Combined potential of future long-baseline and reactor experiments

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We investigate the determination of neutrino oscillation parameters by experiments within the next ten years. The potential of conventional beam experiments (MINOS, ICARUS, OPERA), superbeam experiments (T2K, NO\textit{\nu}A), and reactor experiments (D-CHOOZ) to improve the precision on the “atmospheric” parameters $\Delta m^2_{31}$, $\theta_{23}$, as well as the sensitivity to $\theta_{13}$ are discussed. Further, we comment on the possibility to determine the leptonic CP-phase and the neutrino mass hierarchy if $\theta_{13}$ turns out to be large.

Triggered by the spectacular results in neutrino physics during the previous ten years \cite{1}, several new experimental projects are under way in this field. In this note we investigate where we could stand in the determination of neutrino oscillation parameters in ten years from now, by considering the experiments which are under construction or under discussion now, but could deliver physics results within the anticipated time scale. In particular we consider the conventional beam experiments MINOS \cite{2}, and the CERN to Gran Sasso (CNGS) experiments ICARUS \cite{3} and OPERA \cite{4}, the superbeam experiments J-PARC to Super-Kamiokande (T2K) \cite{5} and NuMI off-axis (NO\textit{\nu}A) \cite{6}, as well as new reactor neutrino experiments \cite{7} with a near and far detector. The main characteristics of these experiments are given in Tab. 1. For the reactor experiments we use the Double-Chooz proposal (D-CHOOZ) \cite{8} as initial stage setup with roughly $6 \times 10^4$ events, and an optimized setup called Reactor-II, with a slightly longer baseline and $6 \times 10^5$ events. Such a configuration could be realised at several other sites under discussion \cite{7}. The results presented in the following are based on Ref. \cite{9}, where more details on the analysis are available. The simulation of the experiments as well as the statistical analysis is performed with the GLoBES software package \cite{10}.

First we discuss the improvement which can be expected for the “atmospheric” parameters $\Delta m^2_{31}$ and $\sin^2 \theta_{23}$. In Tab. 2 we show the precision at $3\sigma$, which we define as $\left( x^{+3\sigma} - x^{-3\sigma} \right) / x^0$, where $x^{+(-)3\sigma}$ is the $3\sigma$ upper (lower) bound, and $x^0$ is the best fit value of the quantity $x$. We compare in the table the precision of the conventional beams (MINOS+CNGS) and the superbeams to the current precision, as obtained from a global fit to SK atmospheric and K2K long-baseline data \cite{11}. In the last row we show the precision which can be obtained by combining all experiments. We observe from these numbers, that the accuracy on $\Delta m^2_{31}$ can be improved by

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Label & $L$ [km] & $\langle E_\nu \rangle$ & $t_{\text{run}}$ & channel \\
\hline
\textbf{Conventional beam experiments:} & & & & \\
MINOS & 735 & 3 GeV & 5 yr & $\nu_\mu \to \nu_{\mu,e}$ \\
ICARUS & 732 & 17 GeV & 5 yr & $\nu_\mu \to \nu_{e,\mu,\tau}$ \\
OPERA & 732 & 17 GeV & 5 yr & $\nu_\mu \to \nu_{e,\mu,\tau}$ \\
\textbf{Off-axis superbeams:} & & & & \\
T2K & 295 & 0.76 GeV & 5 yr & $\nu_\mu \to \nu_{e,\mu}$ \\
NO\textit{\nu}A & 812 & 2.22 GeV & 5 yr & $\nu_\mu \to \nu_{e,\mu}$ \\
\textbf{Reactor experiments:} & & & & \\
D-CHOOZ & 1.05 & $\sim$ 4 MeV & 3 yr & $\nu_e \to \nu_e$ \\
Reactor-II & 1.70 & $\sim$ 4 MeV & 5 yr & $\nu_e \to \nu_e$ \\
\hline
\end{tabular}
\caption{Characteristics of the considered experiments.}
\end{table}
True value of $\Delta m_{31}^2$ [10$^{-3}$ eV$^2$] as a function of the true value of $\Delta m_{31}^2$; $\theta_{23}^{\text{true}} = \pi/4$.

Table 2

|          | $|\Delta m_{31}^2|$ | $\sin^2 \theta_{23}$ |
|----------|---------------------|----------------------|
| current  | 88%                 | 79%                  |
| MINOS+CNGS | 26%               | 78%                  |
| T2K      | 12%                 | 46%                  |
| NO$\nu$A | 25%                 | 86%                  |
| Combination | 9%               | 42%                  |

one order of magnitude, whereas the accuracy on $\sin^2 \theta_{23}$ will be improved only by a factor two.

The numbers of Tab. 2 depend to some extent on the true value of $\Delta m_{31}^2$. Therefore, we show in Fig. 1 the precision as a function of this parameter. We observe that for all experiments the sensitivity suffers for low values of $\Delta m_{31}^2$. For $\Delta m_{31}^2 \gtrsim 2 \times 10^{-3}$ eV$^2$ T2K will provide a precise determination of $\Delta m_{31}^2$ at the few % level. Although NO$\nu$A can put a comparable bound on $\Delta m_{31}^2$ from below, the upper bound is significantly weaker, and similar to the bound from MINOS. The reason for this is a strong correlation between $\Delta m_{31}^2$ and $\theta_{23}$, which disappears only for $\Delta m_{31}^2 \gtrsim 3 \times 10^{-3}$ eV$^2$. From the right panel of Fig. 1 one can see that for $\Delta m_{31}^2 \sim 2 \times 10^{-3}$ eV$^2$ only T2K is able to improve the current bound on $\sin^2 \theta_{23}$. One reason for the rather poor performance on $\sin^2 \theta_{23}$ is the fact that these experiments are sensitive mainly to $\sin^2 2\theta_{13}$. This implies that for $\theta_{23} \approx \pi/4$ it is very hard to achieve a good accuracy on $\sin^2 \theta_{23}$, although $\sin^2 2\theta_{23}$ can be measured with relatively high precision [12].

Let us now discuss the sensitivity to $\sin^2 2\theta_{13}$, i.e. we assume a true value $\theta_{13} = 0$ and investigate the obtainable upper bound on $\sin^2 2\theta_{13}$. The sensitivities of the various experiments are summarized in Fig. 2, where the impact of systematics, correlations and degeneracies is indicated by the shading. One immediately observes that the $\sin^2 2\theta_{13}$-limit from beam experiments is strongly affected by parameter correlations and degeneracies [13], whereas reactor experiments provide a “clean” measurement of $\sin^2 2\theta_{13}$, dominated by statistics and systematics [14].

The dependence of the $\sin^2 2\theta_{13}$-limit on the true value of $\Delta m_{31}^2$ is illustrated in Fig. 3. Again we observe that the sensitivity of all experiments gets rather poor for low values of $\Delta m_{31}^2$. For $\Delta m_{31}^2 \sim 2 \times 10^{-3}$ eV$^2$ we find roughly an improvement of a factor 2 from conventional beam experiments (MINOS+ICARUS+OPERA combined), a factor 4 from D-CHOOZ, and a factor
Figure 2. Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL for the true values $\Delta m^2_{31} = 2 \times 10^{-3}$ eV$^2$, $\Delta m^2_{21} = 7 \times 10^{-5}$ eV$^2$.

Figure 3. Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL as a function of the true value of $\Delta m^2_{31}$.

Note that an optimised reactor experiment such as Reactor-II has the potential for even better $\sin^2 2\theta_{13}$-sensitivities than the superbeams (compare Fig. 2).

Now we assume a relatively large value $\sin^2 2\theta_{13} = 0.1$, close to the current bound, and investigate what we can learn within the next ten years about the CP-phase $\delta$ and the neutrino mass ordering. First we note that all the experiments will be able to establish the non-zero value. However, we will be confronted with allowed regions in the $\theta_{13}$-$\delta$-plane (see Figs. 8 and 9 of Ref. [9]). None of the experiments on their own can give any information on the CP-phase $\delta$ and on the mass hierarchy. The determination of $\sin^2 2\theta_{13}$ from beam experiments is strongly affected by the correlations with $\delta$, and especially for NO$\nu$A also correlations with other parameters are important. Moreover, the inability to rule out the wrong mass hierarchy leads to a further ambiguity in the determination of $\sin^2 2\theta_{13}$. In contrast, since the $\bar{\nu}_e$-survival probability does not depend on $\delta$, Reactor-II provides a clean determination of $\sin^2 2\theta_{13}$ at the level of 20% at 90% CL.

If all experiments are combined the complementarity of reactor and beam experiments allows to exclude up to 40% of all possible values of the CP-phase for a given hierarchy. The wrong hierarchy can be ruled out at modest CL with $\Delta \chi^2 \simeq 3$ due to matter effects in NO$\nu$A. However, at high CL still all values of $\delta$ are allowed, and moreover, even for a given hierarchy CP-conserving and CP-violating values of $\delta$ cannot be distinguished at 90% CL. We add that these results depend to some extent on the true value of $\delta$.

So far we have considered only neutrino running for the superbeams, since it is unlikely that significant data can be collected with antineutrinos within ten years from now. Nevertheless, it might be interesting to investigate the potential of a neutrino-antineutrino comparison. In Fig. 4 we show the results from T2K+NO$\nu$A with 3 yrs of neutrinos + 3 yrs of antineutrinos each (left), in comparison with the case where the antineutrino running is replaced by Reactor-II (right). We find that antineutrino data at that level does neither solve the problems related to the CP-phase nor to the hierarchy. Still CP-violating and CP-conserving values cannot be distinguished at 90% CL. Moreover, the determination of $\sin^2 2\theta_{13}$ is less precise than from the reactor measurement. To benefit from antineutrino measurements a significantly longer measurement period would be necessary, to obtain large enough data samples.

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Figure 4. Antineutrino running vs Reactor-II. We show the 90% CL (solid curves) and 3σ (dashed curves) allowed regions in the $\sin^2 2\theta_{13}$-$\delta$-plane for the true values $\sin^2 2\theta_{13} = 0.1$ and $\delta = \pi/2$. The blue/dark curves refer to the allowed regions for the normal mass hierarchy, whereas the red/light curves refer to the sgn($\Delta m^2_{31}$)-degenerate solution (inverted hierarchy), where the projections of the minima onto the $\sin^2 2\theta_{13}$-$\delta$-plane are shown as diamonds (normal hierarchy) and dots (inverted hierarchy). For the latter, the $\Delta \chi^2$-value with respect to the best-fit point is also given.

REFERENCES
1. See e.g. contributions of M. Chen, K. Inoe, T. Kajita, these proceedings.
2. E. Ables et al. (MINOS) FERMILAB-PROPOSAL-P-875; K. Grzelak, these proceedings.
3. P. Aprili et al. (ICARUS) CERN-SPSC-2002-027; F. Ronga, these proceedings.
4. D. Duchesneau (OPERA), hep-ex/0209082; G. Rosa, F. Ronga, these proceedings.
5. Y. Itow et al., hep-ex/0106019; K. Kaneyuki, these proceedings.
6. D. Ayres et al., hep-ex/0210005; P. Litchfield, these proceedings.
7. K. Anderson et al., hep-ex/0402041; M. Goodman, M. Shaevitz, these proceedings.
8. F. Ardellier et al., hep-ex/0405032; G. Mention, these proceedings.
13. see e.g. S. Rigolin, these proceedings.