A (middle panel) and DUNE (bottom panel). The hierarchy is assumed to be NH.

For an illustration, we show the calculated transition probability with and without NSI for T2K (top panel), NO$\nu$A (middle panel) and DUNE (bottom panel) by assuming hierarchy as NH in Fig. 1 for neutrinos. In the figure, the light shaded regions correspond to probability in the standard oscillation (SO) paradigm, whereas the dark shaded green, red, and blue regions represent the additional contribution to the oscillation probability, which are coming from NSI parameters $\varepsilon_{e\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{e\tau}$ respectively. From the figure, we can see that the NSI contribution to oscillation probability is noteworthy in presence of $\varepsilon_{e\tau}$ and $\varepsilon_{e\mu}$ parameters,
Oscillation Parameter & True Value \\
\sin^2 \theta_{12} & 0.32 \\
\sin^2 2\theta_{13} & 0.1 \\
\sin^2 \theta_{23} & 0.5, 0.41 (LO), 0.59 (HO) \\
\Delta m_{atm}^2 & 2.4 \times 10^{-3} \text{ eV}^2 \text{ for NH} \\
& -2.4 \times 10^{-3} \text{ eV}^2 \text{ for IH} \\
\Delta m_{21}^2 & 7.6 \times 10^{-5} \text{ eV}^2 \\
\delta_{CP} & 0^\circ \\

TABLE II: The true values of oscillation parameters considered in the simulations are taken from [64].

whereas the contribution from $\varepsilon_{\mu\tau}$ is negligible. It can also be seen from the figure that there is significant change in the oscillation probability in the presence of NSIs for both NO$\nu$A and DUNE, whereas for T2K, the effect is found to be rather small, i.e., NO$\nu$A and DUNE are more sensitive to NSI effects. We can also see that there is a substantial change in the oscillation probability of DUNE experiment in the presence of NSI. Therefore, DUNE experiment can be used to investigate various effect of NSI, which are expected to be observed in the long baseline experiment. Moreover, NSI can even affect the results, which require much precision on their measurements for the determination of the unknowns in neutrino sector, of the currently running experiments like T2K and NO$\nu$A.

IV. NSI EFFECT ON PHYSICS POTENTIAL OF LONG BASELINE EXPERIMENTS

The primary objective of long baseline experiments is the determination of the various unknowns (Neutrino mass ordering, CP violating phase and octant of atmospheric mixing angle) in the phenomenon of neutrino oscillation. In this section, we discuss the effect of LFV-NSI on the determination of these unknowns. From the previous section, we found that the NSI parameter $\varepsilon_{e\tau}$ can significantly change the oscillation probability. Therefore, for simplicity, we focus on the effect of $\varepsilon_{e\tau}$ on the determination of other unknowns in neutrino
oscillation sector. We also compare the effect of NSIs on physics potential of different experiments that have been considered in this paper. All the sensitivities are computed by using GLoBES.

A. Effect on the determination of neutrino mass ordering

So far, we do not know whether the hierarchy of neutrino mass is Normal ($m_1 < m_2 << m_3$) or Inverted ($m_3 << m_1 < m_2$). The MSW effect, the so called matter effect plays a crucial role in the determination of neutrino mass hierarchy, because unlike vacuum oscillation, they give different contributions to oscillation probability for NH and IH, as one can see from the top panel of Fig. 2. Therefore, a thorough study of effect of NSIs on the determinations of MH is of great importance in oscillation physics.

FIG. 2: Neutrino appearance probability for the $\nu_\mu \rightarrow \nu_e$ without NSI (top panel) and with NSI (bottom panel) by assuming both NH (red) and IH (blue) for T2K (left panel), NOνA (middle panel) and DUNE (right panel).

However, if we compare the top and bottom panels of Fig. 2 we can see that there is considerable overlap between the hierarchies in the presence of NSIs and this overlap will
worsen the hierarchy determination capability of long-baseline experiments. Further, the MH sensitivity as a function of true values of Dirac CP phase $\delta_{CP}$ is shown in Fig. 3. In the figure, the solid blue line corresponds to the MH sensitivity in SO, which is obtained by comparing true event spectrum as NH and test event spectrum as IH. The blue band in the figure shows the variation in MH sensitivity for different values of $\delta_{e\tau}$ with $\varepsilon_{e\tau} = 0.3$. In all cases, we do marginalization over SO parameters in their allowed parameter space and add a prior on $\sin^2 2\theta_{13}$. From the figure, it is clear that though the presence of NSI worsen MH sensitivity, there is a possibility to determine mass hierarchy for T2K (NO$\nu$A) above $2\sigma$ ($3\sigma$) for 30% (75%) of parameter space of $\delta_{CP}$.

**B. Effect on the determination of octant of $\theta_{23}$**

The precision measurements of atmospheric neutrino oscillation data by Super-Kamiokande experiment prefers a maximal mixing of $\theta_{23}$, i.e, $\theta_{23} = \pi/4$. However, disappearance measurements of MINOS [55], point towards non-maximal mixing, which contradicts the measurements of Super-Kamiokande. Therefore, there are two possibilities, either $\theta_{23} < \pi/4$, so called Lower Octant (LO) or $\theta_{23} > \pi/4$, so called Higher Octant (HO). The T2K disappearance measurement, which provides the most precise value of $\theta_{23}$, indicates that $\theta_{23}$ is near to maximal. However, T2K data along with reactor data show that
\( \theta_{23} \) is in higher octant. The resolution of such tension between LO and HO of atmospheric mixing angle is one of the challenging goal of long baseline neutrino oscillation experiments. In this section, we discuss the effect of LFV-NSI on the resolution of octant of atmospheric mixing angle.

![Neutrino appearance probability](image)

**FIG. 4:** Neutrino appearance probability for the \( \nu_\mu \rightarrow \nu_e \) without NSI (top panel) and with NSI (bottom panel) by assuming both HO (red) and LO (blue) for T2K (left panel), NO\( \nu \)A (middle panel) and DUNE (right panel).

The octant degeneracy is merely a consequence of inherent structure of three flavour neutrino oscillation probability, where a set of oscillation parameters gives disconnected regions in neutrino oscillation parameter space and it makes too difficult to find the true solution. However, the matter effect in long baseline experiments can help to resolve the octant of \( \theta_{23} \) [65], since the oscillation probability gives different contributions to HO and LO as one can see from the upper panels of Fig. 4. From the lower panels of the figure, it can be seen that there is considerable overlap between the lower and higher octants in the presence of LFV-NSI, which will worsen the sensitivity of long baseline experiments in the determination of octant of \( \theta_{23} \). Moreover, the octant sensitivity as a function of true value of \( \sin^2 \theta_{23} \) is given in Fig. 5. The octant sensitivity is obtained by comparing true event
FIG. 5: Octant sensitivity as a function of true values of \( \sin^2 \theta_{23} \). The blue line in the figure corresponds to octant without NSI, whereas light blue band in the figure shows the octant sensitivity in presents of NSI (\( \varepsilon_{e\tau} = 0.3 \)) in the allowed range of \( \delta_{e\tau} \) for T2K (left panel), NO\( \nu \)A (middle panel) and DUNE (right panel). Neutrino MH is assumed to be Normal Hierarchy spectrum (HO/LO) with test event spectrum (LO/HO). While calculating the \( \chi^2 \), we do marginalization over SO parameter space in their allowed values and add a prior on \( \sin^2 2\theta_{13} \). From the figure, we can see that there is a possibility of enhancement in the sensitivity of octant of atmospheric mixing angle in the presence of LFV-NSIs, though LFV-NSIs worsen the sensitivity.

C. Effect on the determination of CP violating phase \( \delta_{CP} \)

One of the main objectives of long-baseline neutrino oscillation experiments is the determination of the CP violation (CPV) in the leptonic sector. Therefore, it is crucial to study the effect of NSI on the determination of CPV at T2K, NO\( \nu \)A and DUNE experiments. The direct measurement of CP violation can be obtained by looking at the difference in the transition probability of CP conjugate channels i.e, by analyzing the \( \nu_e \) appearance and \( \bar{\nu}_e \) appearance probabilities.

We use the observable so called CP asymmetry \( (A_{CP}) \) to quantify the effects due to CP violation and it is defined as

\[
A_{CP} = \frac{P_{\mu e} - \overline{P}_{\mu e}}{P_{\mu e} + \overline{P}_{\mu e}}
\]

(7)

where \( P_{\mu e} \) is the \( \nu_e \) appearance probability and \( \overline{P}_{\mu e} \) is \( \bar{\nu}_e \) appearance probability. Fig. 6 shows the CP asymmetry bands for T2K (left panel), NO\( \nu \)A (middle panel) and DUNE.
FIG. 6: The CP asymmetry bands for T2K (left panel), NOνA (middle panel) and DUNE (right panel) without NSI (light coloured band) and with NSI (dark coloured band) by assuming both NH (top panel) and IH (bottom panel). The solid black line corresponds to CP asymmetry for $\delta_{CP} = 0$ without NSI, whereas the dashed white line corresponds to CP asymmetry for $\delta_{CP} = 0$ with NSI ($\varepsilon_{e\tau} = 0.3$).

FIG. 7: The CPV potential as a function of true values of $\delta_{CP}$ for T2K (left panel), NOνA (middle panel) and DUNE (right panel) without NSI (solid blue line) and with NSI (band).
(right panel) without NSI (light coloured band) and with NSI (dark coloured band) by assuming both normal (top panel) and inverted (bottom panel) hierarchies. The solid black line corresponds to CP asymmetry for $\delta_{CP} = 0$ without NSI, whereas the dashed white line corresponds to CP asymmetry for $\delta_{CP} = 0$ with NSI ($\varepsilon_{e\tau} = 0.3$). The dark bands in the figure show the impact of the phase of LFV-NSI parameter on $A_{CP}$. Therefore, the dark bands correspond to the fake CP signals which are coming from NSI. From the figures, we can see that there is not much change in the asymmetry with NSI and without NSI in the case of T2K, whereas in the case of NO$\nu$A the bands show that there is significant change in the asymmetry with NSI and without NSI. Moreover, the change in the asymmetry is quite large in the case of DUNE. From the figure, it is clear that NSI can give fake CP signals even without considering contributions from the intrinsic phase ($\delta_{e\tau}$) of NSI parameter and therefore, it is very difficult to determine the CP violation in the presence of NSIs.

The CP violation sensitivity as a function of true values of $\delta_{CP}$ for T2K (left panel), NO$\nu$A (middle panel) and DUNE (right panel) is shown in Fig. 7. The CP violation sensitivity is obtained by comparing the true event spectrum and test event spectrum with $\delta_{test}^{CP} = 0, \pi$. We do marginalization over the SO parameter space and add a prior on $\sin^2 \theta_{13}$. From the figure, it is clear that there is a possibility to determine CP violation above 2$\sigma$, 3$\sigma$ and 5$\sigma$ with 30%, 60% and 60% of $\delta_{CP}$ parameter space for T2K, NO$\nu$A and DUNE respectively.

V. DEGENERACIES AMONG OSCILLATION PARAMETERS IN PRESENCE OF LFV-NSI

One of the major issues in neutrino oscillation physics is the parameter degeneracy among the oscillation parameters. In the standard oscillation physics, there are four-fold degeneracies among the oscillation parameters and they are known as octant degeneracy and mass hierarchy (sign of $\Delta m_{31}^2$) degeneracy. In this section, we present a simple way to understand the degeneracies among the oscillation parameters in the presence of LFV-NSI parameter $\varepsilon_{e\tau}$, by using bi-probability plots i.e., CP trajectory in a $P_{\nu_{\mu} \to \nu_{e}} - P_{\bar{\nu}_{\mu} \to \bar{\nu}_{e}}$ plane and $\delta_{CP}$-$A_{CP}$ plane.

In Fig. 8 we show the bi-probability plots for T2K ($E = 0.6$ GeV, $L = 295$ km), NO$\nu$A ($E = 2$ GeV, $L = 810$ km) and DUNE ($E = 3$ GeV, $L = 1300$ km) for both NH (solid line) and IH (dashed line) where dark (light) colour plot corresponds to HO (LO). In the
FIG. 8: The CP trajectory for T2K (left), NO\(\nu\)A (middle) and DUNE (right) with (bottom panel) and without (top panel) NSIs.

In the standard oscillation paradigm, the NH and IH ellipses are well separated in the case of DUNE experiment, compared with T2K and NO\(\nu\)A experiments. This means that DUNE experiment has highest mass hierarchy determination capability. However, the ellipses in presence of LFV-NSI overlap with each other, which will significantly worsen the hierarchy determination capability of DUNE experiment. It can also be seen from the figure that octant degeneracy can be resolved by using all the three experiments, since the light coloured ellipses are well separated from dark coloured ellipse in the SO. Whereas the octant resolution capability of NO\(\nu\)A and DUNE experiments become worsen in presence of LFV-NSI, because there is significant overlap between the CP trajectories of HO and LO in presence of LFV-NSI. Moreover, there present new types of degeneracies among oscillation parameters in presents of LFV-NSI.

Now, we focus on the bi-probability plot of DUNE with NSI (bottom right panel) of Fig. 8...
for a detailed discussion on the resolution of parameter degeneracies among the oscillation parameters. One can see from the figure that

- If $\delta_{e\tau} = -180^\circ$, then the points in the $P(\nu_\mu\rightarrow\nu_e) - P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ plane are well separated in the case of NH-HO and IH-HO, which is a clear indication of mass hierarchy determination even in presence of LFV-NSI. Whereas, the capability of MH is reduced in the case of IH-LO and NH-LO. It is also noted from the figure that, NH(IH)-HO and NH(IH)-LO are also well separated, which means that octant determination is possible in this case.

- If $\delta_{e\tau} = -90^\circ$, then it is extremely difficult to infer any definitive conclusion about the determination of both mass hierarchy and octant, since all the four degenerate points in $P(\nu_\mu\rightarrow\nu_e) - P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ plane are very close to each other.

- If $\delta_{e\tau} = 0$, then all the four degenerate points are very close to each other in $P(\nu_\mu\rightarrow\nu_e) - P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ plane and therefore it is extremely difficult to make any decisive prediction about the determination of both mass hierarchy and octant.

- If $\delta_{e\tau} = 90^\circ$, then the points correspond to NH-HO and IH-HO in $P(\nu_\mu\rightarrow\nu_e) - P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ plane are very well separated, which is an indication of MH determination. However, the capability of determination of mass hierarchy is reduced in the case of LO. It is also noted that octant determination is poor in this case.

All the above predictions are made under the assumptions that the value of LFV-NSI $\varepsilon_{e\tau}$ is near to its upper bound and the value of CP violating phase is near to its currently preferred value i.e, $\delta_{CP} = -90^\circ$. Moreover, these predictions point toward that the mass hierarchy and octant determinations are possible even in the presence of LFV-NSI, if $\delta_{e\tau} = -180^\circ$ or $90^\circ$.

Another simple way to understand the parameter degeneracies among the oscillation parameters is by simply looking at the CP-asymmetry, which is defined in Eqn. 7. CP-asymmetry as a function of $\delta_{CP}$ for NH-LO, NH-HO, IH-LO and IH-HO for DUNE experiment is given in Fig. 9. The top left panel of the figure shows the CP asymmetry in standard oscillation and it can be seen from the figure that CP asymmetry is more in LO than in HO for both NH and IH. The rest of three in the top panel show the CP asymmetry in presence of NSI with $\delta_{e\tau} = 0, -90^\circ, \text{ and } 90^\circ$ respectively. It is clear from the figure that LFV-NSI
FIG. 9: The parameter degeneracy among the oscillation parameter in $\delta_{CP}$-CP asymmetry plane for DUNE experiment. The top left panel shows the degeneracies in SO, whereas the other three panels show the degeneracy in presence of LFV-NSI with $\delta_{e\tau} = 0$, -90, and 90 respectively. The bottom panel shows the $A_{CP}$ for NH-HO, NH-LO, IH-LO and IH-LO in presence of NSI ($\varepsilon_{e\tau} = 0.3$ and $\delta_{e\tau} = [\pi : \pi]$).

introduces other degeneracies among the standard oscillation parameters. Moreover, the bottom panel shows the $A_{CP}$ for NH-HO, NH-LO, IH-LO and IH-LO in presence of NSI ($\varepsilon_{e\tau} = 0.3$ and $\delta_{e\tau} = [\pi : \pi]$). Therefore, degeneracy resolution in presence of NSI extremely complicated. It also noted that degeneracy resolution capability is mainly depend on the value of $\delta_{e\tau}$, for instance if $\delta_{e\tau} = 90^\circ$, then CP-asymmetry for IH-LO and IH-HO are almost same and one cannot distinguish between them.

**A. Correlation between $\delta_{CP}$ and $\theta_{23}$**

In this section, we discuss the effect of LFV-NSI on the allowed parameter space of $\sin^2 \theta_{23}$ and $\delta_{CP}$. We show the $2\sigma$ C.L. regions for $\sin^2 \theta_{23}$ vs. $\delta_{CP}$ with true $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and true $\delta_{CP} = -90^\circ$ in Fig. [10] for T2K (top panel) and DUNE (bottom panel) experiments. From the figure, we can see that there is significant change in the allowed parameter space in presence of LFV-NSI for DUNE.
FIG. 10: The $2\sigma$ C.L. regions for $\sin^2 \theta_{23}$ vs. $\delta_{CP}$ with true $\sin^2 \theta_{23} = 0.41 \ (0.59)$ for LO (HO) and true $\delta_{CP} = -90^\circ$. The top panel corresponds to T2K and bottom panel corresponds to DUNE experiments.

VI. SUMMERY AND CONCLUSIONS

We have investigated the implications of LFV-NSIs on the physics potential of various neutrino oscillation experiments. We found that the discovery reach for the unknowns in oscillation physics by the experiments that we have considered can be altered significantly in the presence of LFV-NSIs. Moreover, we found that the degeneracy discrimination capability of all the experiment will worsen in the presence of LFV-NSI, since it leads to new degeneracies among the oscillation parameters other than the existing degeneracies in standard oscillation physics. We also found that the possibility of misinterpretation of oscillation data in the presence of new physics scenarios (NSIs), give rise to wrong determination of octant of atmospheric mixing angle, neutrino mass hierarchy and the CP violation.

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