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Three-flavour neutrino oscillation update and comments on possible hints for a non-zero θ_{13}

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We provide a short summary of three-flavour neutrino oscillation parameters as determined from a global fit to 2008 data, and we comment on possible hints in favour of a non-zero value of the mixing angle θ_{13} found in arXiv:0806.2649. We do confirm a hint from solar + KamLAND data at about 1.5σ, which can be understood from the recent SNO CC/NC measurment. However, we show that a claimed hint from atmospheric data is much less robust. It depends on details of event rate calculations and treatment of theoretical uncertainties. We could identify two data points showing an "excess" (at the 1σ level) in the SK-I multi-GeV e-like data, which seem to be the origin of the slight preference for $\theta_{13} > 0$. We point out that once SK-I and SK-II data are combined this "excess" disappears, and irrespective of the details of the analysis, no "hint" from atmospheric data is obtained for the SK-I and SK-II combined data set. As a result the global fit of all data leads to a best fit value of θ_{13} consistent with zero within less than 1σ.

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1. Introduction

Thanks to the synergy amongst a variety of experiments involving solar and atmospheric neutrinos, as well as man-made neutrinos at nuclear power plants and accelerators neutrino physics has undergone a revolution over the last decade or so by establishing the phenomenon of neutrino oscillations. The parameters relevant for three-flavour neutrino oscillations are three mixing angles, $\theta_{12}, \theta_{13}, \theta_{23}$, and one CP-phase in the unitary lepton mixing matrix, and two mass-squared differences $\Delta m^2_{21} \equiv m^2_2 - m^2_1$ and $\Delta m^2_{31} \equiv m^2_3 - m^2_1$. In this note we summarize the determination of these parameters from present world neutrino oscillation data (Sec. 2), and we give a critical discussion of recent claims for possible hints in favour of a non-zero value of the mixing angle θ_{13} (Sec. 3).

2. Summary of three-flavour oscillation parameters

Table 1 summarizes the results of two recent global fits to world neutrino data from Refs. [1, 2]. For another recent analysis see [3].

	Ref. [1]		Ref. [2] (MINOS updated)	
parameter	best fit$\pm 1\sigma$	3σ interval	best fit$\pm 1\sigma$	3σ interval
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.05–8.34	$7.67^{+0.22}_{-0.21}$	7.07–8.34
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$\pm 2.40^{+0.12}_{-0.11}$	$\pm$(2.07–2.75)	-2.39 ± 0.12 $+2.49 \pm 0.12$	$-$(2.02–2.79) $+$(2.13–2.88)
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67	$0.47^{+0.07}_{-0.06}$	0.33–0.64
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056	$0.003^{+0.015}_{-0.003}$	≤ 0.049

Table 1: Determination of three–flavour neutrino oscillation parameters from 2008 global data [1, 2].

The latest data release from the KamLAND reactor experiment [4] has increased the exposure almost fourfold over previous results [5] to a total exposure of 2881 ton·yr and also systematic uncertainties have been improved. The Sudbury Neutrino Observatory (SNO) has released the data of its last phase, where the neutrons produced in the neutrino neutral current (NC) interaction with deuterium are detected mainly by an array of ^{3}He NC detectors (NCD) [6]. The main impact of the new SNO data is due to the lower value for the observed CC/NC ratio, $(\phi_{\rm CC}/\phi_{\rm NC})^{\rm NCD} = 0.301 \pm 0.033$ [6], compared to the previous value $(\phi_{\rm CC}/\phi_{\rm NC})^{\rm salt} = 0.34 \pm 0.038$ [7]. Since for ^{8}B neutrinos $\phi_{\rm CC}/\phi_{\rm NC} \approx P_{ee} \approx \sin^2\theta_{12}$, adding the new data point on this ratio with the lower value leads to a stronger upper bound on $\sin^2\theta_{12}$. This explains the slightly lower best fit point for $\sin^2\theta_{12}$ found in [1] compared to [2], since the latter does not (yet) include the SNO-NCD result. Data from SNO are combined with the global data on solar neutrinos [8] and with the recent results from Borexino [9], reporting a survival probability of the 0.862 MeV ^{7}Be neutrinos of $P_{ee}^{^7\text{Be,obs}} = 0.56 \pm 0.1$. Fig. 1(left) illustrates how the determination of the leading solar oscillation parameters θ_{12} and Δm^2_{21} emerges from the complementarity of solar and reactor neutrinos. Spectral information from KamLAND data leads to an accurate determination of Δm^2_{21} with the remarkable precision of

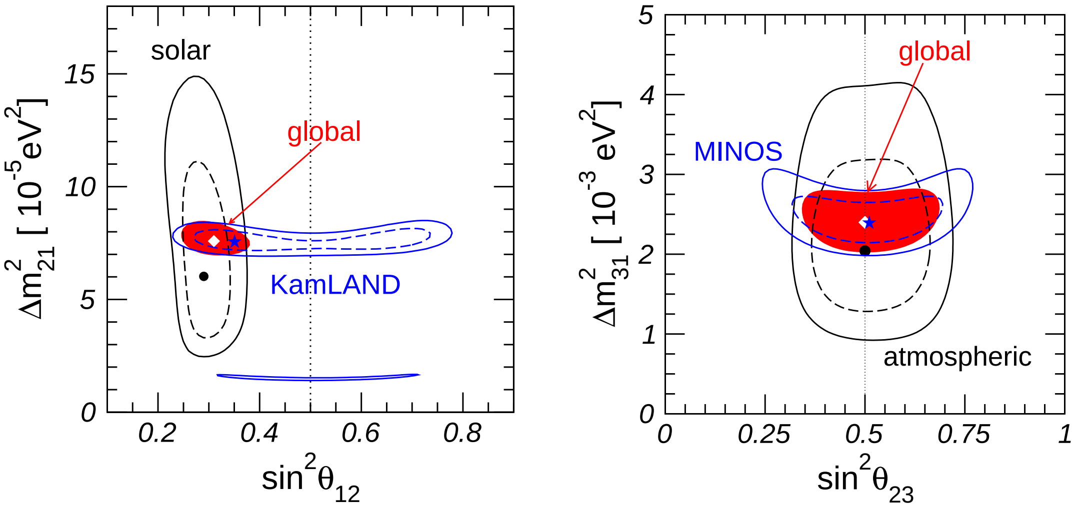

Figure 1: Determination of the leading "solar" and "atmospheric" oscillation parameters [1]. We show allowed regions at 90% and 99.73% CL (2 dof) for solar and KamLAND (left), and atmospheric and MINOS (right), as well as the 99.73% CL regions for the respective combined analyses.

8% at 3σ, defined as $(x^{\text{upper}} - x^{\text{lower}})/(x^{\text{upper}} + x^{\text{lower}})$. KamLAND data start also to contribute to the lower bound on $\sin^2\theta_{12}$, whereas the upper bound is dominated by solar data, most importantly by the CC/NC solar neutrino rates measured by SNO.

The MINOS experiment has reported new results on ν_μ disappearance with a baseline of 735 km based on a two-year exposure from the Fermilab NuMI beam corresponding to a total of 3.36×10^{20} protons on target [10]. The data confirm the energy dependent disappearance of ν_μ, showing significantly less events than expected in the case of no oscillations in the energy range $\lesssim 6$ GeV, whereas the high energy part of the spectrum is consistent with the no oscillation expectation. We combine the long-baseline accelerator data from MINOS as well as from K2K [11] with atmospheric neutrino measurements from Super-Kamiokande [12], using the results of Ref. [13]. In this analysis sub-leading effects of Δm^2_{21} in atmospheric data are neglected, but effects of θ_{13} are included. Fig. 1(right) illustrates how the determination of the leading atmospheric oscillation parameters θ_{23} and $|\Delta m^2_{31}|$ emerges from the complementarity of atmospheric and accelerator neutrino data. The determination of $|\Delta m^2_{31}|$ is dominated by spectral data from the MINOS experiment, where the sign of Δm^2_{31} (i.e., the neutrino mass hierarchy) is undetermined by present data. The measurement of the mixing angle θ_{23} is still largely dominated by atmospheric neutrino data from Super-Kamiokande with a best fit point close to maximal mixing. Small deviations from maximal mixing due to sub-leading three-flavour effects (not included in the analysis of [1, 13]) have been found in Refs. [2, 14], *c.f.* Tab. 1. See, however, also Ref. [15] for a preliminary analysis of Super-Kamiokande. A comparison of these subtle effects can be found in Ref. [16]. At present deviations from maximality are not statistically significant.

The third mixing angle θ_{13} would characterize the magnitude of CP violation in neutrino oscillations and is crucial also for the determination of the neutrino mass ordering. It is the main objective of upcoming reactor and accelerator experiments to measure this parameter. Fig. 2(left) summarizes the information on θ_{13} from present data, which emerges from an interplay of different

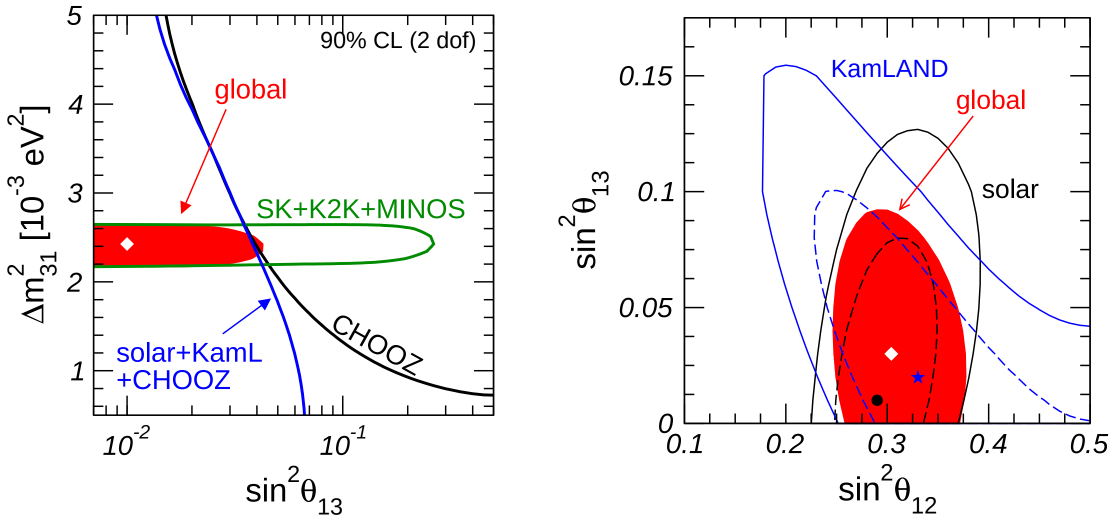

Figure 2: Left: Constraints on $\sin^2\theta_{13}$ from the interplay of different parts of the global data. Right: Allowed regions in the $(\theta_{12}-\theta_{13})$ plane at 90% and 99.73% CL (2 dof) for solar and KamLAND, as well as the 99.73% CL region for the combined analysis. Δm^2_{21} is fixed at its best fit point. The dot, star, and diamond indicate the best fit points of solar, KamLAND, and combined data, respectively.

data sets. An important contribution to the bound comes, of course, from the CHOOZ reactor experiment [17] combined with the determination of $|\Delta m^2_{31}|$ from atmospheric and long-baseline experiments. The results on θ_{13} [1] reported in Tab. 1 imply an upper bound of $\sin^2\theta_{13} < 0.035(0.056)$ at 90% CL (3σ) and the best fit point is consistent with zero within 0.9σ, while Ref. [2] finds the slightly stronger bound $\sin^2\theta_{13} < 0.049$ at 3σ and a $\Delta\chi^2 = 0.04$ for $\theta_{13} = 0$. These differences can be understood by noting that SNO-NCD data is not included in the results from [2], see below for an explanation.

3. Comments on possible hints for a non-zero value of θ_{13}

A recent global analysis of neutrino data [18] obtains a hint for a non-zero value of θ_{13} at 1.6σ, which emerges from a 1.2σ hint from solar+KamLAND data combined with a 0.9σ hint from atmospheric+long-baseline+CHOOZ data. The hint from solar+KamLAND data can be understood by the slight downward shift of the SNO CC/NC ratio due to the SNO-NCD data mentioned in Sec. 2. From the combination of solar and KamLAND data we find a best fit value of $\sin^2\theta_{13} = 0.03$ with $\Delta\chi^2 = 2.2$ for $\theta_{13} = 0$ which corresponds to a 1.5σ effect (86% CL). We illustrate the interplay of solar and KamLAND data in Fig. 2(right). The relevant survival probabilities are given by

$$P_{ee} \approx \begin{cases} \cos^4\theta_{13}\left(1-\sin^2 2\theta_{12}\langle\sin^2\phi\rangle\right) & \text{solar, low energies / KamLAND} \\ \cos^4\theta_{13}\sin^2\theta_{12} & \text{solar, high energies} \end{cases}, \tag{3.1}$$

where $\phi = \Delta m^2_{21}L/4E$ and $\langle\sin^2\phi\rangle \approx 1/2$ for solar neutrinos. Eq. (3.1) implies an anti-correlation of $\sin^2\theta_{13}$ and $\sin^2\theta_{12}$ for KamLAND and low energy solar neutrinos. In contrast, for the high energy part of the spectrum, which undergoes the adiabatic MSW conversion inside the sun and which is subject to the SNO CC/NC measurement, a positive correlation of $\sin^2\theta_{13}$ and $\sin^2\theta_{12}$ emerges. As visible from Fig. 2(right) and as discussed already in [13, 19], this complementarity leads to a non-trivial constraint on θ_{13} and it allows to understand the hint for a non-zero value of θ_{13}, which helps to reconcile the slightly different best fit points for θ_{12} (as well as for Δm^2_{21}, see Fig. 1) for solar and KamLAND separately [18, 19, 20, 21]. This trend was visible already in pre-SNO-NCD data, though with a significance of only 0.8σ, see v6 of [13].

The hint arising from atmospheric data is, in our opinion, much more controversial. This preference for a non-zero θ_{13} value was first noted in Ref. [14], and is illustrated in Fig. 24 of that paper (see also [22]). Our attempts to reproduce that figure with our own numerical codes are shown in the left panels of Fig. 3. We have performed three different kinds of calculations:

(A) *old rates, old* χ^2 (black line). This case follows closely the analysis presented in Ref. [13], except for the fact that here we have also included sub-leading Δm^2_{21} effects. Note that the data samples and the χ^2 definition used here are the same as in Ref. [14]; in particular, SK-I data are divided into 55 energy and zenith bins.

(B) *new rates, old* χ^2 (red line). This case differs from the previous one for the details of the event rate calculations, which are now performed as described in the appendix of Ref. [2]; on the other hand, the χ^2 definition and the number of data points are unchanged.

(C) *new rates, new* χ^2 (blue line). This case fully coincides with the three-neutrino analysis presented in Ref. [2]. The treatment of the theoretical uncertainties in the χ^2 definition differs considerably from the previous two cases, and the number of data points is now increased to 90.

For definiteness we consider only normal hierarchy. Our analysis shows that:

- the results of case (A) are qualitatively very similar to those shown in Fig. 24 of Ref. [14]. In particular, the data favor $\cos\delta = -1$ and disfavor $\cos\delta = +1$, indicating that a relevant contribution to the effect comes from the interference term Δ_3 (see Eq. 44 of Ref. [14]). Indeed, from the lower-left panel we see that the hint for non-zero θ_{13} disappears for $\Delta m^2_{21} = 0$, in agreement with [14];

- on the other hand, the *strength* of the preference for non-zero θ_{13} in our analysis (A) is only 0.5σ, much weaker than the 0.9σ found in Ref. [14]. Since the χ^2 definition and the experimental data are the same for both analyses, we conclude that the discrepancy must arise from differences in the rate calculations. Indeed, a comparison between our cases (A) and (B) in Fig. 3 shows that the statistical relevance of the signal strongly depends on the details of the Monte-Carlo: for example, for case (B) the hint of non-zero θ_{13} is only at the 0.2σ level, *i.e.* practically inexistent;

- details of the data binning and the theoretical uncertainties are also very important, as can be seen by comparing cases (B) and (C), which are based on identical rate calculations. In case (C) the preference for non-zero θ_{13} is again as strong as in case (A), but now the hint persists also for $\Delta m^2_{21} = 0$.

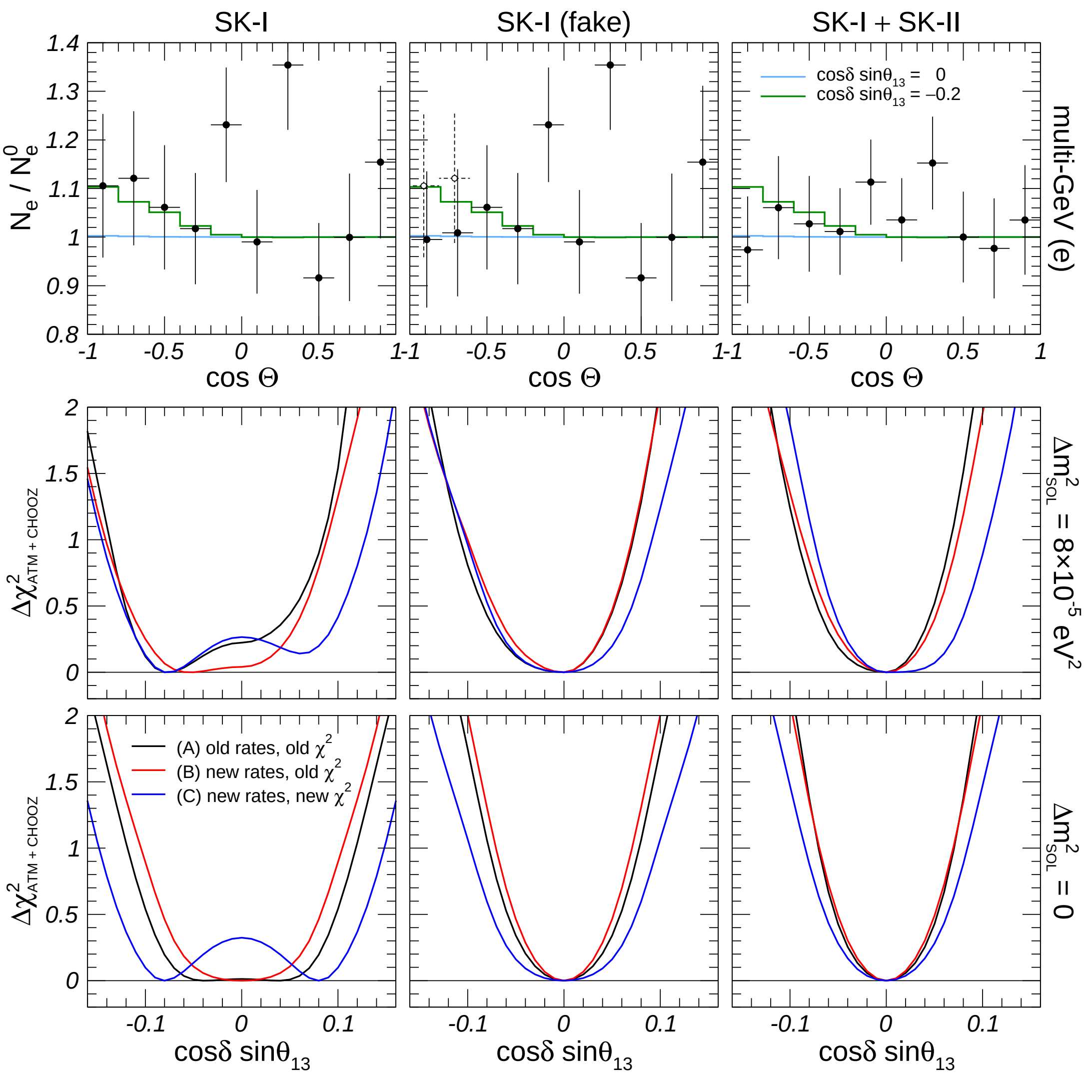

Figure 3: Zenith distribution for multi-GeV e-like events (upper panels), and $\Delta\chi^2$ dependence on $\cos\delta \sin\theta_{13}$ for $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2 (middle panels) and for $\Delta m^2_{21} = 0$ (lower panels). The fits include the CHOOZ data as well as the full atmospheric data samples for SK-I (left panels), SK-I with modified multi-GeV e-like data (central panels) and SK-I + SK-II (right panels). The black, red and blue lines correspond to different analyses. See text for details.

It is quite difficult to trace the preference for non-zero θ_{13} to the effect of a single data sample. Clearly, the asymmetry between the two values $\cos\delta = \pm 1$ shows that the interference term Δ_3, mostly relevant for sub-GeV data, plays an important role. On the other hand, other samples are affected by θ_{13}, and as we have seen the details of the statistical analysis determine whether the hint appears also when the interference term is suppressed (*e.g.*, for $\Delta m^2_{21} = 0$), or not. As an example, in the upper panels of Fig. 3 we show the contribution of multi-GeV e-like data to the effect. It is clear from this plot that the first two bins of this sample are better fitted with a non-zero value of θ_{13}. To assess the relevance of this contribution, in the middle and right panels of Fig. 3 we repeat the calculations described above for a different choice of experimental data:

- in the middle panels, we artificially reduce the first two bins of SK-I multi-GeV *e*-like events by 10%. As can be seen, with this simple change the hint in favor of non-zero θ_{13} completely disappears, *irrespective* of the details of the rate calculations and of the statistical analysis, and also of the inclusion of sub-leading Δm^2_{21} effects. We conclude therefore that the excess in these two bins somewhat "triggers" the hint for non-zero θ_{13};

- in the right panels, we repeat our fits for the combination of SK-I and SK-II data. As can be seen from the upper panel, the "excess" in the first bins of multi-GeV *e*-like data no longer appears once SK-II data are also included. The lower panels show that the results are very similar to the "fake" SK-I data displayed in the middle panels, and in particular no preference for non-zero θ_{13} is present.

In the light of these results, we conclude that (1) the statistical relevance of the claimed hint for non-zero θ_{13} from atmospheric data depends strongly on the details of the rate calculations and of the χ^2 analysis, and (2) the hint is the result of a statistical fluctuation in SK-I data which disappears after the inclusion of SK-II data. Since in the atmospheric neutrino analysis used in [1, 13] no hint for $\theta_{13} > 0$ is present, the indication from solar data becomes weakened in the global analysis, leading to the θ_{13} result quoted in Tab. 1, consistent with zero at 0.9σ. We believe that the present "indication" for a non-zero θ_{13} should not be taken more serious than a $\sim 1\sigma$ effect (which of course implies that it will be true with a probability of $\sim$ 68%) and has to wait for being confirmed or refuted by upcoming experiments.

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