Global analysis of neutrino parameters

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Framework: Neutrino oscillations are a well-estabilished quantum phenomenon in which neutrinos can change their flavor during propagation. The origin of this phenomenon comes from the fact that flavor (i.e., interaction) eigenstates are not the same of mass (i.e., propagation) eigenstates. Instead, the two basis are related by a unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \quad (1)$$

Here ν_i are the mass eigenstates with mass m_i. By convention $m_1 < m_2 \ll m_3$ (Normal Hierarchy, NH) or $m_3 \ll m_1 < m_2$ (Inverted Hierarchy, IH). Since oscillations depend only to $\delta m_{ij}^2 = m_j^2 - m_i^2$ oscillation experiments can probe only two mass square differences and not absolute neutrino masses. Although mass square differences are well known, the true hierarchy is still unknown. The unitary matrix $\mathbf{U}$ can be parameterized as the product of three unitary matrices $\mathbf{U}_{ij}$

$$\mathbf{U} = \mathbf{U}_{23}(\theta_{23}) \cdot \mathbf{U}_{13}(\theta_{13}, \delta) \cdot \mathbf{U}_{12}(\theta_{12}) , \quad (2)$$

with

$$\begin{aligned} \mathbf{U}_{23}(\theta_{23}) &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \\ \mathbf{U}_{13}(\theta_{13}, \delta) &= \begin{pmatrix} C_{13} & 0 & S_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{-i\delta} & 0 & C_{13} \end{pmatrix} \\ \mathbf{U}_{12}(\theta_{12}) &= \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} , \end{aligned} \quad (3)$$

where we have used the shorthand $C_{ij} \equiv \cos\theta_{ij}$ and $S_{ij} \equiv \sin\theta_{ij}$ with $\theta_{ij} \in [0, \pi/2]$ are three mixing angles and $\delta \in [0, 2\pi]$ is a phase related to CP violation in the leptonic sector. In particular, the effect of the phase δ on neutrino oscillations is that $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ (CP violation effect) or $P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \bar{\nu}_\alpha)$ (T violation effect), where P is the conversion probability, unless $\delta = 0, \pi$. For simplicity, in the following we refer simply to CP violations.

Neutrino oscillations are thus dependent by six parameters that must be fitted by data: three mixing angles, one phase δ and two mass square differences that we choose as $\delta m^2 = m_2^2 - m_1^2$ and Δm^2 defined as $|m_3^2 - (m_1^2 + m_2^2)/2|$. The hierarchy is determined by the sign of Δm^2: $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Table 1
Best fit and 3σ range of all oscillation parameters.

Parameter	Best fit	3σ range
$\delta m^2/10^{-5}\text{eV}^2$ (NH, IH)	7.54	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH, IH)	3.07	2.59 – 3.59
$\Delta m^2/10^{-3}\text{eV}^2$ (NH)	2.43	2.19 – 2.62
$\Delta m^2/10^{-3}\text{eV}^2$ (IH)	2.42	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.35 – 6.63
δ/π (NH)	1.08	—
δ/π (IH)	1.09	—

Here is impossible to review the complete neutrino theory and phenomenology, so we address the interested reader to one of the many reviews on this topic (see, e.g., Ref. [1]). We want instead to briefly summarize the main results of Ref. [2].

Until very recently, only θ_{12} and θ_{23} was measured with great accuracy, while θ_{13} as well the phase δ was unknown (to be more precise, only an upper limit was settled on θ_{13}). Last year, short baseline reactor experiments (RENO, Daya Bay) have definitely established that $\theta_{13} > 0$ at $\sim 5\sigma$, by observing $\overline{\nu}_e$ disappearance from near to far detectors. In particular, Daya Bay and RENO have measured $\sin^2\theta_{13} \simeq 0.023 \pm 0.003$ and $\sin^2\theta_{13} \simeq 0.029 \pm 0.006$, respectively. Consistent indications were also found in the Double Chooz reactor experiment.

In neutrino oscillations, CP violation is a genuine 3ν effect which may be observed (provided that $\delta \neq 0, \pi$) only if all the mixings θ_{ij} and the squared mass differences $m_i^2 - m_j^2$ are nonzero. The fact that θ_{13} has been proven to be non zero opens the possibility to observe CP violation effects in neutrino oscillations.

Results: In Ref. [2] we have performed a complete analysis of the whole neutrino oscillation phenomenology (i.e., results from solar, atmospheric, short and long baseline reactor, and long baseline accelerator neutrino experiments) updated up the data released at the *Neutrino*

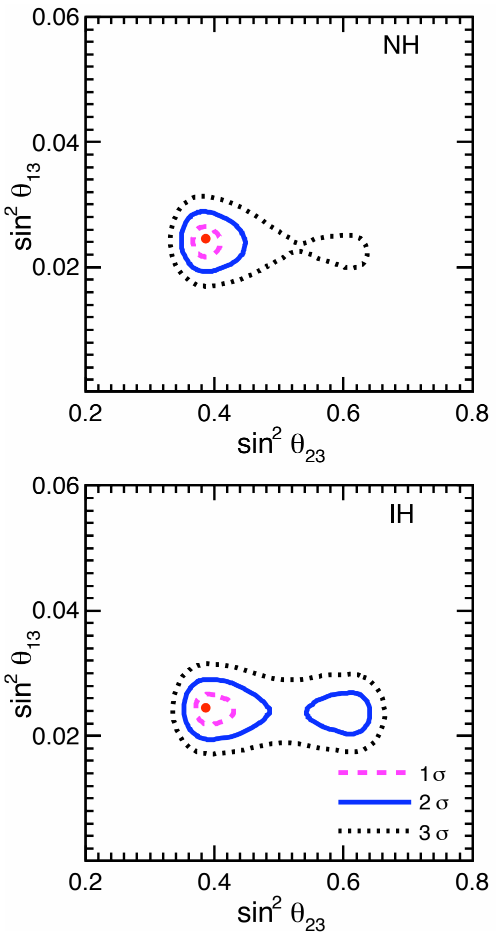

Figure 1. Allowed zones at 1, 2 and 3σ in the $(\sin^2\theta_{23}, \sin^2\theta_{13})$ plane for Normal (upper plot) and Inverted Hierarchy (lower plot).

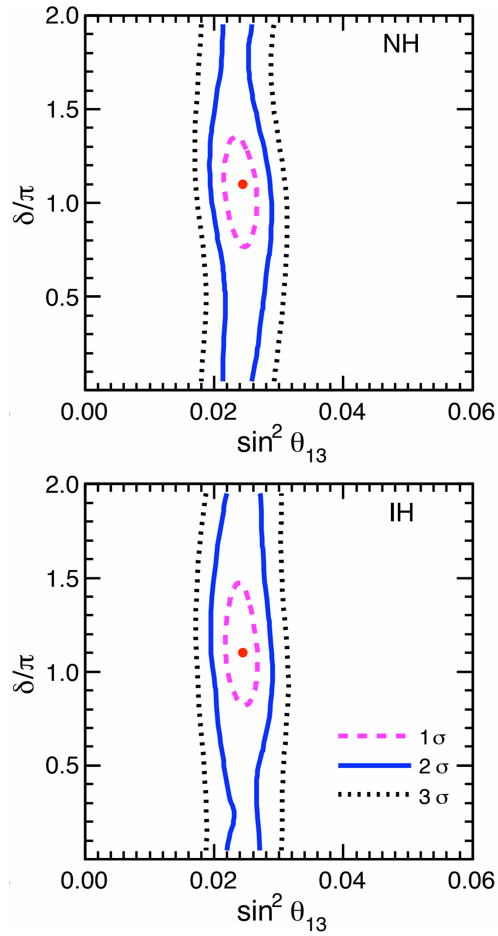

Figure 2. Allowed zones at 1, 2 and 3σ in the $(\sin^2\theta_{13}, \delta)$ plane for Normal (upper plot) and Inverted Hierarchy (lower plot).

2012 Conference [3].[1] The main new results are summarized in Figs. 1 and 2. In Fig. 1 are shown the allowed zones at 1, 2 and 3σ in the $(\sin^2\theta_{23}, \sin^2\theta_{13})$ plane for Normal (upper plot) and Inverted Hierarchy (lower plot). We derive that at more than 2σ data prefer θ_{23} in the first octant (while previous analysis and data favored maximal mixing $\theta_{23} = \pi/4$). This is a very important information to design future long-baseline experiments.

In Fig. 2 are shown the allowed zones at 1, 2 and 3σ in the $(\sin^2\theta_{13}, \delta)$ plane for Normal (upper plot) and Inverted Hierarchy (lower plot), although there are not significative differences between the two plots. A marginal (2σ) preference for $\delta \sim \pi$ emerges from the data, but the results ar far to be conclusive.

In Table 1 are shown the results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 3σ ranges for the 3ν mass-mixing parameters.

[1]We did not include the controversial results coming from MiniBooNE and LSND short baseline accelerator experiments, which give indications for further sterile neutrino states.

Concerning the hierarchy, a slight preference for NH respect to IH emerge from the fit $[(\chi^{NH})^2_{\text{best fit}} - (\chi^{IH})^2_{\text{best fit}} \simeq -0.35]$, but at the moment this difference is statistically irrelevant and can easily change with new data.

In Ref. [2] we also discuss the interplay between oscillation and nonoscillation data, in particular the search for absolute neutrino masses with β, $0\nu2\beta$ experiments and cosmological data. We address the interested reader to Ref. [2] for this issue.

REFERENCES

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