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Neutrino Oscillation Physics

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Abstract

We present a global analysis of neutrino oscillation data, including in particular the high-precision measurements of the last SM mixing angle θ_{13} at reactors, which have confirmed previous indications in favor of $\theta_{13} > 0$. We focus on the correlations between θ_{13} and the mixing angle θ_{23}, as well as between θ_{13} and the neutrino CP-violation phase δ. Assuming normal hierarchy, we find possible hints about the other two unknowns, namely: a slight preference for the first θ_{23} octant, and a possible indication for non-zero CP violation (with $\sin\delta < 0$), although at the level below 2σ for both the two cases. Note that the second hint appears also in inverted hierarchy, but with even lower statistical significance. No palpable difference between normal and inverted mass hierarchy emerges from the data.

Keywords: Neutrino mass and mixing, Neutrino interactions

1. Introduction

Current neutrino oscillation experiments (except for a few anomalous results) can be interpreted within a three-neutrino framework, where the three flavor states $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau)$ are quantum superpositions of three light mass states $\nu_i = (\nu_1, \nu_3, \nu_3)$ via a unitary mixing matrix $U_{\alpha i}$, depending on three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and one possible CP-violating phase δ [1, 2].

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 [3]. The latter condition is experimentally established, and can be expressed in terms of the two independent parameters $\delta m^2 = m_2^2 - m_1^2 > 0$ [1] and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ [4], where $\Delta m^2 > 0$ and < 0 correspond to normal (NH) and inverted (IH) mass spectrum hierarchy, respectively.

At present we know five oscillation parameters, each one with an accuracy largely dominated by a specific class of experiments, namely: θ_{12} by solar data, θ_{13} by short baseline (SBL) reactor data, θ_{23} by atmospheric data, mainly fron Super.Kamiokande (SK), δm^2 by long-baseline reactor data from KamLAND (KL), and Δm^2 by long-baseline (LBL) accelerator data, mainly from MINOS and T2K. However, the available data are not yet able to determine the mass hierarchy, to discriminate the θ_{23} octant, or to discover CP violation effects. A worldwide research program is underway to address such open questions and the related experimental and theoretical issues [2].

In this context, the global neutrino data analysis performed in [5] (for alternative analyses see [6, 7]) has been useful to get the most restrictive bounds on the known parameters, via the synergic combination of results from different classes of oscillation searches, providing, at the same time, some guidance about the unknown oscillation parameters.

Indeed, it should be remarked that we had previously obtained hints in favor of $\sin^2\theta_{13} \sim 0.02$ from a detailed analysis of solar and long-baseline reactor data [8, 9] (see also [10] for similar, independent hints), consistently with an earlier (weak) preference for $\theta_{13} > 0$

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from atmospheric neutrinos [4, 9]. The hints became a $\sim 2\sigma$ indication for $\theta_{13} > 0$ in combination with early appearance data from the MINOS long-baseline accelerator experiment [11], and provided a $> 3\sigma$ evidence by including the remarkable low-background appearance data from the T2K experiment [12]. The Daya Bay and RENO measurements have shown that our global 3ν analyses in [8, 9, 12]—the latest of a series started two decades ago [13]—were on the right track in the hunt to θ_{13}. See also [14, 15, 16] for other recent analyses of θ_{13} constraints prior to the Daya Bay and RENO results.

To this regard, two years ago the short-baseline (SBL) reactor experiments Daya Bay [17] and RENO [18] 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 $\sin^2\theta_{13} \simeq 0.023 \pm 0.003$ [19] and $\sin^2\theta_{13} \simeq 0.029 \pm 0.006$ [18, 20], respectively. Consistent indications were also found in the Double Chooz reactor experiment with far detector only ($\sin^2\theta_{13} \simeq 0.028 \pm 0.010$) [21, 22]. All these reactor data are in good agreement with the results of our global analysis of oscillation data in [12], which provided $\sin^2\theta_{13} = 0.021$–$0.025$ at best fit, with a 1σ error of ± 0.007.

With $\sin^2\theta_{13}$ as large as 2–3×10^{-2}, the door is open to CP violation searches in the neutrino sector, although the road ahead appears to be long and difficult [23, 24]. In particular, it makes sense to update the analysis in [5] by including the most recent data from the different experiments. Accordingly, with respect to [5], we include in our updated analysis, for the first time reported in [25], the recent SBL reactor data from Daya Bay [26] and RENO [27], which reduce significantly the range of θ_{13}. We also include the latest appearance and disappearance event spectra published in 2013 and at the beginning of 2014 by the LBL accelerator experiments T2K [28, 29, 30] and MINOS [31, 32, 33], which not only constraint the known parameters (Δm^2, θ_{23}, θ_{13}), but, in combination with other data, provide some guidance on the θ_{23} octant and on the leptonic CP violation.

More explicitly, we find a slight overall preference for $\theta_{23} < \pi/4$ and for nonzero CP violation with $\sin\delta > 0$; however, for both parameters, such hints exceed 1σ only for normal hierarchy. No significant preference emerges for normal versus inverted hierarchy. Among the various results which can be of interest, we find it useful to report the preferred $N\sigma$ ranges of each oscillation parameter and covariance plots of selected couples of parameters, as well as to discuss their stability and the role of different data sets in the global analysis.

The present work is structured as follows. In Sec. 2 we describe some methodological issues. In Sec. 3 we summarize the constraints on the single mass-mixing oscillation parameters. In Sec. 3 we discuss the results of our analysis in terms of covariance among the parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, δ), for both normal and inverted hierarchy. We draw our conclusions in Sec. 5. More details about the present analysis can be found in [25].

2. Global 3ν analyses: some methodological issues

No single oscillation experiment can sensitively probe, at present, the full parameter space spanned by (δm^2, $\pm\Delta m^2$, θ_{12}, θ_{13}, θ_{23}, δ). Therefore, it is necessary to group in some way the experimental data, in order to study their impact on the oscillation parameters. For instance, in [12] we showed that consistent indications in favor of nonzero θ_{13} emerged from two different datasets, one mainly sensitive to δm^2 (solar plus KamLAND experiments) and another mainly sensitive to Δm^2 (CHOOZ plus atmospheric and LBL accelerator experiments). In this work we adopt an alternative grouping of datasets, which is more appropriate to discuss interesting features of the current data analysis, such as the covariance among the parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, δ) in both mass hierarchies.

2.1. LBL + solar + KamLAND data

We remind that LBL accelerator data (from the K2K, T2K, and MINOS experiments) in the $\nu_\mu \to \nu_\mu$ disappearance channel probe dominantly the Δm^2-driven amplitude

$$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = \cos^2\theta_{13}\sin^2\theta_{23}\cdot \cdot(1-\cos^2\theta_{13}\sin^2\theta_{23})\ , \quad (1)$$

which is slightly octant-asymmetric in θ_{23} for $\theta_{13} \neq 0$. In the $\nu_\mu \to \nu_e$ appearance channel, the dominant Δm^2-driven amplitude is

$$|U_{\mu 3}|^2|U_{e3}|^2 = \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\ , \quad (2)$$

which is definitely octant-asymmetric in θ_{23} for $\theta_{13} \neq 0$. In both the appearance and the disappearance channels, subdominant terms driven by δm^2 and by matter effects can also contribute to lift the octant symmetry and to provide some weak sensitivity to sign(Δm^2) and to δ. As already noted in [12], the T2K and MINOS indications in favor of $\nu_\mu \to \nu_e$ appearance induce an anti-correlation, via Eq. (2), between the preferred values of $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$. This covariance is relevant in the analysis of the θ_{23} octant degeneracy [34] and has an indirect impact also on the preferred ranges of δ via subdominant effects.

In order to make the best use of LBL accelerator data, it is thus useful to: (1) analyze both disappearance and appearance data at the same time and in a full 3ν approach; (2) combine LBL with solar and KamLAND data, which provide independent constraints on $(\delta m^2, \theta_{12}, \theta_{13})$ and thus on the subdominant 3ν oscillation terms. As discussed below, once the (relatively well known) oscillation parameters $\sin^2\theta_{12}$, δm^2 and Δm^2 are marginalized away, interesting correlations emerge among the remaining parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, δ).

In this work, the previous LBL data used in [5] are updated with the inclusion of the T2K disappearance constraints [29] and of the latest T2K appearance data [28, 30]. We note that recent MINOS $\overline{\nu}_\mu$ disappearance data are no longer in disagreement with previous ν_μ results. Therefore, it makes sense to use both ν and $\overline{\nu}$ MINOS appearance and disappearance data which we take from [31, 32, 33]. For later purposes, we note that recent T2K and (especially) MINOS data are best fit for slightly non-maximal mixing ($\sin^2 2\theta_{23} \simeq 0.94$–$0.98$ roughly corresponding to the octant-symmetric values $\sin^2\theta_{23} \sim 0.4$ or 0.6). A slight preference for non-maximal mixing emerged also from our analysis of K2K LBL data in [4].

2.2. Adding SBL reactor data

After grouping LBL accelerator plus solar plus KamLAND data (LBL + solar + KamLAND), it is important to add the independent and "clean" constraints on θ_{13} coming from SBL reactor experiments in the $\nu_e \to \nu_e$ disappearance channel, which probe dominantly the Δm^2-driven amplitude

$$|U_{e3}|^2(1 - |U_{e3}|^2) = \sin^2\theta_{13}\cos^2\theta_{13}\ . \qquad (3)$$

In the reactor dataset, subdominant terms are slightly sensitive to $(\delta m^2, \theta_{12})$ and, as noted in [35] and discussed in [36], probe also the neutrino mass hierarchy. We include far-detector data from CHOOZ [37] and Double Chooz [22] and near-to-far detector constraints from Daya Bay [19] and RENO [18, 20]. We do not include data from pre-CHOOZ reactor experiments, which mainly affect normalization issues.

Indeed, the analysis of reactor experiments without near detectors depends, to some extent, on the absolute normalization of the neutrino fluxes, which we choose to be the "old" (or "low") one, in the terminology of [12]. We shall also comment on the effect of adopting the "new" (or "high") normalization recently proposed in [38, 39]. Constraints from Daya Bay and RENO are basically independent of such normalization, which is left free in the official analyses and is largely canceled by comparing near and far rates of events [17, 18]. At present, it is not possible to reproduce, from published information, the official Daya Bay and RENO data analyses with the permill accuracy appropriate to deal with the small systematics affecting near/far ratios. We think that, for the purposes of this work, it is sufficient to take their measurements of $\sin^2 2\theta_{13}$ at face value, as gaussian constraints on such parameter. Luckily, such constraints appear to depend very little on the Δm^2 parameter within its currently allowed range; see the $(\Delta m^2, \sin^2 2\theta_{13})$ prospective sensitivity plots in [40] (Daya Bay) and [41] (RENO).

As shown in [34], LBL data in disappearance and appearance mode generally select [via Eqs. (1) and (2)], two degenerate $(\theta_{23}, \theta_{13})$ solutions, characterized by nearly octant-symmetric values of θ_{23} and by slightly different values of θ_{13}. By selecting a narrow range of θ_{13}, precise reactor data can thus (partly) lift the θ_{23} octant degeneracy [34] (see also [42]). Amusingly, the fit results in Sec. 3 resemble the hypothetical, qualitative 3ν scenario studied in [34].

2.3. Atmospheric neutrino data

After combining the (LBL + solar + KamLAND) and (SBL reactor) datasets, we finally add the Super-Kamiokande atmospheric neutrino data (SK atm.), as reported for the joint SK phases I–IV in [43, 44]. The SK data span several decades in neutrino and antineutrino energy and pathlengths, both in vacuum and in matter, in all appearance and disappearance channels involving ν_μ and ν_e, and thus they embed an extremely rich 3ν oscillation physics.

In practice, it is difficult to infer —from atmospheric data— clean 3ν information beyond the dominant parameters (Δm^2, θ_{23}). Subdominant oscillation effects are often smeared out over wide energy-angle spectra of events, and can be partly mimicked by systematic effects. For this reason, "hints" coming from current atmospheric data should be taken with a grain of salt, and should be possibly supported by independent datasets. For instance, we have attributed some importance to a weak preference for $\theta_{13} > 0$ found from atmospheric SK data in [4], only after it was independently supported by solar+KamLAND data [9] and, later, by LBL accelerator data [12]. Similarly, we have typically found a preference of atmospheric SK data for $\theta_{23} < \pi/4$ [4, 12]; in the next Section, we shall argue that such preference now finds some extra support in other datasets, and thus starts to be an interesting frontier to be explored.

In this work, the analysis of SK atmospheric neutrino data (phases IIV) [43, 44] is essentially unchanged with respect to [5]. We remind the reader that such data involve a very rich oscillation phenomenology which is sensitive, in principle, also to subleading effects related to the mass hierarchy, the θ_{23} octant and the CP phase δ. However, within the current experimental and theoretical uncertainties, it remains difficult to disentangle and probe such small effects at a level exceeding $1\sigma - 2\sigma$ [4]. Moreover, independent 3ν fits of SK I-IV data [5, 6, 44] converge on some but not all the hints about subleading effects, as discussed later. Therefore, as also argued in [5], we prefer to add these data only in the final LBL Acc. + Solar + KL + SBL Reac. + SK Atm. combination, in order to separately gauge their effects on the various 3ν parameters.

Finally, we shall also report the relative preference of the data for either NH or IH, as measured by the quantity $\chi^2_{\min}(IH) - \chi^2_{\min}(NH)$ This quantity cannot immediately be translated into "$N\sigma$" by taking the square root of its absolute value, because it refers to two discrete hypotheses, not connected by variations of a physical parameter. We shall not enter into the current debate about the statistical interpretation of $\Delta\chi^2_{I-N}$ because, as shown in the next Section, its numerical values are not yet significant enough to warrant a dedicated discussion.

3. Results on single oscillation parameters

In this Section we graphically report the results of our global analysis for each single oscillation parameter, making use of an of increasingly richer data sets, grouped in accordance with the methodology discussed in the previous Section.

Figures 1, 2 and 3 show the $N\sigma$ curves for the data sets defined in the previous Section. In each figure, the solid (dashed) curves refer to NH (IH); the two curves basically coincide for δm^2 and θ_{12}, since they are determined by Solar+KL data, which are largely insensitive to the hierarchy. For each parameter in Figs. 1-3, the more linear and symmetrical are the curves, the more gaussian is the associated probability distribution.

Figure 1 refers to the combination LBL Acc. + Solar + KL, which, by itself, sets highly significant lower and upper bounds on all the oscillation parameters but δ. In the figure, the relatively strong appearance signal in T2K [29] dominates the lower bound on θ_{13}, and also drives the slight but intriguing preference for $\delta \sim 1.5\pi$: indeed, for $\sin\delta \sim 1$, the CP-odd term in the $\nu_\mu \to \nu_e$ appearance probability [45, 46] is maximized [29]. It should be noted that current MINOS appearance data generally prefer $\sin\delta > 0$ [32, 33]; however, the stronger T2K appearance signal largely dominates in the global fit. On the other hand, MINOS disappearance data [32, 33] drive the slight preference for non-maximal θ_{23}, as compared with nearly maximal θ_{23} in

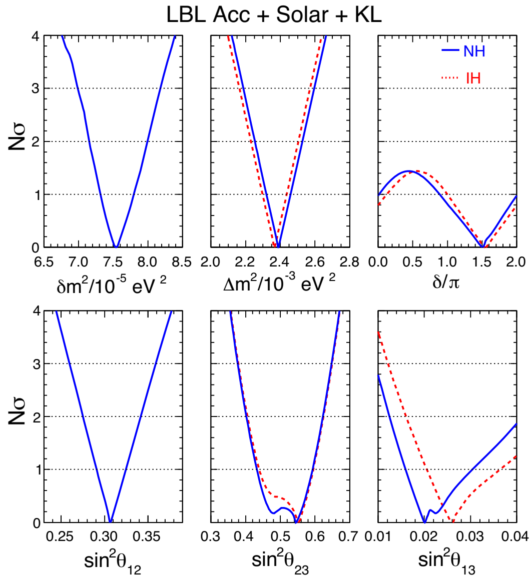

Figure 1: Combined 3ν analysis of LBL accelerator + Solar + KamLAND data. Bounds on the oscillation parameters in terms of number of standard deviations from the best fit $N\sigma$. Solid (dashed) lines refer to NH (IH). The horizontal dotted lines mark the 1σ, 2σ and 3σ levels for each parameter.

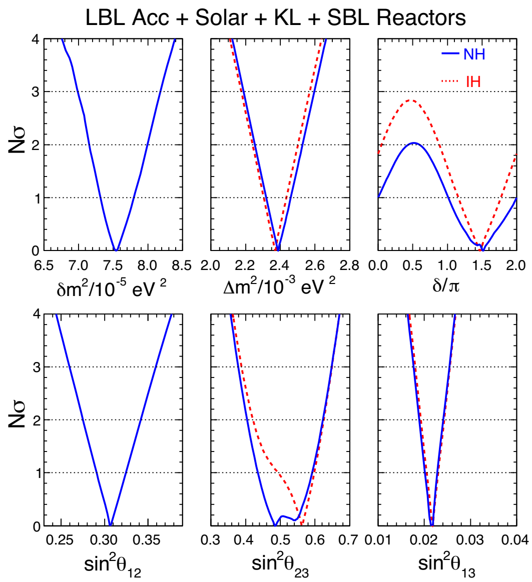

Figure 2: As in Fig. 1, but adding SBL reactor data.

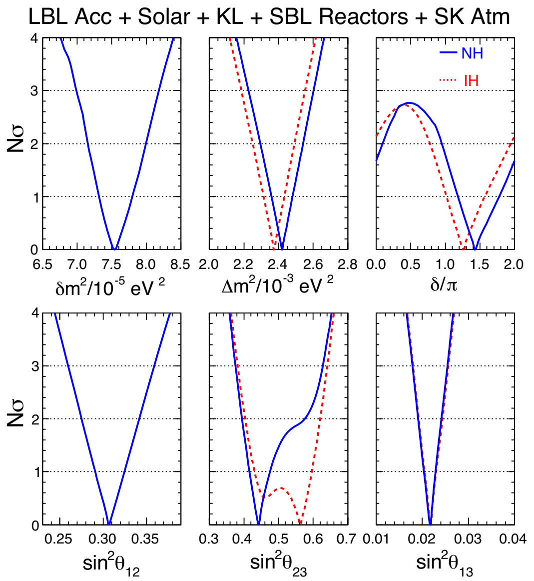

Figure 3: As in Fig. 2, but adding SK atmospheric data. Present global fit to all ν data.

T2K [28, 30]. The (even slighter) preference for the second θ_{23} octant is due to the interplay of LBL accelerator and Solar + KL data, as discussed in the next Section.

Figure 2 shows the results obtained by adding the SBL reactor data, which strongly reduce the θ_{13} uncertainty. Further effects of these data include: (i) a slightly more pronounced preference for $\delta \sim 1.5\pi$ and $\sin\delta < 0$, and (ii) a swap of the preferred θ_{23} octant with the hierarchy ($\theta_{23} < \pi/4$ in NH and $\theta_{23} > \pi/4$ in IH). These features will be interpreted in terms of parameter covariances in the next Section.

Figure 3 shows the results obtained by adding the SK atmospheric data, thus obtaining the most complete data set. The main differences with respect to Fig. 2 include: (i) an even more pronounced preference for $\sin\delta < 0$, with a slightly lower best fit at $\delta \sim 1.4\pi$; (ii) a slight reduction of the errors on Δm^2 and a relatively larger variation of its best-fit value with the hierarchy; (iii) a preference for θ_{23} in the first octant for both NH and IH, which is a persisting feature of our analyses. The effects (ii) and (iii) show that atmospheric neutrino data have the potential to probe subleading hierarchy effects, although they do not yet emerge in a stable or a significant way.

In the three figures an intriguing feature is the increasingly pronounced preference for nonzero CP violation with increasingly data sets, although the two CP conserving cases ($\delta = 0, \pi$) remain allowed at $< 2\sigma$ in both NH and IH, even when all data are combined (see Fig. 3). It is worth noticing that the two maximally CP-violating cases ($\sin\delta = \pm 1$) have opposite likelihood: while the range around $\delta \sim 1.5\pi$ ($\sin\delta = -1$) is consistently preferred, small ranges around $\delta \sim 0.5\pi$ ($\sin\delta = +1$) appear to be disfavored (at more than 2σ in Fig. 3). In the next few years, the appearance channel in LBL accelerator experiments will provide crucial data to investigate these hints about ν CP violation, with relevant implications for models of leptogenesis.

From the comparison of the three figures one can also notice a generic preference for non-maximal mixing ($\theta_{23} \neq 0$), although it appears to be weaker than in our previous analyses, essentially because the most recent T2K data [28, 30] prefer nearly maximal mixing, and thus "diluite" the opposite preference coming from MINOS [31, 33] and atmospheric data [4]. Moreover, the indications about the octant appear to be somewhat unstable in different combinations of data. In the present analysis, only atmospheric data consistently prefer the first octant in both hierarchies, but the overall significance remains at the level of $\sim 2\sigma$ in NH and is much lower in IH. These fluctuations show how difficult is to reduce the allowed range of θ_{23}. In this context, the disappearance channel in LBL accelerator experiments will provide crucial data to address the issue of non-maximal θ_{23} in the next few years.

Finally, we comment on the size of $\Delta\chi^2_{I-N}$, which, by construction, is not apparent in Figs. 1-3. We find $\Delta\chi^2_{I-N} = -1.3, -1.4, +0.3$ for the data sets in Figs. 1, 2 and 3, respectively. Unfortunately, such values are both small and with unstable sign, and do not provide us with any relevant indication about the hierarchy.

4. Global 3ν analysis: correlations between θ_{13}, θ_{23} and δ

In this Section we show the allowed regions for selected couples of oscillation parameters, and discuss some interesting correlation effects.

Figure 4 shows the results of the analysis in the plane ($\sin^2\theta_{23}$, $\sin^2\theta_{13}$), for both normal hierarchy (NH, upper panels) and inverted hierarchy (IH, lower panels). It is understood that all the other parameters are marginalized away. From left to right, the panels refer to increasingly rich datasets: LBL accelerator + Solar + KamLAND data (left), plus SBL reactor data (middle), plus SK atmospheric data (right).

In the left panels, a slight negative correlation emerges from LBL appearance data, since the dominant

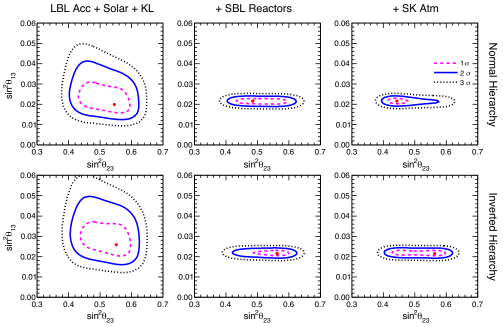

Figure 4: Results of the analysis in the plane charted by $(\sin^2\theta_{23}, \sin^2\theta_{13})$, all other parameters being marginalized away. From left to right, the regions allowed at 1, 2 and 3σ refer to increasingly rich datasets: LBL+solar+KamLAND data (left panels), plus SBL reactor data (middle panels), plus SK atmospheric data (right panels). Best fits are marked by dots. The three upper (lower) panels refer to normal (inverted) hierarchy.

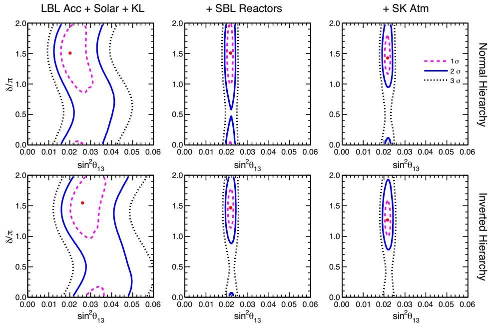

Figure 5: Results of the analysis in the plane charted by $(\sin^2\theta_{13}, \delta)$, all other parameters being marginalized away. From left to right, the regions allowed at 1, 2 and 3σ refer to increasingly rich datasets: LBL+solar+KamLAND data (left panels), plus SBL reactor data (middle panels), plus SK atmospheric data (right panels). A preference emerges for δ values around π in both normal hierarchy (NH, upper panels) and inverted hierarchy (IH, lower panels).

oscillation amplitude contains a factor $\sin^2\theta_{23}\sin^2\theta_{13}$ via Eq. (2). The contours extend towards relatively large values of θ_{13}, in particular for IH, in order to accomodate the relatively strong T2K appearance signal [29]. However, Solar + KamLAND data provide independent (although weaker) constraints on θ_{13} and, in particular, prefer $\sin^2\theta_{13} \sim 0.02$ in our analysis. This value is on the "low" side of the allowed regions and thus responsible for the relatively high value of θ_{23} at best fit, namely, for the second octant preference in both NH and IH. However, when current SBL reactor data are included (middle panels), a slightly higher value of θ_{13} ($\sin^2\theta_{13} \simeq 0.023$) is preferred with very small uncertainties: this value is high enough to shift the best-fit value of θ_{23} from the second to the first octant in NH, but not in IH. Finally, the inclusion of SK atmospheric data (right panels) provides in our analysis an overall preference for the first octant, which is however quite weak in IH. Unfortunately, as previously mentioned, the current hints about the θ_{23} octant do not appear particularly stable or convergent.

Figure 5 shoes the results of the analysis in the plane $(\sin^2\theta_{13}, \delta/\pi)$. The conventions used are the same as in Fig. 4. Since the boundary values $\delta/\pi = 0$ and 2 are physically equivalent, each panel could be ideally "curled" by smoothly joining the upper and lower boundaries.

The behavior of the CP violating phase δ is at the focus of current research in neutrino physics. In the left panels of Fig. 5 there is a remarkable preference for $\delta \sim 1.5\pi$, with a compromise reached between the relatively high values of θ_{13} preferred by the T2K appearance signal and the relatively low values preferred by Solar + KL data. In the middle panel, SBL reactor data strengthen this trend by reducing the covariance between θ_{13} and δ. It is quite clear that we can still learn much from the combination of accelerator and reactor data in the next few years. Finally, the inclusion of SK atmospheric data in the right panels also add some statistical significance to this trend, with a slight lowering of the best-fit value of δ.

5. Conclusions

In the light of the recent results coming from reactor and accelerator experiments, and of their interplay with solar and atmospheric data, we have updated the estimated $N\sigma$ ranges of the known 3ν parameters, $\Delta m^2, \delta m^2, \theta_{12}, \theta_{23}, \theta_{13}$, and we have revisited the status of the current unknowns, sign(Δm^2), sign$(\theta_{23} - \pi/4)$ and CP violation phase δ.

In order to understand how the various constraints and hints emerge from the analysis, and to appreciate their (in)stability, we have considered increasingly rich data set, starting from the combination of LBL accelerator + Solar plus KamLAND data, then adding SBL reactor data, and finally including atmospheric data. We have discussed the results both on single parameters and on selected couples of correlated parameters.

The results of the global analysis of all data are shown in Fig. 3, from which one can derive the ranges of the known parameters. One can appreciate the high accuracy reached in the determination of the known oscillation parameters; in particular, as compared with a previous analysis [5], one can appreciate a significant reduction of the θ_{13} uncertainties, and some changes in the $(\Delta m^2, \theta_{23})$ ranges.

We have also discussed in some detail the status of the unknown parameters. It turns out that the hints about θ_{23} octant appear somewhat unstable at present, while those about δ (despite being statistically weaker) seem to arise from an intriguing convergence of several pieces of data. Concerning the hierarchy, i.e. sign(Δm^2), we find no significant difference between normal and inverted mass ordering. However, assuming normal hierarchy, we find possible hints about the other two unknowns, namely: a slight preference for the first θ_{23} octant, and a possible indication for non-zero CP violation (with $\sin\delta < 0$), although at the level below 2σ for both the two cases. Note that the second hint appears also in inverted hierarchy, but with even lower statistical significance.

In the near or medium term, there are interesting plans to address the hierarchy issue via medium baseline reactor experiments [47, 48] capable to observe the interference between δm^2 and $\pm\Delta m^2$. Current long baseline accelerator experiments will probably improve the current indications on the θ_{23} octant and on the favored δ range, but with a significance exceeding 2σ only in the most favorable cases [49]. In a far future, more powerful accelerator searches are being planned to get indications at higher confidence level, especially for CP violation and mass hierarchy [50]. In this context, large-volume atmospheric neutrino detectors may also provide important probes of matter effects, mass hierarchy and θ_{23} [51, 52]. Of course, such expectations and the current planning of near- and far-future projects might be significantly altered by unexpected discoveries, e.g., of new neutrino states or new interactions, which might emerge at any time in this surprising and vibrant field of research.

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