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Revealing the Majorana nature of neutrinos through a precision measurement of the CP phase

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Abstract. We show that it is possible to reveal the nature of neutrino by measuring the Majorana phase at the DUNE experiment. The Majorana phase is activated in the neutrino oscillation framework due to the introduction of a decoherence environment. Being that depending on the value of the Majorana phase and the intensity of decoherence, the measurement of the Dirac CP violation phase $\delta_{\rm CP}$ can be highly spoiled. We will notice the latter by comparing the measurements of the CP phases that will take place in DUNE and T2HK. Finally, we will also assess the possibility of the measurement itself of the Majorana phase at DUNE.

1. Introduction

There have been theoretical proposals that sustain that the neutrino system can suffer quantum decoherence due to its interaction with a pervasive environment, represented, for instance, by a foamy space-time or composed by virtual black holes (see references therein [1]). In this study, we disregard the origin of the decoherence environment following a model-independent analysis. This approach contemplates the interaction between the neutrino system and the environment encoded in the elements of the so-called decoherence matrix [1, 2]. It is has shown that the Majorana CP phases will become evident in the modified neutrino oscillation probability depending on which elements of the decoherence matrix are turned on, see [2] and references therein.

In this paper, we explore the latter situation and evaluate how much the appearance of the Majorana CP phase in the modified neutrino oscillation probability could distort the measurement of the Dirac CP phase in future long-baseline neutrino experiments. We go a step further and assess the capacity of constraining the Majorana CP phase in the DUNE experiment [3, 4].

2. Theoretical formalism

The evolution of the neutrino system interacting with an (unknown) environment is obtained through the Lindblad master equation, which is given by [1]:

$$\frac{\partial \hat{\varrho}'(t)}{\partial t} = -i[\hat{H}_{\rm osc}, \hat{\varrho}'(t)] + \mathcal{D}[\hat{\varrho}'(t)] \quad (1)$$

where $\hat{\varrho}'(t)$ is the neutrino density matrix, $\hat{H}_{\rm osc}$ is the Hamiltonian of the neutrino system and $\mathcal{D}[\hat{\varrho}'(t)] = \frac{1}{2}\sum_j \left([\hat{A}_j, \hat{\varrho}'(t)\hat{A}_j^\dagger] + [\hat{A}_j\hat{\varrho}'(t), \hat{A}_j^\dagger]\right)$, the term responsible for the non-unitary evolution (e.g. the decoherence phenomena). As usually treated [1], we rewrite the Eq. (1) by expanding the operators $\hat{\varrho}'(t)$, $\hat{H}_{\rm osc}$ and $\hat{A}_j$ $(j = 1,..,8)$ as follows: $\hat{\varrho}'(t) = \sum \rho'_\mu t_\mu$, $\hat{H}_{\rm osc} = \sum h_\mu t_\mu$, and $\hat{A}_j = \sum a_\mu^j t_\mu$ where μ is running from 0 to 8, t_0 is the identity matrix and t_k the Gell-Mann matrices $(k = 1,...,8)$. Thus, imposing the conditions of the time-increase of von Neumann entropy and the conservation of probability, we get:

$$\dot{\varrho}'_0 = 0, \quad \dot{\varrho}'_k = (H_{kj} + D_{kj})\varrho'_j = M_{kj}\varrho'_j \tag{2}$$

where $H_{kj} = \sum_i h_i f_{ijk}$ (f_{ijk} is the structure constant of SU(3)). The $\varrho'^\alpha(t) = e^{(\mathbf{H}+\mathbf{D})t}\varrho'^\alpha(0) = e^{\mathbf{M}t}\varrho'^\alpha(0)$ where ϱ' is an eight column vector compose by the ϱ'_k and $\mathbf{H}$, $\mathbf{D}$ and, $\mathbf{M}$, are the 8×8 matrix version of H_{kj}, D_{kj} and, M_{kj}, respectively. The decoherence matrix $\mathbf{D} = \mathbf{D}^d + \mathbf{D}^{nd}$, with its diagonal part $\mathbf{D}^d = -\Gamma \times \mathbb{I}$ in terms of a single decoherence parameter Γ, while $\mathbf{D}^{nd}$ is the off-diagonal part, in which is activated only the element $[\mathbf{D}^{nd}]_{28} = -\Gamma/\sqrt{3}$ that maximizes the CP violation effects related to the Majorana phase [2]. Hence, we obtain the neutrino oscillation probability formula, that combines standard oscillation (SO) and quantum decoherence (DE) (see details in [2]):

$$\begin{aligned} P^{\rm SO \bigoplus DE}_{\nu_\mu\to\nu_e} &= \frac{\left(1 - e^{-\bar{\Gamma}}\right)}{3} + P^{\rm SO}_{\nu_\mu\to\nu_e} e^{-\bar{\Gamma}} \\ &+ \frac{\bar{\Gamma}}{3}\sin 2\theta_{12}\sin^2\theta_{23}\sin\phi_1 e^{-\bar{\Gamma}} + ... \end{aligned} \tag{3}$$

where $\bar{\Gamma} = \Gamma L$ (L is the source-detector distance), $P^{\rm SO}_{\nu_\mu\to\nu_e}$ is the standard neutrino oscillation formula, ϕ_1 is the Majorana phase and θ_{12}, and θ_{23} are the mixing angles from the Pontecorvo-Maki-Nagawa-Sakata (PMNS) matrix. Now, it is useful to calculate the CP violation asymmetry $\Delta P = P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e}$:

$$\Delta P^{\rm SO \bigoplus DE} \simeq \Delta P^{\rm SO} e^{-\bar{\Gamma}} + \frac{2\bar{\Gamma}}{3}\sin 2\theta_{12}\sin^2\theta_{23}\sin\phi_1 e^{-\bar{\Gamma}} + ... \tag{4}$$

In Fig. 1 are displayed the expectations from Eq. (4). where the $\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)$ transition probability is numerically calculated at DUNE baseline, $L = 1300$ km for $\Gamma = 2.5 \times 10^{-24}$ GeV and for the SO parameters [2]: $\theta_{12} = 33.82°$, $\theta_{13} = 8.61°$, $\theta_{23} = 48.3°$, $\Delta m^2_{21} = 7.39 \times 10^{-5}\text{eV}^2$, and $\Delta m^2_{31} = 2.523 \times 10^{-3}\text{eV}^2$ (normal hierarchy), these are going to be maintained throughout this manuscript. Here it is clear how the overall negative (positive) sign of the decoherence contribution for $\phi_1/\pi = -0.5$ ($\phi_1/\pi = 0.5$) diminish (increases) the ΔP amplitude, whilst for $\phi_1/\pi = 0.0$ is, as expected, nearly equal to the SO case.

3. Analysis and Results

We generate data samples for the DUNE and T2HK experiments using GLoBES [5], nuSQuIDS [6], where the configuration and inputs are from [3, 4, 7, 8]. In the case of DUNE, we consider 5 years of exposure per neutrino and antineutrino mode. Meanwhile, we have that for T2HK 3 and 9 years for neutrino and antineutrino mode, respectively. These data samples are generated taken as non-zero values Γ^{true} and ϕ_1^{true} and setting on $\delta_{\rm CP}^{true}/\pi = 1.4$, value inspired by the hint obtained in the T2K experiment [9]. It is a well-justified choice to take the latter as the true value of the Dirac CP phase since the quantum decoherence effects are small. The $\bar{\Gamma} \sim \mathcal{O}(0.001)$, the result of multiplying the T2K's source-detector distance and the magnitude of the decoherence parameters we probe here. In this way, we can safely assume that the

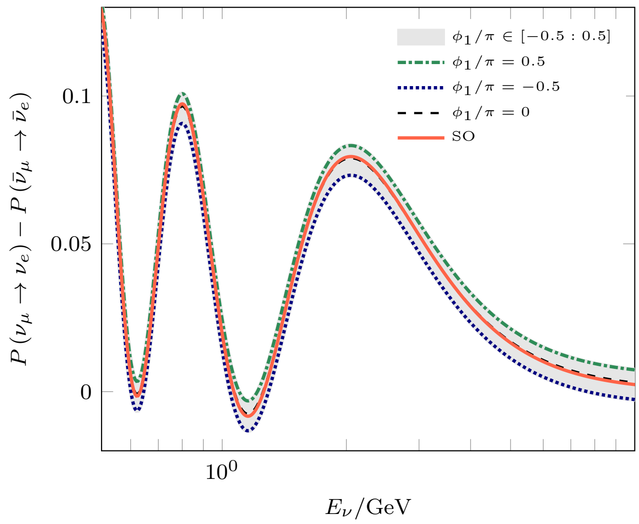

Figure 1. CP asymmetry depending on the neutrino energy. The off-diagonal decoherence parameter is $[\mathbf{D}^{nd}]_{28} = -\Gamma/\sqrt{3}$. We consider $\delta_{\rm CP}/\pi = 1.4$, and $\Gamma = 2.5\times10^{-24}$GeV.

measurement of the Dirac CP violation phase at T2HK, an experiment with the same source-detector distance as T2K, should remain the same (than T2K) undistorted by the DE effects. Therefore, our strategy is to take the T2HK Dirac CP violation phase simulated measurement as a benchmark point for pure SO physics, from where we quantify any deviation of the DUNE Dirac CP violation measurement affected by DE effects. The χ^2 analysis used for DUNE and T2HK is described in [2]. This analysis compares SO as the theoretical hypothesis versus the simulated data that includes the SO and DE effects. The $\Delta\chi^2$ is given by:

$$\begin{aligned}\Delta\chi^2 =&\chi^2(\theta_{13}^{test}, \delta_{\rm CP}^{test}; \theta_{13}^{true}, \delta_{\rm CP}^{true}, \Gamma^{true}, \phi_1^{true}) \\ &- \chi^2_{min}(\theta_{13}^{fit}, \delta_{\rm CP}^{fit}; \theta_{13}^{true}, \delta_{\rm CP}^{true}, \Gamma^{true}, \phi_1^{true})\end{aligned} \quad (5)$$

where θ_{13}^{fit} and $\delta_{\rm CP}^{fit}$ are the best-fit points that minimizes the χ^2, considering priors at 3σ for the oscillation parameters but $\delta_{\rm CP}$. The DUNE and T2HK $\Delta\chi^2$ contours, projected into $\sin^2\theta_{13}$ vs $\delta_{\rm CP}$ planes and obtained after marginalizing over the remaining SO parameters, are displayed in Fig. 2. As pointed out above, the $\sin^2\theta_{13}^{fit}$ and $\delta_{\rm CP}^{fit}$ points for T2HK coincides with the undistorted true oscillation parameters. From that standpoint, the $\sin^2\theta_{13}^{fit}$ for DUNE suffers a modest increment with respect to the true value ($= 0.0224$), explicitly shown in Table. 1. This minor growth is consequence of fitting the data, which incorporates the energy-independent increase of the SO$\bigoplus$DE probability amplitude (see the first and third term of Eq. 3). The values of $\delta_{\rm CP}^{fit}$ for DUNE, displayed in Table. 1, imply that for $\phi_1/\pi = -0.5(0.5)$ the magnitude of the CPV asymmetry is attenuated (maximized), which is nothing more than the expression of the need of adjusting the reduction (increase) of ΔP, when $\phi_1/\pi = -0.5(0.5)$, seen in Fig. 1. The shifting, in terms of σ, from the $\sin^2\theta_{13}^{fit}$ ($\delta_{\rm CP}^{fit}$) (for DUNE) to the true one (for T2HK) is represented by the vertical (horizontal) projection into the dashed line axis, draw in Fig. 2. All these shifting values are shown in Table 1, where for $\Gamma = 3.5(2.5)\times10^{-24}$GeV is, for $\phi_1/\pi = -0.5$, equal to $0.87(0.55)\sigma$ and $5.39(4.28)\sigma$, for $\sin^2\theta_{13}^{fit}$ and $\delta_{\rm CP}^{fit}$, respectively. Being the latter the most pronunaced displacements. While, the lesser ones are found for $\phi_1/\pi = 0.5$ with $0.54(0.31)\sigma$ and $0.13(0.08)\sigma$ for $\sin^2\theta_{13}^{fit}$ and $\delta_{\rm CP}^{fit}$, respectively. Without going into a more complex analysis, a rough way to distinguish between the different values taken here for ϕ_1 can be achieved using the ratio ($\mathcal{R}$), defined as the number of σ deviation for $\sin^2\theta_{13}^{fit}$ divided by the corresponding ones for $\delta_{\rm CP}^{fit}$. We get that, for $\Gamma = 3.5(2.5)\times10^{-24}$ GeV, $\mathcal{R} = \{0.16(0.13), 0.30(0.30), 4.15(3.9)\}$ for $\phi_1/\pi = \{-0.5, 0.0, 0.5\}$, correspondingly. These values seems to indicate that it would be possible to well separate the negative range from the positive range of ϕ_1/π.

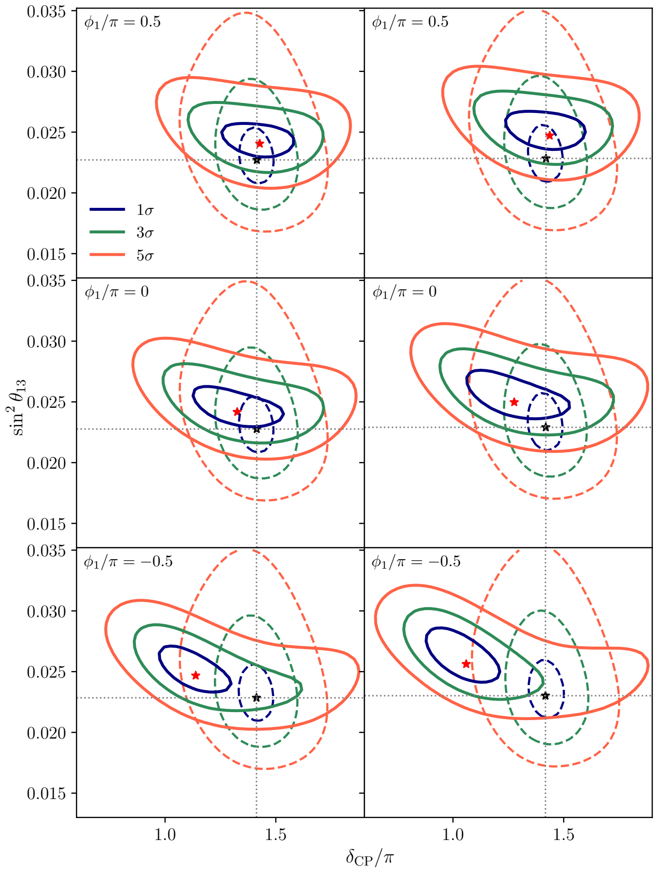

Figure 2. The solid and dashed lines are decoherence with $[\mathbf{D}^{nd}]_{28} = -\Gamma/\sqrt{3}$ for the DUNE and T2HK experiments, respectively. The left column is $\Gamma = 2.5 \times 10^{-24}$GeV and the right column is $\Gamma = 3.5 \times 10^{-24}$GeV. We consider $\delta_{\rm CP}^{true}/\pi = 1.4$.

Table 1. Fitted values for $\sin^2\theta_{13}$, $\delta_{\rm CP}$ and their respective shifts in terms of σ units. We consider $\delta_{\rm CP}^{true}/\pi = 1.4$.

$\Gamma = 2.5 \times 10^{-24}$GeV	$\phi_1/\pi = 0.5$	$\phi_1/\pi = 0$	$\phi_1/\pi = -0.5$
$\sin^2\theta_{13}^{fit}$	0.0241	0.0242	0.0247
N_σ	0.31σ	0.35σ	0.55σ
$\delta_{\rm CP}^{fit}/\pi$	1.43	1.33	1.13
N_σ	0.08σ	1.17σ	4.28σ
$\Gamma = 3.5 \times 10^{-24}$GeV	$\phi_1/\pi = 0.5$	$\phi_1/\pi = 0$	$\phi_1/\pi = -0.5$
$\sin^2\theta_{13}^{fit}$	0.0247	0.0250	0.0256
N_σ	0.54σ	0.69σ	0.87σ
$\delta_{\rm CP}^{fit}/\pi$	1.44	1.28	1.06
N_σ	0.13σ	2.34σ	5.39σ

Motivated by the last results, we go beyond and evaluate the DUNE's ability of constraining the Majorana phase ϕ_1 and the decoherence parameter Γ. For achieving the aforementioned purpose, we perform a χ^2 analysis assuming (SO) plus decoherence (DE) as theoretical hypothesis and testing $\phi_1/\pi = -0.5, 0, 0, 5$ for $\Gamma = 4.5, 5.5 \times 10^{-24}$ GeV. In Fig. 3 the different allowed regions are depicted for 68 % and 90 % C.L., being obtained at DUNE experiment the following measurements: $\phi_1/\pi = -0.50 \pm 0.35(0.32)$ and $\phi_1/\pi = 0.50 \pm 0.35(0.32)$ for $\Gamma = 4.50 \pm 1.38(5.50 \pm 1.42) \times 10^{-24}$ GeV. For $\phi_1/\pi = 0.0 \pm 0.19(0.15)$ we have $\Gamma = 4.50 \pm 1.42(5.50 \pm 1.46) \times 10^{-24}$ GeV. It is interesting to point out that either for $\phi_1/\pi = -0.5$ or $+0, 5$ the corresponding allowed regions excludes $\phi_1/\pi = 0.0$ at 90% C.L., for both values of Γ.

4. Conclusions

In this work, there are two highlights pointed out. First, the spoiling of the measurement of the Dirac CP violation phase. A measurement that could help us to explain the matter-antimatter asymmetry present in the Universe. Second, to identify the source of the spoiling: quantum decoherence and the Majorana phase, constraining the latter at DUNE, when $\phi_1/\pi = -0.5$ (or equivalently $\phi_1/\pi = 1.5$), with similar precision than the one exhibited by T2K in obtaining its Dirac CP phase hint [9]. Measuring the Majorana phase in a neutrino oscillation experiment would be a novel way to discover the neutrino nature.

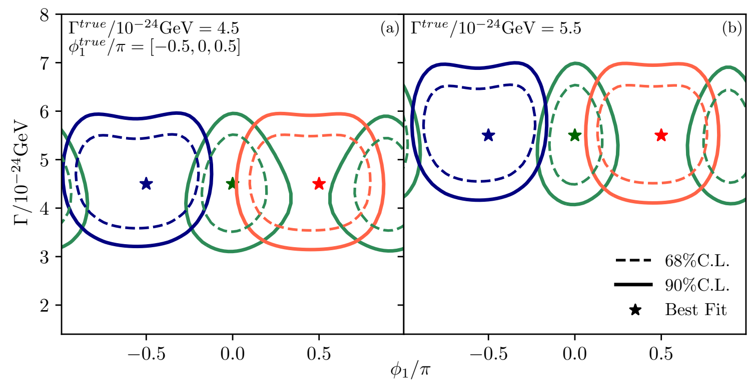

Figure 3. DUNE's ability to constrain the decoherence parameter and the Majorana phase. The blue, green and red lines represent $\phi^{true}/\pi = -0.5, 0, 0.5$, respectively.

4.1. Acknowledgments

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