

Probing new physics scenarios using high energy events at the NOvA far detector

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NuMI Off-axis ν_e Appearance (NOvA) experiment is an ongoing long-baseline neutrino oscillation experiment. The primary channels of interest are the ν_e , $\bar{\nu}_e$ appearance, ν_μ , $\bar{\nu}_\mu$ disappearance channels analyzed in the energy window $1 < E_\nu < 4$ GeV. However, NOvA far detector sees nontrivial high-energy ν_e , $\bar{\nu}_e$ events in the energy range $4 < E_\nu < 20$ GeV. These high-energy events provide us with an opportunity to investigate the subleading new physics scenarios. In this context, we study the sensitivity of the NOvA experiment to constrain the nonstandard interaction (NSI) parameters and environmental decoherence parameters. We observe that by including high energy events (signal + background) the degeneracy around $\epsilon_{e\tau} \sim 1.6$ can be removed throughout the δ_{CP} and $\delta_{e\tau}$ range. Further, we examine the role of signal versus beam background events in removing this degeneracy. In addition, we constrain the decoherence parameter Γ considering events from $1 < E_\nu < 20$ GeV. Later, assuming the presence of decoherence in nature we obtain the allowed regions in θ_{23} and δ_{CP} plane.

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I. INTRODUCTION

The discovery of the neutrino oscillation phenomenon has established that neutrinos do have a (tiny) mass. This overwhelming evidence challenges the boundaries of the standard model (SM) of particle physics and motivates us to search for a more consistent theory. In this context, the study of new physics scenarios (contributions from subleading effects) are crucial as they provide the explanation to beyond the standard model (BSM) physics phenomenon. The ongoing and upcoming high precision neutrino oscillation experiments play pivotal role in the quest for new physics phenomenon. In this work, we analyze the far detector (FD) simulated events at NOvA experiment in the presence of two new physics (NP) paradigms, nonstandard interactions (NSIs) [1–3] and environmental decoherence [4–6]. Here we consider individual effect of NSI and environmental decoherence on the neutrino propagation.

Environmental decoherence is the phenomenon that arises due to the interaction of neutrinos with the stochastic

environment during propagation. This interaction leads to the loss of coherence among the neutrino mass states.¹ Additionally, neutrinos could interact with earth matter via NSI (cannot be explained in the SM scenarios). Both the phenomenon, NSI and environmental decoherence, play a subleading (but significant) role in the standard neutrino oscillation framework.

Several studies have discussed neutrino oscillations in the framework of NSI and decoherence. Here, we provide some references relevant to the NOvA experiment. In Ref. [12–14] authors have pointed out the tension in latest NOvA and T2K results [15,16] could be improved considering NSI in the analysis.² Recent analysis of NOvA data [15] ($1 < E_\nu < 5$ GeV) in the presence of NSI has reported the bounds on NSI parameters $\epsilon_{e\mu} \leq 0.3$, $\epsilon_{e\tau} \leq 0.4$ and predicted a degeneracy with the standard oscillation (SO) at $\epsilon_{e\tau}$ and $\delta_{CP} + \delta_{e\tau} = 270^\circ$ [18]. In Ref. [19] authors have analyzed the latest NOvA data considering NSI phenomenon in the theory and shown that $\epsilon_{e\tau}$ encounters degeneracy (with SO) for full range of standard CP phase $\delta_{CP} \in [0:360^\circ]$ and nonstandard CP phase $\delta_{e\tau} \in [0:360^\circ]$. On the other hand, authors in Ref. [20] have proposed environmental decoherence to explain the shift in θ_{23} from its maximal mixing in the NOvA data. In a recent analysis [21] authors have constrained decoherence

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¹This effect is different from neutrino wave packet decoherence [7–11].

²Considering scalar NSI authors have updated the analysis in the Appendix of Ref. [17].

parameters considering $1 < E_\nu < 5$ GeV NOvA FD events. Analyzing high-energy appearance events ($1 < E_\nu < 12$ GeV) at NOvA FD, authors in Ref. [22] have constrained the standard oscillation parameters and concluded the sensitivity remains almost unaffected. In this paper we analyze events from $1 < E_\nu < 20$ GeV at NOvA FD to study the sensitivity to new physics scenarios namely NSI and environmental decoherence parameters.

In order to analyze the effects of NSI and decoherence at high energy we include the events from high-energy tail ($4 < E_\nu < 20$ GeV) along with the events from standard analysis window of NOvA i.e., $1 < E_\nu < 4$ GeV. We employ these events in the determination of NSI parameters $\epsilon_{e\tau}$ and $\epsilon_{e\mu}$ one at a time. Including high-energy events we show that the $\epsilon_{e\tau}$ degeneracy observed in Ref. [19] can be removed throughout the δ_{CP} and $\delta_{e\tau}$ range. Further, we examine the role of signal versus beam background events in removing this degeneracy. Furthermore, we display the sensitivity to the decoherence parameter (Γ) considering energy power-law dependency ($\Gamma \propto E^n$, where n is the power-law index) and obtain the upper bounds on Γ . We compare the upper bounds obtained from $1 < E_\nu < 4$ GeV with bounds from high-energy events ($1 < E_\nu < 20$ GeV). In addition, assuming decoherence in nature we illustrate the uncertainty in the determination of θ_{23} considering events from $1 < E_\nu < 4$ GeV and $1 < E_\nu < 20$ GeV.

This paper is organized as follows. In Sec. II we provide simulation details and analysis method. In Sec. III we show results for effects of NSI at high energy and, in Sec. IV effects of environmental decoherence at high energy. We summarize our results in Sec. V.

II. SIMULATION DETAILS

NOvA is an ongoing long baseline neutrino oscillation experiment that uses NuMI beam facility at Fermilab. The experiment consists of two detectors, one near detector (ND) at the Fermilab site and a FD located at Ash River, Minnesota. A NuMI beam (Ref. [23]) is delivered with an off-axis angle 14.6 mrad to the FD. The FD is ~ 810 km away from the source and receives a narrow beam with the flux peak ~ 1.8 GeV. This corresponds to first oscillation peak in the atmospheric sector. During propagation from source to detector, neutrinos experience the Earth's crust density ~ 2.84 gm/cm³.

We simulate the NOvA experiment using publicly available GLoBES software packages [24,25]. In the experimental definition file we adopt fiducial target mass 14 kt. The experiment utilizes total exposure of 13.6×10^{20} protons on target (POT) for ν and 12.5×10^{20} POT for $\bar{\nu}$ which correspond to 6 years of running in ν mode and 3 years of running in $\bar{\nu}$ mode with an hourly-averaged beam power 742 kW. We adopt energy resolution function $\sigma_E = \alpha E + \beta\sqrt{E} + \gamma$, where $\alpha = 0.11(0.09)$, $\beta = 0$, $\gamma = 0$ for

TABLE I. True oscillation parameters and 3σ ranges have been considered in our analysis are taken from Refs. [15,28].

Parameters	True values	Test ranges
$\sin^2 \theta_{12}$	0.307	Fixed
$\sin^2 \theta_{13}$	0.021	[0.02:0.02405]
$\sin^2 \theta_{23}$ NH (IH)	0.57 (0.56)	[0.38:0.64]
δ_{CP} NH (IH)	0.82π (1.52π)	[0:2 π]
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	7.53	Fixed
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$ NH (IH)	2.41 (-2.45)	[± 2.29 : ± 2.54]

e -like (μ -like) events [26,27]. We implement these information and reproduce the standard event rates as provided in recent NOvA results [15]. To obtain the event spectrum we use the standard parameters listed in Table I.

Additionally, to calculate the numerical oscillation probability in the presence of NSI, we deploy *snu.c* [29,30] extension with GLoBES. On the other hand, we incorporate a *new probability engine* (based on open quantum system) in GLoBES to implement the effect of environmental decoherence.

A. Analysis

For our analysis purpose we include the events from ν_μ ($\bar{\nu}_\mu$) $\rightarrow \nu_e$ ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$) $\rightarrow \nu_\mu$ ($\bar{\nu}_\mu$) channels as these are the relevant channels considered to achieve scientific goals at NOvA experiment. We generate simulated events in the true and test spectra assuming different hypotheses; then, we compare them statistically. We mention the details of true and test theoretical hypotheses while discussing the respective results. To perform the analysis we incorporate Poisson χ^2 function which is defined as

$$\chi^2 = \min_{\alpha_s, \alpha_b} \sum_{\text{channels}} 2 \sum_i \left[N_i^{\text{test}} - N_i^{\text{true}} + N_i^{\text{true}} \log \left(\frac{N_i^{\text{true}}}{N_i^{\text{test}}} \right) \right] + \frac{\alpha_s^2}{\sigma_s} + \frac{\alpha_b^2}{\sigma_b}, \quad (1)$$

where, N_i^{test} represents the number of test events and N_i^{true} the true events (signal and background) in i th bin. α_s and α_b refer to the systematic parameters of the signal and background, while σ_s and σ_b are the corresponding uncertainties. The following systematic uncertainties are considered in our analysis; signal normalization (5%), signal tilt (5%), background normalization (5%), background tilt (2.5%), and are incorporated using *pull method* [31,32]. These uncertainties are defined at a rule level and not at a channel level.

In our analysis we include both ν_μ , $\bar{\nu}_\mu$ high-energy events along with ν_e , $\bar{\nu}_e$ events. However, we find that the disappearance channels (ν_μ and $\bar{\nu}_\mu$) are not affected by

the NSI parameters $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ of interest. Therefore, in the sensitivity analysis of NSI parameters (Sec. III), we highlight the contributions only from ν_e and $\bar{\nu}_e$ appearance channels. On the other hand, the environmental decoherence significantly affects both the ν_e ($\bar{\nu}_e$)-appearance and ν_μ ($\bar{\nu}_\mu$)-disappearance channels. Therefore, in Sec. IV, we show (in Fig. 7) the high-energy events of ν_μ and $\bar{\nu}_\mu$ also.

III. CONSTRAINING NSI PARAMETERS WITH HIGH-ENERGY EVENTS

Neutrinos interact through weak force as described by the standard model. However, the interactions of neutrinos beyond the SM at a subleading level are not completely ruled out. The effect of these NSIs on neutrino oscillation was first introduced by Wolfenstein in Ref. [1]. Later on, NSIs have widely been studied in the facet of neutrino physics (see reviews [33–37] and references therein). NSI can modify neutrino production, propagation, and detection, leading to deviations from standard oscillation phenomena. In particular, neutrino propagation is affected by neutral current (NC) NSI.³ The new interactions are parametrized in terms of diagonal propagation NSI parameters $\epsilon_{\alpha\alpha}$ and off-diagonal parameters $\epsilon_{\alpha\beta}$ ($=|\epsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$, where $\delta_{\alpha\beta}$ is the nonstandard CP phase.).

In this section, considering the impact of NSIs on neutrino propagation, we give an overview of the mathematical formulation of oscillation probability. Taking into account one nonzero off-diagonal NSI parameter among $\epsilon_{e\tau}$ and $\epsilon_{e\mu}$ at a time (neglecting others),⁴ we present modified oscillation probabilities and event spectra at the NOvA FD. Further, we analyze the two-dimensional sensitivity by projecting χ^2 in $|\epsilon_{e\tau}|$ (or $|\epsilon_{e\mu}|$) versus standard CP -phase δ_{CP} plane and $|\epsilon_{e\tau}|$ (or $|\epsilon_{e\mu}|$) versus nonstandard phase $\delta_{e\tau}$ (or $\delta_{e\mu}$) plane in both the energy window $1 < E_\nu < 4$ GeV and $1 < E_\nu < 20$ GeV.

A. Formulation of oscillation probabilities in the presence of NSI

The effective Lagrangian in the case of NC-NSI described by the dimension-six four-fermion operators is in the following form:

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_C f). \quad (2)$$

³NSI due to charge current (CC) interaction of neutrinos with matter affects the production and detection of neutrinos. In this study, we exclude such impacts, because model independent bounds on the production and detection NSI are typically stronger than the propagation NSI by $\mathcal{O}(1)$.

⁴Appearance channels are significantly affected by the $\epsilon_{e\tau}$ and $\epsilon_{e\mu}$.

Here, G_F is the Fermi constant and $\epsilon_{\alpha\beta}^{fC}$ are the NSI parameters, with $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$ and $C = L, R$. The effective Hamiltonian,

$$H = \frac{1}{2E}[U\text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)U^\dagger + \text{diag}(A, 0, 0) + A\epsilon^m], \quad (3)$$

where, Δm_{jk}^2 ($j, k = 1, 2, 3$) are the mass-squared differences, U is the standard Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, A is the constant matter potential. ϵ^m represents NSI matrix (3×3) including nonstandard matter interaction with elements $\epsilon_{\alpha\beta} \equiv \sum_{f,C} \epsilon_{\alpha\beta}^{fC} \frac{N_f}{N_e}$, where N_f and N_e denote the number density of $f(=e, u, d)$ fermion and electron in the earth matter through which neutrinos propagate. The diagonal elements of ϵ^m are real and off-diagonal elements carry a phase term $\delta_{\alpha\beta}$ in the following form $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$.

After diagonalizing, the effective Hamiltonian in Eq. (3) takes the form,

$$\tilde{H} = \frac{1}{2E}\tilde{U}\text{diag}(0, \tilde{\Delta m}_{21}^2, \tilde{\Delta m}_{31}^2)\tilde{U}^\dagger, \quad (4)$$

with $\tilde{\Delta m}_{jk}^2$ and $\tilde{U}$ are the effective mass-squared differences and modified PMNS matrix, respectively. Considering these effects the modified neutrino oscillation probability can be written as

$$\begin{aligned} P_{\alpha\beta}(L) = & \delta_{\alpha\beta} - 2\sum_{j>k}\text{Re}(\tilde{U}_{\beta j}\tilde{U}_{\alpha j}^*\tilde{U}_{\alpha k}\tilde{U}_{\beta k}^*) \\ & + 2\sum_{j>k}\text{Re}(\tilde{U}_{\beta j}\tilde{U}_{\alpha j}^*\tilde{U}_{\alpha k}\tilde{U}_{\beta k}^*)\cos\left(\frac{\tilde{\Delta m}_{jk}^2}{2E}L\right) \\ & + 2\sum_{j>k}\text{Im}(\tilde{U}_{\beta j}\tilde{U}_{\alpha j}^*\tilde{U}_{\alpha k}\tilde{U}_{\beta k}^*)\sin\left(\frac{\tilde{\Delta m}_{jk}^2}{2E}L\right). \end{aligned} \quad (5)$$

The expression for $\tilde{U}$ and $\tilde{\Delta m}_{jk}^2$ have been obtained considering nonzero $\epsilon_{e\tau}$ and $\epsilon_{e\mu}$ in the Appendix of Ref. [38].

B. Oscillation probabilities and event rates in the presence of $\epsilon_{e\tau}$

In this subsection, we extensively discuss the effect of nonzero $\epsilon_{e\tau}$ (assuming all other NSI parameters to be zero) on the ν_e ($\bar{\nu}_e$)-appearance channel and event rates. The approximate ν_μ appearance probability considering series expansion in small parameters $\eta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, s_{13}, \epsilon_{e\tau}$ up to the first order as shown below,

$$\begin{aligned}
P_{\mu e} = & \frac{2}{\hat{A}-1} \left[\frac{\eta s_{12} c_{12} s_{13} s_{23} c_{23}}{\hat{A}} \left\{ 1 - \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) \right\} \right. \\
& + \eta s_{12} c_{12} s_{23} c_{23}^2 \epsilon_{e\tau} \left\{ -\frac{2-\hat{A}}{\hat{A}} \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) + \frac{2-\hat{A}}{\hat{A}} \right\} \\
& - s_{13} s_{23}^2 c_{23} \epsilon_{e\tau} \left\{ -\cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \frac{\hat{A}+1}{\hat{A}-1} \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) - \frac{\hat{A}+1}{\hat{A}-1} \right\} \\
& - s_{23}^2 c_{23}^2 \epsilon_{e\tau}^2 \left\{ -\cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \frac{\hat{A}}{\hat{A}-1} \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \hat{A} \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) - \frac{1}{\hat{A}-1} - \hat{A} \right\} \\
& \left. - \frac{\hat{A}-1}{\hat{A}^2} \eta^2 s_{12}^2 c_{12}^2 c_{23}^2 \left\{ \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - 1 \right\} - \frac{s_{13}^2 s_{23}^2}{\hat{A}-1} \left\{ \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) - 1 \right\} \right]. \quad (6)
\end{aligned}$$

Here we use the following abbreviation: $\hat{A} \equiv \frac{A}{\Delta m_{31}^2}$, $s_{ij} \equiv \sin \theta_{ij}$, and $c_{ij} \equiv \cos \theta_{ij}$. We can obtain the probabilities corresponding to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel replacing $A \rightarrow -A$, $\delta_{CP} \rightarrow -\delta_{CP}$, $\delta_{e\tau} \rightarrow -\delta_{e\tau}$. We present the numerical appearance probability $P_{\mu e}(P_{\bar{\mu} \bar{e}})$ versus neutrino energy E_ν and simulated event rates versus reconstructed energy E_ν^{reco} in Fig. 1 using Eq. (5). Upper and lower rows correspond to $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels. The plots in the left panel represent probability, while other plots illustrate the event rates. The middle and right panels correspond to events per bin in the energy ranges $1 < E_\nu < 4$ GeV and $4 < E_\nu < 20$ GeV, respectively.

In each of the probability plots (left panel), the black curve represents standard oscillation probability, whereas

the blue band refers to oscillation probability embodying the effect of $|\epsilon_{e\tau}| = 0.4$ with the variable nonstandard phase $\delta_{e\tau} = [0:2\pi]$. The red dotted, magenta dashed and green dot-dashed curves include $|\epsilon_{e\tau}| = 0.4$ with different phases $\delta_{e\tau} = 0$, $\delta_{e\tau} = \pi/2$ and $\delta_{e\tau} = 3\pi/2$, respectively. For $|\epsilon_{e\tau}| = 0.4$ and $\delta_{e\tau} = 0, 3\pi/2$, $P_{\mu e}$ is higher than the standard oscillation probability as can be seen from red dotted and green dot-dashed lines, respectively. On the other hand, $|\epsilon_{e\tau}| = 0.4$, $\delta_{e\tau} = \pi/2$ (magenta) shows lower probability with respect to standard oscillation. In the case of $P_{\bar{\mu} \bar{e}}$ the calculated probability is higher than the standard probability for $\delta_{e\tau} = 0, 3\pi/2$ and lower than std. osc. for $\delta_{e\tau} = \pi/2$ as can be seen from the red, green, and magenta curves, respectively. The standard oscillation curve is degenerate with NSI probability for a combination of

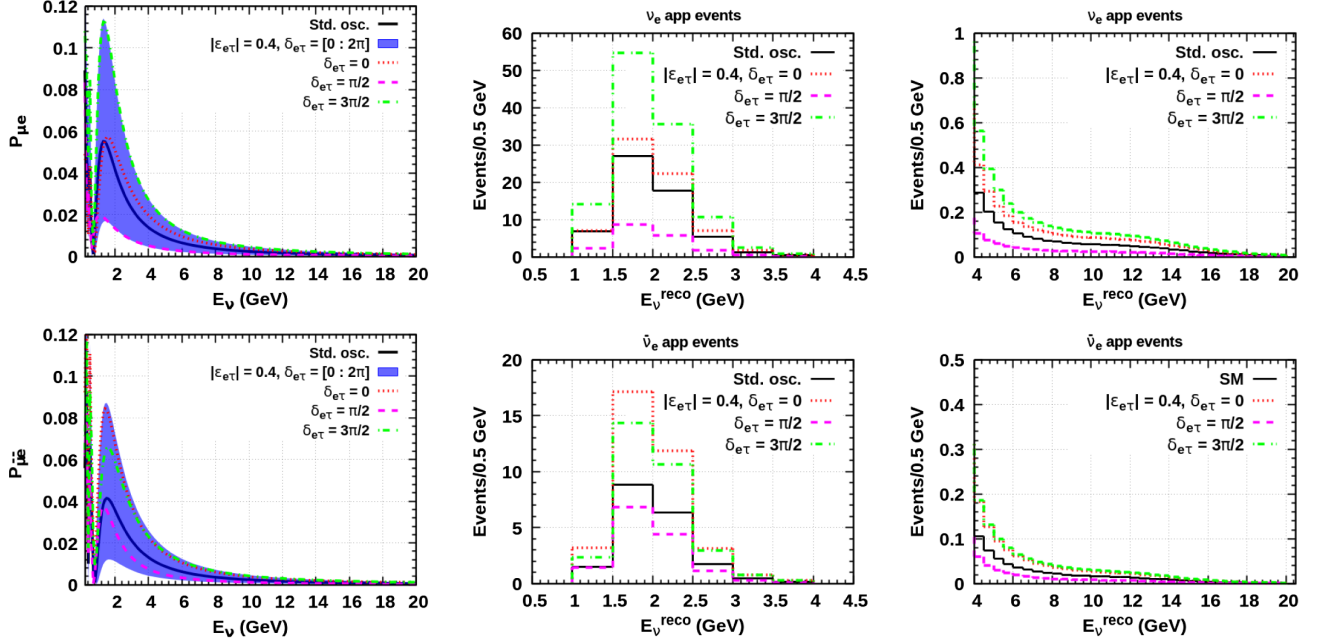


FIG. 1. Appearance probability versus neutrino energy and event rates versus reconstructed energy for ν_e ($\bar{\nu}_e$) in the upper (lower) row. We consider $|\epsilon_{e\tau}| = 0.4$ and corresponding phases to show modified probability and event rates in the presence of nonstandard interaction.

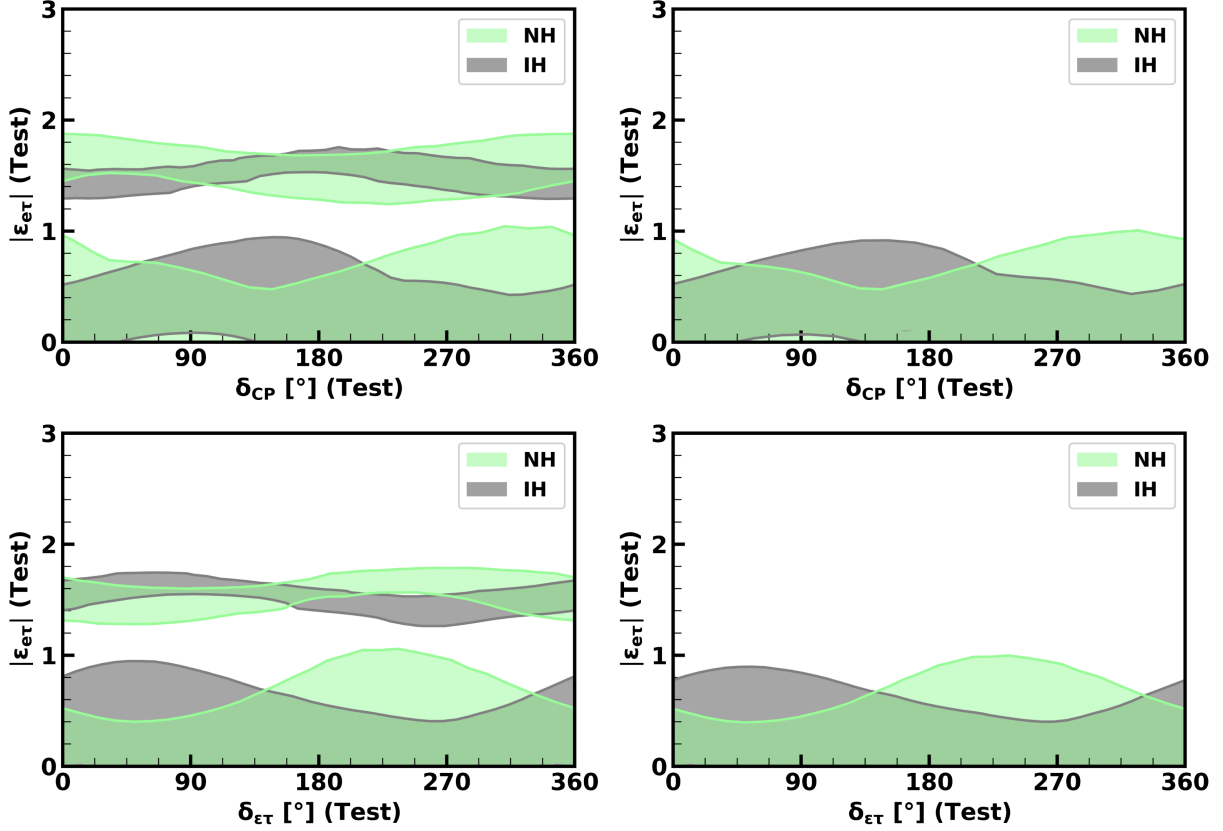


FIG. 2. $\epsilon_{e\tau}$ (test) vs δ_{CP} (test) in the upper row and $\epsilon_{e\tau}$ (test) vs $\delta_{e\tau}$ (test) in the lower row. In the left panel 1–4 GeV and in the right panel 1–20 GeV. Marginalized over θ_{13} , θ_{23} , Δm_{31}^2 , $\delta_{e\tau}$ (δ_{CP}) in upper row (lower row).

$|\epsilon_{e\tau}|$ and $\delta_{e\tau}$ throughout the energy range. We notice the overlap between the blue band and solid black curve that indicates degeneracy between NSI ($|\epsilon_{e\tau}|, \delta_{e\tau}$) and SM case.

In the middle and right panels we depict events spectra corresponding to ν_e (top row) and $\bar{\nu}_e$ (bottom row) appearance channels. We show event rates related to energy ranges $1 < E_\nu < 4$ GeV (middle) and $4 < E_\nu < 20$ GeV (right). The legends are mentioned in the respective plots.

C. Allowed regions in $\epsilon_{e\tau}$ and $\delta_{CP(e\tau)}$ parameter space

In Fig. 2 we show the allowed contours with 95% (1.96σ) CL in the $|\epsilon_{e\tau}| - \delta_{CP}$ plane (top row) and $|\epsilon_{e\tau}| - \delta_{e\tau}$ plane (bottom row). Plots shown in the left and right panels considering energy analysis energy window $1 < E_\nu < 4$ GeV and $1 < E_\nu < 20$ GeV, respectively. We perform the analysis using standard model scenario in the simulated data and only nonzero $\epsilon_{e\tau}$ in the theory. We compute $\Delta\chi^2$ as per the definition,

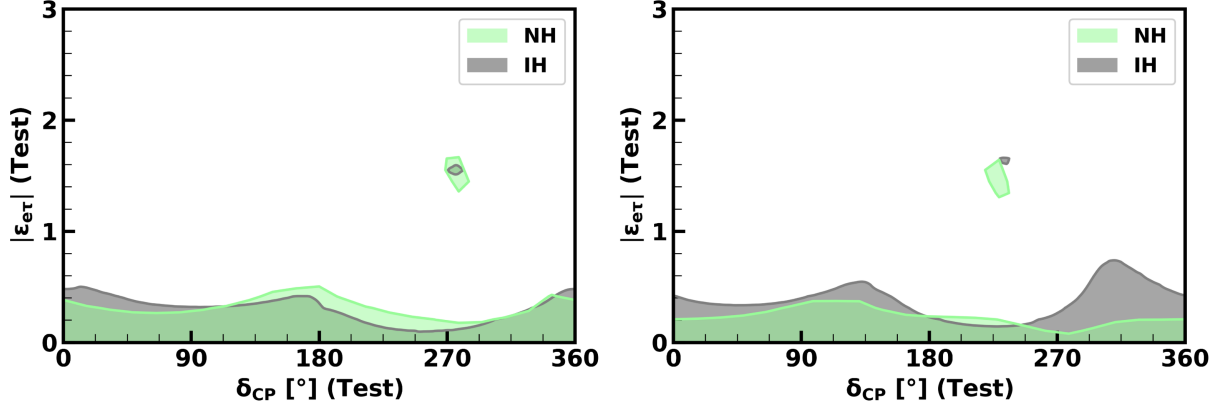
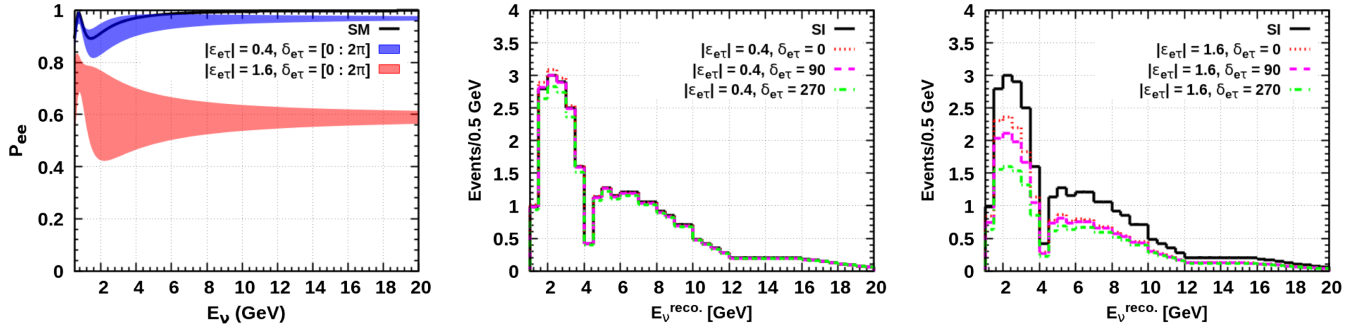
$$\Delta\chi^2 = \chi^2(\epsilon_{e\tau}[\text{true}] = 0, \epsilon_{e\tau}[\text{test}] \neq 0), \quad (7)$$

with true δ_{CP} fixed at 0.82π and marginalize over $\theta_{13}, \theta_{23}, \Delta m_{31}^2$ and $\delta_{e\tau}$. Similarly, we calculate $\Delta\chi^2$ corresponding to $\epsilon_{e\tau}[\text{test}]$ versus $\delta_{e\tau}[\text{test}]$ contour using Eq. (7). Here, we marginalize over $\theta_{13}, \theta_{23}, \Delta m_{31}^2$, and δ_{CP} . We vary

standard and nonstandard CP phase in the full range $0-360^\circ$ and show regions with 95% CL for both the normal hierarchy (NH, green regions) and inverted hierarchy (IH, gray region). The unmentioned oscillation parameters are kept fixed to their true values.

In the top-left plot of Fig. 2 we can see from the green bands (NH) that for each value of δ_{CP} , two bands span the allowed range in $\epsilon_{e\tau}$ parameter space indicating a degeneracy of the form $(\epsilon, \delta) = (\epsilon', \delta')$. Similar behavior is observed for the inverted hierarchy case and can be seen from the gray curve. These results agree with the results in Ref. [19]. After including high-energy simulated events, plots shown in the right panel, we see the degeneracy in the $|\epsilon_{e\tau}|$ is removed for whole range of standard CP -phase δ_{CP} and corresponding nonstandard phase $\delta_{e\tau}$. These observations are true for both the normal and inverted mass hierarchies. We investigate this further in the following.

Firstly to understand the degeneracy in the left panels of Fig. 2, we plot δ_{CP} vs $\epsilon_{e\tau}$ for fixed $\delta_{e\tau}$, $\delta_{e\tau} = 0$ in the left panel and $\delta_{e\tau} = 45^\circ$ in the right panel of Fig. 3. From the left plot, we can see that there is a small degenerate region around $\epsilon_{e\tau} \sim 1.6$ corresponding to the $\delta_{CP} \sim 270^\circ$ for both NH and IH bands. Similarly, in the right plot there is a degenerate region for $\epsilon_{e\tau} \sim 1.6$ around $\delta_{CP} \sim 225^\circ$ i.e., for $\delta_{CP} \sim (270 - 45)$. This can be generalized to the form

FIG. 3. $\epsilon_{e\tau}$ vs δ_{CP} for fixed $\delta_{e\tau} = 0$ in left and $\delta_{e\tau} = 45^\circ$ in right.FIG. 4. P_{ee} vs energy (left) and beam background events per bin with reconstructed energy (middle and right). In the middle $|\epsilon_{e\tau}| = 0.4$ and in the right $|\epsilon_{e\tau}| = 1.6$. We show the plots for different $\delta_{e\tau} = 0, 90^\circ, 270^\circ$ in both the figures.

$\delta_{CP} = 270 - \delta_{e\tau}$ or $3\pi/2$. This can be attributed to a degeneracy in the ν_e and $\bar{\nu}_e$ spectrum between SM and NSI ($\epsilon_{e\tau} \sim 1.6, \delta_{CP} = 270 - \delta_{e\tau}$). This agrees with the conclusions drawn in NOvA Collaboration paper [18].

Further, we investigate the results obtained in the right panel of Fig. 2, where the degenerate bands around $\epsilon_{e\tau} \sim 1.6$ disappear. Here we are adding the high-energy simulated events from $4 < E_\nu < 20$ GeV. Note that this high-energy tail has both signal and background events⁵ contributing to the χ^2 as can be seen from Fig. 1 (signal events) and Fig. 4 (beam background events). Clearly, in comparison, the beam background is dominant compared to the signal events in this energy window. This can be verified from the (4–20) GeV events given in the Table II. To investigate the role of background in removing the degeneracy, we further look into the relevant oscillation channel P_{ee} . Therefore, we illustrate the probability vs E_ν (left panel) and events vs E_ν (assuming $\epsilon_{e\tau} = 0.4$ and $\epsilon_{e\tau} = 1.6$ in the middle and right panels) for the beam background channel $P(\nu_e \rightarrow \nu_e)$ in Fig. 4. In all three plots, the relevant NSI parameters are as listed in the legends. In the left plot,

the blue band (corresponding to $|\epsilon| = 0.4$ and $\delta_{e\tau} \in [0:2\pi]$) has a significant overlap with the SM curve (black curve) and, on the contrary, the red band (corresponding to $|\epsilon| = 1.6$ and $\delta_{e\tau} \in [0:2\pi]$) is well separated from the SM curve, indicating that the degeneracy between SM and NSI ($\epsilon_{e\tau} \sim 1.6, \delta_{CP} = 270 - \delta_{e\tau}$) can be broken when these events are considered in the analysis.⁶ In the middle plot, the curves indicating different values of $\delta_{e\tau}$, $\epsilon_{e\tau} = 0.4$ are close to the SM curve (black) showing very less sensitivity to distinguish between SM and NSI. However, in the right panel the reasonable gap between the SM and NSI curves leads to the elimination of degeneracy in Fig. 2 (right panels).

Furthermore, the χ^2 analysis in Fig. 11 of the appendix B validates the role of beam background from high-energy tail in removing the degeneracy $\epsilon_{e\tau} \sim 1.6$. We show 95% CL region in the $|\epsilon_{e\tau}|$ vs δ_{CP} ($\delta_{e\tau}$) plane in the left (right) plot considering only background (no signal) in the $4 < E_\nu < 20$ GeV energy window. We observe a narrow degeneracy band around $|\epsilon_{e\tau}| \sim 1.6$ in the left plot for the $\delta_{CP} \in [190^\circ:270^\circ]$ in the case of NH. Other than that the

⁵In Appendix A we present the signal plus background event spectra for ν_e and $\bar{\nu}_e$ appearance channels.

⁶We verified that in the case of signal probability $P_{\mu e}$ both the blue and red bands overlap with the SM curve $4 < E_\nu < 20$ GeV.

TABLE II. Signal and background events at HE considering $\epsilon_{e\tau} \neq 0$.

Signal events							
		$\nu_\mu \rightarrow \nu_e$			$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$		
Hypothesis		1–4 GeV	1–20 GeV	4–20 GeV	1–4 GeV	1–20 GeV	4–20 GeV
$ \epsilon_{e\tau} = 0.4$	SM	59.0	61.0	2.0	19.0	19.6	0.6
	$\delta_{e\tau} = 0$	70.0	73	3.0	36.3	37.4	1.1
	$\delta_{e\tau} = \pi/2$	19.0	20.0	1.0	14.1	14.4	0.3
	$\delta_{e\tau} = 3\pi/2$	118.3	122.3	4.0	31.3	32.4	1.1
	Beam background ($\nu_e + \bar{\nu}_e$)						
$ \epsilon_{e\tau} = 0.4$	SM	13.7	29.6	15.9	7.6	16.4	8.8
	$\delta_{e\tau} = 0$	14.1	29.7	15.6	7.8	16.5	8.7
	$\delta_{e\tau} = \pi/2$	13.7	29.3	15.6	7.6	16.2	8.6
	$\delta_{e\tau} = 3\pi/2$	13.0	28.2	15.2	7.2	15.6	8.4
	$ \epsilon_{e\tau} = 1.6$	$\delta_{e\tau} = 0$	10.6	20.9	10.3	5.9	11.6
$\delta_{e\tau} = \pi/2$		9.5	19.4	9.9	5.3	10.7	5.4
$\delta_{e\tau} = 3\pi/2$		7.5	16.3	8.8	4.1	9.0	4.9

degeneracy around $|\epsilon_{e\tau}| \sim 1.6$ is eliminated in both the left and right plots throughout the δ_{CP} and $\delta_{e\tau}$ range in case of both NH and IH. This observation infers that the background events from high-energy tail contribute to eliminate the degeneracy, except the narrow band in the left plot for the $\delta_{CP} \in [190^\circ:270^\circ]$ in the case of NH.

D. Oscillation probabilities and event rates in the presence of $\epsilon_{e\mu}$

In this subsection, we illustrate the appearance probabilities and event rates with respect to neutrino energy assuming nonzero $\epsilon_{e\mu}$. The approximate probability corresponding to $\nu_\mu \rightarrow \nu_e$ channel considering nonzero $\epsilon_{e\mu}$ is

$$\begin{aligned}
P_{\mu e} = & 2 \left[\frac{1}{\hat{A} - 1} \left\{ \frac{\eta s_{12} c_{12} s_{13} s_{23} c_{23}}{\hat{A}} + \eta s_{12} c_{12} s_{23}^2 c_{23} \epsilon_{e\mu} + s_{13} s_{23} c_{23}^2 \epsilon_{e\mu} + \hat{A} s_{23}^2 c_{23}^2 \epsilon_{e\mu}^2 \right\} \right. \\
& \times \left\{ -\cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) + 1 \right\} \\
& - \frac{1}{\hat{A}^2} \{ \eta^2 s_{12}^2 c_{12}^2 c_{23}^2 + 2\eta \hat{A} s_{12} c_{12} c_{23}^3 \epsilon_{e\mu} + \hat{A}^2 c_{23}^4 \epsilon_{e\mu}^2 \} \left\{ \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - 1 \right\} \\
& \left. - \frac{1}{(\hat{A} - 1)^2} \{ s_{13}^2 s_{23}^2 + 2\hat{A} s_{13} s_{23}^3 \epsilon_{e\mu} + \hat{A}^2 s_{23}^4 \epsilon_{e\mu}^2 \} \left\{ \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) - 1 \right\} \right]. \quad (8)
\end{aligned}$$

In the left panel of Fig. 5 we show ν_e (upper) and $\bar{\nu}_e$ (lower) numerical appearance probabilities using Eq. (5). In each of the probability plots we draw five curves; the black curve represents standard oscillation probability, the blue band depicts the resultant probability for $|\epsilon_{e\mu}| = 0.3$ and $\delta_{e\mu} \in [0:2\pi]$, the red dotted, magenta dashed and green dot-dashed curves stand for nonstandard phases $\delta_{e\mu} = 0$, $\delta_{e\mu} = \pi/2$, and $\delta_{e\mu} = 3\pi/2$, respectively. In all the plots we assume NH as the true mass hierarchy.

From the left panel of Fig. 5 the blue band corresponding to nonzero $|\epsilon_{e\mu}| = 0.3$ and $\delta_{e\mu} \in [0:2\pi]$ spans a wide range of probability values both greater and lesser than the standard oscillation probability (black curve). Whereas

for $E_\nu > 7$ GeV, we do not observe degeneracy for the chosen parameters; rather, we see the increase in probabilities with respect to standard oscillation. Additionally, we show the curves corresponding to CP conserving ($\delta_{e\mu} = 0$) and maximal CP violation ($\delta_{e\mu} = \pi/2, 3\pi/2$) using red, magenta and blue lines, respectively.

In the middle and right panels we depict event rates as a function of reconstructed energy ranging from $1 < E_\nu < 4$ GeV and $4 < E_\nu < 20$ GeV, respectively. The top and bottom panels correspond to ν_e and $\bar{\nu}_e$ appearance channels respectively. The relevant legends are listed within each plot. The ν_e and $\bar{\nu}_e$ appearance channels in the middle panel depict the event rates considered by the NOvA Collaboration

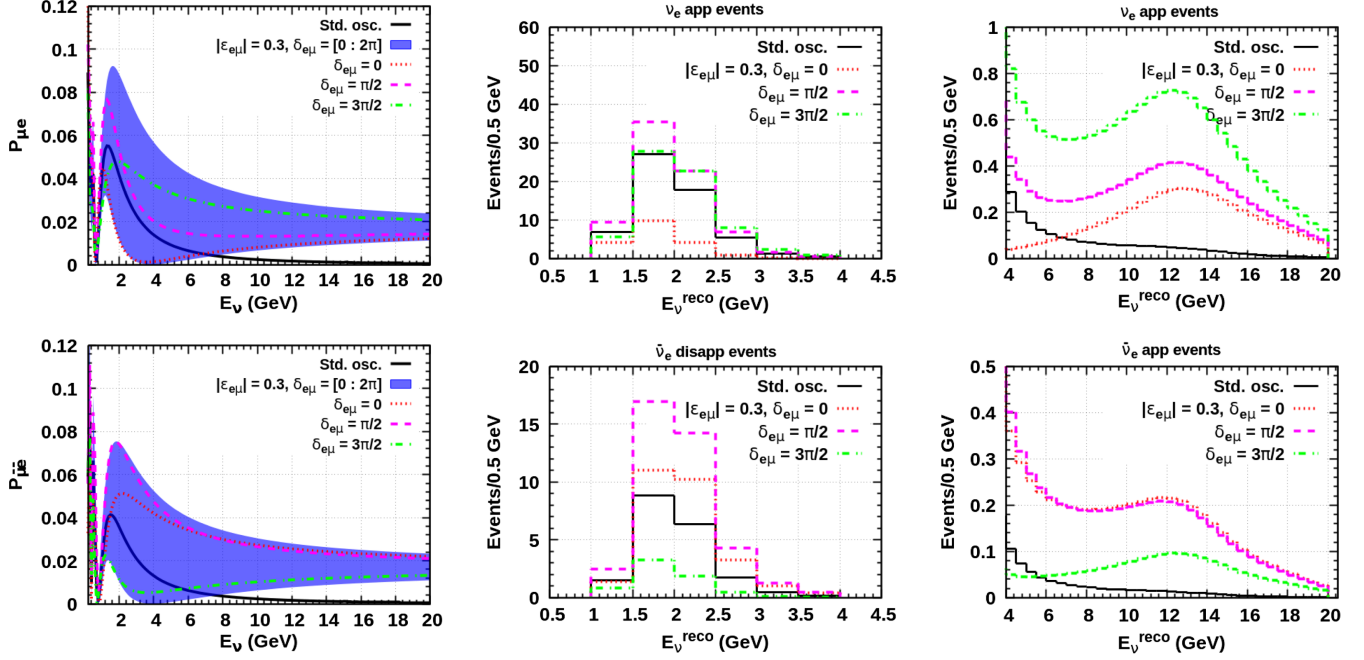


FIG. 5. Appearance probability versus neutrino energy and event rates versus reconstructed energy for ν_e ($\bar{\nu}_e$) in the upper (lower) row. We consider $|\epsilon_{e\mu}| = 0.3$ and corresponding phases to show modified probability and event rates in the presence of nonstandard interaction.

in Ref. [18]. In the rightmost panel we show signal events corresponding to E_ν : 4–20 GeV both for SM and assuming nonzero $\epsilon_{e\mu}$. The trends followed by events spectra in these panels are easily understandable from the corresponding probability plots of the leftmost panels.

E. Allowed regions in $\epsilon_{e\mu}$ and $\delta_{CP(e\mu)}$ parameter space

In Fig. 6 we show two-dimensional sensitivity analysis by projecting χ^2 in $|\epsilon_{e\mu}|(\text{test}) - \delta_{CP}(\text{test})$ plane (upper row) and $|\epsilon_{e\mu}|(\text{test}) - \delta_{e\mu}(\text{test})$ plane (lower row). We plot the contours in the left and right panels considering simulated NOvA events for standard framework ($1 < E_\nu < 4$ GeV) and including high energy ($1 < E_\nu < 20$ GeV), respectively. We calculate $\Delta\chi^2$ hypothesizing standard oscillation in the simulated data in the true spectrum and NSI in the theory and plot 95% CL contour in the $\epsilon_{e\mu}[\text{test}]$ versus $\delta_{CP}[\text{test}]$ plane. We define the $\Delta\chi^2$ as

$$\Delta\chi^2 = \chi^2(\epsilon_{e\mu}[\text{true}] = 0, \epsilon_{e\mu}[\text{test}] \neq 0), \quad (9)$$

for the fix true δ_{CP} at 0.82π and marginalize over $\theta_{13}, \theta_{23}, \Delta m_{31}^2$, and $\delta_{e\mu}$. Similarly, we calculate $\Delta\chi^2$ using Eq. (9) corresponding to $\epsilon_{e\mu}[\text{test}]$ versus $\delta_{e\mu}[\text{test}]$ contour, where we marginalize over $\theta_{13}, \theta_{23}, \Delta m_{31}^2$, and δ_{CP} . We vary δ_{CP} and $\delta_{e\mu}$ in their full range $0 - 2\pi$ and show contours with 95% CL for both the normal hierarchy (NH, green regions) and inverted hierarchy (IH, gray region). The unmentioned oscillation parameters are kept fixed to

their true values. Note that NOvA disfavors the region above the gray line for NH and green line for IH.

From the top-left plot, considering NH, we observe the allowed region (with 95% CL) favors relatively lower $|\epsilon_{e\mu}|$ in the $\delta_{CP} \sim [90^\circ : 220^\circ]$, whereas the contour favors higher $\epsilon_{e\mu}$ elsewhere. For IH, the contour encompasses relatively higher $|\epsilon_{e\mu}|$ in the $\delta_{CP} \sim [90^\circ : 270^\circ]$, while it adopts lower $\epsilon_{e\mu}$ elsewhere. In the bottom-left plot, considering NH (IH), the 95% CL contour favors relatively lower (higher) $|\epsilon_{e\mu}|$ in the $\delta_{e\mu} \sim [220^\circ : 340^\circ]$ ($[180^\circ : 360^\circ]$). The range of $\epsilon_{e\mu}$ corresponding to allowed contours are identical in both the upper and lower plots as well as for NH and IH. This implies that the sensitivity to $\epsilon_{e\mu}$ remains almost unchanged with respect to δ_{CP} or $\delta_{e\mu}$ and irrespective of mass hierarchy. A noteworthy fact is that the contours favor relatively lower $\epsilon_{e\mu}$ in the presence of high-energy events for both the plots in the right panel. This indicates, including high-energy events provides better constraints on $\epsilon_{e\mu}$.

IV. STUDY OF ENVIRONMENTAL DECOHERENCE INCLUDING HIGH-ENERGY EVENTS

Neutrino oscillation data from the experiments rely on the three flavor mixing where the propagation of neutrinos is interpreted as the coherent superposition of mass eigenstates. In this quantum evolution the degree of coherence remains unaffected over the macroscopic distances because of the weak coupling of neutrinos with

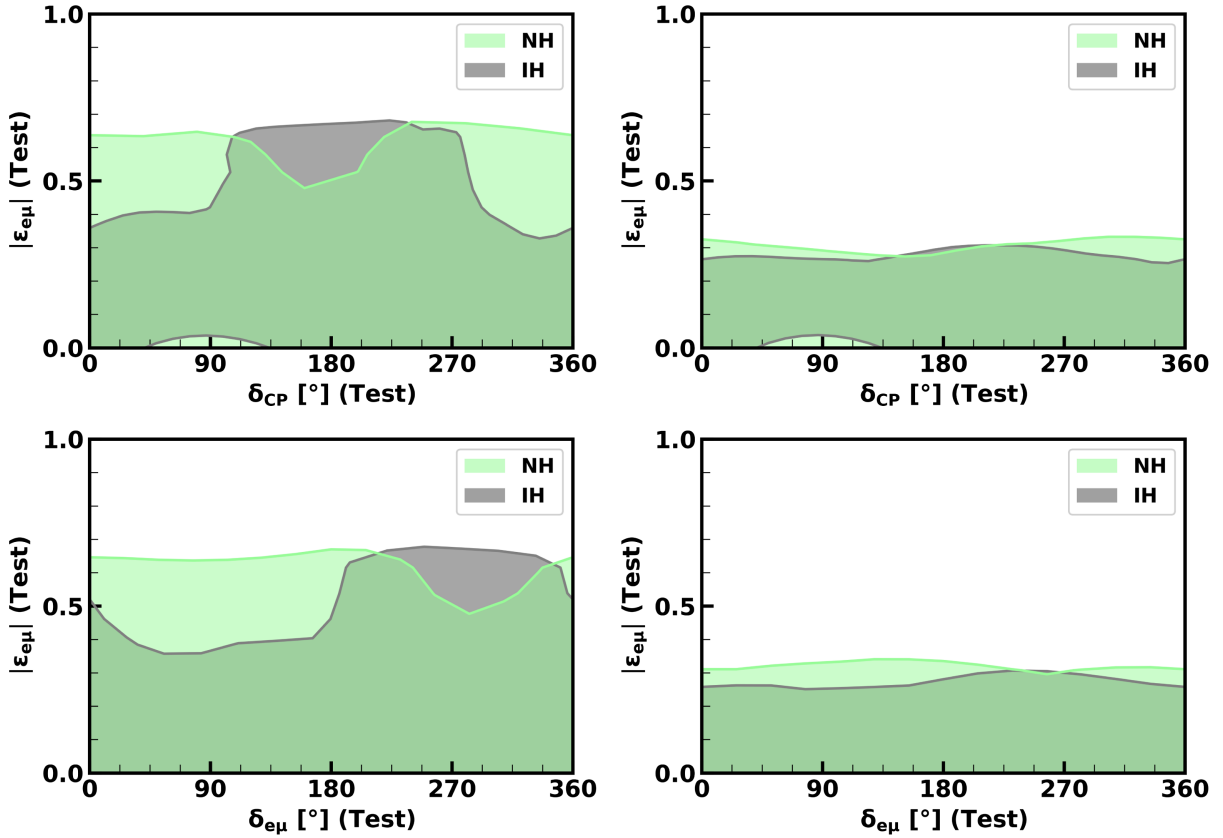


FIG. 6. $\epsilon_{e\mu}$ (test) vs δ_{CP} (test) in the upper row and $\epsilon_{e\mu}$ (test) vs $\delta_{e\mu}$ in the lower row. In the left panel 1–5 GeV and in the right panel 1–20 GeV. Marginalized over θ_{13} , θ_{23} , Δm_{31}^2 , $\delta_{e\mu}$ (δ_{CP}) in upper row (lower row).

matter. Such phenomenon manifests the isolation of neutrino systems from their surroundings while propagation. Nevertheless, neutrinos could interact with the stochastic environment [39], for instance fluctuating space-time at the Planck scale, matter density fluctuation, virtual black hole. This incorporates the loss of coherence in propagating neutrinos states and introduces a nonstandard effect which is known as environmental decoherence. In this phenomenology we assume neutrino (sub)system is an open quantum system and interacts with the environment. In the presence of environmental interaction the neutrino oscillation probability gets modified and carries damping term $e^{-\Gamma L}$, where Γ is the decoherence parameter. Γ could depend on the different power of the neutrino energy as $\Gamma \propto E^n$, here choice of n is based on the various physical origins of decoherence phenomenon.

A. Mathematical formulation of oscillation probabilities

Neutrino propagation in an open quantum system framework introduces loss of coherence due to interaction of neutrino subsystem with the stochastic environment. This loss is incorporated using Lindblad master equation which represents the density matrix evolution as given below [40,41],

$$\frac{d\rho}{dt} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)], \quad (10)$$

where ρ is the density matrix of neutrino states and H is the Hamiltonian of the neutrino subsystem. The damping term $\mathcal{D}[\rho(t)]$ represents the interaction of the neutrino subsystem system and the environment.

In case of neutrino propagation in constant matter density we represent the above equation in the effective mass basis as

$$\frac{d\tilde{\rho}}{dt} = -i[\tilde{H}, \tilde{\rho}(t)] + \tilde{\mathcal{D}}[\tilde{\rho}(t)], \quad (11)$$

here the parameters with tilde represent the effect of constant matter potential. The diagonalized effective Hamiltonian in the mass basis,

$$\tilde{H} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta \tilde{m}_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta \tilde{m}_{31}^2}{2E} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \tilde{\Delta}_{21} & 0 \\ 0 & 0 & \tilde{\Delta}_{31} \end{pmatrix}. \quad (12)$$

Expanding the first term of Eq. (11),

$$[\tilde{H}\tilde{\rho}(t)] = (\tilde{H}\tilde{\rho}(t) - \tilde{\rho}(t)\tilde{H})$$

$$= \begin{pmatrix} 0 & -\tilde{\rho}_{12}(t)\tilde{\Delta}_{21} & -\tilde{\rho}_{13}(t)\tilde{\Delta}_{31} \\ \tilde{\rho}_{21}(t)\tilde{\Delta}_{21} & 0 & -\tilde{\rho}_{23}(t)\tilde{\Delta}_{32} \\ \tilde{\rho}_{31}(t)\tilde{\Delta}_{31} & \tilde{\rho}_{32}(t)\tilde{\Delta}_{32} & 0 \end{pmatrix}. \quad (13)$$

Now, the parametrization of $\tilde{\mathcal{D}}[\tilde{\rho}(t)]$ is obtained by using complete positivity and trace preserving conditions. Applying complete positivity modifies the Lindblad form of the dissipator as [42]

$$\tilde{\mathcal{D}}[\tilde{\rho}(t)] = \frac{1}{2} \sum_{n=1}^{N^2-1} \{[\tilde{\mathcal{V}}_n, \tilde{\rho}\tilde{\mathcal{V}}_n^\dagger] + [\tilde{\mathcal{V}}_n\tilde{\rho}, \tilde{\mathcal{V}}_n^\dagger]\}, \quad (14)$$

where N is the dimension of the Hilbert space and $\tilde{\mathcal{V}}_n$ are the interaction operators. In three-flavor neutrino framework $N = 3$ and we express all the operators as a linear combination of $SU(3)$ generators, the Gell-Mann matrices. Further, we impose an increase in von Neumann entropy $S = -\text{Tr}(\tilde{\rho} \ln \tilde{\rho})$ [43,44] and this is enforced by requiring the $\tilde{\mathcal{V}}_n$ to be hermitian, i.e., $\tilde{\mathcal{V}}_n = \tilde{\mathcal{V}}_n^\dagger$. Additionally,

we assume conservation of average energy $\text{Tr}(\tilde{\rho}\tilde{H})$ of the neutrino subsystem system assured by requiring the $[\tilde{\mathcal{V}}_n, \tilde{H}] = 0$, which gives

$$\tilde{\mathcal{V}}_n = \text{diag}(\tilde{d}_{n,1}, \tilde{d}_{n,2}, \tilde{d}_{n,3}). \quad (15)$$

Additionally, we assume that the $d_{n,j}$ s are constant as neutrinos propagate through earth matter; for instance, like in the case where decoherence arises from quantum gravity. However, from a model independent perspective the parameters $d_{n,j}$ could in principle depend on the matter effect [45], but most studies assume they are independent [21,46,47]. In order to facilitate an easy comparison with the bounds from previous works in the literature we also consider $\tilde{d}_{n,1} \equiv d_{n,j}$. This implies, $\tilde{\mathcal{V}}_n \equiv \mathcal{V}_n$, $\tilde{\mathcal{D}}[\tilde{\rho}] = \mathcal{D}[\tilde{\rho}]$. Therefore,

$$\mathcal{D}[\tilde{\rho}(t)] = \begin{pmatrix} 0 & -\Gamma_{21}\tilde{\rho}_{12}(t) & -\Gamma_{31}\tilde{\rho}_{13}(t) \\ -\Gamma_{21}\tilde{\rho}_{21}(t) & 0 & -\Gamma_{32}\tilde{\rho}_{23}(t) \\ -\Gamma_{31}\tilde{\rho}_{31}(t) & -\Gamma_{32}\tilde{\rho}_{32}(t) & 0 \end{pmatrix}, \quad (16)$$

where, $\Gamma_{jk} = \Gamma_{kj} = \frac{1}{2} \sum_{n=1}^8 (d_{n,j} - d_{n,k})^2$.

Substituting Eqs. (13) and (16) in Eq. (11) we obtain

$$\tilde{\rho}(t) = \begin{pmatrix} \tilde{\rho}_{11}(0) & \tilde{\rho}_{12}(0) \exp -(\Gamma_{21} + i\tilde{\Delta}_{21})^* t & \tilde{\rho}_{13}(0) \exp -(\Gamma_{31} + i\tilde{\Delta}_{31})^* t \\ \tilde{\rho}_{21}(0) \exp -(\Gamma_{21} + i\tilde{\Delta}_{21}) t & \tilde{\rho}_{22}(0) & \tilde{\rho}_{23}(0) \exp -(\Gamma_{32} + i\tilde{\Delta}_{32})^* t \\ \tilde{\rho}_{31}(0) \exp -(\Gamma_{31} + i\tilde{\Delta}_{31}) t & \tilde{\rho}_{32}(0) \exp -(\Gamma_{32} + i\tilde{\Delta}_{32}) t & \tilde{\rho}_{33}(0) \end{pmatrix}. \quad (17)$$

We consider the modified-mixing matrix ($\tilde{U}$) from Ref. [48] to convert mass basis to flavor basis using $\tilde{\rho}^\alpha = \tilde{U}\tilde{\rho}\tilde{U}^\dagger$.⁷ The neutrino transition probability from initial flavor ' ν_α ' to final flavor ' ν_β ' in terms of density matrix is obtained by

$$P_{\alpha\beta}(t) = \text{Tr}[\tilde{\rho}_\alpha(t)\tilde{\rho}_\beta(0)]. \quad (18)$$

The explicit form of the transition probability assuming ultra-relativistic neutrinos ($t \approx L$) is given by [47,49]

$$P_{\alpha\beta}(L) = \delta_{\alpha\beta} - 2 \sum_{j>k} \text{Re}(\tilde{U}_{\beta j} \tilde{U}_{\alpha j}^* \tilde{U}_{\alpha k} \tilde{U}_{\beta k}^*) + 2 \sum_{j>k} \text{Re}(\tilde{U}_{\beta j} \tilde{U}_{\alpha j}^* \tilde{U}_{\alpha k} \tilde{U}_{\beta k}^*) \exp(-\Gamma_{jk}L) \cos\left(\frac{\tilde{\Delta}m_{jk}^2}{2E}L\right)$$

$$+ 2 \sum_{j>k} \text{Im}(\tilde{U}_{\beta j} \tilde{U}_{\alpha j}^* \tilde{U}_{\alpha k} \tilde{U}_{\beta k}^*) \exp(-\Gamma_{jk}L) \sin\left(\frac{\tilde{\Delta}m_{jk}^2}{2E}L\right). \quad (19)$$

Here in Eq. (19), the term $e^{-\Gamma_{jk}L}$ damps the oscillation probability. We analyze the effect of decoherence by considering all the Γ_{jk} as equal (i.e., $\Gamma_{21} = \Gamma_{31} = \Gamma_{32}$) and represent it by a single parameter Γ for simplicity. Further we assume a

⁷In our formalism we consider $\rho, H, \mathcal{D}$ in mass basis. Since we assumed the energy conservation constraint $[\tilde{\mathcal{V}}_n, \tilde{H}] = 0$, this implies $\tilde{\mathcal{V}}_n \propto \tilde{H}$. So, when we rotate $\tilde{H}$, we should also rotate $\tilde{\mathcal{V}}_n$ as $\tilde{\mathcal{V}}_n^{\text{flavor}} = \tilde{U}\tilde{\mathcal{V}}_n\tilde{U}^\dagger$. This has already been taken care in derivation where we obtain $\tilde{\rho}^\alpha = \tilde{U}\tilde{\rho}\tilde{U}^\dagger$, since $\tilde{\rho}(t)$ depends on decoherence parameters. To be explicit, in our calculation $\tilde{\mathcal{V}}_n$ is not invariant under $\tilde{U}$ rotation.

general power law dependency of Γ parameter on the neutrino energy given by

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n, \quad (20)$$

where Γ_0 is constant, E_0 is the reference energy taken as 1 GeV and $n = 0, \pm 1, \pm 2$. Different physical origins explain the decoherence phenomena leading to different integral power law dependencies [21]. However, from Eq. (20) one can note that the oscillation probabilities are sensitive to $n > 0$ when $E_\nu > E_0$. In case of NOvA

experiment $E_\nu \sim 1.8$ GeV is greater than the reference energy (1 GeV), so environmental decoherence plays significant role when $n > 0$ and which could yield stronger constraints on Γ .

It is noteworthy to mention that, the neutrino oscillation probabilities are sensitive to positive powers of n (leftmost panel of Fig. 7). This happens because the energy of the neutrino beam E_ν is greater than the reference energy $E_0 = 1$ GeV ($E_\nu \geq E_0$) in Eq. (20).

The analytical appearance and disappearance probabilities considering perturbative expansion up to the first order in small parameters s_{13} and η are shown below,

$$\begin{aligned} P_{\mu e} = & \frac{2}{\hat{A} - 1} \left[\frac{\eta s_{12} c_{12} s_{13} s_{23} c_{23}}{\hat{A}} \left\{ -e^{-\Gamma_{21}L} \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - e^{-\Gamma_{31}L} \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right. \right. \\ & + \left. \left. e^{-\Gamma_{32}L} \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) + 1 \right\} - \frac{\hat{A} - 1}{\hat{A}^2} \eta^2 s_{12}^2 c_{12}^2 c_{23}^2 \left\{ e^{-\Gamma_{21}L} \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) - 1 \right\} \right. \\ & \left. \left. - \frac{s_{13}^2 s_{23}^2}{\hat{A} - 1} \left\{ e^{-\Gamma_{31}L} \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) - 1 \right\} \right] \end{aligned} \quad (21)$$

and

$$\begin{aligned} P_{\mu\mu} = & 1 + 2 \left[\frac{c_{23}^2}{\hat{A}^2} \eta^2 s_{12}^2 c_{12}^2 + \frac{2c_{23}s_{23}}{\hat{A}(\hat{A} - 1)} \eta s_{12} c_{12} s_{13} + c_{23}^2 s_{23}^2 \left\{ e^{-\Gamma_{32}L} \cos\left(\frac{\Delta m_{32}^2 L}{2E}\right) - 1 \right\} \right. \\ & \left. + \frac{s_{23}^2}{(\hat{A} - 1)^2} s_{13}^2 \left\{ c_{23}^2 e^{-\Gamma_{21}L} \cos\left(\frac{\Delta m_{21}^2 L}{2E}\right) + s_{23}^2 e^{-\Gamma_{31}L} \cos\left(\frac{\Delta m_{31}^2 L}{2E}\right) - 1 \right\} \right]. \end{aligned} \quad (22)$$

B. Oscillation probabilities and event rates

We show the oscillation probability in the presence of decoherence effect using [Eq. (19)] to demonstrate the deviation as compared to standard three flavor scenarios. In the top row of Fig. 7 we depict ν_e -appearance probability and corresponding event rates, and in the bottom row ν_μ -disappearance probability and corresponding event rates. In the left panel we show probabilities as a function of energy. In the middle and right panels we illustrate event rates as a function of reconstructed energy correspond to $1 < E_\nu < 4$ GeV and $4 < E_\nu < 20$ GeV, respectively. We compute the probabilities and event rates numerically considering standard parameters from Table I and assuming decoherence parameter $\Gamma = 10^{-23}$ GeV along with the energy power-law dependencies. In each plot we display the curves corresponding to the standard oscillation and decoherence with power-law indices $n = 0, \pm 1, \pm 2$ as per their respective legends shown in the plots. We tabulate the event rates for all the mentioned cases in Table III.

From the left plots we observe a marginal impact of decoherence on the oscillation probabilities in the energy range $1 < E_\nu < 4$ GeV. Adopting power-law

indices $n = -2, -1$ (red, cyan curves) we notice negligible effect of Γ on the appearance and disappearance channels in the energy window $4 < E_\nu < 20$ GeV. For $n = 0$ (blue) we see the effect of decoherence is less prominent, whereas $n = 1, 2$ lead to a noticeable impact on both the appearance and disappearance probabilities. Additionally ~ 11 GeV we see an increase in $\nu_\mu \rightarrow \nu_e$ probability (top left) and decrease in $\nu_\mu \rightarrow \nu_\mu$ (bottom left) as compared to the corresponding standard oscillation scenario. From these plots we observe that the neutrino oscillation probabilities are deviate from SM case for $n > 0$. This is the consequence of power-law in Eq. (20), since our analysis includes neutrino energy higher than the reference energy i.e., ($E_0 = 1$ GeV). The details of peak that arises around ~ 11 GeV has been discussed in Ref. [50]. The event rates in middle and right panels also follow a similar trend as the oscillation probabilities. For power-law indices $n = 0, 1, 2$ ⁸

⁸Energy independent decoherence when $n = 0$, whereas $n = 1$ refers to the linear energy dependence that could be modeled from *foamy* fluctuations in space-time [51], and $n = 2$ leads to the quadratic energy dependency on Γ could be induced by quantum gravity effect [52].

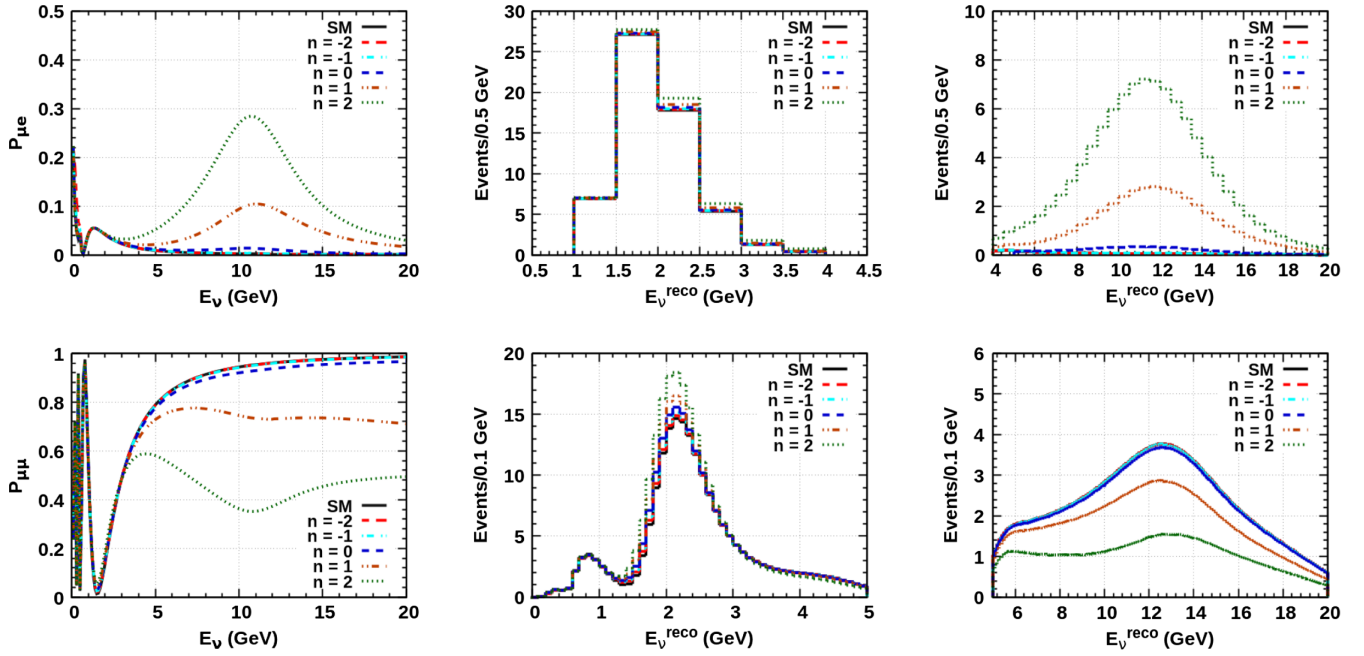


FIG. 7. ν_e appearance probability and event rates in the top row. ν_μ disappearance probability and event events in the bottom row. We assume $\Gamma = 10^{-23}$ GeV.

considering HE events could provide better constraints on Γ .

C. Upper bounds on the decoherence parameter Γ

To obtain the upper bounds on Γ_0 we show two-dimensional χ^2 distribution in the test Γ_0 versus true δ_{CP} plane considering power-law indices $n = 0, 1, 2$. Here we are not showing the corresponding plots for $n = -2, -1$ as the effect of Γ on $P_{\mu e}$ and $P_{\mu\mu}$ is negligible as seen in Fig. 7. We compute the χ^2 values for every true $\delta_{CP} \in [0, 360^\circ]$ by assuming standard oscillation phenomenon in the simulated data and the decoherence scenario in the theory. We provide the definition of χ^2 below,

$$\chi^2_{\Gamma}(\delta_{CP}^{\text{true}}) = \chi^2(\Gamma^{\text{true}} = 0, \Gamma^{\text{test}} \neq 0), \quad (23)$$

and marginalize over test parameters $\delta_{CP}, \theta_{23}, \Delta m_{31}^2$.

In Fig. 8 the left, right and middle plots represent the results for $n = 0, n = 1$, and $n = 2$, respectively. In each of these plots the solid lines depict the χ^2 obtained for the energy range $E_\nu : 1-4$ GeV while the dashed lines show the results for $E_\nu : 1-20$ GeV. The blue and red curves stand for 90% and 95% CL, respectively.

Across all the plots we point out from the solid and dashed curves that including high-energy events ($E_\nu : 1-20$ GeV) provide comparatively better constraint on Γ_{jk} than NOvA standard analysis window $E_\nu : 1-4$ GeV. However, this confirmation is less significant assuming $n = 0$ (left) and dominate with increasing n ($= 1, 2$; middle, right plots). We can explain such behavior from the ν_e -appearance probability and corresponding event rates in Fig. 7. In all the plots we see that 90% (blue) and 95% CL (red) curves are closer to each other therefore we list the bounds corresponding to 90% CL in this section.

TABLE III. Excess number of events in HE ($4 < E_\nu < 20$ GeV) considering $\Gamma \neq 0$.

Channel		Signal events					
		$\nu_\mu \rightarrow \nu_e$			$\nu_\mu \rightarrow \nu_\mu$		
Energy range (GeV)		1-4	1-20	4-20	1-4	1-20	4-20
SM		59.0	61.0	2.0	215.0	589.8	374.8
$\Gamma_0 = 10^{-23}$ GeV	$n = -2$	59.1	61.2	2.1	218.0	592.7	374.7
	$n = -1$	59.3	61.7	2.4	220.8	594.9	374.1
	$n = 0$	59.7	66.0	6.3	225.9	592.3	366.4
	$n = 1$	60.7	101.0	40.3	234.8	529.8	295.0
	$n = 2$	63.0	165.9	102.9	250.1	423.8	173.7

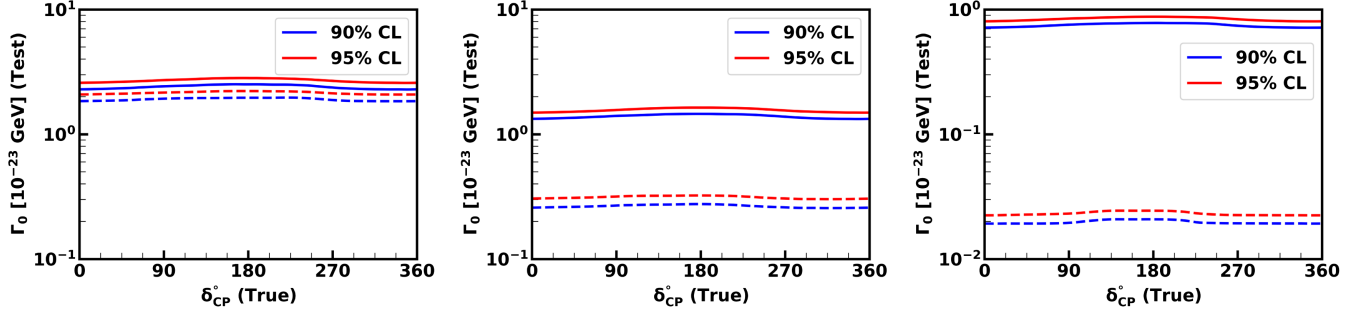


FIG. 8. Constraining Γ_0 using energy range 1–4 GeV (solid lines) and 1–20 GeV (dashed lines). Left, middle and right plots correspond to $n = 0$, $n = 1$, and $n = 2$, respectively. We marginalize over Δm_{31}^2 , θ_{23} , δ_{CP} .

We also notice that the corresponding bounds on Γ remain almost constant (as blue curves are flat) for all values of δ_{CP} . This indicates that the decoherence parameter Γ does not depend on the true value of δ_{CP} .

Considering E_ν : 1–4 GeV the sensitivity at 90% CL to the Γ_0 for $n = 0, 1, 2$ is listed as 2.2×10^{-23} GeV, 1.3×10^{-23} GeV, 7.15×10^{-24} GeV respectively. Whereas analyzing events from E_ν : 1–20 GeV the sensitivity at 90% CL to the Γ_0 for $n = 0, 1, 2$ is listed as 1.82×10^{-23} GeV, 2.52×10^{-24} GeV, 2.0×10^{-25} GeV, respectively. Clearly, for $n = 1, 2$ we note more stringent bounds [by $\mathcal{O}(1)$] when we added high-energy events from E_ν : 4–20 GeV. Notably, in the case of $n = 2$ (rightmost plot) we see a significant improvement in the bounds of Γ in comparison to the results obtained from assuming E_ν : 1–4 GeV and this can be observed from solid and dashed curves. To facilitate a better comparison we list all the bounds in the Table IV.

D. Allowed regions in $\theta_{23} - \delta_{CP}$ plane

In Refs. [20,53], authors have explored the possibility of the existence of environmental decoherence accounting for the tension in the θ_{23} measurement between the T2K and NOvA experiments (can be seen from Fig. 6 of [15]. T2K allows $\theta_{23} = 45^\circ$, whereas NOvA rejects maximal mixing i.e., $\theta_{23} = 45^\circ$). It should be noted that in this work, we consider high-energy NOvA events and energy power law dependency of Γ . In the light of this, we are motivated to investigate if there would be any further changes in the $\theta_{23} - \delta_{CP}$ contour region.

In this subsection we choose to highlight the most stringent bounds on θ_{23} and δ_{CP} imposed by assuming

TABLE IV. Bounds on Γ_0 obtained from Fig. 8 for different power-law indices $n = 0, 1, 2$.

Analysis window	Bounds on $\Gamma_0/10^{-24}$ (GeV)		
	$n = 0$	$n = 1$	$n = 2$
E_ν : 1–4 GeV	22	13	7.15
E_ν : 1–20 GeV	18.2	2.52	0.2

nonzero Γ with a power-law index $n = 2$. We achieve this by assuming decoherence in both the simulated data and the test hypothesis. To obtain the projection of χ^2 in then $\theta_{23} - \delta_{CP}$ test plane we define χ^2 as follows:

$$\chi^2 = \chi^2(\Gamma^{\text{true}}, \delta_{CP}^{\text{true}}, \theta_{23}^{\text{true}}, \delta_{CP}^{\text{test}}, \theta_{23}^{\text{test}}). \quad (24)$$

We marginalize over test Δm_{31}^2 , θ_{13} , and $\Gamma[10^{-24} : 10^{-22}]$ GeV. We consider true values of standard parameters and their test ranges from Table I assuming normal mass ordering. We fix the unmentioned parameters to their true values.

In Fig. 9 we display the projection of χ^2 in the test plane of $\theta_{23} - \delta_{CP}$ plane considering true $\Gamma_0 = 10^{-23}$ GeV (a representative value) and energy power-law indices $n = 0, 1$ and 2 in the top, middle and bottom panel. The left and right plots represent allowed regions considering analysis window of neutrino energy 1 to 4 GeV and 1 to 20 GeV respectively. In both the plots we show the contours corresponding to 68% (gray) and 90% (blue) CL.

From the left plot of Fig. 9 (E_ν : 1–4 GeV) we notice that even in the presence of decoherence the allowed regions of θ_{23} and δ_{CP} are almost the same as in the standard case reported in [15]. This implies that when we consider the ν_e events in the range E_ν : 1–4 GeV the impact of the presence of decoherence, in true spectrum is very minimal (even for power law index $n = 2$). On the contrary, when we considered E_ν : 4–20 GeV (right panel), we note that the allowed regions of θ_{23} for all values of δ_{CP} got more stringent for $n = 1, 2$ and the higher octant of θ_{23} ($\theta_{23} > 45^\circ$) is preferred over the lower octant ($\theta_{23} < 45^\circ$) for $n = 2$.

Furthermore, we observe a disfavor region for $\delta_{CP} \sim 270^\circ$ with 68% CL in both the left and right plots even in the presence of decoherence and the region is allowed with 90% CL. Therefore, in the presence of decoherence the NOvA and T2K tension shown in Ref. [15] (normal ordering plot in Fig. 6), could be uplifted with 90% CL.

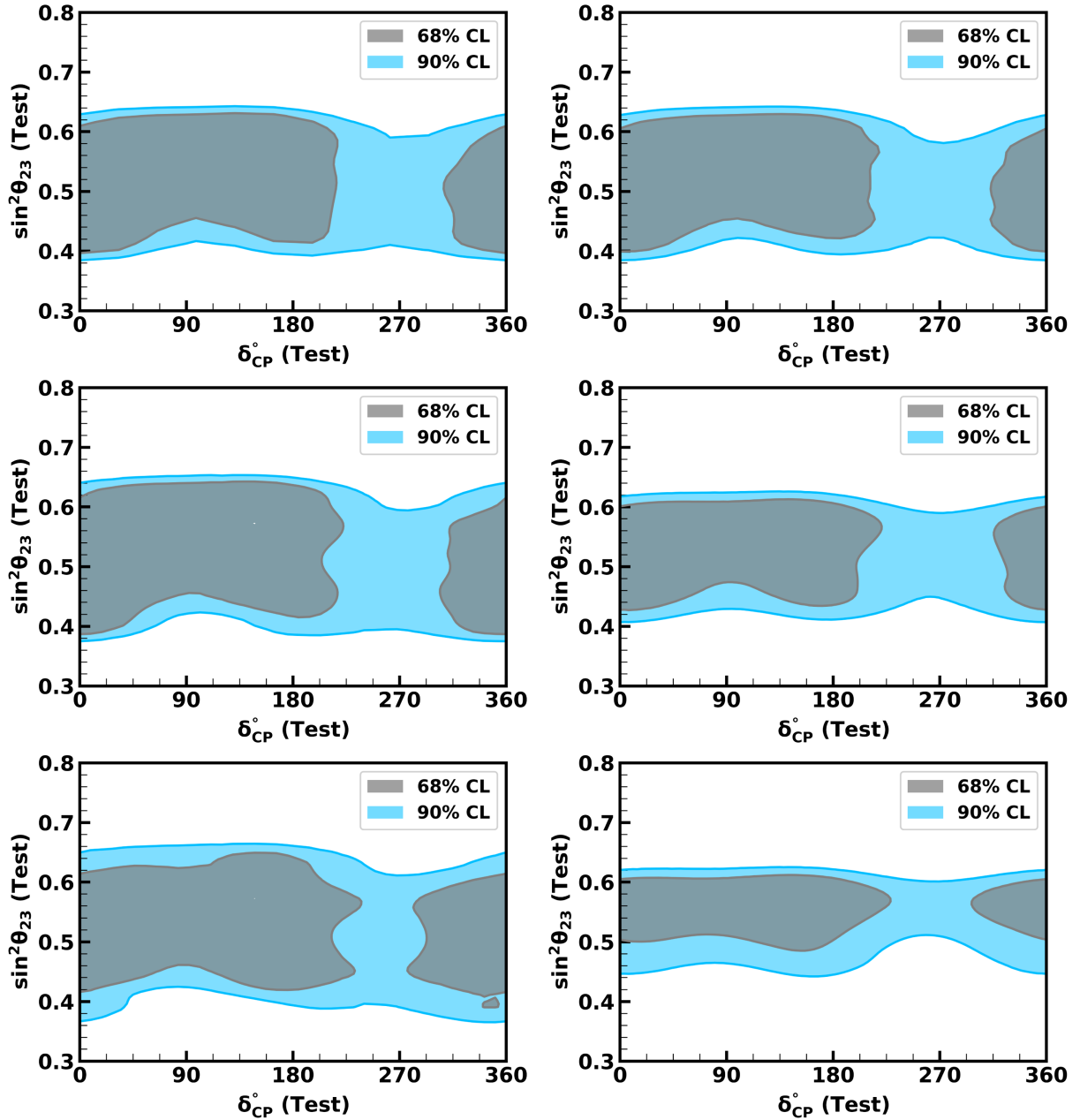


FIG. 9. $\Gamma_{21} = \Gamma_{31} = \Gamma_{32} = 10^{-23}$ GeV in true for $n = 0$ in top row, $n = 1$ in middle row and $n = 2$ in bottom row. In left 1–5 GeV and in right 1–20 GeV. Marginalized over Δm_{31}^2 , θ_{13} , and Γ .

V. CONCLUSIONS

In this paper we have studied the phenomenology of NSI and environmental decoherence by including high-energy neutrino events at NOvA experiment. We have shown the modified oscillation probabilities and event rates at high energy considering effect of one NSI parameters ($\epsilon_{e\mu}, \epsilon_{e\tau}$ at a time) as well as decoherence parameter Γ . We have illustrated the allowed regions with 95% CL in the $|\epsilon_{\alpha\beta}| - \delta_{CP(\alpha\beta)}$ plane taking into account high-energy ν_e and $\bar{\nu}_e$

events. We have obtained the bounds on decoherence parameter Γ considering the power-law dependencies $n = 0, 1, 2$. In the decoherence scenario we have highlighted the bounds on θ_{23} and δ_{CP} imposed by assuming power-law indices $n = 0, 1, 2$ for the analysis window E_ν : 1–20 GeV. Below, we present the summary of the key findings:

- (i) The standard appearance probability and the probability with nonzero $\epsilon_{e\tau}$ exhibit the degeneracy throughout the energy window considered in this

analysis. Interestingly, the degeneracy observed for higher $\epsilon_{e\tau}$ in the $|\epsilon_{e\tau}| - \delta_{CP(e\tau)}$ plane disappears if we include events from high-energy range (E_ν : 4–20 GeV).

- (ii) On the other hand the appearance probability increases at high energy ($E_\nu > 7$ GeV) as compared to standard oscillation probability in the presence of $\epsilon_{e\mu}$ and we do not observe degeneracy with the standard oscillation probability. In addition, the 95% CL contours in $|\epsilon_{e\mu}| - \delta_{CP(e\mu)}$ plane show that $\epsilon_{e\mu}$ can be tightly constrained for all values of δ_{CP} after including high-energy events.
- (iii) In the case of decoherence we have seen an increase in ν_e -appearance probability and events ~ 11 GeV for $n \geq 0$. Including the high-energy events we have obtained stringent upper bounds on Γ specifically for power-law indices $n = 1, 2$.
- (iv) Considering nonzero Γ with $n = 2$, we have shown that θ_{23} is better constrained for all values of δ_{CP} and the higher octant of θ_{23} ($\theta_{23} > 45^\circ$) is preferred over the lower octant ($\theta_{23} < 45^\circ$) including events from E_ν : 4–20 GeV.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: TOTAL SPECTRUM: SIGNAL + BACKGROUND

In Appendix A, we present the list of signal and their respective backgrounds considered in our analysis. Additionally, we plot in Fig. 10 the event spectra (signal + background) with respect to the neutrino energy $0 < E_\nu < 20$ GeV of the primary oscillation channel of NOvA, i.e., ν_e and $\bar{\nu}_e$ appearance channel:

- (i) ν_e appearance signal: $\nu_\mu \rightarrow \nu_e$ and corresponding background: $\nu_e + \bar{\nu}_e$ beam, NC, $\nu_\mu \rightarrow \nu_\mu$ (CC), $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$;
- (ii) $\bar{\nu}_e$ appearance signal: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and corresponding background: $\nu_e + \bar{\nu}_e$ beam, NC, $\nu_\mu \rightarrow \nu_\mu$ (CC), $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (CC), $\nu_\mu \rightarrow \nu_e$;
- (iii) ν_μ disappearance signal: $\nu_\mu \rightarrow \nu_\mu$ and corresponding background: NC, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (CC), $\nu_\mu \rightarrow \nu_e$;
- (iv) $\bar{\nu}_\mu$ disappearance signal: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and corresponding background: NC, $\nu_\mu \rightarrow \nu_\mu$ (CC).

APPENDIX B: $\epsilon_{e\tau}$ VS δ_{CP} ($\delta_{e\tau}$) ASSUMING NO SIGNAL IN E_ν : 5–20 GeV

In Fig. 11, we show $\epsilon_{e\tau}$ vs δ_{CP} and $\epsilon_{e\tau}$ vs $\delta_{e\tau}$ in the left and right, respectively. Here we consider analysis window to be E_ν : 1–20 GeV. In the range E_ν : 1–4 GeV analysis is done considering both signal and background events, whereas in E_ν : 4–20 GeV only background events are taken into account.

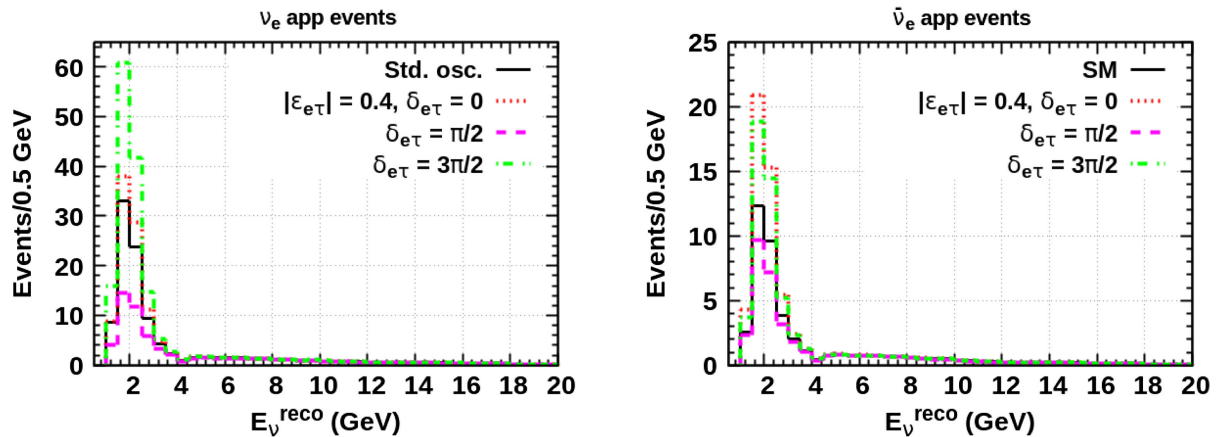


FIG. 10. Signal plus background simulated events spectrum for ν_e and $\bar{\nu}_e$ appearance channels considering nonzero $\epsilon_{e\tau}$.

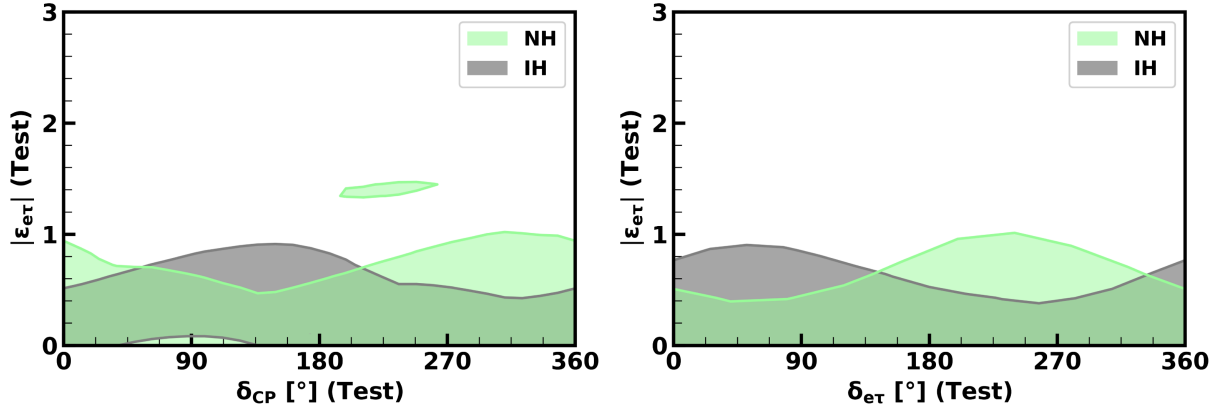


FIG. 11. $\epsilon_{e\tau}$ vs δ_{CP} (left) and $\epsilon_{e\tau}$ vs $\delta_{e\tau}$ (right) considering only background in energy range E_ν : 5–20 GeV.

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