Evidence of $\theta_{13} > 0$ from global neutrino data analysis

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The neutrino mixing angle θ_{13} is at the focus of current neutrino research. From a global analysis of the available oscillation data in a 3ν framework, we previously reported [Phys. Rev. Lett. 101, 141801 (2008)] hints in favor of $\theta_{13} > 0$ at the 90% C.L. Such hints are consistent with the recent indications of $\nu_\mu \to \nu_e$ appearance in the T2K and MINOS long-baseline accelerator experiments. Our global analysis of all the available data currently provides $> 3\sigma$ evidence for nonzero θ_{13}, with 1σ ranges $\sin^2\theta_{13} = 0.021 \pm 0.007$ or 0.025 ± 0.007, depending on reactor neutrino flux systematics. Updated ranges are also reported for the other 3ν oscillation parameters (δm^2, $\sin^2\theta_{12}$) and (Δm^2, $\sin^2\theta_{23}$).

I. INTRODUCTION

Neutrino oscillation experiments have established that neutrino flavor and mass states do mix [1]. In the simplest framework, the three flavor states $(\nu_e, \nu_\mu, \nu_\tau)$ are quantum superpositions of only three light mass states (ν_1, ν_3, ν_3) via a unitary mixing matrix U, parametrized in terms of three rotation angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and one possible CP-violating phase δ in standard notation [1]. The amplitudes and frequencies of flavor oscillation phenomena are governed, respectively, by the θ_{ij} angles and by two squared mass differences, namely,

$$\delta m^2 = m_2^2 - m_1^2 > 0 \tag{1}$$

and, in our convention [2],

$$\Delta m^2 = m_3^2 - \frac{m_2^2 + m_1^2}{2} \ , \tag{2}$$

where $\Delta m^2 > 0$ (< 0) corresponds to normal (inverted) mass spectrum hierarchy. Typically, a single experiment is mainly sensitive to only one of the above mass gaps and to one mixing parameter, although subleading effects driven by the remaining parameters may become relevant in precision oscillation searches.

So far, solar and long-baseline reactor neutrino experiments have measured the mass-mixing parameters (δm^2, θ_{12}) in the $\nu_e \to \nu_e$ channel, while atmospheric and long-baseline accelerator (LBL) experiments have measured (Δm^2, θ_{23}) in the $\nu_\mu \to \nu_\mu$ channel. Conversely, short-baseline reactor experiments, mainly sensitive to (Δm^2, θ_{13}), have set upper—but not lower—bounds on the mixing angle θ_{13}; see [1] for an overview. However, we observed in [3, 4] that the two data sets mainly sensitive to δm^2 and to Δm^2 provided two separate hints in favor of $\theta_{13} > 0$ which, in combination, disfavored the null hypothesis $\theta_{13} = 0$ at 90% C.L. [4].

The statistical significance of the hints, as well as their possible origin in subleading oscillation effects, have been examined in detail and also debated in a number of analyses [5–17], often triggered by new input data and, more recently, also by a new, critical evaluation of older inputs for the reactor neutrino fluxes [18] (see [19–21]). Within the standard 3ν framework (with no extra sterile neutrinos ν_s), the overall statistical significance of $\theta_{13} > 0$ has, so far, not exceeded the level of $\sim 2\sigma$, with a corresponding estimated range $\sin^2\theta_{13} \simeq 0.02 \pm 0.01$, see e.g. [11, 21].

Very recently (June 2011), new relevant results have been announced by two long-baseline accelerator experiments probing the $\nu_\mu \to \nu_e$ appearance channel, which is governed by the (Δm^2, θ_{13}) parameters (although with an additional dependence on θ_{23} and δ, absent in short-baseline reactor experiments). In particular, the Tokai-to-Kamioka (T2K) experiment has observed 6 electron-like events with an estimated background of 1.5 events, rejecting $\theta_{13} = 0$ at the level of 2.5σ [22]. The low background level makes the T2K results particularly important and robust. Shortly after, the Main Injector Neutrino Oscillation Search (MINOS) experiment has reported the observation of 62 electron-like events with an estimated background of 49 events, disfavoring $\theta_{13} = 0$ at 1.5σ [23]. Taken together, these data suggest $\sin^2\theta_{13} \simeq$ few %, in agreement with our previous hints [4] discussed above.

It makes then sense to update our previous global analyses of oscillation data [4, 6, 11] by including the latest T2K and MINOS results, as well as other data which have been published in the last few years. Our main result is

$$\sin^2\theta_{13} = \left\{ \begin{array}{l} 0.021 \pm 0.007\,,\ \text{old reactor fluxes} \\ 0.025 \pm 0.007\,,\ \text{new reactor fluxes} \end{array} \right. \quad (1\sigma)\ , \tag{3}$$

corresponding to a $> 3\sigma$ evidence in favor of nonzero θ_{13} (while previous hints did not exceed the $\sim 2\sigma$ level). We discuss below some details of our current analysis, and a few relevant implications of $\theta_{13} > 0$ for neutrino physics.

II. INPUT DATA AND THEIR ANALYSIS

We briefly summarize the main updates in our global analysis of neutrino oscillations driven by δm^2 and by Δm^2, respectively, with respect to our previous works on the subject.

A. Data sensitive to δm^2

These data include events collected in solar neutrino experiments and in the long-baseline reactor experiment KamLAND. As described in [6, 24], we take as free parameters (δm^2, θ_{12}, θ_{13}), as well as the four geoneutrino event rates corresponding to decays of natural Thorium and Uranium in the KamLAND and Borexino experiments, which are then marginalized away. With respect to [24], we update the KamLAND results on reactor and geoneutrino data [16, 25], and include the Borexino data on ^{7}Be [26] and ^{8}B [27] solar neutrinos. As a side result, we obtain good agreement with the latest geoneutrino analysis performed by the KamLAND collaboration [25].

The interpretation of both solar and reactor neutrino data depend, to some extent, on the estimated fluxes (and their uncertainties) at their sources, namely, the solar and reactor cores, respectively. Concerning solar neutrinos, the long-standing issue of high versus low metallicity (see [28] for a review of the subject) affects only marginally the estimates of the oscillation parameter (e.g., at the level of $\sim 0.1\sigma$ in the solar+KamLAND constraints on $\sin^2\theta_{13}$) and will be ignored in the following. Conversely, a more relevant issue has been recently pointed out in the context of reactor neutrino fluxes, whose detailed reevaluation in [18] suggests an average increase of about 3.5% in normalization, with respect to previously accepted standards [29]. The increase would then indicate extra electron flavor disappearance in KamLAND [19] which, in the context of 3ν oscillations, are expected to induce a small but nonnegligible shift in θ_{12} and θ_{13} [21]. We will thus show results for both "old" [29] and "new" [18] reactor fluxes.

B. Data sensitive to Δm^2

These data include, in our analysis, events collected in the atmospheric neutrino experiment Super-Kamiokande (SK), in the short-baseline reactor experiment CHOOZ, and in the long-baseline experiments K2K, T2K, and MINOS.

With respect to our previous analysis [2], the CHOOZ data [30] are analyzed also with new input reactor fluxes [18], whose higher normalization leads to a small disappearance effects which slightly favors nonzero θ_{13} and weakens its upper bounds [19].

We update the atmospheric neutrino analysis [2, 6] by including SK-II and SK-III data [14, 17], together with improved estimates for the associated systematic errors [31]. However, a reduction of the SK-I+II+III data is unavoidable, since the official SK analysis includes many categories of events, bins, and systematics, which cannot be fully reproduced outside the collaboration, as already noticed [21]. In particular, we exclude from our analysis multi-ring and pion-decay events, and we group together some classes of partially contained events (stopping and through-going) and of upgoing muon events (showering and nonshowering). We think that, despite some unavoidable approximations and loss of information, our analysis remains a useful, independent study of SK atmospheric data within a full 3ν oscillation framework. A similar attitude has been adopted in [13], while the authors in [20] have directly taken the official SK likelihood function for the (Δm^2, θ_{23}, θ_{13}) parameters from a 3ν analysis with δm^2 set to zero [14]. As a consequence, the atmospheric neutrino likelihood adopted in [20] lacks the 3ν subleading oscillation effects driven by δm^2 [32], which are potentially relevant at the current level of accuracy [2, 17].

Concerning long-baseline accelerator data in the $\nu_\mu \to \nu_\mu$ disappearance channel, we maintain our previous K2K analysis without changes [2, 6], but we update the MINOS spectrum analysis from [33]. We do not include MINOS antineutrino disappearance data, which seem to indicate a puzzling deviation from the neutrino best-fit parameters (Δm^2, θ_{23}) [34]. The deviation should be carefully monitored in the future, since it cannot be interpreted in the standard 3ν framework.

In the appearance channel $\nu_\mu \to \nu_e$, we include the preliminary results from [23], by fitting the total (spectrum-integrated) rate of electron-like events at the far detector, taking into account its statistical and systematic errors. We reproduce with good accuracy the marginalized MINOS confidence level contours [23] in the plane charted by the CP phase δ and by the dominant mixing parameter $\sin^2\theta_{23}\sin^2 2\theta_{13}$, for both normal and inverted hierarchy. Last, but definitely not least, the crucial T2K appearance data recently reported in [22] are included by fitting the total (spectrum integrated) rate at the far detector within Poisson statistics. We reproduce with good accuracy the T2K confidence level contours in the plane charted by the CP phase δ and by the mixing parameter $\sin^2 2\theta_{13}$ for fixed values of the other oscillation parameters, in both normal and inverted hierarchy [22]. We emphasize that such fixings are removed in the global analysis below.

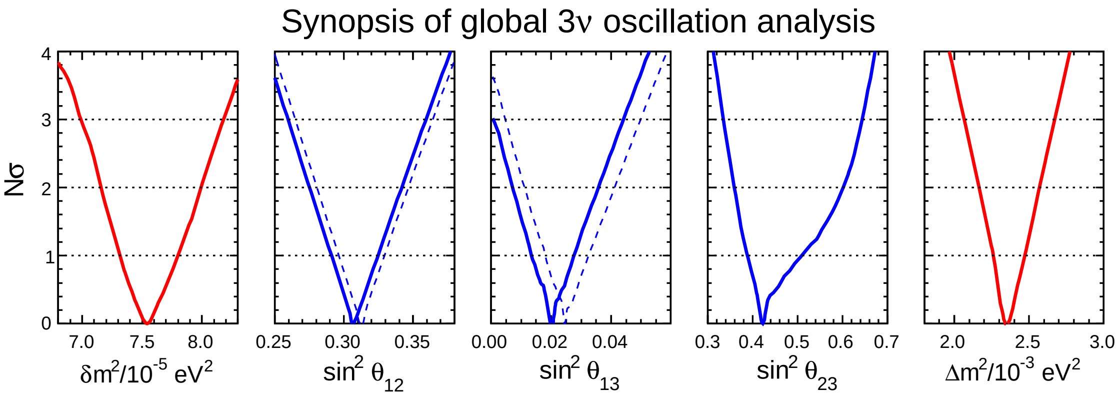

FIG. 1: Global 3ν oscillation analysis. Bounds on the mass-mixing oscillation parameters, in terms of standard deviations from the best fit. Solid (dashed) lines refer to the case with old (new) reactor neutrino fluxes. Note the $> 3\sigma$ evidence for $\theta_{13} > 0$.

C. Three-neutrino analysis

In δm^2-sensitive oscillation searches, the relevant 3ν variables are $(\delta m^2,\ \sin^2\theta_{12},\ \sin^2\theta_{13})$. A very minor dependence of solar neutrinos on $\pm\Delta m^2$ [2, 35] is also kept for the sake of precision.

In Δm^2-sensitive oscillation searches, we take as free parameters $(\pm\Delta m^2,\ \sin^2\theta_{23},\ \sin^2\theta_{13})$, while $(\delta m^2,\ \theta_{12})$ are fixed at their best-fit values from the analysis of δm^2-sensitive experiments. Our atmospheric neutrino analysis is restricted to the two CP-conserving cases $\cos\delta = \pm 1$ [2, 6]; we plan to remove such restriction in the future, so as to analyze both atmospheric and long-baseline accelerator data with unconstrained δ.

In the global fit, note that the common parameter $\sin^2\theta_{13}$ is constrained by both classes of oscillation searches. As in previous works [2, 6, 11], we will present bounds on the continuous parameters

$$(\delta m^2,\ \sin^2\theta_{12},\ \sin^2\theta_{13},\ \sin^2\theta_{23},\ \Delta m^2)\ , \tag{4}$$

marginalized over the four discrete cases

$$[\mathrm{sign}(\Delta m^2) = \pm 1] \otimes [\cos\delta = \pm 1]\ , \tag{5}$$

unless otherwise stated. Concerning Δm^2, note that our convention in Eq. (2) absorbs the trivial δm^2 difference arising in the best-fit values (for normal and inverted hierarchy) of the alternative conventional mass parameters $\Delta m^2_{31} = m^2_3 - m^2_1$ or $\Delta m^2_{32} = m^2_3 - m^2_2$.

A final remark is in order, concerning some issues recently raised by a reevaluation of reactor fluxes [18, 19]. The higher normalization suggested in [18] produces extra disappearance in KamLAND and CHOOZ, which jointly favor higher θ_{13} and θ_{12} in a 3ν framework. However, it also produces a small disappearance effect in very short-baseline experiments (not included in our fit) which is at variance with standard 3ν oscillations, and suggests hypothetical sterile neutrino oscillation driven by a mass gap $\Delta M^2 \sim O(1)$ eV^2 and by relatively small mixing with ν_e [19, 36–39]. Conversely, the old normalization is essentially consistent with the 3ν scenario, but slightly weakens the global indications for $\theta_{13} > 0$. Our educated guess (or prejudice) is that the true normalization may be intermediate between the old and the new one, and that previous normalization errors were underestimated. Anyway, we shall show results for both old and new reactor fluxes, their difference being an indication of the corresponding systematic uncertainties.

III. RESULTS

Figure 1 shows the main results of our global fit, in terms of allowed ranges for each of the oscillation parameters in Eq. (4), as obtained by marginalizing the remaining parameters over all the four discrete cases in Eq. (5). The vertical scale represents the number of standard deviations ($N\sigma = \sqrt{\Delta\chi^2}$) from the best fit point. The lines departing from each best fit would be perfectly straight and symmetric for exactly gaussian error distributions. This is nearly the case for all but the $\sin^2\theta_{23}$ parameter, which shows a skewed preference for the first octant at the level of 1σ, in qualitative agreement with our previous analyses [2, 6]. The estimates of $\sin^2\theta_{13}$ and $\sin^2\theta_{12}$ are affected by reactor flux systematics; in particular, the dashed lines refer to the analysis with new reactor fluxes [18], which turn out to shift both parameters by roughly $+0.005$ with respect to the case with old reactor fluxes (solid lines). In both cases, however, there is a clear evidence in favor of $\sin^2\theta_{13} > 0$, at a confidence level of at least 3σ. This evidence is the most important outcome of our work.

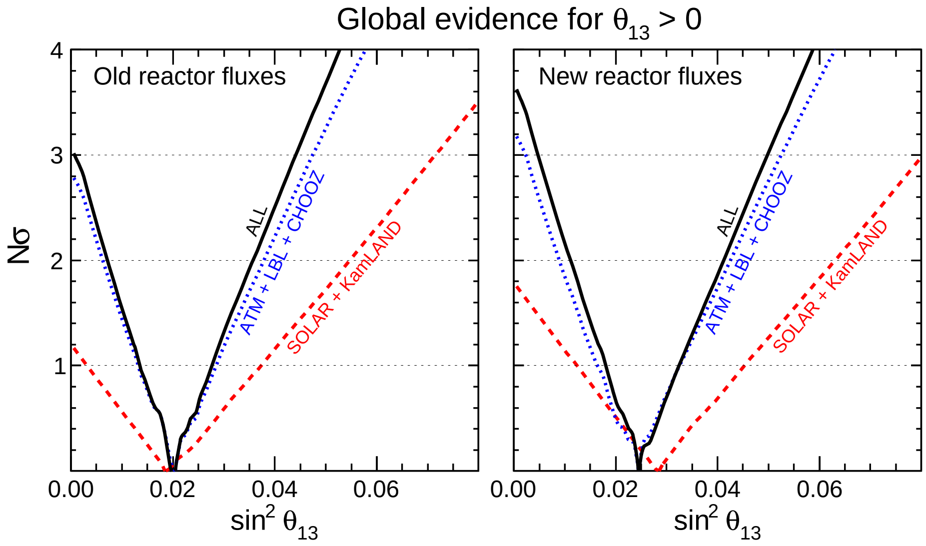

FIG. 2: Breakdown of the evidence for $\theta_{13} > 0$ from the global fit (ALL) into contributions coming from δm^2-sensitive data (Solar+KamLAND) and from Δm^2-sensitive data (ATM+LBL+CHOOZ). The left and right panels refer to old and new fluxes, respectively.

Figure 2 breaks down the global evidence for $\sin^2\theta_{13} > 0$ into two separate contributions coming from the data sets sensitive to either δm^2 (Solar+KamLAND) or Δm^2 (ATM+LBL+CHOOZ), assuming old and new reactor fluxes (left and right panels, respectively). Remarkably, the two data sets agree very well, with best fits rather close to each other in both panels, and with nearly gaussian uncertainties in all cases. The bounds from combined (ALL) data appear to be currently dominated by Δm^2-sensitive experiments—not surprisingly, since the T2K appearance results alone account for more than 2σ [22]. The T2K experiment, currently limited by statistics rather than by systematics, is expected to improve significantly the bounds on θ_{13} in future physics runs [22]. We also find it useful to summarize the $\pm 1\sigma$ ranges of $\sin^2\theta_{13}$ in a different format in Fig. 3, where the solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.

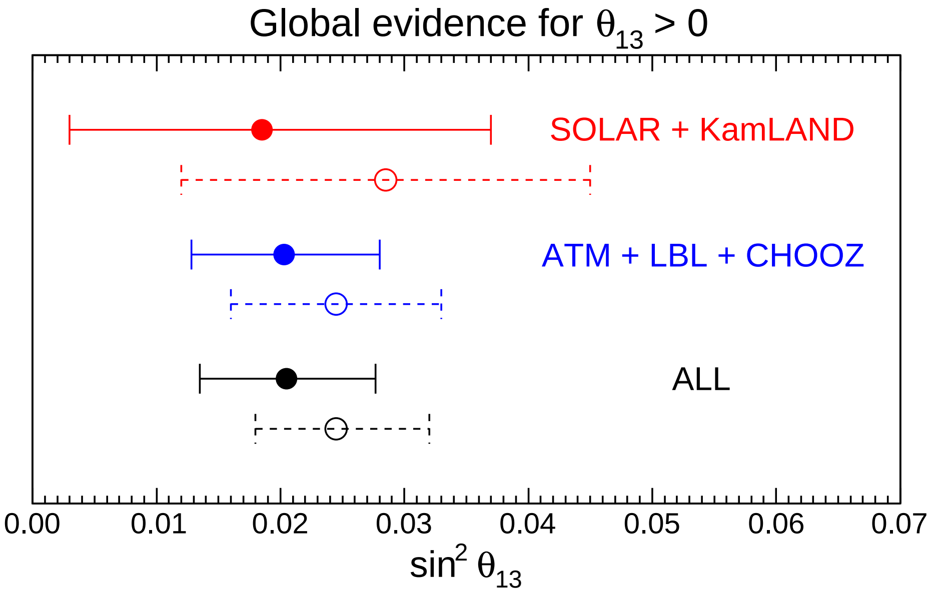

FIG. 3: Global 3ν analysis. Preferred $\pm 1\sigma$ ranges for the mixing parameter $\sin^2\theta_{13}$ from partial and global data sets. Solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the mass-mixing parameters, assuming old reactor neutrino fluxes. By using new reactor fluxes, the corresponding best fits and ranges for $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ (in parentheses) are basically shifted by about +0.006 and +0.004, respectively, while the other parameters are essentially unchanged.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35
		(0.312)	(0.025)		
1σ range	7.32 – 7.80	0.291 – 0.324	0.013 – 0.028	0.39 – 0.50	2.26 – 2.47
		(0.296 – 0.329)	(0.018 – 0.032)		
2σ range	7.16 – 7.99	0.275 – 0.342	0.008 – 0.036	0.36 – 0.60	2.17 – 2.57
		(0.280 – 0.347)	(0.012 – 0.041)		
3σ range	6.99 – 8.18	0.259 – 0.359	0.001 – 0.044	0.34 – 0.64	2.06 – 2.67
		(0.265 – 0.364)	(0.005 – 0.050)		

Table I reports the bounds shown in Figs. 1–3 in numerical form. All the bounds are largely uncorrelated from each other; e.g., the allowed ranges of δm^2 and Δm^2 are basically independent on variations of the mixing angles within their uncertainties (not shown). Nevertheless, we find it useful to report the joint ranges for the mixing parameters $\sin^2\theta_{ij}$, which can be used to test specific predictions of theoretical models for neutrino mixing, and which allow to highlight the impact of recent appearance data.

Figure 4 shows the joint contours at 1, 2 and 3σ ($\Delta\chi^2 = 1$, 4 and 9) for each possible couple of $\sin^2\theta_{ij}$ parameters, in the analysis with old reactor fluxes. Including new fluxes, the best fits and the associated $N\sigma$ contours are all translated by small amounts ($< 1\sigma$) indicated by arrows. As a result of the dominance of T2K data in the θ_{13} fit, the correlation in the ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$) plane induced by δm^2-sensitive data [4, 11] is no longer apparent. Conversely, there is a weak anticorrelation in the ($\sin^2\theta_{23}$, $\sin^2\theta_{13}$) plane for relatively high θ_{13}, due to the fact that the long-baseline $\nu_\mu \to \nu_e$ appearance probability is dominated by the product $|U_{\mu3}U_{e3}|^2 \propto \sin^2\theta_{23}\sin^2 2\theta_{13}$.

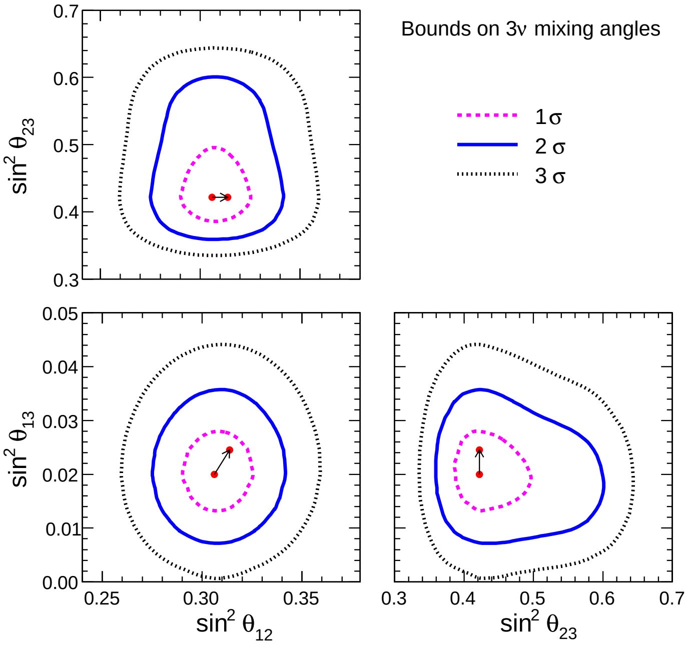

FIG. 4: Global 3ν analysis: Joint contours at 1, 2 and 3σ ($\Delta\chi^2 = 1$, 4 and 9) for couples of $\sin^2\theta_{ij}$ parameters, assuming old reactor neutrino fluxes. For new reactor fluxes, the best fits (and, to a large extent, also the contours) are shifted as indicated by the arrows.

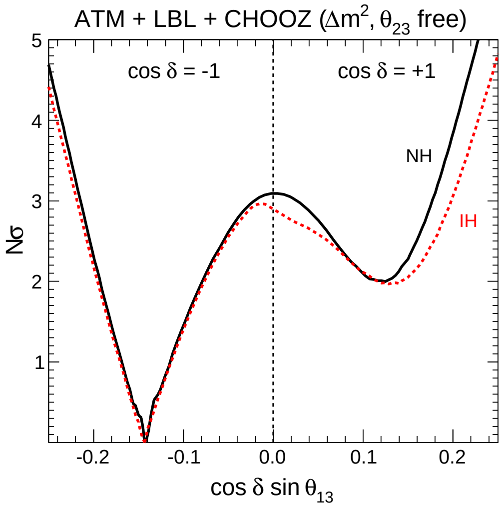

FIG. 5: Standard deviations from the best fit in terms of the variable $\cos\delta\sin\theta_{13}$ for the two CP parities ($\cos\delta = \pm 1$) and for both normal hierarchy (NH) and inverted hierarchy (IH), using the ATM+LBL+CHOOZ data set. The curves refer to the analysis with old reactor neutrino fluxes; similar results (not shown) are obtained for new reactor fluxes.

All the results reported in Figs. 1–4 and in Table I are marginalized over the four discrete cases in Eq. (5). For completeness, we also show in Fig. 5 the breakdown of the θ_{13} bounds over these four options (for the case of old reactor fluxes only), in terms of standard deviation ranges for the parameter $\cos\delta\sin\theta_{13} = \pm\sin\theta_{13}$ in both normal and inverted hierarchy, for the relevant data set ATM+LBL+CHOOZ (while δm^2-sensitive data are δ-independent). We do not find any significant difference in the position and likelihood of the best fits points for normal and inverted hierarchy. However, we find, as in our previous analysis [2], a preference for the CP-conserving case $\cos\delta = -1$ versus $+1$. In [2] we argued that the weak preference for both $\sin^2\theta_{13} > 0$ and $\cos\delta < 0$ were tied by the interference term driven by δm^2 and θ_{13} [32] in the atmospheric neutrino oscillation probability. The preference for $\cos\delta\sin\theta_{13} < 0$ in Fig. 5 appears to be more pronounced ($\sim 2\sigma$) than in [2], presumably because it correlates with the (now more robust) preference for $\sin^2\theta_{13} > 0$. It is intriguing to notice that a weak preference for $\cos\delta\sin\theta_{13} < 0$ has also been found in the preliminary atmospheric 3ν analysis from the SK collaboration [17]. Time will tell if this is another hint or mere fluctuation.

IV. DISCUSSION AND CONCLUSIONS

The hints of $\theta_{13} > 0$ that we pointed out in [3, 4] are consistent with recent T2K [22] and MINOS [23] data and, in combination, provide an evidence for $\theta_{13} > 0$ at the level of $> 3\sigma$. Such evidence, and the preference for values in the range $\sin^2\theta_{13} \simeq 0.01$–$0.04$ at 2σ (see Table I) may have far-reaching consequences in neutrino physics. First of all, it is crucial to experimentally test these findings, not only with further long-baseline appearance data at accelerators, but also with with short-baseline disappearance searches at reactors [15]. If confirmed, the evidence for $\sin^2\theta_{13} \sim$ few % would open the door to CP violation searches in the neutrino sector, with profound implications for our understanding of the matter-antimatter asymmetry in the universe. At the same time, matter effects on ($\pm\Delta m^2$, θ_{13})-driven oscillations appear now as a much more promising tool, from both the experimental and theoretical viewpoint, to derive indications about the hierarchy from neutrino propagation in the Earth or in supernovae. Concerning nonoscillation searches, the evidence for $\theta_{13} > 0$ provides small but "guaranteed" contributions of the third neutrino mass m_3 to both single beta and double beta decay searches, which need to be accounted for in detailed analyses. From a more theoretical viewpoint, relatively large values for θ_{13} will certainly trigger new ideas for model building.

Acknowledgments

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