Constraining new physics scenarios in neutrino oscillations from Daya Bay data

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We perform for the first time a detailed fit to the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance data of the Daya Bay experiment to constrain the parameter space of models where sterile neutrinos can propagate in a large compactified extra dimension (LED) and models where non-standard interactions affect the neutrino production and detection (NSI). We find that the compactification radius $R$ in LED scenarios can be constrained at the level of 0.57 $\mu$m for normal ordering and of 0.19 $\mu$m for inverted ordering, at $2\sigma$ confidence level. For the NSI model, reactor data put a strong upper bound on the parameter $\varepsilon_{ee}$ at the level of $10^{-3}$, whereas the main effect of $\varepsilon_{ae}$ and $\varepsilon_{e\tau}$ is a worsening of the determination of $\theta_{13}$.

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After the recent measure of the reactor angle by T2K [1], Daya Bay [2] and Reno [3] experiments, the standard picture of neutrino oscillation seems now to be very well established, with only few items to be clarified, namely the presence of CP violation in the PMNS mixing matrix and the ordering of the mass eigenvalues. Beyond this standard picture, the possibility that new physics can affect neutrino oscillation is not excluded and, although expected to be small, deserve a closer look. A popular interesting model of new physics in neutrino oscillations is the one where sterile neutrinos can propagate, as well as gravity, in large $\delta$ compactified extra dimensions (LED) [4] whereas the Standard Model (SM) left-handed neutrinos are confined to a four-dimensional brane [5,7]. Experiments based on the torsion pendulum instrument set an upper limit on the largest compactification radius $R < 37 \mu$m for $\delta = 2$ at 95% CL [8]. Much stronger bounds can be set by astrophysics [9] but they are not completely model independent, so an analysis of the constraints coming from neutrino oscillation data still deserves a lot of attention. Since scenarios with only one extra dimension have been already ruled-out [8], we assume to work with an effective 5-dimensional theory in which only the radius $R$ of the largest new dimension is the relevant parameter for neutrino oscillation. Under these assumptions, the transition amplitude $\bar{\nu}_e \rightarrow \bar{\nu}_e$ in vacuum is given by [7]:

$$A_{ee}(L) = \sum_{i=1}^{3} \sum_{n=0}^{\infty} U_{ei}^{\ast} U_{en} [U_{en}^\ast]^2 \exp\left(\frac{\lambda_i^{(n)} L}{2 E_i R^2}\right),$$

where $U_{ei}$ is the first row of the $U_{PMNS}$ matrix, $\lambda_i^{(n)}$ are the eigenvalues of the neutrino mass matrix, $\xi_i \equiv \sqrt{2} m_i R$ (with absolute neutrino masses) and $U_{ei}$ and $U_{en}$ are the elements of the matrix describing the transition between the zero mode and the n-th Kaluza-Klein states [7], $\langle U_{en}^\ast \rangle \simeq \xi_i^2 / n^2$. For the normal ordering (NO) we assume $m_3 > m_2 > m_1 = m_0$, whereas for the inverted ordering (IO) $m_2 > m_1 > m_3 = m_0$. We note that the effect of LED is significant more pronounced in IO than NO because the latter amplitude $A_{ee}^{NO}(L) \sim \xi_1 U_{e1}^2 + \xi_2 U_{e2}^2 + \xi_3 U_{e3}^2$ is dominated by $\xi_1^2 \sin^2 \theta_{13}$, then suppressed by $\theta_{13}$, whereas in the IO $A_{ee}^{IO}(L) \sim \xi_1^2 U_{e1}^2 + \xi_2^2 U_{e2}^2$ and does not suffer of such a suppression. We then expect the IO scenario to give better constraints on $R$ and $m_0$ than the NO case.

Another interesting model of physics beyond the standard three neutrino oscillation is the one called non-standard neutrino interactions (NSI) [10], in which new physics effects can appear at low energy in terms of unknown couplings $\varepsilon_{\alpha\beta}$, generated after integrating out new degrees of freedom, with very large mass scales. In reactor experiments, the new couplings can affect neutrino production ("s") and detection ("d") [11], so the neutrino states are a superposition of pure orthonormal flavor eigenstates [12,13] according to: $|\nu_e^s\rangle = [(1 + \varepsilon^s) |\nu_e\rangle]_e$ and $|\nu_e^d\rangle = [(|\nu_e^s| + \varepsilon^d) |\nu_e^s\rangle]_e$, with $\varepsilon^s$ and $\varepsilon^d$ generic non-unitary transformations. Since the parameters $\varepsilon_{ea}^s$ and $\varepsilon_{ae}^d$ receive contributions from the same higher dimensional operators [13], one can constrain them by the relation $\varepsilon_{ea}^s = \varepsilon_{ae}^d \equiv \varepsilon_{ea} e^{i \Phi_{ea}}$, being $\varepsilon_{ea}$ the modulus and $\Phi_{ea}$ the argument of $\varepsilon_{ea}$. The oscillation probability $P_{ee} \equiv P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ up
to $O(\varepsilon)$ can be obtained by squaring the amplitude $|\nu_\ell^e e^{-iH_L}|^2$:

$$P_{ee} = 1 - \sin^2 \theta_{13} \sin^2 \Delta + 4\varepsilon_{ee} \cos \phi_{ee} - 4\varepsilon_{e\mu} \sin \theta_{13} \sin \theta_{23} \cos 2\theta_{13} \cos (\delta - \phi_{e\mu}) \sin^2 \Delta - 4\varepsilon_{e\tau} \sin \theta_{13} \cos \theta_{23} \cos 2\theta_{13} \cos (\delta - \phi_{e\tau}) \sin^2 \Delta,$$

where $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$, with $L$ being the source-to-detector distance, $E$, the neutrino energy and $\Delta m^2_{31} = m_3^2 - m_1^2$. In the first line of Eq. (2) we can recognize the "zero-distance" term driven by $\varepsilon_{ee}$, which gives a non vanishing contribution even in the limit of very small $L/E$. In addition, $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ appear with only slightly different coefficients. However, contrary to what happens for $\varepsilon_{ee}$, $\varepsilon_{e\mu}, \varepsilon_{e\tau}$ exhibit a strong correlation with the reactor angle which, on the one hand, does not allow to set any stringent bound on them and, on the other hand, can worsen the extraction of $\theta_{13}$ and $\Delta m^2_{31}$ from the data [15–16]. A model-independent analysis [17] has shown that all bounds on production and detection NSI’s are at the level of $10^{-2}$; $\varepsilon_{ee} < 0.041$, $\varepsilon_{e\mu} < 0.025$ and $\varepsilon_{e\tau} < 0.041$, for the CP violating phases no constraints are known.

In this paper we make use of the recent $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance data obtained by the Daya Bay experiment to constrain the parameter space of NSI and LED scenarios. Our main results are that neutrino oscillation data can provide strong upper bounds on $\varepsilon_{ee}$ at the level of $O(10^{-3})$, whereas for $R$ the exclusion limits are between 1 and 2 order of magnitudes below the limits quoted in [8].

The Daya Bay experimental setup we take into account [2] consists of six antineutrino detectors (ADs) and six reactors, D1, D2, L1, L2, L3, L4. The antineutrino spectra emitted by the nuclear reactors and six reactors, D1, D2, L1, L2, L3, L4. The antineutrino candidates are collected in the far hall, EH3, and in the near halls EH1, EH2. A bin-to-bin normalization has been fixed in order to reproduce the unoscillated rates. The antineutrino energy $E_{\bar{\nu}_e}$ is reconstructed by the prompt energy deposited by the positron $E_{\text{prompt}}$ using the approximated relation [2]: $E_{\bar{\nu}_e} \simeq E_{\text{prompt}} + 0.8$ MeV. The energy resolution function is a Gaussian function with $\sigma(E)[\text{MeV}] = 0.08 \sqrt{E/\text{MeV}} - 0.8$. The antineutrino cross section for the inverse beta decay (IBD) process has been taken from [22]. In order to perform a proper statistical treatment of correlations and degeneracy, we used a modified version of the GLoBES software [23] and construct an adequate definition of the $\chi^2$ function [2]:

$$\chi^2(\theta, \Delta m^2, \bar{S}, \alpha_r, \varepsilon_d, \eta_d) = \sum_{d=1}^{6} \frac{36}{3} \left[ M_{d}^{r} - T_{d}^{r} \left(1 + \sum_{r} \omega_{d}^{r} \alpha_{r} + \varepsilon_{d} + \eta_{d}\right)\right]^2 + \sum_{r} \sigma_{r}^{2} + \sum_{d=1}^{6} \left[ \varepsilon_{d}^{2} + \frac{\eta_{d}^{2}}{\sigma_{d}^{2}} \right] + \text{Priors.}$$

In the previous formula, $\bar{S}$ is a vector containing the new physics parameters, $M_{d}^{r}$ are the measured IBD events of the $d$-th detector ADs in the $i$-th bin, $B_{d}^{i}$ the corresponding background and $T_{d}^{i} = T_{i}(\theta, \Delta m^2, \bar{S})$ are the theoretical prediction for the rates. The parameter $\omega_{d}^{r}$ is the fraction of IBD contribution of the $r$-th reactor to the $d$-th detector AD, determined by the approximated relation $\omega_{d}^{r} \sim L_{rd}^{2}/(\sum_{r=1}^{6} L_{rd}^{2})$, where $L_{rd}$ is the distance between the $d$-th detector and the $r$-th reactor. The parameter $\sigma_{r}$ is the uncorrelated detection uncertainty ($\sigma_{d} = 0.2\%$) and $\sigma_{B_{d}}$ is the background uncertainty of the $d$-th detector obtained using the information given in [21]: $\sigma_{B_{1}} = \sigma_{B_{2}} = 8.21$, $\sigma_{B_{3}} = 5.95$, $\sigma_{B_{4}} = \sigma_{B_{5}} = \sigma_{B_{6}} = 1.15$. Eventually, $\sigma_{r} = 0.8\%$ is the correlated reactor uncertainties. The corresponding pull parameters are $(\varepsilon_d, \eta_d, \alpha_r)$. The main relevant point in this discussion is which priors must be implemented in the fitting function. Since Daya Bay has measured $\theta_{13}$ with very high precision, we cannot use its determination to constraint the reactor angle when fitting the new physics parameters, otherwise we would use the same data twice. Similar considerations can also be done for the atmospheric mass difference, which primarily drives the standard oscillation term in $P_{ee}$. So, when studying LED in the plane ($R, m_0$) and NSI in the plane ($\varepsilon_{i\beta}, \phi_{i\beta}$), we adopt the following strategy: we do not impose any constraints of $\theta_{13}$ and we set the uncertainty on $\Delta m^2_{31}$ at values larger than the current determination: $\Delta m^2_{31} = (2.35 \pm 10\%) \times 10^{-3}$ eV$^2$ (we carefully checked that leaving $\Delta m^2_{31}$ completely unconstrained our results do not change). For the atmospheric angle and the solar parameters the situation is a bit different since the standard probability does not depend on them; however, they couple to the new physics parameters, both in LED and NSI scenarios, so we need to impose external constraints, chosen as follows [24]: $\sin^2 \theta_{23} = 0.425 \pm 0.029$ for NO and $\sin^2 \theta_{23} = 0.437 \pm 0.173$ for IO, $\Delta m^2_{21} = (7.54 \pm 0.26) \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.308 \pm 0.017$. Whenever necessary,
the standard CP violating phase \( \delta \) will be considered as a free parameter.

The results in the standard \([\sin^2 2\theta_{13}, \Delta m^2_{31}]\)-plane, instead, are obtained marginalizing also over \( R \) and \( m_0 \) for LED and over \( \varepsilon \) and \( \phi \) for NSI, in the perturbative regions identified by \( \xi_i \equiv \sqrt{2} m_i R < 0.2 \) and \( \varepsilon < 0.041 \), while \( \phi \in [0, 2\pi] \).

We first consider the bounds on the size of the large extra dimension \( R \) and on the lightest neutrino mass, in the \([R, m_0]\)-plane. Our results are shown in left panel of Fig. 1, where we displayed the 1, 2, and 3\( \sigma \) CL regions. Both ordering of the neutrino masses, and the related values of the \( \chi^2_{\text{min}}/\text{dof} \), have been considered: solid lines refer to the NO whereas the dashed ones refer to the IO. The horizontal dashed line represents the future upper limit on \( m_0 \) from the \( \beta \)-decay experiment KA-TRIN [22]. Since the standard oscillation physics already gives a good fit to the data, small values of \( R \) and \( m_0 \) are obviously allowed; the correlation existing among these parameters, however, is quite strong and excludes large values of \( R \) and \( m_0 \). In particular, bounds on the compactification radius can be set at the level of some units of \( 10^{-3} \) \( \mu \)m: \( R < 0.36 \) (0.16) at 1\( \sigma \), \( R < 0.57 \) (0.19) at 2\( \sigma \) and \( R < \) None (0.23) at 3\( \sigma \) for NO (IO). The best fit points (a circle for NO and a square for IO in Fig. 1) and the related \( \chi^2_{\text{min}}/\text{dof} \) have the following values: \( R[\mu \text{m}] = 0.04 \) (0.032), \( m_0[\text{eV}] = 0.16 \) (0.20) with \( \chi^2_{\text{min}}/\text{dof} = 45/106 \) (45/106), where the numbers in parenthesis refer to the IO. However, it is worth to mention that they only have an indicative meaning, since the \( \chi^2 \) function is almost flat in the allowed regions.

It is an interesting question to check whether the new physics parameters introduce some bias in the simultaneous extraction of \( \theta_{13} \) and \( \Delta m^2_{31} \). In the right panel of Fig. 1 we show the 3\( \sigma \) CL allowed region in the \([\sin^2 2\theta_{13}, \Delta m^2_{31}]\)-plane for NO (solid line), IO (dotted line), and the standard model (dashed line) results. We can appreciate an increase of the allowed \( \theta_{13} \) and \( \Delta m^2_{31} \) 3\( \sigma \) CL regions, at the level of 25\% toward smaller reactor angles and 5\% to larger masses. In Tab. 1 we summarise the obtained results, reporting the best fit values and 1\( \sigma \) errors for \( \sin^2 2\theta_{13}, \Delta m^2_{31} \) and the related value \( \chi^2_{\text{min}}/\text{dof} \) for the three scenarios shown in Fig. 1.

The parameter space for the NSI investigation is larger than for LED, consisting of the moduli \( \varepsilon_{ee}, \varepsilon_{e\mu}, \varepsilon_{e\tau} \) and the new CP phases \( \phi_{ee}, \phi_{e\mu}, \phi_{e\tau} \). The study of the allowed regions in the \([\varepsilon_{ee}, \phi_{ee}]\)-plane is performed marginalizing over all the parameters, including \( \varepsilon_{e\mu}, \varepsilon_{e\tau} \) and their phases. The result of}

| Parameter                        | SM   | LED NO | LED IO |
|----------------------------------|------|--------|--------|
| \( \sin^2 2\theta_{13} \)       | 0.085\( ^{+0.015}_{-0.016} \) | 0.082\( ^{+0.021}_{-0.022} \) | 0.078\( ^{+0.018}_{-0.018} \) |
| \( \Delta m^2_{31} \) [eV\(^2\)] | 2.69\( ^{+0.27}_{-0.24} \) | 2.69\( ^{+0.30}_{-0.25} \) | 2.60\( ^{+0.24}_{-0.20} \) |
| \( \chi^2_{\text{min}}/\text{dof} \) | 43/106 | 43/106 | 42/106 |

**TABLE 1: Best fit points and 1\( \sigma \) errors for \( \sin^2 2\theta_{13}, \Delta m^2_{31} \) and the value of \( \chi^2_{\text{min}}/\text{dof} \). Results are for the SM, the LED NO and LED IO cases.**
FIG. 1: Left panel: allowed regions for NO and IO LED model in the $[\log_{10}(R), \log_{10}(m_0)]$-plane at $1\sigma$, $2\sigma$ and $3\sigma$ CL. The best fit points for both hierarchies are indicated with a circle (NO) and a square (IO). Right panel: $3\sigma$ CL in the $[\sin^2(2\theta_{13}), \Delta m^2_{31}]$-plane. The best fit points are indicated with a circle (LED NO), a square (LED IO) and a triangle (SM). The dashed vertical line represents the value of the $\theta_{13}$ quoted by the Daya Bay collaboration [21].

FIG. 2: Left panel: excluded regions in the $[\varepsilon_{ee}, \phi_{ee}]$-plane at 1, 2 and $3\sigma$ CL. The vertical line corresponds to $\varepsilon = 0.041$. Circles are the obtained best fit points. Right Panel: $3\sigma$ CL in the $[\sin^2(2\theta_{13}), \Delta m^2_{31}]$-plane for the SM (dot-dashed), for $\varepsilon_{ee} = \varepsilon_{e\tau} = 0$ (NSI-I solid) and for free parameters (NSI-II dotted). The best fit points are indicated with a circle (NSI-I), a square (NSI-II) and a triangle (SM).

| Parameter | SM | NSI-I | NSI-II |
|-----------|----|-------|--------|
| $\sin^2 2\theta_{13}$ | 0.085$^{+0.015}_{-0.010}$ | 0.084$^{+0.022}_{-0.021}$ | 0.119$^{+0.008}_{-0.009}$ |
| $\Delta m^2_{31}/10^{-3}$ [eV$^2$] | 2.69$^{+0.27}_{-0.24}$ | 2.62$^{+0.22}_{-0.20}$ | 2.65$^{+0.27}_{-0.25}$ |
| $\chi^2_{\text{min}}$/dof | 43/106 | 43/106 | 43/106 |

TABLE II: Best fit points and $1\sigma$ errors for $\sin^2 2\theta_{13}$, $\Delta m^2_{31}$ and the value of $\chi^2_{\text{min}}$/dof. Results are for the SM, the NSI-I and NSI-II cases.

At $3\sigma$. On the other hand, $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ suffer from a strong correlation to $\theta_{13}$ and, therefore, no significant sensitivity has been found. However, they play a major role in the determination of $\theta_{13}$ and $\Delta m^2_{31}$; our analysis shows that, even assuming $\varepsilon_{ee} = 0$, the allowed regions for $\theta_{13}$ are much larger than the SM ones; in addition, the best fit value for $\theta_{13}$ is driven to values larger by roughly $40\%$. On the other hand, the determination of the squared mass difference $\Delta m^2_{31}$ is less affected by this type of new physics and the fit procedures return values very similar to the SM case.

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