Status and prospects of global analyses of neutrino mass-mixing parameters

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Abstract.

We discuss the present knowledge of the neutrino oscillation parameters, the two mass squared differences ($\delta m^2$, $\Delta m^2$), the three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$) and one phase $\delta$. While five out of these six parameters have been measured, the CP-violating phase $\delta$ remains unknown. Moreover, the octant of the mixing angle $\theta_{23}$ and the neutrino mass ordering are still undetermined. We update our previous analysis, by adding to the global fit the recent results presented at The XXVII International Conference on Neutrino Physics and Astrophysics (Neutrino 2016) by the experiments T2K, NOvA, Super-Kamiokande, Daya Bay and RENO.

1. Introduction

Current neutrino oscillation data can be interpreted in a $3\nu$ mass-mixing framework, where the flavor eigenstates $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau)$ are superpositions of the three mass eigenstates $\nu_i = (\nu_1, \nu_2, \nu_3)$ via a unitary mixing matrix depending on three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$) and one possible CP-violating phase $\delta$ [1]. Neutrino oscillations, whose discovery led to the 2015 Nobel Prize, awarded to Takaaki Kajita and Arthur McDonald [2, 3], are driven by the two mass squared differences, $\delta m^2 = m_2^2 - m_1^2$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$. The two cases $\Delta m^2 > 0$ and $\Delta m^2 < 0$ correspond to normal (NO) and inverted (IO) neutrino mass ordering. Five oscillation parameter, the three mixing angles, $\delta m^2$ and $|\Delta m^2|$, are presently known with percent accuracy, while the octant of $\theta_{23}$, the sign of $\Delta m^2$ and the phase $\delta$ are still unknown. In this work we update our global analysis of all available neutrino oscillation data and discuss the status of the known and unknown oscillation parameters. In the $3\nu$ framework, besides the aforementioned oscillation parameters, there are also other unknowns not discussed here, i.e. the absolute neutrino mass scale, the Dirac or Majorana nature of neutrinos and, in this latter case, two Majorana phases.
2. Methodology and Data updates

To present the results of our global analysis, we follow the methodology of Refs. [4, 5, 6]. Since no single oscillation experiment can simultaneously probe all the parameters, we group different data sets to understand how the oscillation parameters are constrained by the results of the various experiments. We start by combining the solar and KamLAND ("Solar + KL") data with those coming from long-baseline accelerator experiments ("LBL Acc"). Therefore, constraints on \((\delta m^2, \theta_{12})\) (and, to some extent, on \(\theta_{13} [5, 6]\)) from Solar+KL data are combined with bounds on the \((\Delta m^2, \theta_{13}, \theta_{23})\) from LBL accelerator experiments. This combination is not by itself very sensitive to \(\delta\) and to the neutrino mass ordering. Subsequently, LBL Acc+Solar+KL data are combined with short-baseline reactor data ("SBL Reactors"), that precisely measure \(\theta_{13}\) and give bounds on \(\Delta m^2\) starting to be comparable with those coming from LBL and atmospheric neutrino data. The synergy between LBL Acc+Solar+KL data and SBL Reactor data significantly improves the sensitivity to \(\delta\) [4]. Finally, we add atmospheric neutrino data ("Atmos"), that are mostly sensitive to \((\Delta m^2, \theta_{23})\) and, subdominantly, to all the other oscillation parameters. We construct a \(\chi^2\) function that depends on the oscillation parameters \((\delta m^2, \pm \Delta m^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta)\) and on a certain number of systematic parameters [4, 5, 7] and we obtain the allowed parameter ranges at \(N^\sigma\), with \(N^2 = \chi^2 - \chi^2_{\text{min}} [1]\). Even when covariance plots involving two parameter are shown, we maintain the same definition for the \(N^\sigma\) ranges. Undisplayed parameters are always marginalized away. For the details of the analysis and the input data sets used see [4, 5]. While the Solar, KamLAND, MINOS and DeepCore IceCube data are unchanged with respect to [4], we update the analysis of the T2K and NOvA experiments [8, 9, 10], both in appearance and disappearance channels. We also update our atmospheric neutrino data analysis by including the latest Super-Kamiokande data [11] (phase I-IV, 0.33 Mtyr exposure). Finally, we also update our SBL analysis by using the latest Daya Bay [12] and RENO [13] data presented at the Neutrino 2016 Conference in London.

3. Results of the global 3\(\nu\) analysis

The results of our global 3\(\nu\) analysis of all the available neutrino oscillation data are summarized in Table 1, where the best-fit values and the allowed 1, 2 and 3\(\sigma\) ranges for the 3\(\nu\) mass-mixing parameters are reported, for both mass orderings. In the last row of the table, the \(\Delta\chi^2\) difference between normal and inverted mass ordering is reported. The NO is favored over the IO, with \(\Delta\chi^2 = \chi^2_{\text{IO}} - \chi^2_{\text{NO}} = 3.6\).

Table 1. Results of the global 3\(\nu\) oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3\(\sigma\) ranges for the 3\(\nu\) mass-mixing parameters. See also Fig. 1 for a graphical representation of the results. We recall that \(\Delta m^2\) is defined as \(m_3^2 - (m_1^2 + m_2^2)/2\), with \(+\Delta m^2\) for NO and \(-\Delta m^2\) for IO. The CP violating phase is taken in the interval \(\delta/\pi \in [0, 2]\). The last row reports the \(\chi^2\) difference between IO and NO.
The bounds on each oscillation parameter are shown in Figure 1, in terms of standard deviations $N_\sigma$ from the best fit. For $\Delta m^2$ and $\sin^2 \theta_{13}$, and to lesser extent also for $\delta m^2$ and $\sin^2 \theta_{12}$, the curves are nearly linear and symmetric, corresponding to gaussian uncertainties. The blue solid lines (NO) and the dashed red lines (IO) coincide for $\delta m^2$ and $\sin^2 \theta_{12}$ since bounds coming from Solar and KamLAND data are independent on the mass ordering, while a small difference is seen in the bounds on $\sin^2 \theta_{13}$. The best fit of $\sin^2 \theta_{23}$ flips from the first to the second octant by changing the mass ordering from normal to inverted, and maximal mixing is excluded in both cases at more than 2$\sigma$. In the case of IO there are two quasi-degenerate minima for $\sin^2 \theta_{23} \sim 0.43$ and $\sin^2 \theta_{23} \sim 0.59$. By defining the average 1$\sigma$ error as $1/6$ of the $\pm 3\sigma$ range, the following fractional uncertainties are obtained by our global fit: $\delta m^2$ (2.4%),
Concerning the phase $\delta$, the preference [4] for negative values of $\sin \delta$ is confirmed. This preference is mostly due to the LBL appearance results, in combination with the measure of $\sin^2 \theta_{13}$ by the SBL experiments. Since the LBL appearance probability contains a CP-violating term proportional to $-\sin \delta \left(\pm \sin \delta\right)$ for neutrinos (antineutrinos) [1], negative values of $\sin \delta$ are expected to produce a slight increase (decrease) of events in $\nu_\mu \to \nu_\tau \left(\bar{\nu}_\mu \to \bar{\nu}_\tau\right)$ oscillations, with respect to the CP-conserving case $\sin \delta = 0$. Therefore, the appearance results of T2K [8, 10] (28 (4) $\nu_\tau \left(\bar{\nu}_\tau\right)$ over 5 (6.9) expected for $\delta = 0$) and of NO$\nu$A [9] (33 $\nu_\tau$ over 8.2 expected for $\delta = 0$) prefer $\delta \sim 3/2\pi$. With respect to [4], where all values of $\delta$ were allowed at 3$\sigma$, now there is a region around $\delta \sim \pi/2$ that is excluded at more than 3$\sigma$. The two CP-conserving cases $\delta = 0, \pi$ are excluded at 2$\sigma$ or more, with the exception of $\delta = \pi$ for IO.

Figure 2 shows the allowed regions in the plane ($\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$). The two panels on the left show the result of the LBL acc+Solar+KL data combination. The two parameters $\sin^2 \theta_{23}$ and $\sin^2 \theta_{13}$ are slightly anticoalescent because of the dependence of the dominant term in the LBL appearance probability on the product $\sin^2 \theta_{13} \sin^2 \theta_{23}$. The preference for relatively low values of $\sin^2 \theta_{13}$ ($\sim 0.02$) of Solar+KL data leads to a weak preference for the first (second) octant for normal (inverted) neutrino mass ordering. In the two middle panels, the combination with SBL reactor data shrinks the $\sin^2 \theta_{13}$ range for both NO and IO, without changing the preferred octant of $\theta_{23}$. Finally, the inclusion of atmospheric data (right panels) alters the $N_\sigma$ contours disfavoring maximal $\theta_{23}$ mixing, but does not change the qualitative preference for the first (second) octant of $\theta_{23}$ for NO (IO), even though for IO there are two quasi-degenerate
Figure 3. As in Fig. 2, but for the \((\sin^2 \theta_{23}, \Delta m^2)\) parameters.

In Figure 3 the octant ambiguity is shown in terms of bounds in the \((\Delta m^2, \sin^2 \theta_{23})\) plane. The fragility of current octant indications stems from the data themselves rather than on the details of the analysis. Actually, nearly maximal mixing is preferred by T2K disappearance and DeepCore atmospheric neutrino data, while nonmaximal mixing is preferred by MINOS, NO\(\nu\)A and SK atmospheric neutrino data.

Figure 4 and 5 show the interplay of the CP-violating phase \(\delta\) with the mixing parameters \(\sin^2 \theta_{13}\) and \(\sin^2 \theta_{23}\). Figure 4 shows the \(N_\sigma\) bounds in the \((\sin^2 \theta_{13}, \delta)\) plane, which is central to interpret the LBL accelerator results in appearance mode. In the two panels on the left, the \(\theta_{23}\) octant ambiguity leads to the structure with wavy bands for the allowed regions. In the central panels, SBL Reactor data significantly shrink the allowed regions, without changing the preference for \(\delta \sim 3\pi/2\). Therefore, more than from a tension between LBL accelerator and SBL reactor data on the preferred \(\theta_{13}\) value, it is correct to say that the preference for \(\delta \sim 3\pi/2\) comes from a synergy of all data, that are currently consistent with each other about \(\theta_{13}\). Finally, the inclusion of atmospheric data (right panels) corroborates the previous indications for \(\delta\), with a global best fit around \(1.3-1.4\pi\) and a slight reduction of the allowed ranges for NO.

Figure 5 shows the \(N_\sigma\) bounds in the \((\sin^2 \theta_{23}, \delta)\) plane. The bounds of Fig. 5 are rather asymmetric and also quite different for the two mass ordering, being the \(\theta_{23}\) octant and the CP-violating phase \(\delta\) still unknown.

We conclude this Section by commenting on \(\Delta \chi^2_{I-N}\) reported in Table 1. From LBL acc+Solar+KL data we get a preference for NO with \(\Delta \chi^2_{I-N} = 1.2\). The difference is nearly unchanged, \(\Delta \chi^2_{I-N} = 1.1\), when SBL results are added and it is \(\Delta \chi^2_{I-N} = 3.6\) with the inclusion of the atmospheric SK and DeepCore data (\(\sim 1.9\sigma\)). Therefore, current data give a weak hint.
for NO, that seems to emerge from consistent indications coming from different data sets, but at present it is cautious to consider these indications about the mass ordering as still very fragile. Indeed, the analysis in [14] finds only a very week preference for NO, with $\Delta \chi^2_{I-N} < 1$. Nevertheless, in the next few years, the new data from T2K and NO$\nu$A and their combination, and later the JUNO [15] experiment, will probably give us some more precise indication on the octant of $\theta_{23}$ and the mass ordering, especially if the present trend in favor of the NO will be confirmed.

4. Conclusions
In this work we have updated our global analysis of neutrino oscillation data by including in our studies the latest experimental results presented at the Neutrino 2016 Conference in London. In particular, the latest long-baseline accelerator data from T2K and NO$\nu$A, the short-baseline results from the reactor experiments Daya Bay and RENO, and the atmospheric neutrino results from Super-Kamiokande have been included in the fit. As a result of the global fit the five known oscillation parameters ($\delta m^2$, $\sin^2 \theta_{12}$, $|\Delta m^2|$, $\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$) have been determined with percent fractional accuracies of $(2.4\%, 5.8\%, 1.6\%, 3.9\%, 9\%)$, respectively. We have discussed the impact of the new data on the three unknowns, the octant of $\theta_{23}$, the neutrino mass ordering and the phase $\delta$. The $\theta_{23}$ octant ambiguity stays essentially unresolved. The best-fit octant of $\theta_{23}$ depends on the mass ordering and it is found in the first octant for NO, in the second one for IO. With respect to our previous global analysis [4], we found a more pronounced preference for the normal mass order at a level of $\sim 1.9\sigma$, with $\Delta \chi^2_{I-N} = 3.6$. Although all the data seem consistently to point in the direction of the NO, it is still premature to affirm that the IO is excluded or even strongly disfavored, and it will be necessary to wait for the new LBL
Figure 5. As in Fig. 2, but for the $(\sin^2 \theta_{23}, \delta)$ parameters.

accelerator results from T2K and NO$\nu$A, and for the first JUNO data, to confirm these very weak indication in favor of the NO. Concerning the CP-violating phase $\delta$, the previous trend preferring $\sin \delta < 0$ (with a best fit at $\delta \simeq 1.3 - 1.4\pi$) is confirmed. Some values of $\delta$ around $\pi/2$ are now excluded at more than $3\sigma$. The two CP-conserving cases $\delta = 0, \pi$ are excluded at about $2\sigma$. The most relevant covariances between pair of oscillation parameters and the impact of different data sets on the bounds obtained have been discussed, to understand the interplay among the various known and unknown parameters, as well as the synergy between oscillation searches in different kinds of experiments.

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