PROCEEDINGS OF SCIENCE

The T2K Near Detector Upgrade

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The T2K experiment is a long-baseline neutrino oscillation experiment that aims to precisely measure neutrino oscillation parameters. The muon (anti)neutrino beam produced at J-PARC is measured at the near detector complex and at the far detector Super-Kamiokande. The major role of the near detector ND280 is to constrain systematic uncertainties that affect neutrino oscillation measurements. T2K is currently upgrading ND280 to fully leverage the expected increase of statistics over the upcoming years and to further improve the constraints on those uncertainties, particularly the ones related to the neutrino interaction model. The capabilities of full polar angle acceptance, lower proton tracking threshold as well as reconstruction of neutron kinematics that this upgrade offers will open the door to explore new physics with unprecedented precision.

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1. Introduction

The T2K experiment [1] measures neutrino oscillation parameters by producing at J-PARC an intense muon (anti)neutrino beam peaked at 600 MeV. This beam is measured 280 m away from the source with a set of near detectors before oscillations to monitor it and constrain systematic uncertainties on the flux and the neutrino interaction models. The far detector, located 295 km further, is Super-Kamiokande (SK) which measures the disappearance of muon (anti)neutrinos and the appearance of electron (anti)neutrinos in the beam.

ND280, the near detector used in the T2K oscillation analysis (OA), consists of two fine-grained detectors, FGD1 and FGD2, which are the target mass for neutrino interactions. They are both made of plastic scintillator bars in layers arranged horizontally and vertically, with additional water layers in FGD2. They are sandwiched between three time projection chambers (TPCs) which allow precise tracking and measurement of the charged particles and their momenta. All of these subdetectors are placed inside the refurbished UA1 magnet.

The current ND280 has an excellent efficiency to reconstruct the muons from neutrino interactions when they are forward with respect to the beam direction. But due to its design this efficiency is significantly degraded for high-angle and backward muons. Therefore, it covers a limited portion of the phase-space in comparison to SK where the acceptance is more isotropic, causing an important source of systematic uncertainties. Furthermore, the ability of ND280 to track protons is limited as it can only reconstruct protons of momenta higher than 450 MeV/c with a maximum efficiency of $\sim 30\%$, which motivates the use of the muon kinematics only in the OA. With the expected increase of beam exposure in the upcoming years, these limitations might start hindering the sensitivity to the oscillation parameters, and particularly the CP-violating phase δ_{CP}. For these reasons, the T2K collaboration is currently upgrading ND280.

2. ND280 upgrade

The ND280 upgrade comprises a set of subdetectors installed at the upstream part of the current ND280. It will consist of a highly-segmented active target called Super-FGD interposed between two horizontal TPCs (HA-TPCs), and these are surrounded by a time-of-flight detector (ToF). This new configuration is expected to significantly improve the efficiency to track high-angle and backward muons, to lower the proton tracking threshold and to even allow the reconstruction of neutron kinematics.

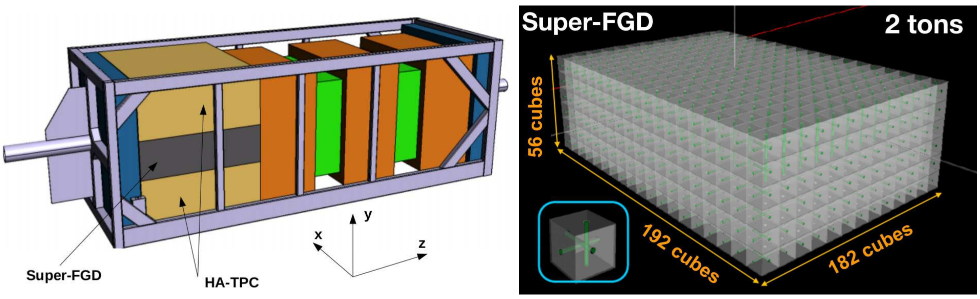

Figure 1: Sketches of the upgraded near detector where the neutrino beam is along the z-direction (left) and the Super-FGD (right).

Super-FGD The Super-FGD consists of about two million cubes of 1 cm per side made of plastic scintillator, providing a target mass of ~ 2 tons. Each cube is covered with a reflective coating to ensure optical isolation and crossed by three orthogonal WLS fibers to capture scintillation light produced by charged particles [3]. Each fiber is read out by a Hamamatsu multipixel photon counter (MPPC) at one end, while on the other end a LED light source allows to calibrate the electronics.
Multiple beam tests have been performed to confirm the Super-FGD concept with smaller prototypes. The first set of tests was conducted at CERN PS facility with charged particles (protons, muons, pions, electrons and positrons) where the measurement of their energy deposition was studied, and particularly the Bragg peak of stopping protons [4]. Another set of tests was performed at LANL with a neutron beamline and the total cross section of neutron interactions as a function of their kinetic energy was measured using event rate depletion along the beam axis [5]. These tests confirmed that the Super-FGD concept meets the requirements.

HA-TPCs On the top and the bottom of the Super-FGD, two HA-TPCs will be installed to track particles escaping the Super-FGD. The design of these new HA-TPCs is similar to that of the current TPCs, with particularly two improvements. The first improvement is the optimized field cage with a design that minimizes the dead space and maximizes the tracking volume. The second improvement is the use of resistive micromegas instead of the standard bulk micromegas. The new resistive micromegas modules are equipped with a resistive layer that spreads the charge predictably over multiple sensitive pads, providing a better space-point resolution [6, 7].
The minimum requirement for the HA-TPCs is the same performance of the existing TPCs, namely a maximum energy resolution of 10% and a spatial resolution below 800 μm for a hit. Various beam tests were performed at CERN [8] and DESY [9] with charged particles, and the results show that these requirements are fully satisfied as displayed in Figure 2.

ToF To distinguish the background due to incoming particles, e.g. cosmic muons, from the products of neutrino interactions in the fiducial volume, a ToF detector consisting of 6 planes fully covers the Super-FGD and the HA-TPCs [10]. Each ToF plane consists of 20 EJ-200 cast plastic scintillator bars of $12 \times 1 \times 230$ cm^3 size. The scintillation light propagates through the scintillator bar and is read out at both ends with 16 MPPCs.
The goal of the ToF detector is to provide a high-precision measurement of the crossing time. The measured resolution from a single bar is below ~ 150 ps as shown in the left plot of Figure 2. With this excellent timing resolution, the ToF will not only serve as a veto to reject the background, but can also be used as a trigger for the calibration of the Super-FGD and HA-TPCs with cosmic muons. It could also help improve particle identification with its precise timing information.

3. Physics impact of the upgrade

Thanks to the granularity of the Super-FGD, the ND280 upgrade is expected to drastically lower the proton tracking threshold down to below 300 MeV/c and allow the reconstruction of neutron kinematics with a resolution of 15 to 30% [11]. The upgrade provides an improved angular coverage of the phase space with a nearly isotropic acceptance as shown in Figure 2, similar to that of the far detector SK. Since the addition of the Super-FGD will double the overall target mass of ND280, significantly larger statistics are expected over the upcoming years.

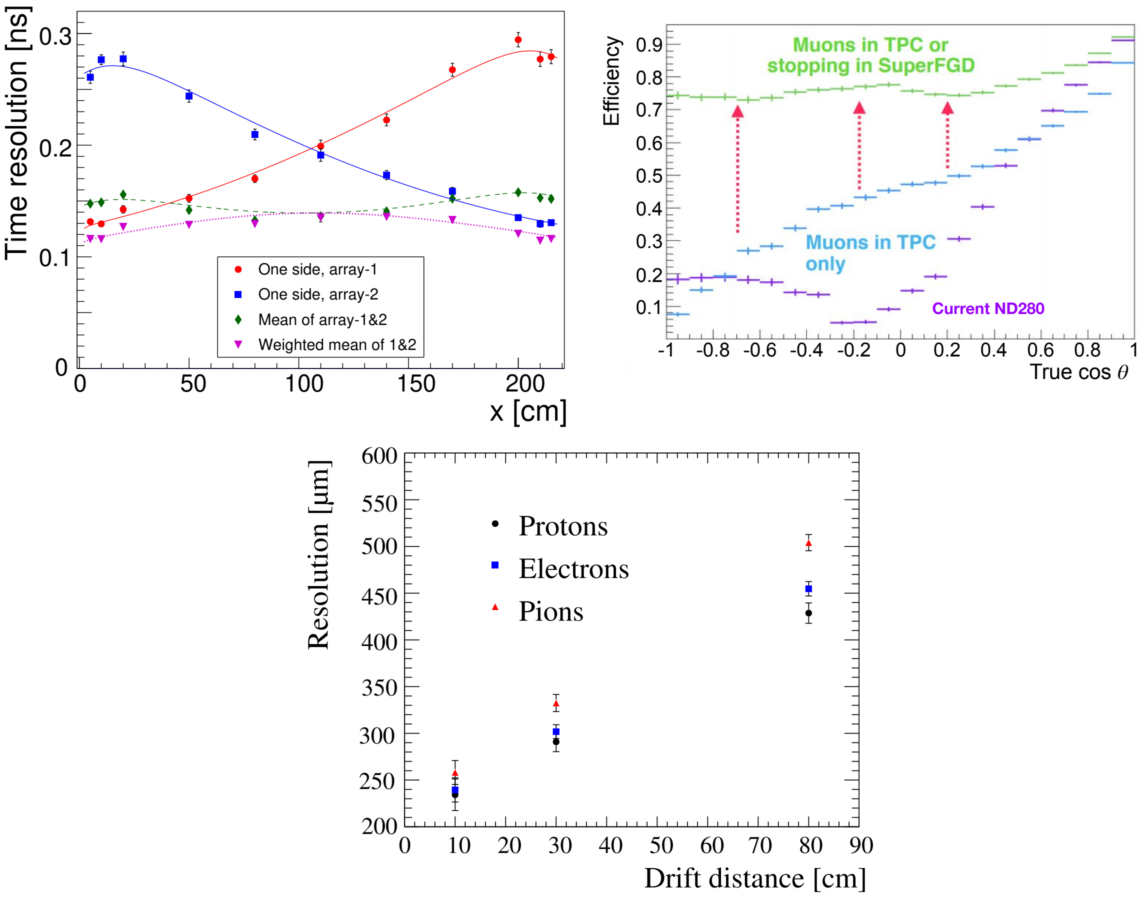

Figure 2: Top left: measured timing resolution of the ToF detector with cosmic muons as a function of the the position on the scintillator bar. Bottom: spatial resolution of the HA-TPC measured using test beams at DESY. Top right: muon detection efficiency compared between the current and the upgraded ND280.

With these improved capabilities of detecting particles produced in neutrino interactions, precise measurements in the projection transverse to the neutrino beam direction will allow to probe nuclear effects. Indeed, the transverse kinematic imbalance can give an enhanced sensitivity to the Fermi motion of initial state nucleons, the final state interactions and the multinucleon processes. Additionally, the transverse momentum imbalance δp_T could allow to select a sample enriched with antineutrino interactions with hydrogen from the region of low δp_T, which would yield improved constraints on the flux uncertainties [12].

4. Conclusion

A new phase is starting for the T2K experiment with the installation of the upgraded ND280 during 2023 with the goal to reduce the systematic uncertainties in the measurement neutrino oscillations. This upgrade is also accompanied by a scaling of the horn currents from 250 to 320 kA as well as an increase of the beam power from 0.5 up to 1.3 MW before the start of Hyper-Kamiokande. All of this will provide a significantly improved sensitivity to the oscillation parameters.

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