Hints of $\theta_{13} > 0$ from Global Neutrino Data Analysis

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Nailing down the unknown neutrino mixing angle θ_{13} is one of the most important goals in current lepton physics. In this context, we perform a global analysis of neutrino oscillation data, focusing on θ_{13}, and including recent results [*Neutrino 2008, Proceedings of the XXIII International Conference on Neutrino Physics and Astrophysics, Christchurch, New Zealand, 2008* (unpublished)]. We discuss two converging hints of $\theta_{13} > 0$, each at the level of $\sim 1\sigma$: an older one coming from atmospheric neutrino data, and a newer one coming from the combination of solar and long-baseline reactor neutrino data. Their combination provides the global estimate $\sin^2\theta_{13} = 0.016 \pm 0.010 (1\sigma)$, implying a preference for $\theta_{13} > 0$ with non-negligible statistical significance ($\sim 90\%$ C.L.). We discuss possible refinements of the experimental data analyses, which might sharpen such intriguing indications.

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Introduction.—In the last decade, it has been established that the neutrino states (ν_e, ν_μ, ν_τ) with definite flavor are quantum superpositions of states (ν_1, ν_2, ν_3) with definite masses (m_1, m_2, m_3) [1]. These findings point towards new physics in the lepton sector, probably originating at very high mass scales [2].

Independently of the origin of neutrino masses and mixing, oscillation data can be accommodated in a simple theoretical framework (adopted hereafter), where flavor and mass states are connected by a unitary mixing matrix U, parametrized in terms of three mixing angles (θ_{12}, θ_{13}, θ_{23}) and one CP-violating phase δ [1]. The mass spectrum gaps can be parametrized in terms of $\delta m^2 = m_2^2 - m_1^2$ and of $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ [3].

Within this framework, the mass-mixing oscillation parameters (δm^2, $\sin^2\theta_{12}$) and (Δm^2, $\sin^2\theta_{23}$) are rather well determined [3]. Conversely, only upper bounds could be placed so far on $\sin^2\theta_{13}$, a dominant role being played by the null results of the short-baseline CHOOZ reactor experiment [4] ($\sin^2\theta_{13} \lesssim$ few%).

Determining a lower bound for θ_{13} (unless $\theta_{13} \equiv 0$ for some unknown reason) is widely recognized as a step of paramount importance in experimental and theoretical neutrino physics [1,2]. Indeed, any future investigation of leptonic CP violation (i.e., of δ), and of the neutrino mass spectrum hierarchy [i.e., of sgn(Δm^2)] crucially depends on finding a nonzero value for θ_{13}. A worldwide program of direct θ_{13} measurements with reactor and accelerator neutrinos is in progress, as recently reviewed, e.g., at the recent *Neutrino 2008* Conference [5].

In this context, any indirect indication in favor of $\theta_{13} > 0$ becomes highly valuable as a target for direct searches. We report here two indirect, independent hints of $\theta_{13} > 0$, one coming from older atmospheric neutrino data, and one from the combination of recent solar and long-baseline reactor data, as obtained by a global analysis of world oscillation searches. For the first time, these hints add up to an overall indication in favor of $\theta_{13} > 0$ at non-negligible confidence level of $\sim 90\%$.

Hint from atmospheric neutrino data.—In a previous analysis of world neutrino oscillation data [3], we found a weak hint in favor of $\theta_{13} > 0$, at the level of $\sim 0.9\sigma$, coming from atmospheric neutrino data combined with accelerator and CHOOZ data (see Figs. 26 and 27 in [3]). We traced its origin in subleading 3ν oscillation terms driven by δm^2 [6], which are most effective at $\cos\delta = -1$ (see Fig. 24 in [3]), and which could partly explain the observed excess of sub-GeV atmospheric electronlike events [7]. Such hint has persisted after combination with further long-baseline (LBL) accelerator neutrino data [8,9], which have not yet placed strong constraints to ν_e appearance. In particular, after including the Main Injector Neutrino Oscillation Search (MINOS) data [10] presented at *Neutrino 2008* [11], and marginalizing over the leading mass-mixing parameters (Δm^2, $\sin^2\theta_{23}$) we still find a $\sim 0.9\sigma$ hint of $\theta_{13} > 0$ from the current combination of atmospheric, LBL accelerator, and CHOOZ data,

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

where the error scales almost linearly up to $\sim 3\sigma$, within the physical range $\sin^2\theta_{13} \geq 0$.

Hint from solar and KamLAND data.—In past years, the above "atmospheric ν hint" was not supported by independent long-baseline reactor and solar neutrino data, which systematically preferred $\theta_{13} = 0$ as best fit, both separately and in combination [3]. Therefore, in the global

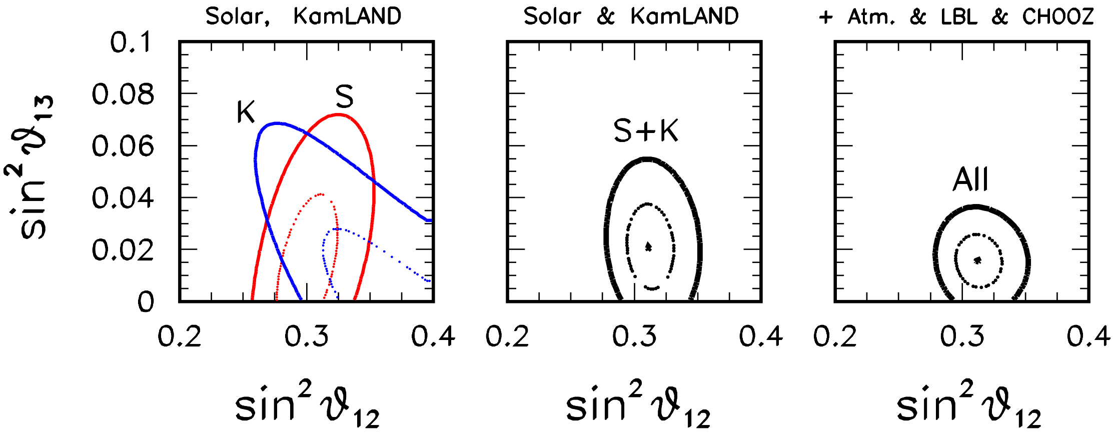

FIG. 1 (color online). Allowed regions in the plane ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$): contours at 1σ (dotted) and 2σ (solid). Left and middle panels: solar (S) and KamLAND (K) data, both separately (left) and in combination (middle). In the left panel, the S contours are obtained by marginalizing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

data analysis, the hint of $\theta_{13} > 0$ was diluted well below 1σ, and could be conservatively ignored [3].

Such a trend has recently changed, however, after the latest data release from the Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) [12], which favors slightly higher values of $\sin^2\theta_{12}$, as compared to solar neutrino data [13] at fixed $\theta_{13} = 0$. As discussed in [14], and soon after in [15], this small difference in $\sin^2\theta_{12}$ can be reduced for $\theta_{13} > 0$, due to the different dependence of the survival probability $P_{ee} = P(\nu_e \to \nu_e)$ on the parameters (θ_{12}, θ_{13}) for solar and KamLAND neutrinos [16]. Indeed, recent combinations of solar and KamLAND data prefer $\theta_{13} > 0$, although weakly [14,15,17].

Remarkably, the recent data from the third and latest phase of the Sudbury Neutrino Observatory (SNO) [18] presented at *Neutrino 2008* [19] further reduce the solar neutrino range for $\sin^2\theta_{12}$ and, in combination with KamLAND data, are thus expected to strengthen such independent hint in favor of $\theta_{13} > 0$. We include SNO-III data in the form of two new integral determinations of the charged-current (CC) and neutral current (NC) event rates [18], with error correlation $\rho \simeq -0.15$ inferred from the quoted CC/NC ratio error [18], but neglecting possible (so far unpublished) correlations with previous SNO data [13]. We ignore the SNO-III elastic scattering (ES) event rate [20], which appears to be affected by statistical fluctuations [18,19] and which is, in any case, much less accurate than the solar neutrino ES rate measured by Super-Kamiokande [21].

In the solar neutrino analysis, we update the total Gallium rate (66.8 ± 3.5 SNU) [22] to account for a recent reevaluation of the GALLEX data [23,24]. The latest Borexino data [25,26], presented at *Neutrino 2008* [27], are also included for the sake of completeness. We do not include the Super-Kamiokande phase-II results [28], which would not provide significant additional constraints. Finally, concerning KamLAND, we analyze the full spectrum reported in [12], and marginalize away the low-energy geoneutrino fluxes from U and Th decay in the fit. We have checked that our results agree well with the published ones (in the case $\theta_{13} = 0$) both on the oscillation parameters (δm^2, $\sin^2\theta_{12}$) and on the estimated geo-ν fluxes [29].

Figure 1 (left panel) shows the regions separately allowed at 1σ ($\Delta\chi^2 = 1$, dotted) and 2σ ($\Delta\chi^2 = 4$, solid) from the analysis of solar (S) and KamLAND (K) neutrino data, in the plane spanned by the mixing parameters ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$). The δm^2 parameter is always marginalized away in the KamLAND preferred region (which is equivalent, in practice, to set δm^2 at its best-fit value 7.67×10^{-5} eV^2). The mixing parameters are positively and negatively correlated 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 $\sin^2\theta_{13} = 0$, merge for $\sin^2\theta_{13} \sim$ few $\times 10^{-2}$. The best-fit (dot) and error ellipses (in black) for the solar + KamLAND combination are shown in the middle panel of Fig. 1. A hint of $\theta_{13} > 0$ emerges at $\sim 1.2\sigma$ level,

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

with errors scaling linearly, to a good approximation, up to $\sim 3\sigma$.

Combination.—We have found two independent hints of $\theta_{13} > 0$, each at a level of $\sim 1\sigma$, and with mutually consistent ranges for $\sin^2\theta_{13}$. Their combination reinforces the overall preference for $\theta_{13} > 0$, which emerges at the level of $\sim 1.6\sigma$ in our global analysis. In particular, Fig. 1 (right panel) shows the 1σ and 2σ error ellipses in the ($\sin^2\theta_{12}$, $\sin^2\theta_{13}$) plane from the fit to all data, which summarizes our current knowledge of electron neutrino mixing [30]. Marginalizing the $\sin^2\theta_{12}$ parameter we get

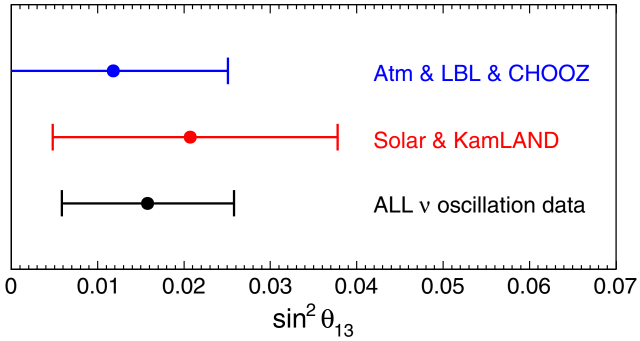

FIG. 2 (color online). Global ν oscillation analysis: Allowed 1σ ranges of $\sin^2\theta_{13}$ from different input data.

$$\sin^2\theta_{13} = 0.016 \pm 0.010 \qquad (1\sigma,\ \text{all oscillation data}), \tag{3}$$

with linearly scaling errors. This is the most important result of our work. Allowed ranges for other oscillation parameters are reported separately [31]. Summarizing, we find an overall preference for $\theta_{13} > 0$ at $\sim 1.6\sigma$ or, equivalently, at ~90% C.L., from a global analysis of neutrino oscillation data, as available after the *Neutrino 2008* Conference. The preferred 1σ ranges are summarized in Eqs. (1)–(3), and are graphically displayed in Fig. 2.

Conclusions and prospects.—In this Letter, we have focused on the last unknown neutrino mixing angle θ_{13}. Within a global analysis of world neutrino oscillation data, we have discussed two hints in favor of $\theta_{13} > 0$, each at the level of $\sim 1\sigma$. Their combination provides an overall indication for $\theta_{13} > 0$ at a non-negligible 90% confidence level. To some extent, the present hints of $\theta_{13} > 0$ can be corroborated by more refined analyses. Concerning atmospheric neutrinos, an official, complete 3ν analysis by the Super-Kamiokande collaboration, including all experimental details, would be very important. The analysis should include δm^2-driven terms in the oscillation probability [32,33], which have been neglected in the official publication [34]. Concerning solar neutrinos, a detailed, fully documented and official combination of all the SNO-I, II, and III data [35] would be helpful to sharpen the bounds on solar ν_e mixing and to contrast them with (future) KamLAND data. The latter would benefit by a further reduction of the normalization error, which is directly transferred to the mixing parameters. In our opinion, such improvements might corroborate the statistical significance of the previous hints by another $\sim 1\sigma$ but, of course, could not replace direct experimental searches for θ_{13} at reactors or accelerators. Two hints make for a stronger indication, but do not make for a compelling proof.

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