NEUTRINO DATA AND IMPLICATIONS FOR θ_{13}

G.L. FOGLI[1,2], E. LISI[2], A. MARRONE[1], A. PALAZZO[3,a] and A.M. ROTUNNO[1]

[1] *Dipartimento di Fisica, Università di Bari, Via Amendola 173, 70126, Bari, Italy*

[2] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bari, Via Orabona 4, 70126 Bari, Italy*

[3] *AHEP Group, Institut de Física Corpuscular, CSIC/Universitat de València, Edifici Instituts d'Investigació, Apt. 22085, 46071 València, Spain*

Pinning down the unknown neutrino mixing angle θ_{13} constitutes one of the most important goals in particle physics in connection with future investigation on CP violation in the leptonic sector. In this context, we present the results of an updated global analysis of neutrino oscillation data, focusing on this eluding parameter. We discuss three independent and converging hints of $\theta_{13} > 0$: A first one coming from atmospheric neutrino data; a the second one from the combination of solar and long-baseline reactor neutrino data; and a third one from the latest MINOS measurements in the appearance ($\nu_\mu \to \nu_e$) channel. Their combination provides a preference for $\theta_{13} > 0$ at the non-negligible statistical significance of the 2σ (95% C.L.). We also discuss possible refinements of the data analyses, which might sharpen the present indication.

1 Introduction

After more than a decade of data-taking, old and new neutrino experiments continue to provide us with precious information to decipher. The latest data not only sharpen the estimates of well known parameters but may disclose the opportunity to probe some of the unknown ones. This may be the case of the smallest and unknown mixing angle θ_{13}, whose determination is a fundamental target in connection with future investigation of CP violation in the leptonic sector.

The first robust upper bound on θ_{13} was established by the CHOOZ experiment[1] at the end of 1997. Since then we have been witnessing a slow but progressive increase in the sensitivity of the neutrino global analyses in constraining this important parameter. Indeed, such analyses

[a]Speaker, email: antonio.palazzo@ific.uv.es

have first corroborated the CHOOZ findings and then have progressively strengthened its upper limit. Therefore, it is not completely surprising that neutrino data now allow us to go beyond the CHOOZ sensitivity. What instead (pleasantly) surprise us is that they, for the first time, point toward a non-zero value of this parameter. Remarkably, an analogous hint has independently emerged in the recent searches of ν_e appearance in MINOS[2], thus reinforcing the statistical significance of the global indication for non-zero θ_{13} (now at the 95% C.L.), together with our hopes of pinning down this fundamental parameter.

In the following we review the current status of neutrino mass and mixing determinations, focusing on such a weak, but nonetheless interesting, indication.

2 The leading parameters

Four of the fundamental parameters driving neutrino oscillations are known with very good precision. Two couples of parameters govern the flavor transitions in the two (almost) distinct "atmospheric" and "solar" sectors — so called from the natural sources used in the first searches for neutrino oscillations. In fact, precision studies of these parameters are now complemented by "artificial" neutrinos produced in reactors and accelerators. Each couple of parameters consists of a mass squared splitting (related to the oscillation frequency) and a mixing angle (related to the amplitude of the relevant oscillation process). In the following we review the status of the determination of these parameters as of May 2009.

2.1 δm^2 *and* θ_{12}

Solar and KamLAND reactor neutrino oscillations are driven by two leading parameters: the smallest mass-squared difference δm^2 and the mixing angle θ_{12}. In our analysis[3] we have included the results from the third phase of the Sudbury Neutrino Observatory (SNO-III)[4], in the form of two integral determinations of the charged current (CC) and neutral current (NC) event rates. Furthermore, we have included the Borexino results[5], and the reevaluated GALLEX datum[6]. Finally, we have incorporated the latest KamLAND measurements[7].

The δm^2 determination is dominated by KamLAND, which now observes the oscillatory pattern over one entire cycle[7]. The situation is quite different for the mixing angle θ_{12}, which is determined by an interplay of both solar and KamLAND data. Indeed, a weak tension is present among the two independent determinations which, as we shall see in more detail in the next section, is at the origin of the"new" hint of $\theta_{13} > 0$. Our three flavor analysis[8], after marginalizion over θ_{13}, provides the following determinations (at the 2σ level),

$$\delta m^2 = 7.67\,(1^{+0.044}_{-0.047}) \times 10^{-5}\ \mathrm{eV}^2\ , \tag{1}$$

$$\sin^2\theta_{12} = 0.312\,(1^{+0.128}_{-0.109})\ , \tag{2}$$

in agreement with our previous estimates[9], and now more precise almost by a factor of two.

2.2 Δm^2 *and* θ_{23}

Atmospheric and long baseline (LBL) neutrino oscillations are mainly driven by two leading parameters: the largest mass-squared difference Δm^2 and the mixing angle θ_{23}. In this case, even in the limit $\theta_{13} = 0$, small effects are induced by the "solar parameters" (δm^2, θ_{12}), which we fix at their best fit values. The determination of the mass-squared difference Δm^2 is now dominated by the disappearance measurements (in the $\nu_\mu \to \nu_\mu$ channel) performed by the accelerator LBL experiment MINOS[10], while the mixing θ_{23} is still better constrained by atmospheric neutrino data. Our global analysis[8] provides the allowed ranges (at the 2σ level),

$$\Delta m^2 = 2.39\,(1^{+0.113}_{-0.084}) \times 10^{-3}\ \mathrm{eV}^2\ , \tag{3}$$

$$\sin^2\theta_{23} \quad = \quad 0.466\,(1^{+0.292}_{-0.215})\ . \tag{4}$$

In comparison with our previous estimates [9], the 2σ error on Δm^2 is reduced from $\sim 15\%$ to $\sim 10\%$, due to the latest MINOS results. It seems reasonable to expect that MINOS will appreciably reduce the uncertainty of *both* parameters starting form the next data release.

3 Hints of $\theta_{13} > 0$

The mixing angle θ_{13}, if different from zero, plays a subdominant role in each of the two sectors considered above, thus providing the main connection among them. In the following we discuss in detail the implications of the latest neutrino data for this parameter.

3.1 Atmospheric data

In [11] we pointed out a weak preference of atmospheric neutrino data[b] (in combination with CHOOZ) for a non-zero value of θ_{13}. We traced a possible source for this preference in subleading 3ν oscillation terms driven by the "solar parameters" [16,17], which could partly explain the observed excess of sub-GeV atmospheric electron-like events. We find such a hint unaltered after combination with current (disappearance) LBL accelerator neutrino data, which are not sufficiently sensitive to θ_{13} [9]. In particular, after inclusion of the latest MINOS (disappearance) data [10], and marginalizing over the leading mass-mixing parameters $(\Delta m^2, \sin^2\theta_{23})$, we still find a $\sim 0.9\sigma$ hint of $\theta_{13} > 0$ from the combination of atmospheric, LBL accelerator (disappearance), and CHOOZ data,

$$\sin^2\theta_{13} = 0.012 \pm 0.013 \quad [1\sigma,\ \mathrm{Atm} + \mathrm{LBL(disapp.)} + \mathrm{CHOOZ}] \tag{5}$$

where the error scales almost linearly up to $\sim 3\sigma$, within the physical range $\sin^2\theta_{13} \geq 0$ (see the magenta long-dashed curve in Fig. 3).

3.2 Solar and KamLAND data

In the past, the previous hint for $\theta_{13} > 0$ was not corroborated by solar and KamLAND data, which preferred $\theta_{13} \simeq 0$ at best fit, both separately and in combination. This trend has recently changed, however, as a consequence of the 2008 data released by KamLAND [7] which, as noted in [18], as well as in [19], prefer values of the mixing angle θ_{12} somewhat higher than those indicated by solar data (and especially by the SNO experiment). As stressed in [18,19], this tension could be alleviated for $\theta_{13} > 0$, as a result of the different dependence of the survival probability $P_{ee} = P(\nu_e \to \nu_e)$ on the mixing angles in KamLAND and SNO, respectively.

In [18] we also remarked that such a preference, although rather small at that time ($\sim 0.5\sigma$), could be potentially corroborated by new solar neutrino data. This has indeed been the case after the inclusion of the new SNO-III data [4], as pointed out in [3].

Figure 1 shows the regions allowed by our current analysis of solar (S) and KamLAND (K) neutrino data, for both $\sin^2\theta_{13} = 0$ (left panel) and a representative non-zero value, $\sin^2\theta_{13} = 0.03$ (right panel). A comparison of the two panels shows that the S and K best-fit regions tend to merge as $\sin^2\theta_{13}$ increases (up to values of few percent).

Figure 2 (left panel) shows again the regions separately allowed from S and K data, but now in the plane spanned by the mixing parameters $(\sin^2\theta_{12}, \sin^2\theta_{13})$. Here the δm^2 parameter is marginalized away in the KamLAND preferred region, which is equivalent, in practice, to set δm^2 at its best fit value. The mixing parameters are positively and negatively correlated

[b] Other atmospheric ν analyses as in [12,13] have found no or weaker hint. An indication for non-zero θ_{13} is instead supported in [14,15].

in the solar and KamLAND regions, respectively, as a result of different functional forms for $P_{ee}(\sin^2\theta_{12}, \sin^2\theta_{13})$ in the two cases. The S and K allowed regions, which do not overlap at 1σ for $\theta_{13} = 0$, merge for $\sin^2\theta_{13} \sim$ few $\times 10^{-2}$. The best fit (dot) and error ellipses for the solar+KamLAND combination are shown in the middle panel of Fig. 2. A hint of $\theta_{13} > 0$ emerges at $\sim 1.2\sigma$ level,

$$\sin^2\theta_{13} = 0.021 \pm 0.017 \ (1\sigma, \ \text{Solar} + \text{KamLAND}) \ , \tag{6}$$

with errors scaling linearly, to a good approximation, up to $\sim 3\sigma$ (see the green short-dashed curve in Fig. 3).

3.3 Combination

The right panel in Fig. 2 shows the 1σ and 2σ error ellipses in the ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$) plane from the fit to all data. The hint of $\theta_{13} > 0$ is reinforced in the combination, with an overall preference emerging at the level of $\sim 1.6\sigma$ ($\sim$90% C.L) [3]:

$$\sin^2\theta_{13} = 0.016 \pm 0.010 \ \ (1\sigma, \ \text{all data 2008}) \ , \tag{7}$$

with linearly scaling errors (see the black solid curve in Fig. 3).

Figure 3 summarizes the bounds we obtain on θ_{13} using different data sets. Note that the preference for nonzero θ_{13} does not emerge significantly from solar and KamLAND data *taken separately*, but rather from *their combination*, which is sensitive to the different (θ_{13}, θ_{12}) dependence of the ν_e survival probability in matter (high-energy solar neutrinos) and vacuum (KamLAND neutrinos). We remark that, as already stressed in [20], a preference for nonzero θ_{13} might also emerge from future solar neutrinos *alone*, by contrasting accurate data at low-energy and high-energy, sensitive to (averaged) vacuum and matter oscillations, respectively. In this respect, present (Borexino) and future low-energy experiments could play an important role.

3.4 A new hint from MINOS?

The first MINOS data in the $\nu_\mu \to \nu_e$ appearance channel have been presented[2] few days before this conference. A weak preference (90% C.L.) for $\theta_{13} > 0$ emerges from the analysis. Although, very prudently, the collaboration does not emphasize this fact, a combination of their results with ours enhances the statistical significance of the global hint. Including the new MINOS results, we estimate

$$\sin^2\theta_{13} = 0.02 \pm 0.01 \ \ (1\sigma, \ \text{all data 2009}) \ , \tag{8}$$

with the global hint now reaching the interesting level of 2 sigma (95% C.L.)

4 Conclusions

The latest neutrino data have contributed to increase our knowledge of neutrino properties. Notably, they have disclosed the opportunity to probe (at an interesting C.L. of 95%) the unknown mixing angle θ_{13}. This indication is especially interesting, because a nonnegligible value of θ_{13} is required for successful CP violation searches in the lepton sector. Lest we be tempted to overestimate the significance of such a weak indication it is salutary to remark that only future data will tell us if the present hints are heralding an emergent signal or they are a mere statistical fluctuation. In this respect, our findings are even more interesting, as they will be subject to direct verification in the near future. Indeed, further accelerator measurements in the $\nu_\mu \to \nu_e$ appearance channel, as well as dedicated reactor experiments in the $\nu_e \to \nu_e$ disappearance channel, are expected to provide new relevant information.

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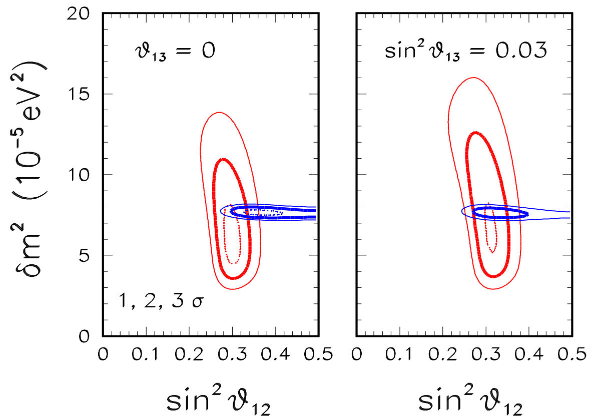

Figure 1: Comparison of the regions allowed by solar and KamLAND data for two fixed values of θ_{13}.

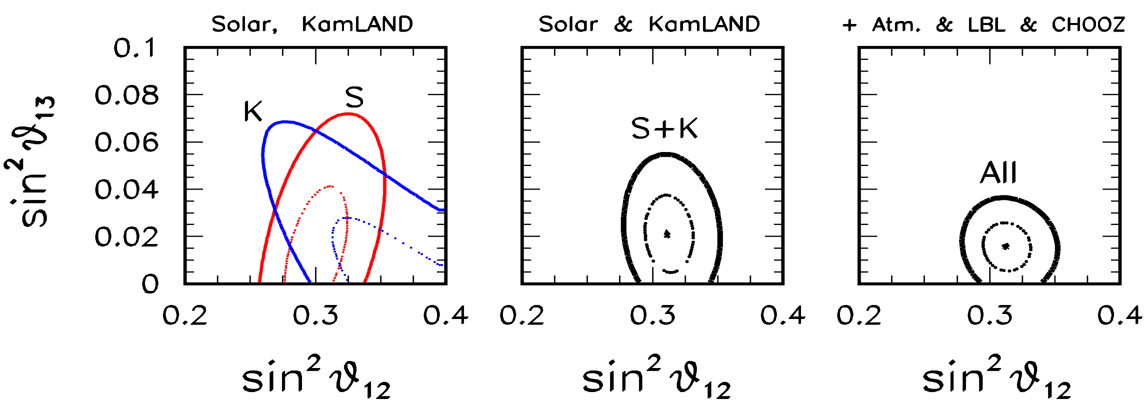

Figure 2: Allowed regions in the plane ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$): contours at 1σ (dotted) and 2σ (solid). Left and middle panels: solar (S) and KamLAND (K) data, separately (left) and in combination (middle). In the left panel, the S contours are obtained by marginalizing the δm^2 parameter as constrained by KamLAND. Right panel: All data.

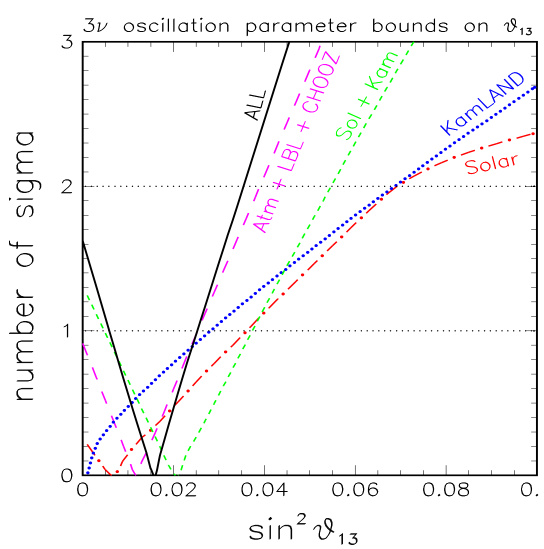

Figure 3: Bounds on θ_{13} obtained using different data sets.