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Resolving the NOνA and T2K tension in the presence of Neutrino Non-Standard interactions

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The current data of the two long-baseline accelerator experiments NOνA and T2K, shows a tension at more than 90% C.L. for 2 degrees of freedom, in the determination of the standard CP-phase $\delta_{\rm CP}$ in case of neutrino normal ordering (NO). NOνA measures the value close to $\delta_{\rm CP} \sim 0.8\pi$, while T2K prefers the value of $\delta_{\rm CP} \sim 1.4\pi$. We show that such a tension can be resolved if one hypothesizes the existence of neutral-current non-standard interactions (NSI) of neutrinos involving the flavor changing type $e-\mu$ or the $e-\tau$ sectors with couplings $|\varepsilon_{e\mu}| \sim |\varepsilon_{e\tau}| \sim 0.2$. Remarkably, our analyses show that in the presence of such NSI, both the experiments point towards the same common value of the standard CP-phase $\delta_{\rm CP} \sim 3\pi/2$, thereby indicating towards the maximal CP-violation in the standard 3ν framework. We also show that the best fit values of the new CP-phases $\phi_{e\mu}$ or $\phi_{e\tau}$ are close to $\sim 3\pi/2$, hence pointing towards the maximal CP-violation in the NSI sector.

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Introduction. The new datasets[1, 2] from the two long-baseline (LBL) accelerator experiments NOνA and T2K were recently presented at the Neutrino 2020 Conference. Interestingly, the measurements on the standard 3-flavor CP-phase $\delta_{\rm CP}$ show an appreciable discrepancy between the two experiments in case of NO, and this lies at more than 90% C.L. for 2 degrees of freedom (d.o.f.). This discrepancy can be attributed either to a statistical fluctuation or to an unknown systematic error,or it may be the signature of some new physics beyond the Standard Model (SM). In particular, these two experiments are of different nature with respect to their sensitivity to the matter effects due to their different baselines (810 km for NOνA and 295 km for T2K). This invites ample of opportunities for the new physics to play an exciting role. In this work we explore the impact of neutral current (NC) non-standard interactions (NSI) of neutrinos in resolving the tension between the two experiments.

Theoretical framework. NSI represents the low-energy manifestation of high-energy physics involving the new heavy states (for a review see [3, 4]) or, the light mediators [5]. As first recognised in [6], NSI of type neutral current (NC) can alter the dynamics of the neutrino flavor oscillation in matter and this can be represented by a dimension-six operator [6]

$$\mathcal{L}_{\rm NC-NSI} \;=\; -2\sqrt{2}G_F\,\varepsilon_{\alpha\beta}^{fC}\left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f\right), \tag{1}$$

where $\alpha, \beta = e, \mu, \tau$ denote the neutrino flavor, $f = e, u, d$ indicate the matter fermions, P represents the projector operator with superscript $C = L, R$ referring to the chirality of the ff current, and $\varepsilon_{\alpha\beta}^{fC}$ are the strengths of the NSI. The hermiticity of the interaction implies $\varepsilon_{\beta\alpha}^{fC} = (\varepsilon_{\alpha\beta}^{fC})^*$. For the neutrino propagation in matter, the effective NSI couplings can be written as

$$\varepsilon_{\alpha\beta} \;\equiv\; \sum_{f,C} \varepsilon_{\alpha\beta}^{fC}\frac{N_f}{N_e} \;\equiv\; \sum_{f=e,u,d}\left(\varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}\right)\frac{N_f}{N_e}, \tag{2}$$

N_f being the number density of f fermion. For the neutral and isoscalar Earth matter, $N_n \simeq N_p = N_e$, which in turn leads to $N_u \simeq N_d \simeq 3N_e$. So, $\varepsilon_{\alpha\beta} \simeq \varepsilon_{\alpha\beta}^{e} + 3\,\varepsilon_{\alpha\beta}^{u} + 3\,\varepsilon_{\alpha\beta}^{d}$. The effective Hamiltonian which governs the neutrino flavors oscillations through the matter gets modified in the presence of NSI, for more details see [7]. In this work we focus only on the flavor changing non-diagonal NSIs $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ [1] along with their associated CP-phases $\phi_{e\mu}$ and $\phi_{e\tau}$ respectively which is a crucial ingredient to resolve the discrepancy between NOνA and T2K we are considering. Let us focus on the conversion probability relevant for the LBL experiments T2K and NOνA. In the presence of NSI, the probability can be expressed as the sum of three terms $P_{\mu e} \simeq P_0 + P_1 + P_2$ which, using a compact notation take the following forms

$$P_0 \;\simeq\; 4 s_{13}^2 s_{23}^2 f^2, \tag{3}$$

$$P_1 \;\simeq\; 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta_{\rm CP}), \tag{4}$$

$$P_2 \;\simeq\; 8 s_{13} s_{23} v |\varepsilon| [a f^2 \cos(\delta_{\rm CP} + \phi) + b f g \cos(\Delta + \delta_{\rm CP} + \phi)], \tag{5}$$

where $\Delta \equiv \Delta m_{31}^2 L/4E$ is the atmospheric oscillating frequency, L is the baseline and E the neutrino energy, $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$, and $v = 2V_{CC}E/\Delta m_{31}^2$. Here $V_{CC} = \sqrt{2}G_F N_e$ is the charged current

[1] $|\varepsilon_{\mu\tau}|$ is strongly constrained by the atmospheric neutrinos, $|\varepsilon_{\mu\tau}| < 8.0 \times 10^{-3}$ [8].

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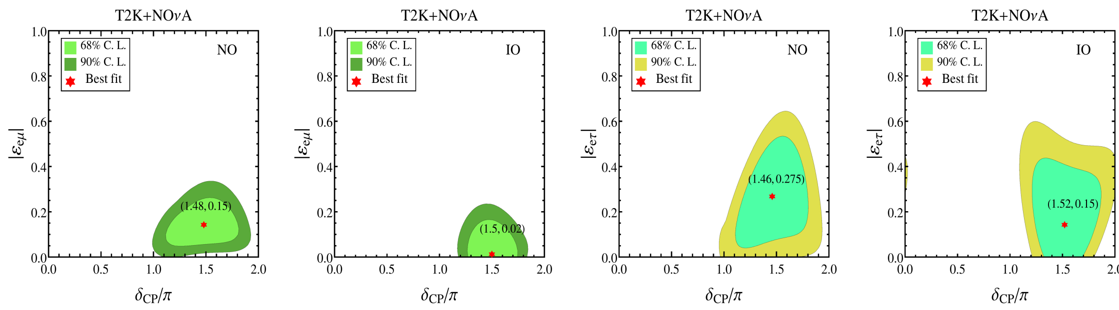

Figure 1: Allowed regions obtained from the combined analysis of T2K and NOνA in the plane $(\delta_{\rm CP}/\pi,\ |\varepsilon_{e\mu}|)$ and $(\delta_{\rm CP}/\pi,\ |\varepsilon_{e\tau}|)$ for both the NO and IO. The contours have been drawn at the 68% and 90% confidence level for 2 d.o.f.. This figure has been taken from [7].

matter potential. For brevity, we have used the notation ($s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$), and also we have,

$$f \equiv \frac{\sin[(1-v)\Delta]}{1-v}, \qquad g \equiv \frac{\sin v\Delta}{v} \tag{6}$$

$$a = s_{23}^2, \quad b = c_{23}^2 \quad \text{if} \quad \varepsilon = |\varepsilon_{e\mu}| e^{i\phi_{e\mu}}, \tag{7}$$

$$a = s_{23}c_{23}, \quad b = -s_{23}c_{23} \quad \text{if} \quad \varepsilon = |\varepsilon_{e\tau}| e^{i\phi_{e\tau}} \tag{8}$$

In the expressions given in Eqs. (3)-(5) for P_0, P_1 and P_2, the sign of Δ, α and v is positive (negative) for normal (inverted) ordering. Similarly for antineutrinos, the sign of all the CP-phases and of the matter parameter v are flipped. Finally, we observe that the third term P_2 purely arises because of the (complex) NSI coupling and it is different from zero only in matter (i.e. if $v \neq 0$). It represents the interference between the matter potential $\varepsilon_{e\mu}V_{CC}$ (or $\varepsilon_{e\tau}V_{CC}$) with the atmospheric wavenumber $\Delta m_{31}^2/2E$.

Numerical Results. Figure 1 reports the results of the combined analyses of T2K and NOνA for both the NO and inverted ordering (IO) in the plane of $\left[|\varepsilon_{e\mu}|, \delta_{\rm CP}\right]$ and $[|\varepsilon_{e\tau}|, \delta_{\rm CP}]$ respectively. It is worth to note that NSI parameter $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ has been taken one at a time. The contours in each panel are shown at 68% and 90% confidence level for 2 d.o.f., where the bestfit point is denoted by a red star. The non-standard CP-phases, the mixing angles θ_{13} and θ_{23}, and the squared-mass Δm_{31}^2 have been marginalized away. From the left most panel, one can see that in case of NO, the non zero value of the NSI coupling $|\varepsilon_{e\mu}|$ is preferred over the standard 3-flavor framework with best fit $|\varepsilon_{e\mu}| = 0.15$. The statistical significance lies at $\sim 2.1\sigma$ ($\Delta\chi^2 = 4.50$). However in case of IO, the preference of non zero $|\varepsilon_{e\mu}|$ is negligible. Now in case of $|\varepsilon_{e\tau}|$ and NO (third panel), there is a 1.9σ ($\Delta\chi^2 = 3.75$) preference of non zero $|\varepsilon_{e\tau}|$ with best fit $|\varepsilon_{e\tau}| = 0.27$, while in case of IO (fourth panel) the preference is only at the 1.0σ with best fit $|\varepsilon_{e\tau}| = 0.15$. It is interesting to note that in all the panels of Fig. 1, the preferred best fit values of $\delta_{\rm CP}$ is close to $3\pi/2$, indicating maximal CP-violation in the standard 3ν sector. For more details about the analyses, see [7].

Figure 2 represents the contours from the combined analysis of T2K and NOνA similar to Fig. 1 for both the NO and IO in the plane of $\left[\varepsilon_{e\mu}, \phi_{e\mu}\right]$ and $[\varepsilon_{e\tau}, \phi_{e\tau}]$ respectively. The standard CP-phase $\delta_{\rm CP}$, the mixing angles θ_{23} and θ_{13}, and the squared-mass Δm_{31}^2 are marginalized away. Interestingly in case of NO, the preferred value for both the new CP-phases $\phi_{e\mu}$ and $\phi_{e\tau}$ is close to $3\pi/2$, so indicating maximal CP-violation also in the NSI sector. The black dashed line in each

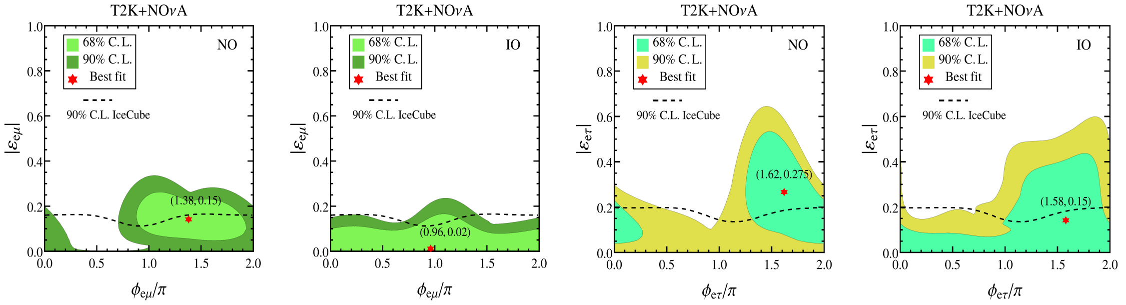

Figure 2: Allowed regions determined from the combined analysis of T2K and NOνA in the plane $(\phi_{e\mu}/\pi,\ |\varepsilon_{e\mu}|)$ and $(\phi_{e\tau}/\pi,\ |\varepsilon_{e\tau}|)$ for both the NO and IO. The contours have been drawn at the 68% and 90% confidence level for 2 d.o.f.. The dashed curves correspond to the upper bounds (90% C.L., 2 d.o.f.) derived from the IceCube data [9]. This figure has been taken from [7].

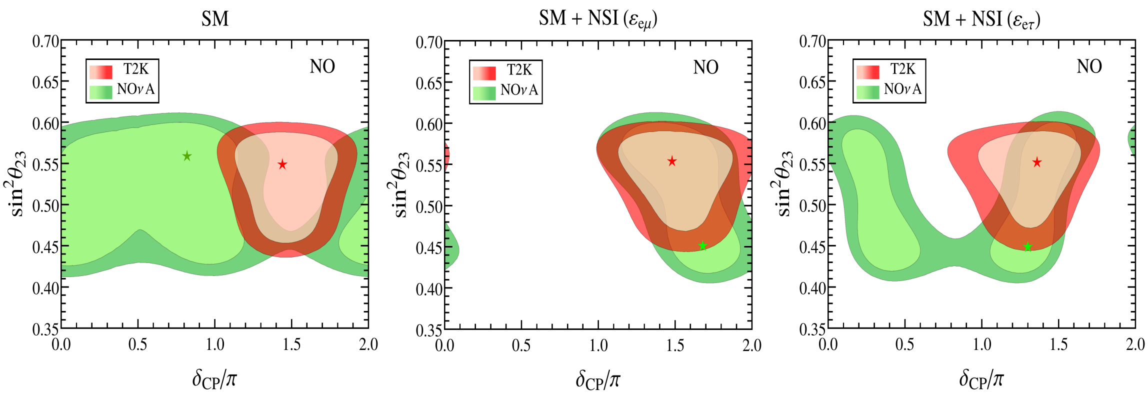

Figure 3: Allowed regions derived separately by T2K and NOνA for NO in the plane $(\delta_{CP}/\pi,\ \sin^2\theta_{23})$. Left panel represents the SM case and middle (right) panel corresponds to the NSI in the $e-\mu$ $(e-\tau)$ sector. In the middle panel we have considered the NSI parameters at their best fit values obtained from 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.. This figure has been taken from [7].

panel corresponds to the upper bounds given by the analysis of the IceCube data [9]. It can be seen that the bounds we have obtained from the combined analysis, are compatible with that of IceCube.

Let us now try to understand how the preference of the non-zero values of the NSI couplings in the $e-\mu$ and $e-\tau$ sectors help to resolve the tension between the NOνA and T2K measurement on δ_{CP}. In Fig. 3 we display the 68% and 90% C.L. allowed regions for 2 d.o.f. in the plane spanned by the standard CP-phase δ_{CP} and the atmospheric mixing angle θ_{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. The red (green) contours correspond to T2K (NOνA) respectively. From the left panel it is clearly evident that the discrepancy between the NOνA and T2K lies at more than 90% confidence level. NOνA (T2K) prefers values close to $\delta_{CP} \sim 0.8\pi$ ($\sim 1.4\pi$). In the middle and right panel the contours have been drawn considering the best fit values of the NSI parameters obtained from the combined analysis of both the experiments as shown in Fig. 1 and Fig. 2 respectively. We can see that in presence of NSI both in the middle and right panel, the tension between the two experiments is resolved. The best fit values of $\delta_{\rm CP}$ are almost same for both the panel and they are close to $\sim 3\pi/2$. Interestingly, this is also the value very close to the one preferred by T2K. It can be understood from the fact that due to short baseline (295 km) T2K has low sensitivity to the matter effects and thereby to the NSI, whereas NOνA has a longer baseline (810 km) and hence more sensitive to matter effects as well as to NSI. As a result, the standard CP-phase $\delta_{\rm CP}$ measured by T2K can be considered more faithful. It is worth to mention that in the SM case, the IO is slightly preferred over NO ($\chi^2_{\rm NO} - \chi^2_{\rm IO} = 1.87$). Now in presence of NSI, there is moderate preference of NO over IO in $e-\mu$ sector ($\chi^2_{\rm NO} - \chi^2_{\rm IO} = -2.56$), whereas in $e-\tau$ sector, there is no such preference ($\chi^2_{\rm NO} - \chi^2_{\rm IO} = -0.21$). For more details see [7].

Conclusions. In this work, we explored the impact of NSI on resolving the discrepancy between the two long-baseline experiments T2K and NOνA in the measurement of standard CP-phase $\delta_{\rm CP}$. We found that this discrepancy can be resolved if one considers the flavor changing neutral current non-standard interactions of neutrinos of type involving $e-\mu$ and $e-\tau$ sectors. We hope that the future LBL accelerator data as well as the atmospheric data would shed more light in confirming the existence of NSI hypothesis.

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References

[1] A. Himmel, *New Oscillations Results from NOνA Experiment*, *Talk presented at Neutrino 2020, 22 Jun 2020 -2 Jul 2020, Virtual Meeting* (2020).

[2] P. Dunne, *Latest Neutrino Oscillations from T2K*, *Talk presented at Neutrino 2020, 22 Jun 2020 -2 Jul 2020, Virtual Meeting* (2020).

[3] Y. Farzan and M. Tortola, *Neutrino oscillations and Non-Standard Interactions*, *Front.in Phys.* **6** (2018) 10, [arXiv:1710.09360].

[4] P. S. Bhupal Dev et al., *Neutrino Non-Standard Interactions: A Status Report*, in *NTN Workshop on Neutrino Non-Standard Interactions St Louis, MO, USA, May 29-31, 2019*, 2019. arXiv:1907.00991.

[5] Y. Farzan and I. M. Shoemaker, *Lepton Flavor Violating Non-Standard Interactions via Light Mediators*, *JHEP* **07** (2016) 033, [arXiv:1512.09147].

[6] L. Wolfenstein, *Neutrino Oscillations in Matter*, *Phys.Rev.* **D17** (1978) 2369–2374.

[7] S. S. Chatterjee and A. Palazzo, *Nonstandard Neutrino Interactions as a Solution to the NOνA and T2K Discrepancy*, *Phys. Rev. Lett.* **126** (2021), no. 5 051802, [arXiv:2008.04161].

[8] **IceCube** Collaboration, M. G. Aartsen et al., *Search for Nonstandard Neutrino Interactions with IceCube DeepCore*, *Phys. Rev.* **D97** (2018), no. 7 072009, [arXiv:1709.07079].

[9] T. Ehrhardt, *Search for NSI in neutrino propagation with IceCube DeepCore*, *Talk presented at 4th Uppsala workshop on Particle Physics with Neutrino Telescopes* (2019).

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