Non-standard neutrino interactions as a solution to the NOνA and T2K discrepancy

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The latest data of the two long-baseline accelerator experiments NOνA and T2K, interpreted in the standard 3-flavor scenario, display a discrepancy. A mismatch in the determination of the standard CP-phase δCP extracted by the two experiments is evident in the normal neutrino mass ordering. While NOνA prefers values close to δCP ≈ 0.8π, T2K identifies values of δCP ≈ 1.4π. Such two estimates are in disagreement at more than 90% C.L. for 2 d.o.f.. We show that such a tension can be resolved if one hypothesizes the existence of complex neutral-current non-standard interactions (NSI) of the flavor changing type involving the e − μ or the e − τ sectors with couplings |εeμ| ≈ |εeτ| ≈ 0.2. Remarkably, in the presence of such NSI, both experiments point towards the same common value of the standard CP-phase δCP ≈ 3π/2. Our analysis also highlights an intriguing preference for maximal CP-violation in the non-standard sector with the dynamical NSI CP-phases having best fit close to φeμ ≈ φeτ ≈ 3π/2.

Introduction. The two LBL experiments NOνA and T2K have recently released new data at the Neutrino 2020 Conference [1][2]. Intriguingly, the two experiments display a moderate tension preferring values of the standard 3-flavor CP-phase δCP, which are in disagreement. While this discrepancy may be imputable to a statistical fluctuation or to an unknown systematic error, it may represent the first sign of physics beyond the Standard Model (SM). In particular, one should note that the two experiments are different with respect to their sensitivity to the matter effects, due to the different baselines (810 km for NOνA and 295 km for T2K). This evokes the fascinating possibility that new physics may be at work in the form of non-standard neutrino interactions (NSI).

Theoretical framework. NSI may constitute the low-energy manifestation of high-energy physics of new heavy states (for a review see [3][7]) or, they can be related to light mediators [8][9]. As first noted in [10], NSI can alter the dynamics [10][12] of the neutrino flavor conversion in matter. The presence of NSI can have a sizeable impact on the interpretation of current LBL data. Notably, in the recent work [13], it has been evidenced that they may even obscure the correct determination of the neutrino mass ordering (NMO) [1]. The impact of NSI on present and future new-generation LBL experiments has been widely explored (see for example [14][30]).

The NSI can be represented by a dimension-six operator [10]

\[ \mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fC} (\bar{\nu}_\gamma \gamma^\mu P_L \nu_\beta) (\bar{T}_\gamma \gamma P_C f) , \]

where α, β = e, μ, τ indicate the neutrino flavor, f = e, u, d denote the matter fermions, superscript C = L, R refer to the chirality of the ff current, and εfC are the strengths of the NSI. The hermiticity of the interaction implies

\[ \varepsilon_{\alpha\beta}^{fC} = (\varepsilon_{\alpha\beta}^{fC})^\dagger . \] (2)

For neutrino propagation in the Earth, the relevant combinations are

\[ \varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon_{\alpha\beta}^f N_f = \sum_{f=e,u,d} (\varepsilon_{fL}^{e\alpha} + \varepsilon_{fR}^{e\alpha}) \frac{N_f}{N_e} , \] (3)

\[ N_f \] being the number density of f fermion. For the Earth, we can consider neutral and isoscalar matter, with Nn ≈ Np ≈ Ne, in which case Nn ≈ Nl ≈ 3Ne. Therefore,

\[ \varepsilon_{\alpha\beta} \approx 3 \varepsilon_{\alpha\beta}^{e} + 3 \varepsilon_{\alpha\beta}^{u} + 3 \varepsilon_{\alpha\beta}^{d} . \] (4)

The NSI alter the effective Hamiltonian of neutrino propagation in matter, which in the flavor basis reads

\[ H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & k_{21} & 0 \\ 0 & 0 & k_{31} \end{pmatrix} U^\dagger + V_{\text{CC}} \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} , \] (5)

where \( U \) is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, which depends on three mixing angles (θ12, θ13, θ23) and the CP-phase δCP. The parameters \( k_{21} \equiv \Delta m_{21}^2/2E \) and \( k_{31} \equiv \Delta m_{31}^2/2E \) represent the solar and atmospheric wavenumbers, where \( \Delta m_{21}^2 \equiv m_2^2 - m_1^2 \), while \( V_{\text{CC}} \) is the charged-current matter potential

\[ V_{\text{CC}} = \sqrt{2}G_F N_e \approx 7.6 Y_e \times 10^{-14} \left[ \frac{\rho}{\text{g/cm}^3} \right] \text{eV} , \] (6)

where \( Y_e = N_e/(N_p + N_n) \approx 0.5 \) is the relative electron number density in the Earth crust. It is useful to introduce the dimensionless quantity \( v = V_{\text{CC}}/k_{31} \), which measures the sensitivity to matter effects. Its absolute value

\[ |v| = \frac{V_{\text{CC}}}{k_{31}} \approx 8.8 \times 10^{-2} \left[ \frac{E}{\text{GeV}} \right] , \] (7)
will appear in the expressions of the $\nu_\mu \rightarrow \nu_e$ conversion probability. We here emphasize that in T2K (NO$\nu$A) the first oscillation maximum is reached respectively for $E \approx 0.6$ GeV ($E \approx 1.6$ GeV). This implies that matter effects are a factor of three bigger in NO$\nu$A ($v \approx 0.14$) than in T2K ($v \approx 0.05$). This suggests that NO$\nu$A may be sensitive to NSI to which T2K is basically insensitive, so explaining the apparent disagreement among the two experiments when their results are interpreted in the standard 3-flavor scheme.

In the present manuscript, we focus on flavor nondiagonal NSI, that is $\varepsilon_{\alpha\beta}$'s with $\alpha \neq \beta$. More specifically, we consider the couplings $\varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau}$, which, as will we discuss below, introduce a dependency on their dynamical CP-phase in the appearance $\nu_\mu \rightarrow \nu_e$ probability\footnote{The $\nu_\mu \rightarrow \nu_\mu$ disappearance channel is sensitive to the $\mu - \tau$ NSI but this can be safely ignored because of the very strong upper bound put by the atmospheric neutrinos $|\varepsilon_{\mu\tau}| < 8.0 \times 10^{-3}$ \cite{37}. (see also \cite{33}).}. Let us focus on the conversion probability relevant for the LBL experiments T2K and NO$\nu$A. In the presence of NSI, the probability can be expressed as the sum of three terms\footnote{Interestingly, an analogous splitting of the transition probability is valid in the presence of oscillations driven by a sterile neutrino \cite{10}. In that case, however, the origin of the new interference term $P_2$ is kinematical, and it is operative also in vacuum.}

$$P_{\mu e} \approx P_0 + P_1 + P_2,$$

which, using a compact notation similar to \cite{20}, take the following forms\footnote{The expression of $P_0$ is different for $\varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau}$ and, in Eq. (10), one has to make the replacements\footnote{The expression of $P_3$ is different for $\varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau}$ and, in Eq. (11), one has to make the replacements\footnote{The expression of $P_2$ is different for $\varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau}$ and, in Eq. (12), the sign of $\Delta$, $\alpha$ and $v$ is positive (negative) for NO (IO). We recall that the expressions of the probability provided above hold for neutrinos and that the corresponding formulae for antineutrinos can be derived by flipping in Eqs. (9)-(11) the sign of all the CP-phases and of the matter parameter $v$. Finally, we observe that the third term $P_2$ encodes the dependency on the (complex) NSI coupling and it is different from zero only in matter (i.e. if $v \neq 0$). It is generated by the interference of the matter potential $\varepsilon_{\mu\mu}V_{CC}$ (or $\varepsilon_{\tau\tau}V_{CC}$) with the atmospheric wavenumber $k_{31}$ (see the discussion in \cite{14}).}

\begin{align}
P_0 & \approx 4s_{13}^2 s_{23}^2 f^2, \\
P_1 & \approx 8s_{13}c_{12}c_{13}s_{13}c_{23}a f g |\Delta + \delta_{CP}|, \\
P_2 & \approx 8s_{13}c_{23} v |(a f^2 \cos(\delta_{CP} + \phi) + b f g \cos(\Delta + \delta_{CP} + \phi))|,
\end{align}

where $\Delta = \Delta m^2_{31}/L/\lambda E$ is the atmospheric oscillating frequency, $L$ is the baseline and $E$ the neutrino energy, and $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$. For brevity, we have used the notation $(s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij})$, and following \cite{41}, we have introduced

$$f \equiv \frac{\sin(1 - v)\Delta}{1 - v}, \quad g \equiv \frac{\sin v \Delta}{v}.$$ \hspace{1cm} (12)

In Eq. (11) we have assumed for the NSI coupling the general complex form

$$\varepsilon = |\varepsilon| e^{i \phi}.$$ \hspace{1cm} (13)

The expression of $P_0$ is different for $\varepsilon_{\mu\mu}$ and $\varepsilon_{\tau\tau}$ and, in Eq. (10), one has to make the replacements

$$a = s_{23}^2, \quad b = e_{23} \quad \text{if} \quad \varepsilon = |\varepsilon_{\mu\mu}| e^{i \phi_{\mu\mu}},$$ \hspace{1cm} (14)

$$a = s_{23} c_{23}, \quad b = - s_{23} c_{23} \quad \text{if} \quad \varepsilon = |\varepsilon_{\tau\tau}| e^{i \phi_{\tau\tau}}.$$ \hspace{1cm} (15)

In the expressions given in Eqs. (9)-(11) for $P_0$, $P_1$ and $P_2$, the sign of $\Delta$, $\alpha$ and $v$ is positive (negative) for NO

\textit{Data used in the analysis.} We extracted the datasets of NO$\nu$A and T2K from the latest data released in \cite{1} and \cite{2}. We fully incorporate both the disappearance and appearance channels in both experiments. In our analysis we use the software GLoBES \cite{42,43} and its additional public tool \cite{44}, which can implement NSI. In our analysis we have marginalized over $\theta_{313}$ with 3.4% 1 sigma prior with central value $\sin^2 \theta_{313} = 0.0219$ as determined by Daya Bay \cite{45}. We have fixed the solar parameters $\Delta m^2_{31}$ and $\theta_{12}$ at their best fit values estimated in the recent global analysis \cite{46}.

\textit{Numerical Results.} Figure 1 reports the results of the analysis of the combination of T2K and NO$\nu$A for NO (left panels) and IO (right panels). The upper (lower) panels refer to $\varepsilon_{\mu\mu}(\varepsilon_{\tau\tau})$ taken one at a time. Each panel displays the allowed regions in the plane spanned by the relevant NSI coupling and the standard CP-phase $\delta_{CP}$.

The non-standard CP-phases, the mixing angles $\theta_{23}$ and $\theta_{13}$, and the squared-mass $\Delta m^2_{31}$ are marginalized away. We display the allowed regions at the $1\sigma$ and $2\sigma$ level for 1 d.o.f. and denote with a star the best fit point. From the left upper panel we can appreciate that in NO there is a $\sim 2.1\sigma$ ($\Delta \chi^2 = 4.5$) preference for a non-zero value of the coupling $|\varepsilon_{\mu\mu}|$, with best fit $|\varepsilon_{\mu\mu}| = 0.15$. In the right upper panel we see that in IO the preference for NSI is negligible. The lower panels depict the situation for the coupling $|\varepsilon_{\tau\tau}|$. In NO there is a preference at the $1.9\sigma$ ($\Delta \chi^2 = 3.75$) with best fit $|\varepsilon_{\tau\tau}| = 0.27$, while in IO the preference is only at the 1.0$\sigma$ with best fit $|\varepsilon_{\tau\tau}| = 0.15$. It is interesting to note how in all four cases the preferred value for the CP-phase $\delta_{CP}$ is close to $3\pi/2$. We will come back later on this important point.

Figure 2 shows the results of the analysis of the combination of T2K and NO$\nu$A similar to Fig. 1. In this case, however, each panel displays the allowed regions in the plane spanned by the relevant NSI coupling ($|\varepsilon_{\mu\mu}|$ or $|\varepsilon_{\tau\tau}|$) and the corresponding CP-phase ($\phi_{\mu\mu}$ or $\phi_{\tau\tau}$). The standard CP-phase $\delta_{CP}$, the mixing angles $\theta_{23}$ and $\theta_{13}$, and the squared-mass $\Delta m^2_{31}$ are marginalized away. It is intriguing to note how in the NO case the preferred value for both the new CP-phases $\phi_{\mu\mu}$ and $\phi_{\tau\tau}$ is close to $3\pi/2$, so indicating a maximal CP-violation also in the NSI sector. In Table I we report the best fit values of the NSI couplings together with the CP-phases and the value of $\Delta \chi^2 = \chi^2_{SM} - \chi^2_{SM+NSI}$ for a fixed choice of the NMO.

In order to understand how the preference for a non-zero NSI coupling arises, it is useful to look to what hap-
FIG. 1. Allowed regions determined by the combination of T2K and NOνA for NO (left panels) and IO (right panels). The upper (lower) panels refer to $\varepsilon_{e\mu}$ ($\varepsilon_{e\tau}$) taken one at a time. The contours are drawn at the 1σ and 2σ level for 1 d.o.f.

FIG. 2. Allowed regions determined by the combination of T2K and NOνA for NO (left panels) and IO (right panels). The upper (lower) panels refer to $\varepsilon_{e\mu}$ ($\varepsilon_{e\tau}$) taken one at a time. The contours are drawn at the 1σ and 2σ level for 1 d.o.f.

pens separately to NOνA and T2K. For this purpose, in Fig. 3 we display the allowed regions in the plane spanned by the standard CP-phase $\delta_{CP}$ and the atmospheric mixing angle $\theta_{23}$ in the NO case. The left panel refers to the SM case, while the middle and right panels concern the SM+NSI scenario with NSI in the $e - \mu$ and $e - \tau$ sectors respectively. In the middle and right panels we have taken the NSI parameters at their best fit values of the combined analysis of NOνA and T2K. More specifically, $|\varepsilon_{e\mu}| = 0.15$, $\phi_{e\mu} = 1.38\pi$ (middle panel) and $|\varepsilon_{e\tau}| = 0.275$, $\phi_{e\tau} = 1.62\pi$ (right panel). The contours are drawn at the 68% and 90% C.L. for 2 d.o.f. In the SM case a clear mismatch in the determination of the CP-phase $\delta_{CP}$ among the two experiments is evident. While NOνA prefers values close to $\delta_{CP} \sim 0.8\pi$, T2K identifies a value of $\delta_{CP} \sim 1.4\pi$. Such two estimates, which have a difference of phase of about $\pi/2$, are in disagreement at more than the 90% C.L. for 2 d.o.f. The reduction of the tension between the two experiments obtained in the presence of NSI is evident both in the middle and right panels where the best fit values of $\delta_{CP}$ are very close to the common value $\delta_{CP} \sim 3\pi/2$. We see that the value of $\delta_{CP}$ preferred by T2K is basically unchanged in the presence of NSI as this experiment has a reduced sensitivity to matter effects. As a consequence the value of $\delta_{CP}^{T2K} \sim 3\pi/2$ identified by T2K can be considered a faithful estimate of its true value both in SM and in SM+NSI scenarios. In contrast, NOνA due to the enhanced sensitivity to matter effects, if NSI are not taken into account (left panel), identifies a fake value of $\delta_{NOvA}^{CP} \sim 0.8\pi$. In NOνA, the preference for the true value of $\delta_{CP} \sim 3\pi/2$ is restored once the NSI are taken into account (middle and right panels). Therefore, it seems that NSI offer a very simple and elegant way to solve the discrepancy among the two experiments. We also note that the allowed regions for NOνA are qualitatively different in the $e - \mu$ and $e - \tau$ NSI cases. In fact, in the first case there is a single allowed region while in the second case there are two degenerate lobes. This different behavior can be traced to the fact that the transition probabilities are different in the two cases. More specifically, the sign in front of the coefficient $b$ of $P_2$ in Eq. (11) [see Eqs. (14) and (15)] is opposite in the two scenarios.

For completeness, in Fig. 4 we report the one-dimensional projections on the standard oscillation parameters $\delta_{CP}$, $\theta_{23}$ and $|\Delta m^2_{31}|$ from the combination of NOνA and T2K attained by expanding the $\chi^2$ around the minimum value obtained when the SM, SM+NSI ($\varepsilon_{e\mu}$) and the SM+NSI ($\varepsilon_{e\tau}$) hypotheses are accepted as true. The upper, middle and lower panels refer respec-

| NMO | NSI | $|\varepsilon_{\alpha\beta}|$ | $\phi_{\alpha\beta}/\pi$ | $|\varepsilon_{e\mu}|$ | $\phi_{e\mu}/\pi$ | $|\varepsilon_{e\tau}|$ | $\phi_{e\tau}/\pi$ | $\Delta \chi^2$ |
|-----|-----|-----------------|------------------|-----------------|------------------|-----------------|------------------|------------------|
| NO  | $\varepsilon_{e\mu}$ | 0.15 | 1.38 | 1.48 | 4.50 |
|     | $\varepsilon_{e\tau}$ | 0.27 | 1.62 | 1.46 | 3.75 |
| IO  | $\varepsilon_{e\mu}$ | 0.02 | 0.96 | 1.50 | 0.07 |
|     | $\varepsilon_{e\tau}$ | 0.15 | 1.58 | 1.52 | 1.01 |
FIG. 3. Allowed regions determined separately by T2K and NOνA for NO in the SM case (left panel) and with NSI in the $e-\mu$ sector (middle panel) and in the $e-\tau$ sector (right panel). In the middle panel we have taken the NSI parameters at their best fit values of T2K + NOνA ($|\varepsilon_{e\mu}| = 0.15, \phi_{e\mu} = 1.38\pi$). Similarly, in the right panel we have taken $|\varepsilon_{e\tau}| = 0.275, \phi_{e\tau} = 1.62\pi$. The contours are drawn at the 68% and 90% C.L. for 2 d.o.f. The comparison of the middle and right panels with the left one clearly evidences the reduction of the tension between the two experiments in the presence of NSI of both types.

Conclusions. In this paper we have investigated the impact of NSI on the tension recently emerged in the latest T2K and NOνA data. Our main result is that such a tension can be resolved by non-standard interactions (NSI) of the flavor changing type involving the $e-\mu$ and $e-\tau$ flavors. We underline that, apart from the LBL accelerator data, it would be very important to complement our study considering the atmospheric neutrino data. To this regard, we mention the recent IceCube DeepCore analysis [49], which starts to probe values of the NSI couplings below $\sim 0.2$, close but not incompatible to those relevant to the present analysis. We also hope that SuperKamiokande may provide an updated analysis of the atmospheric data in the presence of NSI, which is currently unfeasible from outside the collaboration.

In this manuscript we have focused on the current data provided by NOνA and T2K. Needless to say, it would be interesting to consider the sensitivity to NSI of the future LBL experiments. In particular, we foresee that a careful comparison of T2HK and DUNE should be very informative. On the one hand T2HK, with its short 295 km baseline should be able to determine the standard parameters almost independently of NSI. On the other hand, DUNE with its 1300 km baseline should manifest striking effects induced by NSI and allow their identification. Of course, the determination of the NMO is expected to become more challenging in the presence of new physics. To this respect we underline the importance of experiments like JUNO which are insensitive to (both standard and non-standard) matter effects and will allow us to identify the NMO (and other standard oscillation parameters) independently of hypothetical NSI. Finally, we note that independent measurements of the NSI couplings relevant for NOνA and T2K may also come in the future from experiments that probe the coherent elastic neutrino nucleus scattering.

Note. In the final stage of preparation of our manuscript the paper [49] appeared discussing a similar scenario.

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FIG. 4. One-dimensional projections of the standard parameters determined by the combination of T2K and NOνA for NO (continuous curves) and IO (dashed curves).

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