

Global analysis of neutrino oscillation experiments

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We present the results of our global fit to neutrino oscillation data. We show the obtained values of the oscillation parameters and discuss the remaining open issues in neutrino oscillations, such as CP violation, atmospheric octant problem and neutrino mass ordering. To determine the neutrino mass ordering we combine the oscillation results also with data from decay experiments and cosmological observations.

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1. Neutrino oscillations

Since the discovery of neutrino oscillations approximately 20 years ago, experiments have become more and more powerful, bringing the oscillation studies into the precision era. The transition probability from a flavor α to a flavor β is described by $P_{\alpha\beta}(E, L) = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* e^{i \frac{\Delta m_{kj}^2 L}{2E}}$, where E is the energy of the neutrino and L the distance traveled by it. The mixing matrix U can be parameterized as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$. Therefore, we need six parameters to describe neutrino oscillations: the two mass splittings Δm_{31}^2 , Δm_{21}^2 , 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 combined global fit can provide better determinations, since the advances and sensitivities of all experiments can be used in this way. In Ref. [1] we have performed this combination to extract the oscillation parameters from all available data so far. The combined global analysis leads to the values summarized in Tab. 1 and plotted in Fig. 1, where we marginalized over all the other five parameters. In the following we will shortly address the remaining unknowns in neutrino oscillations.

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2 \theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94

Table 1: Neutrino oscillation parameters summary determined from the global fit [1]. The ranges for inverted ordering refer to the local minimum for this neutrino mass ordering.

2. The CP-phase

The main sensitivity to the CP-phase δ comes from the long-baseline accelerator experiment T2K, although some sensitivity comes also from atmospheric data of Super-Kamiokande and also from the other current accelerator experiment NOVA. These experiments have already some sensitivity on their own, but it increases importantly once combined with the reactor experiments which measure the reactor angle θ_{13} . However, as can be seen in the lower right panel of Fig. 1 a large part of the parameters space remains allowed.

3. The atmospheric octant

The mixing angle θ_{23} is measured by all the long-baseline experiments. The values of the second octant ($\sin^2 \theta_{23} > 0.5$) are degenerate with values in the first octant ($\sin^2 \theta_{23} < 0.5$), which

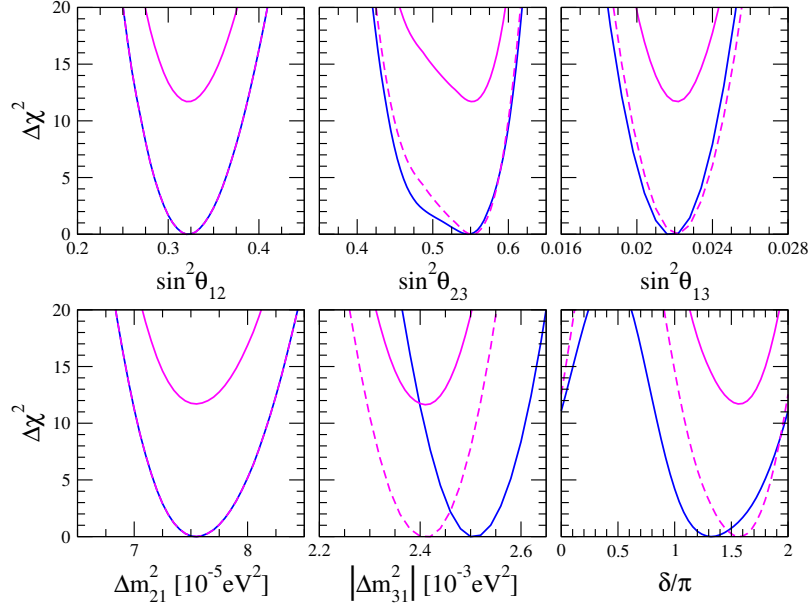


Figure 1: Summary of neutrino oscillation parameters. Blue lines correspond to normal ordering and magenta lines to inverted. The $\Delta\chi^2$ -profiles for inverted ordering are plotted with respect to the minimum for this neutrino mass ordering (dashed) as well as with respect to the global minimum (solid lines).

makes it very difficult to measure its exact value. The closer the value lies to maximality ($\sin^2 \theta_{23} = 0.5$), the more difficult it gets to break this degeneracy. While the current best fit lies in the second octant, first octant solutions are still allowed at close to 1σ level, as can be seen in the upper middle panel of Fig. 1.

4. The neutrino mass ordering

The last unknown is the neutrino mass ordering, referred to as normal if $\Delta m_{31}^2 > 0$ and as inverted if $\Delta m_{31}^2 < 0$. The combination of all oscillation data gives us now a preference for normal ordering of approximately 3σ , as seen in Fig. 1. To obtain stronger results it is possible to combine these data with observations from decay experiments and Cosmology. However, in doing this one has to be careful in the treatment of priors [2]. Using the most conservative parameterizations we obtain a total preference of about 3.5σ in favor of the normal neutrino mass ordering [3].

References

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