Three-flavor neutrino oscillations and beyond

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Abstract. In this work we summarize the current status of global neutrino oscillation analyses in the three-neutrino framework. We first describe the different data samples included in the global fit, emphasizing the role of each of them in constraining a given set of parameters. Next, we discuss the main improvements obtained thanks to the consideration of the latest experimental data. The status of the yet-unknown parameters, such as the true neutrino mass ordering, the Dirac CP-violating phase and the octant of the atmospheric mixing angle is also commented. Finally, we discuss some scenarios where the measurement of the reactor mixing angle or the CP violation phase could be significantly affected by the presence of neutrino physics beyond the Standard Model.

1. Introduction

The discovery of neutrino oscillations constitutes a major milestone in astroparticle physics over the last few decades. Solar and atmospheric neutrino studies were the first to give convincing evidence for neutrino conversion. By studying the distortion in the neutrino spectra, laboratory experiments based at reactor and accelerators have played a key role in selecting neutrino oscillations as the conversion mechanism at work. Reactor and accelerator experiments have now brought the field of neutrino oscillations to the precision era, contributing significantly to sharpen the determination of the oscillation parameters. Particularly relevant was the input of the KamLAND experiment in elucidating the nature of the solution to the solar neutrino puzzle. Precision tests of the oscillation picture have already a long history, and remain as timely as ever. Indeed, one can probe neutrino NSI with atmospheric, reactor as well as solar neutrino data, where the robustness of the solar neutrino oscillation description has been questioned [1, 2]. Likewise, the effect of neutrino non-unitarity of the lepton mixing matrix, expected if neutrino masses arise a la seesaw [3], could lead to important ambiguities in probing CP violation in neutrino oscillations [4]. These need to be taken up seriously in the design of future oscillation experiments [5, 6].

2. Neutrino oscillation data

We now describe the new data samples used in this updated global neutrino oscillation analysis [7] focusing on the new data appeared since our previous global analysis [8].

An is our previous global fits to neutrino oscillations [9, 8], here we consider the most recent results from the solar experiments Homestake, Gallex/GNO, SAGE, Borexino, SNO and the first three solar phases of Super-Kamiokande. Here we have updated our solar oscillation analysis including the 2055-day day/night spectrum from the fourth phase of Super-Kamiokande [10].
Regarding reactor neutrino experiments, we have included the electron antineutrino disappearance spectrum of Daya Bay corresponding to 1230 days of data [11], the 500 live days prompt reactor spectra from RENO [12] as well as the Double Chooz event energy spectrum from the far-I and far-II data periods [13]. Thanks to the large statistics and the reduction of systematical errors, Daya Bay has provided the most precise determination of the reactor mixing angle to date. Likewise, thanks to the improved spectral fit analysis, RENO is now sensitive to the neutrino oscillation phase [12].

Concerning atmospheric neutrinos, we have included the 3-year data from IceCube DeepCore [14] and the 863-day atmospheric data from ANTARES [15] neutrino telescope. The DeepCore experiment, reporting atmospheric data in the range between 6.3 GeV and 56.2 GeV (quite below the energy threshold of IceCube), has become competitive with long-baseline experiments in the determination of the atmospheric neutrino oscillation parameters. On the contrary, ANTARES sensitivity is not competitive with long–baseline experiments yet, although it is expected that an update in the near future will help improving their sensitivity to the atmospheric neutrino oscillation parameters.

Our analysis includes also the latest T2K, and NO\(\nu\)A data, as well as the final results from the K2K and MINOS experiments. For the T2K experiment, we consider the most recent neutrino and antineutrino data samples, corresponding to \(7.48 \times 10^{20}\) POT and \(7.47 \times 10^{20}\) POT, respectively, where 66 disappearance \(\bar{\nu}_\mu\) events and 4 appearance \(\bar{\nu}_e\) events have been recorded [16, 17]. Thanks to the combination of neutrino and antineutrino channel results, T2K has achieved a mild CP sensitivity, being the first experiment able to exclude certain values of the CP phase at more than 2\(\sigma\). In our global fit we also include the latest results for \(\nu_\mu\)-disappearance and \(\nu_e\)-appearance of the NO\(\nu\)A experiment [18, 19]. The analysis of the NO\(\nu\)A Collaboration slightly disfavors inverted mass ordering, with \(\Delta \chi^2 = -0.47\), while maximal atmospheric mixing is disfavored at around 2.6\(\sigma\).

3. Three–flavour neutrino global analysis

Here we summarize the main results obtained in Ref. [7]. The best fit points as well as the 1\(\sigma\) and 3\(\sigma\) allowed regions for all the parameters are given in Table 1. The allowed regions in the different two-dimensional panels are provided in Fig. 1. First, we find that the recent atmospheric neutrino data from ANTARES and IceCube-DeepCore already provide a precise determination of the atmospheric oscillation parameters, clearly dominated by DeepCore. On the other hand, the new reactor data, mainly thanks to Daya Bay, provide a significantly improved determination of \(\theta_{13}\). They also start contributing to the measurement of the atmospheric mass splitting. However, one finds that atmospheric parameters are mainly constrained by long-baseline data. We also find that the latest NO\(\nu\)A neutrino results disfavour maximal mixing, \(\theta_{23} = \pi/4\), at more than 2\(\sigma\). In any case, maximal mixing remains allowed at 99% C.L. in the global fit.

In what follows we will focus on the main open challenges of the three-neutrino picture: CP violation and the mass ordering as well as the \(\theta_{23}\) octant problem.

From the analysis of long–baseline neutrino oscillation data, we find that he current global sensitivity to the CP phase is dominated by the T2K experiment, with some added rejection against \(\delta = \pi/2\) obtained after combining with the other experiments. Thus, for normal ordering (NO), \(\delta = \pi/2\) is disfavoured at 2.7\(\sigma\). The rejection against \(\delta = \pi/2\) is found to be stronger for inverted ordering (IO) mass spectrum, where it is excluded at 3.7\(\sigma\), with respect to the minimum in IO. The current preferred value of \(\delta\) for both mass orderings lies close to 3\(\pi/2\).

Concerning the sensitivity to the neutrino mass ordering, our global fit shows a slight preference for NO, with \(\Delta \chi^2 = 4.3\). Part of this sensitivity comes from the mismatch between the preferred values of \(\theta_{23}\): NO\(\nu\)A prefers non-maximal \(\theta_{23}\) while T2K prefers values close to
χ preference for NO over IO with ∆ where the overlap of the preferred regions is significantly reduced. This tension results in a maximal. Both experiments have better agreement in the NO case than for the case of IO, where the overlap of the preferred regions is significantly reduced. This tension results in a preference for NO over IO with $\Delta \chi^2 = 3.6$. Extra contributions coming from the remaining data samples achieve the overall rejection against IO obtained from the global fit. In particular, there is another tension, now between the preferred values for $\theta_{13}$ for long-baseline and reactor experiments. While in NO the best fit for long-baseline experiments alone ($\sin^2 \theta_{13} = 0.0225$) is close to the global one ($\sin^2 \theta_{13} = 0.0216$), mostly constrained by reactors, this is not the case for IO ($\sin^2 \theta_{13} = 0.0285$). Given the very good precision of the $\theta_{13}$ measurement in reactor experiments, this mismatch implies a further worsening of the quality of the fit for IO, adding up to the total preference of $\Delta \chi^2 = 4.3$ for the normal mass ordering.

The analysis of long-baseline, atmospheric and reactor data is relevant to discriminate the correct octant of $\theta_{23}$. Long-baseline data show a preference for non-maximal values of $\theta_{23}$ for the two mass orderings, while the combination with atmospheric data provides a further constraint on the allowed region for $\theta_{23}$, improving at the same time the status of maximal mixing. Besides that, for the case of IO, the inclusion of atmospheric data in the analysis produces a jump of the best fit value of $\theta_{23}$ to the second octant, although values of $\theta_{23}$ in the first octant are still allowed with $\Delta \chi^2 \sim 1$. The combination with reactor experiments in the global neutrino fit barely modifies the best fit value of $\theta_{23}$ or the preference for a given octant in any of the mass orderings. Nevertheless, the octant preference described above is still far from robust. Indeed, besides the best fit values indicated in Table 1, for NO we find a local minimum at $\sin^2 \theta_{23} = 0.596$ with $\Delta \chi^2 = 2.1$ with respect to the global minimum. Conversely, for IO we find a local minimum at $\sin^2 \theta_{23} = 0.426$ with $\Delta \chi^2 = 3.0$ with respect to the global minimum for this ordering. Maximal atmospheric mixing is disfavoured at $\Delta \chi^2 = 6.0$ for the case of NO. For IO, maximal $\theta_{23}$ is disfavoured at $\Delta \chi^2 = 9.6$ with respect to the global minimum in IO.

In summary, we note that the improved precision on $\theta_{13}$ follows mainly from the Daya Bay data. Thanks to the combination of T2K neutrino and antineutrino data, we have now an improved sensitivity to CP violation. Concerning the octant of $\theta_{23}$, the current global analysis prefers the lower octant, in contrast to the previous one in Ref. [8]. We have found that for

| parameter                  | best fit ± 1σ | 3σ range  |
|----------------------------|---------------|-----------|
| $\Delta m^2_{21} \ [10^{-5} \text{eV}^2]$ | 7.56±0.19     | 7.05–8.14 |
| $\Delta m^2_{31} \ [10^{-3} \text{eV}^2]$ (NO) | 2.55±0.04     | 2.43–2.67 |
| $|\Delta m^2_{31}| \ [10^{-3} \text{eV}^2]$ (IO) | 2.47±0.05     | 2.34–2.59 |
| $\sin^2 \theta_{12}/10^{-1}$              | 3.21±0.18     | 2.73–3.79 |
| $\sin^2 \theta_{23}/10^{-1}$ (NO)         | 4.30±0.20     | 3.84–6.35 |
| $\sin^2 \theta_{23}/10^{-1}$ (IO)         | 5.98±0.17     | 3.89–4.88 & 5.22–6.41 |
| $\sin^2 \theta_{13}/10^{-2}$ (NO)         | 2.155±0.090   | 1.89–2.39 |
| $\sin^2 \theta_{13}/10^{-2}$ (IO)         | 2.155±0.092   | 1.90–2.39 |
| $\delta/\pi$ (NO)                         | 1.40±0.31     | 0.00–2.00 |
| $\delta/\pi$ (IO)                         | 1.56±0.22     | 0.00–0.17 & 0.83–2.00 |

Table 1. Neutrino oscillation parameters summary determined from this global analysis. The ranges for inverted ordering refer to the local minimum of this neutrino mass ordering.
Figure 1. Allowed regions at 90, 95 and 99% C.L. from the global fit to neutrino oscillations in Ref. [7], for normal (lines) and inverted mass ordering (colored regions). The star indicates the global best fit point, corresponding to NO, while the circle indicates the local minimum in IO.

NO the lower atmospheric octant is preferred with $\Delta \chi^2 = 2.1$, while for the case of IO we obtain a local minimum in the second octant at $\Delta \chi^2 = 4.3$ with respect to the global minimum. Maximal atmospheric mixing is disfavoured at $\Delta \chi^2 = 6.0$ for the case of NO. Finally, our global fit shows a slight preference for normal neutrino mass ordering, with $\Delta \chi^2 = 4.3$. As discussed in the previous section, the sensitivity to the mass ordering comes partly from the tension in the preferred values of $\theta_{23}$ in T2K and NO$\nu$A, found to be stronger for the case of IO. Therefore, the sensitivity to the mass ordering obtained in our global fit can be significantly modified if the measurements of $\theta_{23}$ at these long-baseline experiments converge in the future. Note also that the mismatch between the values of $\theta_{13}$ preferred by long–baseline and reactor data for IO also gives a relevant contribution to the global sensitivity to the mass ordering.

4. Neutrino oscillations in presence of new physics beyond the Standard Model

In the previous section we have seen how the precision in the determination of the best-known oscillation parameters has improved thanks to the recent long-baseline neutrino oscillation and reactor data. Also the sensitivity to mass ordering, CP violation and the octant of the atmospheric angle has improved, although we are still far from a robust measurement. The presence of new physics beyond the Standard Model may affect significantly the results obtained within the current neutrino oscillation picture. For example, nonstandard neutrino interactions (NSI) with matter and non-unitary (NU) neutrino mixing, expected in seesaw models of neutrino mass generation, may significantly reduce the sensitivities. Indeed, it has been shown that
NSI may affect the precision measurements of $\theta_{13}$ and $\delta_{CP}$ at reactor [20] and accelerator [21] experiments. On the other hand, NU mixing can largely affect the sensitivity to $\delta_{CP}$ in the future experiment DUNE [6]. This is illustrated in Fig. 2, where the DUNE sensitivity for the standard case (black line) is compared with the modified sensitivities in the presence of NU for different assumptions on the parameters characterizing the deviations from unitarity, $\alpha_{ii}$.

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