PROCEEDINGS OF SCIENCE

Global analysis of neutrino oscillation experiments

Christoph Andreas Ternes[a,b,*]

[a] *INFN, Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy*

[b] *Dipartimento di Fisica, Università di Torino, via P. Giuria 1, I–10125 Torino, Italy*

E-mail: ternes@to.infn.it

In this talk I present the results from our global fit to neutrino oscillation data. Neutrino oscillation experiments have reached a very good level in precision. Due to correlations among parameters a global fit combining many different datasets can give more precise results than a single experiment on its own. I will present the results of the latest global fit performed by our group and focus on the remaining unknowns in the standard picture: Atmospheric octant, CP violation and neutrino mass ordering.

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1. Introduction

Neutrino oscillations have been investigated intensively over the last few decades. In the standard three-neutrino paradigm the transition probability depends on six parameters: two independent mass splittings Δm^2_{31}, Δm^2_{21}, the three mixing angles θ_{12}, θ_{13}, θ_{23} and the CP-phase δ. While many experiments measure some of the parameters rather well, a global fit can provide even better determinations, since the advantages and sensitivities of all experiments can be used in a combined way. In Ref. [1] we have performed this combination to extract the oscillation parameters. Our results are in good agreement with the results from the other global fit groups, see Refs. [2, 3]. The combined global analysis leads to the values summarized in Tab. 1. In the following we will shortly address the main features of the current global fit.

parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21}\,[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

Table 1: Neutrino oscillation parameters summary determined from the global analysis.

2. Well measured parameters

The solar parameters θ_{12} and Δm^2_{21} have only been measured by KamLAND and the solar neutrino experiments. After combining with data from other experiments the determination of the solar parameters improves further, due to a better determination of θ_{13}, but the effect is only marginal. In contrast, the measurement of the remaining oscillation parameters emerge from the combinations of several data sets. From these four parameters, only θ_{13} and $|\Delta m^2_{31}|$ have been already measured with good precision at oscillation experiments. Concerning the mixing angle θ_{13}, the measurement is clearly dominated by reactor experiments. The contribution from other experiments to this result is negligibly small. Regarding the absolute value of the atmospheric mass splitting, $|\Delta m^2_{31}|$, we found that its determination comes mainly from long-baseline accelerators and from Daya Bay, although the contribution from atmospheric experiments is still important.

3. The CP-phase

The CP-phase δ is measured by the long-baseline accelerator experiments T2K and NOνA. This phase induces opposite shifts in the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probabilities and,

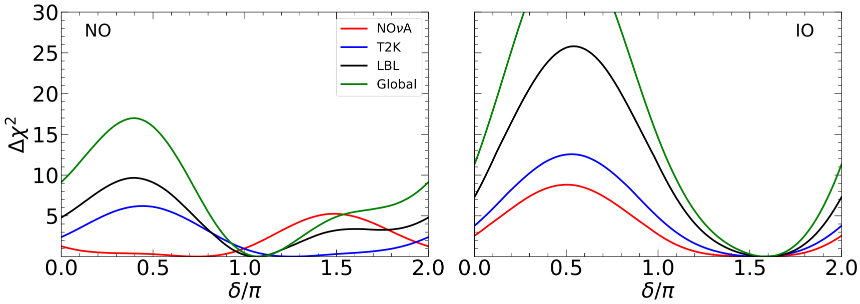

Figure 1: $\Delta\chi^2$ profiles for δ obtained from the analysis of NOνA (red), T2K (blue), all long-baseline data (black) and from the global fit (green).

therefore, information on this parameter can be obtained by analyzing neutrino and antineutrino oscillation data in the appearance channels. In Fig. 1 we show the $\Delta\chi^2$ profiles for the CP-violating phase δ as obtained from the analysis of data from T2K (blue) and NOνA (red), the combination of all long-baseline data (black) and the result from the global fit (green). As can be seen, for normal neutrino mass ordering (NO; left panel), a tension arises between the determinations of δ obtained from T2K and NOνA data. This does not happen for inverted ordering (IO; right panel), for which NOνA shows better sensitivity to δ and also an excellent agreement with T2K. The inclusion of reactor data can help to improve the determination of δ, due to the existing correlation between the CP phase and θ_{13}. From the global combination, we obtain the best fit value for the CP phase at $\delta = 1.08\pi$ (1.58π) for NO (IO). The CP-conserving value $\delta = 0$ is disfavored with $\Delta\chi^2 = 9.1$ (11.3), but the other CP-conserving value, $\delta = \pi$, remains allowed with $\Delta\chi^2 = 0.4$ in NO, while it is excluded with $\Delta\chi^2 = 14.6$ in IO. Note that due to this tension, the determination of δ in the current global fit is worse than it used to be in the last fit that we performed [4].

4. The atmospheric octant

Accelerator and atmospheric oscillation experiments measure the disappearance of muon (anti)neutrinos and are mainly sensitive to $\sin^2 2\theta_{23}$ and can therefore not resolve the octant of the angle: in other words, they can not determine if $\sin^2\theta_{23} > 0.5$ or $\sin^2\theta_{23} < 0.5$. However, due to matter effects in the neutrino trajectories inside the Earth, this degeneracy is slightly broken for atmospheric neutrino oscillation experiments. Also, the quantity $\sin^2\theta_{23}$ enters directly in the appearance channels of these experiments and, hence, the degeneracy can be further broken when including the electron neutrino samples in the fit. Although θ_{23} is not measurable in reactor neutrino experiments, their data help in the determination of θ_{23} by breaking a degeneracy between θ_{23} and θ_{13}. After combining all data samples, we find the best fit value of θ_{23} in the upper octant, with lower octant solutions slightly disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for normal (inverted) mass ordering. Maximal atmospheric mixing is disfavoured with $\Delta\chi^2 = 7.8$ (8.5) for normal (inverted) ordering.

5. The neutrino mass ordering

Here, we briefly discuss the results of our present analysis on the neutrino mass ordering. Combining all neutrino oscillation data, we obtain a preference for normal mass ordering with respect to the inverted one with a value of $\Delta\chi^2 = 6.4$. This corresponds to a 2.5σ preference in favor of NO. The preference comes from a series of (small or large) tensions in the different data sets used in our analysis. We refer the interested reader to Ref. [1] for the details. Due to the aforementioned tension in the measurement of δ, the result is weaker than in our last analyses on the neutrino mass ordering, see Refs [4, 5]. Non-oscillation data can provide additional information on the neutrino mass ordering, see Ref. [6] for an updated analysis. We use data from β-decay experiments, $0\nu\beta\beta$ searches (note that these bounds only apply if neutrinos are Majorana particles) and from cosmological observations. Care has to be taken in performing these combinations, since an un-careful treatment of prior distributions of the variables can lead to very biased results, see Ref. [7]. However, even after combining all data, we find only a preference [6] of around 2.7σ, below the 3σ mark reached previously [4, 5].

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