Future leptonic *CP* phase determination in the presence of NSI

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(Received 15 June 2023; accepted 16 October 2023; published 13 November 2023)

The precise determination of the leptonic *CP*-phase is one of the major goals for future generation long baseline experiments. On the other hand, if new physics beyond the Standard Model exists, a robust determination of such a *CP*-phase may be a challenge. Moreover, it has been pointed out that, in this scenario, an apparent discrepancy in the *CP*-phase measurement at different experiments may arise. In this work, we investigate the determination of the Dirac *CP*-phase and the atmospheric mixing angle θ_{23} at several long-baseline configurations: ESSnuSB, T2HKK, and a DUNE-like experiment. We use the nonstandard neutrino interactions (NSI) formalism as a framework. We found that complementary between ESSnuSB and a DUNE-like experiment will be favorable to obtain a reliable value of the *CP*-phase, within the aforementioned scenario. Moreover, the T2HKK proposal can help to constrain the matter NSI parameters.

DOI: 10.1103/PhysRevD.108.095024

I. INTRODUCTION

The success in neutrino physics in the last decades gives us a clear picture of the standard three oscillation parameters. The determination of the mixing angles and squared mass differences at present is remarkable, with only a few challenges to face, such as the octant problem. In this standard scenario, determining the *CP*-violating phase is the next precision physics goal and will be tackled by the next generation of long-baseline experiments (LBL). Current measurements of this important observable have been reported, mainly by NOvA and T2K collaborations. Their results seem to differ and might be a puzzle to solve if this difference persists. Recently, it has been pointed out [1,2] that the discrepancy in the measurement of the leptonic *CP*-violating phase δ_{CP} experienced by the NOvA [3] and T2K [4] experiments, can be alleviated by considering new physics beyond the Standard Model. In particular, it has been considered that this new physics can be parametrized in the framework of nonstandard neutrino interactions (NSI) [5–8]. Future generation of LBL experiments will provide new *CP* measurements with improved sensitivities that can probe this scenario. This is the case of future proposals such as a DUNE-like experiment [9], the Hyper-Kamiokande proposal [10], T2HKK [11], and the more recent ESSnuSB [12].

In general, DUNE will have a good discrimination among the corresponding vector, scalar NSI and sterile neutrino scenarios [13]. Furthermore, in Ref. [14], improvements on the energy resolution at DUNE to enhance the matter NSI sensitivity were studied. It was shown in [15,16], that for sizable NSI, DUNE will be capable of determine the off-diagonal NSI parameters including the extra *CP*-violating phases ϕ.

On the other hand, source and detector charged current NSI at the European Spallation Source Neutrino Super Beam (ESSnuSB) and DUNE were investigated in Refs. [17,18], it was found that the incorporation of a near detector improves the sensitivity to NSI at ESSnuSB, therefore competitive limits are achieved. Besides, the authors of Ref. [19] explored the benefits of a near detector at ESSnuSB, which refines the sensitivity to matter NSI. For instance, the authors of Ref. [20] studied the implications of matter NSI (sensitivities, degeneracies, determination) at separate neutrino long-baseline (LBL) experiments including DUNE and the Tokai-to-Hyper-Kamiokande-and-Korea (T2HKK) proposal.

In this work, we explore NSI effects on matter, within the framework examined in [1,2], considering the effect of one

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flavor changing matter NSI parameter at a time, as well as the inclusion of all the matter NSI parameters, we focus on both the electron neutrino appearance channel $P(\nu_\mu \to \nu_e)$ and the muon neutrino disappearance channel $P(\nu_\mu \to \nu_\mu)$. Concretely, we will explore the complementary to matter NSI among future LBL experiments namely, ESSnuSB, T2HKK, and a DUNE-like experiment.

The structure of the paper is as follows. In Sec. II, we review and develop the framework of matter NSI. Section III explains the characteristics and assumptions made in our simulation. Sensitivities and main results are developed in Secs. IV and V. Finally, we give our conclusions in Sec. VI.

II. FRAMEWORK

Different kinds of physics beyond the Standard Model can be studied, from the phenomenological point of view, using the formalism of nonstandard neutrino interactions (NSI). Essentially, NSI describes any new physics that, at low energies, can be parametrized by the Lagrangian

$$\mathcal{L} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fC} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_C f). \tag{1}$$

Here, $\alpha, \beta = e, \mu, \tau$ refer to the neutrino flavor, $f = e, u, d$ stand for the target fermions, P indicates the projector operator, with the superscript $C = L, R$ indicating the chirality of the ff current; finally, $\epsilon_{\alpha\beta}^{fC}$ are the strengths of the NSI.

For neutrinos propagating through the Earth on a matter background, the NSI contribution to the Hamiltonian will be proportional to the corresponding fermion density (e, u, and d) times the given NSI parameter. We can parametrize the three relevant contributions in a single parameter, $\epsilon_{\alpha\beta}$, as

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \epsilon_{\alpha\beta}^{f} \frac{N_f}{N_e} \coloneqq \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}) \frac{N_f}{N_e}, \tag{2}$$

where N_f corresponds to the number density of the f fermion. In this article, we will work in the approximation where, for the Earth, $N_n \simeq N_p = N_e$, then $N_u \simeq N_d \simeq 3N_e$. Therefore,

$$\epsilon_{\alpha\beta} \simeq \epsilon_{\alpha\beta}^{e} + 3\epsilon_{\alpha\beta}^{u} + 3\epsilon_{\alpha\beta}^{d}. \tag{3}$$

With this notation, we can write the NSIs contribution to the effective Hamiltonian of the neutrino propagation in matter, in the flavor basis,[1] as

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + A^{\mathrm{CC}} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}\right]. \tag{4}$$

Here, E is the neutrino energy, $U \coloneqq R_{23}(\theta_{23})U_{13}(\theta_{13},\delta)R_{12}(\theta_{12})$ is the leptonic mixing matrix, $M^2 = \mathrm{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)$ is the diagonal mass-matrix, $A^{\mathrm{CC}} = 2\sqrt{2}G_F N_e E$ is the standard charged current matter potential. We consider complex NSI, where $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$ for $\alpha \neq \beta$, which may contribute to CP-violation in the leptonic sector.

Using this Hamiltonian, we compute the exact survival and conversion probability expressions. This computation was done by using the GLoBES software [21,22], especially its additional NSI tool [23,24]. For instance, approximate analytic expressions for the oscillation probability in the presence of matter NSI exist in the literature for both $P(\nu_\mu \to \nu_\mu)$ [14,20,25] and $P(\nu_\mu \to \nu_e)$ channels [1,25–27].

In this work we will explore the NSI as a solution to the discrepancy observed between the central values of the NOvA and T2K leptonic-CP measurements. According to the scenario investigated in [1,2], T2K (which is a practically vacuum oscillation experiment), determines the true value of the leptonic CP-phase $\delta_{CP} \sim 1.4\pi$ [4,28]. On the other hand, the NOvA experiment (with more matter interactions) measures a value of $\delta_{CP} \sim 0.8\pi$ [3], in presence of matter NSI the CP-phase $\delta_{\mathrm{NOvA}} \sim \delta_{\mathrm{T2K}} + \phi$, where the extra CP-violating phase ϕ is induced from the NSI effects, either $\phi = \{\phi_{e\mu}\,\mathrm{or}\,\phi_{e\tau}\} \sim 3/2\pi$ and effective couplings $|\epsilon_{e\mu}| \sim |\epsilon_{e\tau}| \sim 0.2$ [1,2]. At the probability level:

$$P(\epsilon = 0, \delta_{\mathrm{meas}}) = P(\epsilon, \delta_{\mathrm{true}}). \tag{5}$$

The detailed explanation of the phase relationships can be found elsewhere (e.g., in the Supplemental Material of Ref. [2]). This scenario, where ambiguities in the determination of the leptonic CP-violating phase δ_{CP} at NOvA and T2K arise via flavor changing matter NSI parameters $(|\epsilon_{e\tau}|, \phi_{e\tau})$ was explored in [29]. A related study at the probability level can be found in the literature [30]. Furthermore, as shown by the authors of [31], the combination of the proposed MOMENT experiment with the NOvA and T2K datasets can help in determining the Dirac CP-phase δ_{CP} in the presence of NSI.

For instance, relatively large NSI ($\epsilon_{e\tau} \sim 0.3$–$0.5$) can appear in radiative neutrino mass models (see, e.g., [32,33]). Moreover, sizable NSI can be induced in models with light mediators [34–39]. Alternatively, the determination of the neutrino mass ordering might be spoiled by the presence of matter NSI [27]. Lately, the authors of Ref. [13] investigate the potential of the Deep Underground Neutrino Experiment (DUNE) to probe new physics scenarios, which are motivated by the aforementioned NOvA and T2K results.

[1]Notice that we use the Hermiticity condition of the interaction, that is, $\epsilon_{\alpha\beta}^{fC} = (\epsilon_{\beta\alpha}^{fC})^*$.

III. EXPERIMENTAL SETUP AND SIMULATION

This section presents the characteristics and assumptions performed in our study. For this work, we will focus on the ESSnuSB proposal and its impact in a combined analysis with a future DUNE-like experiment. Moreover, we will analyze a two detector ESSnuSB configuration as well as the T2HKK proposal. The European Spallation Source plans to start operations in the year 2035. It will be the most powerful spallation source in Europe, and a Long-baseline neutrino program is contemplated [40]. This LBL proposal, ESSnuSB, considers using an intense proton beam of 2.5 GeV in Lund, Sweden. Its main purpose will be the search for the neutrino CP phase by locating a far detector inside a mine. Among the options available in the region, the more promising, according to their particle physics program [40], are the ones located at 360 and 540 km. However, other mines exist at different distances, such as 260 and 1090 km. Besides searching for CP-violation, ESSnuSB also plans to search for cosmological and supernovae neutrinos as well as to set new limits to the proton lifetime.

In the case of a DUNE-like experiment, the proposal contemplates a detection technology based on liquid argon, with a 40 kton mass, located at 1300 km from the source, a proton beam with a 1.2 MW power.

On the other hand, the Tokai to Hyper-Kamiokande and Korea (T2HKK) program [11] consists of a two-detector experimental setup for the discovery of the Dirac CP-violating phase δ_{CP}, which employs a (near) detector located at the Kamioka site at 295 km from the beam at Japan Proton Accelerator Research Complex (J-PARC) in Japan and the second (far) detector at a distance of 1100 km in Korea. Several off-axis angles (OA°) fluxes are in consideration, from which we will use the two-degree off-axis (OA2°) configuration of the fluxes from both the near and far detectors.

We use the GLoBES software [21,22] and its additional NSI tool [23,24] in this analysis. Regarding the ESSnuSB setup, the matter densities are assumed to be $\rho = (2.6, 2.75, 2.8, 2.84)\ \mathrm{g/cm^3}$ for the (200, 360, 540, 1090) km baselines, respectively. In addition, for the case of a single experimental arrangement with two baselines, we have considered two identical detectors, an *intermediate* detector at the closest distance from the neutrino beam and a far detector at the longest distance, with a total detector mass $m_{\mathrm{tot}} = m_{\mathrm{Near}} + m_{\mathrm{Far}} = 538$ kt, evenly distributed among the detectors. Moreover, we suppose the default systematic uncertainties of 10% and 15% normalization for signal and background, respectively, and a 0.01% energy calibration error for all types of events. According to Ref. [12], the effect of correlation for a bin-to-bin analysis is relatively mild. Therefore, as a crude approximation, we implement the systematic uncertainties as uncorrelated [17,41]. Other specifications for the ESSnuSB follow closely the previous work of Ref. [42].

For the DUNE-like experiment, we use the specifications and available files from the Technical Design Report (TDR) [9,43], which uses a 120 GeV proton beam of 1.2 MW power, with a matter density assumed to be $\rho = 2.848\ \mathrm{g/cm^3}$. Moreover, this configuration considers a 40 kt detector with an exposure of 13 years equally divided among (anti)neutrino modes.

Regarding the T2HKK simulation, the fluxes, cross sections, and efficiencies follow the description from Ref. [44], corresponding to a 2° off-axis (OA2°) flux configuration at both the near and far detectors. Furthermore, the energy resolution has a width σ_E/E of 8.5% for both e^- and μ^- respectively. Moreover, the near detector is located at 295 km, with a second identical detector at 1100 km. The total mass is 560 kt, equally divided among the detectors [45]. The total exposure time corresponds to 13 $\mathrm{MW \cdot yr}$, which corresponds to a total 2.7×10^{22} POT, 10 years of running time at 1.3 MW power [20] evenly distributed among (anti)neutrino modes. In addition, a matter density of $\rho = 2.6\ \mathrm{g/cm^3}$ at the 295 km and $\rho = 2.84\mathrm{g/cm^3}$ at the 1100 km baseline has been considered. We assume a normalization uncertainty of 2.5% for the signal rates and 5% (20%) for the appearance (disappearance) background rates [20,41]. As in the case of ESSnuSB, we implement the systematic uncertainties as uncorrelated, an approach that has been followed by other authors [46].

As far as neutrino oscillation parameters are concerned, the true values used in this analysis are: $\Delta m^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{31} = 2.55 \times 10^{-3}\ \mathrm{eV}^2$, $\theta_{12} = 34.3°$, $\theta_{13} = 8.53°$, $\theta_{23} = 49.26°$, $\delta_{CP} = 1.4\pi$; corresponding to the best-fit values for normal ordering (NO) from Salas *et al.* [47] (except for δ_{CP}, unless otherwise specified, we take the best fit from T2K [4,28]), in all our results the NO is considered.[2] For oscillation parameter priors, we assume a 1σ error of 5% for Δm^2_{21}, Δm^2_{31}, θ_{12}, and θ_{23}. We also assume 3% for θ_{13} and 10% for the leptonic CP-violating phase δ_{CP} [49]. Furthermore, for all the baselines in consideration, a 1σ uncertainty of 3% on the standard matter density was assumed. Besides, when we consider NSI matter effects from the $(e-\mu)$ sector, we set $|\epsilon_{e\mu}| = 0.19$ and $\phi_{e\mu} = 1.5\pi$ consistent with their best fit from Ref. [2]. In addition, matter NSI effects from the $(e-\tau)$ sector are set to their best-fit values from Ref. [1], $|\epsilon_{e\tau}| = 0.275$ and $\phi_{e\tau} = 1.62\pi$, all the remaining matter NSI parameters were fixed to zero.

IV. NSI SENSITIVITY

In this section, we outline the calculation of sensitivities to the NSI parameters. We employ a chi-squared test to quantify the statistical significance of matter NSI oscillations

[2] We have verified that our results do not significantly change by using the best fit values from Ref. [48].

using neutrino and antineutrino datasets. The χ^2 function[3] is given as

$$\chi^2 = \sum_{\ell} \tilde{\chi}^2_{\ell} + \chi^2_{\rm prior}, \quad (6)$$

where the corresponding $\tilde{\chi}^2_{\ell}$ function for each channel $\ell = (\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e), \nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu))$, which in the large data size limit is

$$\tilde{\chi}^2_{\ell} = \min_{\xi_j} \left[\sum_{e}^{N,F} \sum_{i}^{n_{\rm bins}} \frac{(N^{3\nu}_{i,e} - N^{3\nu+{\rm NSI}}_{i,e}(\Omega, \Theta, \{\xi_j\}))^2}{\sigma^2_{i,e}} + \sum_{j}^{n_{\rm syst}} \left(\frac{\xi_j}{\sigma_j}\right)^2 \right]. \quad (7)$$

The $N^{3\nu}_i$ are the simulated events at the ith energy bin considering the standard three neutrino oscillations framework. $N^{3\nu+{\rm NSI}}_i$ are the computed events at the ith energy bin with the model assuming matter NSI oscillations. $\Omega = \{\rho, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{21}, \Delta m^2_{31}\}$ is the set of matter density and oscillation parameters, $\Theta = \{|\epsilon_{e\mu}|, \phi_{e\mu}, |\epsilon_{e\tau}|, \phi_{e\tau}\}$ is the set of NSI parameters and $\{\xi_j\}$ are the nuisance parameters to account for the signal, background normalization, and energy calibration systematics respectively. Moreover, $\sigma_i = \sqrt{N^{3\nu}_i}$ is the statistical error in each energy bin, while σ_j are the signal, background normalization, and energy calibration errors (see Sec. III). The summation index e runs over either the corresponding (single) experiment at two different baselines (near and far) or the combination of two separate experimental setups. Furthermore, the implementation of external input for the standard oscillation parameters on the χ^2 function is performed via Gaussian priors

$$\chi^2_{\rm prior} = \sum_{k}^{n_{\rm priors}} \left\{ \frac{(\Omega_{k,{\rm true}} - \Omega_{k,{\rm test}})^2}{\sigma^2_k} + \frac{(\Theta_{k,{\rm true}} - \Theta_{k,{\rm test}})^2}{\sigma^2_k} \right\}, \quad (8)$$

the central values of the oscillation parameter priors Ω_k are set to their true or best-fit value for normal ordering [47], and the central values of the matter density change for the different experiments in consideration (see Sec. III). σ_k is the uncertainty on the oscillation prior, which corresponds to a 1σ error of 5% for Δm^2_{21}, Δm^2_{31}, θ_{12}, and θ_{23}, 3% for θ_{13}, 10% for the leptonic CP-violating phase δ_{CP} [49] and 3% for the matter density ρ. Furthermore, the central values of the priors Θ_k change depending on the hypothesis in consideration. When marginalization over NSI parameters from either the $e-\mu$ or $e-\tau$ sector is required, a 1σ error σ_k of 30% is assumed. The summation index k runs over the corresponding test oscillation parameters to be marginalized. Moreover, the expected number of events at the ith energy bin was calculated as in [50] (see, e.g., Ref. [42] as well).

V. RESULTS

In this section, we present our results for the different experimental configurations, emphasizing the matter NSI scenario (considering one $\epsilon_{\alpha\beta}$ parameter at a time) motivated by the discrepancy in the measurement of the leptonic CP-violating phase δ_{CP} experienced by NOvA and T2K [1,2]. We will focus on the constraints on the δ_{CP} phase in the presence of NSI. We will show the complementary between the ESSnuSB and other current proposals such as T2HKK and, especially, DUNE.

We will show the sensitivity to matter NSI parameters by combining two different long baseline experiments. We have studied the case of the ESSnuSB and its combined restrictive power when we also consider a DUNE-like (TDR) experiment. In this case we have taken into account either the ESSnuSB setup at 360 km or 540 km [51]. Since the ESSnuSB is still in a proposal, we have also computed the results of a ESSnuSB configuration with two LBL detectors, to see if the combination may help to improve the robustness of their CP phase measurement. We have also confronted this result with the case of the T2HKK proposal, that already considers two detectors in its experimental setup.

To illustrate, our analysis we will contrast two different cases: the standard three neutrino oscillation scenario and the case where NSI is present in matter evolution. In the first case, we calculate our results assuming the standard oscillation picture and fitting the data assuming a given true value of δ_{CP} and $\sin^2(\theta_{23})$ and varying for the test values. As stated in Sec. III, we consider as true values $\theta_{23} = 49.26°$ and $\delta_{CP} = 1.4\pi$. For the standard + NSI case, we have considered either the NSI parameters $\phi_{e\mu}$ and $|\epsilon_{e\mu}|$ or $\phi_{e\tau}$ and $|\epsilon_{e\tau}|$ as free parameters that are marginalized away in the fit, again for the same fixed true values of δ_{CP} and $\sin^2(\theta_{23})$. We will consider NSI parameters that are different from the SM case (*i.e.* different from zero), but that mimic the SM solution in the matter case as noted by the authors of Refs. [1,2]. In the following, we will show the results of the standard-only analysis as solid lines, while we will show the NSI case with dashed lines. Moreover, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), marginalizing over all NSI parameters, taking into account the bounds from IceCube and global analysis with and without CEνNS data from COHERENT [52,53].[4] The diagonal NSI parameters were varied from $|\epsilon_{ee} - \epsilon_{\mu\mu}| \leq 0.5$, $|\epsilon_{\tau\tau} - \epsilon_{\mu\mu}| \leq 0.04$,

[3]More details on the implementation of the χ^2 function, systematical errors and priors in the GLoBES software [21,22] can be found in [50].

[4]As shown in Figs. 9 and 12 of [52], the inclusion of CEνNS data (COHERENT) does not improve the constraints on the NSI parameters for $\Delta\chi^2 \lesssim 2\sigma$. Besides, the incorporation of COHERENT constraints are valid under certain considerations [2,52].

and we have considered $\epsilon_{\mu\mu} = 0$, taking advantage of the freedom to redefine the diagonal elements up to a global constant [15,31]. The corresponding off-diagonal entries were varied from $|\epsilon_{e\mu}| \leq 0.19$, $|\epsilon_{e\tau}| \leq 0.2$, $|\epsilon_{\mu\tau}| \leq 0.023$, and, finally, the extra NSI *CP*-phases were varied from $0 \leq \phi_{\alpha\beta} \leq 2\pi$. Although we do not consider the LMA-Dark region [54] in the SM + Full NSI analysis, we have also studied it and found that in this case the DUNE sensitivity to the *CP*-violating phase can be completely lost. For all cases, all the remaining standard oscillation parameters were marginalized.

A. DUNE + ESSnuSB

An interesting case is the expected sensitivity from the combination of a future DUNE-like detector and ESSnuSB with a baseline of 540 km. Before showing our results, we briefly summarize the main complementary characteristics of these two projects.

For the corresponding LBL experiments of interest, we can estimate an average matter density $\rho \sim 3.0$ g/cm^3. Besides, the approximate energy for MSW resonance occurs at $E \sim$ GeV. Since the flux for ESSnuSB (360 km or 540 km) peaks at $E \sim \mathcal{O}(0.1)$ GeV (see Fig. (1) of Ref. [55]), matter effects for this facility are not expected to be significant. Therefore, for our purposes, in the case of a standard three neutrino oscillation framework (SM) as well as the SM + NSI case, we assume $\delta_{CP} \sim 1.4\pi$ for ESSnuSB, which is consistent with the best fit from the similar experiment T2K [4,28]. Also, within this scenario, ESSnuSB should be able to measure a δ_{CP} value that is unaffected by the presence of matter NSI.

For the case of DUNE, with an average neutrino energy $E \sim 3$ GeV, the situation is opposite, and matter effects are expected to be relevant. In this case, we will consider $\delta_{CP} = 1.4\pi$ as the true value in both, the SM and SM + NSI scenarios.

We illustrate the above discussion in Fig. 1, where we show our results for the sensitivity to (δ_{CP}, $\sin^2\theta_{23}$) at 68% CL and 90% CL with and without the presence of NSI. In the left panel of this figure, we show the ESSnuSB 540 km configuration, and the corresponding case for a experiment of the type of DUNE appears in the right panel. As mentioned, the solid lines refer to the standard oscillation case, and the dashed ones stand for the NSI sensitivity. For both standard and NSI analysis, we have marginalized all other standard oscillation parameters. In the NSI case, we consider the flavor-changing $e\mu$ case, marginalized considering a 1σ error of 30% around their best fit ($|\epsilon_{e\mu}| = 0.19$, $\phi_{e\mu} = 1.5\pi$) from [2]. We can see that ESSnuSB sensitivity to the mixing angle is worse than the expected sensitivity in DUNE, while the sensitivity to the δ_{CP} phase is better for the ESSnuSB proposal. In addition, from the left panel of Fig. 1, we observe that after matter NSI affects are included at ESSnuSB, the determination of the δ_{CP}-phase and the mixing angle θ_{23} is practically unchanged.

In order to observe the effect of the combined sensitivity of these two proposals, we display in Fig. 2 our results of the allowed 68% CL and 90% CL contours in the (δ_{CP}, $\sin^2\theta_{23}$) plane for the combined DUNE-like and ESSnuSB 540 km setup. We have marginalized all other standard oscillation parameters.

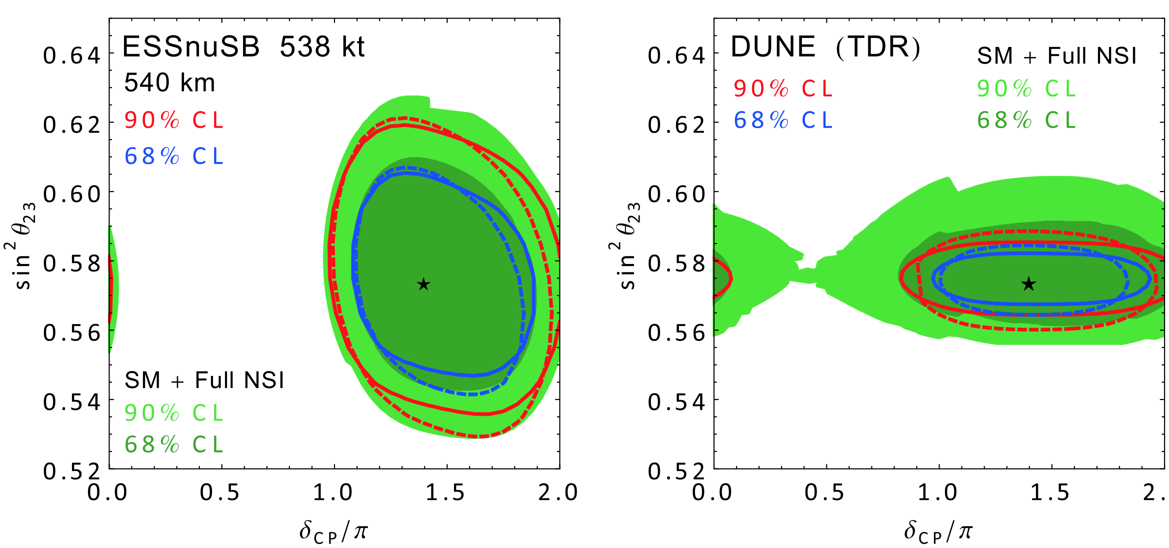

FIG. 1. Expected allowed regions in the (δ_{CP}, $\sin^2\theta_{23}$) plane. The standard 3ν scenario (SM) is displayed in (solid lines) while (dashed lines) show the case with (SM + NSI) assuming the best fit values ($|\epsilon_{e\mu}| = 0.19$, $\phi_{e\mu} = 1.5\pi$) from Ref. [2]. The left panel presents an ESSnuSB setup at 540 km from the source while the right panel sets the DUNE-like (TDR) configuration. Finally, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), see text for a detailed explanation.

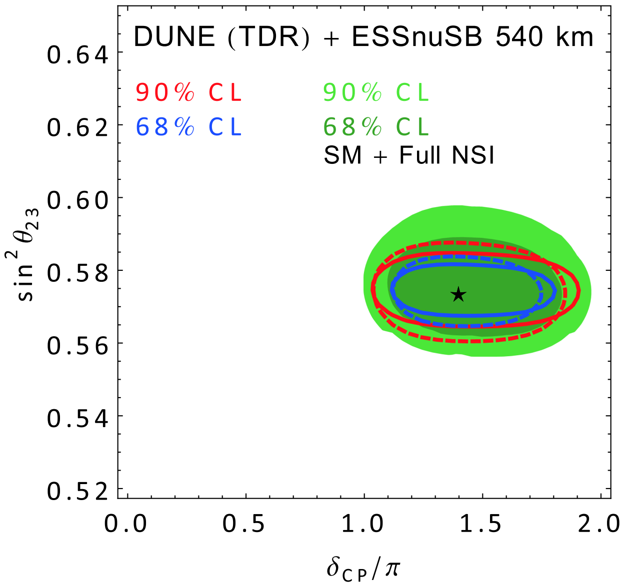

FIG. 2. Expected allowed regions in the (δ_{CP}, $\sin^2\theta_{23}$) plane plane for the combined DUNE-like (TDR) and ESSnuSB 540 km configuration. The standard 3ν oscillation framework (SM) is show in (solid lines) while (dashed lines) display the scenario with (SM + NSI) assuming the best fit values ($|\epsilon_{e\mu}| = 0.19$, $\phi_{e\mu} = 1.5\pi$) from Ref. [2]. Finally, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), see text for a detailed explanation.

We can also study the case of an $e\tau$ flavor-changing NSI to identify its impact on the sensitivity to the *CP*-violating phase. For this purpose, in Fig. 3, we show the effect of nonzero matter NSI parameters ($\epsilon_{e\tau}$) on the sensitivity to the Dirac *CP*-violating phase δ_{CP} and the mixing angle θ_{23}. The corresponding allowed 68% CL and 90% CL contours in the (δ_{CP}, $\sin^2\theta_{23}$) plane are displayed. The left panel refers to the ESSnuSB 360 km configuration, while the right panel assumes the DUNE (TDR) case. We have marginalized all other standard oscillation parameters. Besides, the ($|\epsilon_{e\tau}|$, $\phi_{e\tau}$) parameters are marginalized, considering a 1σ error of 30% around the best fit ($|\epsilon_{e\tau}| = 0.275$, $\phi_{e\tau} = 1.62\pi$) quoted in [1]. We observe that the ESSnuSB sensitivity to the mixing angle is worse than the expected sensitivity in DUNE, while the sensitivity to the δ_{CP} phase is slightly better for the ESSnuSB proposal. Moreover, from Figs. 1 and 3, we observe that if $\delta_{CP} \sim 1.4\pi$ is realized in nature, a DUNE-like experiment still allows the best fit from NOvA, $\delta_{CP} \sim 0.8\pi$ at 90% CL. On the other hand, either of the ESSnuSB configurations will be able to exclude the NOvA best fit at 90% CL.

We also show, in Fig. (4), the impact of nonzero matter NSI parameters ($\epsilon_{e\tau}$) on the expected sensitivity of the Dirac *CP*-violating phase δ_{CP} and the mixing angle θ_{23}. The corresponding expected sensitivity at 68% CL and 90% CL is displayed in this figure. We have marginalized all other standard oscillation parameters.

B. Two baseline configuration

In this subsection, we investigate the constraining power to matter NSI parameters using a single experiment with two baselines (ESSnuSB or T2HKK). Such a setup can probe matter NSI effects within the NSI framework [1,2]. Although the ESSnuSB proposal has not considered

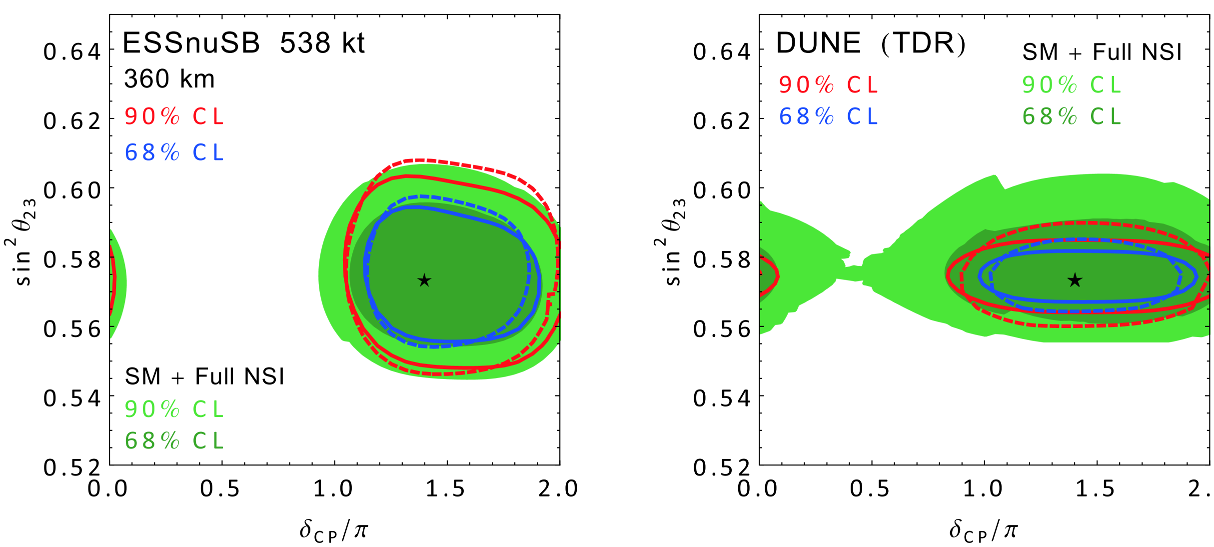

FIG. 3. Expected allowed regions in the (δ_{CP}, $\sin^2\theta_{23}$) plane. The standard 3ν framework (SM) is show in (solid lines) while (dashed lines) display the scenario with (SM + NSI) assuming the best fit values ($|\epsilon_{e\tau}| = 0.275$, $\phi_{e\tau} = 1.62\pi$) from Ref. [1]. The left panel presents an ESSnuSB setup at 360 km from the source while the right panel sets the DUNE-like (TDR) configuration. Finally, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), see text for a detailed explanation.

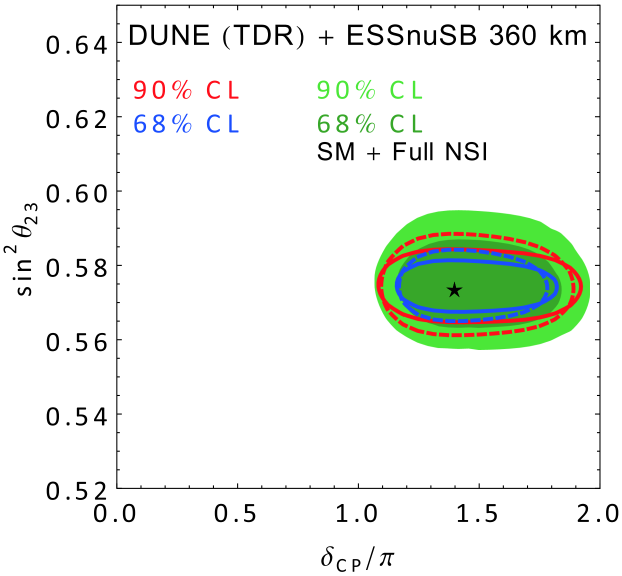

FIG. 4. Expected allowed regions in the (δ_{CP}, $\sin^2\theta_{23}$) plane for the combined DUNE-like (TDR) and ESSnuSB 360 km configuration. The standard 3ν framework (SM) is show in (solid lines) while (dashed lines) display the scenario with (SM + NSI) where we set ($|\epsilon_{e\tau}| = 0.275$, $\phi_{e\tau} = 1.62\pi$), corresponding to the best fit values from Ref. [1]. Finally, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), see text for a detailed explanation.

the use of two different baselines simultaneously, it is worth it to study this possibility now that the project is in its first stages. In the following subsections, we will assume that such a setup is feasible. We will work under the hypothesis that both detectors can be considered as aligned with the beam, implying an on-axis neutrino flux for both.

Regarding a two baseline configuration at ESSnuSB, from the existing mines in Sweden, the corresponding Renstrom mine is located at a distance of $L \sim 1090$ km from the source at Lund, while the Garpenberg mine is located at $L \sim 540$ km. Both mines are at roughly 1 km depth. Besides increasing sensitivity to δ_{CP}, θ_{23}, and NSI from more exposure to SB neutrinos, a second detector at the Renstrom mine will contribute to the full physics program at ESSnuSB, which is the measurement of proton decay, atmospheric (solar) neutrinos, supernovae neutrinos, and geoneutrinos [12,40,49].

Moreover, we consider as a possibility, a detector located at 200 km from the source at Lund with a second detector placed at the Garpenberg mine at 540 km. For instance, the authors of Ref. [56] explored the physics potential at ESSnuSB (200, 360, 540) km baselines, respectively, within the nonunitarity of the leptonic mixing matrix scenario. Although, no available mines aligned with the Garpenberg mine, and the source at Lund exists at 200 km. We will illustrate the benefits of such an arrangement to probe the aforementioned matter NSI framework. However, the ESSnuSB 200–540 km configuration might not accomplish the complete ESSnuSB physics program [40].[5]

We also consider the case of the T2HKK experiment, where we employ the configurations from [44]. This study can provide a preliminary perspective of the T2HKK constraining power within the matter NSI framework [1,2]. For this experimental setup, we also show the results for the expected sensitivity to the flavor-changing NSI parameters for both ($\phi_{e\mu}$ and $|\epsilon_{e\mu}|$) and ($\phi_{e\tau}$ and $|\epsilon_{e\tau}|$) since the perspectives are promising in this case.

As shown in Fig. 5, the expected allowed contours in the corresponding ($|\epsilon|$, ϕ) planes are consistent with the allowed regions determined by the combination of the NOvA and T2K datasets from the left panel of Fig. 2 [1]. However, as already noticed, the IceCube DeepCore [53] constraints exclude most part of the preferred parameter space. For comparison, we can notice that, as discussed in Ref. [13], a DUNE-like experiment will be able to determine the matter NSI parameters from the ($e-\mu$) and ($e-\tau$) sectors with a precision of around [10–20]% for the NO.

1. Impact of NSI on oscillation precision measurements

In this subsection, we consider the effects of matter flavor changing ($e-\mu$) NSI parameters on the oscillation parameters. More precisely, the expected allowed regions in the ($\delta_{CP}, \sin^2\theta_{23}$) plane for both, the SM as well as the (SM + NSI) scenario will be shown. Both electron neutrino appearance and muon neutrino disappearance events are considered in our analysis, while all the remaining oscillation parameters are marginalized. Furthermore, for the matter NSI, the ($|\epsilon_{e\mu}|$, $\phi_{e\mu}$) parameters are marginalized, considering a 1σ error of 30% around the true values ($|\epsilon_{e\mu}| = 0.19, \phi_{e\mu} = 1.5\pi$), which were fixed to their best fit from Ref. [2] (see, e.g., Fig. 2). In addition, we display in solid green contours (SM + Full NSI) the expected sensitivities marginalizing over all the matter NSI parameters.

In Fig. 6, we introduce our results for the expected sensitivity at 68% CL and 90% CL in the (δ_{CP}, $\sin^2\theta_{23}$) plane. The left panel shows the ESSnuSB 540-1090 km setup, the middle panel displays the corresponding ESSnuSB 200-540 km configuration, and the rightmost panel shows the corresponding T2HKK setup. Besides the standard three neutrino mixing scenario, we have included the effects of nonzero matter NSI parameters from the ($e-\mu$) sector.

[5]While it is true that the alignment of the two detectors setup is a rough approximation (there should be some off-axis neutrino-flux), our implementation of a two-detector ESSnuSB configuration gives a perspective on the future determination of the *CP*-phase in the presence of NSI at ESS, which can be complementary to the T2HKK proposal and may justify a further, more detailed study.

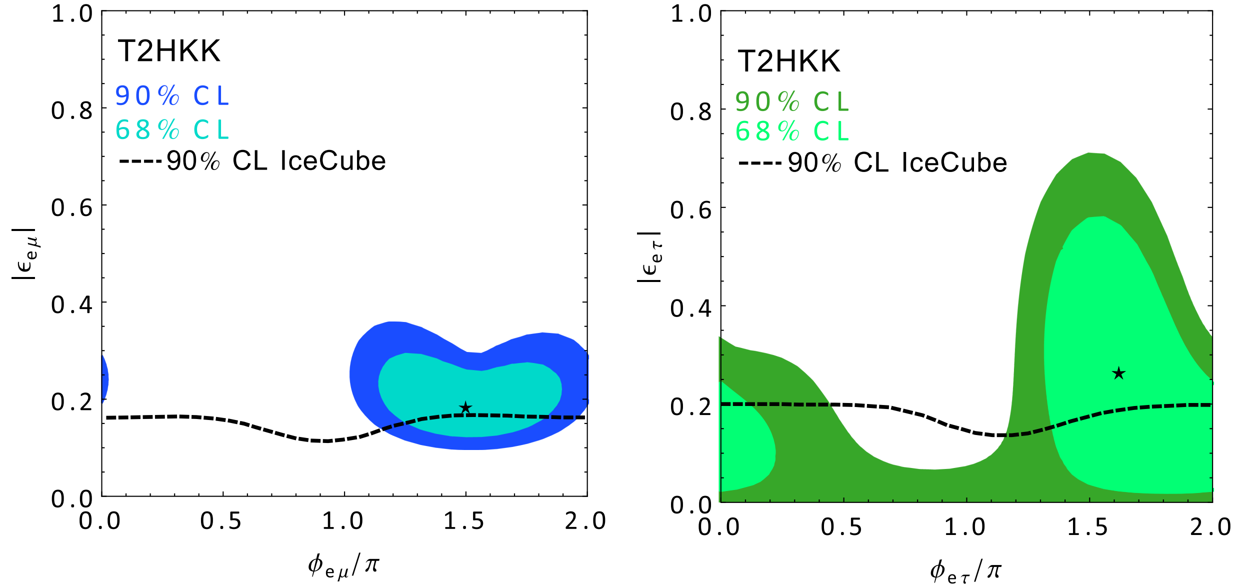

FIG. 5. Expected allowed regions in the ($|\epsilon|$, ϕ) plane for the T2HKK OA2° configuration. Assuming NSI best fit values from Refs. [1,2]. Furthermore, we also show the 90% CL bounds from the IceCube DeepCore data [53].

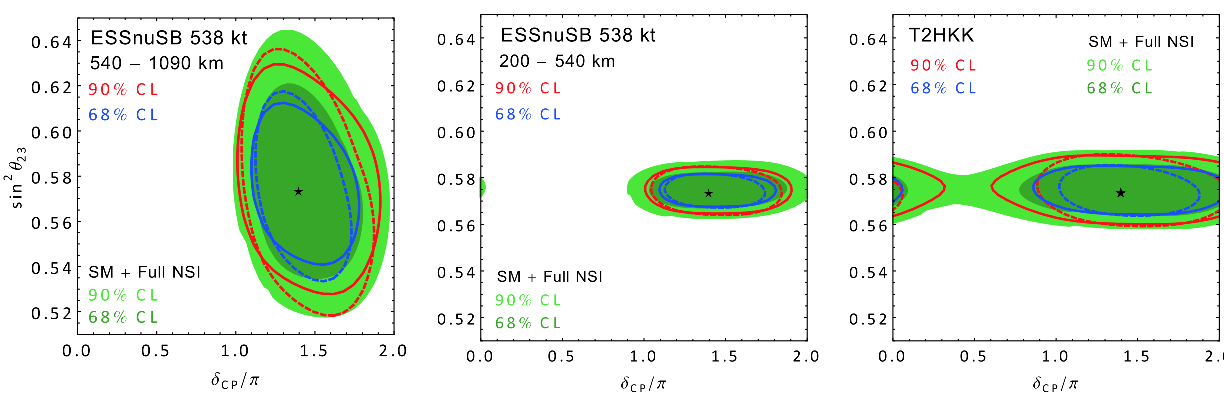

FIG. 6. Expected allowed regions in the (δ_{CP}, $\sin^2\theta_{23}$) plane. The standard 3ν oscillation framework (SM) is show in (solid lines) while (dashed lines) display the scenario with (SM + NSI) where we set ($|\epsilon_{e\mu}| = 0.19$, $\phi_{e\mu} = 1.5\pi$), corresponding to the best fit values from Ref. [2]. The left and middle panels display the ESSnuSB setup with two baselines at either 540–1090 km or 200–1090 km from the source, while the rightmost panel sets the T2HKK configuration. Finally, we display in green solid contours the expected allowed regions considering all the NSI entries (SM + Full NSI), see text for a detailed explanation.

From the figure shown above, we can notice that, for the future precision measurements of the Dirac CP-violating phase δ_{CP}, even in the presence of matter NSI, the determination of δ_{CP} at ESSnuSB would not be considerably affected. Therefore at ESSnuSB, the determined value of δ_{CP} can be considered a faithful estimate of its true value both in the SM and in the SM + NSI scenarios. Moreover, even if the leptonic CP-phase $\delta_{CP} = (0 \text{ or } \pi)$, ESSnuSB will be able to measure the possible NSI phases for large enough values of the flavor changing parameter, $|\epsilon|$, as shown, for example, in Fig. 3 of Ref. [19]. On the other hand, for DUNE (right panel Fig. 1) and T2HKK (rightmost panel of Fig. 6), the presence of matter NSI modifies the determination of δ_{CP}. As far as the mixing angle θ_{23} precision is concerned, the inclusion of matter NSI does not have a significant impact on its determination at T2HKK. On the other hand, the determination of the mixing angle, θ_{23}, would be slightly affected at the ESSnuSB 540–1090 km configuration.

VI. CONCLUSIONS

This paper analyzed the determination of the leptonic CP-violating phase, δ_{CP}, in the presence of matter NSI from the flavor-changing $e\mu$ and $e\tau$ sectors, as well as the incorporation of all the NSI parameters at several future

LBL setups. We show that the ESSnuSB setup, located at 540 km or 360 km (a practical vacuum oscillation experiment), will be able to determine a faithful value of δ_{CP} regardless of matter NSI effects. On the other hand, if the NOvA and T2K discrepancy on the *CP*-phase measurement continues, a DUNE-like experiment, where matter effects are significant, will be capable of determining the corresponding matter NSI parameters with compelling precision, as shown in Ref. [13]. Moreover, we have illustrated that DUNE will offer a superior sensitivity to the atmospheric mixing angle, θ_{23}, relative to the ESSnuSB configuration. We have also shown that to obtain a reliable measurement of δ_{CP}, the combination of ESSnuSB and DUNE synergies would be beneficial.

In addition, we investigated the constraining power for the leptonic *CP*-phase value at several experimental configurations with two baselines. The ESSnuSB 540–1090 km setup can contribute to the full physics program at ESSnuSB while being able to determine the Dirac *CP*-phase at good precision. Furthermore, the ESSnuSB 200–540 km configuration offers an opportunity to improve precision measurements on δ_{CP} as well as θ_{23}, with respect to the single baseline ESSnuSB setup. Last but not least, within the aforementioned scenario, the T2HKK proposal will have a notable sensitivity to the matter NSI parameters. The restrictive power to the leptonic *CP*-phase may be modest in the configuration that we have studied. However, its determination of the atmospheric mixing angle θ_{23} is robust with respect to matter effects.

ACKNOWLEDGMENTS

We would like to thank L. J. Flores for his participation in early stages of this project. This work was partially supported by SNII-México and CONAHCyT research Grant: A1-S-23238. We acknowledge the anonymous referee for the illuminating comments and suggestions.

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