The standard three-neutrino ($3\nu$) oscillation framework is being increasingly refined by results coming from different sets of experiments, using neutrinos from solar, atmospheric, accelerator and reactor sources. At present, each of the known oscillation parameters [the two squared mass gaps ($\delta m^2$, $\Delta m^2$) and the three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$)] is dominantly determined by a single class of experiments. Conversely, the unknown parameters [the mass hierarchy, the $\theta_{23}$ octant and the CP-violating phase $\delta$] can be currently constrained only through a combined analysis of various (eventually all) classes of experiments. In the light of recent new results coming from reactor and accelerator experiments, and of their interplay with solar and atmospheric data, we update the estimated $N\sigma$ ranges of the known $3\nu$ parameters, and revisit the status of the unknown ones. Concerning the hierarchy, no significant difference emerges between normal and inverted mass ordering. A slight overall preference is found for $\theta_{23}$ in the first octant and for nonzero CP violation with $\sin\delta < 0$; however, for both parameters, such preference exceeds $1\sigma$ only for normal hierarchy. We also discuss the correlations and stability of the oscillation parameters within different combinations of data sets.

I. INTRODUCTION

The vast majority of experimental results on neutrino flavor oscillations converge towards a simple three-neutrino ($3\nu$) framework, where the flavor states $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau)$ mix with the massive states $\nu_i = (\nu_1, \nu_2, \nu_3)$ via three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$) and a possible CP-violating phase $\delta \, [1]$. The observed oscillation frequencies are governed by two independent differences between the squared masses $m_i^2$, which can be defined as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, where $\Delta m^2 > 0$ and $< 0$ correspond to normal hierarchy (NH) and inverted hierarchy (IH), respectively \[2\]. At present we know five oscillation parameters, each one with an accuracy largely dominated by a specific class of experiments, namely: $\theta_{12}$ by solar data, $\theta_{13}$ by short-baseline (SBL) reactor data, $\theta_{23}$ by atmospheric data, mainly from Super-Kamiokande (SK), $\delta m^2$ by long-baseline reactor data from KamiLAND (KL), and $\Delta m^2$ 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 $\theta_{23}$ octant, or to discover CP-violating effects. A worldwide research program is underway to address such open questions and the related experimental and theoretical issues \[3\].

In this context, global neutrino data analyses \[4–7\] may be useful to get the most restrictive bounds on the known parameters, via the synergic combination of results from different classes of oscillation searches. At the same time, such analyses may provide some guidance about the unknown oscillation parameters, a successful example being represented by the hints of $\sin^2 2\theta_{13} \sim 0.02 \, [8–11]$, which were discussed before the discovery of $\theta_{13} > 0$ at reactors \[12–14\]. Given the increasing interest on the known oscillation parameters, as well as on possible hints about the unknown ones, we find it useful to revisit the previous analysis in \[1\], by including new relevant data which have become available recently (2013–2014), and which turn out to have an interesting impact on the fit results.

In particular, with respect to \[1\], we include the recent SBL reactor data from Daya Bay \[15\] and RENO \[16\], which reduce significantly the range of $\theta_{13}$. 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 \[17–19\] and MINOS \[20, 21\], which not only constrain the known parameters ($\Delta m^2$, $\theta_{23}$, $\theta_{13}$) but, in combination with other data, provide some guidance on the $\theta_{23}$ octant and on leptonic CP violation. To this regard, 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 $1\sigma$ only for normal hierarchy. No significant preference emerges for normal versus inverted hierarchy. Among the various fit results which can be of interest, we find it useful to report both the preferred $N\sigma$ ranges of each oscillation parameter and the 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.

Our work is structured as follows: In Sec. II we discuss some methodological issues concerning the analysis of different data sets and their combination. In Sec. III and IV we present, respectively, the updated ranges on single oscillation parameters, and the covariances between selected couples of parameters. We pay particular attention to the (in)stability and (in)significance of various hints about unknown parameters, also in comparison with other recent (partial or global) data analyses. Finally, we summarize our work in Sec. V.
II. METHODOLOGY

In this Section we briefly discuss the various data sets used and how they are combined in the global fit.

A. LBL Acc. + Solar + KL data

Concerning LBL accelerator data, we include the observed energy spectra of events, in both appearance (muon-to-electron flavor) and disappearance (muon-to-muon flavor) oscillation modes, as presented by the T2K [17,19] and MINOS [20,23] experiments. The theoretical spectra are calculated through a suitably modified version of the GLoBES software package [21,22]. We have verified that our fits reproduce very well the regions allowed at various C.L. in [17,18,20,23] under the same restrictive assumptions made therein on specific oscillation parameters (e.g., by limiting their range or fixing them a priori). However, we emphasize that no restrictions are applied in the global fit discussed in the next Section, where all the 3ν parameters are free to float.

At the current level of accuracy, LBL accelerator data (disappearance plus appearance) are known to be sensitive not only to the dominant parameters (±Δm², θ23, θ13), but also to the subdominant parameters (δm², θ12) and δ. For this reason, as argued in [4], it is convenient to analyze LBL accelerator data in combination with solar and KL data, which provide the necessary input for (δm², θ12). We remark that “Solar + KL” data (here treated as in [4]) provide a preference for sin²θ13 ~ 0.02 in our analysis, which plays a role in the combination “LBL Acc. + Solar + KL,” as discussed in the next Section.

B. Adding SBL reactor data

After the recent T2K observation of electron flavor appearance, the combination of LBL Acc. + Solar + KL data can provide a highly significant measurement of θ13 which, however, is somewhat correlated with two unknowns affecting LBL data: the CP violating phase δ and the θ23 octant. It is thus important to add the accurate and (δ, θ23)-independent measurement of θ13 coming from SBL reactor experiments, within a “LBL Acc. + Solar + KL + SBL Reac.” combination. In this work, SBL reactor neutrino data are statistically treated as in [26], with the further inclusion of the most recent data from Daya Bay [15] and RENO [16].

C. Adding atmospheric neutrino data

In this work, the analysis of SK atmospheric neutrino data (phases I–IV) [27,29] is essentially unchanged with respect to [4]. 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 θ23 octant and the CP phase δ [30]. However, within the current experimental and theoretical uncertainties, it remains difficult to disentangle and probe such small effects at a level exceeding ~ 1σ–2σ [2]. Moreover, independent 3ν fits of SK I–IV data [4,11,29] converge on some but not all the hints about subleading effects, as discussed later. Therefore, as also argued in [4], 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.

D. Conventions for allowed regions

In each of the above combined data analyses, the six oscillation parameters (Δm², δm², θ12, θ13, θ23) are left free at fixed hierarchy (either normal or inverted). Parameter ranges at N standard deviations are defined through $N\sigma = \sqrt{\chi^2 - \chi_{\text{min}}^2}$. As in [4], this definition is maintained also in plots involving two parameters, where it is understood that the previous Nσ ranges are reproduced by projecting the two-dimensional contours over one parameter axis [4]. It is also understood that, in each figure, all undisplayed parameters are marginalized away.

Finally, we shall also report the relative preference of the data for either NH or IH, as measured by the quantity $\Delta\chi^2_{\text{NH}} = \chi^2_{\text{min} (IH)} - \chi^2_{\text{min} (NH)}$. This quantity cannot immediately be translated into “Nσ” 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 $\Delta\chi^2_{\text{NH}}$ [31,53] because, as shown in the next Section, its numerical values are not yet significant enough to warrant a dedicated discussion.

III. RANGES OF OSCILLATION PARAMETERS

In this Section we graphically report the results of our global analysis of increasingly richer data sets, grouped in accordance to the previous discussion.

Figures 1, 2 and 3 show the Nσ curves for the data sets defined in Sec. II A, II B and II C, respectively. In each figure, the solid (dashed) curves refer to NH (IH); however, only the NH curve is shown for the δm² and θ12.
parameters, since the very tiny effects related to the NH-IH difference are unobservable in the fit. [Also note that the \( \delta m^2 \) and \( \theta_{12} \) constraints change very little in Figs. 1–3.] For each parameter in Figs. 1–3, the more linear and symmetrical are the curves, the more gaussian is the probability distribution associated to that parameter.

Figure 1 refers to the combination LBL Acc. + Solar + KL, which already sets (without the need of atmospheric and reactor data) highly significant lower and upper bounds on all the oscillation parameters, except for \( \delta \). In this figure, the relatively strong appearance signal in T2K [17] plays an important role: it dominates the lower bound on \( \theta_{13} \), and also drives the slight but intriguing preference for \( \delta \approx 1.5\pi \), since for \( \delta \approx -1 \) the CP-odd term in the \( \nu_e \rightarrow \nu_{\mu} \) appearance probability [33, 38] is maximized [17]. The trend wins over the current MINOS preference for \( \sin \delta \gtrsim 0 \) [21, 23], since the T2K appearance signal is stronger than the MINOS one and dominates in the global fit. On the other hand, MINOS disappearance data [21, 23] still lead to a slight preference for nonmaximal \( \theta_{23} \), as compared with nearly maximal \( \theta_{23} \) in the T2K data fit [18, 19]. The (even slighter) preference for the second \( \theta_{23} \) 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 (with respect to Fig. 1) the SBL reactor data, whose primary effect is a strong reduction of the \( \theta_{13} \) uncertainty. Secondary effects include: (i) a slightly more pronounced preference for \( \delta \approx 1.5\pi \) and \( \sin \delta < 0 \), and (ii) a swap of the preferred \( \theta_{23} \) 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 (with respect to Fig. 2) the SK atmospheric data in the most complete data set. It thus represents a synopsis of the current constraints on each oscillation parameter, according to our global 3\( \nu \) analysis. 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 \( \delta \approx 1.4\pi \); (ii) a slight reduction of the errors on \( \Delta m^2 \) and a relatively larger variation of its best-fit value with the hierarchy; (iii) a preference for \( \theta_{23} \) in the first octant for both NH and IH, which is a persisting feature of our analyses [2, 4]. 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 significant way. Concerning the effects (i), it should be noted that the existing full 3\( \nu \) analyses of atmospheric data [6, 29], as well as this work, consistently show that such data prefer \( \delta \approx 1.5\pi \) or slightly below, although with still large uncertainties. Table I summarizes in numerical form the results shown in Fig. 3.

When comparing Figs. 1–3, it is interesting to note an increasingly pronounced preference for nonzero CP violation with increasingly rich data sets, although the two CP-conserving cases (\( \delta = 0, \pi \)) remain allowed at \( \lesssim 2\sigma \) 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 \( \delta \approx 1.5\pi \) (\( \sin \delta \approx -1 \)) is consistently preferred, small ranges around \( \delta \approx 0.5\pi \) (\( \sin \delta \approx +1 \)) appear to be disfavored (at \( > 2\sigma \) in Fig. 3). In particular, for the specific case of NH and at \( \sim 90\% \) C.L. (\( \sim 1.6\sigma \)), only the range \( \sin \delta < 0 \) is allowed in Fig. 3, while the complementary one is disfavored, with the two CP-conserving cases being just “borderline.” In the next few years, the appearance channel in LBL accelerator experiments will provide crucial data to investigate these intriguing CP violation hints.

From the comparison of Figs. 1–3 one can also notice a slight overall preference for nonmaximal mixing (\( \theta_{23} \neq 0 \)), although it appears to be weaker than in [4], essentially because the most recent T2K data prefer nearly maximal mixing [18, 19], and thus “dilute” the opposite preference coming from MINOS [21, 23] 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 consistently prefer the first octant in both hierarchies, but the global fit significance is non-negligible (\( \sim 90\% \) C.L.) only in NH (see Fig. 3). By excluding LBL accelerator data from the global fit, the significance of \( \theta_{23} < \pi/4 \) would raise to \( \sim 2\sigma \) in NH and \( \sim 1.5\sigma \) in IH (not shown). It should be noted that, in a recent 3\( \nu \) global fit [4], the preferred octant toggles with the hierarchy, while in the latest atmospheric 3\( \nu \) analyses from the SK collaboration [28, 29] (without LBL accelerator data) the second octant is preferred in both NH and IH. We remark that such differences in the \( \theta_{23} \) fit results should not be considered as conflicting with each other, since they are all compatible within the (still large) quoted uncertainties.

We also emphasize that no atmospheric \( \nu \) analysis performed outside the SK collaboration [4, 7] can possibly reproduce in detail the official SK one, which currently includes hundreds of bins and > 150 systematic error sources [27]; on the other hand, this level of complexity also hinders the interpretation of subleading effects at the \( \sim 1\sigma \) level, such as those related to (non)maximal mixing, which are diluted over many data points and whose size is comparable to systematic uncertainties. We continue to argue, as discussed in [4], that our slight preference for \( \theta_{23} < \pi/4 \) in atmospheric \( \nu \) data stems from a small but persisting overall excess of low-energy electron-like events; see also [4] for a similar discussion. We are unable to trace the source of a slight preference for \( \theta_{23} > \pi/4 \) in the official SK analysis. In any case, these fluctuations in atmospheric fit results show how difficult it is to reduce the allowed range of \( \theta_{23} \) on the basis of atmospheric neutrino data only. In this context, the disappearance channel in LBL accelerator experiments will provide independent and increasingly accurate data to address the issue of nonmaximal \( \theta_{23} \) 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 \( \Delta \chi^2_{i-N} = -1.4, -1.1, -0.3 \) for the data sets in Figs. 1, 2, and 3, respectively. Such values are both small and decreasing with increasingly rich data sets; thus, they do not provide us with relevant indications about the hierarchy.
FIG. 1: Combined 3ν analysis of LBL Acc. + Solar + KL data: Bounds on the oscillation parameters in terms of standard deviations $N\sigma$ from the best fit. Solid (dashed) lines refer to NH (IH). The horizontal dotted lines mark the 1σ, 2σ and 3σ levels for each parameter (all the others being marginalized away). See the text for details.
FIG. 2: As in Fig. 1, but adding SBL reactor data.
FIG. 3: As in Fig. 2, but adding SK atmospheric data in a global 3ν analysis of all data.
IV. COVARIANCES OF OSCILLATION PARAMETERS

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

Figure 4 shows the global fit results in the plane charted by \( \sin^2 \theta_{23}, \Delta m^2 \), in terms of regions allowed at 1, 2 and 3\( \sigma \) (\( \Delta \chi^2 = 1, 4 \) and 9). Best fits are marked by dots, and it is understood that all the other parameters are marginalized away. From left to right, the panels refer to increasingly rich datasets, as previously discussed: LBL accelerator + solar + KamLAND data (left), plus SBL reactor data (middle), plus SK atmospheric data (right). The upper (lower) panels refer to normal (inverted) hierarchy. This figure shows the instability of the \( \theta_{23} \) octant discussed above, in a graphical format which is perhaps more familiar to most readers. It is worth noticing the increasing \( \Delta m^2 \) uncertainty. In this context, the measurement of \( \Delta m^2 \) at SBL reactor experiments (although not yet competitive with accelerator and atmospheric experiments\(^{[15]}\)) may become relevant in the future: being \( \theta_{23} \)-independent, it will help to break the current correlation with \( \theta_{23} \) and to improve the overall \( \Delta m^2 \) accuracy in the global fit.

Figure 5 shows the allowed regions in the plane charted by \( \sin^2 \theta_{23}, \sin^2 \theta_{13} \). Let us consider first the left panels, where a slight negative correlation between these two parameters emerges from LBL appearance data, as discussed in\(^{[4]}\). The contours extend towards relatively large values of \( \theta_{13} \), especially in IH, in order to accommodate the relatively strong T2K appearance signal\(^{[17]}\). However, solar + KL data provide independent (although weaker) constraints on \( \theta_{13} \) and, in particular, prefer \( \sin^2 \theta_{13} \sim 0.02 \) in our analysis. This value, being on the “low side” of the allowed regions of \( \theta_{13} \), leads (via anticorrelation) to a best-fit value of \( \theta_{23} \) on the “high side” (i.e., in the second-octant) for both NH and IH. However, when current SBL reactor data are included in the middle panels, a slightly higher value of \( \theta_{13} \) is preferred \( \sin^2 \theta_{13} \sim 0.023 \) with very small uncertainties: this value is high enough to flip the \( \theta_{23} \) best fit from the second to the first octant in NH, but not in IH.

It is useful to compare the left and middle panels of Fig. 5 with the analogous ones of Fig. 1 from our previous analysis\(^{[4]}\): the local minima in the two \( \theta_{23} \) octants are now closer and more degenerate. This fact is mainly due to the persisting preference of T2K disappearance data for nearly maximal mixing\(^{[15]}\), which is gradually diluting the MINOS preference for nonmaximal mixing\(^{[22]}\). Moreover, accelerator data are becoming increasingly competitive with atmospheric data in constraining \( \theta_{23} \)\(^{[19]}\). Therefore, although we still find (as in previous works\(^{[2, 4]}\)) that atmospheric data alone prefer \( \theta_{23} < \pi/4 \), the overall combination with current non-atmospheric data (right panels of Fig. 5) makes this indication less significant than in previous fits (compare, e.g., with Fig. 1 in\(^{[4]}\)), especially in IH where non-atmospheric data now prefer the opposite case \( \theta_{23} > \pi/4 \). The fragility of the \( \theta_{23} \) octant fit (with and without atmospheric neutrinos) was also noted in the recent analysis\(^{[6]}\). In conclusion, the overall indication for \( \theta_{23} < \pi/4 \) in both NH and IH (right panels of Fig. 5) is currently weaker than in our previous analysis\(^{[4]}\); in particular, its significance reaches only \( \sim 1.6 \sigma \) (90\% C.L.) in NH, while it is \( < 1 \sigma \) in IH. Further accelerator neutrino data will become increasingly important in assessing the status of \( \theta_{23} \) in the near future.

### TABLE I: Results of the global 3\( \nu \) oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3\( \sigma \) ranges for the 3\( \nu \) mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that \( \Delta m^2 \) is defined herein as \( m_3^2 - (m_1^2 + m_2^2)/2 \), with +\( \Delta m^2 \) for NH and −\( \Delta m^2 \) for IH. The CP violating phase is taken in the (cyclic) interval \( \delta/\pi \in [0, 2] \).

| Parameter | Best fit | 1\( \sigma \) range | 2\( \sigma \) range | 3\( \sigma \) range |
|-----------|----------|----------------------|----------------------|----------------------|
| \( \delta m^2/10^{-5} \text{ eV}^2 \) (NH or IH) | 7.54 | 7.32 – 7.80 | 7.15 – 8.00 | 6.99 – 8.18 |
| \( \sin^2 \theta_{12}/10^{-1} \) (NH or IH) | 3.08 | 2.91 – 3.25 | 2.75 – 3.42 | 2.59 – 3.59 |
| \( \Delta m^2/10^{-3} \text{ eV}^2 \) (NH) | 2.43 | 2.37 – 2.49 | 2.30 – 2.55 | 2.23 – 2.61 |
| \( \Delta m^2/10^{-3} \text{ eV}^2 \) (IH) | 2.38 | 2.32 – 2.44 | 2.25 – 2.50 | 2.19 – 2.56 |
| \( \sin^2 \theta_{13}/10^{-2} \) (NH) | 2.34 | 2.15 – 2.54 | 1.95 – 2.74 | 1.76 – 2.95 |
| \( \sin^2 \theta_{13}/10^{-2} \) (IH) | 2.40 | 2.18 – 2.59 | 1.98 – 2.79 | 1.78 – 2.98 |
| \( \sin^2 \theta_{23}/10^{-1} \) (NH) | 4.37 | 4.14 – 4.70 | 3.93 – 5.52 | 3.74 – 6.26 |
| \( \sin^2 \theta_{23}/10^{-1} \) (IH) | 4.55 | 4.24 – 5.94 | 4.00 – 6.20 | 3.80 – 6.41 |
| \( \delta/\pi \) (NH) | 1.39 | 1.12 – 1.77 | 0.00 – 0.16 ⊕ 0.86 – 2.00 | — |
| \( \delta/\pi \) (IH) | 1.31 | 0.98 – 1.60 | 0.00 – 0.02 ⊕ 0.70 – 2.00 | — |
FIG. 4: Results of the analysis in the plane charted by \((\sin^2 \theta_{23}, \Delta m^2)\), all other parameters being marginalized away. From left to right, the regions allowed at 1, 2 and 3\(\sigma\) refer to increasingly rich datasets: LBL accelerator + 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.

FIG. 5: As in Fig. 4, but in the plane \((\sin^2 \theta_{23}, \sin^2 \theta_{13})\).
FIG. 6: As in Fig. 4, but in the plane ($\sin^2 \theta_{13}, \delta/\pi$).

FIG. 7: As in Fig. 4, but in the plane ($\sin^2 \theta_{23}, \delta/\pi$).
Figure 6 shows the allowed regions in the plane \((\sin^2 \theta_{13}, \delta/\pi)\), which is at the focus of current research in neutrino physics. In the left panels, with respect to previous results in the same plane [4], there is now a more marked preference for \(\delta \sim 1.5\pi\), where a compromise is reached between the relatively high \(\theta_{13}\) values preferred by the T2K appearance signal, and the relatively low value preferred by solar + KL data. In the middle panel, SBL reactor data strengthen this trend by reducing the covariance between \(\theta_{13}\) and \(\delta\). 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 adds some statistical significance to this trend, with a slight lowering of the best-fit value of \(\delta\).

Figure 7 completes our discussion by showing the allowed regions in the plane \((\sin^2 \theta_{23}, \delta/\pi)\). The shapes of the allowed regions are rather asymmetrical in the two \(\theta_{23}\) octants, which are physically inequivalent in the flavor appearance phenomenology of accelerator and atmospheric neutrinos. Therefore, reducing the octant degeneracy will also help, indirectly, our knowledge of \(\delta\). Eventually, more subtle covariances may be studied in this plane [37], but we are still far from the required accuracy.

V. SUMMARY AND CONCLUSIONS

In the light of recent new data (circa 2013-2014) 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 \((\Delta m^2, \delta, \theta_{12}, \theta_{13}, \theta_{23})\), and we have revisited the status of the current unknowns \([\text{sign}(\Delta m^2), \text{sign}(\theta_{23} - \pi/4), \delta]\). The results of the global analysis of all data are shown in Fig. 3 and in Table I, from which one can derive the ranges of the known parameters; in particular, as compared with a previous analysis [4], one can appreciate a significant reduction of the \(\theta_{13}\) uncertainties, and some changes in the \((\Delta m^2, \theta_{23})\) ranges.

We have also discussed in detail the status of the unknown parameters. Concerning the hierarchy \([\text{sign}(\Delta m^2)]\), we still find no appreciable difference between normal and inverted mass ordering. With respect to [4], we continue to find an overall preference for the first \(\theta_{23}\) octant, but with a lower statistical significance, which exceeds 1σ only in NH. This feature of the current analysis is mainly due to the persisting preference of (increasingly accurate) T2K disappearance data for nearly maximal mixing [19], as opposed to somewhat different indications coming from the analysis of MINOS [23] and atmospheric data [4]. Probably the most intriguing feature of the current data analysis is the emergence of an overall preference for nonzero CP violation around \(\delta \sim 1.4\pi\) (with \(\sin \delta < 1\)) at \(\gtrsim 1\sigma\) level, while some ranges with \(\sin \delta > 1\) are disfavored at \(\gtrsim 2\sigma\).

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 sets, starting from the combination of LBL accelerator plus solar plus KamLAND data, then adding SBL reactor data, and finally including atmospheric data. We have discussed the fit results both on single parameters and on selected couples of correlated parameters. We remark that the \(\theta_{23}\) octant issue appear somewhat unstable at present, while the hints about \(\delta\) (despite being still statistically weak) seem to arise from an overall convergence of several pieces of data. Of course, these might just be fluctuations: the search for \([\text{sign}(\Delta m^2), \text{sign}(\theta_{23} - \pi/4), \delta]\) is still open to all possible outcomes. In this context, joint 3ν analyses of LBL accelerator data (in both appearance and disappearance mode) and SBL reactor data have the potential to bring interesting new results in the next few years.

Acknowledgments

F.C., G.L.F., E.L., A.M., and D.M. acknowledge support from the Istituto Nazionale di Fisica Nucleare (INFN, Italy) through the “Astroparticle Physics” research project. A.P. acknowledges support from the European Community through a Marie Curie Intra-European Fellowship, grant agreement PIEF-GA-2011-299582 “On the Trails of New Neutrino Properties.” He also acknowledges partial support from the European Union FP7 ITN INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442). Preliminary results of this work were presented by E.L. at NNN13, XIV International Workshop on Next generation Nucleon Decay and Neutrino Detectors (Kashiwa, Japan, 2013), at NuPhys 2013, Topical research meeting on Prospects in Neutrino Physics (London, UK, 2013); and at ICFA 2014, European meeting of the International Committee for Future Accelerators (Paris, France, 2014).
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