

Sensitivity of DUNE in the presence of off-diagonal scalar NSI parameters

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Scalar nonstandard interactions (SNSI) present an exciting pathway for probing potential new physics that extends beyond the Standard Model (BSM). The scalar coupling of neutrinos with matter can appear as a subdominant effect that can impact the neutrino oscillation probabilities. The uniqueness of these interactions lies in their direct effect on the neutrino mass matrix, which makes oscillations sensitive to the absolute neutrino mass. The impact of SNSI scales linearly with matter density, which motivates its exploration in the long-baseline sector. The presence of SNSI can influence the key measurements in the field of neutrino physics, including the determination of the leptonic CP phase (δ_{CP}), neutrino mass ordering, and θ_{23} octant. The precise determination of δ_{CP} is one of the major goals of the Deep Underground Neutrino Experiment (DUNE), which is an upcoming long-baseline experiment. A better understanding of the impact of SNSI on CP measurement sensitivities is crucial for accurate interpretation of δ_{CP} phase. We have analytically explored the dependence of probabilities on the absolute ν masses and fundamental mixing parameters in the presence of SNSI. We observe that the presence of off-diagonal SNSI elements $|\eta_{\alpha\beta}|$ and their associated phases $\phi_{\alpha\beta}$ can significantly affect the CP -measurement sensitivities at DUNE. We note that CP -violation sensitivities also depend on the absolute neutrino masses. We look for constraining the off-diagonal parameters for different lightest neutrino masses. We observe that $|\eta_{\alpha\beta}|$ is more tightly constrained if the neutrino mass is higher. We also explore their correlation with δ_{CP} , investigating potential degeneracies that can arise due to SNSI phases ($\phi_{\alpha\beta}$). We also perform a correlation study among different SNSI elements.

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I. INTRODUCTION

Neutrino physics has undergone significant advancements over the past few decades, with substantial progress made in understanding the properties of neutrinos. The excellent ability of the Standard Model (SM) to explain the phenomena around us makes it evident that SM is an effective theory and that any new physics beyond SM is suppressed at low energies. The experimental confirmation of neutrino oscillations implies that neutrinos (ν 's) have mass and that neutrino flavors can change in the course of their propagation. This was a milestone that reshaped our understanding and provided evidence for physics beyond the Standard Model. The neutrinos are described in the

standard 3ν paradigm, with three active neutrino flavors (ν_e, ν_μ, ν_τ) defined as the superposition of three definite mass eigenstates (ν_1, ν_2, ν_3). The production, propagation, and detection of these neutrinos are solely mediated by weak interactions.

With high-precision accelerator experiments like T2K [1] and NO ν A [2,3], neutrino oscillation physics is at the dawn of the precision measurement era, allowing a robust test of the 3ν paradigm. Most of the neutrino oscillation parameters are very precisely measured, in particular, $|\Delta m_{31}^2|$, Δm_{21}^2 , θ_{12} , and θ_{13} . However, there exist three unknowns, i.e., the leptonic CP -violating phase (δ_{CP}), the sign of Δm_{31}^2 , and the octant of θ_{23} . Driven by significant advancements in beam technology, detector capabilities, and analysis methods, the upcoming long-baseline (LBL) experiments like the Deep Underground Neutrino Experiment (DUNE) [4], HK [5,6], and P2SO [7] will have the capability to solve these three key unknowns remaining in the field of neutrino physics. Currently, T2K data has shown a preference for maximal CP violation with $\delta_{CP} \sim 3\pi/2$ [8], whereas NO ν A data has no preference for either CP violation or conservation [9]. The tension in T2K and NO ν A data can be an indication of new physics beyond the Standard Model [10]. In order to quantify

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leptonic CP -violation (CPV), a precise measurement of all the other oscillation parameters is necessary. Many studies on the impact of precision measurements and their interplay have been done as shown in Refs. [11–16].

While the three-flavor oscillation framework has been remarkably successful in explaining most neutrino data, there is growing interest in exploring potential deviations from this paradigm that could arise from new physics scenarios. With the increasing sensitivity of the detectors with state-of-the-art technologies, it has now become crucial to probe and understand such subdominant new physics scenarios. In the neutrino sector, the new physics effects include the possibility of more than three neutrino states, neutrino decay [17–22], nonstandard interactions (NSIs) [23–60], Lorentz Invariance Violation [61–75], quantum decoherence [76–80], etc. Wolfenstein first proposed the concept of NSI with generally parametrized vector and axial vector currents in his seminal paper [81] on matter effect in neutrinos. The vector-mediated NSI can generically be of CC, type which affects the production, propagation, and detection of neutrinos or NC type, which affects only production and detection. In the last two decades, both theoretical and phenomenological exploration of vector NSI have been done extensively in the literature. The presence of NSI introduces various degeneracies in oscillation and scattering experiments, which may highly affect the precision measurement of neutrino oscillation parameters [23,24,26–30,37,39,44–46,82–94]. This makes the complementary measurement of NSI parameters crucial for the robust interpretation of data from future sophisticated experiments.

One of the primary goals of current and future neutrino experiments is the precise measurement of the δ_{CP} phase. This measurement is crucial for understanding the matter-antimatter asymmetry in the universe, as CP violation in the lepton sector could potentially contribute to the observed dominance of matter over antimatter. A nonzero value of the CP phase in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) [95–98] matrix is indispensable for a viable explanation of the asymmetry observed in the universe based on leptogenesis [99,100]. The appearance probability channel in accelerator-based experiments is the most straightforward way to investigate leptonic CPV [101–105]. In measuring the leptonic CP phase, the presence of NSI can have a huge impact as they may introduce new sources of CP violation apart from the Dirac CP phase. The presence of new CP -violating phases may alter the relationship between the measured oscillation parameters and the Dirac CP phase [83]. In the standard scenario, DUNE has the potential to observe CP violation at 5σ confidence level (CL) after ten years of data taking for more than 50% of the δ_{CP} values [106]. The presence of vector NSI can spoil the CPV sensitivities at DUNE as shown in [86]. The NSI-SI degeneracies and the interplay of their moduli and phases have been explored in [44] for precise CP phase measurement.

The Ref. [107] explores the impact of new physics scenarios on distinguishing between intrinsic and extrinsic CP violation at LBL experiments. However, by exploiting the flexibility of the tunable beam line in DUNE, better discrimination of NSI from standard interaction (SI) can be achieved, as presented in [108]. In Ref. [109], it is shown that synergy among different experiments can lift the δ_{CP} -hierarchy degeneracy and hence provide better sensitivity toward CP violation. The authors in Ref. [110] have studied the sensitivity of DUNE + T2HKK toward δ_{CP} measurement in the presence of one sterile neutrino. In Ref. [111], it is shown that combining data from the T2K and NO ν A could break the degeneracy between neutrino mass hierarchies and δ_{CP} . In a recent study [14], authors have explored the possibility of enhanced CP -violation sensitivity by combining data from DUNE, T2HK, and T2HKK. In Ref. [112], the authors have suggested the exploration of the disappearance channel for determining CP violation, which will help in the robustness of δ_{CP} measurement.

Beyond the well-established vector NSI, scalar field-mediated NSI [58] presents a fascinating avenue for exploring new physics beyond the Standard Model. Unlike vector NSI, scalar NSI (SNSI) directly modifies the neutrino masses through their Yukawa-like terms in the Lagrangian. This results in a distinct phenomenological signature in neutrino experiments, as shown by various recent studies. In Refs. [59,113], the authors have explored the CPV sensitivities at DUNE considering only the diagonal SNSI elements and performed a synergy study of DUNE, T2HK, and T2HKK. A similar study is also performed for DUNE and P2SO with diagonal SNSI elements for CPV and octant sensitivities in [114]. They have also explored the constraining capabilities of DUNE and P2SO toward these diagonal SNSI parameters. The authors in Ref. [48] have explored the possibility of constraining the absolute neutrino mass in the presence of SNSI at DUNE. The impact on the neutrino mass ordering is studied in Ref. [115] in the context of LBL experiments, i.e., DUNE, HK, and HK + KNO. The authors in Ref. [116] have explored the possibility of distinguishing between different new physics scenarios, such as the presence of sterile neutrinos, vector, and SNSI at NO ν A, T2K, and DUNE. In Ref. [117], the effect of SNSI on δ_{CP} measurement is studied in the context of the ESSnuSB experiment. Reference [49] has explored SNSI using $\nu(\bar{\nu})$ disappearance in oscillation data at different experiments. The studies like [118,119] have set bounds on SNSI within cosmological and astrophysical limits, though these constraints are relatively loose. The authors of [120] have constrained SNSI parameters considering the JUNO experiment. In Ref. [121], the authors have explored the sensitivities at DUNE and compared DUNE's constraint with other nonoscillatory probes. In Ref. [122], the authors have constrained the SNSI parameters with solar neutrino data and also with the combination of reactor data.

Given the constraints on the off-diagonal SNSI parameters, our choice of SNSI parameter values lies within the bounds.

Note that, unlike the vector NSIs, which are mediated by vector currents, SNSIs are scalar-mediated interactions that do not exhibit any distinction between neutrinos and antineutrinos. Additionally, SNSI appears as a medium-dependent correction to the neutrino mass term with no energy dependence. This makes the effects of SNSI fundamentally different from vector NSI. Hence, the ability of the experiment to disentangle leptonic CP -phase δ_{CP} from SNSI can become more challenging. This will introduce more degeneracies between SNSI and other oscillation parameters as it will affect the interpretation of ν -oscillation data. In this work, we build upon these efforts by conducting a comprehensive study on the effects of off-diagonal SNSI parameters $\eta_{\alpha\beta}$ on the CP -measurement sensitivities at DUNE. We perform a model-independent analysis, exploring the impact of $|\eta_{\alpha\beta}|$ and their associated phases $\phi_{\alpha\beta}$ on the ν -oscillation probabilities. We particularly explore the impact of $\phi_{\alpha\beta}$ phases in the presence of SNSI on the CP -measurement sensitivities. This is particularly important as the additional phases can introduce complexities and degeneracies in the δ_{CP} measurement. A better understanding of the impact is essential for accurately isolating the intrinsic CP -violating phase. This study will shed light on the impact of SNSI phases and the reliability of CP phase measurements at upcoming long-baseline neutrino experiments, i.e., DUNE. We put bounds on the off-diagonal elements at a given statistical significance for different mass scales. We also explore the correlation between different SNSI elements that may lead to possible degeneracies.

This article is organized as follows. In Sec. II, we cover the theoretical background of scalar nonstandard interactions of neutrinos. We then provide details of the technical aspects of DUNE and the simulation framework in Sec. III. We have analytically explored the dependence of oscillation probabilities on the absolute neutrino masses in presence of SNSI in Sec. IV where the individual SNSI contribution to the appearance oscillation channel is presented. In Sec. V, we study the impact of off-diagonal SNSI elements ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) and their corresponding phases ($\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu\tau}$) on the numerically calculated oscillation probabilities. We particularly focus on the oscillation channels, i.e., $P_{\mu e}$ and $P_{\mu\mu}$ to explore the effects at the probability level. We consider a single nonzero $\eta_{\alpha\beta}$ element at a time to understand the role of each individual parameter unless otherwise mentioned. In Sec. VI, we examine how SNSI affects the CP -measurement sensitivities. We explore DUNE's sensitivity toward simultaneous measurement of δ_{CP} and $\eta_{\alpha\beta}$ in Sec. VI A. We study the impact of $|\eta_{\alpha\beta}|$ and $\phi_{\alpha\beta}$ on the CP -violation sensitivities for different neutrino masses in Sec. VI B. DUNE's capability to constrain the off-diagonal SNSI parameters for different lightest neutrino

masses is also presented in Sec. VII. We then explore the correlation among different SNSI elements considering the DUNE experiment in Sec. VIII. We summarize our findings in Sec. IX.

II. THEORETICAL BACKGROUND

The interaction of neutrinos with fermions via a scalar-mediated particle can have interesting phenomenological consequences. In the presence of scalar nonstandard interactions, the effective Lagrangian can be written as [81,123–126]

$$\mathcal{L}_{\text{eff}}^s = \frac{y_f y_{\alpha\beta}}{m_\phi^2} [\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)] [\bar{f}(p_1) f(p_4)], \quad (1)$$

where $y_{\alpha\beta}$ and y_f represent the coupling of scalar mediator ϕ with neutrinos ($\nu_{\alpha,\beta}$ with $\alpha, \beta = e, \mu, \tau$) and fermions/antifermions ($f/\bar{f}$). Note that the background medium of fermions on Earth is nonrelativistic. The quantity n_f represents the number density of environmental fermions in Earth matter, which is assumed to be nonrelativistic. The presence of SNSI leads to a modification in the Dirac equation as shown below

$$\bar{\nu}_\beta \left[i \partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\sum_f n_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0. \quad (2)$$

The Hamiltonian for standard neutrino-matter interactions in the flavor basis can be written as,

$$\mathcal{H}_{\text{matter}} = E_\nu + \frac{M M^\dagger}{2E_\nu} \pm V_{\text{SI}}. \quad (3)$$

Here, M represents the neutrino mass matrix in the flavor basis and $\mathcal{U}$ represents the PMNS mixing matrix. The Eq. (3) can also be expressed as,

$$\begin{aligned} \mathcal{H}_{\text{eff}} = E_\nu + \frac{1}{2E_\nu} \mathcal{U} \cdot \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \cdot \mathcal{U}^\dagger \\ + \text{diag}(V_{CC}, 0, 0). \end{aligned} \quad (4)$$

As seen in Eq. (2), the contribution of SNSI arises as a medium-dependent addition to the neutrino mass matrix. The uniqueness of SNSI is that it can mimic the dependence on the true neutrino mass matrix. The effective Hamiltonian governing the ν oscillations in the presence of SNSI can be rewritten as,

$$\mathcal{H}_{\text{SNSI}} \equiv E_\nu + \frac{M_{\text{eff}} M_{\text{eff}}^\dagger}{2E_\nu} \pm V_{\text{SI}}. \quad (5)$$

Here, $M_{\text{eff}} = M + \delta M$, with $\delta M \equiv \frac{\sum_f n_f y_f y_{\alpha\beta}}{m_\phi^2}$. We have followed the parametrization of δM as shown in the

Refs. [58,59,113] and the form of the matrix is shown in Eq. (6), where $\eta_{\alpha\beta}$ are dimensionless quantities.

$$\delta M \equiv S_m \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^* & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^* & \eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix} \quad (6)$$

The dimensionless parameters $\eta_{\alpha\beta}$ quantify the strength of SNSI and the scaling factor S_m is merely introduced to re-express δM in mass dimensions. In our work, the scaling factor is fixed at $S_m \equiv \sqrt{2.55 \times 10^{-3}} \text{ eV}$, which corresponds to the magnitude of a typical atmospheric mass-squared splitting. In this work, M_{eff} is chosen to be Hermitian, which is possible if the mediator is a real scalar. This allows the diagonal SNSI ($\eta_{\alpha\alpha}$) parameters to be real and the off-diagonal SNSI ($\eta_{\alpha\beta}$) parameters to be complex, as $\eta_{\alpha\beta} = |\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$. Here, $|\eta_{\alpha\beta}|$ are the magnitudes of the off-diagonal SNSI elements and $\phi_{\alpha\beta}$ are the corresponding phases. In presence of SNSI, the neutrino oscillations will not only depend on the mass-squared differences but also on the absolute neutrino masses.

It may be noted that there have so far been no direct stringent experimental constraints on the $\eta_{\alpha\beta}$ parameters. A recent strong constraint on the SNSI parameters considering solar and reactor neutrino data is available in Ref. [122]. The constraints on SNSI strongly depend on the absolute

neutrino mass scale, i.e., value of the lightest neutrino mass. We look into the possible combinations of $|\eta_{\alpha\beta}|$ and the absolute neutrino masses as the presence of SNSI brings in the dependence on the neutrino mass scale. To get a ballpark approximation, we define a ratio $\mathcal{R}_{\text{SNSI}}$ as shown in Eq. (7) to estimate the relative contribution of SNSI at the Hamiltonian level. This allows us to explore the impact of a single nonzero SNSI parameter on the neutrino oscillation Hamiltonian.

$$\mathcal{R}_{\text{SNSI}} = \left| \frac{H_{\text{SNSI}}[i, j]}{H_{\text{SI}}[i, j]} \right|_{\text{max}} \quad (7)$$

Here, $H_{\text{SNSI}}[i, j]$ and $H_{\text{SI}}[i, j]$ represent the ij^{th} element of the SNSI contribution to the effective Hamiltonian and the standard Hamiltonian, respectively. To eliminate an overall constant phase, the [1, 1] diagonal element is subtracted from all diagonal ratios. This results in eight distinct ratios and the element with the maximum value is used for further analysis. In Fig. 1, we explore the parameter space of $|\eta_{\alpha\beta}| - m_1$ (top panel) and $\phi_{\alpha\beta} - m_1$ (bottom panel) for illustrative purposes. The neutrino oscillation parameters are fixed at values shown in Table I. The observations from Fig. 1 are listed below.

- (i) The range of $|\eta_{\alpha\beta}|$ becomes narrower with the increase in the lightest neutrino mass (m_1) as seen in the top panel. We note that different combinations

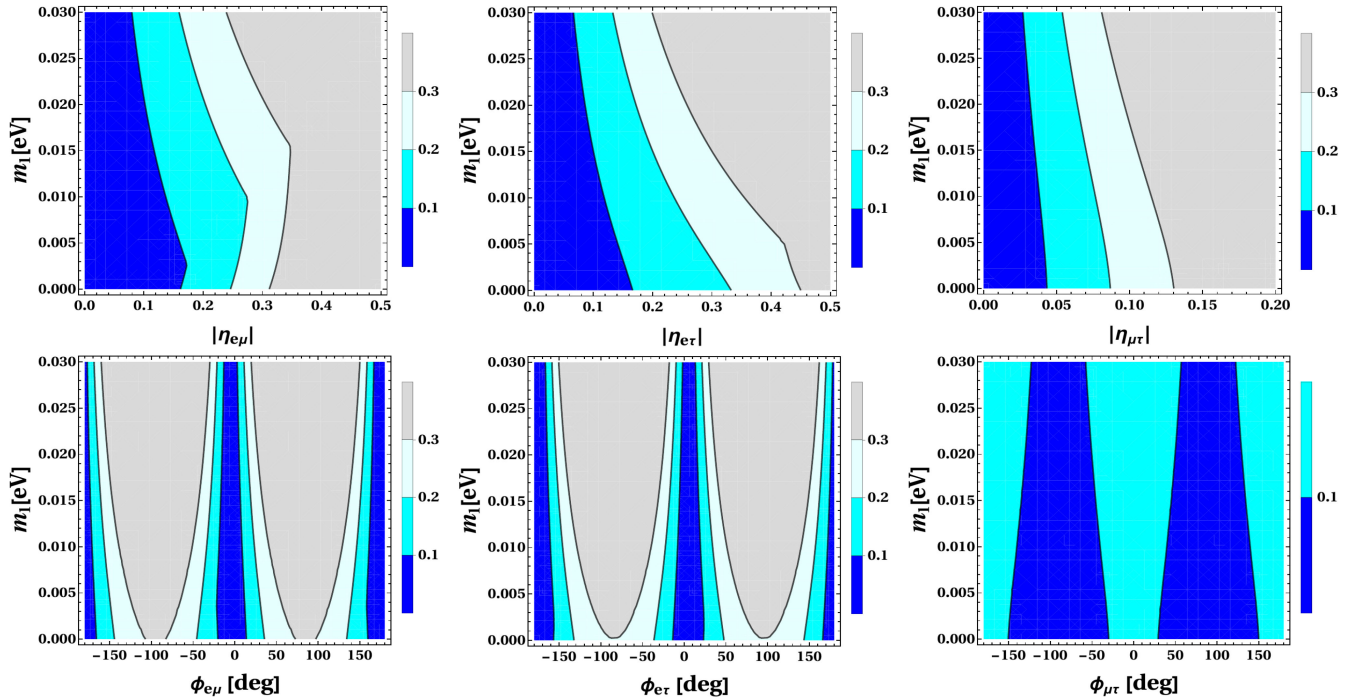


FIG. 1. Contour plot for $\mathcal{R}_{\text{SNSI}}$ in the parameter space of $|\eta_{\alpha\beta}| - m_1$ (top panel) and $\phi_{\alpha\beta} - m_1$ (bottom panel) for normal mass ordering. In the top panel, $|\eta_{\alpha\beta}|$ is varied while fixing $\phi_{\alpha\beta} = 0^\circ$ with $|\eta_{e\mu}|$ (left), $|\eta_{e\tau}|$ (middle), and $|\eta_{\mu\tau}|$ (right). In the bottom panel, $\phi_{\alpha\beta}$ is varied while fixing $|\eta_{\alpha\beta}| = 0.05$ with $\phi_{e\mu}$ (left), $\phi_{e\tau}$ (middle), and $\phi_{\mu\tau}$ (right). The neutrino oscillation parameters are fixed at values shown in Table I.

TABLE I. Neutrino oscillation parameters are presented with their corresponding marginalization range [134,135].

Parameters	θ_{12} (°)	θ_{13} (°)	θ_{23} (°)	Δm_{21}^2 (10^{-3} eV ²)	Δm_{31}^2 (10^{-5} eV ²)	δ_{CP} (°)
Values	33.51	8.44	47	7.56	2.55	−90
Marginalization	Fixed	Fixed	40–50	Fixed	2.45–2.60	[−180, 180]

of $|\eta_{\alpha\beta}|$ and m_1 can lead to a similar level of relative contribution. We also observe that the range of $|\eta_{\mu\tau}|$ (top right) is narrower compared to $|\eta_{e\mu}|$ (top left) and $|\eta_{e\tau}|$ (top center).

- (ii) We observe that the variation of $\mathcal{R}_{\text{SNSI}}$ for $\phi_{e\mu}$ (bottom left) and $\phi_{e\tau}$ (bottom middle) is similar. The contours for $\phi_{\mu\tau}$ are much wider compared to the other SNSI phases.

Based on the observed contours, we have restricted our choice of $|\eta_{\alpha\beta}|$ such that $\mathcal{R}_{\text{SNSI}}$ remains small. We have now performed the study using $|\eta_{\alpha\beta}| = 0.05$ and $m_1 = 10^{-5}$ eV as token values in this work for representative purposes unless otherwise mentioned. A comprehensive discussion of the parameter space ($m_\phi, \sqrt{y_\nu y_e}$) is available in the Ref. [121]. The range of $\eta_{\alpha\beta}$ is possible with light enough scalar that can survive the experimental constraints from supernovae [127,128], meson and lepton decays [129], neutrino electron scattering [130], neutrino trident production [131], big bang nucleosynthesis [132], and coherent scattering [133]. None of them exclude the parameter region, with both the mediator mass and couplings being tiny. These bounds are compatible with the range of $\eta_{\alpha\beta}$ for our choices of $|\eta_{\alpha\beta}|$ and ν mass (m_1).

The presence of off-diagonal phases $\phi_{\alpha\beta}$ can play an important role in the measurement of δ_{CP} . The phases $\phi_{\alpha\beta}$ may significantly modify the ν -oscillation probabilities. It may also affect DUNE's sensitivity toward CP measurement as it can introduce additional complexities and degeneracies. A deeper understanding of these impacts is crucial for accurately isolating the intrinsic CP -violating phase. This study will illuminate the effects of $\phi_{\alpha\beta}$ phases due to SNSI, enhancing the reliability of CP phase measurements at upcoming LBL experiments such as DUNE.

III. EXPERIMENTAL DETAILS AND NUMERICAL ANALYSIS

We first describe the specifics of the experimental configurations of DUNE and then elaborate on the details of the simulation procedure. Our study has specifically addressed DUNE [4,136–139], which is a leading accelerator-based neutrino experiment set to be hosted at Fermilab. The Long-Baseline Neutrino Facility at Fermilab is capable of providing 1.1×10^{21} protons on target annually through its 1.2 MW proton beam, which will generate the neutrinos for the experiment. The peak energy of the beam is expected to be around $E_\nu \sim 2.5$ GeV. The project encompasses two detectors, with the near

detector located 60 meters underground at Fermilab, with a baseline of 574 meters. Meanwhile, the far detector, with a baseline of 1300 km, will be positioned 1.5 km beneath the Earth's surface at the Sanford Underground Research Facility in South Dakota. The far detector module will have four liquid argon time projection chambers (LArTPC), each with a fiducial mass of 10 kt. The cutting-edge technologies will deliver outstanding capabilities for energy reconstruction, particle identification, and tracking, enabling unparalleled precision in the study of neutrino properties. The average density for the DUNE baseline is 2.8482 g/cm³. The matter density variation with distance for DUNE has been studied in Refs. [136,140,141]. The details of detection channels and systematic uncertainties for DUNE are described in Table II.

We simulate the DUNE experiment using the General Long Baseline Experiment Simulator (GLOBES) [143–145]; a sophisticated C-based framework used for simulating LBL neutrino oscillation experiments. The numerical calculation of low-level information, i.e., event rates and oscillation probabilities, is possible with GLOBES. In addition, the framework also allows the extraction of statistical $\Delta\chi^2$ for any simulated LBL experiment. The computation of statistical $\Delta\chi^2$ helps in the sensitivity studies of long-baseline experiments. In our work, the statistical significance for the sensitivity studies considering the DUNE experiment is extracted from the GLOBES framework. The statistical χ^2 for the distinction between the standard interaction and the effects due to scalar nonstandard interactions can be defined as,

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{[N_{\text{true}}^{i,j} - N_{\text{test}}^{i,j}]^2}{N_{\text{true}}^{i,j}}. \quad (8)$$

The variables $N_{\text{true}}^{i,j}$ and $N_{\text{test}}^{i,j}$ indicate the count of true events and test events in the $\{i, j\}^{\text{th}}$ bin. The $\{i, j\}$ represents the summation over all the energy bins and the rules/oscillation channels defining an experiment. In addition, the systematic errors can be incorporated by using the “pull method” [143,146] with the help of nuisance parameters (ζ_k) as shown in Eq. (9). The “pull method” incorporates the impact of each independent source of systematic uncertainty. As a result, the event rates can be redefined as $N_{\text{test}}^{i,j} \rightarrow N_{\text{test}}^{i,j}(\zeta_k) \equiv N_{\text{test}}^{i,j} \cdot (1 + \zeta_k)$ and $\chi^2 \rightarrow \chi^2(\zeta_1, \dots, \zeta_k)$. The terms that include nuisance parameters are generally referred to as pull terms and the χ_{pull}^2 is obtained by minimizing over all the nuisance parameters.

TABLE II. Detection channels and systematic uncertainties for DUNE [136,142].

Experimental detail	Detection channels	Normalization error	
		Signal	Background
DUNE, Baseline = 1300 km			
L/E = 1543 km/GeV	$\nu_e(\bar{\nu}_e)$ appearance	2% (2%)	5% (5%)
Fiducial mass = 40 kt (LArTPC)	$\nu_\mu(\bar{\nu}_\mu)$ disappearance	5% (5%)	5% (5%)
Runtime = 6.5 yr ν + 6.5 yr $\bar{\nu}$			

$$\chi^2_{\text{pull}} = \min_{\{\zeta_j\}} \left(\chi^2(\zeta_1, \dots, \zeta_k) + \sum_{j=1}^k \frac{\zeta_j^2}{\sigma_{\zeta_j}^2} \right). \quad (9)$$

Here, ζ_k represents the nuisance parameters and σ_{ζ_k} corresponds to the associated systematic uncertainties. We have modified the GLoBES framework accordingly to incorporate the effects of SNSI. We have used the effective neutrino Hamiltonian in the presence of SNSI as shown in Eq. (5). The true values of the standard neutrino oscillation parameters are fixed at values as summarized in Table I. We have also marginalized over the oscillation parameters θ_{23} , Δm_{31}^2 , and δ_{CP} in the range shown in Table I. As shown in the global analysis of neutrino data [134,135,147], a slight preference for normal ordering over inverted ordering can be seen. In this work, we show the results assuming the normal neutrino mass ordering as the true mass ordering.

Note that the parameters used in our analysis are consistent with the typical parameter space examined in long-baseline experiments. The presence of SNSI may introduce degeneracies and a full reanalysis of the solar neutrino data in the presence of $\eta_{\alpha\beta} \neq 0$ could provide complementary information. It demands a detailed treatment of the solar neutrino data with varying densities and we would like to refer here to a recent article on the analysis of solar neutrino data with SNSI [122]. Given the constraints on the off-diagonal SNSI parameters, our choice of SNSI parameter values lies within the bounds. We have restricted our study to the phenomenology of SNSI at LBL experiment only (i.e., DUNE), considering its impact on CP -measurement sensitivities. The terrestrial experiments like DUNE may not be able to resolve degeneracies that arise in the presence of SNSI due to the uniformity of the matter density. A varying matter density will help study SNSI as its effects are proportional to matter density. By marginalizing over the standard oscillation parameters along with the SNSI parameters, we aim to study the effects of SNSI on the CP phase by accounting for the uncertainties while simplifying the analysis and retaining

physical insights. The marginalization of the SNSI parameters $|\eta_{\alpha\beta}|$ and $\phi_{\alpha\beta}$ has been performed wherever necessary. As SNSI scales linearly with matter density, we have defined the values of SNSI parameters $\eta_{\alpha\beta}$ at matter density $\rho = 2.9 \text{ g/cm}^3$ in this work. Considering the LBL sector, the impact of rescaling $\eta_{\alpha\beta}$ for varying density is nominal. For δ_{CP} -measurement studies, we consider only a single nonzero off-diagonal SNSI parameter at a time for the statistical analysis. However, in the correlation studies, we have considered two nonzero SNSI parameters at a time. The SNSI introduces a dependence of neutrino oscillations on the absolute neutrino masses.

IV. SNSI CORRECTIONS TO STANDARD OSCILLATION PROBABILITIES

The analytic expressions are important as they can provide insights for a deeper understanding of the effects of new physics scenarios in terms of fundamental neutrino mixing parameters. In this section, we have calculated the analytic expressions for $P_{\mu e}$ considering a single nonzero SNSI parameter ($|\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$). The SNSI corrections to the standard neutrino oscillation probabilities can be analytically expressed as shown in the Eqs. (10)–(12). These expressions have been perturbatively calculated by expanding small parameters α , $\sin\theta_{13}$, and $\eta_{\alpha\beta}$ following the Cayley-Hamilton theorem [148], which can explain the general trends observed in the numerical probabilities. In these expressions, we have presented only the SNSI contribution for the off-diagonal elements ($|\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$), taking only one nonzero element at once. Using these expressions, the overall impact of SNSI can be independently explained as a direct dependence on the neutrino masses (m_i), $|\eta_{\alpha\beta}|$, and $\phi_{\alpha\beta}$. The expressions also highlight the dominant contribution from SNSI and its dependence on the fundamental neutrino mixing parameters. The SNSI contribution to the appearance oscillation channel in the presence of $|\eta_{e\mu}|e^{i\phi_{e\mu}}$ can be expressed as,

$$P_{\mu e}(|\eta_{e\mu}|e^{i\phi_{e\mu}}) = 8s_{13}s_{23} \frac{\sin[\Delta(A_e - 1)]}{(A_e - 1)} \frac{1}{(A_e - 1)} \left[\frac{(A_e - 1)}{A_e} c_{23}^2 \sin[\Delta A_e] \cos[\Delta + \delta_{CP} + \phi_{e\mu}] \times (m_1 s_{12}^2 + m_2 c_{12}^2) \right. \\ \left. + s_{23}^2 \sin[\Delta(A_e - 1)] \cos[\delta_{CP} + \phi_{e\mu}] \times m_3 \right] \times \left(\frac{S_m}{\Delta m_{31}^2} \right) |\eta_{e\mu}| \quad (10)$$

where, $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$,

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad A_e = \frac{2E_\nu V_{\text{SI}}}{\Delta m_{31}^2}, \quad \Delta = \frac{\Delta m_{31}^2 L}{4E_\nu}.$$

- (i) In the presence of SNSI, the oscillation probabilities will also depend on the absolute neutrino masses and the expressions can be expressed in terms of mass factors. In Eq. (10), we present the SNSI contribution in the presence of $\eta_{e\mu}$, which can be expressed as factors of $(m_1 s_{12}^2 + m_2 c_{12}^2)$ and m_3 . The SNSI phase $\phi_{e\mu}$ appears in cosine terms along with δ_{CP} . This can lead to degeneracies in the presence of SNSI and also affect the CP measurement.

The SNSI contribution to the appearance oscillation channel in the presence of $|\eta_{e\tau}|e^{i\phi_{e\tau}}$ can be expressed as,

$$P_{\mu e}(|\eta_{e\tau}|e^{i\phi_{e\tau}}) = 8s_{13}c_{23}s_{23}^2 \frac{\sin[\Delta(A_e - 1)]}{(A_e - 1)} \frac{1}{(A_e - 1)} \left[-\frac{(A_e - 1)}{A_e} \sin[\Delta A_e] \cos[\Delta + \delta_{CP} + \phi_{e\tau}] \times (m_1 s_{12}^2 + m_2 c_{12}^2) \right. \\ \left. + \sin[\Delta(A_e - 1)] \cos[\delta_{CP} + \phi_{e\tau}] \times m_3 \right] \times \left(\frac{S_m}{\Delta m_{31}^2} \right) |\eta_{e\tau}|. \quad (11)$$

- (ii) In presence of $\eta_{e\tau}$, the probability contribution can be expressed in factors of mass terms, i.e., $(m_1 s_{12}^2 + m_2 c_{12}^2)$ and m_3 as shown in Eq. (11). The mass dependence is similar to Eq. (10) with SNSI phase $\phi_{e\tau}$ arising in cosine terms with δ_{CP} as seen for $\eta_{e\mu}$. This will affect the measurement of the CP phase.

The SNSI contribution to the appearance probability in the presence of $|\eta_{\mu\tau}|e^{i\phi_{\mu\tau}}$ can be expressed as,

$$P_{\mu e}(|\eta_{\mu\tau}|e^{i\phi_{\mu\tau}}) = s_{13}s_{23}^2 \sin(2\theta_{12}) \frac{\sin[\Delta(A_e - 1)]}{(A_e - 1)A_e} \frac{1}{(A_e - 1)} [A_e(2 \sin[\Delta] \cos[2\theta_{23}] \cos[\Delta A_e + \delta_{CP} - \phi_{\mu\tau}] \\ + \sin[\Delta(A_e - 1) + \delta_{CP} - \phi_{\mu\tau}] - 2 \sin[\Delta(1 - A_e) + \delta_{CP} - \phi_{\mu\tau}] + \sin[\Delta(A_e + 1) + \delta_{CP} - \phi_{\mu\tau}]) \\ - 4c_{23}^2 \sin(\Delta A_e) \cos(\delta_{CP} + \Delta - \phi_{\mu\tau})](m_1 - m_2) \times \left(\frac{S_m}{\Delta m_{31}^2} \right) |\eta_{\mu\tau}|. \quad (12)$$

- (iii) In Eq. (12), we have presented the SNSI contribution in the presence of $\eta_{\mu\tau}$. Unlike other cases, we here observe a dependence only on the mass factor $(m_1 - m_2)$. However, a more complicated dependence on the additional phase $\phi_{\mu\tau}$ is observed where $\phi_{\mu\tau}$ appears in sine and cosine terms with δ_{CP} .

The mass dependence of $P_{\mu e}$ in presence of $\eta_{e\mu}$ and $\eta_{e\tau}$ appears as factors of $(m_1 s_{12}^2 + m_2 c_{12}^2)$ and m_3 . Due to this dependence, the SNSI contribution for these elements increases with higher values of the lightest neutrino mass. However, for $\eta_{\mu\tau}$ the mass dependence arises as a factor of $(m_1 - m_2)$, which leads to a suppression of the SNSI contribution for increasing ν mass. From these analytic expressions, we have seen that the presence of SNSI can complicate the measurement of the Dirac CP phase. The presence of off-diagonal $\phi_{\alpha\beta}$ phases can mimic CP violation and can potentially hamper the measurement of the true CP phase. Note that the direct dependence of the probabilities on the neutrino masses complicates the analytic calculations. The off-diagonal elements with the additional phases can add significant complexity to the derivations. In this work, we primarily explore the impact of the SNSI phases in the complete allowed region

$\phi_{\alpha\beta} \in [-180^\circ, 180^\circ]$, and for illustration, we also show the impact for a token value of $\phi_{\alpha\beta} = -90^\circ$. The calculated analytic expressions can explain the general trends observed in the numerical probabilities. These expressions have also been validated by comparing them with the numerically calculated probabilities (as shown in the Appendix). The probability expressions for diagonal SNSI elements can be found in Ref. [149].

V. ANALYZING OSCILLATION PATTERNS THROUGH $P_{\mu e}$ AND $P_{\mu\mu}$

In Fig. 2, we have explored the impact of off-diagonal SNSI parameters ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) and their associated phases ($\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu\tau}$) on the appearance ($P_{\mu e}$) and disappearance ($P_{\mu\mu}$) channel. We study for the DUNE experiment, which has a baseline of 1300 km. Here, we have considered only a single nonzero parameter at a time. We have listed all the values of neutrino oscillation parameters used for the simulation in Table I. We have fixed the lightest neutrino mass at $m_1 = 0$ eV. We have plotted $P_{\mu e}$ (top panels) and $P_{\mu\mu}$ (bottom panels) as a function of the neutrino energy, which is varied in the range

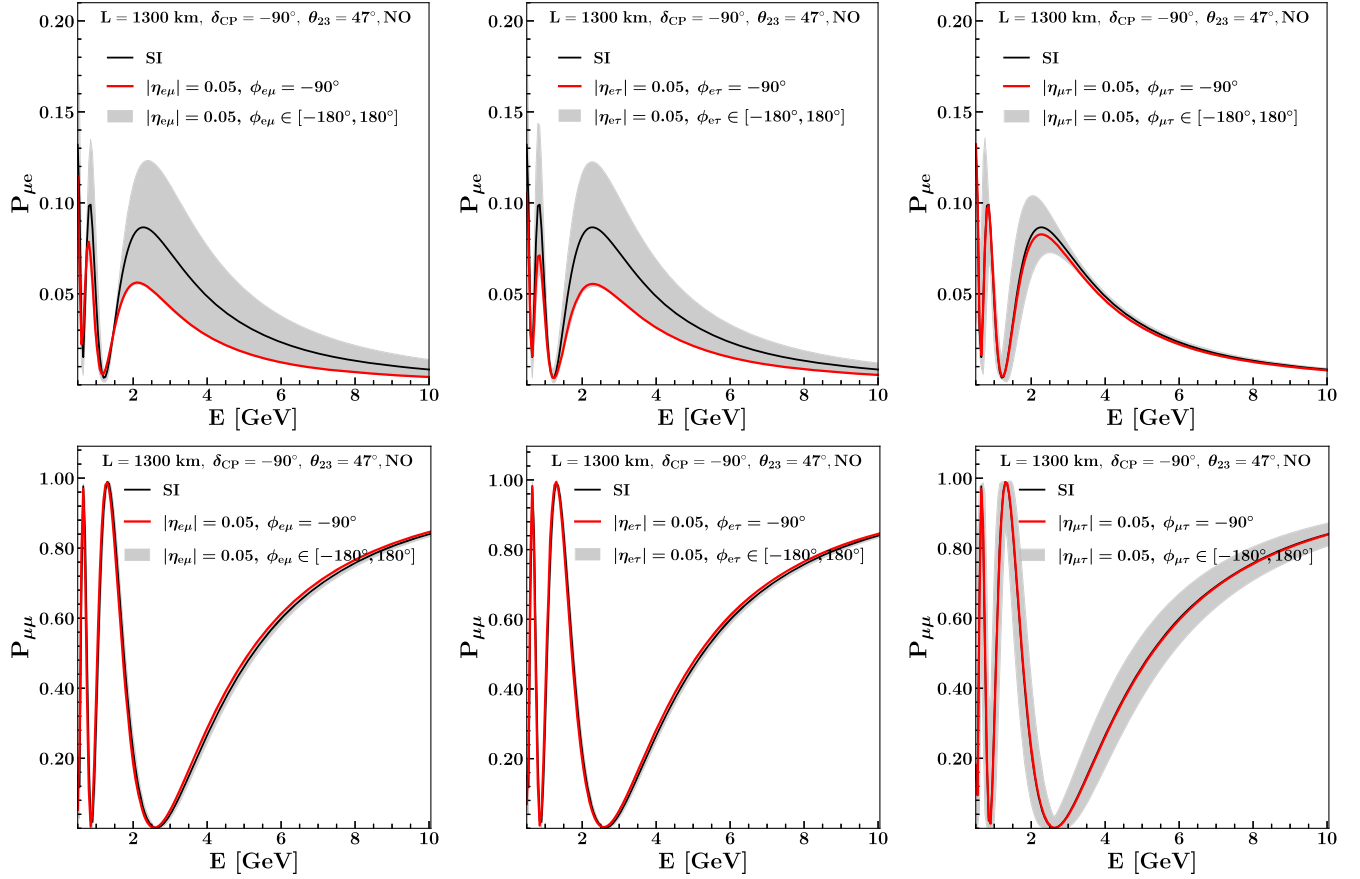


FIG. 2. Impact on the probabilities $P_{\mu e}$ (top panel) and $P_{\mu\mu}$ (bottom panel) due to the presence of SNSI elements $\eta_{e\mu}$ (left panel), $\eta_{e\tau}$ (middle panel), and $\eta_{\mu\tau}$ (right panel) for varying neutrino energy from 0.5–10 GeV for the DUNE experiment, i.e., a baseline of 1300 km. The black line represents the SI ($\eta_{\alpha\beta} = 0$) case. The gray-shaded region indicates the variation in probabilities due to phase $\phi_{\alpha\beta}$ varied in $[-180^\circ, 180^\circ]$ with $|\eta_{\alpha\beta}| = 0.05$. The red line represents the scenario with $|\eta_{\alpha\beta}| = 0.05$ and $\phi_{\alpha\beta} = -90^\circ$.

0.5–10 GeV. The probabilities are numerically calculated using the modified GLOBES framework. The black lines represent the standard interaction (SI) case. The impact of SNSI on $P_{\mu e}$ and $P_{\mu\mu}$ for the case $|\eta_{\alpha\beta}| = 0.05$ and $\phi_{\alpha\beta} \in [-180^\circ, 180^\circ]$ is shown by the shaded gray band. The red lines are for the chosen $|\eta_{\alpha\beta}| = 0.05$ and $\phi_{\alpha\beta} = -90^\circ$. The observations from the top panel of Fig. 2 are stated below,

- (i) In presence of $\eta_{e\mu}$ and $\eta_{e\tau}$, we see a suppression in the probability values for varying neutrino energies. The nonzero values of the $\phi_{e\mu}$ phase can significantly modify the probabilities, as shown by the gray-shaded region. Depending on the value of the phase $\phi_{e\mu}$, we observe either an enhancement or a suppression in the probabilities.
- (ii) In presence of $\eta_{\mu\tau}$, we observe a nominal suppression in the probability around the first oscillation maxima. In contrast to the presence of $\phi_{e\mu}$ and $\phi_{e\tau}$, the phase $\phi_{\mu\tau}$ results in a narrower band, indicating a smaller effect, which is more noticeable below $E < 3$ GeV.

The observations from the bottom panel of Fig. 2 are stated below,

- (i) In the left and middle panels, we observe that the presence of SNSI elements $\eta_{e\mu}$ and $\eta_{e\tau}$ has no significant effect on the disappearance oscillation channel.
- (ii) The presence of $\eta_{\mu\tau}$ (right panel) can bring a shift of peaks and dips with neutrino energy for $P_{\mu\mu}$, which shows the dependence on $\phi_{\mu\tau}$.

The appearance channel ($P_{\mu e}$) is sensitive to both δ_{CP} and SNSI, which can lead to degeneracies for certain combinations of δ_{CP} and $|\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$. The disappearance channel ($P_{\mu\mu}$) is relatively less sensitive to δ_{CP} and may provide an independent probe of SNSI effects. This independence from δ_{CP} is indeed an advantage for isolating the effects of SNSI, which may help resolve degeneracies. However, we observe in Fig. 2 that unlike $P_{\mu e}$, the oscillation channel $P_{\mu\mu}$ is affected only by $\eta_{\mu\tau}$.

In order to quantitatively explore the impact of SNSI on $P_{\mu e}$ over the δ_{CP} parameter space, we define a quantity $\Delta P_{\mu e}$ as

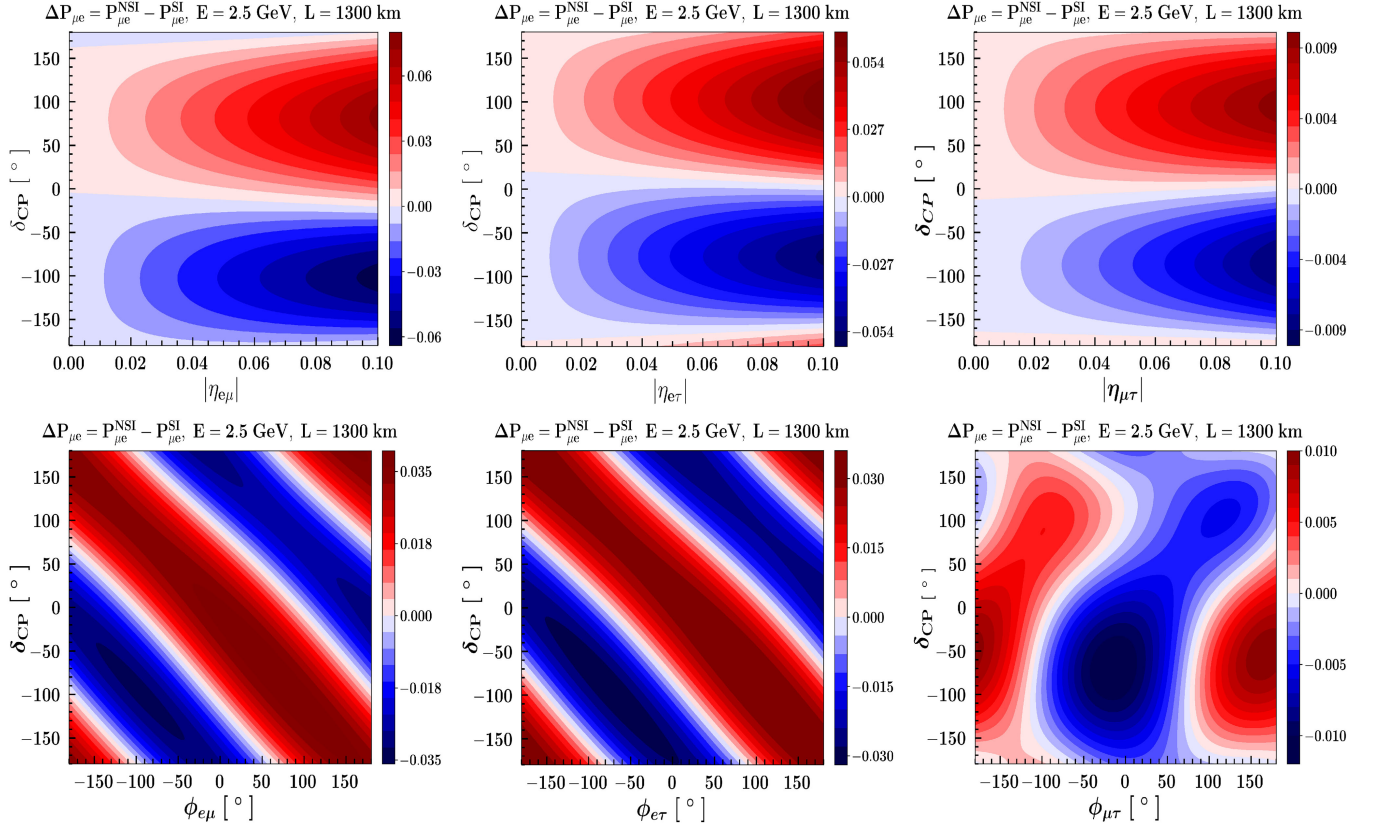


FIG. 3. Plot of $\Delta P_{\mu e} = P_{\mu e}^{\text{NSI}} - P_{\mu e}^{\text{SI}}$ in $(|\eta_{\alpha\beta}| - \delta_{CP})$ and $(\phi_{\alpha\beta} - \delta_{CP})$ parameter space in the top and bottom panels, respectively. The neutrino energy is fixed at the first oscillation maximum (i.e., $E = 2.5$ GeV) for DUNE. The vertical axes correspond to δ_{CP} and the horizontal axes correspond to $\eta_{\alpha\beta}$. The left, middle, and right panels represent the case of $\eta_{e\mu}$, $\eta_{e\tau}$, and $\eta_{\mu\tau}$, respectively.

$$\Delta P_{\mu e} = P_{\mu e}^{\text{NSI}} - P_{\mu e}^{\text{SI}}. \quad (13)$$

Here, $P_{\mu e}^{\text{NSI}}$ is the numerically calculated appearance probability in the presence of SNSI and $P_{\mu e}^{\text{SI}}$ is the appearance probability in the absence of SNSI.

In Fig. 3, we study the impact of $(|\eta_{e\mu}|, |\eta_{e\tau}|, |\eta_{\mu\tau}|)$ and $(\phi_{e\mu}, \phi_{e\tau}, \phi_{\mu\tau})$ in the complete δ_{CP} parameter space in the top and bottom panels, respectively. We examine the effects of SNSI on $P_{\mu e}$ for the whole δ_{CP} parameter space to look for potential regions of degeneracies at the probability level. We have fixed the energy at the first oscillation maximum, i.e., $E \sim 2.5$ GeV and baseline $L = 1300$ km (DUNE). We have plotted $\Delta P_{\mu e}$ with δ_{CP} varied $\in [-180^\circ, 180^\circ]$. Note that the other mixing parameters have been set to the values described in Table I. The left, middle, and right panels represent the cases of $\eta_{e\mu}$, $\eta_{e\tau}$, and $\eta_{\mu\tau}$, respectively. In the oscillograms, the different shades of red (blue) contours correspond to $\Delta P_{\mu e} > 0$ ($\Delta P_{\mu e} < 0$). We list our observations as follows:

- (i) In presence of $\eta_{e\mu}$ (top-left panel), multiple degenerate regions appear in the $(|\eta_{e\mu}| - \delta_{CP})$ parameter space with the same impact on $\Delta P_{\mu e}$. These degeneracies at the probability level highlight an intrinsic

ambiguity in the precise determination of δ_{CP} . A similar pattern of degenerate regions is also observed for $\eta_{e\tau}$ (top-middle panel). In contrast, the impact of $\eta_{\mu\tau}$ (top-right panel) on $\Delta P_{\mu e}$ is relatively weaker, which indicates a reduced sensitivity to this parameter. Notably, the effects induced by $\eta_{e\mu}$, $\eta_{e\tau}$, and $\eta_{\mu\tau}$ exhibit approximate symmetry around $\delta_{CP} \approx 0^\circ$.

- (ii) In presence of $\phi_{e\mu}$ (bottom-left panel) and $\phi_{e\tau}$ (bottom-middle panel), we observe a similar pattern of degeneracies in the δ_{CP} parameter space. However, a more complex dependence is observed for $\phi_{\mu\tau}$ (bottom-right panel), although with considerably weaker impact compared to the other SNSI phases.

In Fig. 4, we explore the CP -asymmetry parameter as a function of δ_{CP} . We define the CP asymmetry parameter as

$$A_{CP}^{\mu e} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}. \quad (14)$$

Here, $P_{\mu e}$ and $\bar{P}_{\mu e}$ denote the appearance probabilities for neutrinos and antineutrinos, respectively. The left, middle, and right panels correspond to the SNSI scenarios with $\eta_{e\mu}$, $\eta_{e\tau}$, and $\eta_{\mu\tau}$, respectively. The top row corresponds to $m_1 = 0$ eV, while the bottom row represents $m_1 = 0.01$ eV.

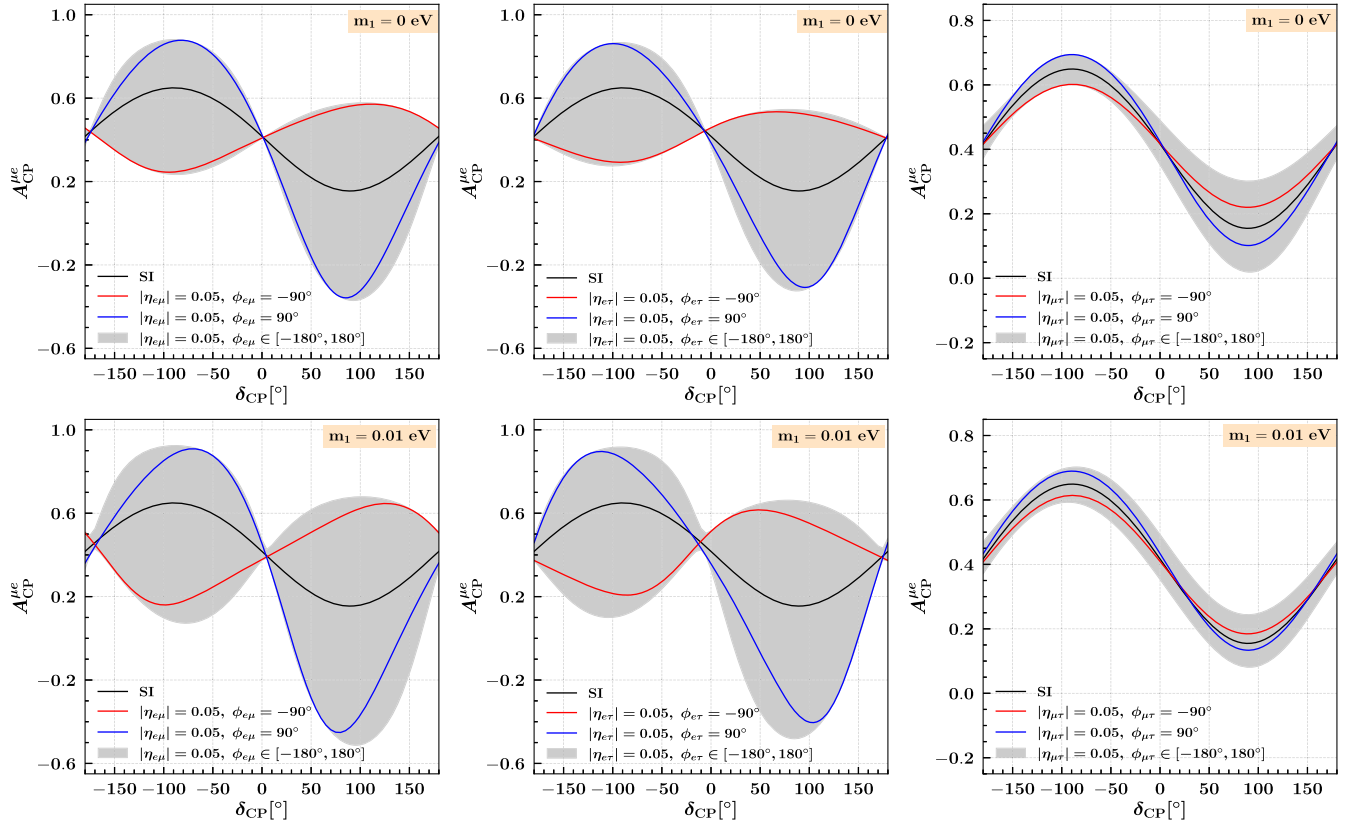


FIG. 4. CP asymmetry parameter $A_{CP}^{\mu e}$ as a function of δ_{CP} in presence of off-diagonal SNSI parameters $\eta_{e\mu}$ (left panel), $\eta_{e\tau}$ (middle panel), $\eta_{\mu\tau}$ (right panel). The black line represents the SI case. The gray band represents the impact of $\phi_{\alpha\beta}$ varied in $[-180^\circ, 180^\circ]$. The blue (red) line corresponds to the SNSI scenario when phase $\phi_{\alpha\beta} = 90^\circ$ (-90°).

- (i) The black curve represents the SI case where the peak (dip) appears around $\delta_{CP} \sim -90^\circ$ ($+90^\circ$). This is due to a greater separation between $P_{\mu e}$ and $\bar{P}_{\mu e}$ at $\delta_{CP} \sim -90^\circ$.
- (ii) In presence of $\eta_{e\mu}$ and $\eta_{e\tau}$, a similar pattern can be observed. However, for specific choices of $\phi_{\alpha\beta}$, the position of the peak and the dip changes as shown for $\phi_{\alpha\beta} = -90^\circ$ by the red curve. In contrast, the pattern of $A_{CP}^{\mu e}$ closely resembles the SI case in presence of $\eta_{\mu\tau}$ with small enhancements/suppression.
- (iii) For $m_1 = 0$ eV scenario, the CP asymmetry parameter shows a stronger dependence on the SNSI phases $\phi_{e\mu}$ and $\phi_{e\tau}$ than on $\phi_{\mu\tau}$. This trend also holds true for a higher m_1 value. For the $m_1 = 0.01$ eV scenario, the $\phi_{e\mu}$ and $\phi_{e\tau}$ bands broaden near the peaks and dips of the asymmetry curve. Interestingly, the impact of $\phi_{\mu\tau}$ on $A_{CP}^{\mu e}$ reduces for $m_1 = 0.01$ eV, which can be understood from the probability expressions.

VI. CP -MEASUREMENT SENSITIVITIES IN PRESENCE OF $|\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$

We observe that the presence of off-diagonal SNSI elements, along with their associated phases, can

significantly modify the oscillation probabilities. Several regions of degeneracy at the probability level are also observed. This may affect the δ_{CP} measurement sensitivities at the upcoming long-baseline experiment DUNE. In Sec. VI A, we first explore the δ_{CP} -constraining capability at DUNE in the presence of SNSI elements $\eta_{\alpha\beta}$. We also study the impact of SNSI on the CPV sensitivities at DUNE in Sec. VI B.

A. δ_{CP} -constraining capability

We explore the δ_{CP} constraining capability in presence of off-diagonal SNSI elements ($\eta_{e\mu}$, $\eta_{e\tau}$, $\eta_{\mu\tau}$) at DUNE. We investigate the impact of $|\eta_{\alpha\beta}|$ and corresponding phases $\phi_{\alpha\beta}$ on the δ_{CP} measurement. The CLs of 3σ , 2σ , and 1σ are represented by the black, red, and blue solid lines, respectively. We have assumed normal mass ordering as the true ordering. All the oscillation parameters are fixed at values shown in Table I.

In Fig. 5, we have a two-dimensional plane of $(\delta_{CP} - |\eta_{\alpha\beta}|)$ with varying δ_{CP} along the horizontal axes and $|\eta_{\alpha\beta}|$ along the vertical axes. We have varied the test values of δ_{CP} in the complete parameter space $[-180^\circ, 180^\circ]$ and $|\eta_{\alpha\beta}|$ in the range $[0, 0.1]$. We have fixed the lightest neutrino mass at $m_1 = 0$ eV. We have

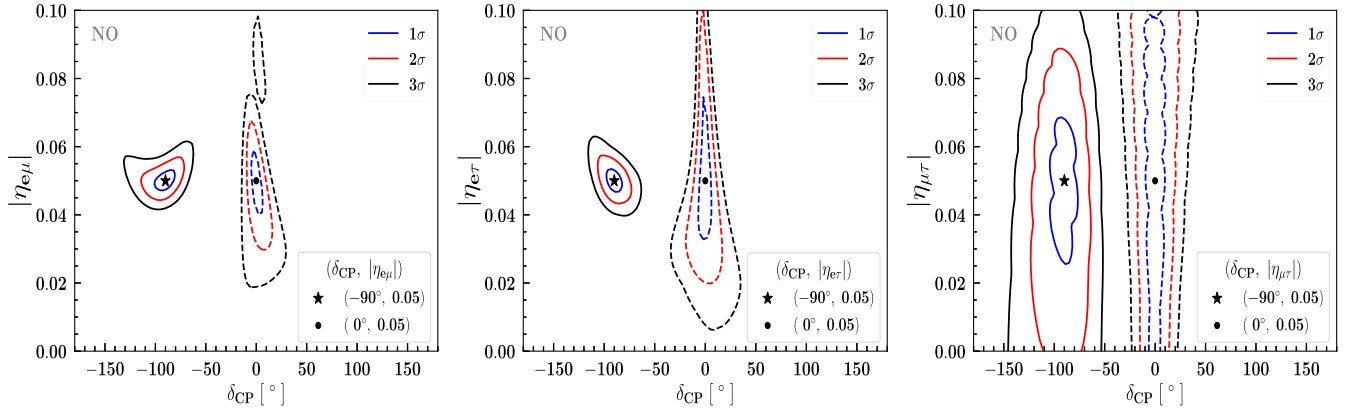


FIG. 5. Sensitivity of DUNE to $|\eta_{e\mu}|$ (left panel), $|\eta_{e\tau}|$ (middle panel), $|\eta_{\mu\tau}|$ (right panel), and the leptonic CP -phase δ_{CP} . The blue, red, and black colored lines represent the 1σ , 2σ , and 3σ CL, respectively. However, the solid CL lines represent the scenario when $(\delta_{CP}^{\text{true}}, |\eta_{\alpha\beta}^{\text{true}}|)$ is fixed at $(-90^\circ, 0.05)$ and the dashed CL lines represent the scenario when $(\delta_{CP}^{\text{true}}, |\eta_{\alpha\beta}^{\text{true}}|)$ is fixed at $(0^\circ, 0.05)$. The corresponding $\phi_{\alpha\beta}$ values for all the cases are fixed at -90° .

also marginalized over the oscillation parameters θ_{23} , Δm_{31}^2 and corresponding phases $\phi_{\alpha\beta}$. We have considered two cases where, in the first case, the true value of $(\delta_{CP}^{\text{true}}, |\eta_{\alpha\beta}^{\text{true}}|)$ is fixed at $(-90^\circ, 0.05)$ and the corresponding CLs are represented by the solid lines. In the second case, the true value is fixed at $(0^\circ, 0.05)$ and the CLs are represented by the dashed lines. In both cases, the $\phi_{\alpha\beta}$ is fixed at -90° . The black star signifies the true values. The observations from Fig. 5 are listed below.

- (i) In the left panel, with true values of $(\delta_{CP}^{\text{true}}, |\eta_{\alpha\beta}^{\text{true}}|)$ fixed at $(-90^\circ, 0.05)$, we observe that δ_{CP} is well constrained in the range $\delta_{CP} \approx [-140^\circ, -60^\circ]$ and $\eta_{e\mu} \approx [0.04, 0.06]$. The allowed region remains constrained in the negative half-plane of δ_{CP} . For the $\delta_{CP}^{\text{true}} = 0^\circ$ scenario, we observe a weaker constraint about $|\eta_{e\mu}|$ but the constraining along δ_{CP} improves.
- (ii) In the middle panel, we observe a similar constraint on δ_{CP} restricted only in the negative plane within

the range $\delta_{CP} \approx [-120^\circ, -60^\circ]$ for $\eta_{e\tau}$ with $(\delta_{CP}^{\text{true}}, |\eta_{\alpha\beta}^{\text{true}}|)$ fixed at $(-90^\circ, 0.05)$. For $\delta_{CP}^{\text{true}} = 0^\circ$, we observe a slightly weaker constraint on the δ_{CP} with range $\delta_{CP} \in [-40^\circ, 30^\circ]$. However, it spreads in the complete $\eta_{e\tau}$ range.

- (iii) In the right panel, we see that δ_{CP} can be constrained in the range $\approx [-150^\circ, -50^\circ]$. However, no constraint on $\eta_{\mu\tau}$ is possible.

In Fig. 6, we plot a two-dimensional plane spanning the $(\delta_{CP} - \phi_{\alpha\beta})$ parameter space, where the color scheme is the same as used in Fig. 5. Similar to the previous figure, we consider two different scenarios in this analysis. In the first scenario, we consider that the true values of $(\delta_{CP}^{\text{true}}, \phi_{\alpha\beta}^{\text{true}})$ are fixed at $(-90^\circ, -90^\circ)$ and the resulting CLs are shown by the solid lines. In the second scenario, the true value is fixed at $(0^\circ, -90^\circ)$ and the CLs are shown by dashed lines. The black star signifies the true values. All the other oscillation parameters used for simulation are as described in Table I.

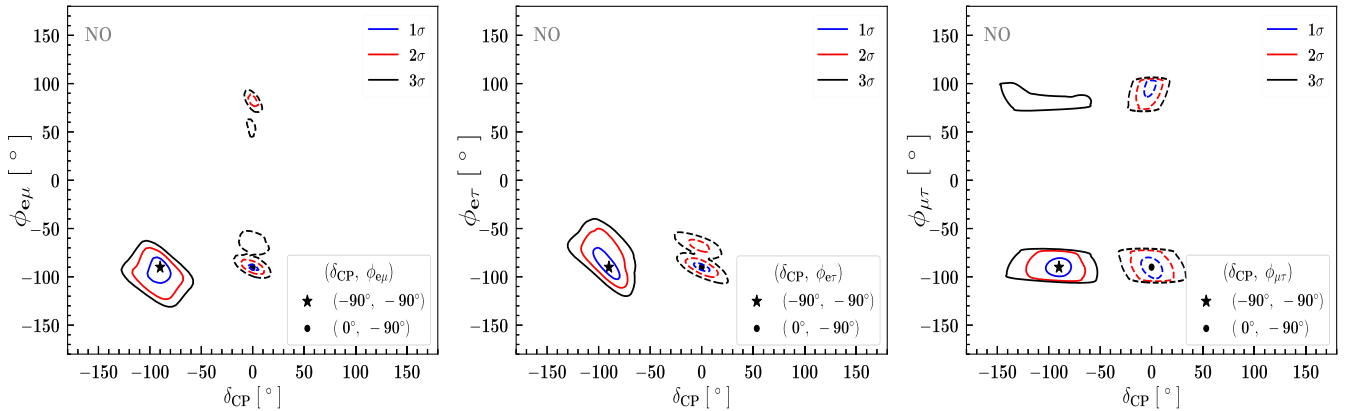


FIG. 6. Sensitivity of DUNE to $\phi_{e\mu}$ (left panel), $\phi_{e\tau}$ (middle panel), $\phi_{\mu\tau}$ (right panel) and the leptonic CP -phase δ_{CP} . The value of $|\eta_{\alpha\beta}^{\text{true}}|$ is fixed at 0.05 for all the cases. The solid lines represent the scenario when $(\delta_{CP}^{\text{true}}, \phi_{\alpha\beta}^{\text{true}})$ is fixed at $(-90^\circ, -90^\circ)$ and the dashed lines represent the scenario when $(\delta_{CP}^{\text{true}}, \phi_{\alpha\beta}^{\text{true}})$ is fixed at $(0^\circ, -90^\circ)$.

We have fixed the lightest neutrino mass at $m_1 = 0$ eV. We have fixed $|\eta_{\alpha\beta}^{\text{true}}| = 0.05$ for all the cases and varied $\phi_{\alpha\beta}$ in the complete parameter space.

- (i) In the left panel with $(\delta_{CP}^{\text{true}}, \phi_{\alpha\beta}^{\text{true}})$ fixed at $(-90^\circ, -90^\circ)$, we see that δ_{CP} is well constrained in the negative half-plane within the range $\delta_{CP} \in [-140^\circ, -30^\circ]$. For $\delta_{CP}^{\text{true}} = 0^\circ$, we observe a much better constraint on δ_{CP} with $\delta_{CP} \in [-50^\circ, 50^\circ]$. However, we find multiple degenerate regions around $\delta_{CP} = 0^\circ$ at 3σ CL.
- (ii) In presence of $\phi_{e\tau}$, the constraint on δ_{CP} is relatively weaker in comparison to $\phi_{e\mu}$ as seen in the middle panel. For a $\delta_{CP}^{\text{true}} = 0^\circ$ scenario, we observe a degenerate region at 2σ CL.
- (iii) The presence of $\phi_{\mu\tau}$ leads to degenerate regions that can be prominently seen in the right panel. The degenerate regions in the positive and negative $\phi_{\mu\tau}$ plane are observed for $\phi_{\mu\tau} \sim \pm 90^\circ$. This can compromise DUNE's sensitivity toward CP violation in the presence of SNSI. We make similar observations for both $\delta_{CP}^{\text{true}}$ scenarios. This is evident from the oscillogram in the bottom panel of Fig. 3, where we observe that $\delta_{CP} = -90^\circ$ can lead to degeneracies for $\phi_{\mu\tau} \sim \pm 90^\circ$.

We see that the presence of off-diagonal SNSI can significantly affect the δ_{CP} measurement. The nonzero phases $\phi_{\alpha\beta}$ can give rise to degeneracies and further hamper the CP -measurement sensitivities at DUNE.

B. Impact on CP -violation sensitivities

We explore the sensitivity of DUNE toward measuring the leptonic CP -violating phase δ_{CP} in the presence of off-diagonal SNSI parameters $(\eta_{e\mu}, \eta_{e\tau}, \eta_{\mu\tau})$. CPV sensitivity quantifies how well an experiment can distinguish between CP -conserving ($\delta_{CP} = [0, \pm\pi]$) and CP -violating values of δ_{CP} . For the analysis, we can define the sensitivity for CPV as

$$\Delta\chi_{CPV}^2(\delta_{CP}) = \min[\chi^2(\delta_{CP}, \delta_{CP}^{\text{test}} = 0), \chi^2(\delta_{CP}, \delta_{CP}^{\text{test}} = \pm\pi)]. \quad (15)$$

We obtain the minimum of $\Delta\chi_{CPV}^2$ for all the δ_{CP} values to measure CP violation in the complete δ_{CP} parameter space. We assume the normal mass ordering as the true ordering and a higher θ_{23} octant as the true octant. We define $\sigma = \sqrt{\Delta\chi^2}$ as the CPV significance, where 3σ (5σ) CL are

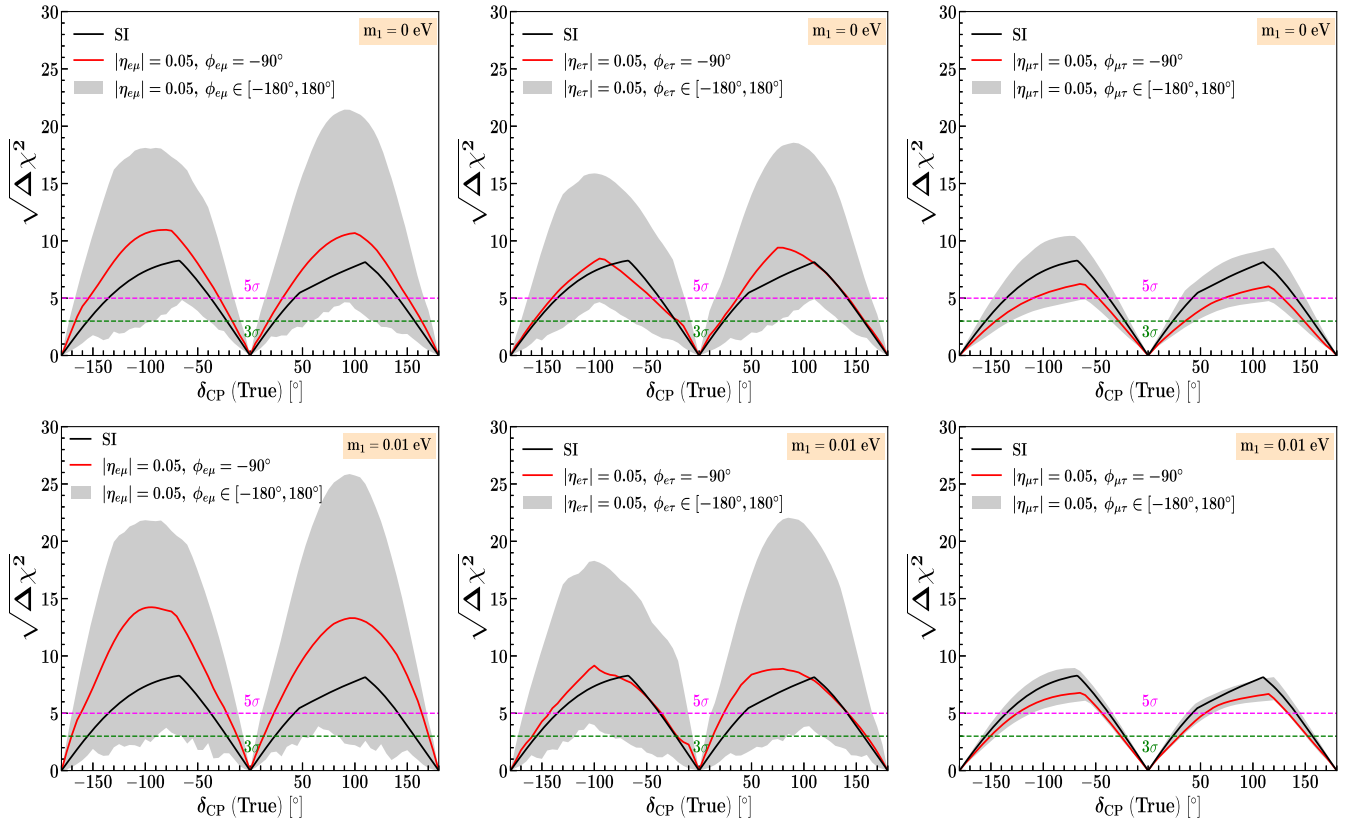


FIG. 7. CPV sensitivity of DUNE in presence of off-diagonal SNSI parameters $|\eta_{e\mu}|$ (left panel), $|\eta_{e\tau}|$ (middle panel), $|\eta_{\mu\tau}|$ (right panel). The black line corresponds to SI ($\eta_{\alpha\beta} = 0$) case. The gray band signifies the impact of $\phi_{\alpha\beta}$ varied in $[-180^\circ, 180^\circ]$ with $|\eta_{\alpha\beta}| = 0.05$. The red line corresponds to SNSI case $|\eta_{\alpha\beta}| = 0.05$, $\phi_{\alpha\beta} = -90^\circ$. The top (bottom) panel corresponds to $m_1 = 0$ eV ($m_1 = 0.01$ eV). The dashed green and magenta lines represent 3σ and 5σ CL, respectively.

represented by the horizontal lines at $\sqrt{\Delta\chi^2} = 9$ (25), respectively. We have marginalized the standard oscillation parameters in their 3σ allowed range as shown in Table I. We have also additionally marginalized over the SNSI parameters $|\eta_{\alpha\beta}| \in [0, 0.1]$. In all panels, the black solid line corresponds to the SI case, whereas the red solid line represents the $|\eta_{\alpha\beta}| = 0.05$, $\phi_{\alpha\beta} = -90^\circ$ case. The green (magenta) dashed line representing 3σ (5σ) CL is used as a reference. In Fig. 7, we have plotted the significance, i.e., $\sigma = \sqrt{\Delta\chi^2}$ along the vertical axes and varied the $\delta_{CP}^{\text{True}}$ along the horizontal axes. In each panel, we have additionally varied the corresponding phase $\phi_{\alpha\beta}$ in the range $[-180^\circ, 180^\circ]$. The impact on the CPV sensitivities for varying $\phi_{\alpha\beta} \in [-180^\circ, 180^\circ]$ is represented by the shaded gray band. To explore the dependence of the CPV sensitivity on absolute neutrino mass, we have studied the CPV sensitivity for two chosen m_1 values, i.e., 0 eV (top panel), 0.01 eV (bottom panel). Our observations are listed below as

- (i) The presence of $\phi_{\alpha\beta}$ can significantly enhance or suppress the CPV sensitivities at DUNE. We see that the sensitivity in presence of the SNSI phase can drop below 5σ CL for certain combinations of δ_{CP} and $\phi_{e\mu}$. We also note that the dependence of the sensitivity on the phase $\phi_{e\mu}$ and $\phi_{e\tau}$ is more prominent as compared to $\phi_{\mu\tau}$. This can be understood from the behavior of $P_{\mu e}$ in presence of $\phi_{\alpha\beta}$ as shown in Fig. 2. This also holds true for a higher value of the lightest neutrino mass.
- (ii) An asymmetry in the $\phi_{\alpha\beta}$ band is observed for the positive and negative δ_{CP} half-plane. This asymmetrical nature of the sensitivity can be understood from the CP asymmetry parameter $A_{CP}^{\mu e}$, which is explored in Fig. 7.
- (iii) For illustrative purposes, we have also presented the sensitivity assuming the SNSI phase $\phi_{\alpha\beta}$ to be -90° , which is represented by the red curve. For the given scenario, in presence of $\eta_{e\mu}$ ($\eta_{\mu\tau}$), we note an

enhancement (suppression) in the sensitivity. However, in presence of $\eta_{e\tau}$, the characteristic double peak of the CPV sensitivity is observed to shift toward a lower value of δ_{CP} .

- (iv) For $m_1 = 0.01$ eV (bottom panel), we note that the sensitivity can drop to 3σ CL in presence of $\eta_{e\mu}$ and $\eta_{e\tau}$. A higher value of lightest neutrino mass leads to a broadening of the $\phi_{\alpha\beta}$ band in presence of $\eta_{e\mu}$ (bottom-left panel) and $\eta_{e\tau}$ (bottom-middle panel), which highlights the impact of the SNSI phase on the CPV sensitivity. However, for $\eta_{\mu\tau}$ (bottom-right panel), we observe a narrowing of the $\phi_{\mu\tau}$ band. This can be explained by the dependence of the CP -asymmetry parameter on m_1 as shown in Fig. 7. For $\eta_{\mu\tau}$, the SNSI probability contribution appears in a term with mass dependence as $(m_1 - m_2)$. The absolute value of this term decreases with m_1 and consequently, the dependence on $\phi_{\mu\tau}$ also reduces.

VII. SENSITIVITY TO OFF-DIAGONAL SNSI ELEMENTS

We constrain the off-diagonal SNSI elements ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) by considering the simulation of the DUNE experiment in the modified GLoBES framework. In presence of SNSI, neutrino oscillation experiments can become sensitive to the neutrino mass scale. We have also probed the impact of different values of the lightest neutrino mass on constraining the parameters. The oscillation parameters used for simulation are tabulated in Table I. We have followed a similar marginalization for the standard oscillation parameters. In Fig. 8, we have constrained the off-diagonal SNSI elements $|\eta_{e\mu}|$, $|\eta_{e\tau}|$, and $|\eta_{\mu\tau}|$, which are represented by the black, red, and blue lines, respectively. We have plotted the $\sqrt{\Delta\chi^2}$ profiles along the vertical axes after marginalizing over the mixing parameters θ_{23} , Δm_{31}^2 , and δ_{CP} . We have varied $|\eta_{\alpha\beta}|$ along the horizontal axes. We have considered normal ordering as the true ordering and

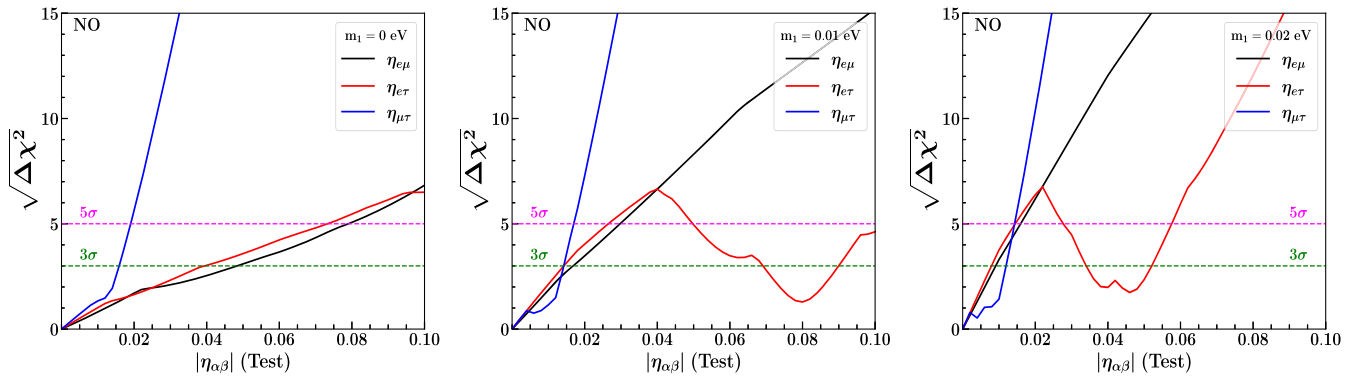


FIG. 8. DUNE's sensitivity to the SNSI parameters $|\eta_{e\mu}|$, $|\eta_{e\tau}|$ and $|\eta_{\mu\tau}|$ are shown by black, red, and blue lines, respectively. The left, middle, and right panels correspond to the lightest neutrino mass fixed at $m_1 = 0$ eV, $m_1 = 0.01$ eV, and $m_1 = 0.02$ eV, respectively. The dashed lines in magenta and green indicate the 5σ and 3σ CL.

TABLE III. Bounds on SNSI parameters at 5σ CL obtained from the simulation of DUNE for different m_1 values.

Parameters	Bounds at 5σ CL		
	$m_1 = 0$ eV	$m_1 = 0.01$ eV	$m_1 = 0.02$ eV
$ \eta_{e\mu} $	0.08	0.03	0.016
$ \eta_{e\tau} $	0.074	0.026	0.014
$ \eta_{\mu\tau} $	0.02	0.018	0.014

the higher θ_{23} octant as the true octant. The 3σ and 5σ CL are represented by the dashed lines in green and magenta, respectively. We present the constraints for three different values of the lightest neutrino mass at $m_1 = 0$ eV (left panel), 0.01 eV (middle panel), and 0.02 eV (right panel).

- (i) We observe a better sensitivity for $\eta_{\mu\tau}$ compared to $\eta_{e\mu}$ and $\eta_{e\tau}$. This can be explained by the dependence of $\eta_{\mu\tau}$ on both the appearance and disappearance oscillation channels as shown in Fig. 2. The SNSI elements $\eta_{e\mu}$ and $\eta_{e\tau}$ can affect only $P_{\mu e}$, whereas $\eta_{\mu\tau}$ can modify both $P_{\mu e}$ and $P_{\mu\mu}$. This results in a better sensitivity for $\eta_{\mu\tau}$.
- (ii) With the increase in the lightest neutrino mass, the constraints on $\eta_{e\mu}$ and $\eta_{e\tau}$ significantly improve. This is due to the fact that $\eta_{e\mu}$ and $\eta_{e\tau}$ have greater dependence on m_1 as compared to $\eta_{\mu\tau}$. The SNSI contribution in the presence of $\eta_{\mu\tau}$ appears with the $m_1 - m_2$ term, which decreases with an increase in m_1 for NO. This dependence can be explicitly seen in the probability expressions in Sec. IV.
- (iii) We also observe a minima for $m_1 = 0.01$ eV (0.02 eV) at $\eta_{e\tau} = 0.08(0.046)$. We note that both these minima are local minima that can arise due to the degeneracy of the SNSI scenario with the SI. For the calculation of $\Delta\chi^2$, we have marginalized over δ_{CP} , Δm_{31}^2 , and θ_{23} , which leads to a certain combination of the oscillation parameters and SNSI values, which mimics the SI case.

The bounds on the off-diagonal SNSI parameters at 5σ CL as obtained from the simulation of the DUNE experiment are shown in Table III. Overall, the increase in the value of the lightest neutrino mass leads to better constraints on the off-diagonal elements. In addition, the constraining is significantly better, particularly for the element $\eta_{\mu\tau}$.

VIII. CORRELATION AMONG THE $\eta_{\alpha\beta}$ PARAMETERS

This section explores the correlation between different SNSI elements, taking the DUNE experiment as a case study. To study the correlation, we consider two nonzero SNSI parameters at a time out of the diagonal ($\eta_{ee}, \eta_{\mu\mu}, \eta_{\tau\tau}$), off-diagonal ($|\eta_{e\mu}|, |\eta_{e\tau}|, |\eta_{\mu\tau}|$), and associated phases

($\phi_{e\mu}, \phi_{e\tau}, \phi_{\mu\tau}$). We have explored four different scenarios: a) both elements are diagonal; b) both elements are off-diagonal; c) one element is diagonal and the other is off-diagonal; d) one element is off-diagonal ($\eta_{\alpha\beta}$) and the other is the associated phase ($\phi_{\alpha\beta}$). In all cases, we have plotted the allowed regions at 1σ , 2σ , and 3σ C.L. on the two-dimensional planes. The values of the oscillation parameters used for the simulation are as described in Table I. We have fixed the lightest neutrino mass at $m_1 = 0$ eV. We have chosen the normal mass ordering as the true mass ordering and the higher θ_{23} octant as the true octant.

In Fig. 9, we have explored the correlation between the diagonal ($\eta_{ee}, \eta_{\mu\mu}, \eta_{\tau\tau}$) and off-diagonal ($|\eta_{e\mu}|, |\eta_{e\tau}|, |\eta_{\mu\tau}|$) elements. We have marginalized over the oscillation parameters $\Delta m_{31}^2, \theta_{23}, \delta_{CP}$, and the associated SNSI phases $\phi_{\alpha\beta}$. We then obtain the minimum $\Delta\chi^2$ by varying the SNSI parameters in the fit data. We have plotted the diagonal elements on the vertical axes and varied the values of the parameters $\in [-0.15, 0.15]$. We varied the off-diagonal elements in the horizontal axes $\in [0, 0.15]$. For each case, the true value of the parameters is fixed at (0.05, 0.05). The observations are listed below as

- (i) In top-left panel, a positive correlation is observed between the parameters η_{ee} and $|\eta_{e\mu}|$, which is also observed in the $\eta_{ee}-|\eta_{e\tau}|$ plane (top-middle panel). This correlation arises as certain combinations of these two parameters can lead to degeneracies with the considered true scenario.
- (ii) A weaker but similar correlation between $|\eta_{\mu\tau}|$ (right panel) and the diagonal elements $\eta_{ee}, \eta_{\mu\mu}$, and $\eta_{\tau\tau}$ can be seen. The probability contribution of $\eta_{\mu\tau}$ is comparable to that of the diagonal elements, which results in wider degenerate regions mimicking the true scenario. The degenerate regions seen at 1σ CL are due to the marginalization of the oscillation parameters. However, for the η_{ee} and $\eta_{\mu\tau}$ combination, we observe a moderate correlation.
- (iii) In other combined scenarios for $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$, we observe no significant correlation. It is because the appearance probability is primarily driven by the off-diagonal parameters $|\eta_{e\mu}|$ and $|\eta_{e\tau}|$ in presence of diagonal elements $\eta_{\mu\mu}$ (middle panel) and $\eta_{\tau\tau}$ (bottom panel).

In top panel of Fig. 10, we have explored the correlation among the diagonal elements ($\eta_{ee}, \eta_{\mu\mu}, \eta_{\tau\tau}$) only. For the diagonal element case, we marginalize only over the oscillation parameters $\Delta m_{31}^2, \theta_{23}$, and δ_{CP} . In the middle panel of Fig. 10, we have examined the correlation among the off-diagonal elements ($|\eta_{e\mu}|, |\eta_{e\tau}|, |\eta_{\mu\tau}|$) only. For the off-diagonal case, we have additionally marginalized over the associated phases $\phi_{\alpha\beta}$. The true values of the SNSI parameters are fixed at $(\eta_{\alpha\alpha}, |\eta_{\alpha\beta}|) \equiv (0.05, 0.05)$ and $(|\eta_{\alpha\beta}|, \phi_{\alpha\beta}) \equiv (0.05, -90^\circ)$.

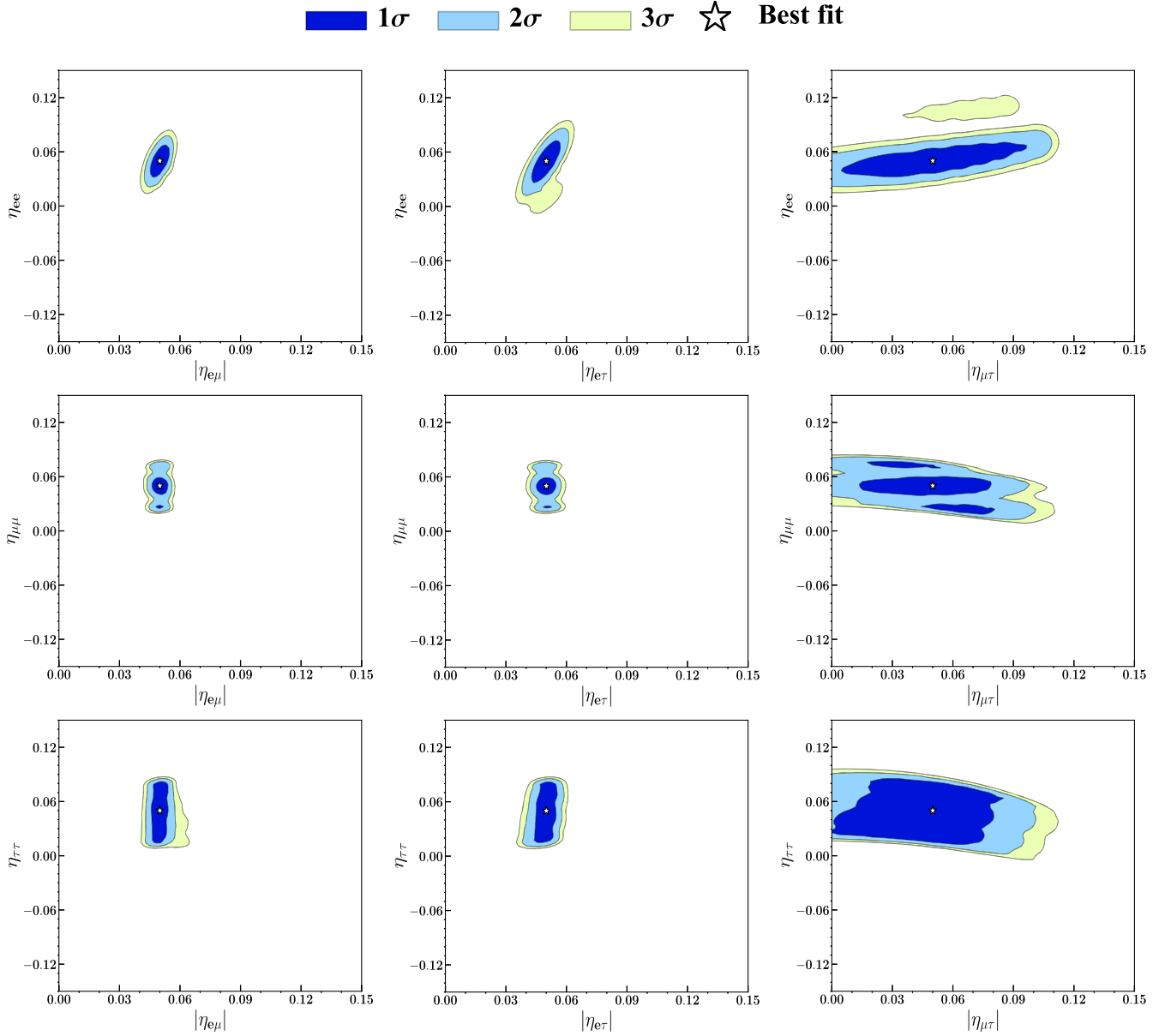


FIG. 9. Correlation between diagonal (η_{ee} , $\eta_{\mu\mu}$, $\eta_{\tau\tau}$) and off-diagonal ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) NSI elements at DUNE. The blue, cyan, and green colors represent the 1σ , 2σ , and 3σ allowed regions, respectively. The best-fit point is represented by the white solid star. For each case, the true value of the parameters is fixed at (0.05, 0.05) for illustrative purposes. The corresponding NSI phases $\phi_{\alpha\beta}$ for off-diagonal elements are fixed at -90° .

- (i) Among the diagonal elements, we observe a moderate correlation only for the combination of $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ elements, as they exhibit a similar impact at the probability level. However, the effect of η_{ee} is significantly stronger compared to $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$, which results in no observed correlation.
- (ii) Similarly, for the off-diagonal elements, we observe a negative correlation between $\eta_{e\mu}$ and $\eta_{e\tau}$. However, for the other combinations, we observe a weak negative correlation as shown in the middle panels of Fig. 10.

In bottom panel of Fig. 10, we have explored the correlation between off-diagonal ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) elements and their corresponding phases ($\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu\tau}$). The true values are fixed at $(\phi_{\alpha\beta}, |\eta_{\alpha\beta}|) \sim (-90^\circ, 0.05)$.

- (iii) For the combined scenario of $\eta_{\mu\tau}$ and $\phi_{\mu\tau}$, we observe a degeneracy for $\phi_{\mu\tau} \approx \pm 90^\circ$. Within the given marginalization, a certain combination of the oscillation parameters for $\phi_{\mu\tau} = +90^\circ$ mimics the true scenario, resulting in a degeneracy. No significant correlation is observed for the other parameters.

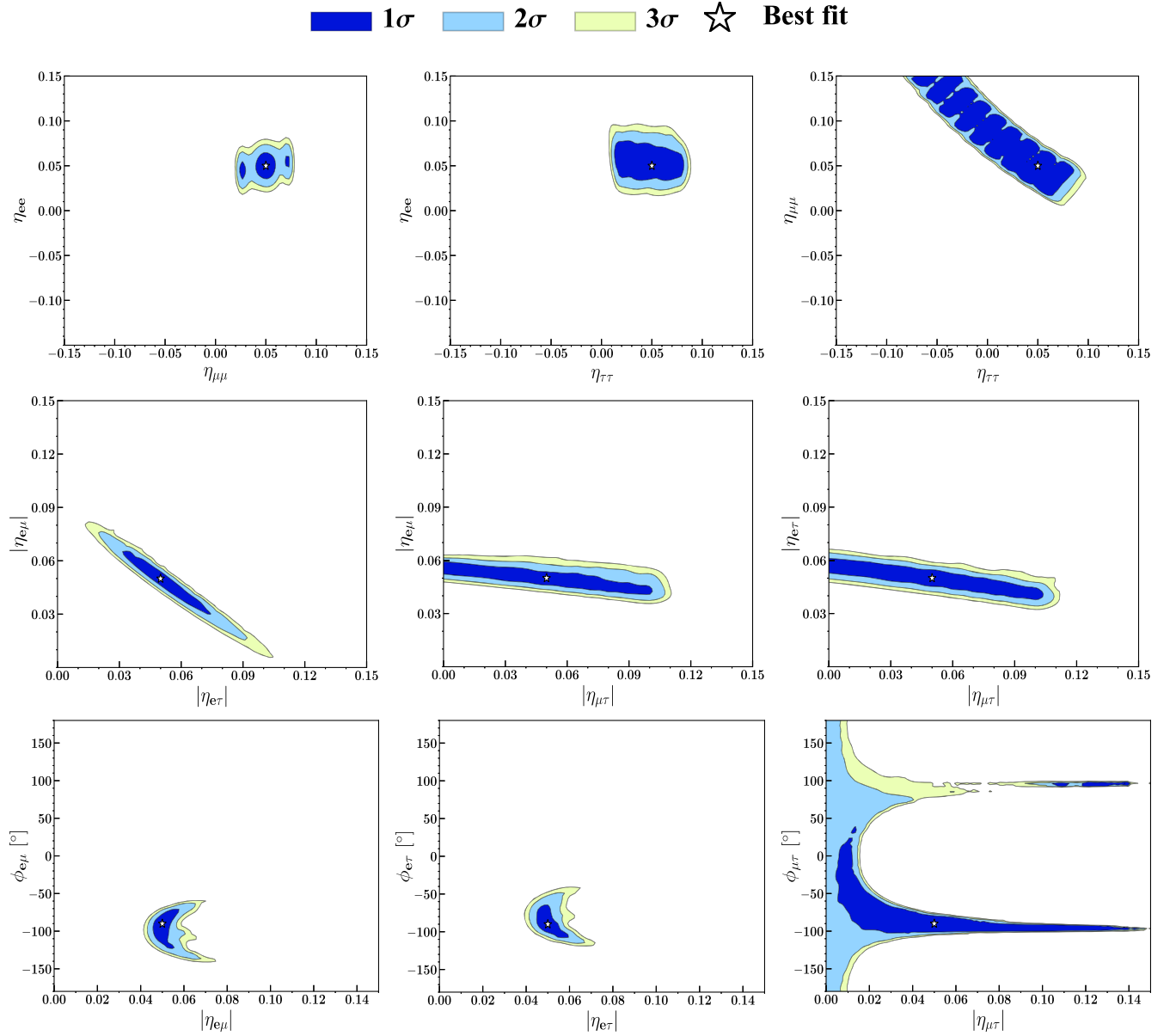


FIG. 10. Top panel: Correlation among the diagonal elements (η_{ee} , $\eta_{\mu\mu}$, $\eta_{\tau\tau}$) only. Middle panel: Correlation among the off-diagonal elements ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) only. Bottom panel: Correlation among the off-diagonal elements ($|\eta_{e\mu}|$, $|\eta_{e\tau}|$, $|\eta_{\mu\tau}|$) and phases ($\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu\tau}$). The blue, cyan, and green colors represent the 1σ , 2σ , and 3σ allowed regions, respectively. The white solid star represents the best-fit point.

IX. SUMMARY AND CONCLUSION

In this work, we have considered the upcoming LBL experiment DUNE, which has a baseline of 1300 km with a fiducial volume of 40 kton to be situated at Sanford Underground Research Facility. It will have a peak energy of around 2.5 GeV. It offers very high sensitivity to the neutrino mass ordering, leptonic CP phase, and the octant of θ_{23} . We have discussed the capability of this upcoming LBL experiment to determine the leptonic CP phase in the presence of scalar nonstandard interactions. We have analytically explored the dependence of neutrino oscillation

probabilities on the absolute ν masses and other mixing parameters in presence of $|\eta_{\alpha\beta}|$ and $\phi_{\alpha\beta}$. We first discuss how the presence of off-diagonal SNSI elements and their associated phases can deviate the probabilities from the standard interaction scenario. We find that the impact of $|\eta_{e\mu}|$ and $|\eta_{e\tau}|$ on the $P_{\mu e}$ channel is significant. However, for a choice of $|\eta_{\alpha\beta}|$, the phases $\phi_{e\mu}$ and $\phi_{e\tau}$ have a greater impact on the probabilities in comparison to $\phi_{\mu\tau}$. We illustrate the differences in the probabilities by defining a quantity $\Delta P_{\mu e}$ in the two-dimensional ($|\eta_{\alpha\beta}| - \delta_{CP}$) and ($\phi_{\alpha\beta} - \delta_{CP}$) plane at the first oscillation maximum. In presence of $\eta_{e\mu}$ and $\eta_{e\tau}$, we

find interesting degenerate regions at the probability level. The impact of $\eta_{\mu\tau}$ on $\Delta P_{\mu e}$ is relatively very small. We also observe multiple degenerate regions in the presence of phases $\phi_{\alpha\beta}$, which can complicate the measurement capability of δ_{CP} at DUNE.

We have explored the δ_{CP} -constraining capability in the presence of off-diagonal SNSI elements $|\eta_{\alpha\beta}|$ and corresponding phases $\phi_{\alpha\beta}$. We observe that the constraining is much better in the presence of $|\eta_{e\mu}|$ and $|\eta_{e\tau}|$ as compared to $|\eta_{\mu\tau}|$. The presence of phases $\phi_{e\mu}$ and $\phi_{e\tau}$ shows similar constraining of the leptonic CP phase. However, we observe a degeneracy in presence of $\phi_{\mu\tau}$ around $\sim \pm 90^\circ$. We have also explored the impact of off-diagonal SNSI on the CPV sensitivities at DUNE for different values of the lightest neutrino mass. We find that the phases $\phi_{e\mu}$ and $\phi_{e\tau}$ can significantly modify the sensitivities in comparison to $\phi_{\mu\tau}$. We have also imposed constraints on the off-diagonal elements at 5σ CL. We observe that $\eta_{\mu\tau}$ is most tightly constrained, and the constraining of the other elements improves significantly for a higher value of the neutrino mass. We have also examined the correlation of the SNSI parameters across different elements and phases, revealing correlations among various parameters. In particular, we find that the correlation between $|\eta_{\mu\tau}|$ and $\phi_{\mu\tau}$ leads to the degenerate regions observed in the δ_{CP} measurement. This study has shed light on the impact of off-diagonal SNSI elements and associated phases on the CP -measurement sensitivities at DUNE.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: COMPARISON OF ANALYTIC AND NUMERICAL PROBABILITIES IN THE PRESENCE OF $|\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$

The probabilities have been perturbatively calculated by expanding in the small parameters α , s_{13} ($\equiv \sin \theta_{13}$), and the SNSI parameter $\eta_{\alpha\beta} \equiv |\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$. We have followed the Cayley-Hamilton theorem [148] to calculate the transition amplitude. In Fig. 11, we have compared the analytic and numerical probabilities in the presence of SNSI parameters. We have plotted the analytic and numerical probabilities as a function of neutrino energy in the range 0–10 GeV. The dashed (solid) lines represent the numerical (analytic) probabilities. We have also shown different choices of the SNSI phase $\phi_{\alpha\beta}$.

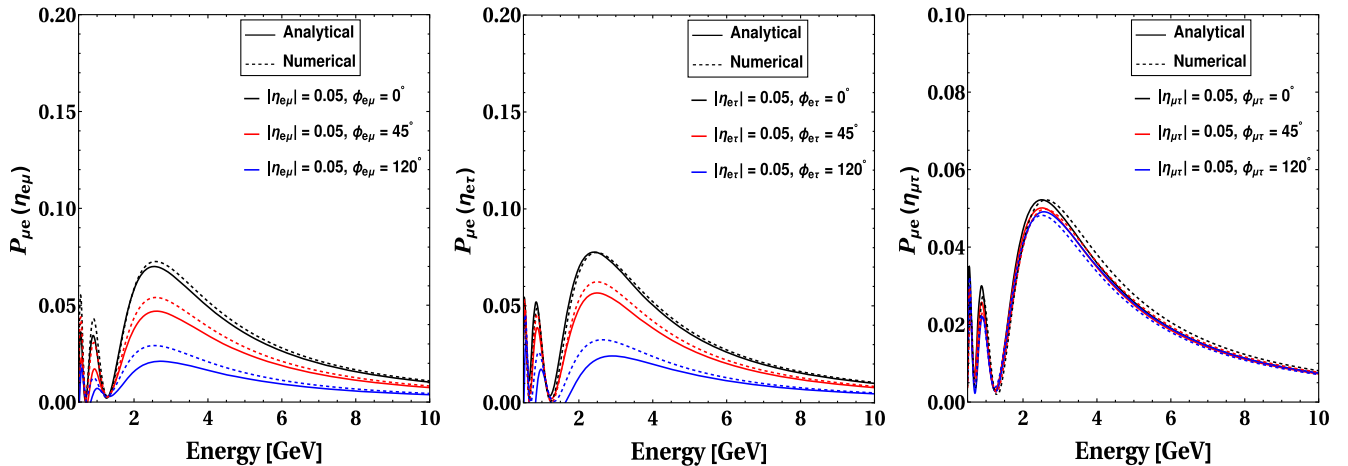


FIG. 11. Comparison of analytic (solid) and numerical (dashed) appearance probability ($P_{\mu e}$) in presence of $\eta_{e\mu} = |\eta_{e\mu}|e^{i\phi_{e\mu}}$ (left panel), $\eta_{e\tau} = |\eta_{e\tau}|e^{i\phi_{e\tau}}$ (middle panel), and $\eta_{\mu\tau} = |\eta_{\mu\tau}|e^{i\phi_{\mu\tau}}$ (right panel).

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