New physics effects on coherence in neutrino oscillations: A model independent analysis

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In this work we study the effects of non-standard neutrino matter interactions on the coherence embedded in the system of oscillating neutrinos. The coherence parameter used in this work quantifies the inherent quantumness of the system. The new physics effects on the coherence parameter are incorporated in a model independent way by using the language of effective field theory. We then analyze these non-standard interaction effects on coherence in the context of upcoming DUNE experiment. The recent global analyses [JHEP 1906, 055 (2019)] of neutrino oscillation data show that LMA-LIGHT sector of $\theta_{12}$ with normal mass ordering along with LMA-DARK sector with inverted mass ordering provide a good fit to all data. We find that while the first solution decreases the coherence in the system in comparison to the standard model prediction for all values of neutrino energy $E$ and $CP$ violating phase $\delta$ (except in the narrow region around $E \sim 2$ GeV), a large enhancement in the value of coherence parameter in the entire $(E - \delta)$ plane is possible for the DARK octant of $\theta_{12}$ with inverted ordering. The enhancement is more protuberant in the region around $E \sim 4$ GeV where maximum neutrino flux is expected in the DUNE experiment.

I. Introduction

The present understanding of fundamental interactions of nature is encapsulated in a theory known as the Standard Model (SM) of the strong and electroweak interactions. The SM successfully survived stringent tests of their efficacy in several high precision experiments. Although SM successfully accounts for the phenomena within its domain, still it cannot be considered as the quintessential theory of fundamental interactions. This is because there are several phenomenon which SM simply cannot explain. These include the observed baryon asymmetry, gravitational interactions and the origin and nature of dark matter and dark energy. Therefore one needs to explore physics beyond SM.

The phenomena of neutrino oscillation implies physics beyond the SM as the neutrinos are assumed to be massless within the SM whereas the observation of neutrino oscillations implies that neutrinos have a non-zero mass. Few measurements in the muon sector, for instance, the anomalous magnetic moment [1,2] and the charge radius of the proton extracted from muonic hydrogen [3] are indications of beyond SM physics. A hint of lepton flavor non-universality, in disagreement with the SM, has been observed in the decays induced by the quark level transitions $b \rightarrow c \ell \nu$ ($l = e, \mu, \tau$) [4] and $b \rightarrow s \ell^+ \ell^-$ ($l = e, \mu$) [5,6]. Several model independent analyses identified the Lorentz structure of possible new physics in these decay modes [7-20]. These Lorentz structures can be generated in new physics models, such as $Z'$ and leptoquark models, and hence can account for the observed anomalies in semi-leptonic $B$ decays.

The existence of these new particles can also affect the pattern of neutrino oscillations. A convenient way to describe these new physics effects in neutrino interactions in the electroweak broken phase are the so called non-standard interaction (NSI) parameters [21-27]. The SM Lagrangian contains only renormalizable interactions with canonical dimensions $D \leq 4$. Assuming that new physics exists at some high energy $\Lambda$, the effects of this new physics interactions at the energy scale much below $\Lambda$, can be described in a model independent way by including higher dimensional operators constructed out of the SM fields. In this work, we restrict our analyses to dimension-6 operators which are expected to give observable contributions for energy $<< \Lambda$. The upcoming generation of neutrino-experiments will be sensitive to the sub-leading effects like NSI with matter fields. This will generate some new ambiguities during the extraction of values of the unknown parameters involved in the dynamics of neutrino oscillation which directly affects the coherence embedded in neutrino system.

The quantum mechanical phenomena of neutrino oscillation is a consequence of superposition principle which makes the quantum coherence an indispensable part of the system. The system of oscillating neutrinos can maintain quantum coherence over a long distance which can be detected in long baseline experiments. Hence, neutrinos can prove to be promising candidates for various tasks related to quantum information. In recent years, various measures of quantum correlations [28-31] have also been studied in the neutrino sector. The experimentally observed neutrino oscillations can violate the classical bounds of these measures [32-40]. However, the degree of violation of these correlation measures cannot be considered as a measure to quantify the coherence of the system because their maximum value depends on the channel parameters [41-43]. Therefore, in the context of quantum information, coherence becomes a fundamental concept which can signalize the quantum behavior of the system and it also shows the departure from its classical behav-
ior. It can be rigorously characterized in the context of quantum resource theory. Recently, quantum coherence has been quantified in terms of experimentally observed neutrino survival and transition probabilities [33]. In this work we study the coherence embedded in the neutrino system in the presence of physics beyond SM. The effects of new physics on the coherence parameter is incorporated in a model-independent approach within the framework of effective field theory.

A global analysis of oscillation data with nonstandard neutrino interaction in three flavor scenario was performed in [20]. In [20] observables sensitive to the CP-violating phase (such as $\nu_e$ and $\bar{\nu}_e$ appearance at long baseline experiments) were excluded from the fit and hence the constraints were obtained on the CP-conserving part only. Further, as some approximations ($\Delta_2 \rightarrow 0$ in atmospheric and long baseline CP-conserving experiments) were used to simplify the calculations, the effect of mass ordering was greatly reduced. This analysis was performed for both scenarios: first (LMA-LIGHT) and second (LMA-DARK) octant solution of solar mixing angle $\theta_{12}$. Recently this global analysis has been extended to include complex NSI neutral current interaction with quarks for observables sensitive to the leptonic CP-violating phase and mass ordering [27]. In [27] they have analyzed all the four combinations, i.e., LIGHT and DARK sector with normal ordering (NO) and inverted ordering (IO) of mass states, in which two solutions, LIGHT octant with NO and Dark octant with IO, are favoured in global analysis of oscillation data. In view of these updates, we study the effects of NSI on the quantum coherence of the neutrino system in a model-independent approach within the context of DUNE experimental set-up [43].

In this paper, we start with the general formalism to incorporate the NSI effects in the dynamics of neutrino oscillations in Sec. II. Then in Sec. III the calculation and a model independent analysis of NSI effects on coherence parameter is provided in the context of upcoming Deep Underground Neutrino Experiment (DUNE). Finally, we conclude in Sec. IV.

II. NSI effects on neutrino oscillations

The new physics neutrino-matter interactions can be charged current (CC) as well as neutral current (NC) interactions. Both NSI-NC and NSI-CC can modify the inelastic neutrino scattering cross sections with other SM fermions. While the scattering bounds on NSI-CC are rather stringent, these bounds are quite weaker for NSI-NC. The charged-current NSI of neutrinos with matter (i.e., $\nu_e, \nu_\mu, \nu_\tau$) can affect the production and detection of neutrinos in general, called zero distance effect and can become discernible in near detectors. On the other hand, the NSI-NC with two neutrinos can also affect the forward coherent scattering as the neutrino propagate through matter via so called Mikheev-Smirnov-Wolfenstein (MSW) mechanism [45] [46]. Consequently, a significantly enhanced effect of NSI-NC can be seen in large baseline oscillation experiments where neutrinos have to travel through a large region of matter. Therefore, we consider the neutral-current interactions driven by NSI relevant to neutrino propagation in matter. The Lagrangian for neutral current NSI neutrino interactions can be written as

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha,\beta} (\bar{\nu}_{\alpha} \gamma^\mu P_L \nu_{\beta}) (\bar{\nu}_\mu P f),$$

where $G_F$ is the Fermi constant, $\alpha$ and $\beta$ are flavor indices, $P_L$ & $P_R$ are the projection operators and $f$ is the charged fermion. Here, $\epsilon^{f,P}_{\alpha,\beta} \sim \mathcal{O}(G_F)$ represents the strength of the new interaction with respect to the SM interaction which is quantified by $G_F$. If the flavor of neutrinos participating in the interaction is considered to be independent of the charged fermion type, one can write

$$\epsilon^{f,P}_{\alpha,\beta} \equiv \epsilon^{\alpha}_i \epsilon^{\beta}_j \xi^{f,P}_{ij}$$

where matrix elements $\epsilon^{\alpha}_i$ correspond to the coupling between neutrinos and the coefficients $\xi^{f,P}_{ij}$ represent the coupling to the charged fermions. Hence the Lagrangian becomes

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{\alpha}_i \epsilon^{\beta}_j (\bar{\nu}_{\alpha} \gamma^\mu P_L \nu_{\beta})$$

$$\times \sum_f \xi^{f,P}_{ij} (\bar{\nu}_\mu P f).$$

The Hamiltonian for the evolution of neutrino-state, in mass eigenstate basis, including NSI effect can be written as $\mathcal{H}_m = \mathcal{H}_m + U^{-1} V_f U$, where $\mathcal{H}_m = \text{diag}(E_1, E_2, E_3)$ and $U$ is the $3 \times 3$ unitary (PMNS) matrix which differs from the usual one by an overall phase matrix $P = \text{diag}(e^{i\delta}, 1, 1)$ and represented as,

$$\begin{pmatrix}
    c_{12} c_{13} & s_{12} c_{13} e^{i\delta} & s_{13} \\
    -s_{12} c_{23} e^{-i\delta} - c_{12} s_{13} c_{23} & c_{12} c_{23} - s_{12} s_{13} e^{i\delta} & s_{12} c_{13} e^{i\delta} \\
    s_{12} s_{23} e^{-i\delta} - c_{12} s_{13} c_{23} & -c_{12} c_{23} - s_{12} s_{13} e^{i\delta} & c_{12} c_{13} e^{i\delta}
\end{pmatrix}$$

(4)

This rephasing does not affect the probability expressions in the absence of NSI. The advantage of this convention of $U$-matrix is that one can easily perform the CPT-transformation, $H_{vac} \rightarrow -H_{vac}^*$, as just by doing simple replacements, such as

$$\Delta_{31} \rightarrow -\Delta_{31} + \Delta_{21} \rightarrow -\Delta_{32},$$

$$\theta_{12} \rightarrow \pi/2 - \theta_{12},$$

$$\delta \rightarrow \pi - \delta.$$  

(5)

The matter part $V_f$ of the Hamiltonian including the operators corresponding to the NSI effect is given as

$$V_f = A \begin{pmatrix}
    1 + \epsilon_{ee}(x) & \epsilon_{e\mu}(x) & \epsilon_{e\tau}(x) \\
    \epsilon_{e\mu}^*(x) & \epsilon_{\mu\mu}(x) & \epsilon_{\mu\tau}(x) \\
    \epsilon_{e\tau}^*(x) & \epsilon_{\mu\tau}^*(x) & \epsilon_{\tau\tau}(x)
\end{pmatrix},$$

(6)
with \( A = \sqrt{2} G_F N_e(x) \). Here, +1 in the 1 \times 1 element of \( V_f \) corresponds to the standard matter interaction of neutrinos and

\[
\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} \epsilon_{\alpha\beta}^f,
\]

represents the non-standard part. Here, \( N_f(x) \) is the number density of fermion \( f \) as a function of the distance \( x \) travelled by neutrino. According to the quark-structure of protons (p) and neutrons (n), we can write

\[
N_p(x) = 2N_p(x) + N_n(x), \quad N_n(x) = N_p(x) + 2N_n(x).
\]

Therefore, from Eq. (7) and (8) we can write

\[
\epsilon_{\alpha\beta} = (2 + Y_e) \epsilon_{\alpha\beta}^e + (1 + 2Y_n) \epsilon_{\alpha\beta}^n,
\]

with \( Y_e = N_e/N_e, \) \( N_e \) is the number density of electrons and \( N_p = N_e \). The CPT-transformation of \( H_{vac} \), in which neutrino evolution remains invariant, involves the change of the octant of \( \theta_{12} \) (DARK octant with \( \theta_{12} > 45^\circ \)) and also the change in the sign of \( \Delta m^2 \). The octant selection of mixing-angle \( \theta_{12} \) becomes important when neutrino is traveling through a dense material medium as the possibility of NSI increases. For example, the deficit of solar neutrinos at the detectors can be resolved by considering the vacuum mixing angle in the light-side \((0 \leq \theta_{12} \leq \frac{\pi}{4})\) with standard neutrino-matter interactions as well as the dark-side solution \((\frac{\pi}{4} \leq \theta_{12} \leq \frac{\pi}{2})\) with large enough values of NSI parameters \( \Delta m^2 \).

To include CPT-transformation in matter-part of Hamiltonian, the replacements are

\[
[\epsilon_{ee} - \epsilon_{\mu\mu}] \to -[\epsilon_{ee} - \epsilon_{\mu\mu}] - 2, \\
[\epsilon_{\tau\tau} - \epsilon_{\mu\mu}] \to -[\epsilon_{\tau\tau} - \epsilon_{\mu\mu}], \\
\epsilon_{\alpha\beta} \to -\epsilon_{\alpha\beta}^* (\alpha \neq \beta).
\]

The evolution of mass eigenstate \( \psi_m \) can be given by

\[
\psi_m(L) = e^{-iH_m L} \psi_m(0) \equiv U_m(L) \psi_m(0).
\]

In order to obtain the evolution operator \( U_m \) in the mass eigenstate basis, we use the formalism given in [43]. Using Cayley-Hamilton’s theorem, which implies that, in the characteristic equation of a \( N \times N \) matrix \( M \), i.e., \( \det(M - \lambda I) = 0 \), the eigenvalue \( \lambda \) can be replaced by the matrix \( M \) itself, hence reducing the number of terms in the exponential series \( e^M \) to \( N \). Hence the exponential term of the matrix \( -i H_m \) can be expended as

\[
e^{-iH_m L} = \phi e^{-iLT} = \phi \left[a_0 I + a_1(-iLT) + a_2(-iLT)^2\right] = \phi \left[a_0 I - iLT a_1 - L^2T^2 a_2\right],
\]

Here \( T \) is the traceless matrix calculated from the Hamiltonian as \( T = H_m - Tr(H_m)I/3 \), where \( \text{Tr}(H_m) = E_e + A(1 + \epsilon_{ee} + \epsilon_{\mu\mu} + \epsilon_{\tau\tau}) \) and \( E_e = E_1 + E_2 + E_3 \). The coefficients \( a_{0,1,2} \) can be calculated in terms of eigenvalues of \( T \) matrix, i.e., \( \lambda_a, a = 1,2,3 \) and the coefficient \( c_1 = \text{det}(T) \text{Tr}(T^{-1}) \). One can finally write the evolution operator \( U_m \) and also \( U_f \) (in flavor state basis) as

\[
U_m(L) = e^{-iH_m L} = \phi \sum_{a=1}^3 e^{-i\lambda_a T} \frac{1}{3\lambda_a^2 + c_1} \left[(\lambda_a^2 + c_1)I + \lambda_a T + T^2\right],
\]

\[
U_f(L) = e^{-iH_f L} = U e^{-iH_m L} U^{-1} \phi \sum_{a=1}^3 e^{-i\lambda_a T} \frac{1}{3\lambda_a^2 + c_1} \left[(\lambda_a^2 + c_1)I + \lambda_a T + T^2\right],
\]

where \( \phi = e^{-iLT \text{Tr}(H_m)/3} \) and \( \tilde{T} \equiv UTU^{-1} \). The parameters \( \epsilon_{\alpha\beta} \) can have complex values, however, in this paper we consider them to be real.

### III. NSI effects on quantum coherence

If a system is represented by a state \( \rho = |\psi\rangle \langle \psi| \) then the existence of coherence in the system is quantified by its non-zero off-diagonal elements. For a completely incoherent state, the off-diagonal elements are zero. Among several measures, we use the \( l_1 \)-norm of coherence which is expressed as the sum of the absolute values of off-diagonal elements of the density matrix \( \rho \), such as

\[
\chi_f = \sum_{i \neq j} |\rho_{ij}|.
\]

The maximum attainable value of \( \chi_f \) is \( d - 1 \) where \( d \) is the dimension of the system. For neutrino system, \( \rho \) can be calculated using the neutrino state represented by \( |\psi(t)\rangle \equiv |\nu_\alpha(t)\rangle = \sum_{i=1,2,3} U_{fi}(t) |\nu_\beta\rangle, \) with \( j = 1,2,3 \) and \( \beta = e, \mu, \tau \). Here \( U_{fi} \) are elements of the evolution operator in flavor basis. Hence coherence in the presence of NSI, \( \chi_f^{NSI} \), can be calculated using Eq. (13). For SM interactions, coherence can then be obtained as \( \chi_f^{SM} = \lim_{\epsilon_{\alpha\beta} \to 0} \chi_f^{NSI} \).
In the following, we present our results for \( \chi_f^{SM} \) and \( \chi_f^{NSI} \) in the context of experimental set-up for upcoming long-baseline accelerator experiment DUNE. Hence we have \( \alpha = \mu \) for accelerator \( \nu_\mu \) beam, the baseline \( L \) is 1300 Km and matter density potential is taken to be \( A = 1.01 \times 10^{-13} \text{ eV} \). Further, oscillation parameters are as \( \theta_{13} = 33.82^\circ \) (in case of SM interaction as well as for LMA-LIGHT solution), \( \theta_{23} = 49.6^\circ, \theta_{13} = 8.61^\circ, \Delta_{21} = 7.39 \times 10^{-5}\text{eV}^2 \) and \( |\Delta_{32}| = 2.525 \times 10^{-3}\text{eV}^2 \). Due to CPT-transformation given in Eq. (5), the mixing-angle \( \theta_{12} \) obtains the value 56.18° for LMA-DARK solution.

The NSI parameters are taken from refs. [26, 27]. In Ref. [26], the bounds on NSI parameters were obtained mainly by using constraints from observables such as the disappearance data from solar and KamLAND experiments, atmospheric neutrino data from Super-K, DeepCore and IceCube experiments along with the long-baseline (LBL) experimental data such as \( \nu_\mu \) and \( \bar{\nu}_\mu \) disappearance as well as \( \nu_e \) and \( \bar{\nu}_e \) appearance data from MINOS, \( \nu_\mu \) and \( \bar{\nu}_\mu \) disappearance data from T2K and \( \nu_\mu \) disappearance data from NOvA experiment. These observables are not sensitive to \( \delta \)-value and the sign of mass squared difference \( \Delta_{31} \) and hence the NSI parameters were the same for both signs of \( \Delta_{31} \). This analysis was updated in ref. [27] by including all relevant data in the neutrino sector which includes observables having functional dependence on the CP violation phase as well as the sign of the \( \Delta_{31} \), i.e., \( \nu_e \) and \( \bar{\nu}_e \) appearance data from T2K and NOvA. In both of these works, the allowed parameter space for NSI couplings were obtained for the LIGHT \( (\theta_{12} < 45^\circ) \) (LMA-LIGHT solution) and DARK \( (\theta_{12} > 45^\circ) \) (LMA-DARK solution) octant.

The NSI parameters corresponding to LMA-LIGHT octant are \( \epsilon_{ee} = \epsilon_{ee} - \epsilon_{\mu\mu} \approx 1.35415, \epsilon_{e\tau} = \epsilon_{e\tau} - \epsilon_{\mu\tau} \approx 0.33027, \epsilon_{e\mu} \approx -0.03539, \epsilon_{e\tau} \approx -0.46244 \) and \( \epsilon_{\mu\tau} \approx -9.229 \times 10^{-3} \). For LMA-DARK sector these values are \( \epsilon_{ee} \approx -6.67, \epsilon_{e\tau} \approx 0.0936, \epsilon_{e\mu} \approx 0.02929, \epsilon_{e\tau} \approx -0.131406 \) and \( \epsilon_{\mu\tau} \approx -3.1275 \times 10^{-3} \). These values were updated in [27] by including observables sensitive to the leptonic CP-violating phase and mass ordering in the global fit. The following NSI parameters were obtained for two favoured solutions:

- **LMA-LIGHT sector with normal ordering:** \( \tilde{\epsilon}_{ee} \approx -0.1, \tilde{\epsilon}_{e\tau} \approx 0.01, \epsilon_{e\mu} \approx -0.06, \epsilon_{e\tau} \approx -0.1, \epsilon_{\mu\tau} \approx -0.01 \).
- **LMA-DARK sector with inverted ordering:** \( \tilde{\epsilon}_{ee} \approx -1.8, \tilde{\epsilon}_{e\tau} \approx -0.01, \epsilon_{e\mu} \approx 0.06, \epsilon_{e\tau} \approx -0.07, \epsilon_{\mu\tau} \approx -0.01 \).

We first study the impact of NSI on coherence parameter using results of ref. [26]. We then see how these results change in view of updated results obtained in [27]. The results of our analysis are presented in Figs. [1] and [2]. In these figures the observable quantifying coherence, \( \chi_f \), is shown in the plane of the neutrino-energy.
$E$ (in GeV) and the CP-violating phase $\delta$ for both positive (upper panel) and negative (lower panel) signs of $\Delta_{31}$. The range of $E$ along with the baseline length $L$ correspond to the DUNE experimental set-up.

The results shown in the left panel of Fig. 1 correspond to the value of coherence parameter in the SM. It can be seen from the figure that within the SM, the range of $\chi_f$ is $(0.1, 1.67)$ for both positive and negative signs of $\Delta_{31}$. However, for positive $\Delta_{31}$, $\chi_f^{SM} \geq 1.5$ i.e., have large coherence in the energy range 4-6 GeV (the maximum neutrino flux is expected around 4 GeV for DUNE experiment) for all values of CP violating phase. For the case of negative $\Delta_{31}$, the value of coherence parameter is relatively reduced. Thus we see that within the SM, the quantumness of system which we have quantified in terms of coherence, is sensitive to the sign of $\Delta_{31}$ as well as the CP violating phase.

The middle panel of Fig. 1 shows $\chi_f^{{NSI}}$ for LMA-LIGHT solution corresponding to NSI inputs calculated in [26]. The effect of NSI is to reduce the quantumness for positive $\Delta_{31}$ and enhance for the negative sign. For positive $\Delta_{31}$, it can be seen that the NSI effect results in an overall decrease in coherence in the entire $E - \delta$ plane barring few small regions such as $\delta \in (0 - 2)$ and $(5 - 6)$ for $E \in (4 - 6)$ GeV, where we see a marginal increase in comparison to the SM scenario. For negative $\Delta_{31}$, there is an overall emplacement in the coherence of the system due to NSI effects. This enhancement is more prominent in the energy range 4-6 GeV for all values of $\delta$ phase along with energy around 2 GeV for $\delta \in (0 - 2)$ and $(4 - 6)$.

The results for LMA-DARK solution are depicted in right panel of Fig. 1. It can be seen from the figure that for normal mass hierarchy, the NSI effects provide large enhancement in coherence for $E \leq 2$ GeV. For $E \geq 2$ GeV, there is marginal suppression in $\chi_f$. For inverted mass hierarchy, there is overall suppression in coherence. These observations are true for all values of CP violating phase.

We now present results using the NSI parameters obtained by including $\nu_e$ and $\overline{\nu}_e$ appearance data from T2K and NO$\nu$A in the global fit to neutrino oscillation data [27]. Based on goodness of fit, two solutions were obtained: LMA-LIGHT solution with NO and LMA-DARK solution with IO. The results are presented in Fig. 2.

The upper plot in the right panel of Fig. 2 depicts $\chi_f^{{NSI}}$ for LMA-LIGHT solution with NO using the updated NSI parameter obtained in ref. [27]. The $\chi_f^{{NSI}}$ plot for this solution using results of ref. [26] is shown in the upper plot of middle panel of Fig. 1. By comparing these plots, it can be seen that the value of $\chi_f^{{NSI}}$ using the updated results marginally decreases for $E > 3$ GeV for all values of $\delta$. However, $\chi_f^{{NSI}}$ is enhanced around

\[ E \leq 3 \text{ GeV}, \quad \delta \in (0 - 2) \text{ and } (4 - 6) \text{ GeV}. \]
\(E \sim 2\) GeV for complete range of \(CP\) violating phase. Therefore for LMA-LIGHT solution with NO, NSI effects decrease the coherence in the system in comparison to the SM prediction except in the narrow region around \(E \sim 2\) GeV.

The situation is drastically different for the case of LMA-DARK solution with IO using the updated results. This can be seen by comparing the lower plot in the right panel of Fig. (2) with the lower plot of right panel of Fig. (1). It is obvious that the updated values of NSI parameters result in a large enhancement in the value of coherence parameter in the entire \((E - \delta)\) plane. This enhancement is more prominent in the region around \(E \sim 4\) GeV where maximum neutrino flux is expected in the DUNE experiment. Hence for LMA-DARK solution with IO, the effect of NSI is to increase the inherent coherence of the system in energy range corresponding the maximum neutrino flux in the DUNE experiment.

### IV. Conclusions

In this work we study the impact of new physics on coherence embedded in the system of oscillating neutrinos. The non-standard interaction effects on coherence are incorporated in a model-independent way within the framework of effective field theory where higher dimensional operators are added to the SM Lagrangian. Here we restrict our analysis to dimension-6 operators. Recently, a global analysis of all relevant neutrino oscillation data in the presence of non-standard interaction was performed in [27]. This analysis included constraints from \(\bar{\nu}_e\) and \(\nu_e\) appearance data from T2K and NOvA due to which the allowed non-standard interaction parameter space is now different for normal and inverted mass orderings. Further, it was observed that two scenarios, LMA-LIGHT solution with normal ordering and LMA-DARK solution with inverted ordering, provide a good fit to all data. In the DUNE experimental set-up, we find that the first solution marginally decreases the value of coherence parameter in comparison to the SM. For the LMA-DARK solution with inverted ordering, the coherence in the system is enhanced around \(E \approx 4\) GeV, the energy corresponding to maximum neutrino flux at DUNE, for almost all values of \(CP\) violating phase.

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