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# T2K and the measurement of $\theta_{13}$

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**Summary.** — A new generation of oscillation experiments optimized to measure $\theta_{13}$ is ready to start. The T2K experiment will look for $\nu_e$ appearance in an intense $\nu_\mu$ beam generated at the J-Parc accelerator complex in Japan. The Double Chooz and Daya Bay experiments will look for the disappearance of $\overline{\nu}_e$ generated by nuclear reactors. Performances, complementarity and competition of these accelerator and reactor experiments will be shortly illustrated.

PACS 14.60.Lm – Ordinary neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$).
PACS 14.60.Pq – Neutrino mass and mixing.

## 1. – Introduction

Three parameters of neutrino oscillations are still unknown: the mixing angle $\theta_{13}$, the mass hierarchy sign($\Delta m^2_{23}$) and the $CP$ phase $\delta_{CP}$; they are all fundamental parameters of the standard model. The mixing angle $\theta_{13}$ is the key parameter of three-neutrino oscillations and regulates at the first order all the oscillation processes that could contribute to the measurement of sign($\Delta m^2_{23}$) and $\delta_{CP}$.

The best direct experimental limit on $\theta_{13}$ comes from the Chooz reactor experiment [1]. A world limit can be derived [2] by a full $3\nu$ analysis of all the neutrino oscillation experiments. The fact that the world limit ($\sin^2\theta_{13} \leq 0.035\,(0.056)$ at 90% ($3\sigma$) CL) provides a looser value than the Chooz limit ($\sin^2\theta_{13} \leq 0.027\,(0.058)$ at 90% ($3\sigma$) CL) indicates that the best fit for $\theta_{13}$ is different from zero, although at small statistical significance, as discussed in [3].

A preliminary analysis of the MINOS experiment [4] shows a $1.5\sigma$ excess of $\nu_e$-like events in the far detector that could be interpreted as a manifestation of a non-zero value of $\theta_{13}$.

Experimental $\theta_{13}$ searches at the accelerators look for evidence of $\nu_e$ appearance in an intense $\nu_\mu$ beam in excess of what is expected from the solar terms. The $\nu_\mu \to \nu_e$ experimental sensitivity with conventional $\nu_\mu$ beams is limited by an intrinsic $\nu_e$ beam contamination of about 1%. Furthermore, neutral pions in both neutral current and charged current interactions can fake an electron providing also a possible background for the $\nu_e$'s.

 

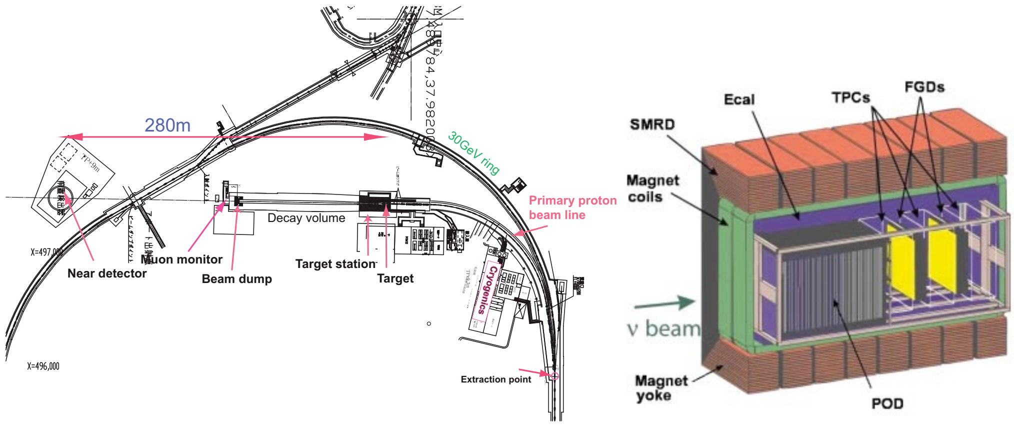


Fig. 1. – Left panel: the layout of the T2K beam line, showing the location of primary proton beam line, target station, decay volume, beam dump, muon monitors and near neutrino detectors. Right panel: sketch of the T2K ND280 off-axis near detector.

Experimental searches for non-zero values of $\theta_{13}$ can also be conducted at the reactors by looking at $\overline{\nu}_e$ disappearance, as discussed in sect. **3**. The limiting factor in these experiments is the amount of the systematic errors. Two reactor experiments are ready to start in the near future: Double Chooz in France [5] and Daya Bay in China [6]. For a review of experimental methods for measuring $\theta_{13}$ see also [7].

## 2. – T2K

The T2K (Tokai-to-Kamioka) experiment [8] will use a high-intensity off-axis neutrino beam generated by a 30 GeV proton beam at J-PARC (Japan Proton Accelerator Research Complex) fired to the Super Kamiokande detector, located 295 km from the proton beam target. The schematic view of the T2K neutrino beam line is shown in fig. 1 left.

A sophisticated near detector complex (ND280) will be built at a distance of 280 m from the target. This complex has two detectors: one on-axis (neutrino beam monitor) and the other off-axis. This off-axis detector (fig. 1 right) is a spectrometer built inside the magnet of the former experiments UA1 and NOMAD, operating with a magnetic field of 0.2 T. It includes a Pi-Zero detector (POD), a tracking detector made by three time projection chambers (TPC's) and two fine-grained scintillator detectors (FGD's), a $4\pi$ electromagnetic calorimeter (Ecal), and a side muon range detector (SMRD). Neutrino rates in the close detector will be about 160000 $\nu_\mu$ (3200 $\nu_e$) interactions/ton/y at the nominal beam intensity of $0.75\,\mathrm{MW} \cdot 10^7\,\mathrm{s}$.

ND280 is expected to calibrate the absolute energy scale of the neutrino spectrum with 2% precision, measure the non-QE/QE ratio at the 5–10% and monitor the neutrino flux with better than 5% accuracy. The momentum resolution of muons from the charged current quasi-elastic interactions (CCQE) should be better than 10%. The $\nu_e$ fraction should be measured with an uncertainty better than 10%. A measurement of the neutrino beam direction, with a precision better than 1 mrad, is required from the on-axis detector.

The sensitivity of T2K in measuring the atmospheric parameters through the $\nu_\mu$ disappearance is shown in fig. 2 (T2K is expected to collect about 16000 $\nu_\mu$ interactions

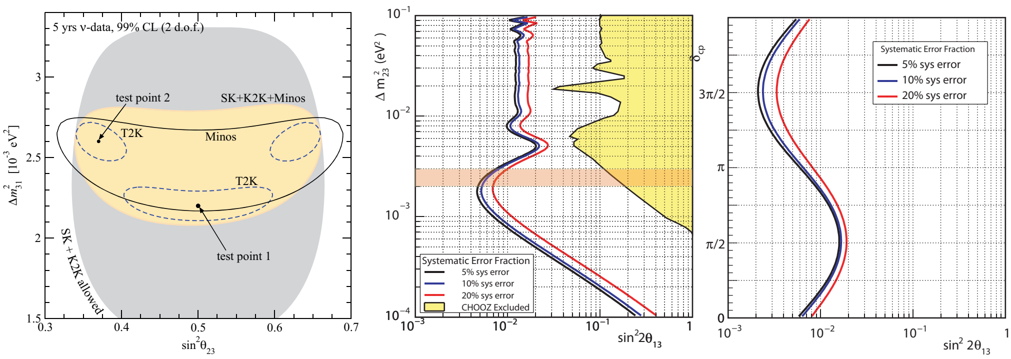


Fig. 2. – Left panel: 99% CL contours for two test points selected within the 99% allowed values by the world fits [2]. They are computed for 5 years data taking at 0.75 MW/year, and 5% systematic errors. The T2K values are taken from [9]. Also shown are the allowed regions by fits to SuperKamiokande+K2K and to Minos only. Central panel: 90% CL sensitivity to $\sin^2 2\theta_{13}$, computed for 5 years data taking at 0.75 MW/year. compared with the Chooz limit in the $\sin^2 2\theta_{13}$ *vs.* $\Delta m^2_{23}$ plane, assuming $\delta_{CP} = 0$ and normal hierarchy, for three different choices of the systematic errors. Right plot: the same sensitivity computed in the $\delta_{CP}$ *vs.* $\sin^2 2\theta_{13}$ plane, assuming $\Delta m^2_{23} = 2.5 \cdot 10^{-3}\,\text{eV}^2$ and normal hierarchy.

in 5 years at the nominal beam intensity, neglecting the oscillations). Figure 2 center and right show the sensitivity in measuring $\theta_{13}$. The experiment will reach a factor 20 improvement with respect to the Chooz limit.

The commissioning of the neutrino beam line successfully started on April, 24, 2009. Data taking is scheduled to start end 2009, integrating the first year $0.1\,\text{MW} \cdot 10^7\,\text{s}$ protons, allowing for a $\sin^2 2\theta_{13}$ sensitivity of $\sin^2 2\theta_{13} \simeq 0.1$ (90%CL, $\Delta m^2_{23} = 2.5 \cdot 10^{-3}\,\text{eV}^2$, $\delta_{CP} = 0$, normal hierarchy.).

The T2K setup has been designed to be scalable [8]. The J-PARC beam intensity can be upgraded up to 1.6 MW and a new water Čerenkov detector with a fiducial 25 times bigger than Super Kamiokande, Hyper Kamiokande [8], can be build in the Kamioka region. This upgraded set-up could provide very interesting sensitivites to leptonic $CP$ violation provided that the $\theta_{13}$ value is high enough to be discovered by the first stage of T2K.

## 3. – T2K and the reactor experiments

Reactor experiments can measure $\theta_{13}$ by detecting $\overline{\nu}_e$ disappearance at the atmospheric $\Delta m^2$, a truly complementary approach with respect to the accelerator appearance searches.

While the appearance sensitivity is modulated by the unknown value of $\delta_{CP}$, the disappearance sensitivity is insensitive to this parameter. Their combination provides a powerful sensitivity plot where the $\delta_{CP}$ modulation is reduced and the overall sensitivity increased(1). This is illustrated in fig. 3 left where the nominal, final, sensitivity of T2K

(1) On the other hand, reactor experiments, having no sensitivity to the atmospheric parameters, need the information of an accelerator experiment to delimit the $\Delta m^2_{23}$ range where they probe $\theta_{13}$

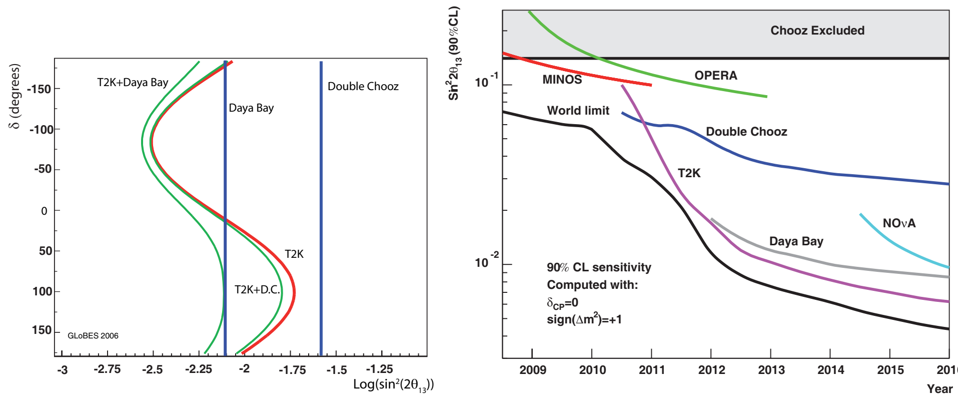


Fig. 3. – Left panel: 90% CL $\sin^2 2\theta_{13}$ sensitivity of T2K, Double Chooz, and Daya Bay, as function of $\delta_{CP}$. Also shown are the combinations of T2K with Double Chooz and with Daya Bay, as computed with Globes [10]. Right panel: evolution of experimental $\sin^2 2\theta_{13}$ sensitivities as a function of time. All the sensitivities are taken from the proposals of the experiments. For T2K it is assumed a beam power of 0.1 MW the first year, 0.75 MW from the third year and a linear transition in between. NO$\nu$A sensitivity is computed for $6.5 \cdot 10^{20}$ pot/y, 15 kton detector mass, neutrino run. Accelerator experiments sensitivities are computed for $\delta_{CP} = 0$ and normal hierarchy, for all the experiments $\Delta m^2_{23} = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$. The sensitivity curves are drawn starting after six months of data taking.

is compared with the sensitivities of the reactor experiments Double Chooz and Daya Bay.

It is of some interest to have a look to the expected sensitivities of accelerator and reactor experiments in the near future. Figure 3 right shows the evolution of the $\theta_{13}$ sensitivities as a function of time. From the plot one can derive that in the next 5 years or so the $\theta_{13}$ parameter will be probed with a sensitivity about 25 times better than the present limit.

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