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Recent results from T2K

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T2K (Tokai to Kamioka) is a Japan-based long-baseline neutrino oscillation experiment designed to measure (anti)neutrino flavor oscillations and taking data since 2010. Since 2014 has started a campaign to measure the phase δ_{CP}, an unknown element of the Pontecorvo-Maki-Nakagawa-Sakata matrix, that can provide a test of the violation or conservation of the Charge-Parity (CP) symmetry in the lepton sector. To achieve this goal, T2K is taking data with a neutrino and antineutrino enhanced beam investigating asymmetries in the electron neutrino and antineutrino appearance probabilities. The most recent results showed that the CP-conserving cases are excluded at 90% confidence level. One of the largest systematic uncertainties affecting neutrino oscillation measurements comes from limited knowledge of (anti)neutrino-nucleus interactions. The T2K experiment has a wide range of programs measuring neutrino interaction cross-section using detectors in its near detector complex. In this work an overview of the latest T2K neutrino oscillation and cross-section measurements are presented. Afterward, the intense program of upgrades, which promises to improve the sensitivities of the experiment, will be discussed.

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1. The T2K experiment

The T2K (Tokai to Kamioka) experiment is a long-baseline neutrino oscillation experiment based in Japan [1]. The (anti)neutrino beam is produced by the J-PARC accelerator complex located in Tokai, Ibaraki prefecture. The beam is produced using a proton beam accelerated up to 30 GeV that impinges on a graphite target producing pions and kaons that travel through the decay volume and decay in muons and muon (anti)neutrino.

A near detector complex is located 280 m from the beam target. It consists of two detectors: one on the beam axis, called INGRID and the other off-axis, called ND280. The first serves as monitor of the neutrino beam profile and direction. It is made of 14 identical modules of iron and scintillator layers arranged in a cross centered on the beam axis. ND280 is located off-axis and consists of several sub-detectors placed inside the refurbished UA1/NOMAD magnet, which provides a magnetic field of 0.2 T. A π^0 detector (P0D) made of scintillator layers alternated with water bags; two fine-grained detectors (FGDs) that are used as target for neutrino interactions: the upstream FGD consists of scintillator bars arranged in x and y directions with respect to the beam direction, while in the downstream FGD there are water layers alternated with scintillator layers; FGDs are installed between three Time Projection Chambers (TPCs) employed for 3D track reconstruction, particle identification, and determination of charge and momentum; an electromagnetic calorimeter (ECal) surrounds all the inner detectors. It consists of layers of lead alternated with plastic scintillator and allows the reconstruction of tracks and showers. The magnet is instrumented with plastic scintillator called Side Muon Range Detectors (SMRD) that are used both as veto for the cosmic rays and as detector for the particle generated by neutrino interactions.

A new set of detectors located at 1.5 degrees off-axis has been recently installed in the ND280 pit. At this location the neutrino energy peak is 0.86 GeV. It is made of two detectors called WAGASCI (WAter Grid SCIntillator Detector) that are scintillators with a GRID structure filled with water and a spectrometer called BabyMIND[2]. Data have been take in 2019 and 2020 and analyses are underway.

The far detector, also placed off-axis is Super-Kamiokande (SK)[3]. It is located in the Kamioka mine at 295 km from the beam target. SK is a 50 kton water Čerenkov detector. The inner part is equipped with around 11000 20-inch PMTs. The outer by around 2000 8-inch PMTs. It is characterized by a very good muon/electron identification very important for the oscillation analysis.

The off-axis strategy allows to have a narrower beam with an energy peaked around 600 MeV. This reduce the high energy tail and maximize the appearance probability and minimize the disappearance since the peak of the flux correspond to the oscillation maximum.

The main interaction channels at such energies are charged-current (CC) quasi-elastic (CCQE), CC resonant pion production (CC-RES) and CC deep inelastic scattering (CC-DIS). Since neutrinos interact with a bounded nucleon, nuclear effects alter the expected final state particle types and kinematics. Indeed, correlations between nucleons can lead to 2p2h processes. Another possible process is the scattering or the absorption of the final state hadrons in the nuclear environment, called final state interactions (FSI), which can also produce additional final state particles. Such neutrino interactions are simulated using the Monte Carlo (MC) event generator NEUT version 5.4.0.

The reconstruction of the true neutrino interaction type is limited not only by the unavoidable nuclear effects but also by detector acceptance and efficiencies. To minimize model dependence we define experimental observables using final states topologies.

2. Oscillation analysis

In order to extract the oscillation parameters T2K performs Frequentist and Bayesian analyses. First, we define a model that predicts the event spectra at both the near and far detectors. Such predictions are extracted by simulating the neutrino flux and cross-sections tuned with external experimental data and detector response.

In the Frequentist framework, we fit this model to the ND280 data and obtain tuned values and constraints for both flux and cross-section systematic uncertainties. The result of such fit is propagated to SK as a multivariate normal distribution described by a covariance matrix and the best-fit values for each parameter associated to flux and cross-section systematic uncertainties. At this point, we perform a fit to SK data to extract the oscillation parameters. In the context of the Bayesian analysis, we perform a simultaneous Markov Chain Monte Carlo (MCMC) sampling of ND280 and SK likelihoods.

T2K started data taking in 2010 and collected data with ν and $\bar{\nu}$ beams. The results discussed here are with 1.97×10^{21} proton on target (POT) taken in ν beam mode and 1.63×10^{21} POT in $\bar{\nu}$-mode.

To constrain neutrino flux and cross-section we select neutrino charged-current interactions in both ND280 FGDs. These samples are divided in three sub-samples based on the pion multiplicity in the final state: CC-0π, CC-$1\pi^+$, and CC-Other. Compared with previous analysis we doubled the statistics, increasing the sensitivity of our ND280 measurements[4]. In $\bar{\nu}$-mode we have improved the selection moving from a multiple-track based to one similar to the selection we use in ν-mode with the difference that we have a CC-$1\pi^-$ sample. For the data set taken in $\bar{\nu}$-mode we also select neutrino interactions since it is a large background. In the context of the Frequentist analysis, we perform an extended binned likelihood fit to the number of selected events in every sample as a function of muon kinematics, having as penalty term our current knowledge of flux and cross-section. The prior uncertainty on the flux has been reduced from ~8% to ~5% using the data taken by the experiment NA61/SHINE using a T2K replica target[5]. The cross-section model and parametrization was updated compared to the previous analysis[4]. The nuclear model employed to simulate quasi-elastic interactions has been changed to be based on the so called ”Benhar Spectral Function“ model[6], while previously the Relativistic Fermi Gas model was used.

The quantitative agreement between the model and data has been assessed computing the prior model p-value. It has obtained fitting 2000 variations of the systematic uncertainties and was found to be 74%, showing that our model is a good fit to data.

At SK we select five samples: three in neutrino beam mode and other two in antineutrino beam mode. We have 1 muon-like ring (1Rμ) and 1 electron-like ring (1Re) sample in both modes, while we have 1 electron-like 1 decay-electron ring (1Re1de) in neutrino mode only. The decay-electron is produced in $\pi \rightarrow \mu$ decays. In antineutrino mode we do not have this sample since the π^- produced in this interaction is more likely absorbed.

The systematic uncertainties affecting the SK samples are reduced considerably by the ND280 fit. For instance, the systematic uncertainty on ν-1Rμ sample moves from 13% to 3% and from 13.8% to 4.7% on the ν-1Re sample.

The measured value for the mixing angle θ_{13} is consistent with the constraint from reactor experiments and it is compatible with maximal CP-violation as shown in Fig. 1.

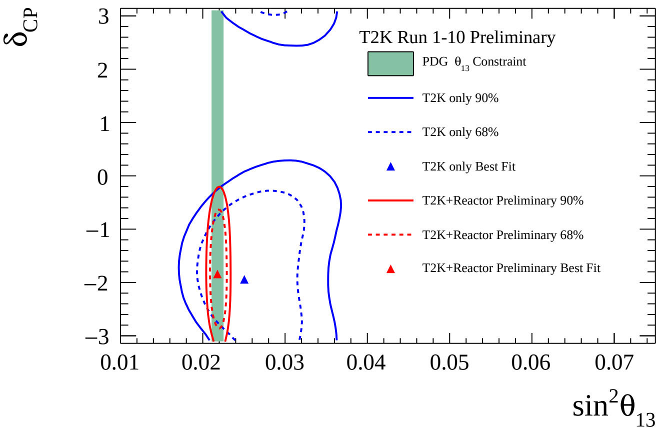

Figure 1: 68% and 90% credible intervals from the marginalised $\sin^2\theta_{13} - \delta_{CP}$ posterior distribution with (red) and without (blue) the reactor constraint (green band) applied.

The results on atmospheric parameters are reported in Fig. 2 and compared with results from other experiments. The new data at the FD has reduced compatibility with maximal mixing, which is now outside of the 1σ confidence interval. While the upper octant is favored at 1σ CL, our data is still compatible with both octant hypotheses at 90% CL. We have performed robustness studies that have showed a bias on Δm^2_{32} of 0.869×10^{-5}eV^2/c^4, which has been added as an additional Gaussian uncertainty.

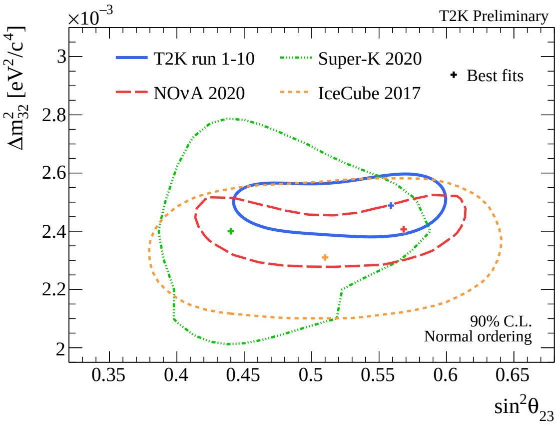

Figure 2: Comparison of the 90% confidence levels of Δm^2_{32} and $\sin^2\theta_{23}$ for different neutrino oscillation experiments with T2K latest results.

As show in Fig. 3 (left) T2K data prefer values of $\delta_{CP} \sim -\pi/2$. The plot on the right in Fig. 3 shows the $\Delta\chi^2$ distributions for δ_{CP} in both mass orderings with confidence intervals calculated using the Feldman-Cousins method. Value of $\delta_{CP} > 0$ are excluded at 3σ confidence level (CL), whereas the CP-conserving values $= 0, \pi$ are excluded at 90% CL, in particular $= \pi$ is just inside the 2σ CL interval. The 90% CL interval is $[-3.01, -0.52]$ ($[-1.74, -1.07]$) for normal (inverted) hierarchy. The largest $\Delta\chi^2$ change that we have seen in any of our robustness studies would cause left (right) edge of 90% CL to move by 0.073 (0.080).

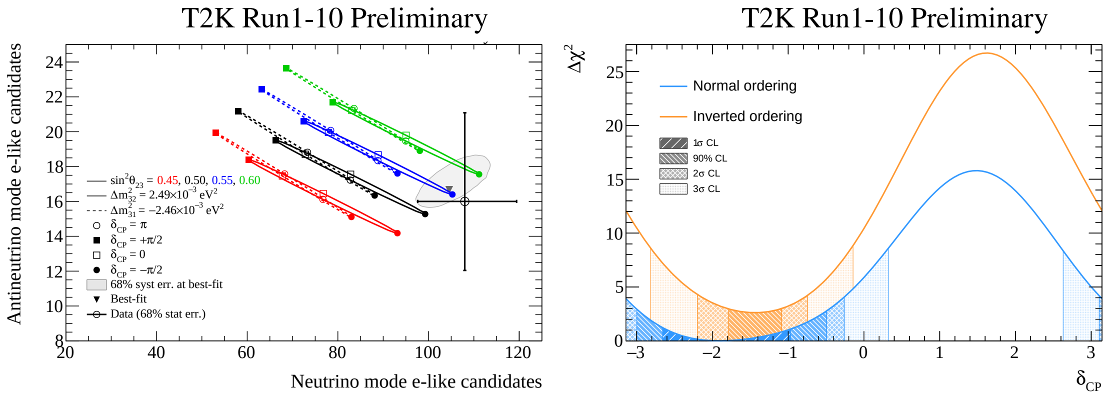

Figure 3: Left: Number of electron antineutrino versus neutrino candidates with the predicted number of events for different sets of oscillation parameter compared with the observed data. The grey contours contain the predicted number of events for 68% of simulated experiments obtained varying systematic and oscillation parameters around the best-fit value from the fit to data. The triangle shows the predicted number of events with both oscillation and systematic parameters at their best-fit values.
Right: $\Delta\chi^2$ distribution in δ_{CP} for the fit to data, including the reactor constraint. The confidence intervals are calculated using the Feldman-Cousins method.

We are currently working on the next iteration of the oscillation analysis and we plan the following improvements:

- Additional sample at SK called Multi-Ring (MR): muon neutrino CC interactions with 2 muon-like rings and 1 decay-electron or 1 or 2 muon-like rings and 2 decay-electrons;
- Split the CC-0π sample depending on the presence or not of protons. The two samples have a different sensitivity to nuclear effects which can help constraining better our cross-section modeling which will be also updated;
- Improve neutrino selection at ND280 isolating CC interactions with π^0s by looking at the photons in ECal or the e^+e^- pairs in the TPCs. This increases the purity of the CC-0π and CC-$1\pi^+$ samples and help constraining the new MR sample at SK;
- Update the flux prediction using the latest NA61/SHINE data.

3. Cross section measurements

T2K has a wide cross section measurement program: multiple targets, fluxes and detectors at different off-axis angles provide abilities to investigate neutrino-nucleus scattering in different and complementary ways[8, 9].

Neutrino scattering understanding is vital for the interpretation of neutrino oscillation since it affects background estimation and energy reconstruction. One of the largest systematic uncertainties in neutrino oscillation comes from neutrino interaction modeling and in particular from the modeling of nuclear effects[10].

One good probe of the latter is the transverse kinematics imbalance (TKI) in neutrino interactions in the plane transverse to the neutrino direction. Starting from the projection of the momentum of the particles produced in a neutrino interaction on the plane transverse to the neutrino direction, it is possible to define TKI variables[11–14]. Recently we published the first measurement of the TKI in the ν_μ charged-current single-π^+ production channel containing at least one proton as function of three variables: the emulated nucleon momentum (p_N), the transverse boosting angle ($\delta\alpha_T$), and the double-transverse momentum imbalance (δp_{TT})[15]. The first probes the Fermi motion inside the nucleus and in case of different FSI strength the peak can shift and a long tail is observed. The second is flat in absence of nuclear effects. The third, which is defined as the projection of the momentum of the proton and pion on the axis perpendicular to the plan defined by the neutrino and the muon, is zero if there are no nuclear effects, while Fermi motion and FSI cause a broad distribution.

The comparison of the extracted cross-section as function of these three variables with the different models implemented in different MC events generators is shown in Fig. 4 (for details about the MC generators used in the comparisons see Ref. [15]). For the emulated nucleon momentum Relativistic and Local Fermi Gas nuclear models are strongly disfavored at small p_N and almost all models over-predict the peak region. For $\delta\alpha_T$ the current statistics and detector capabilities limit our sensitivity. For δp_{TT} the model sensitivity comes mostly from central bins and the tail is mostly contributed by FSI. In general more sophisticated nuclear models are needed to describe the data.

4. Future prospects

T2K was originally approved to collect 7.8×10^{21} POT driven by the sensitivity to θ_{13}. In 2016 the Collaboration proposed to extended the data taking until 2026, with the primary goal of reaching 3σ CL on CP-violation. To achieve this goal we need to reduce the systematic uncertainties and collect more data.

We plan to increase the beam power up to 1.3 MW and horns current up to 320 kA, and to upgrade the off-axis near-detector[16]. For the former the plan is to upgrade the Main Ring power supply in 2021 and to upgrade the main ring RF in 2025. With the first upgrade, the beam power will go above 800 kW in 2023 and once the upgrade will be over we expect to reach a beam power of 1 MW or above around 2027. For the upgrade ND280, the plan is to replace the upstream detectors with a new detector called SuperFGD, which consists in 2 million 1cm scintillator cubes read by three wavelength shifting fibers, located between two TPCs equipped with resistive MicroMegas and surrounded by scintillator planes that will be used to measure the particle Time-Of-Flights. The construction is planned to start in Fall 2022 and taking data early 2023. The main improvements will be: improved muon reconstruction efficiency, lower threshold for protons, measure neutron kinematics and increased target mass.

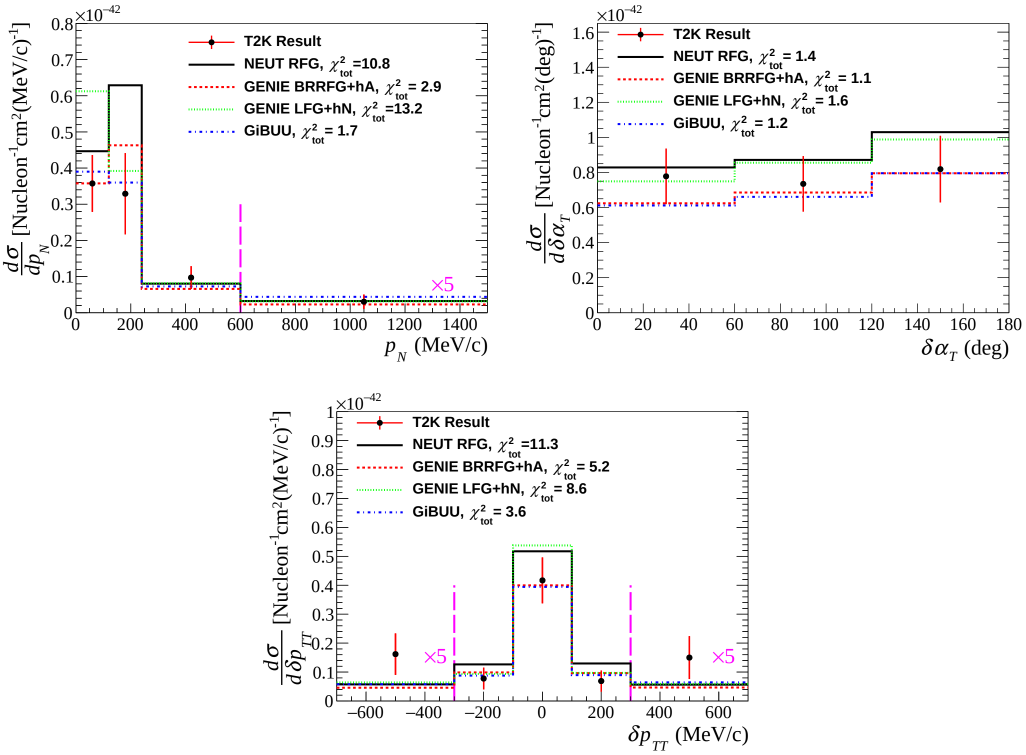

Figure 4: Measured differential cross sections per nucleon as a function of p_N (top left), $\delta\alpha_T$ (top right), and δp_{TT} (bottom) together with predictions from NEUT, GENIE, and GiBUU. In the tails of δp_{TT} and p_N (beyond the magenta lines), the cross sections are scaled by a factor of 5 for better visualization. The legend also shows the χ^2_{tot}.

5. Conclusions

In summary, the latest neutrino oscillation results use a total of 3.6×10^{21} POT with significant improvements to the analysis. The CP-conservation is excluded at 90% CL, compatibility with maximal mixing was reduced and the upper octant is favored at 1σ CL. In the next iteration of the oscillation analysis we expect new ND280 and SK samples, and improved flux prediction and uncertainty. T2K cross-section measurements are focused on understanding nuclear effects since they are the largest source of uncertainty in neutrino oscillation measurements. They show that more sophisticated nuclear models are favoured but more data are needed to draw a more clear conclusion. The Collaboration is working on the beam line upgrade to reach 1.3 MW and the upgrade of the off-axis ND280. Combined analysis with NOνA and SK, which were not discussed in this work, are underway.

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