Analysis of the atmospheric neutrino data in terms of $3\nu$ oscillations

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A global analysis of atmospheric and reactor neutrino data is presented in terms of three–neutrino oscillations. We consider in our analysis both contained events and upward-going $\nu$-induced muon events, including the previous data samples of Fréjus, IMB, Nusex, and Kamioka experiments as well as the full 71 kton-yr (1144 days) Super–Kamiokande data set, the recent 5.1 kton-yr contained events of Soudan–2 and the results on upgoing muons from the MACRO detector. After presenting the results for the analysis of atmospheric data alone, we add to our data sample the reactor bound of the CHOOZ experiment, showing and important complementarity between the atmospheric and reactor limits which results in a stronger constraint on the allowed value of $\theta_{13}$.

1. Introduction

Super–Kamiokande high statistics data $^{[1,2]}$ indicate a clear deficit in the $\nu_\mu$ atmospheric events, while $\nu_e$ events appear to be in good agreement with the Standard Model (SM) prediction. Nowadays, the present status of two–family oscillations clearly favour the $\nu_\mu \rightarrow \nu_\tau$ channel, while the $\nu_\mu \rightarrow \nu_e$ scenario is finally excluded $^{[1]}$; this behaviour is also strengthened by the recent results of reactor experiments $^{[3]}$. However, a complete understanding of the phenomenological picture emerging from the atmospheric neutrino data require to investigate the whole three–neutrino parameter space.

In this paper we present a global analysis of atmospheric and reactor neutrino data in terms of three–family neutrino oscillations. We include in our analysis all the contained events as well as the upward-going neutrino-induced muon fluxes, including both the previous data samples of Fréjus $^{[4]}$, IMB $^{[5]}$, Nusex $^{[6]}$ and Kamioka experiments $^{[7]}$ and the full 71 kton-yr Super–Kamiokande data set $^{[2]}$, the recent 5.1 kton-yr contained events of Soudan–2 $^{[8]}$ and the results on upgoing muons from the MACRO detector $^{[9]}$. We also determine the constraints implied by the CHOOZ reactor experiments $^{[3]}$.

In Sec. $^{[2]}$ we give a brief introduction to the atmospheric neutrino problem, describing the data samples, the statistical analysis and the theoretical calculation of the conversion probabilities for atmospheric and reactor neutrinos in the framework of three–neutrino mixing. In Sec. $^{[4]}$ we describe our results for atmospheric neutrino fits, both by themselves and also in combination with the reactor data. Finally in Sec. $^{[3]}$ we summarize the work and present our conclusions.

2. Data samples and statistical analysis

Underground experiments can record atmospheric neutrinos both by direct observation of their interactions inside the detector (the so-called contained events), and by indirect detection of the muons produced by charged current interactions in the vicinity of the detector (upgoing–muons events).

Contained events have been recorded at six underground experiments, using either water-Cerenkov detectors (Kamiokande $^{[7]}$, IMB $^{[5]}$ and Super–Kamiokande $^{[2]}$) or iron calorimeters (Fréjus $^{[4]}$, NUSEX $^{[6]}$ and Soudan–2 $^{[8]}$). For Kamiokande and Super–Kamiokande, the contained data sample is further divided into sub-GeV events, with visible energy below 1.2 GeV, and multi-GeV events, with lepton energy above this cutoff. Sub-GeV events arise from neutrinos of several hundreds of MeV, while multi-GeV events are originated by neutrinos with energies of several GeV.
Concerning upgoing muons events, in our analysis we considered the latest results from Super–Kamiokande [2] and from the MACRO [9] experiment. For Super–Kamiokande, the data sample is further divided into stopping muons, if the muon stops inside the detector, and through–going muons, if the muon track crosses the full detector; for the MACRO experiment, we only considered through–going events. On average, stopping muons arise from neutrinos with energies around ten GeV, while through–going muons are originated by neutrinos with energies around hundred GeV.

In order to study the results for the different types of atmospheric neutrino data, we have defined the following combinations of data sets:

- FINKS (10 points): the $e$-like and $\mu$-like event rates from the five experiments Fréjus, IMB, Nusex, Kamiokande sub-GeV and Soudan–2;
- CONT–UNBIN (16 points): the rates in FINKS together with Kamiokande multi-GeV and Super–Kamiokande sub- and multi-GeV $e$-like and $\mu$-like event rates, without including the angular information;
- CONT–BIN (40 points): same as CONT–UNBIN, but also including the angular information (5 angular bins) for Kamiokande multi-GeV and SK sub- and multi-GeV.
- UP–$\mu$ (25 points): muon fluxes for stopping (5 angular bins) and through–going (10 bins) muons at Super–Kamiokande and MACRO;
- SK (35 points): the full Super–Kamiokande data sample (both contained and through–going events);
- ALL–ATM (65 points): the full data sample of all atmospheric neutrino data.

For each of these combinations we have performed a $\chi^2$ analysis by computing the $\chi^2$ as a function of the neutrino oscillation parameters. Following closely the analysis of Refs. [10,11], we have used the actual number of $e$-like and $\mu$–like events, rather than just their ratios, paying attention both to the correlations between the sources of errors in the muon and electron predictions and to those amongst the errors of different energy data samples. Thus we define $\chi^2$ as

$$\chi^2 = \sum_{I,J} \Delta N_I \cdot (\sigma^2_{\text{exp}} + \sigma^2_{\text{th}})^{-1} \cdot \Delta N_J,$$

(1)

$$\sigma^2_{IJ} = \sigma_{\alpha}(A)\rho_{\alpha\beta}(A,B)\sigma_{\beta}(B).$$

(2)

where $\Delta N_I \equiv N^{exp}_I - N^{th}_I$, $N^{th}_I$ being the predicted number of events (or the predicted value of the flux, in the case of upgoing muons) and $N^{exp}_I$ the corresponding experimental measurement. Here $I, J$ stand for any combination of experimental data sets and event-types considered, i.e. $I = (A, \alpha)$ and $J = (B, \beta)$ where $A, B$ label the different data samples and $\alpha, \beta$ denote the flavour of the final lepton. Finally, $\sigma^2_{IJ}$ is the error matrix containing the theoretical/experimental errors, $\rho_{\alpha\beta}(A,B)$ is the correlation matrix and $\sigma_{\alpha}(A)$ is the theoretical/experimental error for the number of $\alpha$–like events in the A experiment.

A detailed discussion of the errors and correlations used in our analysis can be found in Ref. [11], as well as in the appendices of Refs. [10,11], both for contained and for the upgoing muon data analysis.

In general, the determination of the oscillation probabilities require the solution of the Schrödinger evolution equation of the neutrino system in the Earth–matter background. For a CP-conserving three–flavour scenario, this equation reads

$$\frac{d\vec{\nu}}{dt} = \mathbf{H} \vec{\nu}, \quad \mathbf{H} = \mathbf{R} \cdot \mathbf{H}_0^d \cdot \mathbf{R}^\dagger + \mathbf{V},$$

(3)

where $\vec{\nu} \equiv (\nu_e, \nu_\mu, \nu_\tau)$, $\mathbf{R}$ is the orthogonal matrix connecting the flavour basis and the mass basis in vacuum, $\mathbf{H}_0^d$ is the vacuum Hamiltonian and $\mathbf{V}$ describes charged-current forward interactions in matter:

$$\mathbf{H}_0^d = \frac{1}{2E_\nu} \text{diag} (-\Delta m^2_{21}, 0, \Delta m^2_{32})$$

(4)

$$\mathbf{V} = \text{diag} \left( \pm \sqrt{2}G_F N_e, 0, 0 \right).$$

(5)

In general, the neutrino transition probabilities depend on five parameters, namely the two mass-squared differences $\Delta m^2_{21}, \Delta m^2_{32}$ and the three
mixing angles $\theta_{12}, \theta_{13}, \theta_{23},$ however in order to accommodate both solar and atmospheric neutrino data into a unified framework an hierarchy between $\Delta m^2_{21}$ and $\Delta m^2_{32}$ is required:

$$\Delta m^2_{\odot} = \Delta m^2_{21}, \quad \Delta m^2_{\text{atm}} = \Delta m^2_{32} \Rightarrow \Delta m^2_{21} \ll \Delta m^2_{32}. \quad (6)$$

As a consequence, for what concerns the analysis of atmospheric neutrino events it is safe to set $\Delta m^2_{21} = 0$, in which case the angle $\theta_{12}$ also cancels out and the matrix $\mathbf{R}$ can be written as:

$$\mathbf{R} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -s_{13}c_{23} & -s_{23} & c_{23}c_{13} \end{pmatrix}. \quad (7)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. As a result, the $3\nu$ propagation of atmospheric neutrinos can be well described in terms of only three parameters: $\Delta m^2_{23}, \theta_{23}$ and $\theta_{13}$.

When $\theta_{13} = 0$, atmospheric neutrinos involve only $\nu_\mu \rightarrow \nu_\tau$ conversions, and in this case there are no matter effects, so that the solution of Eq. (6) is straightforward and the survival probability takes the well-known vacuum form

$$P_{\mu\mu} = 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right), \quad (8)$$

where $L$ is the path-length traveled by neutrinos of energy $E_\nu$. On the other hand, in the general case of three–neutrino scenario with $\theta_{13} \neq 0$ the presence of the matter potentials requires a numerical solution of the evolution equations in order to obtain the oscillation probabilities for atmospheric neutrinos $P^m_{\alpha\beta}$, which are different for neutrinos and anti-neutrinos because of the reversal of sign in Eq. (4). In our calculations, we have used for the matter density profile of the Earth the approximate analytic parameterization of the PREM model given in Ref. [12].

The CHOOZ experiment [22] searches for disappearance of $\bar{\nu}_e$ produced in a power station with two pressurized-water nuclear reactors with a total thermal power of 8.5 GW (thermal). At the detector, located at $L \approx 1$ Km from the reactors, the $\bar{\nu}_e$ reaction signature is the delayed coincidence between the prompt $e^+$ signal and the signal due to the neutron capture in the Gd-loaded scintillator. Since no evidence was found for a deficit of measured vs. expected neutrino interactions, the result of this experiment is a bound on the oscillation parameters describing the mixing of $\nu_e$ with all the other neutrino species. Under the assumption $\Delta m^2_{21} \approx 0$, the only relevant parameters are $\theta_{13}$ and $\Delta m^2_{31} \approx \Delta m^2_{32}$, and in Fig. 1 we show the exclusion plot in this plane. From this figure we see that at 99% CL the region $\Delta m^2_{32} \gtrsim 10^{-3}$ eV$^2$ and $0.044 \leq \tan^2 \theta_{13} \lesssim 23$ is excluded.

3. Results of the analysis

The first result of our analysis refers to the no-oscillation hypothesis. As can be seen from the fifth column of Table 1 the $\chi^2$ values in the absence of new physics clearly show that the experimental data are totally inconsistent with the SM hypothesis; in fact, the global analysis (ALL-ATM combination) gives $\chi^2_{5M} = 191.7/(65 \, \text{d.o.f.})$, corresponding to a probability $\lesssim 10^{-14}$. This result is rather insensitive to the inclusion of the CHOOZ reactor data, as can be seen from the last line of Table 1. Therefore, the Standard Model can be safely ruled out. In
It is evident that, despite of the large statistics provided by Super–Kamiokande, it is not possible from the information on the total event rates only (i.e. without taking into account the angular dependence) to place any upper bound on $\Delta m_{32}^2$, and even the lower bound $\Delta m_{32}^2 > 2 \times 10^{-3}$ eV$^2$ is rather weak. Moreover, none of the sets can provide a relevant constraint neither on $\tan^2 \theta_{13}$ nor on $\tan^2 \theta_{23}$.

Conversely, in Fig. 3 we display the allowed regions in $(\tan^2 \theta_{23}, \Delta m_{32}^2)$ for the combinations CONT–BIN, UP–$\mu$ and ALL–ATM, which also include the information on the angular distribution of the incoming neutrinos. For what concerns contained events (CONT–BIN), let us note that the upper bound on $\Delta m_{32}^2$ is now rather strong (better than $10^{-2}$ eV$^2$) as a consequence of the fact that no suppression for downgoing $\nu_\mu$ neutrinos is observed. This imposes a lower bound on the neutrino oscillation length and consequently an upper bound on the mass difference. However contained events alone still allow values of

### Table 1
Minimum $\chi^2$ values and best-fit points for various sets of atmospheric neutrino data.

| Data Set       | d.o.f. | $\tan^2 \theta_{13}$ | $\tan^2 \theta_{23}$ | $\Delta m_{32}^2$ [eV$^2$] | $\chi^2_{\text{SM}}$ | $\chi^2_{\text{min}}$ |
|----------------|--------|-----------------------|-----------------------|--------------------------|-----------------------|-----------------------|
| FINKS          | 10–3   | 1.                    | > 100                 | $0.9 \times 10^{-3}$     | 29.9                  | 14.8                  |
| CONT–UNBIN     | 16–3   | 0.33                  | > 100                 | $4.2 \times 10^{-3}$     | 58.1                  | 18.4                  |
| CONT–BIN       | 40–3   | 0.03                  | 1.6                   | $2.5 \times 10^{-3}$     | 115.1                 | 41.3                  |
| SK–CONT        | 20–3   | 0.03                  | 0.89                  | $2.3 \times 10^{-3}$     | 80.7                  | 14.5                  |
| UP–$\mu$       | 25–3   | 0.23                  | 3.3                   | $7.1 \times 10^{-3}$     | 50.3                  | 25.1                  |
| SK             | 35–3   | 0.005                 | 1.3                   | $2.8 \times 10^{-3}$     | 131.4                 | 27.8                  |
| ALL–ATM        | 65–3   | 0.03                  | 1.6                   | $3.3 \times 10^{-3}$     | 191.7                 | 61.7                  |
| ALL–ATM + Chooz| 66–3   | 0.005                 | 1.4                   | $3.1 \times 10^{-3}$     | 191.8                 | 62.5                  |

### Table 2
Upper bounds on $\theta_{13}$ at 90 and 99% CL from the analysis of the different samples and combinations of atmospheric neutrino data.

| Data Set       | $\tan^2 \theta_{13}$ | $\theta_{13}$ [deg] |
|----------------|-----------------------|----------------------|
|                | min  | 90%  | 99%  | min  | 90%  | 99% |
| FINKS          | 1.   | 16.4 | 42.7 | 76.1° | 81.3° |
| CONT–UNBIN     | 0.33 | 10.0 | 13.6 | 72.5° | 74.8° |
| CONT–BIN       | 0.03 | 0.97 | 2.34 | 44.6° | 56.8° |
| UP–$\mu$       | 0.23 | 0.55 | 7.71 | 36.5° | 70.2° |
| SK             | 0.005 | 0.33 | 0.68 | 29.8° | 39.5° |
| ALL–ATM        | 0.03 | 0.34 | 0.57 | 30.1° | 37.0° |
| ALL–ATM + Chooz| 0.005 | 0.043 | 0.08 | 11.7° | 15.5° |

contrast, the $\chi^2$ for the global analysis decreases to 61.7/(62 d.o.f.) (or 62.5/(63 d.o.f.) including CHOOZ), acceptable at the 51% CL, when oscillations are assumed.

Table II also gives the minimum $\chi^2$ values and the resulting best-fit points for the various combinations of data sets considered. Note that for FINKS, CONT–UNBIN and UP–$\mu$ combinations the best-fit point is characterized by a rather large value of $\tan^2 \theta_{13}$, while all the other data set favour a value very close to 0. The corresponding allowed regions in the $(\tan^2 \theta_{23}, \Delta m_{32}^2)$ plane at 90, 95 and 99% CL for the different combinations are depicted in Figs. 2 and 3. Note that the value $\tan^2 \theta_{13} = 0$ corresponds to pure $\nu_\mu \rightarrow \nu_\tau$ oscillations, and in this case the contour regions are symmetric under the transformation $\theta_{23} \rightarrow \pi/4 - \theta_{23}$ due to the cancellation of matter effects (cfr. Eq. 8).

In Fig. 2 we present the allowed regions in $(\tan^2 \theta_{23}, \Delta m_{32}^2)$ for different values of $\tan^2 \theta_{13}$, for the FINKS and CONT–UNBIN combinations.
\[ \Delta m_{32}^2 < 10^{-3} \text{ eV}^2. \]

Note also that the allowed region is still rather large for \( \tan^2 \theta_{13} \approx 0.7 \) and at 99% CL it only disappears for \( \tan^2 \theta_{13} \approx 2.4 \).

This situation is completely reversed when considering upgoing muon events (UP–\( \mu \)). This combination is complementary to CONT–BIN, in the sense that the corresponding data sets are completely disjoint. In contrast to the CONT–BIN case, now the upper bound on \( \Delta m_{32}^2 \) is much weaker (\( \approx 3 \times 10^{-2} \text{ eV}^2 \)), while the lower bound is now stronger. Again, no relevant bound can be put on \( \theta_{13} \) from the analysis of upgoing events alone.

Due to the complementarity between the properties of the CONT–BIN and UP–\( \mu \) combinations, merging them into a single data set leads to much stronger constraints on the parameter space. In the lower panel of Fig. 3 we show the allowed regions in \( (\tan^2 \theta_{23}, \Delta m_{32}^2) \) from the combined analysis of all the atmospheric neutrino data (ALL–ATM). Due to the large statistics provided by the Super–Kamiokande experiment, \( \Delta m_{32}^2 \) is strongly bounded both from above and from below. Moreover no region of parameter space is allowed (even at 99% CL) for \( \tan^2 \theta_{13} \gtrsim 0.6 \); therefore, this limit can be considered as the strongest bound which can be put on \( \tan^2 \theta_{13} \) from the analysis of atmospheric events alone.

All these features can be more quantitatively observed in Fig. 4, where we show the dependence of \( \Delta \chi^2 \) on \( \tan^2 \theta_{13} \) and \( \Delta m_{32}^2 \), for the different combination of atmospheric neutrino events. In these plots all the neutrino oscillation parameters which are not displayed have been “integrated out”, i.e. the displayed \( \Delta \chi^2 \) is minimized with respect to all the non-displayed variables. From the left panels of Fig. 4 we can read the upper bound on \( \tan^2 \theta_{13} \) that can be extracted from the analysis of the different samples of atmospheric data alone regardless of the values of the other parameters of the three–neutrino mixing matrix; the corresponding 90 and 99% CL bounds are summarized in Table 2. Conversely, from the right panels of Fig. 4 we extract the value of \( \Delta m_{32}^2 \) allowed by the different combinations, irrespective of the values of the other mixing parameters.

In order to illustrate the main effect of varying the angle \( \theta_{13} \) in the description of the angular distribution of atmospheric neutrino events, we show in Fig. 5 the zenith-angle distribution for the Super–Kamiokande experiment. The thick solid
Figure 4. Dependence of $\Delta \chi^2$ on $\tan^2 \theta_{13}$ and on $\Delta m^2_{32}$, for different combinations of atmospheric neutrino events (upper panels) and for the combination ALL–ATM (lower panels, the dashed line includes also CHOOZ). The dotted horizontal lines correspond to 90 and 99% CL.

Figure 5. Zenith-angle distributions for Super–Kamiokande events. The thick solid line is the expected distribution in the SM, while the thin one is the prediction for the overall (ALL–ATM) best-fit point. The dashed (dotted) histogram correspond to the distributions for $\tan^2 \theta_{13} = 0.33$ (0.54), $\tan^2 \theta_{23} = 3.0$ (3.1) and $\Delta m^2_{32} = 3.3 \times 10^{-3}$ eV$^2$, which are marginally allowed at 90 (99)% CL.

This is simply understood since it is clear from Fig. 4 that $e$-like contained events are well accounted for within the no-oscillation hypothesis. From this figure we see that increasing $\tan^2 \theta_{13}$ leads to an increase in all the contained event rates; this is due to the fact that an increasing fraction of $\nu_\mu$ now oscillates as $\nu_\mu \rightarrow \nu_e$ (also $\nu_e$'s oscillate as $\nu_e \rightarrow \nu_\mu$ but since the $\nu_e$ fluxes are smaller this effect is relatively less important) spoiling the good description of the $e$–type data, especially for upgoing multi-GeV electron events. For multi-GeV events all the curves coincide with the SM one for downgoing neutrinos which did

line is the expected distribution in the absence of oscillation (SM hypothesis), while the thin full line represents the prediction for the overall best-fit point of the full atmospheric data set (ALL–ATM, see also Table 1) which occurs at $\tan^2 \theta_{13} = 0.03$. The dashed and dotted histograms correspond to points which are marginally allowed at 90 and 99% CL, respectively, and occur at $\tan^2 \theta_{13} = 0.33$ and 0.54 (cfr. Table 2). For each such $\theta_{13}$ value we choose $\Delta m^2_{32}$ and $\theta_{32}$ so as to minimize the $\chi^2$. Clearly the description of the data is excellent as long as the oscillation is mainly in the $\nu_\mu \rightarrow \nu_\tau$ channel (small $\theta_{13}$);
not have the time to oscillate; this effect is lost in the sub-GeV sample due to the large opening angle between the neutrino and the detected lepton. We also see that for multi-GeV electron neutrinos the effect of $\theta_{13}$ is larger close to the vertical ($\cos \theta = -1$) where the expected ratio of fluxes in the SM $R(\nu_\mu/\nu_e)$ is larger. Conversely the relative effect of $\theta_{13}$ for $\nu_\mu$ is larger close to the horizontal direction, $\cos \theta = 0$. Concerning upward-going muons events, we see that the effect of adding a large $\theta_{13}$ in the expected upward muon fluxes is not very significant. For stopping muons the effect is larger for neutrinos arriving horizontally; this is due, as for the case of multi-GeV $\mu$-like contained events, to the larger $R(\nu_e/\nu_\mu)$ SM flux ratio in this direction which implies a larger relative contribution from $\nu_e$ oscillating to $\nu_\mu$. This feature is lost in the case of through-going muons because it is partly compensated by the matter effects and also by the increase of $\tan^2 \theta_{23}$.

In conclusion we see that the analysis of the full atmospheric neutrino data in the framework of three-neutrino oscillations clearly favours the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis. As a matter of fact the best-fit corresponds to a small value of $\theta_{13} \approx 9^\circ$, but it still allows for a non-negligible $\nu_\mu \rightarrow \nu_e$ component. More quantitatively we find that the ranges of parameters are allowed at 99% CL from this analysis are (see also Table 2):

$$\Delta m^2_{32} : (1.25 \pm 8) \times 10^{-3} \text{ eV}^2,$$
$$\tan^2 \theta_{23} : 0.37 \pm 6.2,$$
$$\tan^2 \theta_{13} : 0 \pm 0.57.$$  \hspace{1cm} (9)

However, one must take into account that these ranges are strongly correlated, as clearly visible in Fig. 6.

We now describe the effect of including the CHOOZ reactor data together with the atmospheric data samples in a combined three-neutrino $\chi^2$ analysis, under the hypothesis $\Delta m^2_{32} < 3 \times 10^{-4} \text{ eV}^2$. The results of this analysis are summarized in Figs. 4 and 6 as well as in the last line of Tabs. 1 and 2. As already discussed, the negative results of the CHOOZ reactor experiment strongly disfavour the region $0.044 \lesssim \tan^2 \theta_{13} \lesssim 23$ if $\Delta m^2_{32} \gtrsim 10^{-3} \text{ eV}^2$, however for smaller values of $\Delta m^2_{32}$ the corresponding bound on $\theta_{13}$ is much weaker. Therefore an independent lower bound on $\Delta m^2_{32}$ is required for the CHOOZ constraint on $\theta_{13}$ to be applicable. To illustrate this point we show in the upper panels of Fig. 6 the allowed regions from the combination of the CONT–BIN events with the CHOOZ data. Comparing them with the corresponding ones from Fig. 4 we see that, although the region $\Delta m^2_{32} > 10^{-3} \text{ eV}^2$ is ruled out as soon as $\theta_{13}$ deviates from zero, there is still a part of the parameter space which survives (at 99% CL) up to $\tan^2 \theta_{13} \approx 0.66$. Thus, even with the large statistics provided by the Super–Kamiokande data and including the CHOOZ result, it is not possible to improve the bound on $\theta_{13}$ using only contained events.

The situation is changed once the upward muon events are included in the analysis. As clearly visible from the central panels of Fig. 6 the UP–$\mu$ data sample disfavours the low mass re-
region $\Delta m_{32}^2 < 10^{-3}$ eV$^2$. As a result, the full 99% CL allowed parameter regions from the global analysis of the atmospheric data ALL–ATM lies in the mass range where the CHOOZ experiment should have observed oscillations for sizeable $\theta_{13}$ values, and this leads to the shift of the global minimum from the combined atmospheric plus CHOOZ data to $\theta_{13} \approx 0$. Thus adding the reactor data has as main effect the strong improvement of the $\tan^2 \theta_{13}$ limit, as can also be seen from the lower-left panel in Fig. 4. Conversely, from the lower-right panel of the same figure we see that the allowed range of $\Delta m_{32}^2$ is almost unaffected.

In conclusion, from the atmospheric and reactor neutrino combined analysis we get the following 99% CL allowed ranges of parameters:

$$\Delta m_{32}^2 : \quad (1.2 \pm 0.6) \times 10^{-3} \text{ eV}^2,$$
$$\tan^2 \theta_{23} : \quad 0.36 \div 3.3,$$
$$\tan^2 \theta_{13} : \quad 0 \div 0.08.$$

4. Summary and conclusions

In this article we have presented a global analysis of both atmospheric and reactor neutrino data in terms of three–flavour oscillations. Our results show that the most favourable scenario is the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis, however from the analysis atmospheric data alone it is not possible to derive a strong bound on $\theta_{13}$, and consequently a non-negligible $\nu_\mu \rightarrow \nu_\tau$ component is still allowed. When the CHOOZ data in included into the analysis, the bound on $\theta_{13}$ is drastically improved, and $e$–like neutrinos completely decouple from the oscillation picture. Conversely, the preferred mixing in the $\nu_\mu \rightarrow \nu_\tau$ channel – described by the angle $\theta_{23}$ – appear to be nearly maximal. Together with the result of solar experiments, which also prefer maximal mixing in $\theta_{12}$ (although in this case the result is still not overwhelming), there seems to be an indication that the ultimate structure of neutrino mixing is bi-maximal. This result is in puzzling contrast with the observed structure of quark mixing, and may indicate that the origin of neutrino masses is intrinsically different from the standard Higgs mechanism which is responsible for the masses of the charged leptons in the Standard Model.

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