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Where we are on θ_{13}: addendum to "Global neutrino data and recent reactor fluxes: status of three-flavour oscillation parameters"

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Abstract. In this addendum to Ref. [1] we consider the recent results from long-baseline $\nu_\mu \to \nu_e$ searches at the T2K and MINOS experiments and investigate their implications for the mixing angle θ_{13} and the leptonic Dirac CP phase δ. By combining the 2.5σ indication for a non-zero value of θ_{13} coming from T2K data with global neutrino oscillation data we obtain a significance for $\theta_{13} > 0$ of about 3σ with best fit points $\sin^2\theta_{13} = 0.013(0.016)$ for normal (inverted) neutrino mass ordering. These results depend somewhat on assumptions concerning the analysis of reactor neutrino data.

keywords: Neutrino mass and mixing; neutrino oscillation; solar and atmospheric neutrinos; reactor and accelerator neutrinos

1. Introduction

Prompted by the recently published indication for electron neutrino appearance by the T2K experiment we have updated the global neutrino oscillation analysis presented in Ref. [1]. The T2K experiment uses a neutrino beam consisting mainly of muon neutrinos, produced at the J-PARC accelerator facility and observed at a distance of 295 km and an off-axis angle of $2.5°$ by the Super-Kamiokande detector. The present data release corresponds to 1.43×10^{20} protons on target [2]. Six events pass all selection criteria for an electron neutrino event. In a three-flavor neutrino oscillation scenario with $\theta_{13} = 0$ the expected number of such events is 1.5 ± 0.3 (syst). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to a significance of 2.5σ. We investigate the implications of this result for the mixing angle θ_{13} and the leptonic Dirac CP phase δ, focusing on long-baseline $\nu_\mu \to \nu_e$ appearance data from T2K and MINOS in sec. 2, whereas the results of the combined analysis of global neutrino oscillation data are presented in sec. 3.

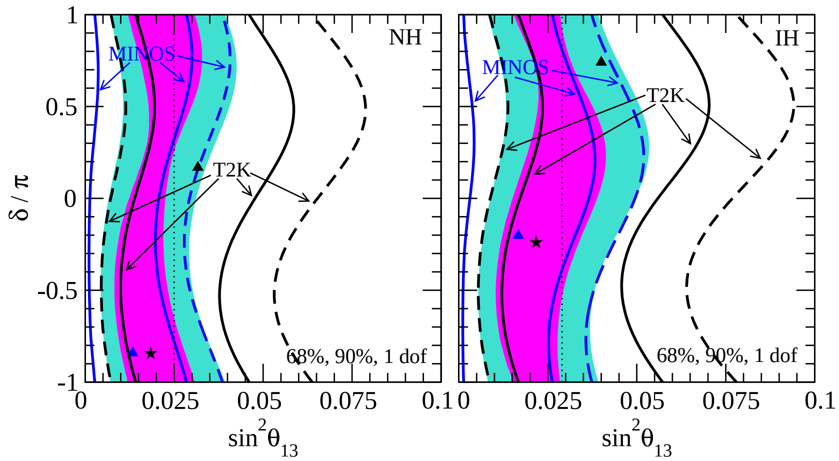

Figure 1. Regions in the $\sin^2\theta_{13} - \delta$ plane at 68% and 90% CL for 1 dof for T2K and MINOS appearance data (curves) and their combination (shaded regions). For all other oscillation parameters we assume best fit values and uncertainties according to Tab. 1, and we include a 5% uncertainty on the matter density. The left (right) panel is for normal (inverted) mass hierarchy. The dotted line shows the 90% CL upper limit on $\sin^2\theta_{13}$ from a combined analysis of all other oscillation data.

2. Long-baseline $\nu_\mu \to \nu_e$ appearance data from T2K and MINOS

For our re-analysis of T2K we use the spectral data shown in Fig. 5 of Ref. [2] given as 5 bins in reconstructed neutrino energy from 0 to 1.2 GeV. Using the neutrino fluxes predicted at Super-Kamiokande in the absence of oscillations provided in Fig. 1 of Ref. [2] we calculate the $\nu_\mu \to \nu_e$ appearance signal by tuning our prediction to the corresponding prediction in Fig. 5 of Ref. [2]. In the fit we include the background distribution shown in that figure with a systematic normalization uncertainty of 23% and adopt the χ^2 definition based on the Poisson distribution. The calculation is performed by using the GLoBES simulation software [3]. Latest MINOS data on the $\nu_\mu \to \nu_e$ channel have been presented in Ref. [4], corresponding to 8.2×10^{20} protons on target, compared to 7×10^{20} used in Ref. [1]. MINOS finds 62 events with an expectation in absence of oscillations of $49.6 \pm 7.0(\text{stat}) \pm 2.7(\text{syst})$, showing no significant indication for $\nu_\mu \to \nu_e$ transitions.

In Fig. 1 we show the region in the $\sin^2\theta_{13} - \delta$ plane indicated by T2K data in comparison to MINOS results. While for T2K we obtain a closed region for $\sin^2\theta_{13}$ at 90% CL ($\Delta\chi^2 = 2.7$), for MINOS we find only an upper bound. The results are clearly compatible and we show the combined analysis as shaded regions, where the upper bound is determined by the MINOS constraint while the lower bound is given by T2K. Best fit values are in the range $\sin^2\theta_{13} \approx 0.015 - 0.023$, depending on the CP phase δ, where the variation is somewhat larger for the inverted mass hierarchy. The dotted lines in the figure indicate the 90% CL upper bound on $\sin^2\theta_{13}$ coming from a combined analysis of the remaining oscillation data, including global reactor, solar, atmospheric, and long-baseline disappearance data.

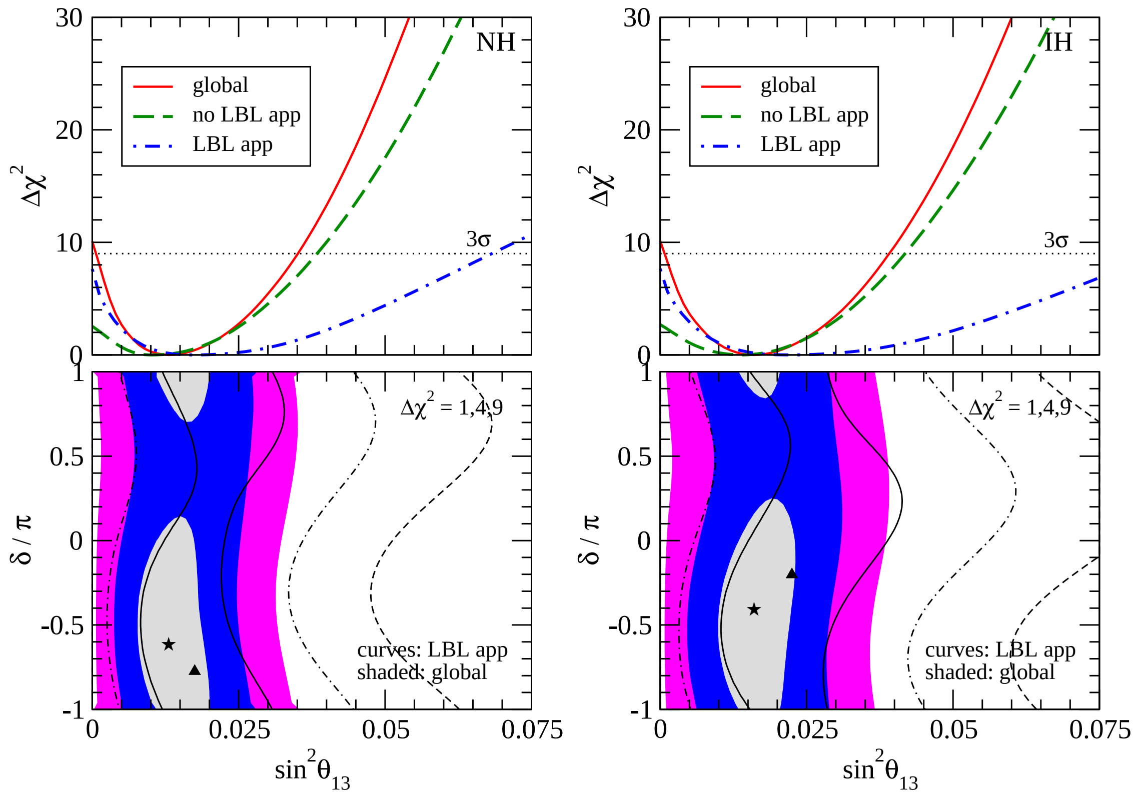

Figure 2. Upper panels: $\Delta\chi^2$ as a function of $\sin^2\theta_{13}$ for T2K and MINOS ν_e appearance data ("LBL app"), all the other global data ("no LBL app"), and the combined global data ("global"). Lower panels: contours of $\Delta\chi^2 = 1, 4, 9$ in the $\sin^2\theta_{13} - \delta$ plane for "LBL app" (curves) and for the global data (shaded regions). We minimize over all undisplayed oscillation parameters. Left (right) panels are for normal (inverted) neutrino mass hierarchy.

3. Global analysis

We move now to the combined analysis of the T2K and MINOS ν_e appearance searches with global neutrino oscillation data as described and referenced in Ref. [1]. For the reactor analysis we use the "recommended" analysis from Ref. [1], which adopts the new reactor neutrino fluxes from Ref. [5] while including short-baseline reactor neutrino experiments with baselines $\lesssim 100$ km in the fit. The results for θ_{13} are summarized in Fig. 2. For both neutrino mass hierarchies we find that the 2.5σ indication for $\theta_{13} > 0$ from T2K gets pushed to the 3σ level ($\Delta\chi^2 = 9$) when combined with the weak hint for a non-zero θ_{13} obtained from the remaining data [1], see also Ref. [6]. We find best fit points at

$$\begin{aligned} &\sin^2\theta_{13} = 0.013\,, \quad \delta = -0.61\pi \qquad \text{(normal hierarchy)},\\ &\sin^2\theta_{13} = 0.016\,, \quad \delta = -0.41\pi \qquad \text{(inverted hierarchy)}. \end{aligned} \tag{1}$$

Due to some complementarity between T2K and MINOS one obtains, after combining with the θ_{13} limit from the rest of the data, a "preferred region" for the CP phase δ at $\Delta\chi^2 = 1$, as seen in Fig. 2. Obviously this preference for the CP phase is not significant.‡ Marginalizing over the CP phase δ (and all other oscillation parameters) we obtain for the best fit, one-sigma errors, and the significance for $\theta_{13} > 0$:

$$\begin{array}{lll} \sin^2\theta_{13} = 0.013^{+0.007}_{-0.005}\,, & \Delta\chi^2 = 10.1\,(3.2\sigma) & \text{(normal)}, \\ \sin^2\theta_{13} = 0.016^{+0.008}_{-0.006}\,, & \Delta\chi^2 = 10.1\,(3.2\sigma) & \text{(inverted)}. \end{array} \qquad (2)$$

As expected the upper bound on $\sin^2\theta_{13}$ is dominated by global data without long-baseline appearance data, whereas the lower bound comes mainly from T2K.

Let us briefly consider the sensitivity of these results to the assumptions on the analysis of reactor neutrino data. As discussed in detail in Ref. [1] there is a slight tension between reactor neutrino fluxes obtained in Ref. [5] and the results of short-baseline reactor neutrino experiments with baselines $\lesssim 100$ km. The increase of reactor neutrino fluxes compared to previous calculations found in Ref. [5] has been confirmed qualitatively by an independent recent calculation [8]. To illustrate the impact on θ_{13} we show the results for two alternative assumptions for the reactor analysis. Adopting the fluxes from Ref. [5] but omitting reactor experiments with baselines $\lesssim 100$ km we find for the best fit, one-sigma errors, and the significance for $\theta_{13} > 0$:

$$\begin{array}{lll} \sin^2\theta_{13} = 0.022 \pm 0.008\,, & \Delta\chi^2 = 13.5\,(3.7\sigma) & \text{(NH)} \\ \sin^2\theta_{13} = 0.026 \pm 0.009\,, & \Delta\chi^2 = 15.2\,(3.9\sigma) & \text{(IH)} \end{array} \quad \text{(no SBL react)} \qquad (3)$$

If instead we do include the short-baseline reactor data but leave the overall normalization of the reactor neutrino flux free we obtain

$$\begin{array}{lll} \sin^2\theta_{13} = 0.011^{+0.007}_{-0.004}\,, & \Delta\chi^2 = 7.7\,(2.8\sigma) & \text{(NH)} \\ \sin^2\theta_{13} = 0.014^{+0.007}_{-0.006}\,, & \Delta\chi^2 = 8.4\,(2.9\sigma) & \text{(IH)} \end{array} \quad \text{(flux free)} \qquad (4)$$

We see that the precise value of the $\sin^2\theta_{13}$ best fit point as well as the significance for $\theta_{13} > 0$ still depend on assumptions on the reactor analysis, as discussed in detail in Ref. [1].

To summarize we display the status for all neutrino oscillation parameters from the global analysis using the default reactor treatment in Tab. 1. If θ_{13} is indeed within the presently indicated range we may expect a confirmation by future T2K data soon. Depending on whether its true value is close to the upper of lower edge of the presently favored range, an independent confirmation of a non-zero θ_{13} may be expected from reactor experiments within few months to few years [9]. After establishing the LMA-MSW solution to the solar neutrino problem, the present 3σ indication for a non-zero θ_{13} may turn out to be first sign for the second necessary ingredient for observable CP violation in neutrino oscillations, see e.g. [10] for a review.

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‡ Prospects to constrain δ with the present generation of experiments have been discussed in Ref. [7].

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.25-2.68$ $-(2.23-2.58)$	$2.14-2.76$ $-(2.13-2.67)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.004–0.028 0.005–0.031	0.001–0.035 0.001–0.039
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0-2\pi$	$0-2\pi$

Table 1. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, and δ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. See Ref. [1] for details and references.

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