PROCEEDINGS OF SCIENCE

Latest oscillation results from T2K

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T2K is an accelerator-based neutrino experiment providing world-leading measurements of the parameters governing neutrino oscillation. T2K data enabled the first 3σ exclusion for some intervals of the CP-violating phase δ_{CP} and precision measurements of the atmospheric parameters Δm^2_{32}, $\sin^2\theta_{23}$.

The experiment uses a beam of muon (anti)neutrinos produced at the Japan Particle Accelerator Research Centre (JPARC) and a series of detectors located at JPARC and in Kamioka, 295 km away, to measure oscillation from neutrino event rates and spectra. The T2K beam will be upgraded with increased power in 2022 and, combined with an upgrade of the ND280 near detector, will usher in a new important physics period for T2K.

During the shutdown, T2K collaboration is working on an updated oscillation analysis to improve the control of systematic uncertainties. A new beam tuning has been developed, based on an improved NA61/SHINE measurement on a copy of the T2K target and including a refined modeling of the beam line materials. New selections have been developed at ND280, with proton and photon tagging, and at Super-Kamiokande, where pion tagging has been extended to muon neutrino samples. After reviewing the latest measurements of oscillation parameters, the status of such new analysis developments and the plan to deploy the beam and ND280 upgrade is presented.

PoS(NuFact2021)054

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6–11 Sep 2021 ****
**** Cagliari, Italy ****

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T2K is an international experiment located in Japan [1]. The beam of muon neutrinos is produced on the eastern shore of Japan and sent to the west, where under Japanese Alps, in the distance of 295 km the oscillations are studied in the far detector.

The beam is created in the Japan Proton Accelerator Research Center. Protons are accelerated to the energy of 30 GeV and then hit the target made of graphite. In the collisions new particles are produced, mostly pions and kaons, which are focused by 3 magnetic horns and directed towards the decay volume where they decay producing neutrinos. By switching the direction of the current in the horns positive (Forward Horn Current, FHC) or negative (Reverse Horn Current, RHC) mesons can be focused, thus obtaining neutrino or antineutrino beam.

In the distance of 280 m from the target the near detector complex is located. It consists of INGRID, an on-axis detector, and two other detectors placed off-axis. One of the called ND280 is a multi-purpose detector equipped with magnetic field. The part used in the oscillation analysis is the tracker which consists of two Fine Grained Detectors (FGDs), one of which is made of scintillator and the other one contains also layers of water. FGDs are sandwiched between Time Projection Chambers (TPCs). They allow for the particle momentum, charge reconstruction and also the identification using the measurement of the energy loss.

The far detector in T2K experiment is Super-Kamiokande, very famous detector containing 50 kiloton of ultrapure water. It is equipped with over 11,000 photomultipliers which detect the Cherenkov light produced by particles traveling through water. The detector can distinguish muons and electrons. The reconstruction of neutrino energy is also possible with quite good accuracy.

T2K started data taking in 2010 and collected data with ν and $\bar{\nu}$ beams. The results presented here, which were for the first time shown at [2], are obtained for Runs 1-10 (2010–2020), with 1.97×10^{21} POT in FHC and 1.63×10^{21} POT in RHC. For FHC, this is an increase of 33% since previous analysis [3, 4].

In general, the analysis is based on the comparison of what is measured in the detector and the predictions based on models for the flux, neutrino interactions and response of both detectors, as well as the oscillation parameters in case of Far Detector. All the models are parametrized and the change of the parameter values in the fitting process results in the change of predictions, allowing to find the parameter values that give the best agreement between data and simulation.

The simulation of the flux [5] starts with the interaction of the primary protons in target done with FLUKA simulator and then what is exiting the target is propagated through the magnetic field in horns and through the decay volume with GEANT 3. The results are reweighted to match the data from NA61/SHINE experiment. In the current analysis the NA61/SHINE data taken with the T2K replica target [6] are used so the flux Monte Carlo is reweighted taking into account momentum, angle and exit point in the target, which means that the re-interactions inside the target are automatically taken into account, leading to smaller model dependency and reduced uncertainty (from $\sim 8\%$ to $\sim 5\%$).

In the energy range of T2K the dominant reaction is the charged current quasi elastic interaction, both for neutrinos and for antineutrinos, but there is a significant contribution from the resonant events and from 2p2h interactions. One has to remember also that the interactions happen in the nucleus. This concerns both the initial state of the target nucleon and also the final state, when produced particles have to be propagated through the nuclear medium before they exit nucleus and can be observed in the detector. T2K uses NEUT generator [7] for simulations of neutrino interactions.

There were significant improvements in the cross-section models in the recent analysis. One of most important was related to the quasi elastic (QE) part and the description of the initial nucleus. Previously, the Relativistic Fermi Gas model was used, which is now changed to the Spectral Function [8], more realistic model based on the shell model of the nucleus and tuned to the experimental data. Since this data were collected with the scattering of electrons on protons, one has to correct for the fact that the neutrinos are interacting with neutrons in case of QE reactions. Data from other experiments show also that some freedom for suppression cross-sections at low Q^2 is needed. Therefore, some parameters were introduced in the model which do not have good physical meaning but allow the low Q^2 suppression. There were also other improvements like the treating of the nucleon binding energy and also changes to models of other reactions: Deep Inelasting scattering, multipion production and also 2p2h.

Summarizing, the treatment of the neutrino interactions is now more sophisticated but also introduces much more parameters to the fit (47 cross-section parameters).

The Near Detector fit is used to find the best values of the flux and cross section parameters which are then used to create the prediction for the Far Detector[1]. The samples of charged current interactions of $\nu_\mu (\bar{\nu}_\mu)$ in tracker are selected and the momentum and emission angle of the $\mu^\pm$ candidate is used in the fit.

In total, there are 18 samples which give sensitivity to different neutrino energy ranges and contain different fractions of the reactions: separate samples for FGD1 and FGD2 detectors (interactions on the hydrocarbon or water); separate samples based on the presence of the pions in the final states: $CC0\pi$, $CC1\pi$ and *CC other*; the dominant component of the beam (ν_μ for FHC, $\bar{\nu}_\mu$ for RHC) and for RHC also the ν_μ component. Comparing to previous analysis, the set of data from the ND280 used in the fit was doubled.

In the ND280 fit the values of the flux and cross section parameters are changed until the best agreement between prediction and data for all 18 samples is found. A test was performed to check if the model was able to cover the phase space region which best describes the data and the P-value of 74% was obtained which shows that data are very consistent with the model. In the fitting process also strong anticorrelations are introduced between the flux and cross section parameters.

As for the Far Detector, five samples of so called one ring events are used in the analysis. A single ring means that only one Cherenkov ring from the charged lepton was observed in the detector and such sample is dominated by QE events. There are two samples of the muon-like events, for FHC and RHC, and 3 samples for electron-like events, one for RHC and two for FHC. The additional FHC one is 1-pion sample, when a delayed Michel electron from $\pi \to \mu \to e$ decay chain was observed in the event.

The μ-like and e-like samples are used together within full 3-flavours oscillations framework. T2K has three fitter groups which use various methods of the analysis. Analyses A and B perform the sequential ND280 and oscillation fits with frequentist approach, while analysis C uses all the samples simultaneously in Bayesian Markov Chain approach. Analysis B uses the lepton kinematics

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[1] In fact, one of three analysis frameworks used in T2K doesn't perform separate fit to ND280 data, but instead fits all Near and Far detector samples simultaneously

for the e-like samples and both analyses A and C use the reconstructed neutrino energy.

In the fit, the parameters of interest are θ_{13}, θ_{23}, $|\Delta m^2_{32}|$ and δ_{CP}. Other oscillation parameters which appear in the probability formula are taken from the Particle Data Group (PDG). The fit is performed using the binned likelihood fit which compares data to the Monte Carlo predictions.

The confidence intervals for δ_{CP} for the frequentist analysis and the Bayesian analysis posterior probability density are shown in Fig. 1 [2]. The preferred regions for δ_{CP} are in agreement in both analyses. The best fit is close to maximum CP violation: $\delta_{CP} = 1.97^{+0.97}_{-0.70}$, and a wide range of the values is excluded. Both CP conserving values, 0 and π, are excluded at 90%, however π is not excluded with 2σ. The largest change in δ_{CP} best fit with respect to the previous analysis [3, 4] comes from the new collected data.

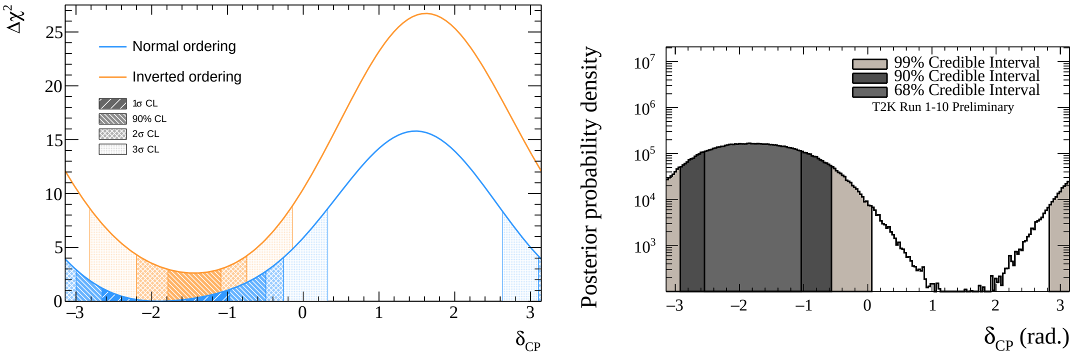

Figure 1: Left: $\Delta\chi^2$ distribution as a function of δ_{CP} (analysis A). Right: δ_{CP} marginalized posterior distribution, marginalized across hierarchies (analysis C).

As for the other oscillations parameters, there is a weak preference for the normal hierarchy, with posterior probability of 0.808. The latest data prefer also the upper octant of θ_{23} and are compatible with maximal mixing.

For the future analysis planned to be released on 2022, except for including new data taken in spring this year with neutrino beam, there are also many improvements ongoing. In particular there will be new samples of events.

In case of ND280, “photon” and “proton” samples will be added for FHC. They will provide additional constraints or tests of the models used.

For the “photon sample” a photon is tagged in ECal. Such photons come mostly from π^0 decays and the sample is dominated by DIS and multipion events. Thanks to that tag the purity of $CC0\pi$ and $CC1\pi$ samples will be about 10% higher.

The $CC0\pi$ samples will be split into two depending on the presence of proton in the final state [9]. Muons in both such samples occupy different regions of the kinematic phase space. The *0proton* sample contains also much higher fraction of true CC QE events. Also, “proton samples” can probe different regions on the true energy and true momentum transfer plane.

One other sample will come from the far detector. It will be so called “multiring sample” for FHC μ-like events [10], where a charged current interactions with the production of one pion is found. The estimation of the systematic errors for this samples is ongoing.

In more distant future, probably the new information on the presence of neutrons in the far detector will be used, thanks to the loading of Super-Kamiokande with the salts of gadolinium [11]. Also, soon the upgrades of the Main Ring accelerator and ND280 will start. Thanks to new power supply for the Main Ring the repetition rate will be two times higher and also more protons per pulse will be delivered. In about 1 year the beam power will be increased to 750 kW and after several years to over 1 MW [12].

In ND280, the π^0 detector will be replaced with a new scintillator detector called SuperFGD sandwiched horizontally between two new High Angle TPCs. The system will be surrounded by Time-Of-Flight planes. Such configuration will significantly increase the angular acceptance, with respect to the old tracker, and the detection threshold will be much lower [13].

Acknowledgments

This work was partially supported by the Ministry of Education and Science (DIR/WK/2017/05) and the National Science Centre (UMO-2018/30/E/ST2/00441), Poland.

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