Probing $\theta_{13}$ with global neutrino data analysis

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Abstract. We discuss the results of an updated global analysis of neutrino oscillation data, focusing on the determination of $\theta_{13}$, the smallest and unknown leptonic mixing angle. We discuss three independent and converging hints of $\theta_{13} > 0$: a first one coming from atmospheric neutrino data; a second one from the combination of solar and long-baseline reactor (KamLAND) neutrino data; and a third one from the latest MINOS measurements in the appearance ($\nu_\mu \rightarrow \nu_e$) channel. Their combination provides an indication for $\theta_{13} > 0$ at the $2\sigma$ (95% C.L.) level.

1. Introduction
The measurement of the third unknown leptonic mixing angle $\theta_{13}$ is a crucial step towards the possible discovery of CP violation in the leptonic sector. The first robust upper bound on this fundamental parameter was established by the CHOOZ reactor experiment [1] in 1998. In the last decade this bound has been corroborated and strengthened by the increasingly refined global neutrino data analyses performed by various groups. The past year (2008), however, for the first time, the world neutrino data have shown an intriguing preference for a non-zero value of $\theta_{13}$ at a non-negligible statistical level [2]. Remarkably, an analogous hint has emerged in the first searches of $\nu_e$ appearance in MINOS [3], reinforcing the statistical significance of the global indication for non-zero $\theta_{13}$, now at the 95% C.L. In the following we review the current status of these weak, but intriguing, indications.

2. The hint from the “atmospheric sector”
In [4] we pointed out a weak preference of atmospheric neutrino data (in combination with CHOOZ) for a non-zero value of $\theta_{13}$. We traced a possible source for this preference in subleading $3\nu$ oscillation terms driven by the “solar parameters” [5, 6], 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 $\theta_{13}$ [7]. In particular, after inclusion of the latest MINOS (disappearance) data [8], and marginalizing over the leading mass-mixing parameters ($\Delta m^2, \theta_{23}$), we still find a $\sim 0.9\sigma$ hint of $\theta_{13} > 0$ from the combination of atmospheric, LBL accelerator (disappearance),
and CHOOZ data,
\[
\sin^2 \theta_{13} = 0.012 \pm 0.013 \quad [1\sigma, \text{ Atm + LBL(disapp.) + CHOOZ}]
\]
where the error scales almost linearly up to \(\sim 3\sigma\), within the physical range \(\sin^2 \theta_{13} \geq 0\). A similar hint has been found in [9, 10], but not in [11, 12]. Given the slight disagreement among equally refined analyses, we deem that only a complete 3-flavor analysis (including the subleading effects induced by the solar parameters) performed by the Super-Kamiokande collaboration can add further relevant information on the issue.

3. The hint from the “solar sector”
As noticed in [13], as well as in [14], the latest KamLAND data [15] prefer values of the mixing angle \(\theta_{12}\) somewhat higher than those indicated by solar data. As stressed in [13, 14], 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 [13] 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 trend has indeed been reinforced by the SNO-III data [16], whose inclusion leads to a hint of \(\theta_{13} > 0\) at the \(\sim 1.2\sigma\) level [2],
\[
\sin^2 \theta_{13} = 0.021 \pm 0.017 \quad (1\sigma, \text{ Solar + KamLAND})
\]
with errors scaling linearly, to a good approximation, up to \(\sim 3\sigma\).

It must be stressed that such a hint arises from a disagreement in the comparison of matter dominated transitions (solar \(\nu\)'s) with vacuum-like oscillations (KamLAND), which, in principle may be due to some unaccounted effect in the propagation of solar neutrinos in the Sun. One such an example is offered by non-standard interactions (NSI), recently investigated in [17], which can mimic the values of \(\theta_{13} > 0\) indicated by the fit. This circumstance, underlines the importance of future reactor searches, which are unaffected by matter effects.

4. The hint from MINOS and the global combination
The first MINOS data in the \(\nu_{\mu} \to \nu_e\) appearance channel [3] have shown a weak preference (90% C.L.) for \(\theta_{13} > 0\). Although, very prudently, the collaboration did not emphasize this fact, a combination of their results with ours enhances the statistical significance of the global hint. Indeed, from the combination of the solar and atmospheric data, without the appearance MINOS results, we find a hint [2], at the 90% C.L.,
\[
\sin^2 \theta_{13} = 0.016 \pm 0.010 \quad (1\sigma, \text{ all data 2008})
\]
which, after inclusion of the MINOS result becomes [2],
\[
\sin^2 \theta_{13} = 0.02 \pm 0.01 \quad (1\sigma, \text{ all data 2009})
\]
implying an overall preference at the level of \(\sim 2\sigma\) (95% C.L.). Figure 1 summarizes the hints we obtain using different data sets and their combinations.

5. Conclusions
The latest neutrino data have disclosed the opportunity to probe the unknown mixing angle \(\theta_{13}\), showing an interesting preference for a nonzero value of this parameter which lies just below the CHOOZ upper limit. At the time of writing these proceedings, new relevant information has become available from the low energy threshold analysis (LETA) performed by the SNO collaboration [18], whose results confirm the trend for a preference for \(\theta_{13} > 0\) in the solar sector.
The MINOS appearance results with doubled statistics are expected soon and will add further information. However, it is difficult that they can change substantially the statistical level of the present global indication, which will likely remain with us until the direct (dis-)confirmation by the new dedicated reactor experiments. The strength of these new experiments relies also in the fact that their inference of $\theta_{13}$ is unaffected by (standard and/or non-standard) matter effects, which instead can alter the indirect inferences of the global analyses [17].

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