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# Neutrino masses and mixings: Status of known and unknown $3\nu$ parameters

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**Abstract**

Within the standard $3\nu$ mass–mixing framework, we present an up-to-date global analysis of neutrino oscillation data (as of January 2016), including the latest available results from experiments with atmospheric neutrinos (Super-Kamiokande and IceCube DeepCore), at accelerators (first T2K $\bar{\nu}$ and NO$\nu$A $\nu$ runs in both appearance and disappearance modes), 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 discuss improved constraints on the five known oscillation parameters ($\delta m^2$, $|\Delta m^2|$, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$), and the status of the three remaining unknown parameters: the mass hierarchy [$\mathrm{sign}(\pm\Delta m^2)$], the $\theta_{23}$ octant [$\mathrm{sign}(\sin^2\theta_{23} - 1/2)$], and the possible CP-violating phase $\delta$. With respect to previous global fits, we find that the reanalysis of KamLAND data induces a slight decrease of both $\delta m^2$ 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 confirm 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 $\theta_{23}$ octant or the mass hierarchy (normal or inverted). Assuming an alternative (so-called LEM) analysis of

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NO$\nu$A data, some $\delta$ ranges can be excluded at $>3\sigma$, and the normal mass hierarchy appears to be slightly favored at ~90% C.L. We also describe in detail the covariances of selected pairs of oscillation parameters. Finally, we briefly discuss the implications of the above results on the three non-oscillation observables sensitive to the (unknown) absolute $\nu$ mass scale: the sum of $\nu$ masses $\Sigma$ (in cosmology), the effective $\nu_e$ mass $m_\beta$ (in beta decay), and the effective Majorana mass $m_{\beta\beta}$ (in neutrinoless double beta decay).


## 1. Introduction

Yellow, blue and dark blue: this is the simple color palette used for painting and penning each of the two-sided Nobel Diplomas awarded to Takaaki Kajita [1] and Arthur B. McDonald [2]. On the left side, one can gaze at an artist's view—sketched with a few broad strokes—of the neutrino transformative trip from the bright yellow Sun, through the Earth's blue darkness, into a blue pool of water [3]. On the right side, one can read the—beautifully and precisely penned—Nobel laureate names and prize motivations, in ink colors that continuously change from deep blue to blue with yellow shades [4]. In a sense, the two sides of the Diplomas evoke the interplay between a broad-brush picture of $\nu$ masses and mixings (the pioneering era) and carefully designed measurements and theoretical descriptions (the precision era), in a continuous feedback between breakthrough and control, that may open the field to further fundamental discoveries [5].

In this paper, we aim at presenting both the broad-brush features and the fine structure of the current picture of neutrino oscillation phenomena, involving the mixing of the three neutrino states having definite flavor $\nu_{e,\mu,\tau}$ with three states $\nu_{1,2,3}$ having definite masses $m_i$ [6]. Information on known and unknown neutrino mass–mixing parameters is derived by a global analysis of neutrino oscillation data, that extends and updates our previous work [7] with recent experimental inputs, as discussed in Sec. 2 (see also [8,9] for previous global analyses by other groups). In Sec. 3, precise constraints (at few percent level) are obtained on four well-known oscillation parameters, namely, the squared-mass differences $\delta m^2 = m_2^2 - m_1^2$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, and the mixing angles $\theta_{12}$ and $\theta_{13}$. Less precise constraints, including an octant ambiguity, are reported for the angle $\theta_{23}$. In this picture, we also discuss the current unknowns related to the neutrino mass hierarchy [sign($\Delta m^2$)] and to the possible leptonic CP-violating phase $\delta$. The trend favoring negative values of $\sin\delta$ appears to be confirmed, with best-fit values around $\delta \simeq 1.3$–$1.4\pi$ (i.e., $\sin\delta \simeq -0.9$). More fragile indications, which depend on alternative analyses of specific data sets, concern the exclusion of some $\delta$ ranges at $>3\sigma$, and a slight preference for normal hierarchy at 90% C.L. The covariances of selected parameter pairs, and the implications for non-oscillation searches, are presented in Secs. 4 and 5, respectively. Our conclusions are summarized in Sec. 6.

## 2. Global analysis: methodology and updates

In this section we discuss methodological issues and input updates for the global analysis. Readers interested only in the fit results may jump to Sec. 3.

In general, no single oscillation experiment can currently probe, with high sensitivity, the full parameter space spanned by the mass–mixing variables ($\delta m^2$, $\pm\Delta m^2$, $\theta_{12}$, $\theta_{13}$, $\theta_{23}$, $\delta$). One can