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Latest Results and Future Prospects from T2K

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T2K is an experiment designed to observe neutrino oscillations with a baseline of 295 km across Japan from Tokai to Kamioka. Its main goal is to measure oscillation parameters (θ_{23}, Δm^2_{32} and θ_{13}) through ν_μ ($\overline{\nu}_\mu$) disappearance and ν_e ($\overline{\nu}_e$) appearance. T2K reported the first measurement of a non-zero θ_{13} mixing angle and the most precise measurement of θ_{23}. T2K also published recently its first result in the search for CP violation in neutrino oscillations combining appearance and disappearance channels for $\nu/\overline{\nu}$ beam. With reactor measurements, the CP conservation hypothesis is excluded at 90 % C.L.

For precision measurements of neutrino oscillation, it is crucial to understand neutrino-nucleus interaction at few-GeV including nuclear effects. To achieve this, T2K published neutrino-nucleus cross-section measurements of various interaction channels at T2K off-axis (ND280) and on-axis (INGRID) near detectors. T2K has made measurements of the ν_μ charged-current interaction without pions in the final state (CC0π) and with a single pion (CC1π^+) on carbon and oxygen. A new measurement of protons out of CC0π interactions (CC0πNp), is expected to provide complementary precision for better understanding of nuclear effects.

In this paper, the latest oscillation and cross-section results using 14.7×10^{20} of ν-mode and 7.56×10^{20} protons-on-target (POT) of $\overline{\nu}$-mode data accumulated before June 2016 are reported.

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1. INTRODUCTION

Neutrino oscillations is a consequence of non-degenerate neutrino masses and flavour mixing. Flavour states are linear superpositions of mass states with a mixing matrix. Therefore, a neutrino can change its flavour in flight. This is neutrino oscillation. Over the last decades, a series of experiments have measured the neutrino oscillation parameters except for θ_{13}. θ_{13} remained unknown, but only an upper limit was measured, until T2K reported indications of a non-zero mixing angle θ_{13} from ν_e appearance [1]. Later reactor experiments [2, 3, 4] conclusively found θ_{13} to be non-zero and measured it precisely. As T2K measures both ν_μ disappearance and ν_e appearance and their CP conjugated channels, T2K has reported a joint analysis of these four modes in order to measure the CP violation phase, δ_{CP}. In this paper, latest oscillation and cross-section results and future prospects are discussed.

2. T2K

T2K (Tokai to Kamioka) in Japan is a "long-baseline experiment" in which neutrino oscillations are studied as neutrinos travel a long distance. The neutrinos produced at the J-PARC accelerator facilities in Tokai are measured at the near detectors in Tokai and the far detector in Kamioka. T2K uses an off-axis beam configuration to maximize the oscillation probability with T2K neutrino flux. With the T2K off-axis angle, 2.5 degrees, neutrino flux is peaked at the energy (0.6 GeV) where the neutrino oscillation is maximum with the T2K baseline (295 km).

The beamline at J-PARC accelerates 3 GeV proton beam up to 30 GeV and sends it to a graphite target, where secondary particles are produced from hadronic productions. These secondary particles are sent to a decay volume where they decay to leptons and corresponding neutrinos. There are two near detector complexes 280 m away from the beam production: one on-axis detector (INGRID) and one off-axis detector (ND280). At the near detectors, neutrino beams are monitored and neutrino interactions prior to oscillations are measured. The far detector (SK) measures neutrino interactions after neutrino oscillations. SK is a large water Čerenkov detector filled with 50,000 tones of ultra-pure water. Charged particles from neutrino interactions are detected via Čerenkov light in water.

3. Oscillation Analysis

3.1 Oscillations at T2K

T2K measures $\nu_\mu/\overline{\nu}_\mu$ disappearance and $\nu_e/\overline{\nu}_e$ appearance. While ν_μ and $\overline{\nu}_\mu$ disappearance probabilities are the same, ν_e and $\overline{\nu}_e$ appearance probabilities are asymmetric due to the matter effect and CP phase δ_{CP}. A joint analysis, which combines all four oscillation modes, can untangle this degeneracy of the CP asymmetry, as the $\nu_\mu/\overline{\nu}_\mu$ disappearance measurement can constrain $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ in addition to the external constraint on $\sin\theta_{13}$ from reactor experiments.

To extract the oscillation parameters, the neutrino events observed at SK are compared to the MC predictions. The MC predictions involve modelling of the flux, the neutrino interactions and detection efficiency as [5]:

$$N_{SK}^{prediction} \sim \sum_{i}^{flavours} P(\nu_i \to \nu_k)\Phi_i^{SK}\sigma_k\varepsilon_{SK}. \quad (3.1)$$

The dominant systematic sources are the flux and neutrino interaction models. Cross-section measurements at ND280 are used to constrain the flux and neutrino interaction uncertainties.

3.2 ND280 Data

Based on identified particles in ND280, in the ν-mode, ν_μ CC interactions are categorized into three final topologies: CC0π (one muon and no pion), CC1π (one muon and one pion), and CCother (all other muon induced topologies). In $\overline{\nu}$-mode, $\overline{\nu}_\mu$ CC interactions are instead categorized into four topologies: μ^+/μ^- 1-track and μ^+/μ^- N-track. μ^+ 1-track sample is where there is only μ^+ reconstructed and μ^+ N-track sample is where there is other tracks than the identified muon. Two μ^- samples are to handle ν background in $\overline{\nu}$ beam as there is large ν contamination in $\overline{\nu}$ beam. This selection aims to constrain the uncertainties on CC quasi-elastic (CCQE) interaction models and the background arising from CC single pion productions.

The measured muon momentum and angle distributions of the selected samples are used to fit the neutrino flux and interaction parameters in MC predictions. Figure 1 shows the measured muon momentum distributions of ν_μ CC0π sample and $\overline{\nu}_\mu$ CC1-track sample before (top) and after (bottom) the fit. The ND280 measurement is shown in data point and MC predictions are separately shown in primary neutrino interaction modes. MC predictions show better agreement with ND280 data after the fit. After the fit, total uncertainties (detector, flux, and neutrino interaction model) on neutrino events observed at SK are reduced down to 6 % from 12 %.

3.3 SK Data

In terms of SK measurements, there have been improvements since 2016. New reconstruction algorithm and fiducial volume have been implemented, hence the event selection at SK has about 30 % more statistics with better efficiency and purity.

Neutrino interaction candidates at SK require a single Čerenkov ring of a charged lepton in order to select quasi-elastic interactions. There are two types of Čerenkov rings: μ-like ring for ν_μ CCQE interactions and e-like ring for ν_e CCQE interactions. Single μ-like ring (1Rμ) events define $\nu_\mu/\overline{\nu}_\mu$ samples and single e-like ring (1Re) events define $\nu_e/\overline{\nu}_e$ samples. T2K has added new 1Re sample with additional delayed e-like ring arising from CC1π^+ interactions, only for ν-mode. This sample is not included for $\overline{\nu}$-mode due to π^- absorption. Figure 2 shows the estimated neutrino energy from lepton kinematics of 1Rμ events (left) and 1Re events (right) for ν-mode.

3.4 Results

The left plot in Figure 3 shows $|\Delta m^2_{32}| - \sin^2\theta_{23}$ contours assuming normal (black) and inverted hierarchy (red) with the reactor constraint on $\sin^2 2\theta_{13}$. The result is consistent with maximal mixing. The right plot in Figure 3 shows $\delta_{CP} - \sin^2\theta_{13}$ contours. The reactor constraint on $\sin^2 2\theta_{13}$ is applied as well. $\sin\delta_{CP} = 0$ is excluded at 2σ [6]. These results are preliminary. The final systematics is pending and an update on neutrino interaction model uncertainties is expected. More details can be found in [7].

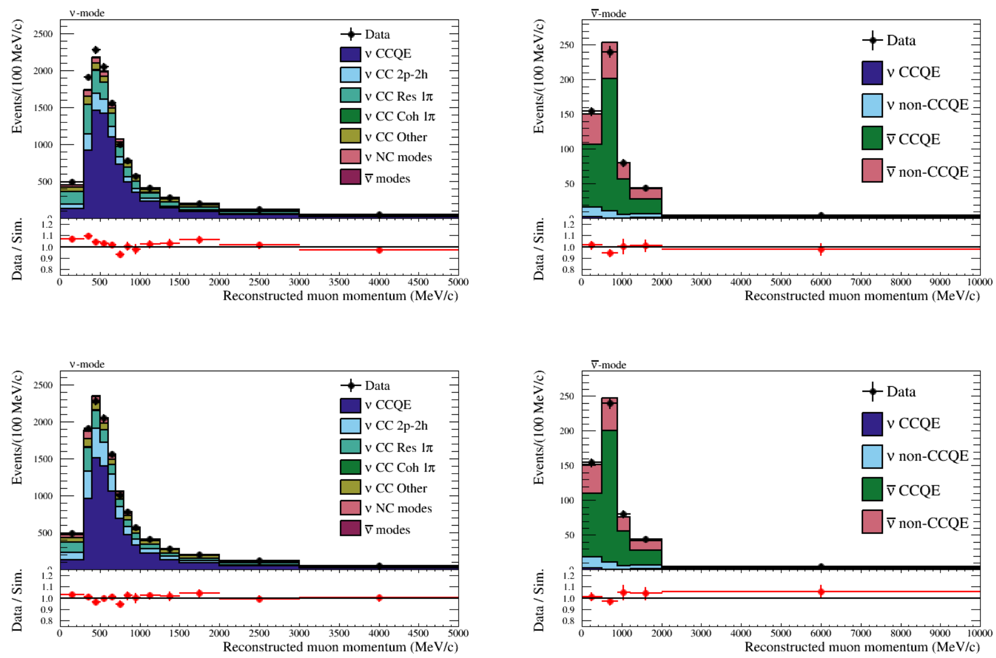

Figure 1: Muon momentum distributions of observed (data point) and MC predicted (histogram) neutrino events at SK for ν_μ CC0π (left) and $\overline{\nu}_\mu$ (right), before (top) and after (bottom) the ND280 fit.

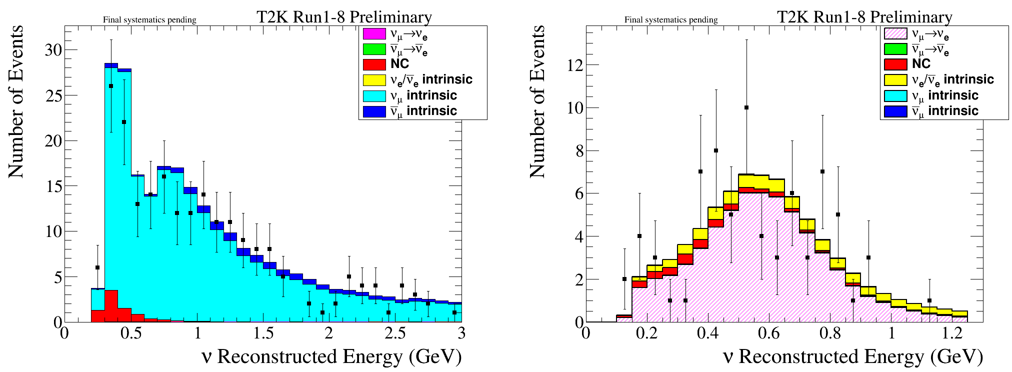

Figure 2: Observed (data point) and MC predicted (histogram) neutrino events at SK selected as 1Rμ (left) and 1Re (right) samples for ν-mode.

4. Cross-section Analysis

4.1 Cross sections at T2K

Accurate knowledge of the neutrino interactions reduces uncertainties on the oscillation analysis, as well as nuclear effects such as final state interaction (FSI) and multi-nucleon processes. At T2K, the main signal is ν_μ charged-current quasi-elastic (CCQE) channels with a significant background from charged-current single pion production (CCRES).

As neutrino interactions are observed only by final state particles, signals are defined as final

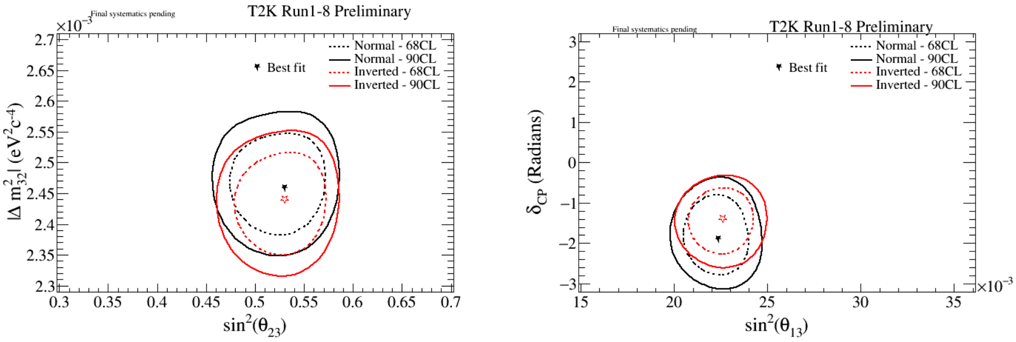

Figure 3: $|\Delta m^2_{32}| - \sin^2\theta_{23}$ contours (Left) and $\delta_{CP} - \sin^2\theta_{13}$ contours (Right) with normal hierarchy (black) and inverted hierarchy (red) are shown. The reactor constraint is applied: $\sin^2 2\theta_{13} = 0.085 \pm 0.05$. The results are preliminary and the final systematics is pending.

state topologies, not by interaction modes. The CC0π selection at T2K is defined as a final topology of one muon and no pion. It aims to selection mainly CCQE events. However, there can be additional contributions other than CCQE in the CC0π selection due to the detector reconstruction inefficiency and nuclear effects such as pion absorption, proton re-scattering, or multi-nucleon ejections to the final state. FSI such as pion absorption or proton re-scattering are reliably modelled in MC, but multi-nucleon processes resulting in multi-nucleon ejections or altering muon kinematics are still needed to be better understood. Measuring CC0π is not enough to explore nuclear effects as the muon utilizes only a part of the final state. Therefore, there is new attempt to include proton reconstruction in an analysis which measures one muon, no pion, and any number of protons (CC0πNp) instead of CC0π at ND280.

In this section, previous ND280 CC0π measurements on carbon and oxygen, and new analysis including protons in a selection will be shown. Other cross-section measurements at ND280 can be found in [8].

4.2 Results

Figure 4 shows the latest results of CC0π on carbon. The ND280 data (points) is shown compared to a theoretical calculation by Nieves [9] with and without including 2p2h components. Figure 5 instead shows the CC0π measurement on oxygen. The theoretical calculation by Martini [10] with random phase approximation (RPA; to include long range correlations) is shown. The results indicate that the data is more in favour of models with 2p2h. But it does not explain how nuclear effects quantitatively contribute to the cross section.

New analysis at ND280, therefore, considers both muon and proton kinematics of the CC0πNp selection. It measures the difference between muon and proton kinematics on the transverse plane of the neutrino beam [11] as described in Figure 6. Measured lepton momentum ($\vec{p}^{\,l}$) and proton momentum ($\vec{p}^{\,p}$) are projected onto the transverse plane. The analysis variables are defined as the difference between the transverse lepton momentum ($\vec{p}^{\,l}_T$) and proton momentum ($\vec{p}^{\,p}_T$) as δp_T, $\delta\phi_T$, and $\delta\alpha_T$. In the CC0πNp selection, CCQE events with no nuclear effects should see a balance between the lepton and hadron kinematics. In other words, any imbalance observed would be an indication of nuclear effects. Right plot in Figure 6 shows the extracted differential cross section

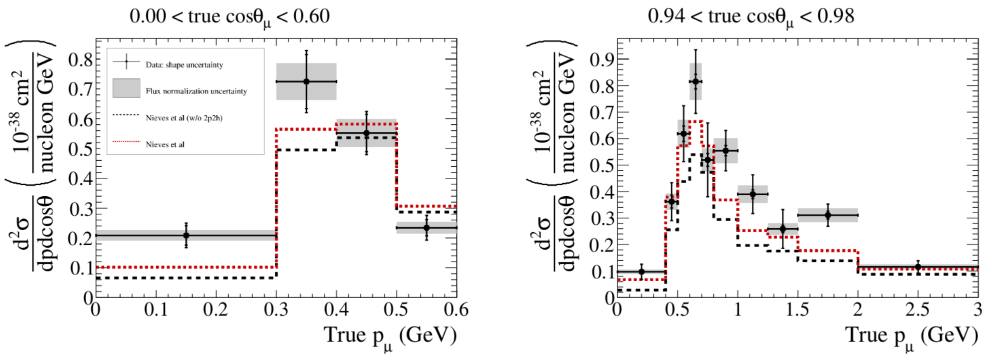

Figure 4: Double-differential CC0π cross sections on carbon in muon momentum and angle: ND280 measurement (points), MC prediction without 2p2h (black dashed histogram) and with 2p2h (red dashed histogram). Nieves model [9] is used for the MC predictions and p-values are provided.

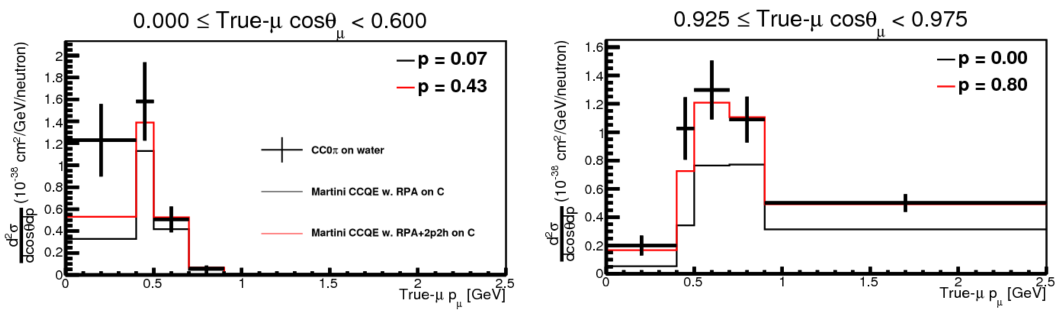

Figure 5: Double-differential CC0π cross sections on oxygen in muon momentum and angle: ND280 measurement (points), MC prediction without 2p2h (black histogram) and with 2p2h (red histogram). Martini model [10] with RPA corrections is used for the MC predictions.

in transverse momentum difference compared with various nuclear models: relativistic Fermi gas (RFG) with random phase approximation (RPA; to include long range correlations), local Fermi gas (LFG), and spectral function (SF) [12]. This analysis is still preliminary, but shows interesting sensitivity to the nuclear models and the best agreement with SF.

5. Future Prospects

There has been a proposal [14] to extend the operation to collect 3 times more POT (7.8×10^{21} POT) than what originally approved (20.0×10^{21} POT). Figure 7 shows the significance of excluding $\sin\delta_{CP} = 0$ as a function of delivered POT (left) and true $\sin\delta_{CP}$ (right). As shown T2K can achieve 3σ level exclusion on CP conserving hypothesis ($\sin\delta_{CP} = 0$) and reduce the systematics uncertainties quite significantly. More details can be found in [15].

6. Conclusion

T2K has performed the joint analysis with doubled neutrino statistics (14.7×10^{20} POT of ν-mode and 7.56×10^{20} POT of $\overline{\nu}$-mode) and improved SK measurements since 2016 and results

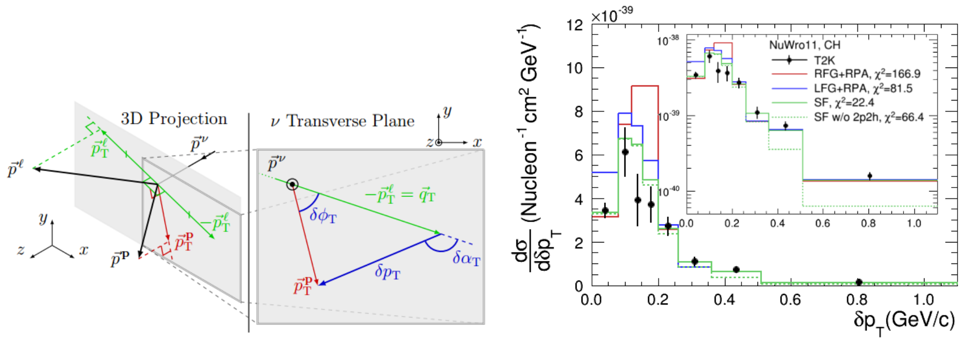

Figure 6: (Left) Definition of single transverse variables used in a study of the CC0πNp selection. (Right) Differential cross section on carbon in δp_T is shown. ND280 measurement (data point) is compared with various nuclear models: RFG with RPA correction (RED), LFG with RPA correction (blue), SF (solid green), and SF without 2p2h (dashed green). For MC predictions, NuWro [13] is used.

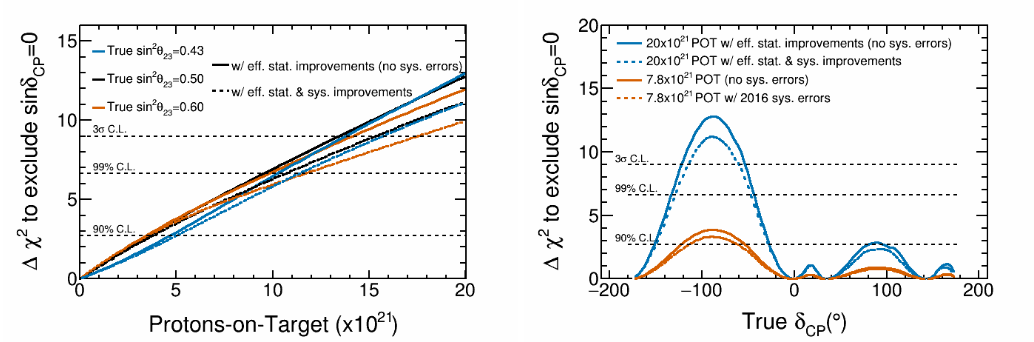

Figure 7: (Left) $\Delta\chi^2$ to $\sin\delta_{CP} = 0$ exclusion as a function of delivered POT. (Right) $\Delta\chi^2$ to $\sin\delta_{CP} = 0$ exclusion as a function of true $\sin\delta_{CP}$.

are reported. The $|\Delta m^2_{32}| - \sin^2 2\theta_{23}$ measurement is consistent with maximal mixing, but the final systematics is pending. The CP conserving hypothesis ($\sin\delta_{CP}$) is excluded at 2σ level.

Cross-section measurements are important for accurate oscillation analyses. To constrain the uncertainties of neutrino interaction models, cross-section measurements at ND280 are used. Along with the existing CC0π measurements, CC0πNp measurement adding the hadronic side is introduced. This is expected to provide further information to understand nuclear effects.

An extension of T2K run has been proposed to collect 3 times more POT and achieve $\sin\delta_{CP} = 0$ exclusion at 3σ level with reduced systematics.

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