

Alleviating the present tension between T2K and NO ν A with nonstandard neutrino interactions

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Since neutrino oscillation was observed, several experiments have been built to measure its parameters. NuMI Off-axis ν_e Appearance (NO ν A) and Tokai-to-Kamioka (T2K) are two long-baseline experiments dedicated to measuring mainly the mixing angle θ_{23} , the charge-parity (CP) conjugation phase δ_{CP} , and the mass ordering. However, there is a tension in current data. The T2K allowed region is in conflict with the region allowed by NO ν A. We propose a nonstandard charged current interaction (CC-NSI) in neutrino production to relieve this tension. The CC-NSI is computed through quantum field theory formalism, where we derive perturbative analytical formulae considering CC-NSI in the pion decay. Within this new approach, we can alleviate NO ν A and T2K tension for CC-NSI complex parameters of order 10^{-3} . We show the new phase has a degeneracy to the Dirac CP phase of the form $\delta_{CP} \pm \phi = 1.5\pi$, being a possible source of violation of charge-parity symmetry.

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I. INTRODUCTION

The neutrino oscillation phenomenon provides evidence of physics beyond the standard model. Since its discovery, several experiments have measured neutrino oscillation parameters [1–4]. One not yet measured is the charge-parity (CP) conjugation phase δ_{CP} that quantifies the asymmetry between particle and antiparticle. The two long-baseline accelerator experiments, NuMI Off-axis ν_e Appearance (NO ν A) and Tokai-to-Kamioka (T2K), were designed to measure this parameter.

The NO ν A and T2K allowed parameter regions are in tension for some time [1,4–6], and it persists in new data [7,8]. In the standard three-neutrino oscillation scenario, each individual experiment has a preference for normal ordering, while their combination indicates a preference for inverted ordering. These results could indicate physics beyond the standard model (BSM). Numerous studies have been dedicated to explaining this tension, exploring various new physics

scenarios, such as nonunitary mixing matrix [9–11], neutral current nonstandard interaction (NSI) in propagation [12–16], light and very light sterile neutrinos [17,18], Lorentz violation [19,20], and dark photon scenarios [21–23].

We propose a novel approach that includes charged current nonstandard interactions (CC-NSI) in neutrino production specifically via pion decay. By adopting an effective field theory (EFT) approach [24–35], we can straightforwardly modify the rate of pion decay to include these nonstandard interactions during production. We have derived, for the first time, a perturbative analytical expression for a neutrino oscillation in matter considering this new interaction at the source. As there are stringent bounds coming from pion decay experiments [36], one may wonder how much room there is for BSM physics to still alleviate the tension. We will show that our proposal not only decreases tension but also provides a better fit to the present data.

The new coupling constant may be complex, which introduces a new charge-parity violation phase. We investigated the interaction between the two phases: one originating from the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix [37,38] and the other from the effects of the new interaction.

In this letter, we demonstrate that the tension is alleviated even if only one new complex parameter can be nonzero.

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We have determined that the absolute value of the new interaction parameter is $(10^{-4}-10^{-3}) \times G_F$, the Fermi constant.

II. NEW PHYSICS IN NEUTRINO SECTOR FROM AN EFT PERSPECTIVE

We consider the nonstandard interactions on neutrino production essentially following the formalism introduced in [24,25,27,31]. The new physics is described by Wilson coefficients of four-fermion effective interactions between neutrinos (ν_β), charged leptons (l_α), and quarks (q_i), $\sim \bar{q}_i \Gamma_A^{ij} q_j \bar{\ell}_\alpha \Gamma'_A{}^{\alpha\beta} P_L \nu_\beta$, where $i, j = u, d, c, s, \dots$ and $\alpha, \beta = e, \mu, \tau$. The index A corresponds to the Lorentz indices of the interaction. All possible combinations of the vertex structure are encoded in Γ, Γ' . Typically, neutrinos are produced via pion decay, and only vector, axial, and pseudoscalar couplings with $q_i = u$, $q_j = d$ contribute. In this letter we only consider the latter, which could be generated by models containing extra pseudoscalars, for instance. We emphasize that, by suitable normalization, our results can be translated to the other cases as well. Explicitly, the effective Lagrangian will then contain the term [24,25,27,31]

$$\mathcal{L}_P \supset \sqrt{2} G_F V_{ud}^{\text{CKM}} \epsilon_{\alpha\beta} (\bar{u} \gamma^5 d) (\bar{\ell}_\alpha P_L \nu_\beta) + \text{H.c.}, \quad (1)$$

where V^{CKM} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix [39,40] and G_F is the Fermi constant. Furthermore, $\epsilon_{\alpha\beta}$ are complex Wilson coefficients that describe the magnitude of the new interaction relative to the weak interaction. The new interaction in Eq. (1) creates another vertex for neutrino production beyond the traditional one [41]. With the new vertex, the total matrix element is a combination of the standard model amplitude ($\mathcal{A}_L^S$) and the new physics amplitude ($\mathcal{A}_P^S$),

$$\mathcal{M}_{ak}^S = U_{ak}^* \mathcal{A}_L^S + [\epsilon U]_{ak}^* \mathcal{A}_P^S. \quad (2)$$

The upper index, S , for the source indicates that the process occurs only in production, since the detection process induced by a pseudoscalar is extremely suppressed [24,25,27]. Therefore, there are no relevant effects on the detection of the new interactions. It should be emphasized that neutrino mass eigenstates are encoded exclusively in PMNS mixing matrices [37,38], so that amplitudes $\mathcal{A}_{L/P}^S$ depend solely on the neutrino flavor. Notice that the off-diagonal terms of $\epsilon_{\alpha\beta}$ violate the lepton flavor number.

III. NEUTRINO EVENT RATE IN THE QFT FORMALISM

The event rate is the physical observable in neutrino oscillation experiments. In the formalism of quantum field

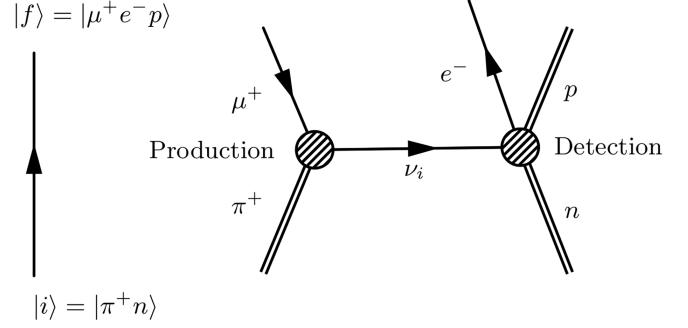


FIG. 1. Quantum field theory computation of neutrino oscillation probability [24–35].

theory (QFT), neutrino production, propagation, and detection are considered a single process. Therefore, the neutrino oscillation is quantified by a single tree diagram, as illustrated in Fig. 1 by the decay $\pi^+ \rightarrow \mu^+ + \nu$ (production) followed by detection $\nu + n \rightarrow p + e^-$. The time direction is from bottom to top. In the production and detection processes, the initial states are the pion and neutron. The detected particles (e.g., charged leptons and protons) are regarded as final states [41]. The neutrino participates in the process as an intermediate state, where the uncertainties of the initial state result in the superposition of massive neutrino states [42].

In this formalism, the neutrino event rate, including CC-NSI in production, is [24,25,27]

$$R_{\alpha\beta}^{\text{CC-NSI}} = \kappa \sum_{kj} e^{-i\Delta_{kj}} \mathcal{U}_{\beta k} \mathcal{U}_{\alpha j}^* \times \int d\Pi_S \mathcal{M}_{ak}^S \overline{\mathcal{M}}_{aj}^S \times \int d\Pi_D |\mathcal{A}_L^D|^2, \quad (3)$$

where α and β denote produced and detected flavor states, respectively, κ is a constant that includes the kinematical factors and target size, $\Delta_{kj} \equiv \frac{\Delta m_{kj}^2 L}{2E_\nu}$, with E_ν being the neutrino energy, L the source-detector distance, and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ the neutrino mass squared difference, and the amplitude $\mathcal{M}_{ak}^S$ is given in Eq. (2). The integrals are over the phase space elements for source (S) and detection (D). We denote by $\mathcal{U}$ the PMNS mixing matrix [37,38] in constant matter [43,44].

The event rate, Eq. (3), is associated with the oscillation probability by the definition: $P_{\alpha\beta}^{\text{NSI}} \equiv R_{\alpha\beta}^{\text{NSI}} / \phi_\alpha^{\text{SM}} \sigma_\beta^{\text{SM}}$, corresponding to the transition $\nu_\alpha \rightarrow \nu_\beta$. It is conveniently written¹ as

$$P_{\alpha\beta}^{\text{CC-NSI}} = \sum_{kj} e^{-i\Delta_{kj}} [(\mathbb{1} - p_\alpha \epsilon) \mathcal{U}]_{ak}^* [(\mathbb{1} - p_\alpha \epsilon) \mathcal{U}]_{aj} \mathcal{U}_{\beta k} \mathcal{U}_{\alpha j}^*, \quad (4)$$

¹This formula is original and it was never published before.

where $p_\alpha = m_\pi/(m_\alpha(m_u + m_d))$, for example, $p_\mu \sim 27$ and $p_e \sim 5500$ represent a chiral enhancement compared to the standard model rate [45]. This is the reason that we choose the pseudoscalar scenario, since the standard model rate is chirality suppressed.

In the end, the effect of CC-NSI consists of substituting the matrix $\mathcal{U}_{ai}$ by $[(1 - p_\alpha \epsilon)\mathcal{U}]_{ai}$. Although we have named Eq. (4) as the probability because of its similarity to the traditional form, the presence of CC-NSI makes the expression effectively unitarity-violating.

In order to analyze the impact of individual CC-NSI parameters on the oscillation probability, we consider two scenarios corresponding to a new source for muon or electron neutrinos. In the EFT formalism, they are implemented by allowing for only one nonzero Wilson coefficient at a time, $\epsilon_{\mu e}$ or $\epsilon_{e\mu}$, respectively. For the experimental analyses of interest, the parameter $\epsilon_{\mu e}$ will modify the signal and $\epsilon_{e\mu}$ will affect the background. In the following, we will discuss the $\epsilon_{\mu e}$ scenario to exemplify the perturbative formalism. Because the initial state in pion decay is muonic

neutrino, we need to calculate the probability $P_{\mu\beta}$. We write for the first time an analytical formula for Eq. (4) in terms of the evolution operator $S^{\text{OSC}} \equiv e^{-iHt}$ for the neutrino Hamiltonian, defined in a standard oscillation scenario. Therefore,

$$P_{\mu\beta}^{\text{CC-NSI}} = |S_{\beta\mu}^{\text{OSC}} - p_\mu \epsilon_{\mu e}^* S_{\beta e}^{\text{OSC}}|^2, \quad (5)$$

where the complex coefficient is explicitly $\epsilon_{\mu e} \equiv |\epsilon_{\mu e}| e^{i\phi_{\mu e}}$. The advantage of writing the probability above is that there is, in the literature, the analytical expression for S^{OSC} with matter effects [46]. It can also be straightforwardly generalized to other CC-NSI scenarios, and other conversion/survival rates.

The most important equation of this paper is the $\nu_\mu \rightarrow \nu_e$ probability with CC-NSI, using an analytical expression *in matter*. We have derived it employing a perturbative approach [46], where the leading terms are given by

$$P_{\mu e}^{\text{NSI}} = 4 \frac{s_{13}^2 s_{23}^2}{(1 - r_a)^2} \sin^2 \frac{(1 - r_a)\Delta L}{2} + \frac{8J_r r_\Delta}{r_a(1 - r_a)} \cos \left(\delta_{\text{CP}} + \frac{\Delta L}{2} \right) \sin \frac{r_a \Delta L}{2} \sin \frac{(1 - r_a)\Delta L}{2} \\ + p_\mu^2 |\epsilon_{\mu e}|^2 + 4p_\mu |\epsilon_{\mu e}| \frac{s_{13} s_{23}}{1 - r_a} \sin \left(\frac{(1 - r_a)\Delta L}{2} \right) \sin \left(\delta_{\text{CP}} - \phi_{\mu e} + \frac{(1 - r_a)\Delta L}{2} \right) + \mathcal{O}(r_\Delta s_{13}, s_{13}^3). \quad (6)$$

From the phenomenological nature of the parameters, $r_\Delta \equiv \Delta m_{21}^2 / \Delta m_{31}^2 \simeq \zeta$ and $\sin \theta_{13} \simeq \sqrt{\zeta}$, with $\zeta \sim \mathcal{O}(10^{-2})$. We also define $\Delta = \Delta m_{31}^2 / 2E_\nu$, L is the distance between the source and detector, and $r_a = a/\Delta$, with $a = \sqrt{2}G_F N_e$ being the matter potential and the reduced Jarskog factor [47,48], $J_r = c_{12}s_{12}c_{23}s_{23}s_{13}$, in shorthand notation $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$. The probability of antineutrino retains the form of Eq. (6) with the replacements $\delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$, $\phi_{\mu e} \rightarrow -\phi_{\mu e}$, and $a \rightarrow -a$.

The analytical formulae are very useful to identify the sources of CP violation. In the standard oscillation scenario, we recall that the survival probability ($P_{\alpha\alpha} = |S_{\alpha\alpha}^{\text{OSC}}|^2$ for neutrinos of flavor α) is a CP -even quantity. Thus, CP -odd effects can only come from processes involving the conversion of flavor between neutrinos (given by $P_{\beta\alpha} = |S_{\alpha\beta}^{\text{OSC}}|^2$ with $\beta \neq \alpha$). In the presence of CC-NSI, this reasoning does not hold, as can be easily checked by considering $\beta = \mu$ in Eq. (5). The case with $\beta = e$ is even more instructive. First, it follows directly from Eq. (5) that the terms quadratic dependent on $|\epsilon_{\mu e}|$ will not depend on δ_{CP} . Second, the leading-order terms given in Eq. (6) show that the presence of CC-NSI induces a term dependent on the difference of phases ($\delta_{\text{CP}} - \phi_{\mu e}$). Since the ratio between the standard CP -violation term in the first line of Eq. (6) (proportional to J_r) to the last term is of order ζ ,

for $p_\mu |\epsilon_{\mu e}| \sim 27 |\epsilon_{\mu e}| > \zeta \sim \mathcal{O}(10^{-2})$, the CC-NSI term may dominate, implying that the experiment may be more sensitive to the difference ($\delta_{\text{CP}} - \phi_{\mu e}$) than the standard CP phase itself. We will show this tendency when we present our numerical results.

Finally, the perturbative formula is in good agreement with the exact one. In fact, most of the energy range of the experiments discussed here exhibits an error of less than one percent [41], including the region of interest for the NO ν A and T2K experiments.

IV. EXPERIMENTAL AND SIMULATION DETAILS

We analyze the effects of CC-NSI in neutrino production by pion decay through two long-baseline experiments: NO ν A and T2K.

The NO ν A experiment [7,49–51] measures muonic neutrino disappearance and electronic neutrino appearance. Its beam is located in the Fermilab laboratory in the United States and it travels 810 km to the detector in Minnesota. Neutrinos go through a matter density of $\rho_{\text{NO}\nu\text{A}} = 2.84 \text{ g/cm}^3$. We adopt the configuration of $13.6(12.5) \times 10^{20}$ protons on target (POT) for (anti)neutrino mode. The mass of the target detector is 14 kt and the neutrino energy range is from 1 up to 5 GeV, with energy spectra peaked at 2.1 GeV.

The T2K experiment [8,52–54] also measures muonic neutrino disappearance and electronic neutrino appearance. The beam is produced at J-PARC laboratory in Japan and travels 295 km to the Super-Kamiokande detector. The density of matter in this experiment is $\rho_{\text{T2K}} = 2.6 \text{ g/cm}^3$. The T2K flux has $19.7(16.3) \times 10^{20}$ POT for the (anti) neutrino mode. The detector has a target mass of 22.5 kt, and the neutrino energy range is from 0.1 to 1.25 GeV, with energy spectra peaked at 0.6 GeV.

The detector response was obtained using the GENIE software [55,56] to model the interaction cross section and the final state distributions, while the energy reconstruction was performed through our own Monte Carlo codes. We use GLOBES [57,58] to calculate the oscillation probabilities and obtain the number of detected events, according to Eq. (3), and to perform the statistical analysis. We fix the solar parameters to their best-fit values [36] $\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2$ and $\sin^2 \theta_{12} = 0.307$, minimizing the function χ^2 over all the other relevant parameters. We put a Gaussian prior on the reactor angle $\sin^2 2\theta_{13} = 0.083 \pm 0.0031$ because it is well measured by other experiments [59–61]. We then present in the following section a quantitative analysis of our model, and the allowed region

for oscillation and CC-NSI parameters for NO ν A and T2K individually as well as combined.

V. ALLEVIATING THE T2K AND NO ν A TENSION

The CC-NSI changes the neutrino oscillation probability, as seen in Eq. (6). In particular, it modifies the dependence on the CP -violation parameters. In the standard oscillation scenario, a common way to illustrate the impact of the still unknown δ_{CP} parameter is to consider the idea of bi-events [62–67] in the plane of electron-neutrino versus antielectron rates. We adopt the same idea here, but for the CC-NSI scenario.

In Fig. 2 we illustrate the influence of the complex CC-NSI by showing the total expected number of events N_e and $\bar{N}_e$ for the conversions $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, respectively. The ellipses [62,67] are generated varying the value of the CP phase, with the remaining parameters being the combined best-fit values for NO ν A and T2K. We consider the two possible mass orderings, the so-called normal ordering (NO) and inverted ordering (IO). In the left (right) panel we use the distance L typical parameter for the NO ν A (T2K) experiment. We also show as dots the best-fit value for δ_{CP} . In the

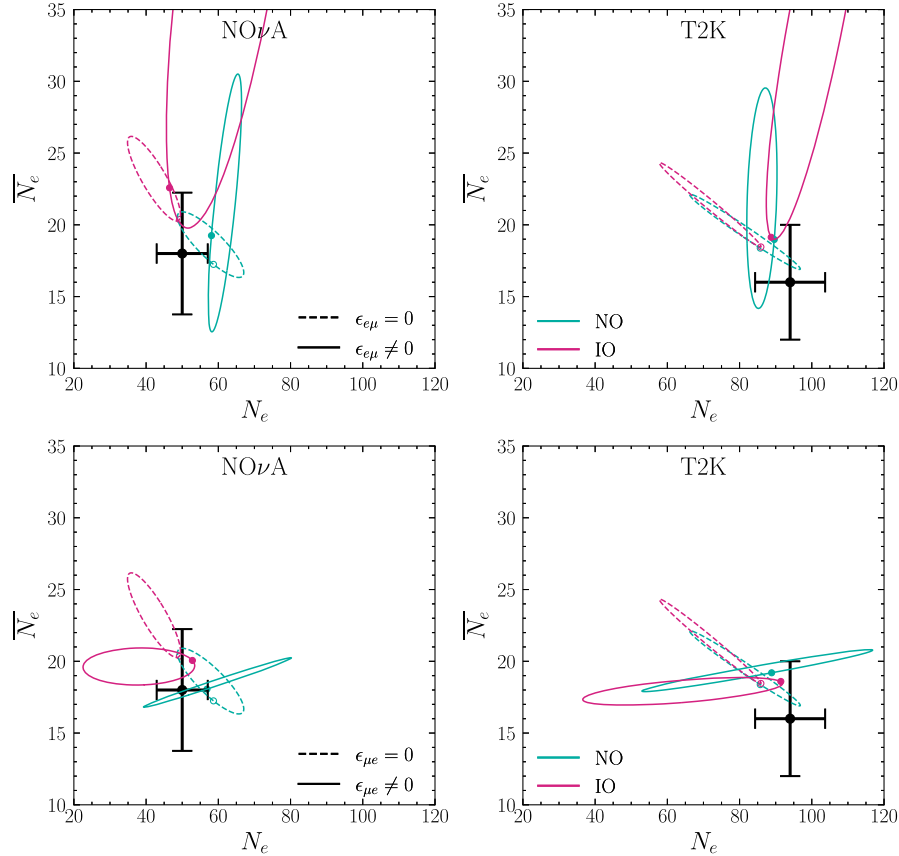


FIG. 2. Bi-events plot in the plane electron number of events and antielectron number of events for NO ν A in the left panel and for T2K in the right panel, while varying δ_{CP} with (solid lines) and without (dashed lines) CC-NSI, in the NO (blue lines) and IO (pink lines). The other parameters are fixed, as explained in the text. Filled (hollow) dots denote the best-fit values of solid (dashed) lines, while crosses represent estimated values of the total number of events given by each collaboration [7,8].

TABLE I. The best-fit values for the NO with the CC-NSI $\epsilon_{e\mu}$ or $\epsilon_{\mu e}$, for the combination NO ν A + T2K. The values in parentheses were obtained after including the bound from the pion decay. In the last line, the plus (minus) sign is for $\epsilon_{e\mu}$ ($\epsilon_{\mu e}$). The phases δ_{CP} and ϕ_X are invariant under addition of multiples of 2π .

NO	$\epsilon_{e\mu} \neq 0$	$\epsilon_{\mu e} \neq 0$
$\sin^2 \theta_{23}/10^{-1}$	5.68 (5.68)	5.69 (5.69)
δ_{CP}/π	1.74 (1.35)	1.08 (1.06)
$ \epsilon_X /10^{-3}$	0.72 (0.70)	1.12 (1.09)
ϕ_X/π	-0.32 (0.08)	-0.49 (-0.53)
$(\delta_{CP} \pm \phi_X)/\pi$	1.42 (1.43)	1.57 (1.59)

standard oscillation scenario, the best-fit parameters are $\sin^2 \theta_{23} = 0.57$, $\Delta m_{31}^2 = 2.50(-2.38) \times 10^{-3} \text{ eV}^2$, and the CP phase $\delta_{CP}/\pi = 1.10(1.51)$, for NO (IO). In the presence of CC-NSI, these best-fit parameters are indicated in Table I, and the squared mass difference for NO is $\Delta m_{31}^2 = 2.50(2.47) \times 10^{-3} \text{ eV}^2$ for the scenario with CC-NSI $\epsilon_{e\mu}$ ($\epsilon_{\mu e}$). For IO, in both scenarios the best-fit value is $\Delta m_{31}^2 = -2.38 \times 10^{-3} \text{ eV}^2$. The experimental value of the total rate for the electron and antielectron neutrinos is represented by the black cross.

For the best-fit values of the CC-NSI parameters, we notice the ellipses change appreciably even though $\epsilon_{\mu e}$ is of order 10^{-3} . The noticeable changes are due to the chiral enhancement term presented in the pion decay $p_\mu \sim 27$, which is always multiplied by $|\epsilon_{\mu e}|$, see Eq. (5). In addition, the phase $\phi_{\mu e}$ introduces a new source of CP violation. The main message from Fig. 2 is, especially for NO ν A, the presence of CC-NSI allows the best-fit values (solid circles) for NO to be closer to the experimental result, in comparison to IO. As we now discuss, this will be essential to alleviate the tension between these two experiments. Data from NO ν A and T2K, the appearance of neutrinos and antineutrinos, disagree when considering the standard

neutrino oscillation model. Each experiment individually prefers NO, but when combined, the preference is for IO. In Fig. 3, we show the allowed region with CC-NSI in δ_{CP} and $\sin^2 \theta_{23}$ parameter space for NO ν A (T2K) in blue (pink) with the 90% CL, for NO and also the combined analysis in black lines. It should be noticed that, by combining both experiments, the allowed region is closer to the scenario of T2K only. On the left-hand side we show the standard oscillation scenario. In the middle panel, we have the effects of CC-NSI considering only the parameter $\epsilon_{e\mu}$, and on the right-hand side only $\epsilon_{\mu e}$. In both cases, the regions overlap completely for NO with the 90% CL, alleviating the tension between the experiments. We quantify in Supplemental Material [41] that the tension decreases in these scenarios. In fact, our analyses were quantified using the GLOBES software [57,58], whose results are summarized in Table II.

A fair estimate of the compatibility of a given model for different datasets is given by the goodness-of-fit parameter [68–70]. The parameter goodness of fit (PG) is defined as $\chi_{PG}^2 \equiv \chi_{\min}^2 - \sum_k (\chi_k^2)_{\min}$, where $\chi_{\min}^2$ and $(\chi_k^2)_{\min}$ are the global minimum and the local minimum. It is illustrative to notice the p -values of the different scenarios in Table II. The higher the p -value is, the more compatible the two experiments are between each other. If the CC-NSI contribution is absent, the p -value for NO is 14%, while for IO it is 70%. It clearly shows the nature of the present tension between the T2K and NO ν A experiments, as each of them, individually, prefers NO. By including the CC-NSI parameter, the p -value for the NO case increases. Notice that for the $\epsilon_{e\mu}$ scenario, the minimum value for $\chi_{\min}^2$ occurs for NO for each experiment individually, as well as for their combination. Then it implies that the tension for the $\epsilon_{e\mu}$ scenario is lifted. For the $\epsilon_{\mu e}$ scenario, the tension is reduced compared to the standard oscillation case.

As seen in Table I, the best fit for the combined analysis for NO has δ_{CP} and the CC-NSI phase different than zero. It is then natural to ask how sensitive the experiments are to

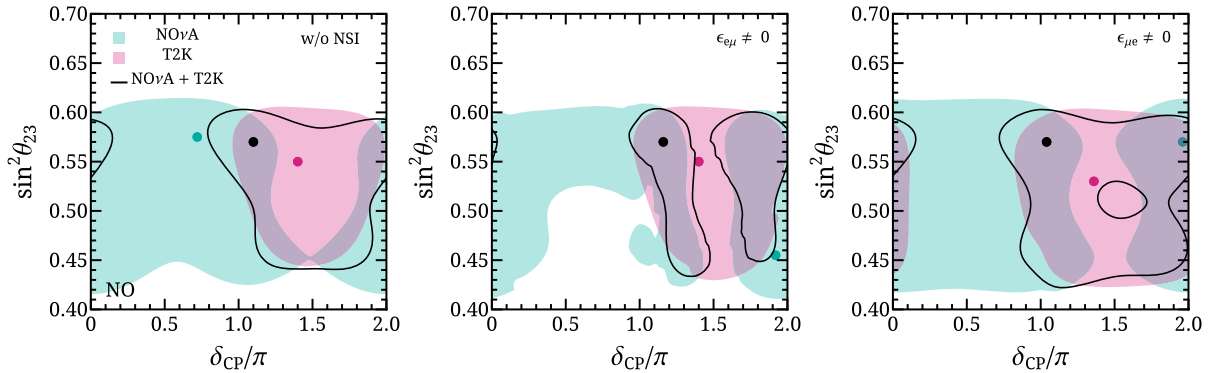


FIG. 3. Allowed region for T2K (pink), NO ν A (blue), and for combined analysis (black line), for NO in the $\sin^2 \theta_{23}$ vs δ_{CP} space, for the 90% confidence level. In the left panel we show the standard oscillation scenario, in the middle panel we show the case with $\epsilon_{e\mu} \neq 0$, and in the right panel the case with $\epsilon_{\mu e} \neq 0$. The dots are the respective best-fit values, see Table I. The plots with $\epsilon_{e\mu}$ or $\epsilon_{\mu e} \neq 0$ were constructed taking into account the pion decay bounds discussed in the text.

TABLE II. We present the values of the χ^2 minimum for the standard oscillation model and CC-NSI scenarios, for the individual datasets of NO ν A and T2K and the combined analysis. The values of the PG test are listed for the four free parameters in the standard oscillation scenario and six with CC-NSI. For the nonstandard scenarios, the pion decay constraints were already taken into account.

$\chi^2_{\min}$	Standard oscillation		$\epsilon_{e\mu}$		$\epsilon_{\mu e}$	
	NO	IO	NO	IO	NO	IO
NO ν A	51.8	52.5	49.3	52.1	51.3	51.9
T2K	107.2	109.2	107.1	108.6	106.7	107.0
NO ν A + T2K	165.9	163.9	161.8	163.9	165.2	162.4
$\chi^2_{\text{PG}}/\text{N}_{\text{par}}$	7.0/4	2.2/4	5.4/6	3.2/6	7.2/6	3.6/6
PPG – value	14%	70%	49%	78%	30%	73%

claim that CP is violated in the leptonic sector. In Fig. 4, we show the allowed regions with the 68 and 90% CL in the parameter space of phases for NO. The left (right) panel corresponds to the parameter space δ_{CP} vs $\phi_{e\mu}$ (δ_{CP} vs $\phi_{\mu e}$). As anticipated from Eq. (6), for $|\epsilon_{\mu e}| \sim \mathcal{O}(10^{-3})$ the conversion probability has a dependence on the phase difference $\delta_{\text{CP}} - \phi_{\mu e}$, which explains the tendency seen on the right panel of Fig. 4. For $\epsilon_{e\mu}$, on the left panel of Fig. 4, there is a dependence on the sum of phases, which is now much more evident. Although the best fits for ϕ_X , δ_{CP} , and $\delta_{\text{CP}} \pm \phi_X$ are all different than 0 (or 2π), the present data combining T2K and NO ν A are not enough to claim leptonic CP violation in the presence of CC-NSI at 1σ CL or higher.

Finally, we contrast the parameter region allowed by NO ν A and T2K data against constraints from other experiments. The same Lagrangian shown in Eq. (1) can induce changes in the leptonic decay rate of the pion, which is one of the best-measured observables [36]. We show in Fig. 5 the allowed region in the real vs imaginary part of the

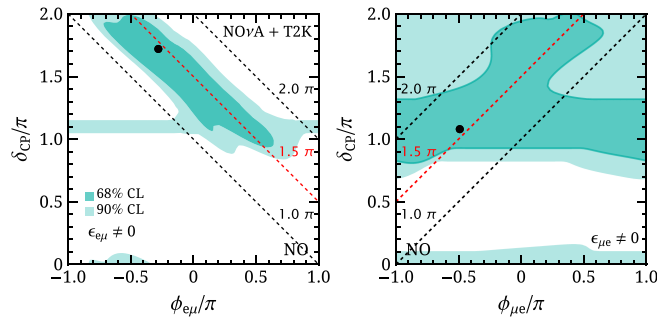


FIG. 4. Allowed region for the 68 and 90% CL for combined T2K and NO ν A data in the parameter space of CP phase of the PMNS matrix δ_{CP} versus the CP phase of CC-NSI parameter $\phi_{\alpha\beta}$, $\alpha, \beta = e, \mu$, for neutrino oscillation with CC-NSI. The left (right) panel is for the normal ordering for the scenario of $\epsilon_{e\mu}$ ($\epsilon_{\mu e}$). The dot point denotes the best-fit parameters (not considering the pion decay bounds), and the dashed lines indicate specific values for the phase sum, $\delta_{\text{CP}} + \phi_{e\mu}$ (left), and phase difference, $\delta_{\text{CP}} - \phi_{\mu e}$ (right).

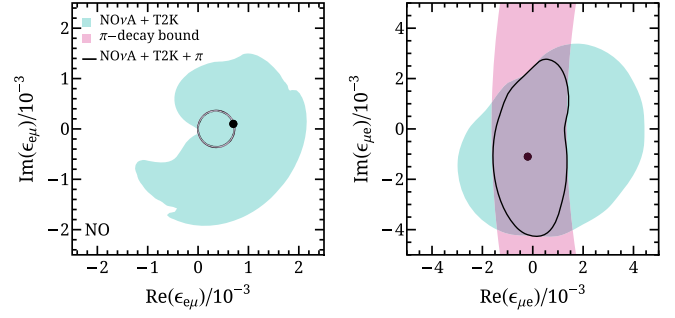


FIG. 5. Bounds for $\epsilon_{e\mu}$ ($\epsilon_{\mu e}$) in the left (right) panel, coming from our analysis (blue curve), the constraints from the π -decay rate (pink curve), and considering both bounds—from oscillation and π -decay experiments—(black curve) at the 90% CL. The best-fit values for the combination are represented by dots.

CC-NSI parameter space, for $\epsilon_{e\mu}$ on the left and $\epsilon_{\mu e}$ on the right panel, in blue. We also show in pink the region allowed by the constraints on pion decay, which is the process with the most stringent bounds to our scenario with CC-NSI [45,71]. The region allowed for neutrino experiments alone is dramatically reduced for the case $\epsilon_{e\mu}$. For the case $\epsilon_{\mu e}$, the main effect is to constrain the real part of the CC-NSI parameter. Including data from the neutrino experiments reduces the allowed region on the imaginary axis from the pion decay experiments alone. The previous constraints obtained from neutrino oscillation experiments were $|\epsilon_{\mu e}| < 4 \times 10^{-3}$ [26,29] and $|\epsilon_{\mu e}| < 2.6 \times 10^{-3}$ [27], and our limits are more stringent. Regarding other proposals in the literature, the overall fit improvement is generally of order 1σ , but in general the degree of mitigation of tension is not available. In our scenario, we have a twofold improvement. We not only have a better overall fit, but also the tension reduces in the CC-NSI scenario. In particular, while the standard scenario has a 1.6σ tension between NO ν A and T2K experiments, for the CC-NSI scenario the tension is reduced to less than 1σ . Moreover, the $\epsilon_{e\mu}$ scenario has an overall fit improvement of 1.6σ when compared to the standard scenario. It makes our solution one of the most promising in the literature. See Supplemental Material [41] for more details.

VI. DISCUSSION AND CONCLUSION

Neutrino oscillation is a unique probe for BSM interactions. Long-baseline neutrino oscillation experiments are particularly sensitive to nonstandard neutrino interactions. We showed that a new pseudoscalar four-fermion interaction between quarks and leptons modifies neutrino production. In this scenario, there is a new source of CP violation from the complex CC-NSI parameter, $\epsilon_{\mu e}$ or $\epsilon_{e\mu}$, thus affecting, in particular, the T2K and NO ν A analyses. We have found for the first time an analytical formula for neutrino propagation in matter in the presence of CC-NSI that is in excellent agreement with the numerical solution.

In the literature, the solution for the T2K-NO ν A tension using CC-NSI was not considered before, mostly because there are stringent bounds coming directly from pion decay experiments. We showed that this bias is not justified by explicitly considering the pion decay bounds as priors in our statistical analyses. In doing so, we have not only reduced the T2K-NO ν A tension, but also provided a better overall fit, in comparison to the standard scenario. The scenario with ϵ_{eu} is particularly promising, being one of the best solutions in the literature.

The nonzero value of the CC-NSI parameter opens a new window to understand the source of CP violation, and it can be tested in future neutrino oscillation experiments.

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