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The Daya Bay and T2K results on $\sin^2 2\theta_{13}$ and non-standard neutrino interactions

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Abstract

We show that the relatively large best fit value of $\sin^2 2\theta_{13} = 0.14$ (0.17) measured in the T2K experiment for fixed values of i) the Dirac CP violation phase $\delta = 0$, and ii) the atmospheric neutrino mixing parameters $\theta_{23} = \pi/4$, $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, can be reconciled with the Daya Bay result $\sin^2 2\theta_{13} = 0.090 \pm 0.009$ if the effects of non-standard neutrino interactions (NSI) in the relevant $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation probabilities are taken into account.

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1. Introduction

Recently the T2K Collaboration reported a measurement of the reactor neutrino mixing angle θ_{13} based on their latest $\nu_\mu \rightarrow \nu_e$ oscillation data [1]. Fixing the values of i) the Dirac CP violation (CPV) phase $\delta = 0$, ii) the atmospheric neutrino mixing angle $\theta_{23} = \pi/4$, iii) $\sin^2 \theta_{12} = 0.306$, iv) $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$ and v) $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, the T2K Collaboration found:

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$$\sin^2 2\theta_{13} = 0.140_{-0.032}^{+0.038} (0.170_{-0.037}^{+0.045}), \quad (1)$$

where the value (the value in brackets) corresponds to neutrino mass spectrum with normal (inverted, IO) ordering (NO). The best fit value of $\sin^2 2\theta_{13}$ reported by the T2K Collaboration is significantly larger than that measured in the reactor neutrino experiments Daya Bay, RENO and Double Chooz [2–4]. The most precise determination of $\sin^2 2\theta_{13}$ was reported by the Daya Bay Collaboration [2]:

$$\sin^2 2\theta_{13} = 0.090_{-0.009}^{+0.008}. \quad (2)$$

Given the uncertainty in the T2K result, Eq. (1), the difference between the values of $\sin^2 2\theta_{13}$ obtained in the T2K and Daya Bay experiments does not seem to be irreconcilable and the most natural explanation of this difference can be attributed to setting $\delta = 0$ and $\theta_{23} = \pi/4$. Indeed, the global analyses of the neutrino oscillation data, including the data from T2K and Daya Bay, performed in [5,6] found a hint for non-zero value of δ and for a deviation of θ_{23} from $\pi/4$: for the best fit values of δ and $\sin^2 \theta_{23}$ the authors of [5] obtained $\delta \simeq 3\pi/2$ and $\sin^2 \theta_{23} = 0.42 - 0.43$. Similar results were obtained in [6].

On-going and future neutrino experiments [1,7,8] have the physics potential to improve the data on the leptonic CP violation phase δ and thus to test the indications for $\delta \sim 3\pi/2$ found in the global analyses [5,6].

In this letter we would like to entertain a different possibility, namely, that the difference between the values of $\sin^2 2\theta_{13}$ found in the T2K experiment for $\delta = 0$, $\theta_{23} = \pi/4$, etc., and in the Daya Bay experiment is due to the presence of new physics in the neutrino sector. More specifically, we consider the effects of non-standard neutrino interactions (NSI) [9,10] on the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation probabilities and show how the values obtained in the two experiments can be reconciled.

2. Basic formalism

In what follows we consider the analytic treatment of Non Standard Interactions (NSI) as described in [11], where it was assumed that NSI can affect both neutrino production and detection processes. Matter effects can be safely neglected in the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation probabilities, relevant for the interpretation of the Daya Bay and T2K data of interest.

Effects of NSI can appear at low energy through unknown couplings $\varepsilon_{\alpha\beta}$, generated after integrating out heavy degrees of freedom. These new couplings can affect neutrino production s and detection d [10], so the neutrino states are a superposition of the orthonormal flavor eigenstates $|v_e\rangle$, $|v_\mu\rangle$ and $|v_\tau\rangle$ [12–14]:

$$|v_\alpha^s\rangle = |v_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |v_\beta\rangle = [(1 + \varepsilon^s)|v\rangle]_\alpha, \quad (3)$$

$$\langle v_\beta^d| = \langle v_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle v_\alpha| = [\langle v|(1 + \varepsilon^d)]_\beta. \quad (4)$$

The oscillation probability can be obtained by squaring the amplitude $\langle v_\beta^d|e^{-iHL}|v_\alpha^s\rangle$:

$$P_{\nu_\alpha^s \rightarrow \nu_\beta^d} = |\langle v_\beta^d|e^{-iHL}|v_\alpha^s\rangle|^2 = |(1 + \varepsilon^d)_{\gamma\beta} (e^{-iHL})_{\gamma\delta} (1 + \varepsilon^s)_{\alpha\delta}|^2.$$

Since the parameters $\varepsilon_{e\alpha}^s$ and $\varepsilon_{\alpha e}^d$ receive contributions from the same higher dimensional operators, one can constrain them by the relation:

$$\varepsilon_{e\alpha}^s = \varepsilon_{\alpha e}^{d*} \equiv \varepsilon_{e\alpha} e^{i\phi_{e\alpha}}, \quad (5)$$

$\varepsilon_{e\alpha}$ and $\phi_{e\alpha}$ being the modulus and the argument of $\varepsilon_{e\alpha}^s$. For $\varepsilon_{\alpha\beta}$ there exist model independent bounds derived in [15], which at 90% C.L. read:

$$\begin{aligned} \varepsilon_{ee} < 0.041, \quad \varepsilon_{e\mu} < 0.025, \quad \varepsilon_{e\tau} < 0.041, \\ |\varepsilon_{\mu e}^{s,d}| < 0.026, \quad |\varepsilon_{\mu\mu}^{s,d}| < 0.078, \quad |\varepsilon_{\mu\tau}^{s,d}| < 0.013, \end{aligned} \quad (6)$$

whereas for the CP violation phases $\phi_{e\alpha}$ no constraints have been obtained so far. These bounds can be further improved, e.g., by future reactor neutrino experiments [12] and at neutrino factories [16], especially the bounds on non-diagonal couplings which are expected to be constrained at the level of $\mathcal{O}(10^{-3})$. Recently it was shown in Ref. [17] that the bound on ε_{ee} can be improved by almost an order of magnitude by the most recent data of the Daya Bay experiment [2], i.e. $\varepsilon_{ee} \lesssim 3.6 \times 10^{-3}$ at 90% confidence level.

In the case of the Daya Bay setup, the relevant features of the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ survival probability at the far and near detectors can be already caught keeping terms up to $\mathcal{O}(\varepsilon)$ in the expansion in the small couplings $|\varepsilon_{\alpha\beta}^{s,d}|$ and neglecting terms of $\mathcal{O}(\Delta m_{21}^2/\Delta m_{31}^2)$ and of $\mathcal{O}(\varepsilon \sin^2 \theta_{13}, \sin^3 \theta_{13})$.

On the other hand, for the T2K setup, the correct dependence on the Dirac phase δ is reproduced keeping the first order terms in Δm_{21}^2 , as discussed in [11].

In the limiting case $\varepsilon_{ee} = 0$ (which is a good approximation since $|\varepsilon_{ee} \cos \phi_{ee}| < \mathcal{O}(10^{-3})$ [17]), the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ survival probability can be written for $\delta = 0$ as:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\hat{\theta}_{13} \sin^2 \left[\frac{\Delta m_{31}^2 L}{4E_\nu} \right], \quad (7)$$

where [18]

$$\begin{aligned} \sin^2 2\hat{\theta}_{13} = \sin^2 2\theta_{13} + 4\varepsilon_{e\mu} \sin 2\theta_{13} \sin \theta_{23} \cos 2\theta_{13} \cos(\phi_{e\mu}) \\ + 4\varepsilon_{e\tau} \sin 2\theta_{13} \cos \theta_{23} \cos 2\theta_{13} \cos(\phi_{e\tau}). \end{aligned} \quad (8)$$

The terms involving the parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ can affect significantly the determination of the reactor angle θ_{13} , as pointed out in [17,18]. Depending on the phases $\phi_{e\mu}$ and $\phi_{e\tau}$, relatively large values of $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ can lead to smaller (for $\phi_{e\mu} = \phi_{e\tau} \simeq 0$), equal (for $\phi_{e\mu} \simeq \phi_{e\tau} + \pi$ and $\varepsilon_{e\mu} \simeq \varepsilon_{e\tau}$) or larger (for $\phi_{e\mu} = \phi_{e\tau} \simeq \pi$) values of θ_{13} than those obtained in the standard case of absence of NSI.

The oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ relevant for the interpretation of the T2K data on $\sin^2 2\theta_{13}$, can be written for $\delta = 0$, $\Delta m_{21}^2/\Delta m_{31}^2 \ll 1$ and taking into account the NSI as:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + P_0 + P_1, \quad (9)$$

where P_0 and P_1 include respectively the zero and the first order contributions of the NSI, derived for $\Delta m_{21}^2 L/(4E_\nu) \ll 1$. Indeed, for the neutrino energy of $E_\nu = 0.1$ GeV we have: $\Delta m_{21}^2 L/(4E_\nu) = 2.7 \times 10^{-4}$ for $L = 0.28$ km, and $\Delta m_{21}^2 L/(4E_\nu) = 0.28$ for $L = 295$ km.

Using the constraints given in Eq. (5) and defining $\varepsilon_{\alpha\beta}^{s,d} = |\varepsilon_{\alpha\beta}^{s,d}| \exp(i\phi_{\alpha\beta}^{s,d})$, we get:

$$\begin{aligned}
P_0 = & -4|\varepsilon_{\mu e}^s| \sin\theta_{13} \sin\theta_{23} \cos(\phi_{\mu e}^s) \sin^2\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \\
& - 4|\varepsilon_{\mu e}^s| \sin\theta_{13} \sin\theta_{23} \sin(\phi_{\mu e}^s) \sin\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \cos\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \\
& - 4\varepsilon_{e\mu} \sin\theta_{13} \sin\theta_{23} \cos(\phi_{e\mu}) \cos 2\theta_{23} \sin^2\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \\
& - 4\varepsilon_{e\mu} \sin\theta_{13} \sin\theta_{23} \sin(\phi_{e\mu}) \sin\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \cos\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \\
& + 8\varepsilon_{e\tau} \sin\theta_{13} \sin^2\theta_{23} \cos\theta_{23} \cos(\phi_{e\tau}) \sin^2\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] + O(\varepsilon \sin^2\theta_{13}) + O(\varepsilon^2), \quad (10)
\end{aligned}$$

$$\begin{aligned}
P_1 = & -|\varepsilon_{\mu e}^s| \sin 2\theta_{12} \cos\theta_{23} \sin\phi_{\mu e}^s \frac{\Delta m_{21}^2 L}{2E_\nu} \\
& + 2\varepsilon_{e\mu} \sin 2\theta_{12} \sin^2\theta_{23} \cos\theta_{23} \cos\phi_{e\mu} \frac{\Delta m_{21}^2 L}{4E_\nu} \sin\left[\frac{\Delta m_{31}^2 L}{2E_\nu}\right] \\
& + \varepsilon_{e\mu} \sin 2\theta_{12} \cos\theta_{23} \sin\phi_{e\mu} \frac{\Delta m_{21}^2 L}{2E_\nu} \left[1 - 2\sin^2\theta_{23} \sin^2\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right]\right] \\
& + 2\varepsilon_{e\tau} \sin 2\theta_{12} \sin\theta_{23} \cos^2\theta_{23} \cos\phi_{e\tau} \frac{\Delta m_{21}^2 L}{4E_\nu} \sin\left[\frac{\Delta m_{31}^2 L}{2E_\nu}\right] \\
& - 2\varepsilon_{e\tau} \sin 2\theta_{12} \sin\theta_{23} \cos^2\theta_{23} \sin\phi_{e\tau} \frac{\Delta m_{21}^2 L}{2E_\nu} \sin^2\left[\frac{\Delta m_{31}^2 L}{4E_\nu}\right] \\
& + O\left(\varepsilon \sin\theta_{13} \frac{\Delta m_{21}^2 L}{4E_\nu}\right) + O(\varepsilon^2). \quad (11)
\end{aligned}$$

In the previous equations, the P_0 term encodes the correlations between θ_{13} and the new physics parameters so, as in the Daya Bay case, we expect a significant impact of degeneracies on the determination of the reactor angle. The term P_1 is subleading, whose magnitude is controlled by $\Delta m_{21}^2 L/(4E_\nu) \ll 1$.

3. Fit results

As we can see from the previous formulae, the parameter space for NSI relevant for our analysis consists of six parameters, the moduli $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu e}^s$ and the phases $\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu e}^s$. However, for the illustrative purposes of the present study it is sufficient to consider a smaller parameter space with just two independent NSI parameters, specified below. We consider two different scenarios: one in which a large $\sin^2 2\theta_{13} = 0.14$ ($\sin^2 2\theta_{13} = 0.17$) for NO (IO) can be reconciled with both the Daya Bay and T2K data and a second where we assume that $\sin^2 2\theta_{13} = 0.09$.

3.1. The case of $\sin^2 2\theta_{13} = 0.14$ (0.17)

In this case we reduced the parameter space assuming:

$$\varepsilon = \varepsilon_{e\mu} = \varepsilon_{e\tau} = \varepsilon_{\mu e}^s, \quad \phi = \phi_{e\mu} = \phi_{e\tau}, \quad \phi_{\mu e}^s = 0. \quad (12)$$

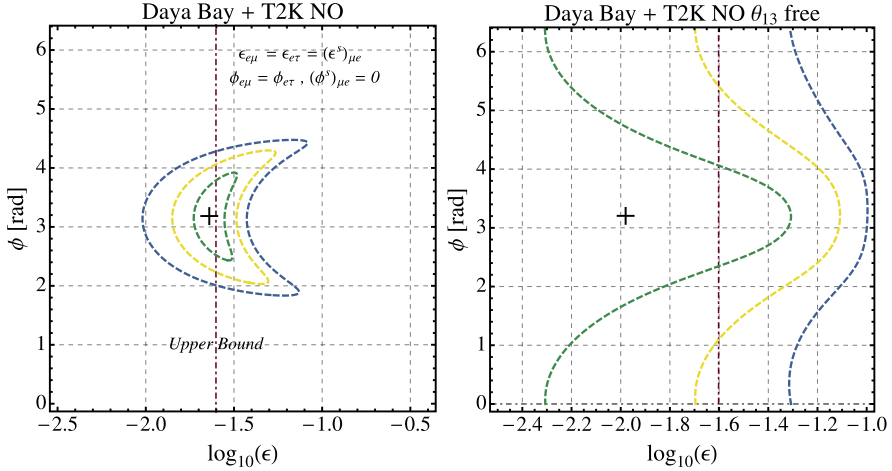


Fig. 1. Allowed regions in the ϕ – $\log_{10}(\epsilon)$ plane, where ϵ and ϕ are respectively the modulus and the phase of the NSI parameter, at 1 σ , 2 σ and 3 σ confidence level (C.L.) for 1 dof fitting the data of the Daya Bay and the T2K experiments in the case of NSI with NO. The best fit points correspond to the crossed points. The vertical lines are at $\log_{10} \epsilon = \log_{10} 0.025$.

The choice of the parameter space is not completely arbitrary. For the large θ_{13} case we need relatively large NSI effects to obtain an effective reactor angle satisfying the Daya Bay measurement.

In Fig. 1 we show the best fit points and the 1, 2 and 3 σ confidence level regions for 1 degree of freedom (dof) after performing a combined fit to the Daya Bay [2] and T2K [1] data (see Appendix A for a detailed description of the fitting procedure). In the left panel of Fig. 1 we fixed $\sin^2 \theta_{12} = 0.306$, $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$, $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, $\delta = 0$ and $\sin^2 2\theta_{13} = 0.140$, whereas in the right panel we allowed θ_{13} to vary freely, using the mean value and the 1 σ error as determined in the T2K experiment, $\sin^2 2\theta_{13}^{\text{T2K}} = 0.140 \pm 0.038$.

Results in the case of inverted hierarchy are shown in Fig. 2; the procedure adopted is the same as the one used to obtain Fig. 1, the only difference being that the fixed value of the reactor angle is now at $\sin^2 2\theta_{13} = 0.170$ and that, when θ_{13} is left free to vary, we used $\sin^2 2\theta_{13}^{\text{T2K}} = 0.170 \pm 0.045$.

As it can be seen, in the left panels of Figs. 1 and 2, the same value of θ_{13} can give a good description of both Daya Bay and T2K data under the hypothesis of relatively large ϵ and for a phase ϕ which is almost CP conserving.

Since we are adopting the preferred T2K value of θ_{13} , it is necessary to allow for relatively large NSI couplings to reconcile $\sin^2 2\theta_{13} = 0.14$ ($\sin^2 2\theta_{13} = 0.17$) with the Daya Bay event distribution. On the other hand, our choice of couplings, Eq. (12), does not lead to a significant change of the fit to the T2K data.

In the case we vary freely θ_{13} (see Appendix A for details) the sensitivity to ϵ is significantly reduced (with the smallest statistical sensitivity at $\phi \sim \pi$), due to the strong correlation between θ_{13} and the NSI parameters [17]. That means that there exist a vast parameter space for NSI for which the data can be fitted simultaneously at the price of changing accordingly the value of θ_{13} . To give an example, at the best fit point we get: $\sin^2 2\theta_{13} = 0.113$ ($\sin^2 2\theta_{13} = 0.130$) for the NO (IO) spectrum.

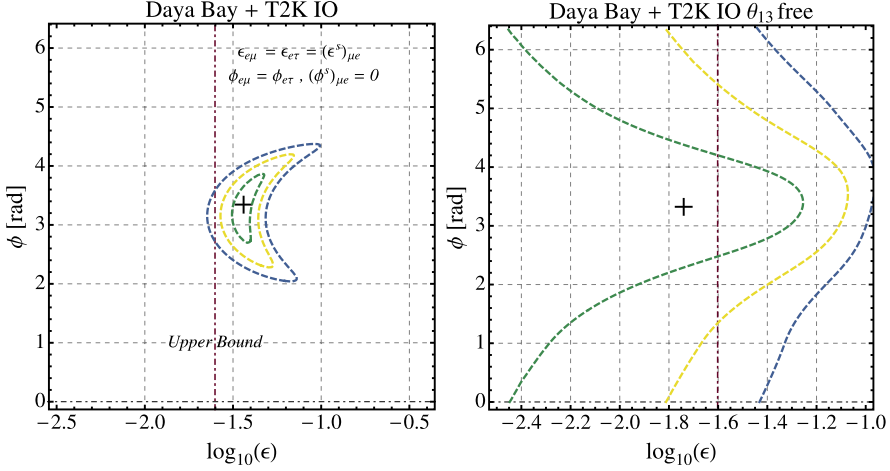


Fig. 2. Same as Fig. 1 but for IO.

Table 1

Best fit points for the $(\log_{10} \varepsilon, \phi)$ parameters obtained in our analysis. NO refers to Fig. 1, IO to Fig. 2.

$(\log_{10} \varepsilon, \phi)$ best fit	Left panel	Right panel
NO	(-1.64, 3.18)	(-1.98, 3.20)
IO	(-1.44, 3.34)	(-1.74, 3.32)

The values of ε, ϕ at the NO(IO) best fit point are given in Table 1. We notice that the confidence level regions are slightly shifted to the left (right) if instead of the assumption in Eq. (12) we impose: $\varepsilon_{e\mu} = 2\varepsilon_{e\tau} = \varepsilon_{\mu e}^s, \phi_{e\mu} = \phi_{e\tau}$ and $\phi_{\mu e}^s = 0$ ($\varepsilon_{e\mu} = \varepsilon_{e\tau} = \varepsilon_{\mu e}^s, \phi_{e\mu} = \phi_{e\tau}$ and $\phi_{\mu e}^s = \pi/2$).

To demonstrate that for the obtained values of the NSI parameters one can describe both the Daya Bay and T2K results, including the spectra, in the Left Panel of Fig. 3 we show the oscillation probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ as a function of L_{eff}/E_ν [2] for the NSI model (solid red line) for NO spectrum and in the absence of NSI (“standard result” (SR)) (dotted black line); the mixing parameters are fixed as follows: $\sin^2 \theta_{12} = 0.306, \Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2, \sin^2 \theta_{23} = 0.5, |\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2, \delta = 0$ and $\sin^2 2\theta_{13} = 0.140, \varepsilon_{e\mu} = \varepsilon_{e\tau} = \varepsilon_{\mu e}^s = 10^{-1.64}, \phi_{e\mu} = \phi_{e\tau} = 3.18$ and $\phi_{\mu e}^s = 0$. The triangular, square and circular data points refer to the EH1, EH2 (near detectors) and EH3 (far detector) Daya Bay locations and have been taken from [2]. The Right Panel of Fig. 3 has been obtained using the same values for the standard oscillation and NSI parameters and shows the number of candidate events in the appearance channel of the T2K experiment. The SR result with $\sin^2 2\theta_{13} = 0.090$ is shown with the dot-dashed line in the left panel and the T2K best fit curve is represented with the blue line in the right panel. As it is clear from these figures, the Daya Bay and the T2K spectral data are well reproduced.

3.2. The case of $\sin^2 2\theta_{13} = 0.09$

In the case of small θ_{13} we reduced the parameter space assuming:

$$\varepsilon = \varepsilon_{e\mu} = \varepsilon_{\mu e}^s, \quad \varepsilon_{e\tau} \neq 0, \quad \phi_{e\mu} = \phi_{\mu e}^s = \pi, \quad \phi_{e\tau} = 0. \quad (13)$$

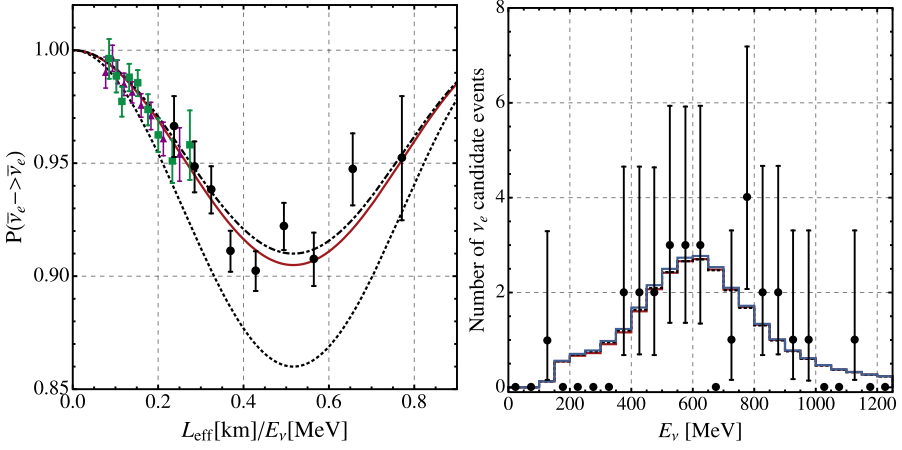


Fig. 3. Left panel. Oscillation probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ as a function of L_{eff}/E_ν for the NSI model (solid red line) and the SR with $\sin^2 2\theta_{13} = 0.140$ (dashed black line) and with $\sin^2 2\theta_{13} = 0.090$ (dot-dashed black line). The triangular, square and circular data points refer to the EH1, EH2 and EH3 locations and have been taken from [2]. Right panel. Number of ν_e candidate events as a function of the neutrino energy for the NSI model (solid red line), the SR (dashed black line) and the T2K best fit curve (solid blue line), the three curves being almost superimposed. The T2K data and the errors have been taken from [1]. See the text for further details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

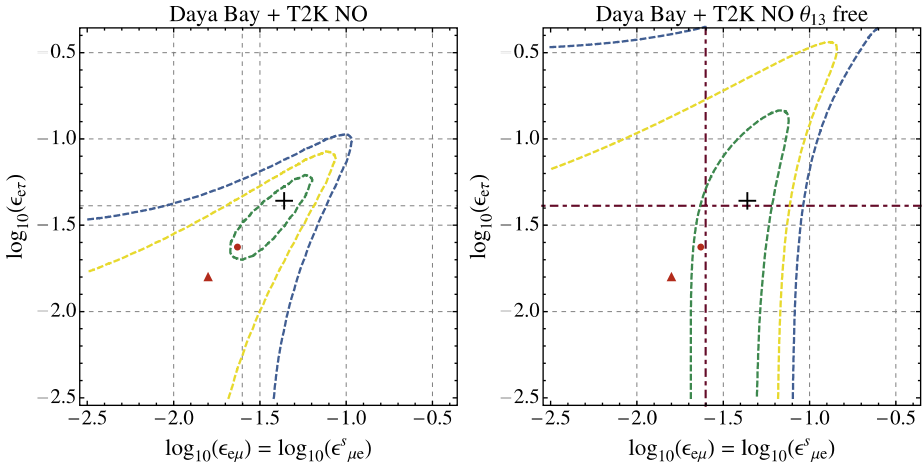


Fig. 4. Allowed regions in the $\log_{10} \epsilon_{e\tau} - \log_{10} \epsilon$ plane, where ϵ and ϕ are respectively the modulus and the phase of the NSI parameter, at 1σ , 2σ and 3σ confidence level (C.L.) for 1 dof fitting the data of the Daya Bay and the T2K experiments in the case of NSI with NO. The best fit points correspond to the crossed points; the vertical lines are at $\log_{10} \epsilon = \log_{10} 0.025$, the horizontal lines at $\log_{10} \epsilon_{e\tau} = \log_{10} 0.041$. The circular and triangular points are at $(\log_{10} \epsilon, \log_{10} \epsilon_{e\tau}) = (-1.63, -1.63)$, $(-1.80, -1.80)$, respectively.

In the case of small θ_{13} the choice in Eq. (13) is dictated by the need of minimizing the NSI effects in the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ survival probability, so that the results of the Daya Bay fit remain unaffected. In the Left Panel of Fig. 4 we show the best fit points and the 1, 2 and 3 σ confidence level regions for 1 dof after performing a combined fit to the Daya Bay and to the T2K data for NO fixing

Table 2

Best fit points for the $(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau})$ parameters obtained in our analysis.

Best fit	Left panel	Right panel
$(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau})$	$(-1.36, -1.36)$	$(-1.36, -1.36)$

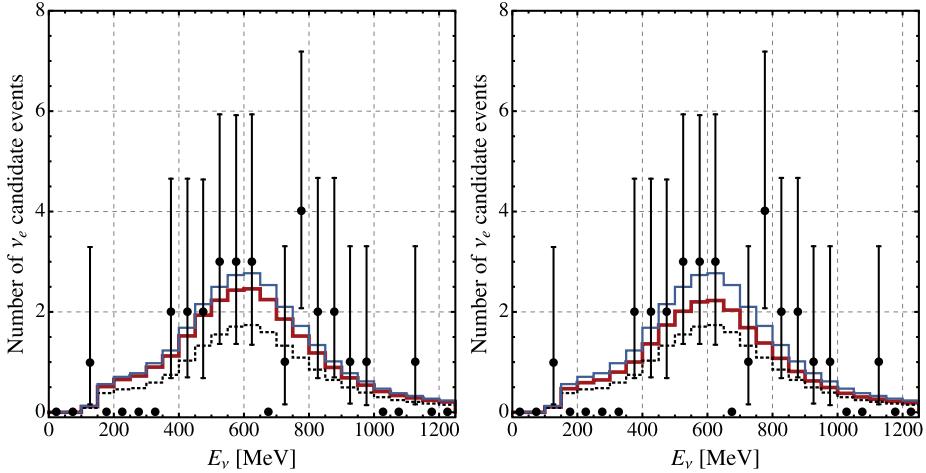


Fig. 5. Left panel. Number of ν_e candidate events as a function of the energy for the NSI model (solid red line) with $(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau}) = (-1.63, -1.63)$, the SR (dashed black line) and the T2K best fit curve (solid thin blue line). The T2K data and the errors have been taken from [1]. Right panel. As in the Left Panel but using $(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau}) = (-1.80, -1.80)$. See the text for further details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$\sin^2 \theta_{12} = 0.306$, $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$, $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, $\delta = 0$ and $\sin^2 2\theta_{13} = 0.09$. In the right panel of Fig. 4 we allowed θ_{13} to vary freely.

We do not show the results for the IO spectrum, because, under the assumptions made for the parameter space, Eq. (13), they are the same as in the NO case.

In contrast to the large θ_{13} case, in order to reconcile the Daya Bay and the T2K spectral data requires that the phase $\phi_{e\mu}$ and $\phi_{e\tau}$ are related through $\phi_{e\mu} \simeq \phi_{e\tau} - \pi$. This ensures that sizeable NSI effects do not spoil the Daya Bay measurement of the reactor angle when $\varepsilon_{e\mu} \sim \varepsilon_{e\tau}$: in fact, $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ is reduced essentially to the standard expression and no significant effect has to be expected from the NSI parameters at leading order. On the other hand, it is clear that relatively large values of ε are needed to fit the T2K data.

We give in Table 2 the best fit points we obtained in our analysis for Fig. 4. Notice that they are close to the current upper limits, reported with dot-dashed lines.

Finally, in Fig. 5 we show the number of candidate events in the appearance channel of the T2K experiment (with mixing parameters fixed at the values discussed below Eq. (13)).

Since the best fit points are outside the current 90% C.L. bounds on the NSI parameters, we show the spectra for two points within the NSI bounds: one point is located in the 1σ region, while the second is located in the 2σ region (see Fig. 4). In the left panel of Fig. 5 we fixed $(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau}) = (-1.63, -1.63)$, in the right panel $(\log_{10} \varepsilon, \log_{10} \varepsilon_{e\tau}) = (-1.80, -1.80)$.

The T2K best fit curve is represented with the blue line. As it is clear from these figures, the T2K spectral data are well reproduced.

4. Conclusions

In the present paper we have analyzed the most recent data of the Daya Bay [2] and the T2K [1] experiments with the aim to study the possibility that NSI effects can reconcile the different values of the reactor angle reported by the two experiments. We recall that the best fit values of $\sin^2 2\theta_{13}$ found in the experiments, $\sin^2 2\theta_{13} = 0.090$ [2] and $\sin^2 2\theta_{13} = 0.140$ (0.170) [1], differ by a factor 1.6 (1.9) in the case of NO (IO) neutrino mass spectrum. The T2K result was obtained under the assumptions: i) the Dirac CP violation phase $\delta = 0$, ii) the atmospheric neutrino mixing angle $\theta_{23} = \pi/4$, iii) $\sin^2 \theta_{12} = 0.306$, iv) $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$ and v) $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$. Given the uncertainty in the T2K result, the difference between the values of $\sin^2 2\theta_{13}$ obtained in the T2K and Daya Bay experiments does not seem to be irreconcilable and the most natural explanation can be attributed to setting $\delta = 0$ and $\theta_{23} = \pi/4$. In this Letter we have entertained a different possibility, namely, that the difference between the values of $\sin^2 2\theta_{13}$ found in the T2K experiment for $\delta = 0$ and in the Daya Bay experiment are due to the presence of new physics in the neutrino sector in the form of non-standard neutrino interactions (NSI). There are altogether six NSI parameters which can affect the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation probabilities, relevant for the interpretation of the Daya Bay and T2K data on $\sin^2 2\theta_{13}$: three complex, in general, NSI effective couplings, whose absolute values and phases are $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu e}^s$ and $\phi_{e\mu}$, $\phi_{e\tau}$, $\phi_{\mu e}^s$. We have considered two extreme cases: one where the true value of θ_{13} is $\sin^2 2\theta_{13} = 0.140$ for NO ($\sin^2 2\theta_{13} = 0.170$ for IO), and the other where the true value is $\sin^2 2\theta_{13} = 0.090$. With the aim of finding a minimal model with few new degrees of freedom for each of the two cases, we have simplified the NSI parameter spaces, assuming $\varepsilon = \varepsilon_{e\mu} = \varepsilon_{e\tau} = \varepsilon_{\mu e}^s$, $\phi = \phi_{e\mu} = \phi_{e\tau}$, $\phi_{\mu e}^s = 0$ for the large θ_{13} case and $\varepsilon = \varepsilon_{e\mu} = \varepsilon_{\mu e}^s$, $\varepsilon_{e\tau} \neq 0$, $\phi_{e\mu} = \phi_{\mu e}^s = \pi$, $\phi_{e\tau} = 0$ for the small θ_{13} one. All other mixing parameters are fixed to $\sin^2 \theta_{12} = 0.306$, $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$, $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, $\delta = 0$. We have found that, contrary to the interpretation that $\delta = 0$ is disfavored in the standard case, following from the global analysis of the neutrino oscillation data [5,6], it is possible to find a good agreement with both the hypothesis of large, $\sin^2 2\theta_{13} = 0.14$ (0.17), and small, $\sin^2 2\theta_{13} = 0.09$, for $\delta = 0$, in well defined regions of the NSI parameter space. In a more general situation in which the NSI can affect the neutrino flux in the near detector and without the restrictions we considered on the parameter space, it will be possible to reconcile the Daya Bay and T2K data in a bigger region of the NSI parameter space within the current upper bounds.

Given the relatively low statistics of the T2K $\nu_\mu \rightarrow \nu_e$ oscillation data, our results on the possible NSI effects should be considered as very preliminary. Future experiments searching the CP violation and/or NSI effects in neutrino oscillations will certainly provide a critical test of the possible NSI effects discussed in the present article.

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Appendix A. The Daya Bay and the T2K experiments

The Daya Bay experimental setup we take into account [19] consists of six antineutrino detectors (ADs) and six reactors; detailed information on the antineutrino spectra emitted by the nuclear reactors and arriving to the detectors can be found in [20–22]. For our analysis we used the data set accumulated during 217 days reported in [2], where the detected antineutrino candidates are collected in the far hall, EH3 (far detector), and in the near halls EH1, EH2 (near detectors).

The antineutrino energy $E_{\bar{\nu}_e}$ is reconstructed by the prompt energy deposited by the positron E_{prompt} using the approximated relation [19]: $E_{\bar{\nu}_e} \simeq E_{\text{prompt}} + 0.8$ MeV. We adopt a Gaussian energy resolution function of the form:

$$R^c(E, E') = \frac{1}{\sigma(E)\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2(E)}}, \quad (14)$$

with $\sigma(E)$ [MeV] = $\alpha \cdot E + \beta \cdot \sqrt{E} + \gamma$ that, for Daya Bay, are $(\alpha, \beta, \gamma) = (0, 0, 0.08)$ MeV. The antineutrino cross section for the inverse beta decay (IBD) process has been taken from [23]. The statistical analysis of the data has been performed using the GLOBES software [24] with the χ^2 function defined as [19]:

$$\chi_{DB}^2(\theta, \Delta m^2, \vec{S}, \alpha_r, \varepsilon_d, \eta_d) = \sum_{d=1}^6 \sum_{i=1}^{36} \frac{[M_i^d - T_i^d \cdot (1 + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_i^d + B_i^d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^6 \left[\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_{B_d}^2} \right] + \text{Priors}, \quad (15)$$

where \vec{S} is a vector containing the new physics parameters, M_i^d are the measured IBD events of the d -th detector ADs in the i -th bin, B_i^d the corresponding background and $T_i^d = T_i(\theta, \Delta m^2, \vec{S})$ are the theoretical prediction for the rates. The parameter ω_r^d is the fraction of IBD contribution of the r -th reactor to the d -th detector AD, determined by the approximated relation $\omega_r^d \sim L_{rd}^{-2} / (\sum_{r=1}^6 1/L_{rd}^2)$, where L_{rd} is the distance between the d -th detector and the r -th reactor. The parameter σ_d is the uncorrelated detection uncertainty ($\sigma_d = 0.2\%$) and σ_{B_d} is the background uncertainty of the d -th detector obtained using the information given in [2]: $\sigma_{B_1} = \sigma_{B_2} = 8.21$, $\sigma_{B_3} = 5.95$, $\sigma_{B_4} = \sigma_{B_5} = \sigma_{B_6} = 1.15$ and $\sigma_r = 0.8\%$ is the correlated reactor uncertainties. The corresponding pull parameters are $(\varepsilon_d, \eta_d, \alpha_r)$. With this choice of nuisance parameters we are able to reproduce the 1σ , 2σ and 3σ confidence level results presented in Fig. 3 of Ref. [2] with high accuracy. The differences are at the level of few percent (see Tables I and II of Ref. [17]).

The T2K experiment [1] consists of two separate detectors, both of which are 2.5 degrees off axis of the neutrino beam. The far detector is located at $L_F = 295$ km from the source, the ND280 near detector is $L_N = 280$ m from the target.

In our analysis we used the public data in [1,25]. The neutrino flux has been estimated following [26]. We fixed the fiducial mass of the near and the far detector respectively as $FM_{\text{ND280}} = 1529$ kg and $FM_{\text{SK}} = 22.5$ kton [27]; a bin to bin normalization has been fixed in order to reproduce the T2K best fit events. For the energy resolution function we adopt the same Gaussian form of Eq. (14) with $(\alpha, \beta, \gamma) = (0, 0, 0.085)$ GeV.

The χ_{T2K}^2 is defined as:

$$\begin{aligned} \chi_{T2K}^2(\theta, \Delta m^2, \vec{S}, \rho, \Omega_d, \alpha_d) &= \sum_{d=1}^2 \sum_{i=1}^{n_{bins}^d} 2 \left[M_i^d - T_i^d \cdot (1 + \rho + \Omega_d) + M_i^d \log \frac{M_i^d}{T_i^d \cdot (1 + \rho + \Omega_d)} \right] \\ &+ \frac{\rho^2}{\sigma_\rho^2} + \sum_{d=1}^2 \frac{\Omega_d^2}{\sigma_{\Omega_d}^2} + \text{Priors}. \end{aligned} \quad (16)$$

In the previous formula, \vec{S} is a vector containing the new physics parameters, M_i^d are the measured events, including the backgrounds (extracted from Fig. 4 of [1]), of the d -th detector in the i -th bin, $T_i^d = T_i^d(\theta, \Delta m^2, \vec{S}, \alpha_d)$ are the theoretical predictions for the rates, θ and Δm^2 are respectively the mixing angles and the squared mass differences contained in the oscillation probability, n_{bins}^d is the number of bins for the d -th detector. The parameter σ_ρ contains the flux, the uncorrelated ν interaction and the final-state interactions uncertainties ($\sigma_\rho = 8.8\%$ Table II of [1]), σ_{Ω_d} the fiducial mass uncertainty for the d -th detector (σ_{Ω_d} has been estimated to be $\sigma_{\Omega_d} = 1\%$ for the far and the near detectors similarly to [28]), α_d are free parameters which represent the energy scale for predicted signal events with uncertainty σ_{α_d} , ($\sigma_{\alpha_d} = 1\%$ [29]).

The corresponding pull parameters are $(\rho, \Omega_d, \alpha_d)$. The measured event rates at the near detector have been estimated rescaling the non oscillated measured event rates at the far detector using the scale factor $L_N^2/L_F^2 \times FM_{ND280}/FM_{SK}$. Our definition of the χ^2 allows to reproduce with high accuracy the 68% and 90% confidence level regions for $\sin^2 2\theta_{13}$ as a function of the CP violation phase δ shown in Fig. 5 of Ref. [1].

We analyzed the whole Daya Bay and T2K data sample using $\chi_{tot}^2 = \chi_{DB}^2 + \chi_{T2K}^2$. We considered two different statistical analysis: i) we fixed all the standard oscillation parameters, ii) we fixed all the standard oscillation parameters except θ_{13} on which we imposed a gaussian prior defined through the mean value and the 1σ error $\sin^2 2\theta_{13} = 0.140 \pm 0.038$, $\sin^2 2\theta_{13} = 0.170 \pm 0.045$ and $\sin^2 2\theta_{13} = 0.090 \pm 0.009$, for the different cases we have analyzed.

Appendix B. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.nuclphysb.2014.06.014>.

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