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New physics vs new paradigms: distinguishing CPT violation from NSI

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Our way of describing Nature is based on local relativistic quantum field theories, and then CPT symmetry, a natural consequence of Lorentz invariance, locality and hermiticity of the Hamiltonian, is one of the few if not the only prediction that all of them share. Therefore, testing CPT invariance does not test a particular model but the whole paradigm. Current and future long baseline experiments will assess the status of CPT in the neutrino sector at an unprecedented level and thus its distinction from similar experimental signatures arising from non-standard interactions is imperative. Whether the whole paradigm is at stake or just the standard model of neutrinos crucially depends on that.

I. INTRODUCTION

The status of the CPT symmetry as one of the cornerstones of particle physics has its origin on the fact that the theorem that protects it, the CPT Theorem [1], is one of the few solid predictions of any local relativistic quantum field theory. This theorem says, roughly, that particle and antiparticle possess the same mass and the same lifetime if they are unstable. The three requirements for the theorem to be proven are

- Locality
- Lorentz invariance
- Hermiticity of the Hamiltonian

which are key ingredients of our theories for reasons other than the status of the CPT symmetry. Precisely because of that, testing CPT is testing our model building strategy and our description of Nature in terms of local relativistic quantum fields.

If CPT is not conserved, one of the assumptions above has to be violated. Quantum gravity, for example, is expected to be non-local. However its effects are suppressed by the Planck mass! But this is exactly the right ball-park for neutrinos to show it. In fact, neutrinos are not only an ideal system to accommodate CPT violation [2] but also the

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most accurate tool to test it as well. In Ref. [3] we have shown that the most stringent limits on CPT violation arise not from the kaon system but from neutrino oscillation experiments. And contrary to the kaon case, these limits will improve in the next years significantly. Given the impact such a result would have, it is crucial to distinguish a true, genuine CPT violation from just a new, unknown interaction, no matter how sophisticated. After all, "outstanding claims require outstanding evidence".

In this work we will confront the presence of intrinsic CPT violation with new neutrino interactions with matter usually known as neutrino non-standard interactions (NSI). NSIs are an agnostic way to parametrize all the CPT preserving possibilities economically and therefore provide the ideal tool to discriminate between a legitimate CPT violation, a phenomenon that challenges our description of Nature in terms of local relativistic quantum fields and a more or less complicated interaction that can be accommodated in the current paradigm. Here we will explore how such a distinction can be made if a different mass and/or mixing pattern is extracted from the experiments when analyzing neutrino and antineutrino data sets separately.

II. THEORETICAL BACKGROUND

Neutrino non-standard interactions with matter are generically parametrized in terms of a low-energy effective four-fermion Lagrangian [4–7]:

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{fX}\left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_X f\right) , \tag{1}$$

where P_X denotes the left and right chirality projection operators $P_{R,L} = (1 \pm \gamma_5)/2$ and G_F is the Fermi constant. The dimensionless coefficient $\epsilon_{\alpha\beta}^{fX}$ quantifies the strength of the NSI between neutrinos of flavour α and β and the fundamental fermion $f \in \{e, u, d\}$.

In the presence of such new non-standard interactions of neutrinos with matter, the effective two-neutrino Hamiltonian governing neutrino propagation in the $\mu - \tau$ sector takes the form

$$H = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix}U^\dagger + A\begin{pmatrix} \epsilon^m_{\mu\mu} & \epsilon^{m*}_{\mu\tau} \\ \epsilon^m_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}\right] , \tag{2}$$

where

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{3}$$

represents the leptonic mixing parametrized by the mixing angle in vacuum θ, E is the neutrino energy and $A = 2\sqrt{2}G_F N_e E$ is the matter potential depending on the electron number density, N_e, along the neutrino trajectory. The parameters $\epsilon^m_{\mu\mu}$, $\epsilon^m_{\mu\tau}$ and $\epsilon^m_{\tau\tau}$ give the relative strength of the non-standard interactions compared to the Standard Model weak interactions. The superscript m indicates that these parameters describe non-standard neutrino matter effects in a medium. In this case, the relevant effective operator corresponds to the vector part of the interaction described in Eq. (1), namely $\epsilon^{fV}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$. Considering a medium formed by first generation fermions, the effective NSI coupling in matter affecting neutrino propagation is given by

$$\epsilon^m_{\alpha\beta} \equiv \epsilon^{eV}_{\alpha\beta} + \frac{N_u}{N_e}\epsilon^{uV}_{\alpha\beta} + \frac{N_d}{N_e}\epsilon^{dV}_{\alpha\beta} , \tag{4}$$

with N_f being the number density for the fermion $f \in \{e, u, d\}$. The flavor changing NSI parameters $\epsilon^m_{\alpha\beta}$ can in general be complex, while the flavor conserving coefficients $\epsilon^m_{\alpha\alpha}$ have to be real to preserve the hermiticity of the Hamiltonian. On the other hand, diagonal terms in the Hamiltonian proportional to the identity matrix do not affect the neutrino oscillation probability, and therefore one can subtract $\epsilon^m_{\mu\mu}$ from the diagonal in the Hamiltonian in Eq. (2). In consequence, oscillation experiments are only sensitive to the combination $\epsilon^m_{\tau\tau} - \epsilon^m_{\mu\mu}$. For simplicity, and given the existence of stronger constraints on the NSI couplings for muon neutrinos compared to tau neutrinos, in the following we will set $\epsilon^m_{\mu\mu} = 0$.

III. ANALYTICAL RESULTS AT THE PROBABILITY LEVEL

In the two–neutrino approximation, the neutrino survival probability for muon neutrinos in matter of constant density is given by

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right), \tag{5}$$

where θ and Δm^2 are the effective mixing angle and effective mass squared difference in matter, respectively. Since there is no CP-phase in the two-neutrino picture, the oscillation probability is the same for neutrinos and antineutrinos. However, this is not true if non-standard neutrino interactions are present, since they affect differently neutrinos and antineutrinos. This difference results basically in a shift in the effective neutrino and antineutrino oscillation parameters, so for neutrinos one would have

$$\Delta m^2_\nu \cos 2\theta_\nu = \Delta m^2 \cos 2\theta + \epsilon^m_{\tau\tau} A\,, \tag{6}$$

$$\Delta m^2_\nu \sin 2\theta_\nu = \Delta m^2 \sin 2\theta + 2\epsilon^m_{\mu\tau} A\,, \tag{7}$$

Similarly, for antineutrinos we write

$$\Delta m^2_{\overline{\nu}} \cos 2\theta_{\overline{\nu}} = \Delta m^2 \cos 2\theta - \epsilon^m_{\tau\tau} A\,, \tag{8}$$

$$\Delta m^2_{\overline{\nu}} \sin 2\theta_{\overline{\nu}} = \Delta m^2 \sin 2\theta - 2\epsilon^m_{\mu\tau} A\,. \tag{9}$$

It is straightforward to see that these equations can be rearranged to express the unknown parameters $\epsilon^m_{\mu\tau} A$, $\epsilon^m_{\tau\tau} A$, Δm^2 and $\sin 2\theta$, i.e. the "physical" parameters, in terms of the four observables Δm^2_ν, $\Delta m^2_{\overline{\nu}}$, $\sin 2\theta_\nu$ and $\sin 2\theta_{\overline{\nu}}$:

$$4\Delta m^4 = \Delta m^4_\nu + \Delta m^4_{\overline{\nu}} + 2\Delta m^2_\nu \Delta m^2_{\overline{\nu}} \cos(2\theta_\nu - 2\theta_{\overline{\nu}})\,, \tag{10}$$

$$\sin^2 2\theta = \frac{\left(\Delta m^2_\nu \sin 2\theta_\nu + \Delta m^2_{\overline{\nu}} \sin 2\theta_{\overline{\nu}}\right)^2}{\Delta m^4_\nu + \Delta m^4_{\overline{\nu}} + 2\Delta m^2_\nu \Delta m^2_{\overline{\nu}} \cos(2\theta_\nu - 2\theta_{\overline{\nu}})}\,, \tag{11}$$

$$2A\epsilon^m_{\tau\tau} = \Delta m^2_\nu \cos 2\theta_\nu - \Delta m^2_{\overline{\nu}} \cos 2\theta_{\overline{\nu}}\,, \tag{12}$$

$$4A\epsilon^m_{\mu\tau} = \Delta m^2_\nu \sin 2\theta_\nu - \Delta m^2_{\overline{\nu}} \sin 2\theta_{\overline{\nu}}\,. \tag{13}$$

From these formulae it is obvious that a measurement of different neutrino and antineutrino mass splittings and/or mixing angles can in principle be explained by neutrino NSI with matter without resorting to CPT violation. Indeed, this idea was used to interpret different measurements in the neutrino and the antineutrino channel in the MINOS experiment [8], although this result was not confirmed by more precise data from MINOS. However, since there are already significant bounds on the values of $\epsilon^m_{\tau\tau}$ and $\epsilon^m_{\mu\tau}$, it is also clear that there will be regions in the NSI parameter space which are excluded and then an experimental preference for such values would rather indicate a signal of CPT violation.

Going back to Eq. (12), if we assume for simplicity the same mixing angles for neutrinos and antineutrinos, $\theta_\nu = \theta_{\overline{\nu}}$, this equation can be rewritten to

$$\Delta(\Delta m^2) = \frac{2A\epsilon^m_{\tau\tau}}{\cos 2\theta} \tag{14}$$

with $\Delta(\Delta m^2) = \Delta m^2_\nu - \Delta m^2_{\overline{\nu}}$. Therefore, in the case of equal mixing angles, we obtain a very simple equation for $\Delta(\Delta m^2)$, which is linear in $\epsilon^m_{\tau\tau}$. In consequence, it is straightforward to interpret a different measurement of the neutrino and antineutrino mass splittings as caused by the presence of neutrino NSI with matter. Nevertheless, as mentioned before, there are experimental bounds available on the NSI couplings that should be taken into account. In Ref. [9] one finds all the current bounds on the NSI parameters. Considering the definition of the effective NSI couplings in Eq. (4), the experimental bound on the diagonal NSI coupling is

$$|\epsilon^m_{\tau\tau}| < 0.11, \text{ at } 90\% \text{ C.L.}, \tag{15}$$

originally obtained in Ref. [10]. Assuming a gaussian distribution, we can extrapolate the previous bound to other confidence levels

$$|\epsilon^m_{\tau\tau}| < n(0.067), \text{ at } n\sigma \text{ C.L.} \tag{16}$$

Therefore, in the presence of NSI, and according to Eq. (14), one can expect a difference in the effective values of the mass splitting measured in the neutrino and antineutrino channel. The size of this deviation is restricted by the existing bounds on the NSI couplings. For instance, at $n\sigma$ C.L., the maximum deviation will be given by

$$\Delta(\Delta m^2) \leq \frac{2A}{\cos 2\theta} \times n(0.067)\,, \tag{17}$$

where we have taken

$$A = 2.27 \times 10^{-4}\,\text{eV}^2 \left(\frac{E}{\text{GeV}}\right) . \tag{18}$$

That corresponds to the density of the Earth crust, $\rho = 3\ g/cm^3$. This result also applies to the flavor violating NSI coupling $\epsilon^m_{\mu\tau}$. In this case, the current bound is given by

$$|\epsilon^m_{\mu\tau}| < 0.018 \text{ at } 90\% \text{ C.L.}, \tag{19}$$

originally given in Ref. [11]. Therefore, assuming equal mixing angles in both sectors, the deviation NSI can induce on the neutrino mass splitting over the antineutrino one can be expressed as

$$\Delta(\Delta m^2) = \frac{4A\epsilon^m_{\mu\tau}}{\sin 2\theta} \leq \frac{4A}{\sin 2\theta} \times n(0.011). \tag{20}$$

The allowed deviations between the neutrino and antineutrino mass splitting as a function of the NSI coupling $\epsilon^m_{\tau\tau}$ ($\epsilon^m_{\mu\tau}$) are shown in the left (right) panel of Fig. 1. There we have chosen $\theta = 41^\circ$, inspired by the best fit value for the atmospheric angle of the global fit of neutrino oscillation parameters in Ref. [12], and the energies $E = 1.0, 2.5, 10$ GeV, being 2.5 GeV the peak energy for ν_e appearance at DUNE, see Ref. [13]. From this figure one can read to which amount a measurement of $\Delta(\Delta m^2)$ different from zero could be induced by NSI instead of being a signal of intrinsic

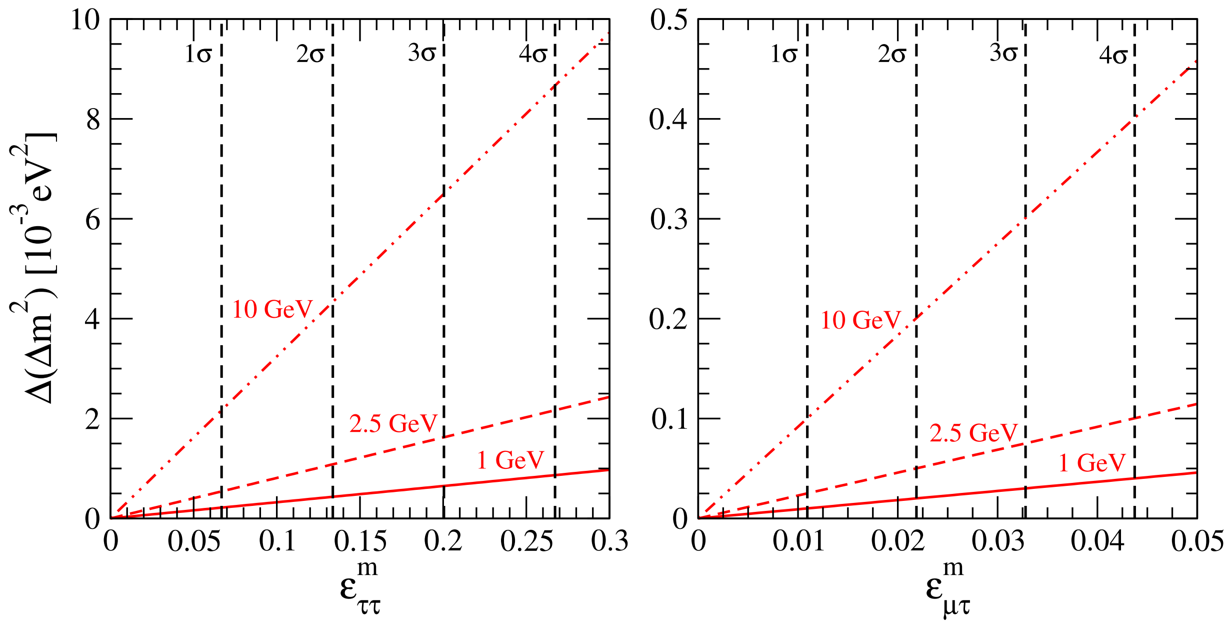

FIG. 1: Left: $\Delta(\Delta m^2)$ as a function of $\epsilon^m_{\tau\tau}$, showing the allowed deviations of $\Delta(\Delta m^2)$ that could be explained with NSI for $\theta = 41°$ and $E = 1.0$ GeV (solid), $E = 2.5$ GeV (dashed) and $E = 10$ GeV (dot-dashed line). Right: The same for $\Delta(\Delta m^2)$ as a function of $\epsilon^m_{\mu\tau}$.

CPT violation. The vertical dashed black lines indicate the current (1-4)σ bounds on $\epsilon^m_{\tau\tau}$ and $\epsilon^m_{\mu\tau}$. The difference in the slope of the two graphs can be understood from two facts: first, the bound on $\epsilon^m_{\mu\tau}$ is stronger than the one for $\epsilon^m_{\tau\tau}$ and second, for the mixing angle of choice, we have $\cos 2\theta \approx 0.14$ and $\sin 2\theta \approx 0.99$, so the deviation potentially induced by $\epsilon^m_{\tau\tau}$ can be much larger. Note that in this section we have assumed equal mixing angles, so that the situation could be even more confusing if one allows for different mixing angles in the neutrino and antineutrino sector. Notice also that these results have been derived at the probability level and, in principle, one can expect the picture to be somehow blurred when the complete analysis of a neutrino experiment is carried out taking into account the full simulated neutrino spectrum and the associated statistical and systematical errors.

IV. RESULTS FROM THE SIMULATION OF DUNE

In Ref. [3] we have shown that, if the results from the separate neutrino and antineutrino analysis of the T2K collaboration [14] turn out to be true, DUNE could measure CPT violation at more than 3σ confidence level. In this section we will analyze if indeed these results could be confused with NSI.

The next generation experiment DUNE will be the so far biggest long baseline neutrino experiment. It will consist of two detectors exposed to a megawatt-scale muon neutrino beam produced at Fermilab. The near detector will be placed near the source of the beam, while a second, much larger, detector comprising four 10-kiloton liquid argon TPCs will be installed 1300 kilometers away of the neutrino source. One of the main scientific goals of DUNE is the precision measurement of the neutrino oscillation parameters. In our work, the simulation of DUNE is performed with the GLoBES package [15, 16] with the most recent DUNE configuration file provided by the experimental collaboration [17]. The expected NSI signal in DUNE is simulated using the GLoBES extension *snu.c* [18, 19]. We assume a total run period of 3.5 years in the neutrino mode and another 3.5 years in the antineutrino mode. Assuming an 80 GeV beam with 1.07 MW beam power, this corresponds to an exposure of 300 kton–MW–years,

parameter	value
Δm^2_{31}	2.60×10^{-3} eV^2
$\Delta\overline{m}^2_{31}$	2.62×10^{-3} eV^2
$\sin^2\theta_{23}$	0.51
$\sin^2\overline{\theta}_{23}$	0.42
Δm^2_{21}, $\Delta\overline{m}^2_{21}$	7.56×10^{-5} eV^2
$\sin^2\theta_{12}$, $\sin^2\overline{\theta}_{12}$	0.321
$\sin^2\theta_{13}$, $\sin^2\overline{\theta}_{13}$	0.02155
δ, $\overline{\delta}$	1.50π

TABLE I: Oscillation parameters considered in the simulation and analysis of DUNE expected data. In terms of the two neutrino parameterization of Sec. II, the notation used in this table is equivalent to $\Delta m^2_{31} = \Delta m^2_{\nu}$, $\Delta\overline{m}^2_{31} = \Delta m^2_{\overline{\nu}}$ and $\theta_{23} = \theta_\nu$, $\overline{\theta}_{23} = \theta_{\overline{\nu}}$.

which corresponds to 1.47×10^{21} protons on target (POT) per year, which amounts basically in one single year to the same statistics accumulated by T2K in all of its lifetime in runs 1–7c. Since here we focus basically on the parameters relevant for $P_{\mu\mu}$, we consider only the disappearance channel in our simulation. We include signals and backgrounds, where the latter include contamination of antineutrinos (neutrinos) in the neutrino (antineutrino) mode, and also misinterpretation of flavors. We have increased the systematic errors due to misidentification of neutrinos by antineutrinos and vice versa by a further 25% over the original error given by the collaboration to account for the fact that, actually, antineutrino backgrounds should not be oscillated with the neutrino oscillation parameters and vice versa. While it is possible to define a customized probability engine in GLoBES, we have checked that the effect of the backgrounds is not appreciable in the final results.

Our strategy is as follows: We perform two simulations of DUNE running 3.5 years only in neutrino mode and 3.5 years only in antineutrino mode. To generate the future data, we assume the parameters presented in Tab. I, assuming different atmospheric mixing angle and mass splitting for neutrinos and antineutrinos, but no NSIs. Then, in the statistical analysis, we scan over the relevant oscillation parameters δ, θ_{13}, θ_{23}, Δm^2_{31} and their antineutrino counterparts[1]. Additionally, we scan over the two NSI parameters in Eq. (2), $\epsilon^m_{\tau\tau}$ and $\epsilon^m_{\mu\tau}$, setting the rest of the parameters including all of the new phases to zero. In this way, we obtain two χ^2 grids, one for neutrinos and another one for antineutrinos. Then, we try to reconstruct the oscillation parameters under the hypothesis of CPT invariance. To do so we calculate the total χ^2 distribution from the sum of the neutrino and antineutrino contributions

$$\chi^2_{\text{total}} = \chi^2(\nu) + \chi^2(\overline{\nu}) , \tag{21}$$

and then marginalize over all the parameters except the one of interest. First of all, we focus our attention in the NSI parameter $\epsilon^m_{\mu\tau}$. The $\Delta\chi^2$ profile obtained for this coupling is shown in the orange line in the left panel of Fig. 2. Here we see that data are consistent with this NSI coupling equal to zero. However, the result is different for the flavour diagonal NSI coupling $\epsilon^m_{\tau\tau}$. The $\Delta\chi^2$ profile for this parameter is plotted in the orange line in the right panel of Fig. 2. From the figure we see our CPT-violating analysis excludes the value $\epsilon^m_{\tau\tau} = 0$ at approximately 4σ, while the best fit is obtained for $\epsilon^m_{\tau\tau} = -0.33$. These results can be explained from the naive formulae in Eqs. (12) and (13). Indeed, if we substitute the T2K best fit values for the oscillation parameters given in Table I, used to simulate future DUNE

[1] We put a prior on $\overline{\theta}_{13}$, due to the precise measurements by the short baseline reactor experiments [20–22].

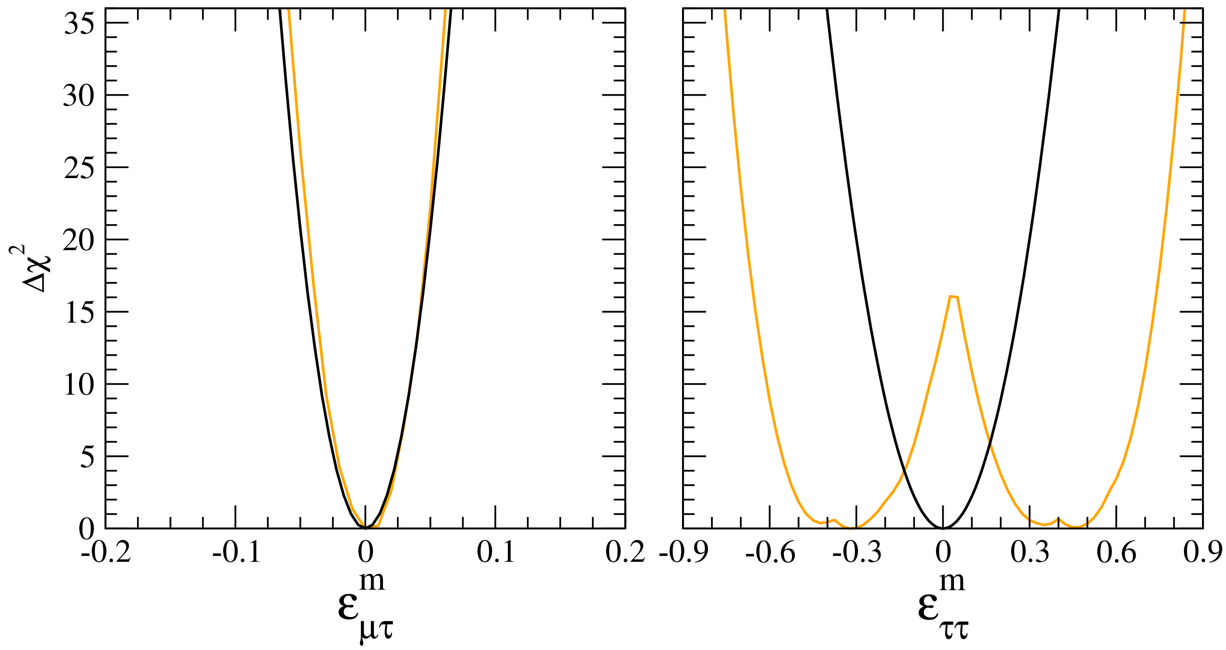

FIG. 2: $\Delta\chi^2$ profile for the NSI couplings $\epsilon^m_{\mu\tau}$ (left) and $\epsilon^m_{\tau\tau}$ (right panel) obtained in our analysis (orange lines). For comparison we show the current experimental bounds on both parameters assuming gaussian errors (black lines).

data, into these formulae, for the peak energy of DUNE, $E = 2.5$ GeV, we obtain $\epsilon^m_{\mu\tau} = 5.8 \times 10^{-3}$ and $\epsilon^m_{\tau\tau} = -0.42$. Therefore, one can conclude that what seems to be CPT violation could be also explained with neutrino NSI with matter. Nevertheless, the best fit value we have obtained in this case for the flavor diagonal coupling, $\epsilon^m_{\tau\tau} = -0.33$, is highly excluded from current experimental data. To visualize this, together with the results obtained in our analysis, we have plotted in Fig. 2 the profile for both NSI parameters from current data assuming gaussian errors (see black lines in both panels). In the right graph one can see that our preferred value for $\epsilon^m_{\tau\tau}$ is actually excluded at close to 5σ. Therefore, if the results from T2K turn out to be true, they would rather hint towards CPT violation than to NSI.

V. SUMMARY

The CPT theorem is a fundamental result in particle physics which states that the combined operation of charge conjugation (C), time reversal (T), and parity (P) in any order is an exact symmetry of any interaction. The proof of the theorem requires only three elements: locality, hermiticity of the Hamiltonian and Lorentz invariance. They all are present in our theories for other reasons than the status of the CPT symmetry itself. In fact any local relativistic quantum field theory preserves CPT, and therefore testing CPT invariance is testing our current paradigm, the way we construct models, the way we describe interactions, in short, the way we understand Nature.

The impact of a potential CPT violation is such that it is imperative to distinguish it from any other unknown physics that can lead to similar experimental signatures. The need for such a distinction is more urgent in the neutrino sector where the future long baseline neutrino experiments will push the CPT invariance frontier to a new level and where neutrinos, due to its uncommon mass generation mechanism, can open unique windows to new physics and new mass scales.

NSIs are a simple way to parametrize any unknown physics which may be relevant to the oscillation analysis. In this work we have shown that, although NSIs can mimic fake CPT violation, its experimental signature can be distinguished from a genuine CPT violation due to the bounds on the strength of the NSI arising from other experiments.

The future cannot be more exciting. If the slight indications of CPT violation in the mixing angles offered by the separate analysis of the neutrino and antineutrino data sets by the T2K Collaboration are confirmed by the DUNE experiment, genuine CPT violation *i.e.* the one that challenges our understanding of Nature in terms of local relativistic quantum field theory will be the only answer. If this were not the case, we explain how the discrimination has to be performed in case a difference is ever found.

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[1] R. F. Streater and A. S. Wightman, *PCT, spin and statistics, and all that* (1989), ISBN 0691070628, 9780691070629.
[2] G. Barenboim and J. D. Lykken, Phys. Lett. **B554**, 73 (2003), hep-ph/0210411.
[3] G. Barenboim, C. A. Ternes, and M. Tórtola, Phys. Lett. **B780**, 631 (2018), 1712.01714.
[4] L. Wolfenstein, Phys. Rev. **D17**, 2369 (1978), [,294(1977)].
[5] J. W. F. Valle, Phys. Lett. **B199**, 432 (1987).
[6] E. Roulet, Phys. Rev. **D44**, 935 (1991), [,365(1991)].
[7] M. M. Guzzo, A. Masiero, and S. T. Petcov, Phys. Lett. **B260**, 154 (1991), [,369(1991)].
[8] J. Kopp, P. A. N. Machado, and S. J. Parke, Phys. Rev. **D82**, 113002 (2010), 1009.0014.
[9] Y. Farzan and M. Tortola, Front. in Phys. **6**, 10 (2018), 1710.09360.
[10] M. C. Gonzalez-Garcia, M. Maltoni, and J. Salvado, JHEP **05**, 075 (2011), 1103.4365.
[11] J. Salvado, O. Mena, S. Palomares-Ruiz, and N. Rius, JHEP **01**, 141 (2017), 1609.03450.
[12] P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tortola, and J. W. F. Valle (2017), 1708.01186.
[13] R. Acciarri et al. (DUNE) (2015), 1512.06148.
[14] K. Abe et al. (T2K), Phys. Rev. **D96**, 011102 (2017), 1704.06409.
[15] P. Huber, M. Lindner, and W. Winter, Comput. Phys. Commun. **167**, 195 (2005), hep-ph/0407333.
[16] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput. Phys. Commun. **177**, 432 (2007), hep-ph/0701187.
[17] T. Alion et al. (DUNE) (2016), 1606.09550.
[18] J. Kopp, Int. J. Mod. Phys. **C19**, 523 (2008), physics/0610206.
[19] J. Kopp, M. Lindner, T. Ota, and J. Sato, Phys. Rev. **D77**, 013007 (2008), 0708.0152.
[20] F. P. An et al. (Daya Bay), Phys. Rev. **D95**, 072006 (2017), 1610.04802.
[21] J. H. Choi et al. (RENO), Phys. Rev. Lett. **116**, 211801 (2016), 1511.05849.
[22] Y. Abe et al. (Double Chooz), JHEP **10**, 086 (2014), [Erratum: JHEP02,074(2015)], 1406.7763.