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Investigating New Physics Signatures with High-Energy Neutrino Events at NOvA

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The NuMI Off-Axis ν_e Appearance (NOvA) experiment is a long-baseline neutrino oscillation experiment primarily designed to study ν_e, $\bar{\nu}_e$ appearance as well as ν_μ and $\bar{\nu}_\mu$ disappearance in the energy range of $1 < E_\nu < 4$ GeV. Interestingly, the NOvA far detector also records a non-negligible number of high-energy ν_e and $\bar{\nu}_e$ events in the extended range of $4 < E_\nu < 20$ GeV. These events, although sub-dominant in standard oscillation analyses, open a window to probe physics beyond the Standard Model.

In this work, we explore the potential of NOvA to constrain new physics scenarios specifically, non-standard neutrino interactions (NSIs) and environmental decoherence, using the high-energy event spectrum observed at the far detector.

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1. Introduction

The overwhelming evidence of non-zero neutrino mass, challenges the boundaries of the SM of particle physics and motivates us to search for a more consistent theory beyond the standard model (BSM). In this context, it is the need of the hour to explore the new physics scenarios to go beyond the precision measurements in neutrino physics. NuMI Off-axis ν_e appearance (NOvA) experiment is an ongoing accelerator based long-baseline neutrino oscillation experiment gathering the data of ν_e, $\bar{\nu}_e$ appearance, ν_μ and $\bar{\nu}_\mu$ disappearance in the energy range of $1 < E_\nu < 4$ GeV to determine the unknown neutrino oscillation parameters. In this work, we analyze the events from $1 < E_\nu < 20$ GeV at NOvA FD to study the sensitivity to NSI and environmental decoherence parameters.

We consider the neutrino system to be an open quantum system where the evolution of the neutrino density matrix is given by the Lindblad master equation [1]

$$\frac{d\rho_m(t)}{dt} = -i\,[H, \rho_m(t)] + \mathcal{D}\,[\rho_m(t)]\,. \tag{1}$$

Here ρ_m represents the density matrix of neutrino system in the mass basis and H is the hamiltonian of the neutrino system. $\mathcal{D}[\rho_m(t)]$ is the damping term that is parametrized after imposing the conditions of complete positivity, trace preservation, increase in von Neumann entropy and energy conservation of the neutrino system. We convert $\rho_m(t)$ into flavor basis using modified PMNS matrix in matter. The probability of transition from initial flavor 'ν_α' to final flavor 'ν_β' in terms of density matrix can be obtained using

$$P_{\alpha\beta}(t) = Tr[\tilde{\rho}_\alpha(t)\tilde{\rho}_\beta(0)]. \tag{2}$$

The explicit form of the transition probability assuming ultra-relativistic neutrinos ($t \approx L$) is given by [2]

$$P_{\alpha\beta}(L) = \delta_{\alpha\beta} - 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right) + 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)$$
$$\exp(-\Gamma_{jk}L)\cos(\frac{\tilde{\Delta}m^2_{jk}}{2E}L) + 2\sum_{j>k} Im\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)\exp(-\Gamma_{jk}L)\sin(\frac{\tilde{\Delta}m^2_{jk}}{2E}L)\,. \tag{3}$$

The decay term $e^{-\Gamma_{jk}L}$ in the above equation represents the effect of decoherence hosts the decoherence parameter Γ_{jk}. The physical origin of the decoherence phenomenon determines how Γ_{jk} depends on the neutrino energy. In this phenomenological work, we consider the general general power law dependency given by [3]

$$\Gamma_{jk}(E_\nu) = \Gamma_0\left(\frac{E_\nu}{E_0}\right)^n\,, \tag{4}$$

where, Γ_0 is constant, E_0 is the reference energy taken as 1 GeV and $n = 0, \pm1, \pm2$.

2. Constraining non-standard interactions using NOvA high energy beam

In the presence of NSI, the oscillation probability can be obtained following Ref. [4], using Eq. 3, while neglecting decoherence effects ($\Gamma_{jk} = 0$). In this case, the modified PMNS matrix $\tilde{U}$ is

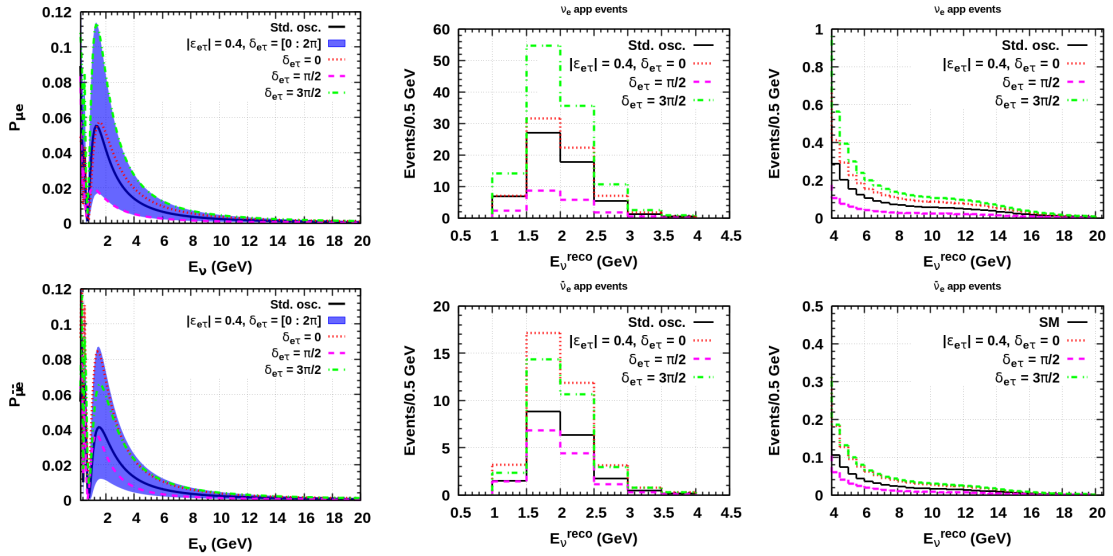

Figure 1: Left panel: Appearance probability vs neutrino energy; middle and right panels: Event rates vs reconstructed energy. Upper and lower panels show ν_e and $\bar{\nu}_e$) events respectively

expressed in terms of the matter potential and the NSI coupling parameters. Later, we incorporated this modified oscillation probability in GLoBES and simulated the NOvA experiment.

Figure 1 shows the numerical appearance probabilities $P_{\mu e}$ and $P_{\bar{\mu}\bar{e}}$ as functions of E_ν in the leftmost panel. The middle and right panels show the corresponding event rates as a function of the reconstructed energy E_ν^{reco} in the regions $1 < E\nu < 4$ GeV and $4 < E\nu < 20$ GeV, respectively. The upper (lower) rows correspond to the $\nu_\mu \to \nu_e$ ($\bar{\nu}\mu \to \bar{\nu}e$) channels. The legends for all curves are provided within the respective plots. For $|\epsilon_{e\tau}| = 0.4$ with $\delta_{e\tau} = 0$ and $3\pi/2$, the appearance probability $P_{\mu e}$ exceeds the standard value, while $\delta_{e\tau} = \pi/2$ yields a lower probability. The same trend is observed for $P_{\bar{\mu}\bar{e}}$, where the probabilities are higher than the standard case for $\delta_{e\tau} = 0$ and $3\pi/2$, and lower for $\delta_{e\tau} = \pi/2$. Across the full energy range, the standard curve overlaps with portions of the NSI band, demonstrating degeneracies between the standard scenario and combinations of $|\epsilon_{e\tau}|$ and $\delta_{e\tau}$.

In fig 2 we analyze the two-dimensional sensitivity by projecting χ^2 in $|\epsilon_{e\tau}|$-δ_{CP} plane and $|\epsilon_{e\tau}|$-$\delta_{e\tau}$ plane where the energy window is $1 < E_\nu < 4$ GeV in the left panel and $1 < E_\nu < 20$ GeV in the right. The degenerate band observed around $\epsilon_{e\tau} \sim 1.6$ disappears when we consider the high energy events (4 – 20 GeV). Same conclusion can be drawn when the true hierarchy is assumed to be inverted hierarchy.

3. Constraining the environmental decoherence parameters Γ_{jk}

In fig 3, We present the oscillation probabilities in the presence of decoherence, computed using Eq. (3). The top row of Fig. 3 shows the ν_e-appearance probability and corresponding event rates, while the bottom row displays the ν_μ-disappearance probability and associated event rates. The left panels plot the probabilities as functions of energy, and the middle and right panels show the reconstructed-energy event spectra in the ranges $1 < E_\nu < 4$ GeV and $4 < E_\nu < 20$

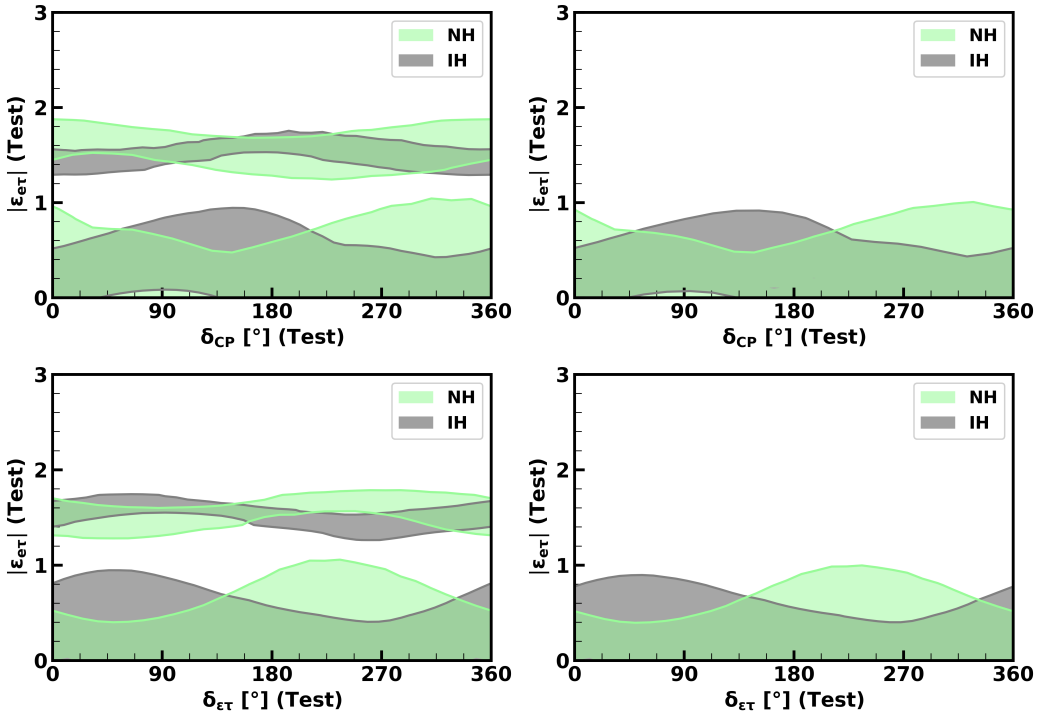

Figure 2: In the left panel E_ν is 1 - 4 GeV and in the right panel E_ν is 1 - 20 GeV. Upper row : $\epsilon_{e\tau}$ (test) vs δ_{CP} (test); Lower row : $\epsilon_{e\tau}$ (test) vs $\delta_{e\tau}$ (test).

GeV, respectively. All probabilities and event rates are numerically evaluated using the standard oscillation parameters from refs. [5, 6], together with a decoherence parameter $\Gamma = 10^{-23}$ GeV including the energy power-law dependency. The legends for all the curves are provided within the respective plots.

To derive upper bounds on Γ_0, we compute the two-dimensional χ^2 distribution in the test–Γ_0 versus true–δ_{CP} plane for power-law indices $n = 0, 1, 2$ (in the case of $n = -2, -1$ decoherence effects on $P_{\mu e}$ and $P_{\mu\mu}$ are negligible as can be seen in Fig. 3). For each true value of $\delta_{CP} \in [0, 360°]$, the simulated data assume standard oscillations, while the theory prediction includes decoherence. The relevant χ^2 is defined as

$$\chi^2_\Gamma(\delta^{\text{true}}_{CP}) = \chi^2(\Gamma^{\text{true}} = 0,\ \Gamma^{\text{test}} \neq 0), \tag{5}$$

with marginalization over δ_{CP}, θ_{23}, and Δm^2_{31}.

In fig. 4 we present Γ_0 vs δ_{CP}, for $n = 0$ (left panel), $n = 1$ (middle panel) and $n = 2$ (right panel) respectively. The solid and dashed lines represent χ^2 bounds obtained for $E_\nu : 1 - 4$ GeV and $E_\nu : 1 - 20$ GeV while the blue and red curves show 90% and 95% CL.

From all the panels it is clear that including high energy events ($E_\nu : 1 - 20$ GeV ; solid curves) constraints the decoherence parameters more stringently when compared to the analysis of events in the range $E_\nu : 1 - 4$ GeV (dashed curves). This improvement is modest for $n = 0$ but becomes increasingly prominent for $n = 1$ and $n = 2$. This pattern is consistent with the behavior seen in Fig. 3. The bounds on Γ are nearly flat across all δ_{CP} values, indicating that the sensitivity to the decoherence parameter is essentially independent of the true δ_{CP}.

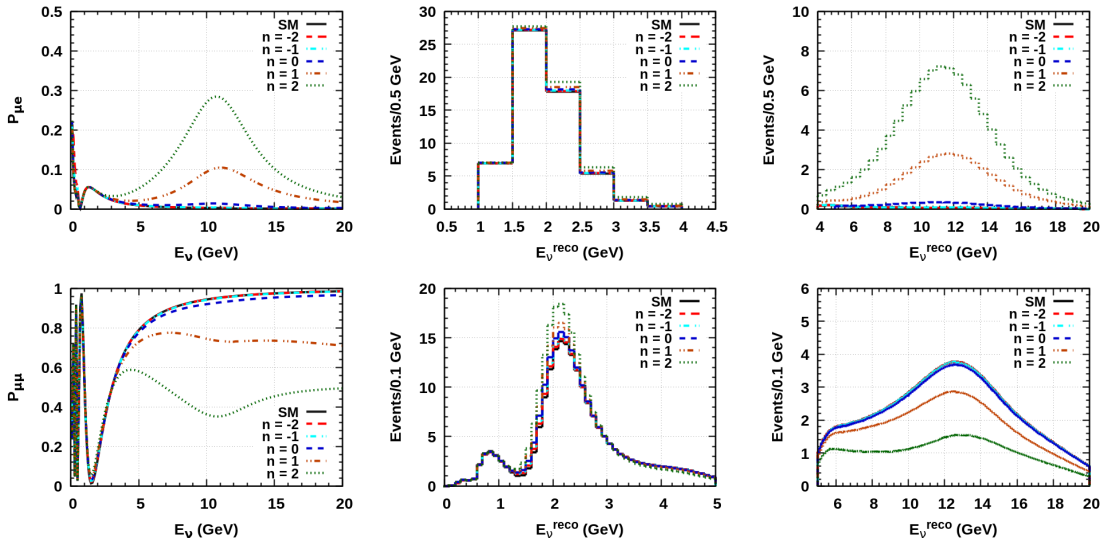

Figure 3: Here we assume $\Gamma = 10^{-23}$ GeV. The top row : ν_e appearance probability and corresponding event rates; bottom row : ν_μ disappearance probability and corresponding event events.

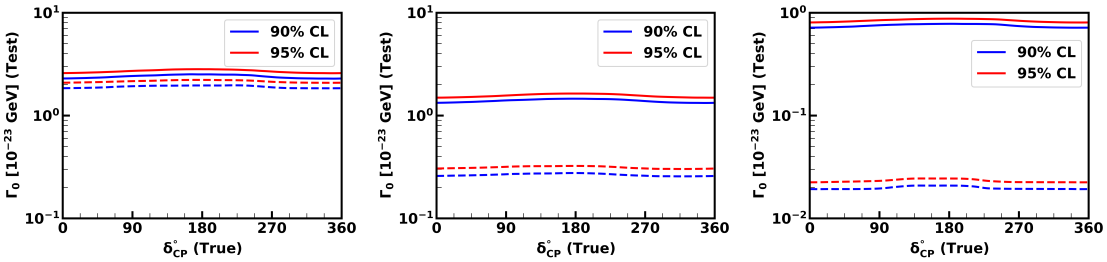

Figure 4: 90% (blue) and 95% (red) CL of Γ_0 vs δ_{CP}.Left, middle and right plots correspond to $n = 0$, $n = 1$ and $n = 2$ respectively. Solid lines : $1 < E_\nu < 4$ GeV and dashed lines : $1 < E_\nu < 20$ GeV

For a comprehensive overview of this analysis (including the study on NSI parameter $\epsilon_{e\mu}$ refer to the following [7, 8].

4. Conclusions

In this work, we observe that High-energy (HE) neutrino events hugely improve NOvA's sensitivity to the off-diagonal NSI parameter $\epsilon_{e\tau}$. The degeneracy observed in $\epsilon_{e\tau}$-δ_{CP} parameter space when $1 < E_\nu < 5$ GeV data are used is removed when high energy events in the range $1 < E_\nu < 20$ GeV (signal + background) are included. In the decoherence analysis, incorporating events from $4 < E_\nu < 20$ GeV in addition to the $0 < E_\nu < 4$ GeV sample lead to stronger constraints on the decoherence parameter Γ, particularly for power-law indices $n = 1$ and $n = 2$.

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