PROCEEDINGS OF SCIENCE

T2K oscillation results

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We present the results of the T2K long baseline neutrino oscillation analysis in the PMNS framework, using the data collected until the summer of 2013, corresponding to a total exposure of 6.57×10^{20} protons on target. We discuss the results of the muon neutrino disappearance analysis, as well as of the joint electron neutrino appearance and muon neutrino disappearance analysis. We also report the results obtained when combining the T2K data with the results of the reactor experiments to constrain the value of θ_{13}, in particular for the measurement of the CP violating phase δ, the neutrino mass hierarchy and the octant of θ_{23}. We find a preference for the normal mass hierarchy and the octant $\sin^2(\theta_{23}) > 0.5$, but with limited statistical significance.

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1. The T2K experiment

The Tokai to Kamioka (T2K) experiment [1] is a long baseline neutrino oscillation experiment which uses a neutrino beam produced by an accelerator at the J-PARC center on the east coast of Japan. The neutrinos are sent towards the far detector Super-Kamiokande where they are detected after 295 km of propagation through the earth. The beam is produced using the conventional method: protons accelerated to 30 GeV hit a graphite target, producing hadrons including pions and kaons. Charged hadrons are then focused by a set of three electromagnetic horns and sent to a decay tunnel where the pions and kaons decay in flight producing neutrinos. This creates an almost pure muon neutrino beam with an intrinsic electron neutrino component of a few percent. At the far detector, we look for the appearance of electron neutrinos in this muon neutrino beam, as well as for the disappearance of muon neutrinos, to estimate four of the parameters of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) model describing neutrino oscillations: θ_{13}, θ_{23}, $|\Delta m^2_{32}|$ and δ.

T2K was the first long baseline experiment to use the off-axis beam technique: the far detector is not located at the center of the neutrino beam, but in a direction making a 2.5° angle with the beam axis. Although this reduces the flux of neutrinos going through the far detector, it increases our ability to study the oscillations of muon neutrinos due to their energy distribution in the off-axis direction: it creates a narrow band neutrino beam, peaked at the energy corresponding to the maximum of the oscillation probability (fig 1). It also reduces the background for ν_e appearance by reducing the high energy tail and the intrinsic ν_e component of the beam. Finally, at those energies the dominant interaction mode is the charged current quasi-elastic (CCQE) one, which allows proper reconstruction of the neutrino energy at the far detector.

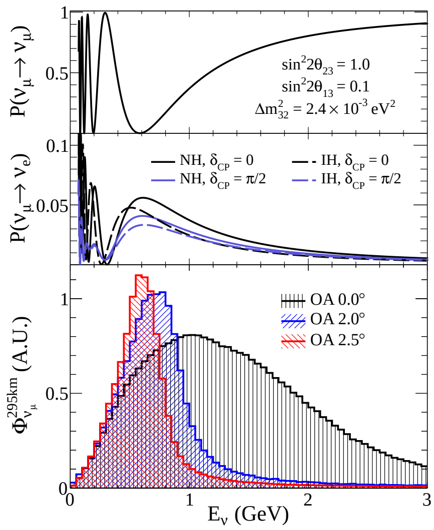

Figure 1: Neutrino flux at the far detector for different off-axis angles, and oscillation probabilities as a function of neutrino energy.

On their way to the far detector, the neutrinos pass through a complex of near detectors located 280 meters from the target. On the axis of the beam, the Interactive Neutrino GRID (INGRID) detector is used to monitor the stability of the neutrino beam, both in terms of rate of interactions and direction [2]. The off-axis angle has to be controlled at better than 1 mrad, which corresponds to a 2% uncertainty on the position of the energy peak at the far detector. In the off-axis direction, the ND280 detector, made of several different detectors inside a 0.2 T magnetic field, is used to constrain the flux and cross section uncertainties.

The far detector Super-Kamiokande is a 50 ktons (22.5 ktons fiducial) water Cerenkov detector, which has been operating since 1996, pursuing a rich physics program outside of T2K. It has good ability to separate between ν_e and ν_μ interactions, which is critical to study the appearance of electron neutrinos in a muon neutrino beam. To be able to select the events corresponding to the T2K beam, it is synchronized with the beamline using GPS.

2. Dataset

The results presented here are based on the first four years of data taking of the experiment, corresponding to a total exposure of 6.57×10^{20} protons on target. All data used here were recorded with the horn polarity favoring the neutrino component of the beam. Over this period, the rate of the interactions observed in the on-axis near detector was stable, and the beam direction was stable within the 1 mrad requirement as can be seen on figure 2.

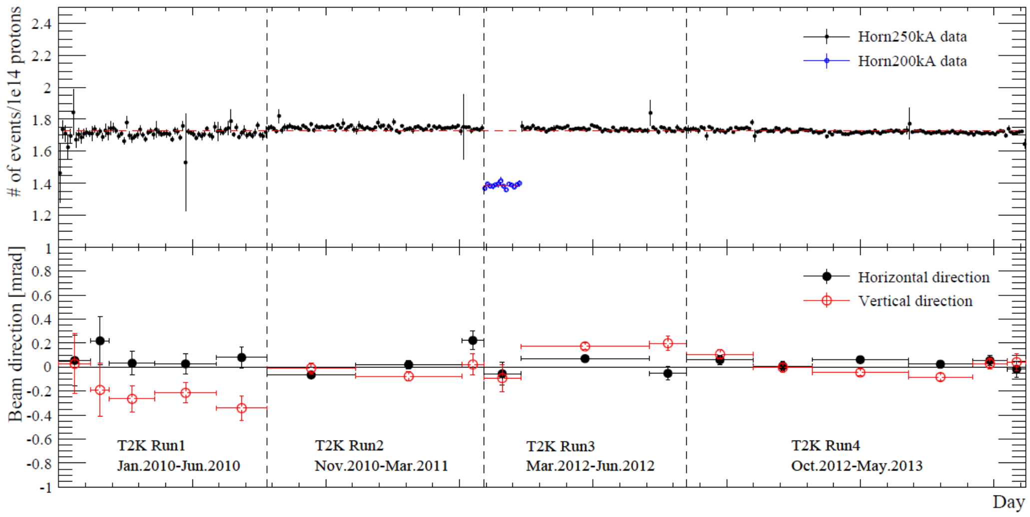

Figure 2: Event rate and beam direction measured by the on-axis near detector.

3. Oscillation analysis

To measure the oscillation parameters, we compare the observations at the far detector to the predictions for a given set of values of the parameters based on a model of the experiment. The values of the oscillation parameters are then estimated using a maximum likelihood fit. The neutrino flux is predicted by simulating the hadronic interactions in the target, and the propagation and decay of the secondary particles produced. This simulation is tuned to the experimental results of the CERN NA61 experiment [3]. Neutrino interactions are simulated based on models with constraints

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from external data using the NEUT neutrino interaction generator [4]. Systematic uncertainties are incorporated at each step: flux prediction, neutrino interactions and cross sections, and response of the detector. Systematic uncertainties for the far detector are evaluated using atmospheric neutrino data, and a π^0 control sample.

The off-axis near detector ND280 is used to constrain the flux uncertainties and some of the neutrino interaction and cross section uncertainties (due to the difference of target materials between the near and far detectors, not all the cross section uncertainties can be constrained using ND280). The measurements done at the near detector significantly improve our ability to predict the neutrino event rates and spectra at the far detector (fig 3): the uncertainty on the predicted number of electron-like events decreases from 25% to 6.3%, and from 23.4% to 7.4% for muon-like events.

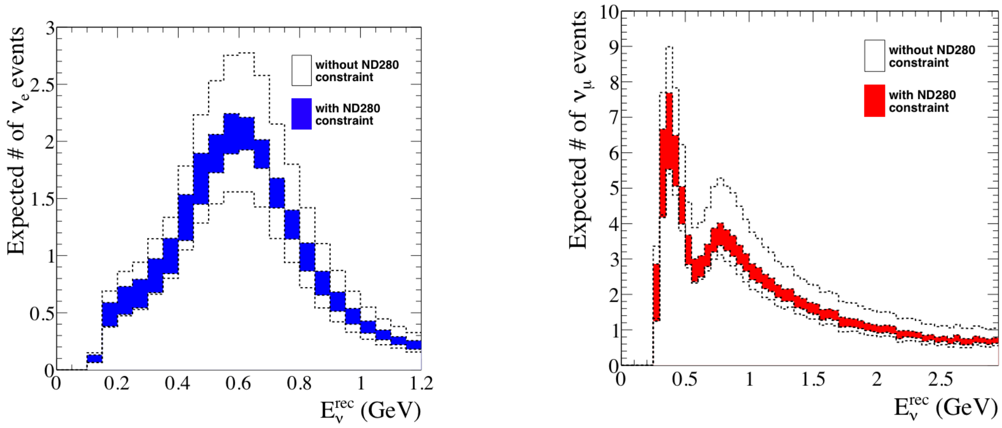

Figure 3: Predicted energy spectra at the far detector for electron-like (left figure) and muon-like (right figure) events and error envelope obtained with and without the ND280 measurements. Oscillation probabilities assuming $\sin^2(2\theta_{13}) = 0.1$, $\sin^2(\theta_{23}) = 0.5$, $\delta = 0$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$ are applied.

4. Muon neutrino disappearance results

In the muon disappearance analysis, we fit the reconstructed energy distribution of the muon-like candidate events which passed the selection cuts to estimate the values of $\sin^2(\theta_{23})$ and $|\Delta m^2_{32}|$, marginalizing over the other oscillation parameters including θ_{13} (with constraint $\sin^2(\theta_{13}) = 0.0251 \pm 0.0035$ [6]) and δ. We obtain the following values for those parameters [5]:

$$\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}\ (0.511 \pm 0.055)$$
$$|\Delta m^2_{32/31}| = 2.51 \pm 0.10 \times 10^{-3}\text{eV}^2\ (2.48 \pm 0.10 \times 10^{-3}\text{eV}^2)$$

in the normal (inverted) mass hierarchy scenario. The given uncertainties correspond to the one-dimensional 68% confidence level (CL) intervals obtained using a method inspired by the Feldman-Cousins unified approach [7]. The two-dimensional CL intervals are compared with results from other experiments on figure 4, where it appears that this result is currently the most precise measurement of $\sin^2(\theta_{23})$. We also note that the best fit value of $\sin^2(\theta_{23})$ obtained corresponds to the maximal disappearance probability for the value of $\sin^2(\theta_{13})$ used.

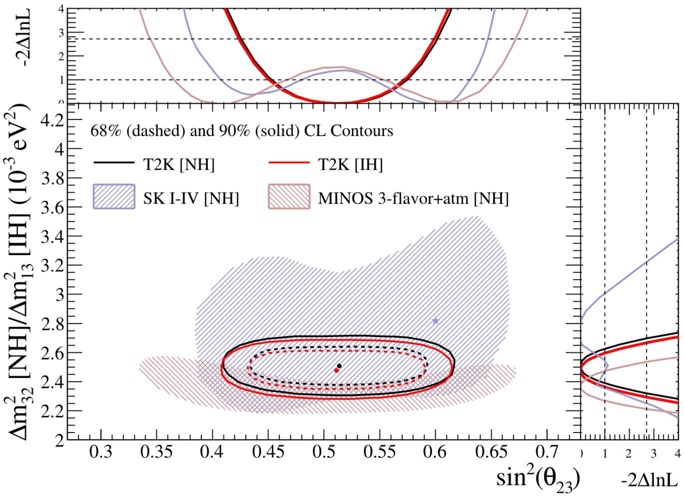

Figure 4: Two-dimensional CL intervals for $\sin^2(\theta_{23})$ and $|\Delta m^2_{32/31}|$, and comparison with the results (90% CL intervals) of the Super-Kamiokande [8] and MINOS [9] experiments.

5. Joint muon neutrino disappearance and electron neutrino appearance analysis results

T2K previously analyzed separately the electron-like candidate events to measure $\sin^2(2\theta_{13})$ and δ [10], and the muon-like candidate events to measure $\sin^2(\theta_{23})$ and $|\Delta m^2_{32/31}|$ as described in the previous section. However, the two sets of observables actually depend on all four oscillation parameters, and therefore should be analyzed together to properly take into account the correlations between the estimates of the oscillation parameters. T2K developed four such joint analyses, which were found to give consistent results. We present here the results obtained with one of them. As in the case of the muon neutrino disappearance analysis, we fit the rate and reconstructed energy spectrum of the muon candidate events. For the electron-like events, we fit the rate and the two-dimensional distribution of the momentum and angle with the beam direction of the particle reconstructed as an electron in the event (method used for the previous T2K electron appearance analysis [10]).

We first consider only the T2K data. The two-dimensional CL intervals obtained for $\sin^2(\theta_{23})$ and $|\Delta m^2_{32/31}|$, and the one-dimensional CL intervals obtained for $\sin^2(2\theta_{13})$ with different fixed values of δ are presented on figure 5. As in the case of the muon disappearance analysis, the best fit value of $\sin^2(\theta_{23})$ (0.52) corresponds to the maximum of the disappearance probability for the best fit value of $\sin^2(2\theta_{13})$. Concerning $\sin^2(2\theta_{13})$, the T2K data favor larger values than the reactor experiments, which leads to interesting effects when combining the two. This is done by adding a penalty term for $\sin^2(2\theta_{13})$ in the likelihood when fitting the T2K data, with a mean value of

0.095 and a sigma of 0.01 [6]. The two-dimensional CL intervals obtained for the atmospheric parameters with this combination are presented on figure 6.

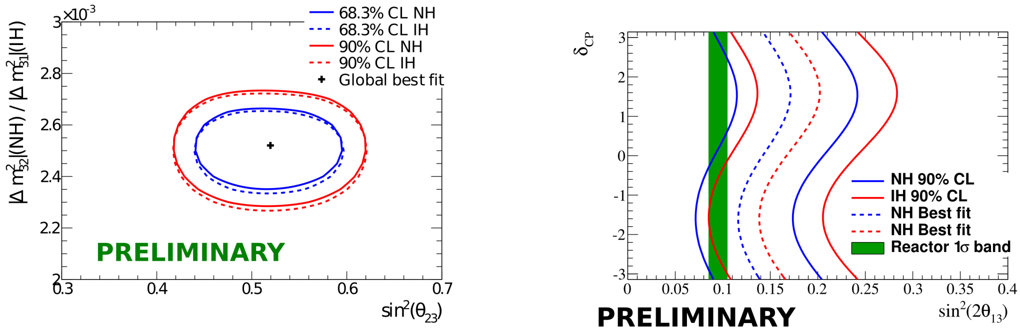

Figure 5: 2D CL intervals obtained for the atmospheric parameters (left figure), and 1D CL intervals obtained for $\sin^2(2\theta_{13})$ with different fixed values of δ (right figure) when fitting T2K data. Reactor values for $\sin^2(2\theta_{13})$ from [6]

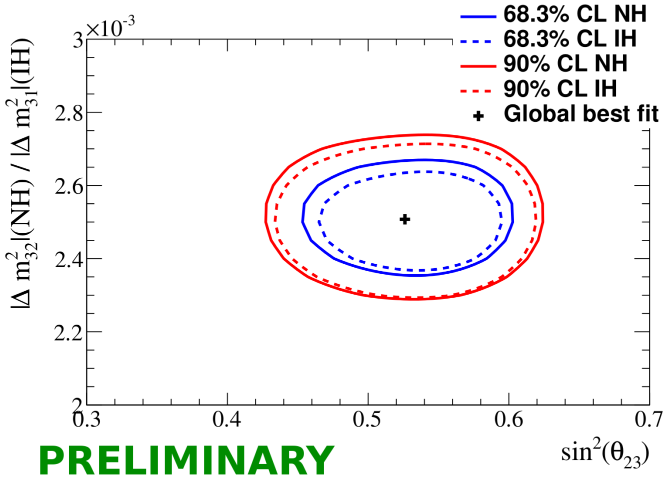

Figure 6: Two-dimensional CL intervals for $\sin^2(\theta_{23})$ and $|\Delta m^2_{32/31}|$ obtained when combining the T2K data with the results of the reactor experiments for $\sin^2(2\theta_{13})$.

In this case, the octant $\sin^2(\theta_{23}) > 0.5$ appears to be favored. We also note that the best fit value of $\sin^2(\theta_{23})$ is larger than the value corresponding to the maximum of the disappearance probability for the best fit value of $\sin^2(2\theta_{13})$ (respectively 0.53 and 0.513). This can be interpreted as coming from a tension between the values of $\sin^2(2\theta_{13})$ favored by the T2K data and the reactor experiments: T2K data favor a larger value of the appearance probability $P(\nu_\mu \to \nu_e)$ than what is obtained in the PMNS framework with the value of $\sin^2(2\theta_{13})$ measured by the reactor experiments. When the value of $\sin^2(2\theta_{13})$ can no longer be increased in the fit due to the extra penalty term, increasing the value of $\sin^2(\theta_{23})$ allows the appearance probability to be increased. A similar pattern can be observed when fitting for δ by marginalizing over the other oscillation parameters (fig 7): in this case values around $\delta = -\pi/2$ which give a larger appearance probability are favored.

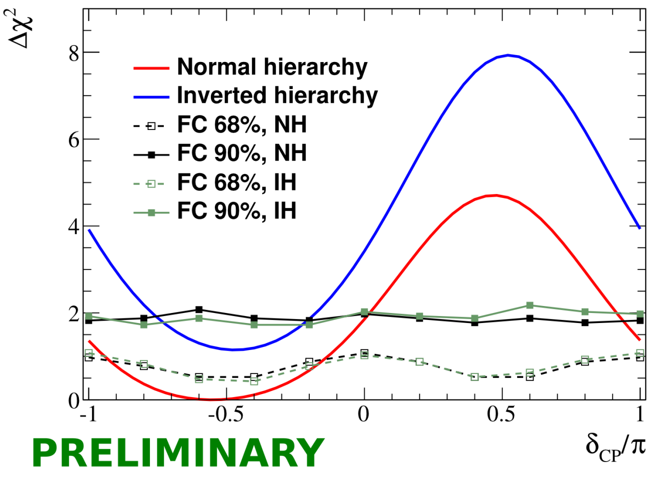

Figure 7: $\Delta\chi^2$ curves obtained when fitting the T2K data for δ constraining $\sin^2(2\theta_{13})$ using the results of the reactor experiments. Values of the $\Delta\chi^2$ corresponding to the boundaries of the 68% and 90% CL intervals obtained with the Feldman-Cousins unified approach are shown.

Due to the cyclicity of δ and the presence of physical boundaries at $\delta = \pm\pi/2$, the Feldman-Cousins unified approach is used to produced CL intervals with proper coverage. We find that some portions of $[-\pi;\pi]$ are outside of the 68% and 90% CL intervals (table 1).

Mass hierarchy	Outside of 68% CL interval	Outside of 90% CL interval
Normal	$[-\pi;-2.92]\cup[-0.46;\pi]$	$[0.06;2.95]$
Inverted	$[-\pi;\pi]$	$[-\pi;-2.29]\cup[-0.71;\pi]$

Table 1: Regions outside of the CL intervals for δ obtained with T2K data and the results of reactor experiments.

The normal hierarchy appears to be favored on figure 7. Using a Bayesian approach, we can compare the different models by looking at the posterior probabilities of the different combinations of octant of $\sin^2(\theta_{23})$ and mass hierarchies (table 2). The T2K data combined with the results of the reactor experiments for $\sin^2(2\theta_{13})$ weakly favor the normal hierarchy and the octant $\sin^2(\theta_{23}) > 0.5$.

	Normal hierarchy	Inverted hierarchy	Row sum
$\sin^2(\theta_{23}) < 0.5$	0.186	0.080	0.266
$\sin^2(\theta_{23}) > 0.5$	0.503	0.231	0.734
Column sum	0.689	0.311	1

Table 2: Posterior probabilities for different model obtained with T2K data and the results of the reactor experiments for $\sin^2(2\theta_{13})$.

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6. Summary

We presented the results of T2K neutrino oscillation analysis using data corresponding to a total exposure of 6.57×10^{20} protons on target. Using T2K data alone, we obtained the current most precise measurement of θ_{23}, $\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}$ (0.511 ± 0.055) in the normal (inverted) mass hierarchy scenario. We found that the T2K data were favoring larger values of $\sin^2(2\theta_{13})$ than the reactor experiments. When combining T2K data with the results of the reactor experiments, we found a weak preference for the normal mass hierarchy and the octant $\sin^2(\theta_{23}) > 0.5$. We also found in this case a preference for values of δ around $-\pi/2$, with some parts of $[-\pi;\pi]$ outside of the 90% CL intervals for δ.

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