ABSTRACT

At the previous Venice meeting NO-VE 2008, we discussed possible hints in favor of a nonzero value for the unknown neutrino mixing angle $\theta_{13}$, emerging from the combination of solar and long-baseline reactor data, as well as from the combination of atmospheric, CHOOZ and long-baseline accelerator $\nu_\mu \to \nu_\mu$ data. Recent MINOS 2009 results in the $\nu_\mu \to \nu_e$ appearance channel also seem to support such hints. A combination of all current oscillation data provides, as preferred range,

$$\sin^2 \theta_{13} \approx 0.02 \pm 0.01 \ (1\sigma) .$$

We review several issues raised by such hints in the last year, and comment on their possible near-future improvements and tests.

1. Introduction

Neutrino flavor oscillations induced by $\nu$ masses and mixings are by now well established. The $3\nu$ oscillation parameter space includes two independent mass-squared differences $(\delta m^2, \Delta m^2)$, and three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$; see [1] for a review. Among these parameters, only $\theta_{13}$ is compatible with zero, with an upper bound dominated by the CHOOZ experiment [2] in the range $\sin^2 \theta_{13} < \text{few} \%$.

A nonzero value of $\theta_{13}$ is crucial to access a possible CP-violating phase $\delta$ [34], to probe the $\nu$ mass hierarchy [i.e., sign$(\pm \Delta m^2)$] via $\nu$ interactions in the Earth [45] or in Supernovae [67], and to discriminate different theoretical models for the neutrino mass matrix [891011]. Therefore, the search for $\theta_{13}$ is a primary objective in the $\nu$ physics program worldwide [1213141516171819], and its determination will also be important for longer-term goals related to the search for new neutrino interactions [202122] or new physics at very high scales relevant for leptogenesis [23].

Given the large and growing interest in the value of $\theta_{13}$, it is worthwhile to investigate if the available data can provide at least some “hints” in favor of $\theta_{13} > 0$, at the level of $\sim 1$–$2\sigma$, before an evidence at $> 3\sigma$ is hopefully found in dedicated searches at reactors [1819] and accelerators [1617].
2. First hints of $\theta_{13} > 0$ (2008)

2.1. Solar+KamLAND neutrino data

At the last Workshop “Neutrino Oscillations in Venice” (NO-VE 2008), we noted $^{24}$ that the combination of solar data and long-baseline reactor data (KamLAND $^{25}$) suggested a weak preference for $\sin^2 \theta_{13} \sim O(10^{-2})$ at $\sim 0.5\sigma$, as a result of a slight difference between the best-fit values of $\sin^2 \theta_{12}$ in the two datasets.

Shortly after, the same effect was independently discussed in Ref. $^{26}$. One month later, at the Neutrino 2008 Conference $^{27}$, new solar data were presented from the third phase of the Sudbury Neutrino Observatory (SNO-III) $^{28,29}$. We then showed that such data corroborated the previous picture at the level of $\sim 1.2\sigma$ $^{30}$.

$$\sin^2 \theta_{13} \simeq 0.021 \pm 0.017 \ (1\sigma, \text{ solar + KamLAND, 2008}).$$

A similar hint (at a slightly higher confidence level of $\sim 1.5\sigma$) was obtained in Ref. $^{31}$, and is also implicit in the results of Ref. $^{32}$. So, several independent analyses have found a weak preference in favor of $\theta_{13} > 0$, using the available (2008) solar and KamLAND data, at the level of $1.2$–$1.5\sigma$.

Figure 1 shows the effect of nonzero $\theta_{13}$ on the regions separately allowed by the latest available data from the solar and KamLAND experiments, at 1, 2 and 3$\sigma$ level (i.e., $\Delta \chi^2 = 1, 4$ and $9$, at fixed $\theta_{13}$). The left and right panels refer to $\theta_{13} = 0$ and to a representative value $\sin^2 \theta_{13} = 0.03$, respectively. Clearly, the two best-fit regions overlap more for $\sin^2 \theta_{13} > 0$. 

Figure 1: Comparison of $n$-$\sigma$ regions allowed by the latest (2008) solar and KamLAND data in the $(\delta m^2, \sin^2 \theta_{12})$ plane, for two fixed values of $\theta_{13}$. 

$\delta m^2 \ (10^{-5} \text{ eV}^2)$

$\sin^2 \theta_{12}$

$\sin^2 \theta_{13} = 0$

$\sin^2 \theta_{13} = 0.03$
Figure 2: Model-independent analysis of $^8$B solar $\nu$ data in SK and SNO, in the plane charted by the $\Phi_B$ flux and by the energy-averaged survival probability $P_{ee}$. The bands represent the regions allowed at 1σ by the NC and CC event rates measured in SNO and by the ES rate measured in SK. The left panel includes only SNO-I and SNO-II data as available in 2005, while the right panel includes only SNO-III data as available in 2008. In each panel, the slanted ellipse represents the combination of NC+CC+ES constraints, while the vertical error bar represents the $\Phi_B$ range predicted by the BS’05 (OP) standard solar model.

Notably, there is no reason to think that the preference for $\theta_{13} > 0$ may be due to a “fluctuation” of the latest SNO-III data, which are actually in very good agreement with previous SNO and Super-Kamiokande (SK) solar $\nu$ data, as we now show.

Figure 2 updates earlier model-independent (and also $\theta_{13}$-independent) analyses of Super-Kamiokande (SK ES) data and SNO neutral-current (NC) and charged-current (CC) data, in the plane charted by the $^8$B $\nu_e$ flux ($\Phi_B$) and by the corresponding, energy-averaged survival probability ($P_{ee}$). The left panel refers to SNO 2005 data (i.e., from SNO phase I and II only), while the right panel includes only SNO-III data as available in 2008. The relative agreement among the 1σ bands constrained by the ES, NC, and CC data, which is already good in the left panel, becomes even better in the right panel. Therefore, the SNO-III data do improve the overall consistency of the high-statistics (ES, NC, CC) data collected in SK and SNO.

In the right plot of Fig. 2, we also note that the global SK+SNO combination (slanted ellipse) compares very well with the $^8$B flux predictions of a reference “standard solar model” (SSM Bahcall-Serenelli-Basu 2005 OP). However, unsolved metallicity discrepancies still prevent a more quantitative comparison of $^8$B neutrino data with SSM’s.
2.2. Super-Kamiokande atmospheric neutrino data

Besides the solar+KamLAND “hint,” which is relatively recent, an older, independent preference for $\theta_{13} > 0$ had already been found in $^1$ at the level of $\sim 0.9\sigma$, from an analysis of atmospheric neutrino data in phase-I of Super-Kamiokande (SK-I), together with CHOOZ and long-baseline accelerator (LBL) data. We traced its origin to subleading $3\nu$ oscillation terms, arising at first order in $\theta_{13}$ and driven by $\delta m^2$ $^37$, which are most effective at $\cos \delta = -1$; see, in particular, Fig. 24 in $^1$. The related effects could partly explain the observed excess of sub-GeV atmospheric electron-like events. This weak hint for $\theta_{13} > 0$ is compatible with the CHOOZ constraints, and is not spoiled by adding LBL data from K2K and MINOS in the $\nu_\mu$ disappearance channel, which are not yet sensitive to $\theta_{13}$ $^{38}$. Our constrained estimate reads $^{30}$

$$\sin^2 \theta_{13} \simeq 0.012 \pm 0.013 \ (1\sigma, \text{Atmos.} + \text{LBL} + \text{CHOOZ}, \ 2008) \ .$$

Unfortunately, subleading $(\delta m^2, \theta_{13})$ effects are generally small in the relevant low-energy atmospheric $\nu$ distributions, and are smeared by the interaction and detection processes $^{114}$. Therefore, their emergence may depend on details of the statistical analysis. An independent, state-of-the-art $3\nu$ global fit of atmospheric $\nu$ data did not find an appreciable preference for $\theta_{13} > 0$ $^{39}$, while another (less documented) analysis $^{40}$ appeared to favor $-\cos \delta \sin \theta_{13} > 0$ as in our case; see also Ref. $^{11}$. $^b$

The authors of Ref. $^{42}$ analyzed several variants in the atmos.+LBL+CHOOZ fit, and found either no hint or, at most, a $0.5\sigma$ one. The latter, although weaker than our $0.9\sigma$ [Eq. (2)], shows similar qualitative features, such as the role of $\delta m^2$-driven terms and the irrelevance of current LBL $\nu_\mu$ disappearance data. It was also observed $^{42}$ that the (still unpublished) SK-II data $^{35}$ prefer $\theta_{13} \simeq 0$, due to a small deficit (rather than an excess) of upgoing multi-GeV electron-like (MG$e$) events. However, we note that preliminary SK-III data seem to show again a small excess in the same event sample $^{27}$. The full analysis of SK-II (and possibly of SK-III and even SK-IV) atmospheric data is underway $^{35}$ and is likely to affect the $\theta_{13}$ constraints.

Unfortunately, the number of SK bins is growing to $O(10^3)$, with $O(10^2)$ systematics $^{35,43,44}$, making it impossible to closely reproduce their data analysis. It is then crucial that the SK Collaboration itself performs a full $3\nu$ analysis including all $(\delta m^2, \theta_{13})$ oscillation terms $^{45}$. Recent PhD thesis works in SK have assumed either $\delta m^2 > 0$ but with $\theta_{13} = 0$ (see Ref. $^{43}$) or $\theta_{13} > 0$ but with $\delta m^2 = 0$ (see Ref. $^{44}$). The latter approximation is also used in $^{31}$. The $3\nu$ approximations adopted in Refs. $^{43,44,431}$ prevent, at present, a direct comparison of their atmospheric $\nu$ results with ours, as far as subtle effects driven by subleading $(\delta m^2, \theta_{13})$ terms are concerned.

$^b$In $^{40,41}$, the appearance of “negative” values of $\theta_{13}$ is the result of an unusual convention, which absorbs into $\theta_{13}$ the negative sign associated to the case $\cos \delta < 0$. 

2.3. Combination of all oscillation data (2008)

We have presented two hints in favor of $\theta_{13} > 0$, one coming from the analysis of solar+KamLAND data [Eq.(1)], and another one from the analysis of published SK-I atmospheric data, together with disappearance constraints from CHOOZ $\nu_e$ and LBL $\nu_\mu$ data [Eq. (2)]. As previously discussed, the second hint appears to have a more fragile status than the first, but we have no compelling reason to revise it at present. Then, by merging the results in Eqs. (1) and (2) in a global neutrino data analysis, we obtain\[30]:

$$\sin^2\theta_{13} \simeq 0.016 \pm 0.010 \ (1\sigma, \ All \ Data, \ 2008) ,$$

(3)

which represents an intriguing indication in favor of $\theta_{13} > 0$ at the 90% C.L. ($\sim 1.6\sigma$).

Figure 3 summarizes our findings, by showing the $n$-$\sigma$ curves ($n$-$\sigma = \sqrt{\Delta \chi^2}$) as a function of $\sin^2\theta_{13}$ (all other oscillation parameters being marginalized) for different combinations of data sets available in 2008. The global combination (thick solid curve) provides, at 1$\sigma$, the range reported in Eq. (3).
3. MINOS $\nu_e$ appearance results and $\theta_{13}$ update (2009)

At this Workshop, recent preliminary MINOS data in the $\nu_\mu \rightarrow \nu_e$ appearance channel have been presented \cite{minos}. The data show a slight overall excess of electron flavor events above the estimated background ($\Delta N_e \simeq 8 \pm 5$), with a statistical significance of $\sim 90\%$ C.L.

If the overall excess $\Delta N_e$ is interpreted in terms of neutrino oscillations, and if the dominant oscillation parameters ($\Delta m^2$, $\sin^2 \theta_{23}$) are fixed at their best-fit values, then one can put degenerate constraints in the plane of the subdominant parameters ($\theta_{13}, \delta$) \cite{minos}. In particular, the degenerate best-fit range is $\sin^2 \theta_{13} \simeq 0.03-0.05$, depending on $\delta$ (and on the hierarchy), while the $90\%$ C.L. bounds are at $\sin^2 \theta_{13} \simeq 0$ (lower) and at $\sin^2 \theta_{13} \simeq 0.07-0.12$ (upper). We tentatively symmetrize the preliminary MINOS 2009 preferred range with just one significant digit as:

$$\sin^2 \theta_{13} \simeq 0.05 \pm 0.03 \ (1\sigma, \ \text{MINOS 2009}) ,$$  \hspace{1cm} (4)

second-digit details being unimportant in this context.\footnote{MINOS $\nu_e$ appearance results can be properly included only after detailed publications of data and of their analyses become available.}

Thus, we might have two independent hints of $\theta_{13} > 0$ at $90\%$ C.L.: one from the global analysis of 2008 data [Eq.(3)], and one from the preliminary MINOS data [Eq. (4)]. Their combination at face value reads:

$$\sin^2 \theta_{13} \simeq 0.02 \pm 0.01 \ (1\sigma, \ \text{All data + MINOS 2009}) ,$$  \hspace{1cm} (5)

which represents an up-to-date, global indication in favor of $\theta_{13} > 0$ at a confidence level of $\sim 95\% \ (\sim 2\sigma)$.

Figure 4 provides a final, graphical overview of the hints in Eqs. (1)–(3) and (5).
4. Near-future prospects

We have seen that several $\sim 1\sigma$ hints seem to converge towards an overall $\sim 2\sigma$ indication in favor of $\theta_{13} > 0$ [Eq. (5)]. This indication will be further tested with more accurate data in the near future.

The SNO experiment is completed, but the final data analysis is in progress and is being performed with a lower energy threshold. Updated SNO results are expected soon. The KamLAND detector continues to take data, but the current purification and calibration processes might delay the next release of reactor neutrino data. In any case, a joint $3\nu$ analysis by the SNO and KamLAND collaborations would be very relevant to test the hint in Eq. (1) which, if confirmed, could be possibly upgraded to the $\sim 2\sigma$ level.

Concerning atmospheric $\nu$'s, the SK collaboration analysis is in progress, at least for phases I+II. It is important that all $(\delta m^2, \theta_{13})$-driven terms are included in a full $3\nu$ oscillation analysis. Higher-statistics LBL data from the MINOS experiment are expected to test more accurately the possible $\nu_e$ excess. Also in this case, a combination of SK+MINOS data might then favor $\theta_{13} > 0$ at an overall $\sim 2\sigma$ level, if indeed $\sin^2 \theta_{13} \sim 0.02$.

In conclusion, if all the hints persist and converge in the next couple of years, then the current global indication in favor of $\theta_{13} > 0$ [Eq. (5)] might be promoted to a $\sim 3\sigma$ level: an exciting scenario, which would suggest early $\theta_{13}$ discoveries in the upcoming, next-generation experiments at reactors and accelerators, opening the door to leptonic CP violation searches.

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