

Impact of lepton flavor universality violation on CP-violation sensitivity of long-baseline neutrino oscillation experiments

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Received: 11 October 2016 / Accepted: 1 January 2017 / Published online: 17 January 2017
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Abstract The observation of neutrino oscillation as well as the recent experimental results on lepton flavor universality (LFU) violation in B meson decays are indications of new physics beyond the standard model. Many theoretical models, which are introduced in the literature as an extension of SM to explain these observed deviations in LFU, lead to a new kind of interactions, the so-called non-standard interaction (NSI) between the elementary particles. In this paper, we consider a model with an additional Z' boson (which is quite successful in explaining the observed LFU anomalies) and analyze its effect in the lepton flavor violating (LFV) $B_d \rightarrow \tau^\pm e^\mp$ decay modes. From the present upper bound of the $B_d \rightarrow \tau^\pm e^\mp$ branching ratio, we obtain the constraints on the new physics parameters, which are related to the corresponding NSI parameters in the neutrino sector by $SU(2)_L$ symmetry. These new parameters are expected to have potential implications in the neutrino oscillation studies and in this work we investigate the possibility of observing the effects of these interactions in the currently running and upcoming long-baseline experiments, i.e., NO ν A and DUNE, respectively.

1 Introduction

The standard model of particle physics, which seems to provide a complete picture of interaction and dynamics of elementary particles with the discovery of Higgs boson at LHC [1, 2], predicts the equality of electroweak couplings of electron and muons, the so-called lepton flavor universality (LFU). However, the observation of neutrino oscillation, which allows mixing between different lepton families of neutrinos, implies that family lepton number is violated, and the violations in LFU are indications of new physics (NP) beyond the SM. Moreover, the deviations in recent obser-

vation of the violation of LFU in semileptonic B decays, both in the case of $b \rightarrow c$ charged-current as well as in the case of $b \rightarrow s$ neutral current transitions, also point toward physics beyond the SM. These results can be summarized as follows:

- About 4.0σ deviation of τ/l universality ($l = \mu, e$) in $b \rightarrow c$ transitions [3], i.e.,

$$R(D^*) = \frac{\text{Br}(B \rightarrow D^* \tau \nu_\tau)}{\text{Br}(B \rightarrow D^* l \nu_l)} = 0.316 \pm 0.016 \pm 0.010,$$

$$R(D) = \frac{\text{Br}(B \rightarrow D \tau \nu_\tau)}{\text{Br}(B \rightarrow D l \nu_l)} = 0.397 \pm 0.040 \pm 0.028, \quad (1)$$

from their corresponding SM values $R(D^*)|_{\text{SM}} = 0.252 \pm 0.003$ [4] and $R(D)|_{\text{SM}} = 0.300 \pm 0.008$ [5]. Since these decays are mediated at tree level in the SM, relatively large new physics contributions are necessary to explain these deviations.

- Observation of 2.6σ deviation of μ/e universality in the dilepton invariant mass bin $1 \text{ GeV}^2 \leq q^2 \leq 6 \text{ GeV}^2$ in $b \rightarrow s$ transitions [6]:

$$R_K = \frac{\text{Br}(B \rightarrow K \mu^+ \mu^-)}{\text{Br}(B \rightarrow K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad (2)$$

from the SM prediction $R_K^{\text{SM}} = 1.0003 \pm 0.0001$.

- CMS recently also searched for the decay $h \rightarrow \tau \mu$ and found a non-zero result of $\text{Br}(h \rightarrow \tau \mu) = 0.84^{+0.39}_{-0.37}$ [7], which disagrees by about 2.4σ from 0, i.e. from the SM value.

These deviations from the SM have triggered a series of theoretical speculations about possible existence of NP beyond the SM. Some of the prominent NP models which can explain these deviations from the SM are: models with

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an extra Z' boson [8,9] and/or additional Higgs doublets [10], models with leptoquarks [11–14] etc. The observation of lepton flavor non-universality effects also provides the possibility of the observation of lepton flavor violating (LFV) decays [15]. Although, so far, there is no concrete evidence of LFV decays, there exist strict upper bounds in many LFV decays such as $\mu \rightarrow e\gamma$ $\mu \rightarrow eee$, etc. [16]. Various dedicated experiments are already planned to search for LFV decays. In this paper, we would like to see the implications of the LFV interactions in various long-baseline neutrino oscillation experiments. In other words, we would like to explore whether it is possible to observe these effects in the long-baseline neutrino oscillation experiments or not. In particular, we will focus on the NP contributions which could affect only the τ sector. This is particularly interesting as the tauonic B decays provide an excellent probe of new physics, because of the involvement of heavy τ lepton. There are a few deviations observed in the leptonic/semileptonic B decays with a τ in the final state. We consider the model with an additional Z' boson, which can mediate flavor changing neutral current (FCNC) transitions at tree level. Z' gauge bosons, which are associated with an extra $U(1)'$ gauge symmetry, are predicted theoretically in many extensions of the SM [17–24], such as grand unified theories (GUTs), left–right symmetric models, E_6 model, supersymmetric models, superstring theories etc. Although the $U(1)'$ charges are in general family-universal, it is not mandatory to be so, and the family non-universal Z' has been introduced in some models, such as in the E_6 model [25–29]. On the experimental side also there are many efforts being made to search for the Z' directly at the LEP, Tevatron, and LHC. With the assumption that the couplings of Z' to the SM fermions are similar to those of the SM Z boson, the direct searches for the Z' can be performed in the dilepton events. At this stage, the lower mass limit has been set as 2.9 TeV at the 95% C.L. with 8 TeV data set by using e^+e^- and $\mu^+\mu^-$ [30] events and this value becomes 1.9 TeV using the $\tau^+\tau^-$ events [31]. However, such constraints from the LHC would not be valid if the Z' boson couples very weakly with the leptons, and thus one has to rely on the hadronic channels.

The paper is organized as follows. In Sect. 2, we discuss the possible hints of new physics from B meson decays and extract the constraints on the lepton flavor violating new NP parameters in the charged lepton sector from the decay mode $B_d \rightarrow \tau^\pm e^\mp$. These parameters are in general related to the corresponding NP parameters in the neutrino sector by the $SU(2)_L$ gauge symmetry. The basic formalism of neutrino oscillation including NSI effects are briefly discussed in Sect. 3. In Sect. 4, we study the effect of NSI parameters on the ν_e oscillation probability and the search for the new CP-violating signals at long-baseline experiments is presented in Sect. 4. Section 5 contains the summary and conclusions.

2 New physics effects from B meson decays

In this section, we would like to see the possible interplay of new physics in the τ -lepton sector considering the decay channels of B meson. For this purpose, we first consider the leptonic decay channel $B^- \rightarrow \tau^- \bar{\nu}$. During the last few years, there has been a systematic disagreement between the experimental and SM predicted value for the branching ratio of $B \rightarrow \tau \nu$ mode. The branching ratio for $B^- \rightarrow \tau \nu_\tau$ is given as

$$\text{Br}(B^- \rightarrow \tau \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{ub}|^2 \tau_{B^-} f_B^2 m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2. \quad (3)$$

This mode is very clean and the only non-perturbative quantity involved in the expression for branching ratio (3) is the decay constant of B meson. However, there is still a tension between the exclusive and inclusive value of V_{ub} at the level of 3σ . This mode has been precisely measured [16] with a value

$$\text{Br}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.14 \pm 0.27) \times 10^{-4}. \quad (4)$$

The latest result from the Belle collaboration [32]

$$\text{Br}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}, \quad (5)$$

also in the line of the previous measurements. Since there is an uncertainty between the $|V_{ub}|$ values extracted from exclusive and inclusive modes, we use the SM fitted value of its branching ratio from the UTfit collaboration [33]

$$\text{Br}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (0.84 \pm 0.07) \times 10^{-4}. \quad (6)$$

This value agrees well with the experimental value (4). However, the central values of these two results differ significantly. One can eliminate the V_{ub} dependence completely by introducing the LFU probing ratio

$$R_{\tau/l}^\pi = \frac{\tau_{B^0} \text{Br}(B^- \rightarrow \tau^- \bar{\nu}_\tau)}{\tau_{B^-} \text{Br}(B^0 \rightarrow \pi^0 l^- \bar{\nu}_l)} = 0.73 \pm 0.15, \quad (7)$$

which has around 2.6σ deviation from its SM prediction of $R_{\tau/l}^{\pi,SM} = 0.31(6)$ [34]. Thus, these deviations may be considered as the smoking gun signal of new physics associated with the tauonic sector. We then proceed to obtain the bound on the lepton flavor violating new physics parameter associated with the τ lepton from the decay mode $B_d \rightarrow \tau^\pm e^\mp$.

2.1 Extraction of the NP parameter from the lepton flavor violating decay process $B_d \rightarrow \tau^\pm e^\mp$

The violation of lepton flavor universality in principle can induce lepton flavor violation. In this section, we will consider the lepton flavor violating decay process $B_d \rightarrow \tau^\pm e^\mp$,

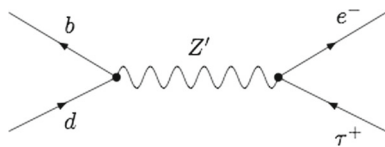


Fig. 1 Feynman diagram for $B_d \rightarrow e^- \tau^+$ in the model with Z' boson, where the blobs represent the tree level FCNC couplings of Z' boson

which is induced by flavor changing neutral current interactions. As an example, here we will consider a simple and well-motivated model, which would induce lepton flavor violating interactions at the tree level, is the model with an additional Z' boson. Many SM extensions often involve the presence of an extra $U(1)'$ gauge symmetry and the corresponding gauge boson is generally known as the Z' boson. Here we consider the model which can induce the lepton flavor violating decays both in the down quark sector and the charged lepton sector [8, 9, 35] at the tree level. Thus, in this model the coupling of the Z' boson to down type quarks and charged leptons can be written generically as

$$\mathcal{L} \supset g' \left[\eta_{db}^L \bar{d} \gamma^\mu P_L b + \eta_{db}^R \bar{d} \gamma^\mu P_R b + \eta_{e\tau}^L \bar{e} \gamma^\mu P_L \tau + \eta_{e\tau}^R \bar{e} \gamma^\mu P_R \tau \right], \tag{8}$$

where g' is the new $U(1)'$ gauge coupling constant, $\eta_{db}^{L/R}$ are the vector/axial-vector FCNC couplings of $\bar{d}b$ quark-antiquark pair to the Z' boson and $\eta_{e\tau}^{L,R}$ are the LFV parameters.

The constraint on the LFV coupling $\eta_{e\tau}$ can be obtained from the lepton flavor violating B decay mode $B_d \rightarrow \tau^\pm e^\mp$. In the SM this decay mode is loop-suppressed with tiny neutrino mass in the loop. However, in the Z' model it can occur at tree level, described by the quark level transition $b \rightarrow d \tau^\pm e^\mp$ and is expected to have significantly large branching ratio. The Feynman diagram for this process in the Z' model is shown in Fig. 1, where the blobs represent the tree level FCNC coupling of Z' boson. The present upper limit on its branching ratio is 2.8×10^{-5} . The effective Hamiltonian describing this process in the Z' model can be given as

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 \times [\bar{d} \gamma^\mu (\eta_{db}^L - \eta_{db}^R \gamma_5) b] [\bar{e} \gamma_\mu (\eta_{e\tau}^L - \eta_{e\tau}^R \gamma_5) \tau], \tag{9}$$

where $M_{Z'}$ is the mass of Z' boson. In order to evaluate the transition amplitude we use the following matrix element:

$$\langle 0 | \bar{d} \gamma^\mu (1 - \gamma_5) b | B_d \rangle = -i f_B p_B^\mu, \tag{10}$$

where f_B is the decay constant of B meson and p_B its momentum. Thus, with Eqs. (9) and (10), one can obtain

the transition amplitude for the process $B_d \rightarrow \tau^- e^+$ as

$$\mathcal{M}(B_d \rightarrow \tau^- e^+) = -\frac{G_F}{\sqrt{2}} \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 i f_B \eta_{db}^R p_B^\mu [\bar{e} \gamma_\mu (\eta_{e\tau}^L - \eta_{e\tau}^R \gamma_5) \tau], \tag{11}$$

and the corresponding branching ratio is given as

$$\text{Br}(B_d \rightarrow \tau^\pm e^\mp) = \frac{G_F^2 \tau_B}{16\pi} \left(\frac{g' M_Z}{g M_{Z'}} \right)^4 \times |\eta_{db}^R|^2 (|\eta_{e\tau}^L|^2 + |\eta_{e\tau}^R|^2) f_B^2 m_\tau^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2} \right)^2, \tag{12}$$

where τ_B is the lifetime of B meson. In order to find the bound on the LFV couplings $\eta_{e\tau}^{L,R}$, we need to know the value of the parameter η_{db} , which can be obtained from the decay process $B_d \rightarrow \mu^+ \mu^-$. The branching ratio for this decay mode has been recently measured by the LHCb [36] and CMS [37] collaborations and the present world average value [38] is given as

$$\text{Br}(B_d \rightarrow \mu^+ \mu^-) = (3.9_{-1.4}^{+1.6}) \times 10^{-10}. \tag{13}$$

The corresponding SM value has been precisely calculated including the corrections of $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s^2)$ with value [39]

$$\text{Br}(B_d \rightarrow \mu^+ \mu^-)|_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}. \tag{14}$$

Although the SM predicted value is in agreement with the experimental result, it does not exclude the possible existence of new physics as the central values of these two results differ significantly. The effective Hamiltonian describing this process is given as

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi} V_{tb} V_{td}^* C_{10} [\bar{d} \gamma^\mu (1 - \gamma_5) b] [\bar{\mu} \gamma_\mu \gamma_5 \mu], \tag{15}$$

where C_{10} is the Wilson coefficient and its value at the m_b scale is given as $C_{10} = -4.245$. The corresponding Hamiltonian in the Z' model is given as

$$\mathcal{H}_{eff}^{Z'} = \frac{G_F}{\sqrt{2}} \left(\frac{g' M_Z}{g M_{Z'}} \right)^2 \times [\bar{d} \gamma^\mu (\eta_{db}^L - \eta_{db}^R \gamma_5) b] [\bar{\mu} \gamma_\mu (C_V^\mu - C_A^\mu \gamma_5) \mu], \tag{16}$$

where C_V^μ and C_A^μ are the vector and axial-vector couplings of the Z' boson to $\mu^- \mu^+$ pair. Including the contribution arising from the Z' exchange to the SM amplitude, one can write the amplitude for $B_d \rightarrow \mu \mu$ process as

$$\begin{aligned} \mathcal{M}(B_d \rightarrow \mu^+ \mu^-) &= i \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi} V_{tb} V_{td}^* f_{B_d} m_{B_d} m_{\mu} C_{10} [\bar{\mu} \gamma_5 \mu] \\ &\times \left(1 + \frac{g'^2 M_Z^2}{g^2 M_{Z'}^2} \frac{2\pi \eta_{db}^R C_A^\mu}{\alpha V_{tb} V_{td}^* C_{10}} \right) \\ &= \mathcal{M}^{SM} \left(1 + \frac{g'^2 M_Z^2}{g^2 M_{Z'}^2} \frac{2\pi \eta_{db}^R C_A^\mu}{\alpha V_{tb} V_{td}^* C_{10}} \right). \end{aligned} \tag{17}$$

Thus, from Eq. (17), one can obtain the branching ratio as

$$\begin{aligned} \text{Br}(B_d \rightarrow \mu\mu) &= \text{Br}(B_d \rightarrow \mu\mu)^{SM} \\ &\times \left| 1 + \frac{g'^2 M_Z^2}{g^2 M_{Z'}^2} \frac{2\pi \eta_{db}^R C_A^\mu}{\alpha V_{tb} V_{td}^* C_{10}} \right|^2. \end{aligned} \tag{18}$$

Assuming the axial-vector coupling of Z' to muon pair, i.e., C_A^μ has the same form as the corresponding SM Z boson coupling to fermion–antifermion pair with value $C_A^\mu = -1/2$. Now with Eq. (18) and considering the $1\text{-}\sigma$ range of experimental and SM predicted branching ratios from (14) and (13), the constraint on the parameter η_{db}^R is found to be

$$0.006 \leq |\eta_{db}^R| \leq 0.014, \tag{19}$$

for $M_{Z'} = 1\text{ TeV}$, where we have used the particle masses and CKM elements from [16]. Using this allowed range of $|\eta_{db}^R|$, the bounds on the LFV couplings $\eta_{e\tau}^{L,R}$ can be obtained by comparing (12) with the corresponding branching ratio $\text{Br}(B_d \rightarrow \tau e) < 2.8 \times 10^{-5}$ [16]:

$$|\eta_{e\tau}^L| = |\eta_{e\tau}^R| < 19.2, \quad \text{for } |\eta_{db}^R| = 0.014, \tag{20}$$

where we have considered $\eta_{e\tau}^L = \eta_{e\tau}^R$. These couplings can be redefined in terms of another set of new couplings as $\varepsilon_{e\tau} = (g'^2 M_Z^2 / g^2 M_{Z'}^2) \eta_{e\tau}$, which can give the relative NP strength in comparison to SM ones as

$$|\varepsilon_{e\tau}^L| = |\varepsilon_{e\tau}^R| < 0.16, \quad \text{for } |\eta_{db}^R| = 0.014, \tag{21}$$

for $g' \simeq g$ and a TeV scale Z' boson, i.e., $M_{Z'} \simeq 1\text{ TeV}$. Since these parameters are related to the corresponding NSI parameters of the neutrino sector by the $SU(2)_L$ symmetry, we now proceed to see their implications in various long-baseline neutrino oscillation experiments. Analogously, one can obtain the bounds on the NSI couplings $\varepsilon_{e\mu}$ from $B_d \rightarrow e\mu$ decay, which are expected to be of the same order as $\varepsilon_{e\tau}$.

3 Neutrino oscillation in the presence of NSIs

Neutrino oscillation [40–46] has been established as a leading mechanism behind the flavor transition of neutrinos, which provides strong evidence for neutrino mass and mixing. Moreover, the three flavor framework of neutrino oscillation is very successful in explaining observed experimental results except few results at very short baseline experi-

ments. Nevertheless, there are few parameters in oscillation framework, which are still not known, for instance the neutrino mass ordering, CP-violating phase and the octant of atmospheric mixing angle. The main objective of the currently running and future up-coming long-baseline experiments is to determine these unknowns. Though these experiments will take a long time to collect the whole oscillation data, phenomenological studies can make predictions on the sensitivity of these experiments, which ultimately help to extract improved oscillation data. In this context, some phenomenological studies regarding the sensitivity of long-baseline experiments can be found in our recent works [47–49]. At this point of time, where the neutrino physics entered into precision era, it is crucial to understand the effect of sub-leading contributions such as Non-standard interactions (NSIs) of neutrinos on the sensitivities of long-baseline neutrino oscillation experiments. It is well known that NSIs of neutrinos [50,51], which derived from various extensions of the SM, can affect neutrino propagation, production, and detection mechanisms which are commonly known as propagation, source and detector NSIs. However, in this paper, we mainly focus on propagation NSIs and their effect on neutrino oscillation. The Lagrangian corresponding to NSIs during the propagation of neutrino is given by [52],

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fC} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_C f), \tag{22}$$

where G_F is the Fermi coupling constant, $\varepsilon_{\alpha\beta}^{fC}$ are the new coupling constants known as NSI parameters, f is a 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 while neutrinos propagate through the earth are those coming from the interaction of neutrinos with matter (e, u , and d), since the earth matter is made up of these fermions only. Therefore, the effective NSI parameter is given by

$$\varepsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{n_f}{n_e} \varepsilon_{\alpha\beta}^f, \tag{23}$$

where $\varepsilon_{\alpha\beta}^f = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$, n_f is the number density of the fermions 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., $n_n \approx n_p = n_e$. Therefore, one can write $\varepsilon_{\alpha\beta}$ as [53]

$$\varepsilon_{\alpha\beta} \approx \sqrt{\sum_C (\varepsilon_{\alpha\beta}^{eC})^2 + (3\varepsilon_{\alpha\beta}^{uC})^2 + (3\varepsilon_{\alpha\beta}^{dC})^2}. \tag{24}$$

Thus, with Eqs. (21) and (24), the bound on the NSI parameter $\varepsilon_{e\tau}$ is found to be

$$\varepsilon_{e\tau} < 0.7, \tag{25}$$

where we have assumed that either left-handed or right-handed couplings would be present at a given time.

NSIs and their consequences can be studied in both model-dependent and -independent approaches by which one can obtain the model-dependent and -independent bounds on the NSI parameters. Recently, considering the model independent approach, we have studied the effect of lepton flavor violating NSIs on physics potential of long-baseline experiments [54]. Moreover, the recent works on the effect of NSI on the measurements of various neutrino oscillation experiments can be found in [55–63]. Since we focus on model-dependent approach in this paper, we consider the LVF decays of B meson in Z' model to get the bound on NSI parameter as discussed in Sect. 2.1. There are many works in the literature, dealing with an extensive study of model-dependent NSI parameters and their effect on neutrino oscillation experiments [64,65]. However, in this work we focus on the lepton flavor violating NSI parameter, where the bound is obtained from the LFV decays of B meson in a Z' model and check its effect on the measurements of CP-violation at the long-baseline experiments like NO ν A and DUNE. This would provide an indirect signal for the existence of Z' boson coming from the long-baseline neutrino experiment results.

3.1 Basic formalism with NSIs

The effective Hamiltonian describing the propagation of neutrinos through matter in the standard three flavor framework is given by

$$\begin{aligned}
 H_{SO} &= H_0 + H_M \\
 &= \frac{1}{2E} U \cdot \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \cdot U^\dagger \\
 &\quad + \text{diag}(V_{CC}, 0, 0),
 \end{aligned}
 \tag{26}$$

where H_0 is the Hamiltonian in vacuum, $\Delta m_{ji}^2 = m_j^2 - m_i^2$ is the neutrino mass squared difference, H_M is the Hamiltonian responsible for the effect of matter, $V_{CC} = \sqrt{2}G_{Fn_e}$ is the potential of matter and U is the PMNS mixing matrix which is described by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and one CP-violating phase (δ_{CP}); it is given by

$$\begin{aligned}
 U_{PMNS} &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix},
 \end{aligned}
 \tag{27}$$

where $c_{ij} = \cos(\theta_{ij})$ and $s_{ij} = \sin(\theta_{ij})$. The NSI Hamiltonian, which describes the new interactions between the matter particles as neutrinos propagate through matter is given by

$$H_{NSI} = V_{CC} \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}
 \tag{28}$$

where $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$ are the complex NSI parameters. Then the neutrino oscillation probability in the presence of NSI is given by

$$P_{(\nu_\alpha \rightarrow \nu_\beta)} = \left| \langle \nu_\beta | e^{-i(H_{SO} + H_{NSI})L} | \nu_\alpha \rangle \right|^2.
 \tag{29}$$

In this paper, we focus on lepton flavor violating NSIs, i.e., the effects of the off-diagonal elements of the matrix (28). Moreover, constraints from terrestrial experiments show that the muon sector is strongly constrained [66], so that one can set $\varepsilon_{e\mu}$ and $\varepsilon_{\mu\tau}$ to zero. Therefore, in our analysis we consider only the contributions from the NSI parameter $\varepsilon_{e\tau}$ and use a conservative value for $\varepsilon_{e\tau}$ as $\varepsilon_{e\tau} \approx 0.3$, consistent with the bound obtained from lepton flavor violating B meson decays, as shown in Eq. (25).

4 Numerical analysis

4.1 Effect of NSI on oscillation probability and event spectra

In this section, we discuss the effect of NSI parameter on the neutrino oscillation probability as well as on the event spectra of long-baseline experiments like NO ν A and DUNE. We use the GLOBES package [67,68] for our analysis. We also use the `snu` plugin [69,70] to incorporate non-standard physics in GLOBES.

The specifications of the long-baseline experiment that we consider in this paper are given in Table 1 and the true values of the oscillation parameters that we use in our calculations are given in Table 2.

To show the effect of NSI parameter $\varepsilon_{e\tau}$ on oscillation probability, we obtain $\Delta P = |P_{NSI} - P_{SI}|$ (where $P_{NSI(SI)}$ denotes the probability with non-standard (standard) interactions) for different baseline length and energy using the neutrino oscillation parameters as given in Table 2. The contour plots for ΔP as a function of neutrino energy and baseline length are given in Fig. 2. The different shades in the figure correspond to different ranges of ΔP . From the figure, we can see that $\Delta P \in (0.02, 0.03)$ and $(0.04, 0.05)$ for NO ν A

Table 1 The experimental specifications

Expt. setup	NO ν A [71–75]	DUNE [76–78]
Detector	Scintillator	Liquid argon
Beam power (MW)	0.77	0.7
Fiducial mass (kt)	14	35
Baseline length (km)	810	1300
Running time (years)	6 ($3\nu+3\bar{\nu}$)	10 ($5\nu+5\bar{\nu}$)

Table 2 The true values of oscillation parameters considered in the simulations

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)
Δm_{atm}^2	$2.4 \times 10^{-3} \text{ eV}^2$ for NH $-2.4 \times 10^{-3} \text{ eV}^2$ for IH
Δm_{21}^2	$7.6 \times 10^{-5} \text{ eV}^2$
δ_{CP}	-90°

($L = 810 \text{ km}$ and $E = 2 \text{ GeV}$) and DUNE ($L = 1300 \text{ km}$ and $E = 2.5 \text{ GeV}$), respectively, for NH, whereas for IH, $\Delta P \in (0.02, 0.03)$ for both NO ν A and DUNE. This implies

that the non-standard interactions can affect the measurement of oscillation parameters at NO ν A and DUNE experiments significantly.

Next, we show the oscillation probabilities as a function of the CP-violating phase for NO ν A (DUNE) in the left (right) panel of Fig. 3. The dark solid (dashed) curve in the figure corresponds to oscillation probability for NH (IH) in the presence of NSI, whereas the light solid (dashed) curve corresponds to oscillation probability for NH (IH) in the standard oscillation. From the figure, we can see that there is an enhancement (diminution) in the probability for CP-violating phase in the range $0^\circ \leq \delta_{CP} \leq 180^\circ$ ($-180^\circ \leq \delta_{CP} \leq 0^\circ$) for both mass hierarchies, if the NSI phase $\delta_{e\tau}$ is zero. Further, the ν_e event spectra for NO ν A and DUNE are shown in Figs. 4 and 5, respectively. From these

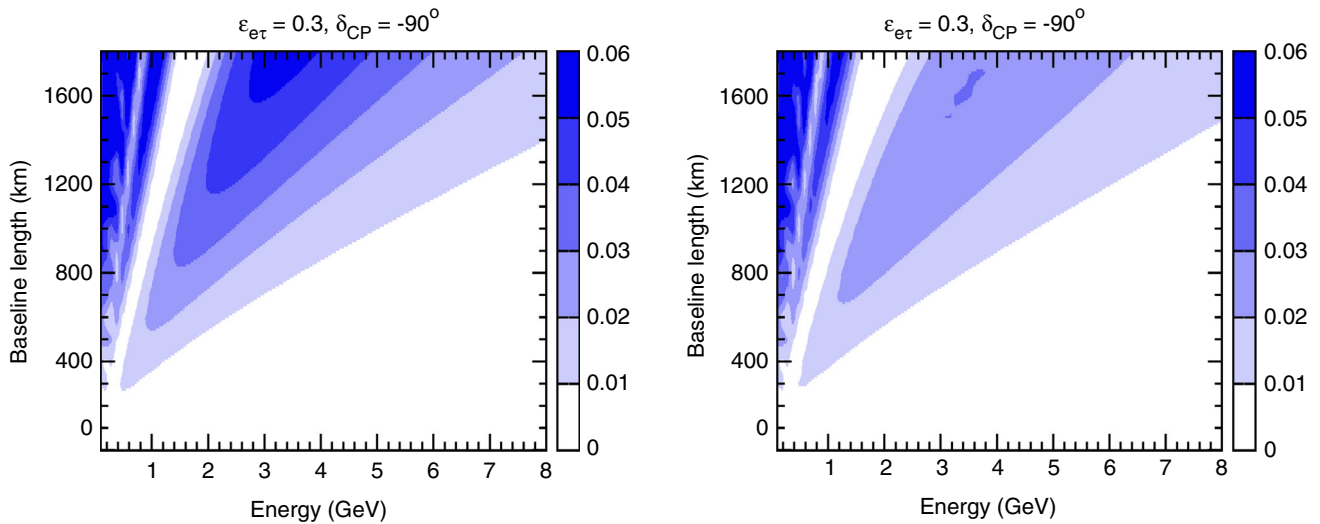


Fig. 2 The $\Delta P = |P_{NSI} - P_{SI}|$ as a function of neutrino energy and baseline length. The left (right) panel corresponds to a normal (inverted) hierarchy

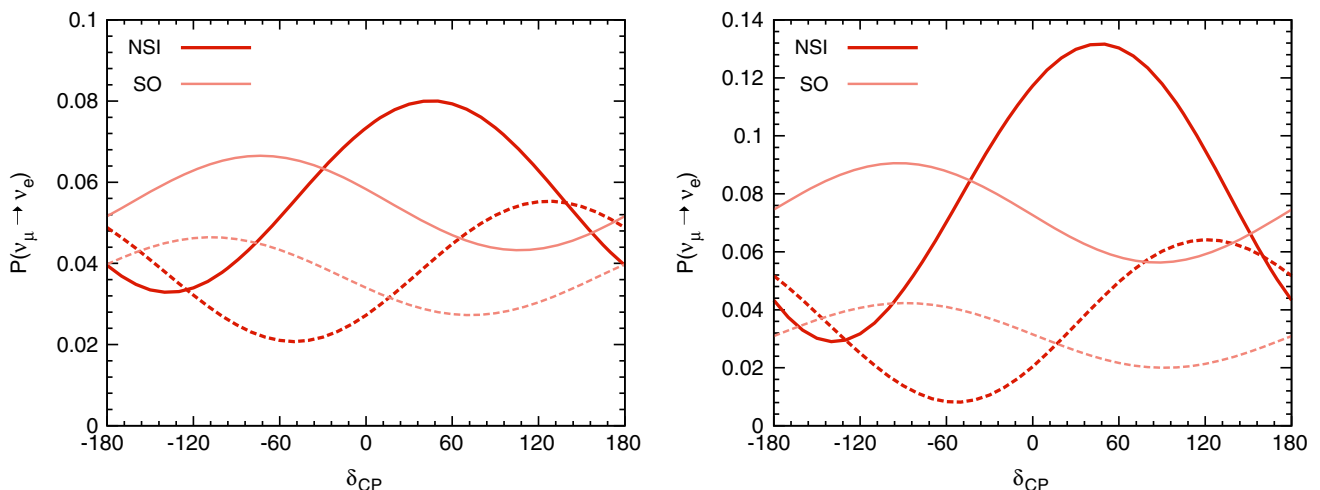


Fig. 3 The left (right) panel shows the appearance oscillation probability for NO ν A (DUNE). The dark (light) colored curves represent the oscillation probability in the presence (absence) of NSI for $\delta_{e\tau} = 0$. The solid (dashed) curves correspond to NH (IH)

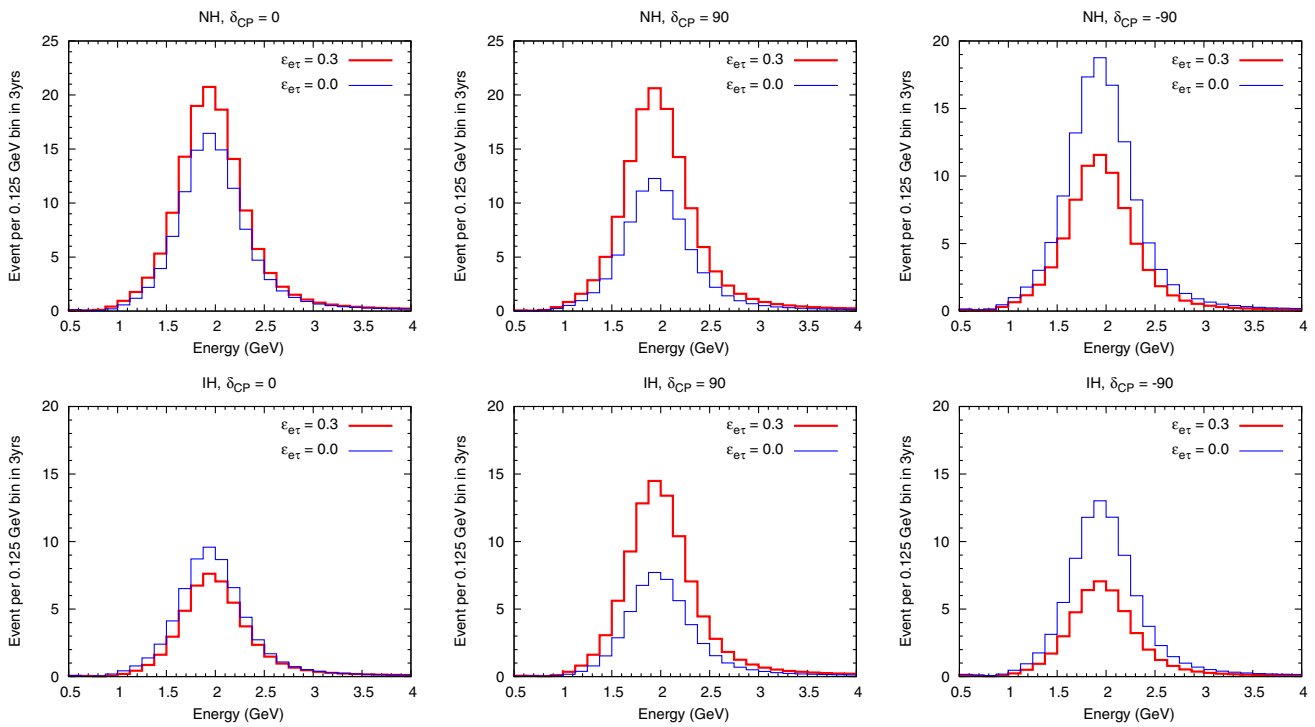


Fig. 4 The event spectra of NOνA for different values of CP-violating phase, i.e., $\delta_{CP} = 0^\circ$ (left panel), $\delta_{CP} = 90^\circ$ (middle panel), and $\delta_{CP} = -90^\circ$ (right panel)

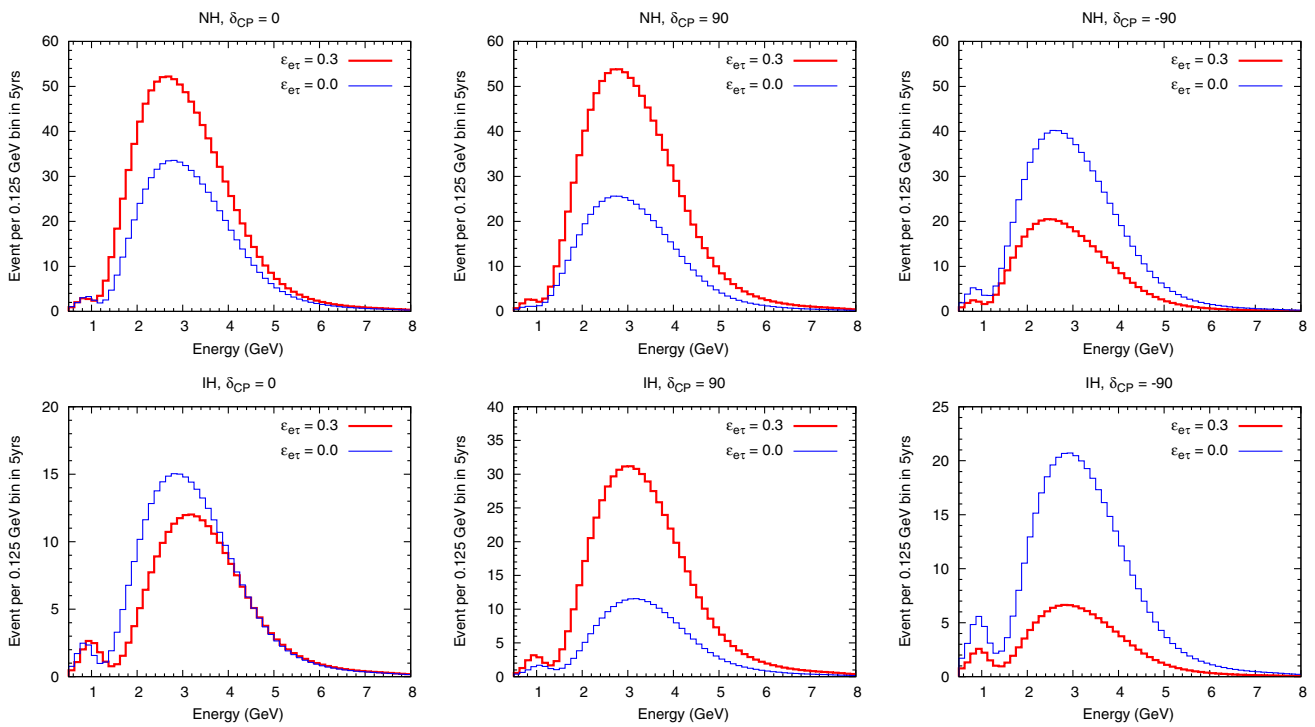


Fig. 5 The event spectra of DUNE for different values of CP-violating phase, i.e., $\delta_{CP} = 0^\circ$ (left panel), $\delta_{CP} = 90^\circ$ (middle panel), and $\delta_{CP} = -90^\circ$ (right panel)

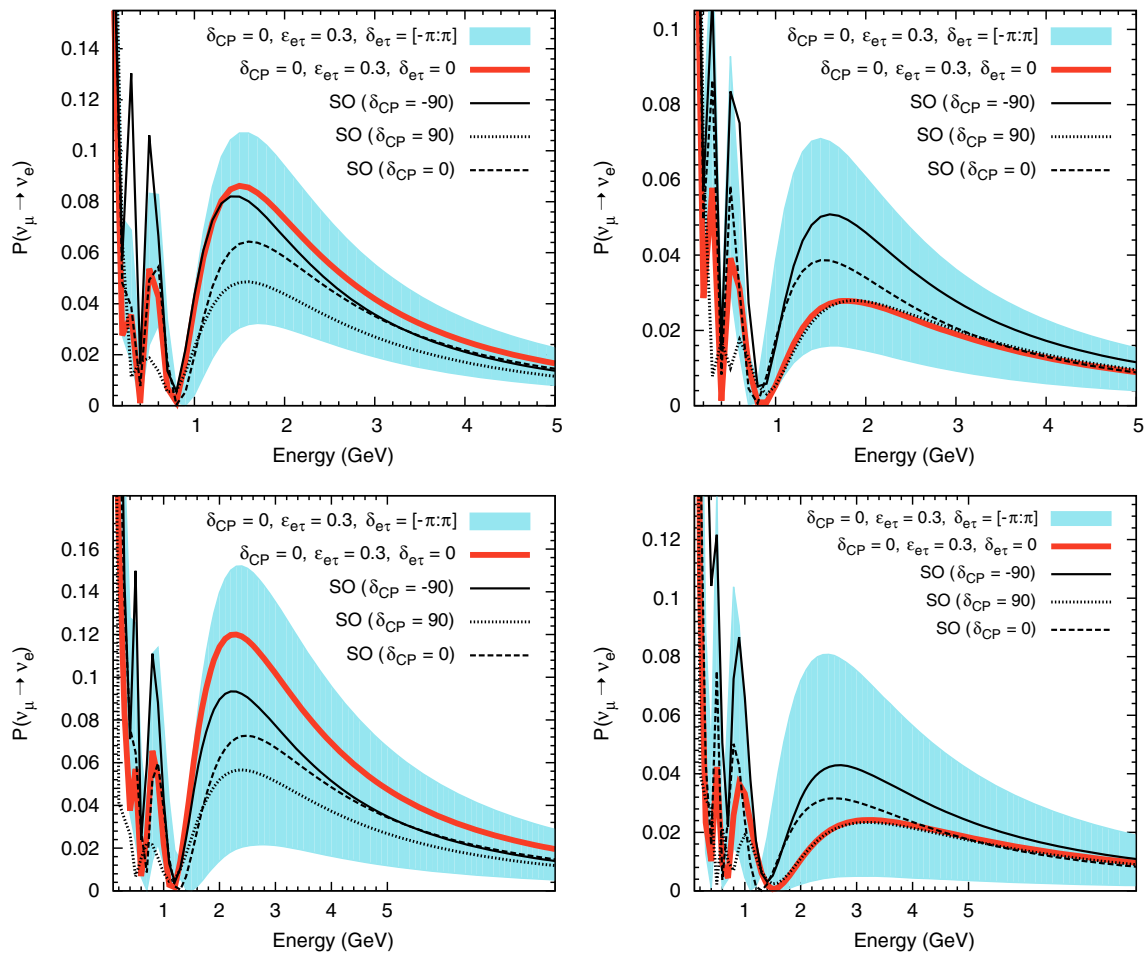


Fig. 6 The $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of neutrino energy for NO ν A (DUNE) in the *top (bottom) panel*. The *left (right) panel* corresponds to NH (IH)

figures, we can see that the event rate in the presence of NSI is larger than that in SO for $\delta_{CP} = 0$ or 90° . Meanwhile, for $\delta_{CP} = -90^\circ$, the event rates in the presence of NSI are lesser than that in SO for $\delta_{e\tau} = 0$.

4.2 Effect of NSI parameter on δ_{CP} sensitivity

The neutrino oscillation probability for the channel $\nu_\mu \rightarrow \nu_e$ for NO ν A (DUNE) is given in the top (bottom) panels of Fig. 6. The light colored band in the figure corresponds to the oscillation probability in the presence of NSI for allowed values of NSI phase parameter $\delta_{e\tau}$ if $\delta_{CP} = 0$. From the figure, we can see that the CP-violating oscillation signals (dark solid and dashed oscillation curves) in SO can mimic the CP-conserving oscillation signal (light solid oscillation curve) in the presence of NSI. This leads to misinterpretation of the oscillation data if NSIs exist in nature. The CP-violation sensitivity ($\chi^2 = \chi^2(\delta_{CP}^{true}) - \chi^2(\delta_{CP}^{test} = 0, 180)$) as a function of δ_{CP} for NO ν A (DUNE) is given in the top (bottom) panel of Fig. 7. The dark solid curve in the fig-

ure corresponds to CPV sensitivity in the presence of NSI, whereas the dark dashed curve in the figure corresponds to CPV sensitivity in SO. From the figure, we can see that NSI can significantly affect CPV sensitivity of both experiments. Though there is significant enhancement in the CPV sensitivity in the presence of NSI for NO ν A, it should be noted that the δ_{CP} coverage for the CPV sensitivity above 1σ is reduced in the presence of NSI compared with that of SO. Whereas for DUNE, the CPV sensitivity is enhanced in the presence of NSI and it is above 5σ for more than 50% allowed values of δ_{CP} in the case of both NH and IH.

5 Summary and conclusions

Conservation of lepton flavor universality is one of the unique features of the SM. However, recently there were a series of experimental results in *B* physics pointing toward possible violations of LFU, both in the charged and neutral current mediated semileptonic decays. Such lepton flavor universal-

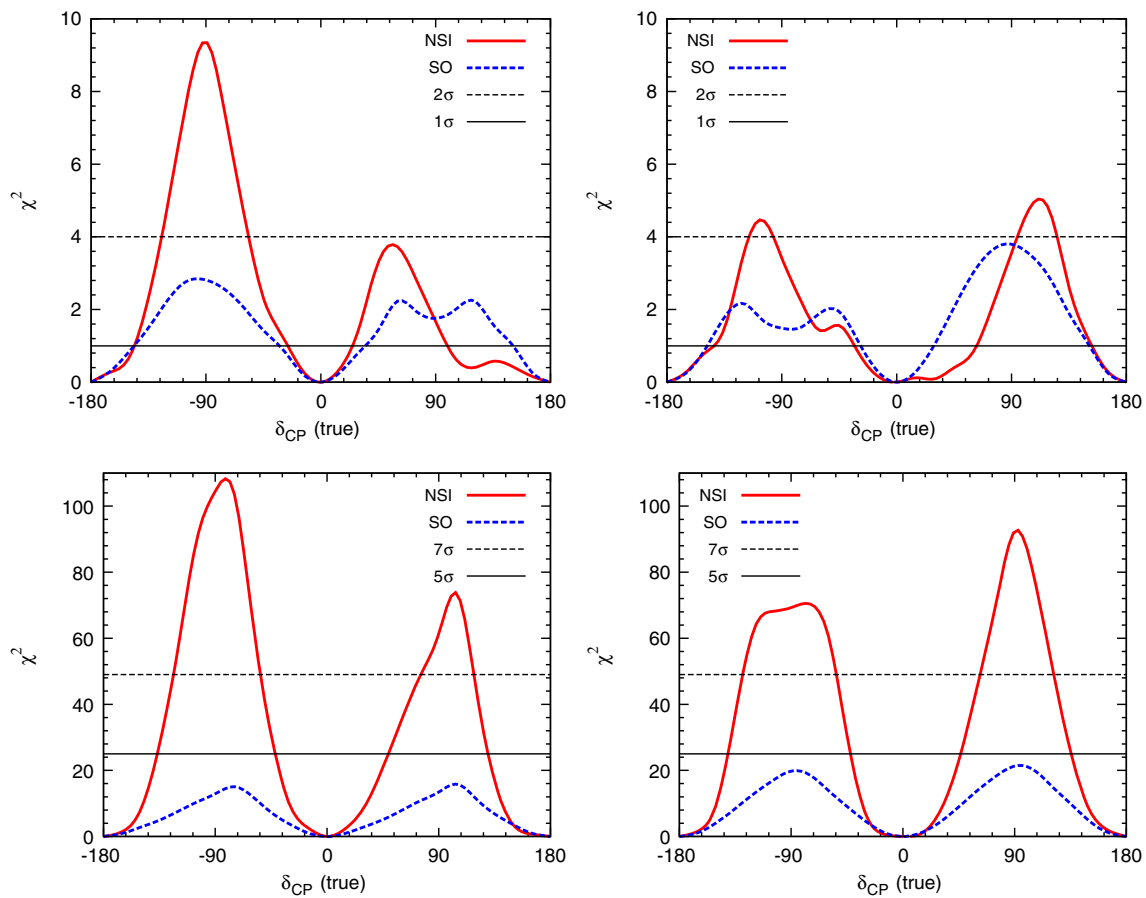


Fig. 7 CP-violation sensitivity as a function of δ_{CP} for NO ν A (DUNE) in the *top* (*bottom*) panel. The *left* (*right*) panel corresponds to NH (IH).

ity violation could in principle also induce lepton flavor violating interactions. Considering the lepton flavor violating decays of B meson, i.e., $B_d \rightarrow \tau^\pm e^\mp$ decay, we constrain the lepton flavor violating couplings in the Z' model using the upper limits of the corresponding branching ratios. We obtained the bound $|\varepsilon_{e\tau}| < 0.7$ from the decay rate. Assuming these NSI parameters in the charged lepton sectors to be related to the corresponding NSI parameters in the neutrino sector by $SU(2)_L$ symmetry, we have studied the possible implications of these new physics interactions in the long-baseline neutrino oscillation experiments. In our analysis we considered a conservative representative value for $\varepsilon_{e\tau}$ as $\varepsilon_{e\tau} = 0.3$ and we have investigated its implications in the CP-violation sensitivity of long-baseline experiments. We found that the NSI parameters in the $e\tau$ sector remarkably affect the ν_e oscillation probability. Moreover, we found that the presence of NSIs leads to a misinterpretation of the oscillation data. The δ_{CP} coverage of NO ν A for CPV sensitivity above 1σ is reduced in the presence of NSIs. However, the CPV sensitivity is enhanced in the presence of NSI and it is above 5σ for more than 50% allowed values of δ_{CP} in the case of both NH and IH for DUNE.

Acknowledgements We would like to thank the Science and Engineering Research Board (SERB), Government of India, for financial support through Grant No. SB/S2/HEP-017/2013. SC would like to thank Dr. Sushant K Raut, Dr. Arnab Dasgupta, Dr. Monojit Gosh, and Mr. Mehedi Masud for many useful discussions regarding GLOBES.

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