PHYSICAL REVIEW D **69**, 017301 (2004)

Addendum to "Solar neutrino oscillation parameters after first KamLAND results"

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(Received 6 August 2003; published 13 January 2004)

In a previous paper, we presented a three-flavor oscillation analysis of the solar neutrino measurements and of the first data from the KamLAND experiment, in terms of the relevant mass-mixing parameters $(\delta m^2, \theta_{12}, \theta_{13})$. The analysis, performed by including the terrestrial neutrino constraints coming from the CHOOZ (reactor), KEK-to-Kamioka (K2K, accelerator), and Super-Kamiokande (SK, atmospheric) experiments, provided a stringent upper limit on θ_{13}, namely, $\sin^2\theta_{13} < 0.05$ at 3σ. We reexamine such an upper bound in light of a recent (although preliminary) reanalysis of atmospheric neutrino data performed by the SK Collaboration, which seems to shift the preferred value of the largest neutrino square mass difference Δm^2 downwards. By taking the results of the SK official reanalysis at face value, and by repeating the analysis of our previous paper with such new input, we find that the upper bound on θ_{13} is somewhat relaxed: $\sin^2\theta_{13} < 0.067$ at 3σ. Related phenomenological issues are briefly discussed.

DOI: 10.1103/PhysRevD.69.017301 PACS number(s): 26.65.+t, 13.15.+g, 14.60.Pq, 91.35.−x

In a previous paper [1], we presented a three-flavor oscillation analysis of data from KamLAND [2] and solar [3] neutrino experiments, in terms of the three mass-mixing parameters relevant for this data set: namely, the smallest square mass difference $(\delta m^2 = m_2^2 - m_1^2)$, and the two mixing angles between the first and the other two neutrino generations (θ_{12} and θ_{13} in standard notation [4]). The analysis included also the constraints coming from the following terrestrial neutrino experiments: CHOOZ (reactor) [5], KEK-to-Kamioka (K2K, accelerator) [6], and Super-Kamiokande (SK, atmospheric) [7]. In particular, an approximate SK +K2K data combination [8] was used to constrain the largest neutrino square mass difference: $\Delta m^2 = (2.7 \pm 0.4) \times 10^{-3}$ eV^2 (1σ) [8]. The parameter Δm^2 was then marginalized away in the 3ν analysis of the CHOOZ spectral data [1,8], which depends on the four parameters $(\Delta m^2, \delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$ [9].

Our summary of the constraints on the 3ν parameters $(\delta m^2, \sin^2\theta_{12}, \sin^2\theta_{23})$ was given in Fig. 9 of Ref. [1], in terms of the projected $\Delta\chi^2$ functions of the global (solar +terrestrial) data fit. The same functions are reported, for the sake of completeness, in Fig. 1 (solid curves). In particular, the following upper bound was obtained on the mixing angle θ_{13} [1]:

$$\sin^2\theta_{13} < 0.05 \quad (3\sigma, \ \text{all data}). \tag{1}$$

After Ref. [1], a thorough analysis [10] of the first K2K spectral data [6] has provided, in combination with SK atmospheric neutrino data [7], a more reliable and accurate estimate of the Δm^2 range [10]:

$$\Delta m^2 = (2.6 \pm 0.4) \times 10^{-3} \ \text{eV}^2 \quad (1\sigma, \text{SK+K2K}). \tag{2}$$

A very similar range has been found in a recent, independent analysis of SK+K2K data [11]. However, the mere decrease of the Δm^2 best-fit value from 2.7 [8] to 2.6 [10,11] (in units of 10^{-3} eV^2) does not induce any perceptible change in the results summarized in Fig. 9 of Ref. [1]. A non-negligible change can be instead induced by a more substantial decrease of Δm^2, as possibly indicated by a new SK data reanalysis [12].

The SK Collaboration has recently presented the preliminary results of a global reanalysis of the previous atmospheric neutrino data (no new data included), which incorporates improvements or changes of various basic ingredients, such as the neutrino interaction simulator, the inner and outer detector simulators, the data reduction process, the event reconstruction algorithm, and the input atmospheric neutrino fluxes [12]. It is claimed that each change slightly shifts the Δm^2 allowed region to lower values, the final best-fit value being $\Delta m^2 = 2 \times 10^{-3}$ eV^2 [12], i.e., 1.5σ below the central value in Eq. (2).

At present, we cannot recover from Ref. [12] enough information to implement the above variations in a thorough, *ab initio* analysis of the SK atmospheric data, and thus we cannot independently check the above claim. However, it is tempting to study, at least in a first approximation, the implications of relatively low Δm^2 values [12] on our previous 3ν analysis [1]. In particular, it is immediate to recognize that a significant downward shift of Δm^2 weakens the upper bound on $\sin^2\theta_{13}$ coming from the CHOOZ data [5]. Since the parameter $\sin^2\theta_{13}$ has an enormous impact on basically all aspects of current and future neutrino phenomenology, we think it useful to reexamine its previous probability distribution [1] in light of the preliminary SK revised results [12].

To this purpose, we derive an approximate $\chi^2_{\mathrm{SK}'}(\Delta m^2)$ function through graphical reduction of the SK mass-mixing parameter fit in Ref. [12], and combine it with our (unaltered) $\chi^2_{\mathrm{K2K}}(\Delta m^2)$ function from the K2K spectral analysis in Ref. [10]. We obtain then the following "revised" estimate for Δm^2,

$$\Delta m^2 = (2.0^{+0.4}_{-0.3}) \times 10^{-3} \ \text{eV}^2 \ (1\sigma, \ \mathrm{SK}' + \mathrm{K2K}), \tag{3}$$

where the errors, although asymmetric, turn out to scale lin-

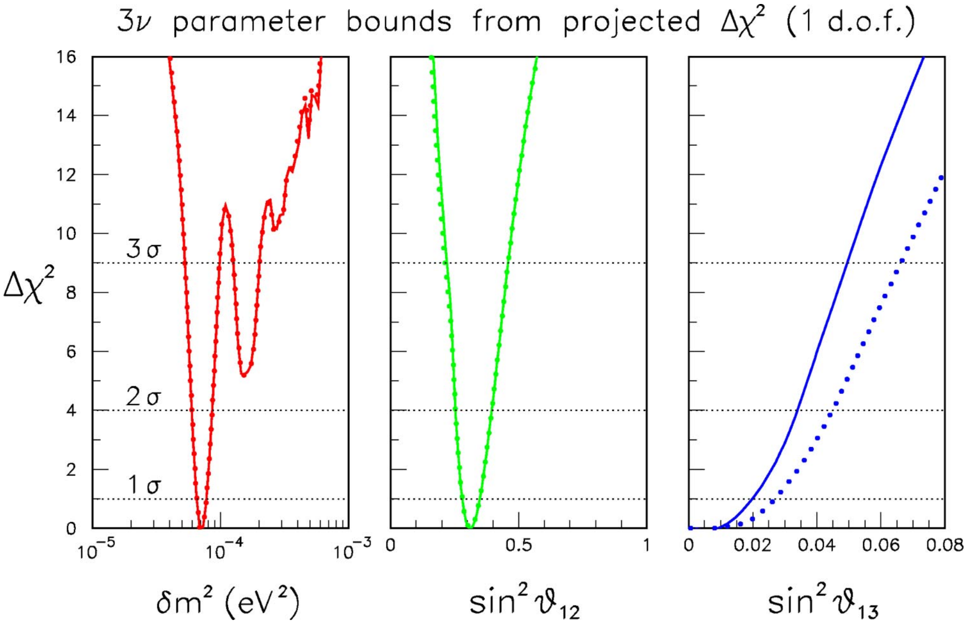

FIG. 1. Three-flavor neutrino oscillations: Projections of the global $\Delta\chi^2$ functions onto each of the $(\delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$ parameters. The *n*-sigma bounds on each parameter (the others being unconstrained) correspond to $\Delta\chi^2 = n^2$. The solid curves show the results of our previous analysis (see Fig. 9 in Ref. [1]). The dotted curves show the effect of the Δm^2 estimate in Eq. (3), which includes the revised SK atmospheric neutrino results from Ref. [12]. No significant change is seen in the fit to δm^2 and $\sin^2\theta_{12}$. Conversely, the fit to the $\sin^2\theta_{13}$ parameter becomes less constraining, the 3σ upper bound being increased from 0.05 to 0.067.

early up to $\sim 3\sigma$.[1] Notice that the above estimate is compatible with the Δm^2 ranges independently preferred by the final analyses of the MACRO [13] and Soudan 2 [14] atmospheric neutrino experiments.

Assuming the Δm^2 input from Eq. (3), we proceed to perform the global 3ν fit as in Ref. [1], all other phenomenological inputs being unchanged. The results are shown in Fig. 1 (dotted curves). As compared with the previous results [1] (solid curves), no noticeable change is seen in the fit to the leading solar ν parameters δm^2 and $\sin^2\theta_{12}$ (left and middle panel in Fig. 1). The constraints on $\sin^2\theta_{13}$ are instead somewhat relaxed, as expected. In particular, the intercept of the line at $\Delta\chi^2 = 9$ with the dotted curve in the right panel of Fig. 1 provides the ''revised'' 3σ upper bound on $\sin^2\theta_{13}$,

$$\sin^2\theta_{13} < 0.067 \quad (3\sigma, \ \text{all data}), \tag{4}$$

to be compared with the previous one in Eq. (1). Essentially, the main effect of the ''revised'' SK atmospheric neutrino results [12] consists in enlarging the upper bounds on $\sin^2\theta_{13}$ by a factor ~ 1.3 at any C.L. This is the main result of our Addendum.

We conclude with a few qualitative comments on possible phenomenological implications of the relatively ''low'' Δm^2 in Eq. (3) and of the relatively ''weak'' upper bound on $\sin^2\theta_{13}$ in Eq. (4). Concerning a long-baseline accelerator experiment, an increase in the upper limit on $\sin^2\theta_{13}$ may, in general, enlarge the discovery potential in the $\nu_\mu \to \nu_e$ channel. On the other hand, low values of Δm^2 imply small $\nu_\mu \to \nu_\tau$ appearance rates $[\propto(\Delta m^2)^2]$ in the same class of experiments. Weakening the bounds on $\sin^2\theta_{13}$ might also weaken future KamLAND limits on θ_{12} (when they will become competitive with solar neutrino limits), since variations of $\sin^2\theta_{12}$ can be partly traded for variations of $\sin^2\theta_{13}$ (both affecting the KamLAND event rate in a similar way). Uncertainties on the mixing angles may then affect other observables, e.g., the effective Majorana mass in neutrinoless double beta decay. Concerning atmospheric neutrinos, low values of Δm^2 and relatively high values of $\sin^2\theta_{13}$ can make subleading 3ν effects somewhat more important. In particular, if the best-fit value of δm^2 in Fig. 1 would increase with future KamLAND data, then atmospheric neutrino analyses at zeroth order in $\delta m^2/\Delta m^2$ might need an upgrade to include higher-order effects. Of course, none of the above effects can be large enough to change significantly the overall picture of the 3ν oscillation phenomenology. However, current or predicted ranges for several parameters and observables might need small readjustments, should the revised SK atmospheric neutrino analysis in Ref. [12] and the Δm^2 estimate in Eq. (3) be basically confirmed by more detailed studies: The ''revised'' upper limit on $\sin^2\theta_{13}$ in Eq. (4) is just one relevant example.

This work was in part supported by the Italian Ministero dell'Istruzione, Università e Ricerca (MIUR) and Istituto Nazionale di Fisica Nucleare (INFN) within the ''Astroparticle Physics'' research project.

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[1] In other words, the function $\chi^2_{\mathrm{SK'+K2K}}$ is well approximated by two half-parabolae. The SK′ label indicates that we are using here the ''revised'' Super-Kamiokande results from Ref. [12].

[1] G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, and A.M. Rotunno, Phys. Rev. D **67**, 073002 (2003).

[2] KamLAND Collaboration, K. Eguchi *et al.*, Phys. Rev. Lett. **90**, 021802 (2003).

[3] Homestake Collaboration, B.T. Cleveland, T. Daily, R. Davis, Jr., J.R. Distel, K. Lande, C.K. Lee, P.S. Wildenhain, and J. Ullman, Astrophys. J. **496**, 505 (1998); SAGE Collaboration, J.N. Abdurashitov *et al.*, Zh. Eksp. Teor. Fiz. **95**, 211 (2002)

[J. Expt. Theor. Fiz. **95**, 181 (2002)]; GNO Collaboration, T.A. Kirsten *et al.*, in *Proceedings of Neutrino 2002*, 20th International Conference on Neutrino Physics and Astrophysics (Munich, Germany, 2002), edited by F. von Feilitzsch and N. Schmitz [Nucl. Phys. B (Proc. Suppl.) **118**, 33 (2003)]; Super-Kamiokande Collaboration, S. Fukuda *et al.*, Phys. Lett. B **539**, 179 (2002); SNO Collaboration, Q.R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011302 (2002). Solar neutrino fluxes are from J.N. Bahcall, M.H. Pinsonneault, and S. Basu, Astrophys. J. **555**, 990 (2001).

[4] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[5] CHOOZ Collaboration, M. Apollonio *et al.*, Phys. Lett. B **466**, 415 (1999); Eur. Phys. J. C **27**, 331 (2003).

[6] K2K Collaboration, M.H. Ahn *et al.*, Phys. Rev. Lett. **90**, 041801 (2003).

[7] E.T. Kearns, in *Proceedings of the 6th International Workshop on Heavy Quarks and Leptons* (Vietri sul Mare, Salerno, Italy, 2002) [Frascati Phys. Ser., **28**, 413 (2002)], hep-ex/0210019.

[8] G.L. Fogli, G. Lettera, E. Lisi, A. Marrone, A. Palazzo, and A.M. Rotunno, Phys. Rev. D **66**, 093008 (2002).

[9] G.L. Fogli, E. Lisi, and A. Palazzo, Phys. Rev. D **65**, 073019 (2002).

[10] G.L. Fogli, E. Lisi, A. Marrone, and D. Montanino, Phys. Rev. D **67**, 093006 (2003).

[11] M.C. Gonzalez-Garcia and C. Pena-Garay, Phys. Rev. D **68**, 093003 (2003).

[12] Y. Hayato, talk at *HEP 2003*, International Europhysics Conference on High Energy Physics (Aachen, Germany, 2003). Website: eps2003.physik.rwth-aachen.de

[13] G. Giacomelli, talk at *HEP 2003* [12].

[14] Soudan 2 Collaboration, M. Sanchez *et al.*, Phys. Rev. D **68**, 113004 (2003).