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NEUTRINO OSCILLATIONS, GLOBAL ANALYSIS AND THETA(13)

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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 θ_{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,

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

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

A nonzero value of θ_{13} is crucial to access a possible CP-violating phase δ [3,4)], to probe the ν mass hierarchy [i.e., sign($\pm\Delta m^2$)] via ν interactions in the Earth [4,5)] or in Supernovae [6,7)], and to discriminate different theoretical models for the neutrino mass matrix [8,9,10,11)]. Therefore, the search for θ_{13} is a primary objective in the ν physics program worldwide [12,13,14,15,16,17,18,19)], and its determination will also be important for longer-term goals related to the search for new neutrino interactions [20,21,22)] or new physics at very high scales relevant for leptogenesis [23)].

Given the large and growing interest in the value of θ_{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$1–2σ, before an evidence at $> 3\sigma$ is hopefully found in dedicated searches at reactors [18,19)] and accelerators [16,17)].

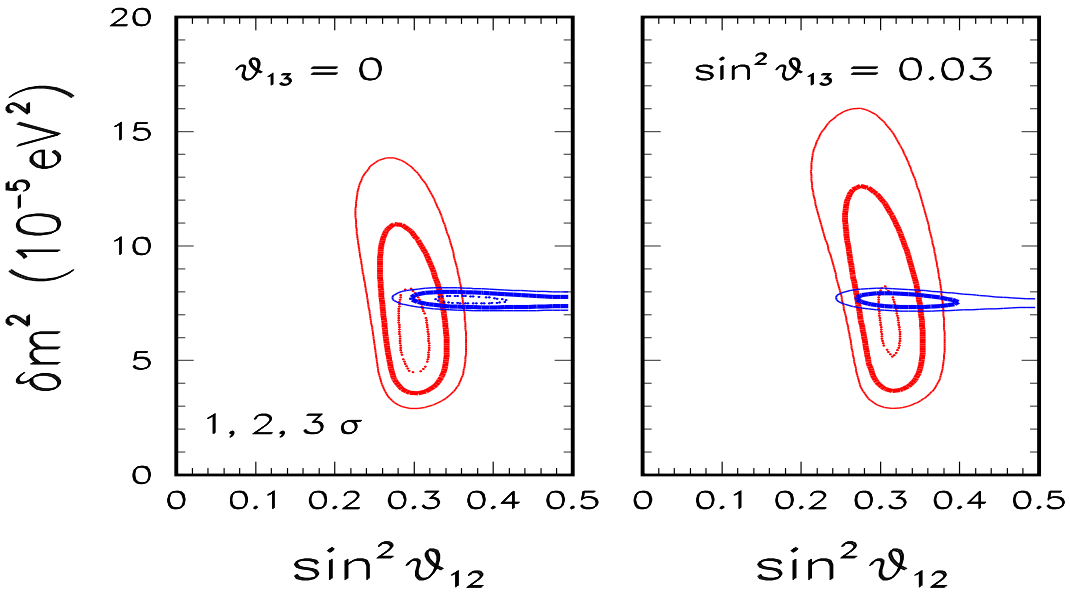

Figure 1: Comparison of n-σ regions allowed by the latest (2008) solar and KamLAND data in the $(\delta m^2, \sin^2\theta_{12})$ plane, for two fixed values of θ_{13}.

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]

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

A similar hint (at a sightly 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 1.2–1.5σ.

Figure 1 shows the effect of nonzero θ_{13} on the regions separately allowed by the latest available data from the solar and KamLAND experiments, at 1, 2 and 3σ level (i.e., $\Delta\chi^2 = 1$, 4 and 9, at fixed θ_{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 $\sin^2\theta_{13} > 0$.

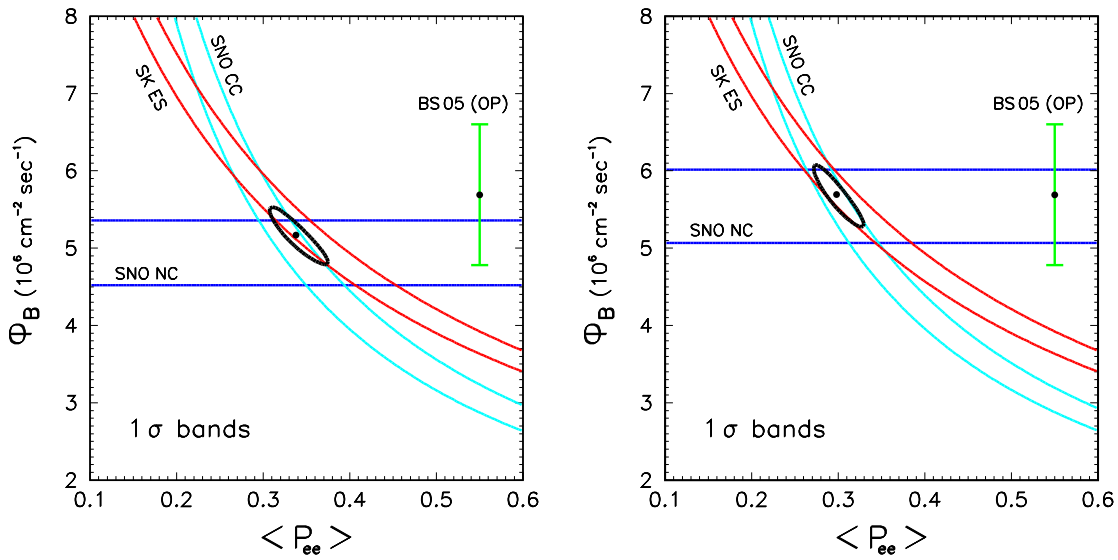

Figure 2: Model-independent analysis of ^{8}B solar ν data in SK and SNO, in the plane charted by the Φ_B flux and by the energy-averaged survival probability P_{ee}. The bands represent the regions allowed at 1σ by the NC and CC event rates measured in SNO and by the ES rate measured in SK. The left 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 Φ_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 ν data, as we now show.

Figure 2 updates earlier model-independent (and also θ_{13}-independent) analyses [33,34,1] of Super-Kamiokande elastic scattering (SK ES) data [35] and SNO neutral-current (NC) and charged-current (CC) data [29], in the plane charted by the ^{8}B ν_e flux (Φ_B) and by the corresponding, energy-averaged survival probability $\langle P_{ee} \rangle$. 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.[a]

[a]In the right plot of Fig. 2, we also note that the global SK+SNO combination (slanted ellipse) compares very well with with the ^{8}B flux predictions of a reference "standard solar model" (SSM Bahcall-Serenelli-Basu 2005 OP) [36]. However, unsolved metallicity discrepancies [32] 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 3ν oscillation terms, arising at first order in θ_{13} and driven by δm^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 ν_μ disappearance channel, which are not yet sensitive to θ_{13} [38)]. Our constrained estimate reads [30)]

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

Unfortunately, subleading (δm^2, θ_{13}) effects are generally small in the relevant low-energy atmospheric ν distributions, and are smeared by the interaction and detection processes [1,4)]. Therefore, their emergence may depend on details of the statistical analysis. An independent, state-of-the-art 3ν global fit of atmospheric ν 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.[41)].[b]

The authors of Ref. [42)] analyzed several variants in the atmos.+LBL+CHOOZ fit, and found either no hint or, at most, a 0.5σ one. The latter, although weaker than our 0.9σ [Eq. (2)], shows similar qualitative features, such as the role of δm^2-driven terms and the irrelevance of current LBL ν_μ 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 (MGe) 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 θ_{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 3ν 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 3ν approximations adopted in Refs. [43,44,31)] prevent, at present, a direct comparison of their atmospheric ν results with ours, as far as subtle effects driven by subleading (δm^2, θ_{13}) terms are concerned.

[b] In [40,41)], the appearance of "negative" values of θ_{13} is the result of an unusual convention, which absorbs into θ_{13} the negative sign associated to the case $\cos\delta < 0$.

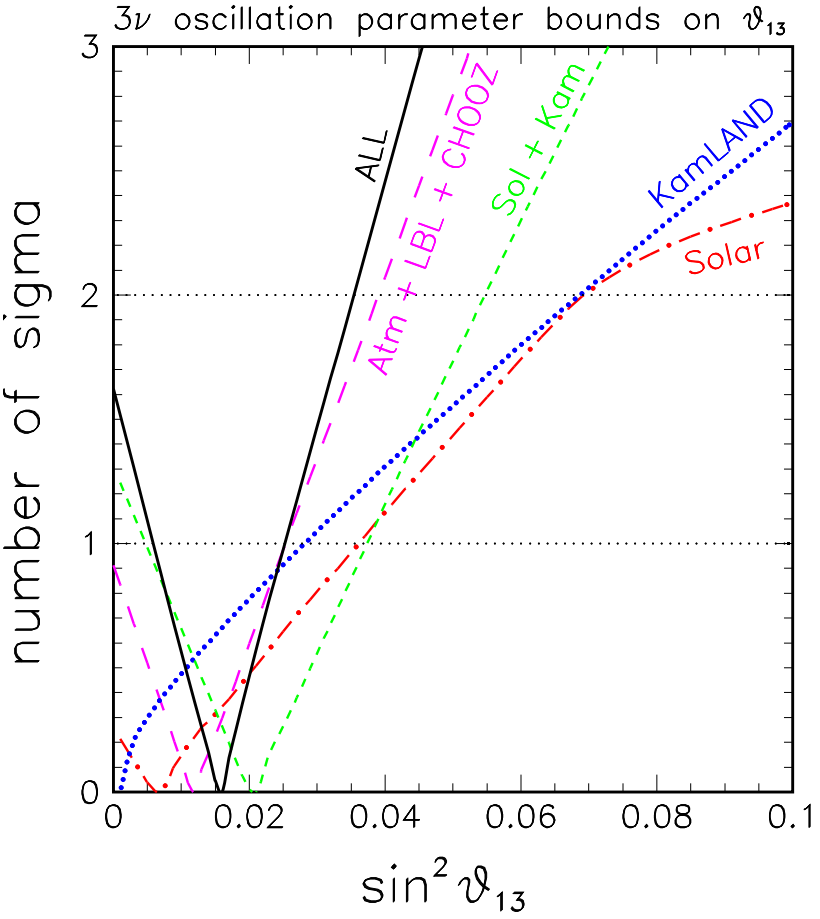

Figure 3: Bounds on θ_{13} from different data sets available in 2008.

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 ν_e and LBL ν_μ 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]:

$$\sin^2\theta_{13} \simeq 0.016 \pm 0.010 \ (1\sigma,\ \text{All Data},\ 2008)\ , \tag{3}$$

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-σ 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 1σ, the range reported in Eq. (3).

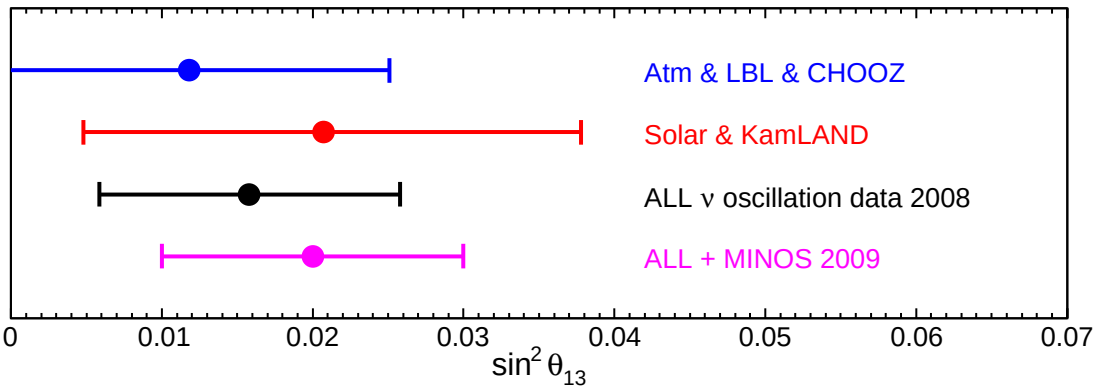

Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

3. MINOS ν_e appearance results and θ_{13} update (2009)

At this Workshop, recent preliminary MINOS data in the $\nu_\mu \to \nu_e$ appearance channel have been presented [15]. 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 ΔN_e is interpreted in terms of neutrino oscillations, and if the dominant oscillation parameters (Δm^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 (θ_{13}, δ) [15]. In particular, the degenerate best-fit range is $\sin^2\theta_{13} \simeq 0.03$–$0.05$, depending on δ (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:

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

second-digit details being unimportant in this context.[c]

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:

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

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).

[c] MINOS ν_e appearance results can be properly included only after detailed publications of data and of their analyses become available.

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 [29]. Updated SNO results are expected soon. The KamLAND detector continues to take data, but the current purification and calibration processes [25] might delay the next release of reactor neutrino data. In any case, a joint 3ν analysis by the SNO and KamLAND collaborations would be very relevant to to test the hint in Eq. (1) which, if confirmed, could be possibly upgraded to the $\sim 2\sigma$ level.

Concerning atmospheric ν's, the SK collaboration analysis is in progress [35], at least for phases I+II. It is important that all (δm^2, θ_{13})-driven terms are included in a full 3ν oscillation analysis [1,45]. Higher-statistics LBL data from the MINOS experiment are expected to test more accurately the possible ν_e excess [15]. 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 persists 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 θ_{13} discoveries in the upcoming, next-generation experiments at reactors [18,19] and accelerators [16,17], opening the door to leptonic CP violation searches.

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