Precision measurement of three neutrino oscillation parameters

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Neutrino oscillations are a quantum phenomenon in which neutrinos can change their flavor during propagation due to the fact that flavor eigenstates are not the same of mass eigenstates. Instead, the two basis are related by a unitary matrix

$$\begin{pmatrix} \hat{\nu}_e \\ \hat{\nu}_\mu \\ \hat{\nu}_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \quad (1)$$

Here $\hat{\nu}_{e,\mu,\tau}$ are the flavor eigenstates (which convert into the corresponding leptons in Charge Current interactions), ν_i 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 $\delta m^2_{jk} = m^2_k - m^2_j$ oscillation experiments can probe only two mass square differences and not absolute neutrino masses. By convention we choose $\delta m^2 = m^2_2 - m^2_1$ and $\Delta m^2 = m^2_3 - (m^2_1 + m^2_2)/2$ as free parameters. The sign of Δm^2 determines the hierarchy ("+" for NH, "−" for IH). This is schematically shown in Fig. 1. 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.

A neutrino $\hat{\nu}_\alpha$ is emitted in interaction eigenstate and thus is a linear combination of mass (propagation) eigenstates ν_i. After that the ν_i's propagate with different de Broglie wavelength:

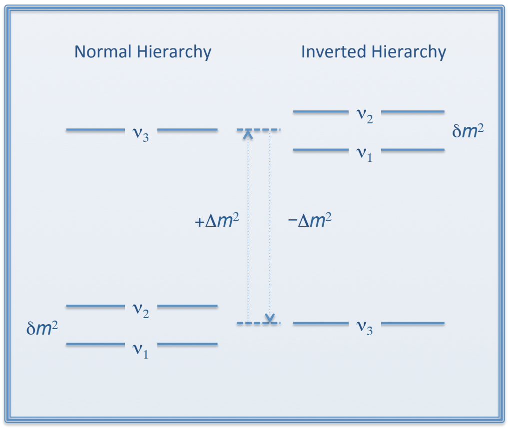

Figure 1. Schematic representation of possible mass neutrino hierarchies.

at detection the final state is in general a different combination of the initial state. As a consequence, there is a nonzero probability to detect the neutrino in a different interaction eigenstate $\hat{\nu}_\beta$, $\beta \neq \alpha$. The conversion probability at distance x from source for a neutrino with energy E_ν is given by

$$\begin{aligned} P_{\alpha\beta}(x) &= \delta_{\alpha\beta} \\ &- 4\sum_{k>j} \Re[U_{\alpha_j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}] \sin^2\left(\frac{\phi_{jk}}{2}\right) \\ &+ 2\sum_{k>j} \Im[U_{\alpha_j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}] \sin\phi_{jk} , \end{aligned} \quad (4)$$

with

$$\phi_{jk} = \frac{\delta m^2_{jk}}{4E_\nu} x . \quad (5)$$

In particular, the effect of the phase δ on neutrino oscillations is that $P_{\alpha\beta} \neq P_{\bar{\alpha}\bar{\beta}}$ (CP violation effect) or $P_{\alpha\beta} \neq P_{\beta\alpha}$ (T violation effect) unless $\delta = 0, \pi$. For simplicity, in the following we refer simply to CP violations. We mention also that for neutrinos traveling in matter (such as Solar neutrinos) the interaction with the background matter modifies substantially the oscillation probability (the so called Mikheyev-Smirnov-Wolfenstein effect). For a review on neutrino oscillation physics and phenomenology see [1].

Within the standard 3ν mass-mixing framework, we have performed an up-to-date global analysis of neutrino oscillation data including the latest available results from experiments with atmospheric neutrinos (Super-Kamiokande and IceCube DeepCore), at accelerators (first T2K $\overline{\nu}$ and NOνA ν runs in both appearance and disappearance mode), and at short-baseline reactors (Daya Bay and RENO far/near spectral ratios), as well as a reanalysis of older KamLAND data in the light of the "bump" feature recently observed in reactor spectra. We have derived improved constraints on the five known oscillation parameters (δm^2, $|\Delta m^2|$, $\sin^2\theta_{12}$, $\sin^2\theta_{13}\sin^2\theta_{23}$), and the status of the three remaining unknown parameters: the mass hierarchy [sign($\pm\Delta m^2$)], the θ_{23} octant [sign($\sin^2\theta_{23}-1/2$)], and the possible CP-violating phase δ. With respect to previous global fits, we find that the reanalysis of KamLAND data induces a slight decrease of both δm^2 and $\sin^2\theta_{12}$, while the latest accelerator and atmospheric data induce a slight increase of $|\Delta m^2|$.

Concerning the unknown parameters, we have confirmed the previous intriguing preference for negative values of $\sin\delta$ (with best-fit values around $\sin\delta \simeq -0.9$), but we find no statistically significant indication about the θ_{23} octant or the mass hierarchy (normal or inverted). Assuming an alternative (so-called LEM) analysis of NOνA data, some δ ranges can be excluded at $> 3\sigma$, and the normal mass hierarchy appears to be slightly favored at $\sim$90% C.L. The details of this work are described in [2] while the results are summarized in Table 1:

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

Parameter	Hierarchy	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2	NH & IH	7.37	7.21 – 7.54
$\sin^2\theta_{12}/10^{-1}$	NH & IH	2.97	2.81 – 3.14
$\Delta m^2/10^{-3}$ eV^2	NH	2.50	2.46 – 2.54
$\Delta m^2/10^{-3}$ eV^2	IH	2.46	2.42 – 2.51
$\sin^2\theta_{13}/10^{-2}$	NH	2.14	2.05 – 2.25
$\sin^2\theta_{13}/10^{-2}$	IH	2.18	2.06 – 2.27
$\sin^2\theta_{23}/10^{-1}$	NH	4.37	4.17 – 4.70
$\sin^2\theta_{23}/10^{-1}$	IH	5.69	4.28 – 4.91
δ/π	NH	1.35	1.13 – 1.64
δ/π	IH	1.32	1.07 – 1.67

In alternative to neutrino oscillations parameters, there are other possible non-oscillatory observables that can in principle give information on neutrino masses and mixing. The first one is Cosmology which is sensitive to the sum of neutrino masses $\Sigma = m_1 + m_2 + m_3$. The second is beta decay experiment that aim to measure the neutrino mass by means of the study of the recoil spectrum of the electron in the reaction $^3H \rightarrow ^3He + e^- + \bar{\nu}_e$. This experiment is sensitive to the effective ν_e mass $m_\beta = \sqrt{\sum_a |U_{ea}|^2 m_a^2}$. The last kind of experiment is the neutrinoless beta decay process which is the hypothetical nuclear decay process $(A,Z) \rightarrow (A,Z{+}2){+}2e^-$ This process is possible only of neutrinos have a Majorana nature (that is neutrinos and antineutrinos are the same particle). Notice that in this case U_{ea} can contain extra phases called "Majorana phases". None of this experiments gave positive evidences for a non zero neutrino mass, yielding only bounds on these parameters.

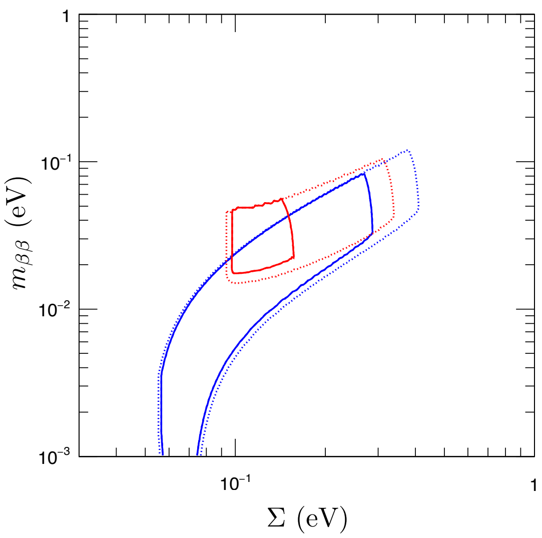

Figure 2. Solid (dashed) lines: allowed zones at 2σ (3σ) level for Σ and $m_{\beta\beta}$ combining oscillatory, non-oscillatory an cosmological data as presented in [3]. Blue (red) line refers to Normal (Inverted) Hierarchy. Absolute χ^2 minimum in NH, $\Delta\chi^2(IH - NH) = 3.2$.

Figure 1 [3] shows the constraints induced by our global 3ν analysis, for either NH (blue curves) or IH (red curves), in the planes charted by the two parameters $m_{\beta\beta}$ and Σ. We have used the "cosmo weak" data are taken by [4]. Blue (red) line refers to Normal (Inverted) Hierarchy. The two scenarios refer to the same χ^2 minimum which occur for Normal Hierarchy. From this figure we see that the Inverted Hierarchy scenario is in tension with data (using the"cosmo strong" data in [4] the IH scenario disappear at 2σ). Future experiments will be able to prove (ore exclude completely) the IH scenario.

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