PROCEEDINGS OF SCIENCE

The T2K Near Detector upgrade

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The T2K, "Tokai to Kamioka", experiment is a long baseline neutrino oscillation experiment located in Japan and dedicated to the measurements of neutrino oscillations parameters. The muon neutrino beam produced at the Japan Proton Accelerator Research Complex is measured first by a set of near detectors, and then, after 295 km, by a far water Cherenkov Super-Kamiokande detector, where the appearance of electron neutrinos in a muon neutrino beam was observed for the first time. The near detector complex is represented by the Interactive Neutrino GRID on-axis detector, designed to control the position and stability of the incoming neutrino beam, and the ND280, magnetized off-axis near detector situated at 280 meters from the neutrino production target. The main purpose of ND280 is to measure and constrain the neutrino flux before oscillations. The current focus of the T2K experiment includes measuring Charge-Parity violation in the lepton sector and improving the current knowledge of neutrino cross-section models. Such goals can be reached by increasing the statistics and reducing systematic uncertainties. Thus, the T2K upgrade program proposes rising in the beam power and modernization of the ND280 near detector. The upgrade includes replacing the π^0 detector with a 3D plastic scintillator fine-grained Super-FGD detector target that will improve hadron reconstruction, and it will be sandwiched between two Time Projection Chambers, allowing high-angle outgoing charged particles to be reconstructed. In addition, the entire structure will be covered with six Time Of Flight planes, which will reduce the background from the interactions outside of the Super-FGD. The performance of each detector upgrade module was tested separately and it was shown that the Super-FGD can reach $\sim$1 ns time resolution and perform proton and neutron reconstruction. The spatial and energy ionization loss resolution of the High-Angle Time Projection Chamber prototype does not exceed 0.8 mm and 10% respectively and Time Of Flight planes can provide 0.14 ns time resolution. In addition, the ND280 physics studies show a promising reduction of neutrino interaction model uncertainties by employing the transverse kinematic variables for current and future ND280 configurations and statistics.

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1. The T2K experiment and motivation for the upgrade

The T2K neutrino experiment situated in Japan includes a near detector complex, composed of off-axis ND280 and on-axis Interactive Neutrino GRID (INGRID) detectors, and a far water Cherenkov Super-Kamiokande detector. It is designed to measure oscillation parameters: θ_{13} and δ_{CP} through $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance and θ_{23} and Δm^2_{32} through ν_μ and $\bar{\nu}_\mu$ disappearance.

To increase the precision and to reach a 3σ or higher significance on Charge-Parity (CP) violation for large δ_{CP} values the T2K upgrade was proposed. It includes an increase in beam power from 500 kW to more than 750 kW with the goal of reaching the final beam power of 1.3 MW and collecting more than 10^{22} POT (Protons on Target). Larger statistics require better control of systematic uncertainties hence the T2K upgrade proposal includes the improvement of the ND280 performance and implies the ND280 upgrade.

2. ND280 upgrade overview

The ND280 detector is devoted to measuring the ν_μ and $\bar{\nu}_\mu$ spectrum and interaction rate and the intrinsic ν_e contamination in the beam in order to predict the expected spectra at Super-Kamiokande (SK) far detector without oscillations.

The current configuration of ND280 includes a set of detectors surrounded by an electromagnetic calorimeter and a UA1 dipole magnet that hosts a side muon range detector (SMRD) and provides a 0.2 T uniform horizontal magnetic field. The neutrino target and tracker part of the ND280 is introduced by the π^0 detector (P0D) devoted to the measurements of the neutral current neutrino reaction background with outgoing single π^0 in the final state and two scintillating fine-grain detectors (FGDs), FGD1 and FGD2 with carbon-hydrogen targets interlayered by three gaseous vertical Time Projection Chambers (TPCs) (Fig.1) devoted to both tracking and particle identification. FGD1 consists of the scintillator solely, while FGD2 houses the water target embedded between the scintillator layers in order to measure the cross-section on water.

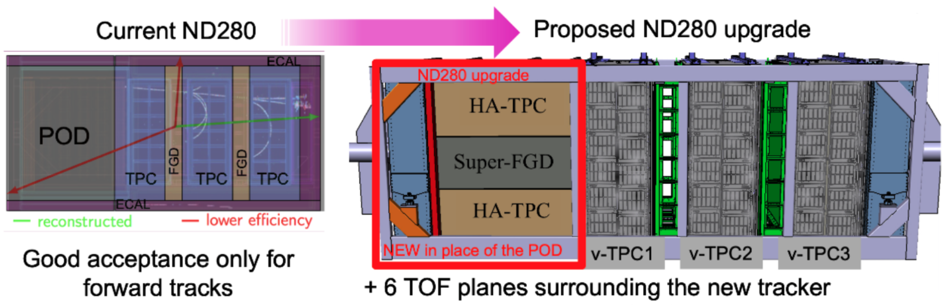

Figure 1: The scheme of the ND280 detector upgrade, in which the neutrino beam travels from the left to the right.

The main motivation for the ND280 upgrade is a limited acceptance of the tracks exiting a neutrino interaction at high angles and a low efficiency to reconstruct the hadronic part of the interactions.

These limitations will be overcome with the ND280 upgrade configuration which inherits the current successful combination of scintillation targets FGDs and vertical TPCs and includes the replacement of the P0D detector by the highly segmented target Super-FGD that allows reducing a threshold on hadrons and low-momentum lepton reconstruction and provides a possibility of neutron detection. Super-FGD will be surrounded by two high-angle TPCs (HA-TPCs) that will allow reconstruction of the high-angle leptons and the whole configuration will be covered by the six Time Of Flight (TOF) planes providing the reduction of the background. The upgraded configuration of ND280 is expected to reduce the overall systematics uncertainty down to 4% and the start of the upgrade installation in Japan is expected in 2023.

3. Super-FGD

The new Super-FGD detector is a fully active plastic scintillation detector of 200x180×60 cm^3 composed of 2 million scintillator plastic cubes of 1x1x1 cm^3. The 2.2 tons target mass, similar to the mass provided by current FGDs, tends to ensure a sufficient number of neutrino interactions. Each cube is equipped with wavelength shifters (WLS) in order to provide a 3D particle track reconstruction. The WLSs guide photons produced by the charged particles to photosensors (multi-pixel photon counters) readout. Using the information of the fired fiber the particle position, deposited energy, and time of the interaction can be precisely identified. Super-FGD allows the reconstruction of charged leptons as well as the hadronic part of the interaction such as protons and neutrons. The latter in particular is crucial to understand better anti-neutrino charged current quasi-elastic Scattering (CCQE) and neutrino-nucleus interactions on two correlated nucleons (2p2h interactions). So far the performance of the detector was tested at CERN [1, 2], for the charged particles of various momenta, and its perfect ability to resolve protons was demonstrated. The time resolution of the prototype was estimated to be 1.14 ns for a single channel. Furthermore, the Super-FGD prototypes were tested at Los Alamos National Laboratory where the total neutron cross-section as a function of neutron kinetic energy was measured [3].

4. High-Angle TPCs

The two HA-TPCs will be installed on the top and on the bottom of the Super-FGD detector with the goal to cover the high-angle region, providing a high-angle track resolution, 3D reconstruction, and measuring particles' charge and momentum. HA-TPCs inherit the design of the existing vertical TPCs, however, there are two main innovations in comparison with the previous design. Firstly, the new field cage is being developed. The one-layer field cage in the upgraded design will replace the old two-layers configuration, reduce the dead space and maximize the tracking volume. Secondary, each high-angle TPC will be equipped with the 8 readout Resistive MicroMegas modules (ERAM) in order to collect a particle signal in each pad, read-out ERAM unit. For HA-TPCs the new ERAM configuration was developed with a number of advantages with respect to the old bulk Micromegas detector configuration. The new ERAM module is equipped with a resistive layer that will allow to spread the charge over multiple pads, therefore, improving the spatial resolution and reducing the number of read-out channels. In order to distinguish electrons and muons with a 3σ separation the deposited energy resolution is required to be better than 10% and spatial resolution less than 0.8 mm in order to reconstruct charged particle momentum.

The HA-TPC performance was tested during several test beams started in 2018. Different HA-TPC prototypes' lengths and various ERAM module designs were exposed to a particle beam and the collected data were analyzed. During the first test beam campaign at CERN, the HA-TPC prototype of 1.5 m was exposed to the beam of various particles with the first version of the ERAM [4]. Then later, in 2019 the shorter chamber equipped with the ERAM of a larger pad size was tested in DESY with an electron beam [5]. Then in 2021, again in DESY, the HA-TPC prototype of one-meter length that corresponds to the final length of one-half of TPC was tested together with the ERAM module with the improved charge spreading.The preliminary results obtained for the data collected during the DESY 2021 test beam campaign fully satisfy the ND280 upgrade requirements and show that dE/dx resolution stays less than 9.6% and spatial resolution less than 0.8 mm for both horizontal and inclined tracks for different peaking time and at various drift distances (Fig. 2).

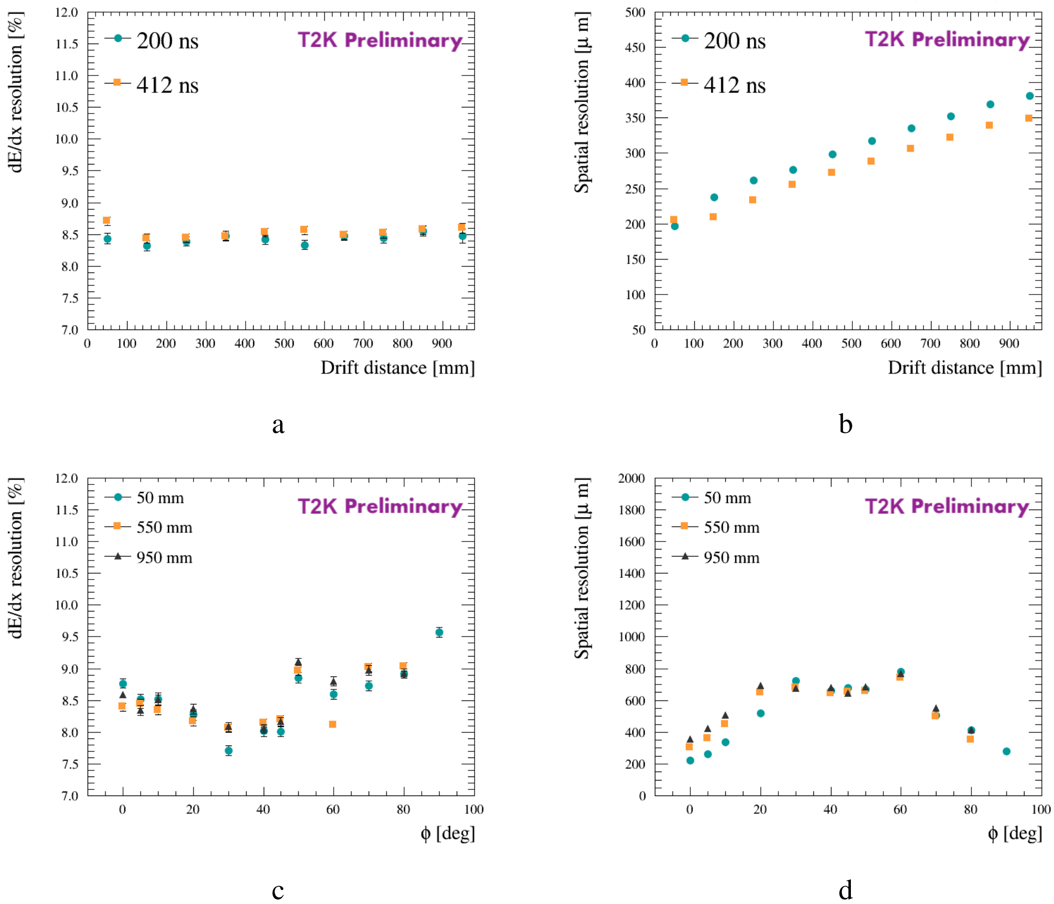

Figure 2: dE/dx (left) and spatial (right) resolution for horizontal tracks versus the drift distances at 412 ns and 200 ns peaking time (a, b) and inclined tracks versus the angles of the inclination in the ERAM plane at 50 mm, 550 mm and 950 mm drift distances (c, d).

5. TOF detectors

The six time-of-flight planes that are aimed at improving particle identification, triggering on cosmic muons, and reducing background from outside of Super-FGD will fully cover two HA-TPCs and Super-FGD modules. The main purpose of the TOFs is to provide a time stamp for each track and by comparing it with the time stamp of Super-FGD identify the direction of the tracks. Each plane consists of 20 scintillator bars and each bar is read out at both ends. The performance of the TOF was tested [6] and the measurements show an excellent time resolution of 140 ps for the single bar test.

6. ND280 upgrade physics studies

The ND280 upgrade has great potential to significantly reduce uncertainties on neutrino flux and cross-section where our knowledge is highly limited by the uncertainties that mostly come from nuclear interactions modeling. The low-threshold ability of Super-FGD to reconstruct hadrons allows a better understanding of neutrino-nuclear interactions and provides a possibility to take more advantage of using transverse kinematic hadron variables (Fig. 3) such as missing transverse momentum ($\delta\vec{p}_T = |\vec{p}^{\,l}_T - \vec{p}^{\,N}_T|$), boosting angle ($\delta\alpha_T$), and visible energy, defined as $E_{vis} = E_\mu + T_N$ (E_μ is muon outgoing energy and T_N is the kinetic energy of the outgoing hadron).

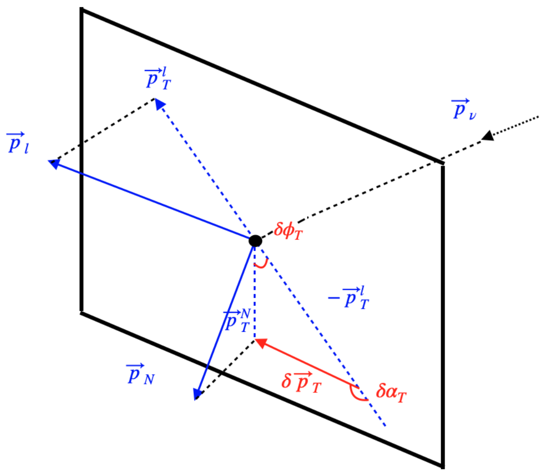

Figure 3: Schematic representation of the transverse kinematic variables.

As it has been shown in [7] the missing momentum allows us to separate CCQE and non-CCQE events and, in the case of anti-neutrino, extract the interactions on hydrogen. In its turn, the boosting angle shape is sensitive to final state interactions and visible energy to nuclear removal energy. In [7] was shown that with the statistics provided by the upgrade and by using transverse kinematics variables the constraint on neutrino (anti-neutrino) interactions can reach 1.5% (2%) for CCQE interactions and less than 5% (10%) for CCQE plus non-quasielastic interactions. The obtained results can be improved by employing the full ND280 model introduced by the set of parameters and their uncertainties that characterize neutrino event rates measured by the ND280 detector. For this purpose within the T2K collaboration, a new fitter GUNDAM was developed, where GUNDAM stands for a Generic Fitter for Upgraded Near Detector Analysis Methods.

To summarize, the focus of current and future ND280 physics studies includes the prediction of the constraints on the neutrino flux and cross-section models for future oscillation analysis using Super-FGD simulation, improving a selection of electron neutrino and anti-neutrinos, studying nucleon final state interactions [8], etc.

7. Conclusions

The T2K experiment is entering its upgrade phase in order to reach 3 sigma significance to CP violation. Consequently, the beam power will be increased from 0.5 W to 1.3 W and followed by the ND280 upgrade. The main components of the upgrade are almost ready for integration and show satisfying performances. Moreover, the physics program shows a promising ability to constrain the systematics uncertainties which would allow for improved measurements of neutrino oscillation parameters.

References

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