Global fits to neutrino oscillation data

Thomas Schwetz

Scuola Internazionale Superiore di Studi Avanzati, via Beirut 2–4, 34014 Trieste, Italy

E-mail: schwetz@sissa.it

Received 31 May 2006
Accepted for publication 7 June 2006
Published 1 September 2006
Online at stacks.iop.org/PhysScr/T127/1

Abstract

I summarize the determination of neutrino oscillation parameters within the three-flavour framework from world neutrino oscillation data with a date of May 2006, including the first results from the MINOS long-baseline experiment. It is illustrated how the determination of the leading ‘solar’ and ‘atmospheric’ parameters, as well as the bound on \( \theta_{13} \) emerge from an interplay of various complementary data sets. Furthermore, I discuss possible implications of sub-leading three-flavour effects in present atmospheric neutrino data induced by \( \Delta m_{21}^2 \) and \( \theta_{13} \) for the bound on \( \theta_{13} \) and non-maximal values of \( \theta_{23} \), emphasizing, however, that these effects are not statistically significant at present. Finally, in view of the upcoming MiniBooNE results I briefly comment on the problem to reconcile the LSND signal.

PACS number: 14.60.Pq

(Some figures in this article are in colour only in the electronic version.)

1. Introduction

In the last 10 years or so we have witnessed huge progress in neutrino oscillation physics. The outstanding experimental results lead to quite a clear overall picture of the neutrino sector. We know that there are two mass-squared differences separated roughly by a factor of 30, and in the lepton mixing matrix there are two large mixing angles, and one mixing angle which has to be small. In this paper I review the present status of neutrino oscillations by reporting the results of a global analysis of the latest world neutrino oscillation data from solar [1–3], atmospheric [4, 5], reactor [6, 7], and accelerator [8, 9] experiments, including the recent data from the MINOS long-baseline (LBL) experiment [9]. This analysis is performed in the three-flavour framework and is based on the work published in [10, 11] (see also the hep-ph archive version 5 of [11] for updated results). In section 2 I discuss the determination of the leading ‘solar’ and ‘atmospheric’ parameters, whereas section 3 deals with the bound on \( \theta_{13} \) from global data. The status of three-flavour oscillation parameters is summarized in table 1. In section 4 a discussion of sub-leading effects in atmospheric data is given, and in section 5 I comment on attempts to reconcile the result of the LSND experiment [12] with the global oscillation data.

2. Leading oscillation parameters

In this section I discuss the determination of the leading oscillation parameters, the ‘solar’ parameters \( \theta_{12}, \Delta m_{21}^2 \), and the ‘atmospheric’ parameters \( \theta_{23}, \Delta m_{31}^2 \). In both cases we have an independent confirmation of neutrino oscillations from very different experiments, and the final allowed regions for the oscillation parameters emerge from an interplay of complementary data. The determination of the mixing angle is dominated by experiments with natural neutrino sources (solar and atmospheric neutrinos), whereas the mass-squared differences are more accurately determined by man-made neutrinos (from reactors and accelerators). This complementarity is illustrated in figure 1.

Details of our solar neutrino analysis can be found in [10] and references therein. We use data from the Homestake, SAGE, GNO, and SK experiments [1], and the SNO day-night spectra from the pure D\(_2\)O phase [2], but the CC, NC, and ES rates from the SNO salt-phase are updated according to the latest 2005 data [3]. The predictions for the solar neutrino fluxes are taken from [13]. For the KamLAND analysis we are using the data from [6] equally binned in \( 1/E_{\text{pe}} \) (\( E_{\text{pe}} \) is the prompt energy deposited by the positron), and we include earth matter effects and flux uncertainties following [14] (see the appendix of [11] for further details).

We observe from figure 1 (left) a beautiful agreement of solar and KamLAND data. Moreover, the complementarity of the two data sets allows a rather precise determination of the oscillation parameters. The evidence of spectral distortion in KamLAND data provides a strong constraint on \( \Delta m_{21}^2 \), and leads to the remarkable precision of 4% at...
Figure 1. Determination of the leading oscillation parameters from an interplay of experiments with natural and artificial neutrino sources (left and middle panels). In the right panel the allowed regions are shown with (coloured regions) and without (contour curves) MINOS data. In the left and middle panels the allowed regions are shown at 90% CL (dashed curves) and 99.73% CL (solid curves and shaded regions), whereas in the right panel regions are shown at 90, 95, 99 and 99.73% CL.

**Table 1.** Best fit values (bf), 1σ errors, relative accuracies at 1σ, 2σ and 3σ allowed ranges of three-flavour neutrino oscillation parameters from a combined analysis of global data.

| Parameter | bf±1σ | 1σ acc. | 2σ range | 3σ range |
|-----------|-------|---------|----------|----------|
| \(\Delta m^2_{21}\) [10^{-3} eV^2] | 7.9 ± 0.3 | 4% | 7.3–8.5 | 7.1–8.9 |
| \(\Delta m^2_{12}\) [10^{-3} eV^2] | 2.5^{+0.22}_{−0.25} | 10% | 2.1–3.0 | 1.9–3.2 |
| \(\sin^22\theta_{12}\) | 0.39^{+0.02}_{−0.03} | 9% | 0.26–0.36 | 0.24–0.40 |
| \(\sin^22\theta_{23}\) | 0.50^{+0.08}_{−0.07} | 16% | 0.38–0.64 | 0.34–0.68 |
| \(\sin^22\theta_{13}\) | – | – | \(\leq 0.025\) | \(\leq 0.041\) |

1σ (compare table 1). Alternative solutions around \(\Delta m^2_{21} \sim 2 \times 10^{-4} eV^2\) (\(\sim 1.4 \times 10^{-5} eV^2\)), which are still present in the KamLAND-only analysis at 99% C.L., are ruled out from the combined KamLAND + solar analysis at about 4σ (5σ). In contrast to \(\Delta m^2_{12}\), the determination of the mixing angle is dominated by solar data. Especially recent results from the SNO experiment provide a strong upper bound on \(\sin^2\theta_{12}\), excluding maximal mixing at more than 5σ.

Oscillations with the ‘atmospheric’ parameters \(\theta_{23}\) and \(\Delta m^2_{13}\) have been established by the atmospheric neutrino data of SK [4]. Details of our re-analysis of the SK-I zenith angle distribution data can be found in [11] and references therein. The allowed region is shown in figure 1 (middle). Also in this case, by now we have an independent confirmation of the effect by experiments based on man-made neutrinos, namely the first generation of LBL accelerator experiments exploring the \(v_\mu\) disappearance oscillation channel. In the K2K experiment [8], the neutrino beam is produced at the KEK proton synchrotron, and originally consists of 98% muon neutrinos with a mean energy of 1.3 GeV. The \(v_\mu\) content of the beam is observed at the SK detector at a distance of 250 km. For the K2K-I and K2K-II data (0.89 \(\times 10^{20}\) p.o.t. in total) 107 events have been detected, whereas 151\textsuperscript{±12}\_{\textup{10}} have been expected for no oscillations.

Recently, first data (0.93 \(\times 10^{20}\) p.o.t.) from the MINOS experiment have been released [9]. A neutrino beam with 98.5% \((v_\mu + v_\nu)\) and a mean energy of 3 GeV is produced at Fermilab and observed at the MINOS detector in the Soudan mine at a distance of 735 km. In the absence of oscillations 177 \(\pm 11\) \(v_\mu\) events with \(E < 10\) GeV are expected, whereas 92 have been observed, which provides a 5.0σ evidence for disappearance. In our re-analysis, we use spectral data divided into 15 bins in reconstructed neutrino energy, and our allowed region from MINOS-only is in very good agreement with the official result [9]. The values of the oscillation parameters from MINOS are consistent with the ones from K2K, as well as from SK atmospheric data. The impact of the data from MINOS in the global analysis is illustrated in figure 1 (right). We find that the best fit point for \(\Delta m^2_{13}\) is shifted upward from 2.2 \(\times 10^{-3}\) eV\(^2\) for SK + K2K to 2.5 \(\times 10^{-3}\) eV\(^2\). In addition, MINOS improves the lower bound on \(\Delta m^2_{13}\), which is increased from 1.4 \(\times 10^{-3}\) eV\(^2\) for SK + K2K to 1.9 \(\times 10^{-3}\) eV\(^2\) at 3σ. The relative accuracy on \(\Delta m^2_{13}\) at 1σ is improved from 14 to 10%. As is obvious from the middle panel of figure 1, the determination of \(\theta_{23}\) is completely dominated by atmospheric data and there is no change due to MINOS. Let us add that the present data cannot distinguish between \(\Delta m^2_{31} > 0\) and \(< 0\), and hence, both, the normal and inverted neutrino mass hierarchies provide equally good fits to the data.

3. The bound on \(\theta_{13}\)

Similar to the case of the leading oscillation parameters, the bound on \(\theta_{13}\) also emerges from an interplay of different data sets, as we illustrate in figure 2. An important contribution to the bound comes, of course, from the CHOOZ reactor experiment combined with the determination of \(\Delta m^2_{13}\) from atmospheric and LBL experiments. However, due to a complementarity of low and high energy solar data, as well as solar and KamLAND data also solar + KamLAND provide a non-trivial constraint on \(\theta_{13}\), see e.g. [10, 11, 15]. We find at
90% CL (3σ) the following limits:

\[ \sin^2 \theta_{13} < \begin{cases} 0.027 (0.058) & \text{CHOOZ + atm + LBL,} \\ 0.033 (0.071) & \text{solar + KamLAND,} \\ 0.020 (0.041) & \text{global data.} \end{cases} \]

The addition of MINOS data leads to a slight tightening of the constraint (the 3σ limit from CHOOZ + atm + K2K is shifted from 0.067 to 0.058 if MINOS is added) because of the stronger lower bound on \( \Delta m^2_{13} \), where the CHOOZ bound becomes weaker (cf figure 2). Note also that the update in the solar model [13] leads to a small shift in the limit from solar + KamLAND data (from 0.079 to 0.071 at 3σ). Both of these updates contribute to the change of the global bound from 0.046 [16] to 0.041 at 3σ.

4. Sub-leading effects in atmospheric neutrinos

In principle, one expects that at some level sub-leading effects will show up in atmospheric neutrinos, involving oscillations with \( \Delta m^2_{21} \), or effects of a finite \( \theta_{13} \), see e.g. [17–21]. An excess of e-like events observed in SK [5] might be a possible hint for such effects, and in [19, 20] a slight preference for non-maximal values of \( \theta_{23} < \pi/4 \) has been found. In contrast, the SK analysis presented in [21] did not confirm that hint.

From a full three-flavour analysis of SK data [22] shown in figure 3 one finds that indeed sub-GeV data prefer a value \( \theta_{23} < \pi/4 \), however, if only multi-GeV data are used the best fit occurs for \( \theta_{23} > \pi/4 \). Summing sub- and multi-GeV data leads incidentally to a cancellation of both effects and the best fit moves again to \( \sin^2 \theta_{23} = 0.46 \) [19]. From these considerations, we conclude that the final result for \( \theta_{23} \) appears as a delicate interplay of different data samples, involving cancellations of opposite trends. Hence the result is rather sensitive to the very fine details of the analysis. Let us stress that the \( \Delta \chi^2 \) contours shown in figure 3 correspond to 9.5, 22, 39 and 90% CL (2 d.o.f.), i.e., there is no significance in these effects. The purpose of this analysis is to show that present data does not allow the obtaining of statistically meaningful indications of non-maximal values of \( \theta_{23} \) nor of nonzero values of \( \theta_{13} \). Nevertheless, sub-leading three-flavour effects in atmospheric oscillations can be explored in future Mt scale water Čerenkov [23] or magnetized iron calorimeter [24] experiments, and may provide complementary information to LBL experiments.

Figure 4 illustrates how details of the atmospheric neutrino analysis affect the bound on \( \sin^2 \theta_{13} \) from CHOOZ + atm + K2K data. It is evident from the figure that the inclusion
of three-flavour effects (from $\theta_{13}$ and/or $\Delta m^2_{31}$), as well as different treatments of systematics lead to an ‘uncertainty’ of about 16% on the bound on $\sin^2 \theta_{13}$ at 2$\sigma$, as indicated by the ‘error bar’ in the figure. Note that the shifts of the global $\theta_{13}$ limit due to MINOS or changes in the solar neutrino analysis reported in section 3 are at the same level as this uncertainty from details in the atmospheric neutrino analysis.

5. The LSND problem

To reconcile the LSND evidence [12] for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with $\Delta m^2 \sim eV^2$ is a long-standing problem for neutrino phenomenology, and the community is eagerly waiting for an experimental answer to this problem from the MiniBooNE experiment [27]. The three required mass-squared differences can be obtained in four-neutrino mass schemes, but such models cannot accommodate the constraints on the mixing [28] (see [11] for an updated analysis). Mass schemes of the $2+2$ type predict that a large fraction of the sterile neutrino participates in solar and/or atmospheric neutrino oscillations, which in both cases is disfavored by the data [28, 29], and therefore such schemes are ruled out at more than 5$\sigma$ CL. The $3+1$ mass spectra are in perfect agreement with solar and atmospheric data, however, they suffer from a tension between the LSND signal and null-result short-baseline disappearance experiments [30, 31], most importantly Bugey [32] and CDHS [33], which disfavors these models at the 3$\sigma$ level.

In [34] a five-neutrino mass scheme of the type $3+2$ has been considered to avoid these constraints, and it is claimed that the disagreement measured by the so-called parameter goodness-of-fit [35] is improved from 0.032% for $(3+1)$ to 2.1%. However, it should be noted that, apart from possible severe conflicts with constraints from cosmology, the best fit point found in [34] seems to be also disfavored from atmospheric neutrino data. As pointed out in [31] atmospheric neutrinos provide a constraint on a parameter $d_{\mu}$, denoting the fraction of $\nu_\mu$ which does not participate in oscillations with $\Delta m^2_{\odot}$. In the $(3+2)$ scheme, this parameter is given by $d_{\mu} = |U_{\mu 4}|^2 + |U_{\mu 5}|^2$, and with the best fit values [34] $U_{\mu 4} = 0.204$, $U_{\mu 5} = 0.224$ one finds $d_{\mu} \approx 0.09$. As visible from figure 5 this value leads to a $\Delta \chi^2 \approx 12.5$ from atmospheric + K2K data, and hence seems to be disfavored at the 3.5$\sigma$ level. Therefore, a re-analysis of the $(3+2)$ scenario including the constraint from atmospheric data seems to be required to judge the viability of this model.

In view of these difficulties to explain the LSND result with neutrino oscillations several alternative mechanisms have been proposed, see [36] for references. In addition to the fact that some of them involve very speculative physics, many of these proposals also have phenomenological problems accommodating all constraints. Scenarios which seem to be in agreement with all present data are a model with a decaying sterile neutrino [36], a four-neutrino mass scheme plus CPT violation [37], and a model based on sterile neutrinos and large extra dimensions [38].

6. Summary

In this paper, I have summarized the status of neutrino oscillations in May 2006, providing updated best fit values and allowed ranges of the three-flavour neutrino oscillation parameters. The impact of the recently released first data from MINOS on the determination of $\Delta m^2_{31}$ as well as on the bound on $\theta_{13}$ has been investigated. Furthermore, sub-leading effects in atmospheric neutrino data have been discussed, stressing that hints for non-maximal values of $\theta_{23}$ and/or nonzero values of $\theta_{13}$ depend on the fine details of the analysis and are not statistically significant. In view of the upcoming results from MiniBooNE I have reviewed once again the problem related to the LSND result, and a confirmation of the effect by MiniBooNE would imply a serious challenge to neutrino oscillation phenomenology.

Acknowledgments

I thank the organizers for the very pleasant and stimulating workshop. The results presented here have been obtained in collaboration with M Maltoni, M A Tórtola and J W F Valle, and in particular I would like to thank M Maltoni for permission to use his atmospheric neutrino code for the analysis of sub-leading effects. T S is supported by a ‘Marie Curie Intra-European Fellowship within the 6th European Community Framework Program’.

References

[1] Cleveland B T et al 1998 Astrophys. J. 496 505
Abdurashitov J N et al (SAGE) 2002 J. Exp. Theor. Phys. 95 181 (Preprint astro-ph/0204245)
Kirsten T et al (GALLEX and GNO) 2003 Nucl. Phys. B (Proc. Suppl.) 118 33
Cattadori C 2004 Talk given at Neutrino04 (Paris, France, 14–19 June 2004)
Fukuda S et al (Super-K) 2002 Phys. Lett. B 539 179
[2] Ahmad Q R et al (SNO) 2002 Phys. Rev. Lett. 89 011302 (Preprint nucl-ex/0204009)
[3] Aharmim B et al (SNO) 2005 Phys. Rev. C 72 055502 (Preprint nucl-ex/0502021)
Global fits to neutrino oscillation data

[4] Fukuda Y et al (Super-K) 1998 Phys. Rev. Lett. 81 1562 (Preprint hep-ex/9807003)
[5] Ashie Y et al (Super-K) 2005 Phys. Rev. D 71 112005 (Preprint hep-ex/0501064)
[6] Araki T et al (KamLAND) 2005 Phys. Rev. Lett. 94 081801 (Preprint hep-ex/0409035)
[7] Apollonio M et al (CHOZ) 2003 Eur. Phys. J. C 27 331 (Preprint hep-ex/0301017)
[8] Aliu E et al (K2K) 2005 Phys. Rev. Lett. 94 081802 (Preprint hep-ex/0411038)
[9] Ables E et al (MINOS) FERMILAB-PROPOSAL-P-875 Falk Harris E 2006 Scandinavian Neutrino Workshop, Uppsala, Sweden, May 2006 http://www-numi.fnal.gov/talks/results06.html
[10] Maltoni M, Schwetz T, Törtola M A and Valle J W F 2003 Phys. Rev. D 68 113010 (Preprint hep-ph/0309130)
[11] Maltoni M, Schwetz T, Törtola M A and Valle J W F 2004 New J. Phys. 6 122 (Preprint hep-ph/0405172)
[12] Aguilar A et al (LSND) 2001 Phys. Rev. D 64 112007 (Preprint hep-ex/0104049)
[13] Bahcall J N, Serenelli A M and Basu S 2005 Astrophys. J. 621 L85 (Preprint astro-ph/0412440)
[14] Huber P and Schwartz T 2004 Phys. Rev. D 70 053011 (Preprint hep-ph/0407026)
[15] Goswami S and Smirnov A Y 2004 Phys. Rev. D 72 053011 (Preprint hep-ph/0411599)
[16] Schwartz T 2005 Acta Phys. Pol. B 36 3203 (Preprint hep-ex/0510331)
[17] Akhmedov E K et al 1999 Nucl. Phys. B 542 3 (Preprint hep-ph/9808270)
Bernabeu J, Palomares Ruiz S and Petcov S T 2003 Nucl. Phys. B 669 255 (Preprint hep-ph/0305152)
[18] Kim C W and Lee U W 1998 Phys. Lett. B 444 204 (Preprint hep-ph/9809491)
Peres O L G and Smirnov A Y 2004 Nucl. Phys. B 680 479 (Preprint hep-ph/0309132)
[19] Gonzalez-Garcia M C, Maltoni M and Smirnov A Y 2004 Phys. Rev. D 70 093005 (Preprint hep-ph/0408170)
[20] Fogli G L, Lisi E, Marrone A and Palazzo A 2005 Preprint hep-ph/0506083
[21] Kajita T 2005 Talk given at NuFact05 (Frascati, Italy, June 21–26) http://www.fnal.infn.it/conference/nufact05/
[22] Maltoni M 2006 private communication
[23] Huber P, Maltoni M and Schwetz T 2005 Phys. Rev. D 71 053006 Maltoni M 2006 Scandinavian Neutrino Workshop, Uppsala, Sweden, May 2006
[24] Petcov S T and Schwartz T 2006 Nucl. Phys. B 740 1 (Preprint hep-ph/0511277)
Goswami S 2006 Phys. Scr. T 127 28
[25] Gonzalez-Garcia M C and Maltoni M 2004 Phys. Rev. D 70 033010 (Preprint hep-ph/0404085)
[26] Hosaka J et al (Super-K) 2006 Preprint hep-ex/0604011
[27] Monroe J (MiniBooNE) 2004 Preprint hep-ex/0409048
[28] Maltoni M, Schwartz T, Tortola M A and Valle J W F 2002 Nucl. Phys. B 643 321 (Preprint hep-ph/0207157)
[29] Gonzalez-Garcia M C, Maltoni M and Pena-Garay C 2001 Phys. Rev. D 64 093001 (Preprint hep-ph/0105269)
[30] Bilenky S M, Giunti C and Grimus W 1998 Eur. Phys. J. C 1 247 (Preprint hep-ph/9607372)
Okada N and Yasuda O 1997 Int. J. Mod. Phys. A 12 3669 (Preprint hep-ph/9606411)
Barger V D, Pakvasa S, Weiler T J and Whisnant K 1998 Phys. Rev. D 58 093016 (Preprint hep-ph/9806328)
Grimus W and Schwartz T 2001 Eur. Phys. J. C 20 1 (Preprint hep-ph/0102125)
[31] Bilenky S M, Giunti C, Grimus W and Schwartz T 1999 Phys. Rev. D 60 073007 (Preprint hep-ph/9903454)
[32] Declais Y et al 1994 Nucl. Phys. B 434 303
[33] Dyda k F et al 1983 Phys. Lett. B 134 281
[34] Sorel M, Conrad J M and Shaevitz M 2003 Phys. Rev. D 70 073004 (Preprint hep-ph/0305255)
[35] Maltoni M and Schwartz T 2003 Phys. Rev. D 68 033020 (Preprint hep-ph/0304176)
[36] Palomares-Ruiz S, Pascoli S and Schwartz T 2005 J. High Energy Phys. JHEP05(09)048 (Preprint hep-ph/0505216)
[37] Barger V, Marfatia D and Whisnant K 2003 Phys. Lett. B 576 303 (Preprint hep-ph/0308299)
[38] Pas H, Pakvasa S and Weiler T J 2005 Phys. Rev. D 72 095017 (Preprint hep-ph/0504096)