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Highlights from T2K

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Abstract. T2K is a long-baseline neutrino experiment designed to measure neutrino oscillations parameters. A high-intensity beam of muon neutrinos produced at the J-PARC accelerator complex is sent towards the near detector facility (the ND280 and INGRID detectors, located 280 m away from the neutrino source) and the far detector, Super-Kamiokande (295 km away). The change in the measured intensity and the composition of the neutrino beam between the near and far detectors are used to provide information on the oscillation parameters. T2K has delivered the world's best measurement of the θ_{23} angle by observing muon neutrino disappearance. It was also the first experiment to observe electron neutrino appearance (2013) with a significance of 7.3 σ, to measure the associated θ_{13} mixing angle, and to provide the first hint of a non-zero δ_{CP} phase. The first running of anti-neutrinos in the T2K experiment shows a clear dip below 1 GeV, as expected for an oscillation signal. The T2K experiment is also capable of providing information on neutrino-nucleon cross sections at energies around 1 GeV, thanks to a large amount of target material present in the near detector facility.
A summary of the recent oscillation measurements as well as selected cross section results are presented.

1 Introduction

The investigation of the neutrino properties in the past two decades conducted by numerous experiments dedicated to this subject has led to extraordinary results. The unique feature of neutrinos is that they can change or "oscillate" from one type to another as they travel over long distances. In 1998 Super-Kamiokande, as the first experiment, measured oscillations of neutrinos generated in the Earth's atmosphere [1]. Next the oscillations of neutrinos coming from the Sun were measured by the SNO experiment in 2001 [2]. The discovery of neutrino oscillations revealed that the neutrinos have finite mass, so we expect that the weak eigenstates are different from the mass eigenstates, in analogy to the quark system. The neutrino mixing is described by a 3x3 unitary matrix, called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [3]. Oscillation probabilities depend on three mixing angles (θ_{13}, θ_{12}, θ_{23}), two independent mass splittings ($|\Delta m^2|$) and one complex CP phase (δ_{CP}) which should be determined experimentally.

Since that time, various neutrino experiments (Super-Kamiokande, K2K, KamLAND, MINOS, T2K, ICARUS, OPERA, Daya Bay, RENO) have been involved in determining the above parameters, describing the phenomenon of the neutrino oscillations. Despite the fact that the values of three mixing angles and two mass splittings are now known, they need to be determined with a better precision in

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particular to check whether there is the maximal mixing in the atmospheric sector. Also, there still remain open questions such as: value of the δ_{CP} describing the CP violation in neutrino sector, and the mass hierarchy in the neutrino mass eigenstates.

2 T2K experiment

T2K is a long-baseline neutrino experiment designed to measure neutrino oscillations parameters. The main goal of T2K is to study and compare ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ transitions in order to measure θ_{13} and explore δ_{cp}, CP violation in the lepton sector. T2K is also designed for precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance to explore θ_{23} ($\bar{\theta}_{23}$) and Δm^2_{23} ($\Delta\bar{m}^2_{23}$) parameters, i.e to test the CPT theorem or new non-standard ν interactions with matter. The cross section measurements in the near and far detectors are additional purposes of the T2K experiment.

The T2K experiment [4] is located in Japan. A high-intensity beam of muon neutrinos produced at the J-PARC accelerator complex is sent towards the near detector facility (the ND280 and INGRID detectors, located 280 m away from the neutrino source) and the far detector, Super-Kamiokande (295 km away). The change in the measured intensity and the composition of the neutrino beam between the near and far detectors are used to provide information on the oscillation parameters. The beam is produced by the conventional method. The 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 (or anti-neutrinos by the reversing current in magnetic horns).

T2K was the first long-baseline experiment using the off-axis beam technique: the far detector, similar to the near ND280 detector, is located in the direction making a 2.5 degrees angle with the beam axis. Despite some reduction in the neutrino flux passing through the far detector, a big advantage is a kinematic focusing of the off-axis beam around the energy corresponding to the maximum of the oscillation probability, which is about 600 MeV. The use of an off-axis neutrino beam, also reduces the background for ν_e appearance in the far detector by reducing the high energy tail which has a relatively large intrinsic ν_e component of the beam. Finally, the dominant interaction mode at these energies is the charged current quasi-elastic (CCQE) one, which allows for the reconstruction of the neutrino energy at the far detector. Additional significant processes are: CCQE-like multi-nucleon interaction, charged current single pion production (CCπ), neutral current single pion production (NCπ). For a precise measurement of oscillation parameters, T2K is equipped with two near detectors [4]: ND280 and INGRID. Short descriptions of the near and far detectors are included in the below subsections.

2.1 INGRID on-axis near detector

The on-axis detector INGRID [5] is used to monitor the beam rate, its direction and stability. It consists of 16 $1m \times 1m \times 1m$ cubic modules. Each module is a "sandwich" of 11 scintillator layers and 10 iron layers. They are surrounded by four veto planes. The modules are arranged as follows: seven horizontally, seven vertically, and two off-diagonally (Figure 1 left). Neutrinos are counted in the detector by reconstructing muons from neutrino charged current interactions. The profile and direction of the neutrino beam are obtained by the use of registered charged current interactions in each module.

2.2 ND280 off-axis near detector

The off-axis detector, ND280 (Figure 1 right) is used to constrain flux and cross-section systematics for oscillation analysis: it measures flux and cross section before the oscillations occur. It consists

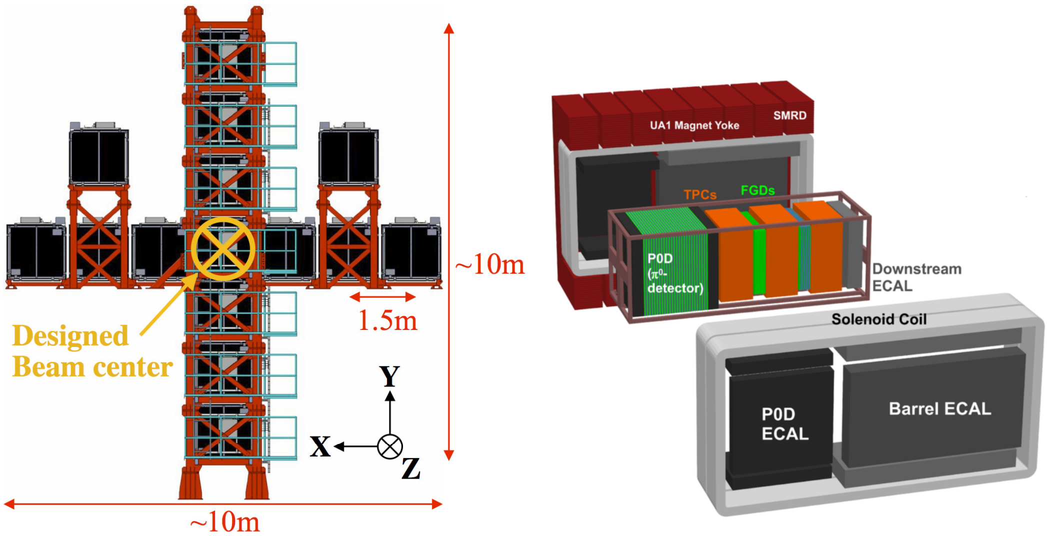


Figure 1. The INGRID on axis near detector (left) and the ND280 off axis near detector (right) [4]

of several sub-detectors: Pi-Zero Detector (P0D) and Tracker as the inner detectors, both surrounded by the electromagnetic calorimeter (ECAL) and then by the Side Muon Range Detector (SMRD). All detector components except the SMRD are placed inside a 0.2 T magnetic field produced by the recycled magnet from the UA1 experiment. The P0D subdetector, placed upstream inside the magnet is a "sandwich" of scintillator planes, lead and brass plates, and a water target. It is customized for the measurement of neutral π^0 production. Gamma rays from π^0 decay are converted to electromagnetic showers in the lead plates, and are recorded in the scintillator detectors. In the downstream of the P0D, two Fine Grained Detectors (FGDs) separated by three Time Projection Chambers (TPCs) are placed. The TPCs can measure the momentum of leptons from the curvature of the track in the magnetic field. The momentum resolution for muons is better than 10 % at 1 GeV. The FGDs consist of scintillator bars. They provide the target material for neutrino interactions and are optimized for detecting the proton recoils. By combining the TPCs and FGDs, the energy spectrum of ν_μ can be precisely measured based on CCQE (Charged Current Quasi-Elastic) neutrino interactions. The FGDs and TPCs form the so-called Tracker system, where the ν_μ and ν_e energy spectra are measured by reconstructing the lepton momentum and by separating electrons from muons using dE/dx. The other detector components, SMRD and ECAL, are installed in the area outside of the P0D and Tracker. The inner part of the detector is surrounded by an electromagnetic calorimeter which can tag escaping electrons and positrons from π^0 decays. Additionally, the outermost SMRD detector (scintillator slabs installed in the magnet yoke) is used to detect muons escaping the inner volume and to tag cosmic ray muons.

2.3 Super-Kamiokande far detector

The far detector, Super-Kamiokande(SK) [6], is a 50 kton water Cherenkov detector located 1000 m underground in the Mozumi Mine in the Japanese Alps. Its inner detector (ID), 22.5 kton of fiducial volume, is viewed by about eleven thousand 20-inch diameter PMTs. The outer detector (OD), which surrounds the ID, is also a water Cherenkov detector. It is used to veto events that enter or exit the inner detector. SK started its operation in 1996. Apart from having its own rich physics program, SK is also used as the far detector of the T2K experiment. It has an excellent ability to separate between the ν_e and ν_μ interactions, which is critical to the study of the appearance of electron neutrinos in a muon neutrino beam. It was verified that the probability of the μ/e misidentification is less than 1 % [7]. The lack of a magnetic field in the far detector makes it impossible to separate between ν and $\bar{\nu}$. The events are synchronized with the beamline with the use of a dedicated GPS system.

3 Analysis strategy

To measure the oscillation parameters, the observed number of neutrino interactions at the far detector is compared with the predicted one. 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. This simulation is tuned to the experimental results of the CERN NA61 experiment [8]. Neutrino interactions are simulated based on models with constraints from external data using the NEUT neutrino interaction generator [9]. Systematic uncertainties are incorporated in each step: flux prediction, neutrino interactions and cross sections, and the response of the detectors. Systematic uncertainties for the far detector are evaluated using atmospheric neutrino data and a π^0 control sample.

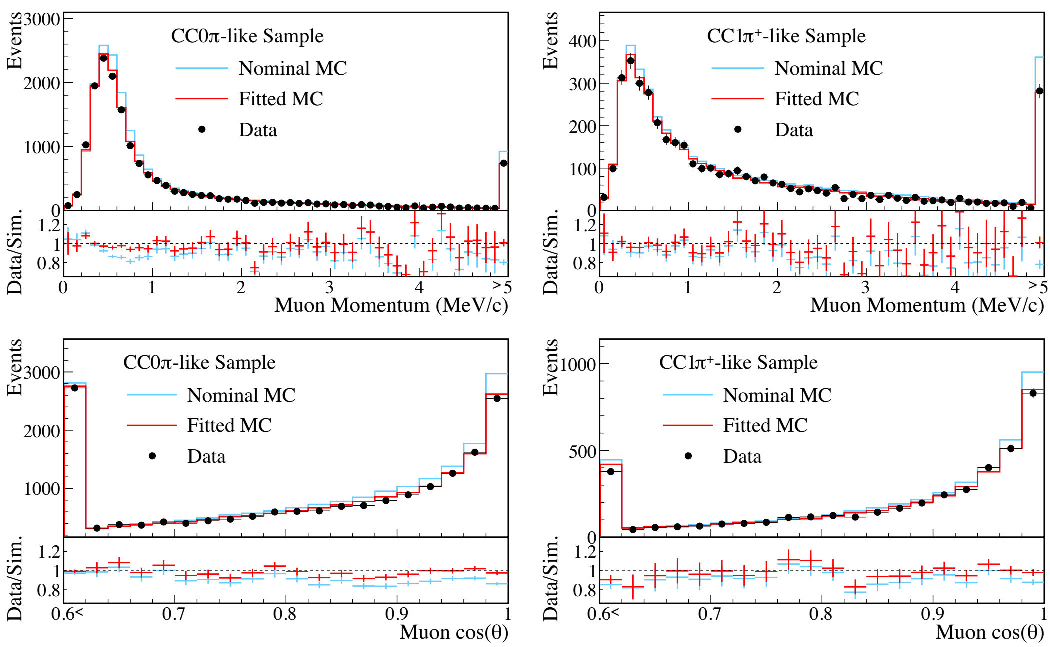


Figure 2. Muon momentum (top) and angle distribution (bottom) for the CC0π -like sample (left) and CC1π-like sample (right) selected in ND280. These are compared to the simulation, broken down into the different reaction types, with all systematic parameters set to their nominal values [10].

The off-axis near detector ND280 is used to constrain the flux uncertainties, some of the neutrino interactions and cross section uncertainties (due to the difference of target materials between the near and far detectors, not all of these uncertainties can be constrained using ND280). The analyses presented in this article were done based on 6.6×10^{20} protons on target for the total neutrino sample and 4.04×10^{20} protons on target for the anti-neutrino sample, respectively. In the ND280 analysis the exclusive sub-samples are selected, based on track topologies in the Tracker of the ND280 detector, to constrain the cross section components: CCQE (CC0π sub-sample), CC resonant single pion cross-section parameters (CC1π sub-sample) and CC multi pions, dominated by deep inelastic processes (CCother sub-sample) for neutrino mode [10]. Because of lower statistics in the anti-neutrino mode, the ND280 fits were done only for two sub-samples : CC1-Track and CC>1 Track to make constrains for CCQE and CCnQE (Charged Current non Quasi Elasic) interactions.

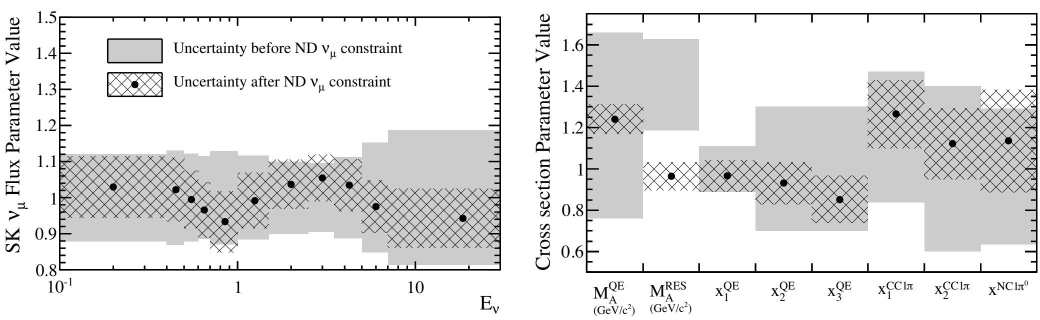


Figure 3. Prior and fitted values and uncertainties for the SK ν^μ flux parameters (left) and cross-section parameters (right) constrained by the near detector analysis for the oscillation analyses. Uncertainties are calculated as the square root of the diagonal elements of the relevant covariance matrix. The value of M_A^{QE} and M_A^{RES} are given in units of GeV/c^2 , and all the other parameters are multiplicative corrections [10].

For each defined sub-sample in the data and Monte Carlo, the two-dimensional plots of muon momentum and angle are prepared. Then the fit which varies the parameters related to neutrino energy spectrum and cross sections is performed to obtain the best agreement between the data and simulation. By fitting MC to the near detector data, new flux and cross-section parameters can be obtained. After the parameters adjustments, the agreements turn out to be excellent, as can be seen in Figure 2. The parameters adjusted in the ND280 analysis are also applied in the SK analysis. The uncertainties in these parameters are in general smaller than those for the prior values, as can be seen in Figure 3. The measurements done at the near detector significantly improve the experimental ability to predict the neutrino event rates and spectra at the far detector (Figure 4). The uncertainties in the predicted number of electron-like events decreases from 25 % to 6.3 %, and from 23.4 % to 7.4 % for muon-like events, respectively.

4 Oscillation analysis of joint electron neutrino appearance and muon neutrino disappearance channels

Initial T2K oscillation analyses were done separately for muon neutrino disappearance events to measure θ_{23}, $|\Delta m^2_{32}|$ and for electron neutrino appearance events to measure θ_{13} and estimate δ_{CP} parameters [11, 12]. However, to properly take into account the correlations between the estimates of all four oscillation parameters, the two sets of the above observables should be analyzed together. Four

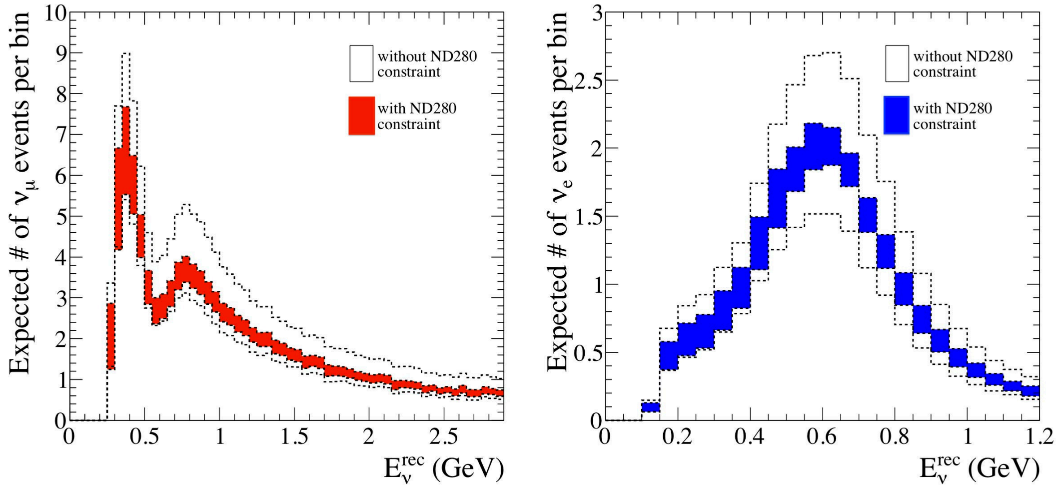


Figure 4. Total error envelopes for the reconstructed energy distributions of ν_μ CC (left) and ν_e CC (right) candidate events, using typical oscillation parameter values, with and without the ND280 constraint applied [10].

independent joint analyses were performed in T2K, and they gave consistent results. Some of them are presented below.

For the muon-like events observed at SK, fits of the rate and the reconstructed energy spectrum of the muon candidate events were done. For the electron-like events, fits of 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 were performed (the method used in the previous T2K electron appearance analysis [12]). The point estimates of the oscillation parameters are found by minimizing the negative log-likelihood :

$$\chi^2 = -2lnL(\vec{\theta}, \vec{g}, \vec{x_s}, \vec{s})$$

where $\vec{\theta}$ represents the vector of the PMNS oscillation parameters, $\vec{g}$ is a vector containing the values of the systematic parameters constrained by the near detector, $\vec{x_s}$ are the cross-section parameters not constrained by the near detector and $\vec{s}$ are the SK detector systematic parameters [10].
The profiled $\Delta\chi^2$ of each oscillation parameter was obtained by minimizing the negative log-likelihood with respect to the systematic parameters and other three oscillation parameters using MINUIT.

Table 1. Point estimates of the oscillation parameters for the joint three-flavor oscillation frequentist analysis, for the normal hierarchy (NH) and inverted hierarchy (IH) [10].

MH	$\Delta m^2_{32}(10^{-3}eV^2/c^4)$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	$\Delta\chi^2$
NH	2.51	0.524	0.0422	1.91	0.01
IH	2.49	0.523	0.0491	1.01	0.00

The point estimates for the oscillation parameters are summarized in Table 1. The value obtained for $\sin^2\theta_{13}$ by T2K is larger than the value found by the reactor experiments (the weighted average of the results from the three reactor experiments Daya Bay, RENO, and Double Chooz which is: $\sin^2\theta_{13reactor} = 0.0243 \pm 0.0026$ [13]). The best-fit value of $\sin^2\theta_{23}$ is consistent with maximal

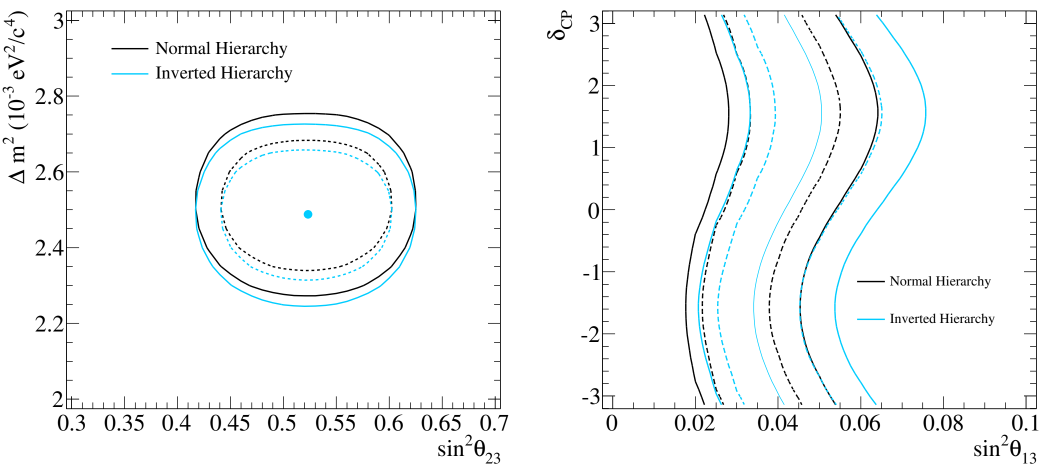


Figure 5. The 68% (dashed) and 90% (solid) C.L. regions, from the analysis without reactor data, with different mass hierarchy assumptions, using $\Delta\chi^2$ with respect to the best-fit point which comes from the inverted hierarchy obtained for the atmospheric parameters (left). The right plot shows one-dimensional confidence intervals in $\sin^2\theta_{13}$ for different values of δ_{CP} [10].

disappearance, and the difference in χ^2 between the solutions for each mass hierarchy is negligible. Figure 5 presents the 68% and 90% C.L. regions for the two mass hierarchy assumptions in the two two-dimensional oscillation parameter spaces ($\sin^2\theta_{23}$, Δm^2_{32}) and ($\sin^2\theta_{13}$, δ_{CP}), constructed using constant $\Delta\chi^2$ with respect to the inverted hierarchy best-fit point. The value of $\sin^2\theta_{23} = 0.524^{+0.057}_{-0.059}$ ($0.523^{+0.055}_{-0.065}$) in the normal (inverted) mass hierarchy scenario obtained in the T2K analysis is the world's most precise value till now.

Table 2. Point estimates of the oscillation parameters for the joint three-flavor oscillation frequentist analysis combined with the results from reactor experiments, for the normal hierarchy (NH) and inverted hierarchy (IH) [10].

MH	$\Delta m^2_{32}(10^{-3}eV^2/c^4)$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	$\Delta\chi^2$
NH	2.51	0.527	0.0248	-1.55	0.00
IH	2.48	0.533	0.0252	-1.56	0.86

The point estimates for the oscillation parameters when the reactor measurements are included in the likelihood function are given in Table 2. The estimate for $\sin^2\theta_{13}$ is smaller than the result obtained with T2K data only, shown in Table 1. The likelihood is maximal for normal mass hierarchy and for δ_{CP} = -π/2, where the appearance probability is largest.

The confidence regions obtained in the ($\sin^2\theta_{23}$, Δm^2_{32}) parameter space are compared with the results from the Super-Kamiokande [14] and MINOS [15] experiments in Figure 6 (left). The results from T2K and MINOS used the latest value of $\sin^2\theta_{13}$ from [16] to fit this parameter whereas the result from SK has $\sin^2\theta_{13}$ fixed to the previous reactor value [13]. The distributions of δ_{CP} when fitting by marginalizing over other oscillation parameters are presented in Figure 6 (right). In this case the values of δ_{CP} around -π/2 are favored. The values of the $\Delta\chi^2$ corresponding to the

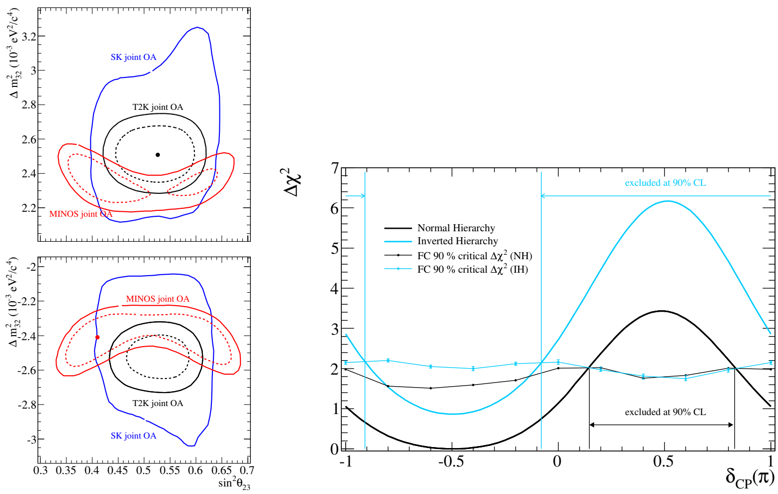


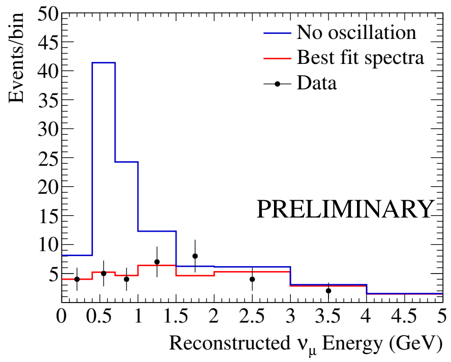
Figure 6. The 68% (dashed) and 90% (solid) C.L. regions for normal (top left) and inverted (bottom left) mass hierarchy combined with the results from reactor experiments in the ($\sin^2\theta_{23}$,Δm^2) space compared to the results from the Super- Kamiokande [14] and MINOS [15] experiments. Profiled $\Delta\chi^2$ as a function of δ_{CP} with the results of the critical $\Delta\chi^2$ values for the normal and inverted hierarchies for the joint fit with reactor constraint, with the excluded regions found overlaid (right) [10].

boundaries of 90% C.L. intervals obtained with the Feldman-Cousins approach [17] for both mass hierarchies are presented also in Figure 6 (right). The figure shows that the excluded regions for δ_{CP} at the 90% C.L are: δ_{CP} =(0.15; 0.83)π for normal hierarchy and δ_{CP} =(-0.08; 1.09)π for inverted hierarchy respectively. The normal hierarchy appears to be favored. Using a Bayesian approach, we can compare different models by looking at the posterior probabilities of different combinations of octant of $\sin^2\theta_{23}$ and mass hierarchies. The T2K data combined with the results of the reactor experiments for $\sin^2\theta_{13}$ weakly favor the normal hierarchy and the octant $\sin^2\theta_{23} > 0.5$.

5 First results from anti-neutrino running

The first preliminary result of $\bar{\nu}_\mu$ disappearance and $\bar{\nu}_e$ appearance analysis is presented here. In the anti-neutrino beam the data collected untill June 2015, which corresponds to 4.04×10^{20} POT, have been used. The applied procedure, which includes the event selection and calculation of the expected Monte Carlo events, is the same as that for neutrino analysis. From Monte Carlo simulations for a no-oscillation scenario 103.6 muon-like events are expected in the SK detector, but only 34 muon-like events were observed.

In this analysis, in order to see potential effects coming from a new physics such as CPT violation or non-standard interactions, we treat (θ_{23}, Δm^2_{32}) for neutrinos and ($\bar{\theta}_{23}$, $\Delta\bar{m}^2_{32}$) for anti-neutrinos as independent parameters and fit data with ($\bar{\theta}_{23}$, $\Delta\bar{m}^2_{32}$). Other oscillation parameters are assumed to be the same for neutrinos and anti-neutrinos and these values are fixed and taken from the ν-mode results from T2K [18] and the Particle Data Group 2014 [19]. The reconstructed anti-neutrino energy spectrum is shown in Figure 7. The evident distortion of the energy spectrum and the reduction of the observed event numbers with respect to the predicted ones can be seen.



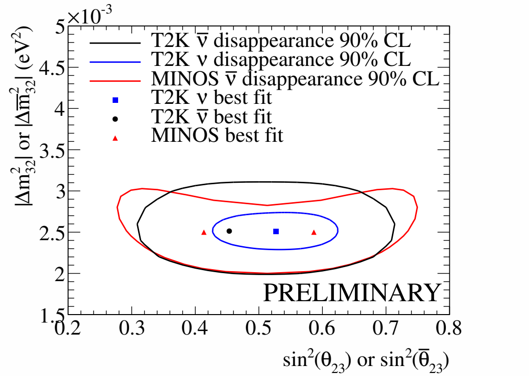


Figure 7. Distribution of reconstructed neutrino energy for 34 muon-like events observed in 4.04×10^{20} POT anti-neutrino beam data (left). Contours of ν mode and $\bar{\nu}$ mode, also for MINOS $\bar{\nu}$ results (right)

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The result of the best-fit oscillation parameters for normal mass hierarchy is :

$$\Delta\bar{m}^2_{32} = 2.50^{+0.3}_{-0.2}\ 10^{-3} eV^2$$

$$\bar{\theta}_{23} = 0.46^{+0.14}_{-0.06}$$

No differences can be observed in the best-fit parameters for normal and inverted hierarchy. The results obtained here are consistent with other experiments: MINOS [20] for anti-neutrino beam and T2K neutrino beam. The comparison is shown in Figure 7 (right). The reduction of the total uncertainty on the muon anti-neutrino disappearance results is not big and passes from 14.4% without the ND280 fit to 11.6% with the use of the ND280 fit results.

In the analysis of $\bar{\nu}_e$ appearance, the selection criteria for $\bar{\nu}$ candidates in the far detector are the same as those for neutrino beam data. As a result, only three events remain as potential candidates of the $\bar{\nu}$ appearance signal. The lack of a field in the far detector makes the separation between ν and $\bar{\nu}$ impossible. The background events include: electron-like events coming from interactions in the far detector, neutrinos from oscillations: $\nu_\mu \rightarrow \nu_e$, misidentified ν_μ (or $\bar{\nu}_\mu$), and original ν_e (or $\bar{\nu}_e$) from decays of muons in the T2K beam.

Table 3. Expected number of events in SK detector with actual 4.04×10^{20} POT for normal hierarchy.

Expected events (NH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288
Background $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389
Background NC	0.349	0.349	0.349
Background other	0.826	0.826	0.826
Total	3.73	4.32	4.85

The expected event number of the background depending on δ_{CP} value and mass hierarchy is presented in Tables 3 and 4. The best-fit oscillation parameters obtained from neutrino beam analysis are assumed, and the number of expected $\bar{\nu}_e$ candidates is calculated for some δ_{CP} for normal and inverted mass hierarchy. The results, as summarized in Tables 3 and 4, changes from 3.73 to 5.45 events.

Table 4. Expected number of events in SK detector with actual 4.04×10^{20} POT for inverted hierarchy.

Expected events (IH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	2.481	3.254	3.939
Background $\nu_\mu \to \nu_e$	0.531	0.423	0.341
Background NC	0.349	0.349	0.349
Background other	0.821	0.821	0.821
Total	4.18	4.85	5.45

The collected statistics are insufficient to confirm or exclude $\bar{\nu}_e$ appearance in the T2K experiment.

6 Other analyses - cross section measurements

Before the T2K experiment started to collect data, only few measurements of the ν cross section in the range energy of the few hundreds of MeV had been performed. The T2K program of the ν cross section measurements on various nuclei is very important from the point of view of the oscillation analyses. As was shown in Section 3, the reduction of systematic uncertainties associated with neutrino interaction cross section measurement and constraints on cross section parameters allow for a more precise prediction of the number of events from neutrino interactions expected in the far detector.

Table 5. List of neutrino cross section measurements in the T2K experiment

no	Cross section	Detector	Target	Reported in
1.	ν_μCC inclusive	Tracker of ND280	CH	PRD 87 092003 (2013)
2.	ν_eCC inclusive	Tracker of ND280	CH	PRL 113 241803 (2014)
3.	ν_μNC elastic	Super-Kamiokande	Water	PRD 90 072012 (2014)
4.	ν_μCC inclusive	INGRID	CH/Fe	PRD 90 052010 (2014)
5.	ν_μCCQE	INGRID	CH	PRD 91 112002 (2015)
6.	ν_μCCQE	Tracker of ND280	CH	Accepted by PRD
7.	ν_μNC π^0	P0D of ND280	CH/Water	Publication in progress
8.	ν_μCC coherent	Tracker of ND280	CH	Publication in progress
9.	ν_μCC π^+	Tracker of ND280	Water	Publication in progress
10.	ν_μCC0π^+	Tracker of ND280	CH	Publication in progress

The information about the already published or ready for publication ν cross section measurements made in both far and near detectors on Hydrocarbon, Iron, Oxygen and Carbon and for different processes is summarized in Table 5.

7 Conclusions

The T2K collaboration has presented updated results of neutrino oscillation analysis based on accumulated 6.6×10^{20} POT neutrino beam data and 4.04×10^{20} POT anti-neutrino beam data collected until June 2015.

The T2K experiment has delivered the currently most precise measurement of the angle θ_{23}, $\sin^2\theta_{23} = 0.524^{+0.057}_{-0.059}$ $(0.523^{+0.055}_{-0.065})$ in the normal (inverted) mass hierarchy scenario.

The T2K data favor larger values of $\sin^2\theta_{13}$ than the reactor experiments. The $\nu_\mu + \nu_e$ joint analysis with the reactor constraint indicates a weak preference for the normal mass hierarchy and the octant of $\sin^2\theta_{23} > 0.5$. There is a preference for values of δ_{CP} around -π/2.

In the $\bar{\nu}_\mu$ disappearance analysis, 34 $\bar{\nu}_\mu$ candidates are found where 103.6 events are expected for no oscillation. The constraints on oscillation parameters, $\Delta\bar{m}^2_{32}$ and $\bar{\theta}_{23}$, are consistent with the results from the MINOS experiment and Δm^2_{32} and θ_{23} parameters from T2K. The present $\bar{\nu}_e$ appearance analysis (three electron-like events found) is statistically limited and cannot strongly favor the appearance hypothesis in comparison with background-only hypothesis. Therefore more anti-neutrino data is needed.

It should be also added, that the cross sections of neutrino interactions measured in the near and far T2K detectors are extremely important from the point of view of the oscillation analyses presented in this paper.

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