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The T2K Near Detector Upgrade

Stefan Roth[a,*] **on behalf of the T2K collaboration**

[a] *Physics Institute III, RWTH Aachen University, Sommerfeldstr. 16, Aachen, Germany*

E-mail: stefan.roth@rwth-aachen.de

To benefit from the expected increase of data due to the upgrade of the beam intensity at the T2K experiment the systematic uncertainties of the neutrino oscillation measurements have to be constrained, too. Systematic uncertainties in neutrino oscillation are dominated by uncertainties related to the modelling of neutrino interactions. To improve the understanding of the nuclear effects an upgrade of the near detector ND280 of the T2K experiment was initiated which will yield better tracking and timing of final state particles. The improvements of the neutrino energy reconstruction based on the new detector capabilities are discussed.

The upgraded ND280 detector will consist of a totally active Super-Fine-Grained-Detector (SFGD) composed of 2 million 1 cm^3 scintillator cubes, two High Angle TPC (HATPC) instrumented with resistive MicroMegas, and a surrounding Time-of-Flight (ToF) detector. It will improve our knowledge of neutrino interactions due to its full polar angle acceptance of the final state particles and a much lower proton tracking threshold. Furthermore, neutron tagging capabilities, in addition to precision timing information, will allow the upgraded detector to measure neutron kinematics from neutrino interactions. Such improvements permit access to a much larger kinematic phase space and the analysis of transverse kinematic imbalances, to offer nuclear physics constraints for T2K analyses. New reconstruction algorithms are being developed to benefit from the improved capabilities of the upgraded near detector.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

*Speaker

PoS(TAUP2023)220

1. Motivation

Neutrino oscillation physics has entered the precision era. In parallel with needing more intensive beams and larger detectors to collect more data, future experiments further require a significant reduction of systematic uncertainties. In neutrino oscillation measurements at T2K, the systematic uncertainties related to the modelling of neutrino interactions are currently dominant [1]. To reduce this uncertainty, a significantly improved understanding of neutrino-nucleus interactions is required to better characterise nuclear effects. To maximize the final state phase space of the events of neutrino-interactions in the ND280 detector and to improve the precision on the event variables an upgrade of the near detector ND280 of the T2K experiment is currently under way.

2. Detector Upgrade

The near detector ND280 of the T2K experiment is designed to measure the energy spectrum and the flavour composition of the neutrino beam 280 m behind the neutrino source, i.e. before the oscillation. In addition, the cross sections of neutrino-interactions are measured to constrain the uncertainties in the modelling of neutrino-nucleus interactions.

With the upgrade of the ND280 detector [2] the reconstruction of the final state will be improved in two different aspects: firstly, the angular acceptance of the detector for charged particles in the final state of neutrino interactions will be increased. Secondly, the reconstruction of the hadronic part of the final state will be extended to lower energies. To achieve these goals, about one third of the volume inside the electromagnetic calorimeter will be equipped with new subdetectors.

The Super-Fine-Grained-Detector (SFGD) consists of about 2 million of $10 \times 10 \times 10$ mm^3 plastic scintillator cubes providing a fully-active and fine segmented detection volume of $1920 \times 560 \times 1840$ mm^3 and a target mass of more than 2.2 tons [3]. It serves as the main neutrino target of the upgraded ND280 detector and will reconstruct and measure the final state particles of neutrino interactions starting at kinetic energies of only a few tenths MeV. Each cube is traversed by three orthogonal wavelength shifting fibers connected to micropixel avalanche MPPC photodiodes. Three fired MPPC uniquely determine the hit cube providing a 3D coordinate of the track hit [4].

A prototype of the SFGD consisting of $24 \times 8 \times 48$ cubes has been tested at the CERN PS T9 beamline [5]. The tests showed the correct functioning of the readout electronics, which was operated in a deadtime-free mode. Analyzing signals from protons stopping inside the detector showed that its dynamic range is sufficient to reconstruct the Bragg peak as depicted in Figure 1 (left). The specific ionization dE/dx showed a clear proton/MIP separation as can be seen in Figure 1 (right).

Above and below the SFGD two new high-angle TPC (HATPC) will detect long-range charged particles from neutrino interactions extending the sensitivity of final state muons to the backward phase space. One HATPC is a gas tight $2.0 \times 0.8 \times 1.8$ m^3 field cage with a central cathode. Each endplate of the two HATPC is instrumented with eight charge readout resistive Micromegas modules summing up to 32 modules in total. The pads of a resistive Micromegas are covered by two layers, first of insulating material and then of resistive material. The resistive layer forms a two-dimensional RC network, which leads to a signal cross-talk with the adjacent pads. This signal sharing improves the spatial resolution considerably.

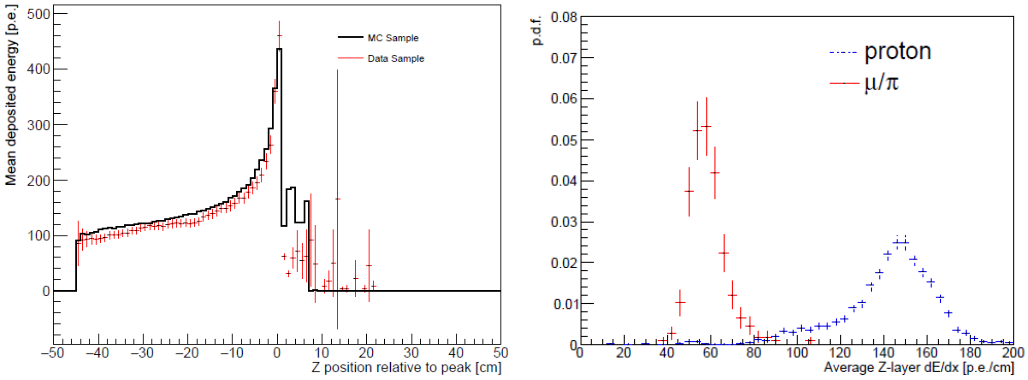

Figure 1: The measurement of the Bragg peak of stopping protons (left) and the result of the dE/dx analysis for tracks of different particle types (right) [5]

All Micromegas modules were characterized on a X-ray test bench measuring for each individual readout pad the mean charge and the charge dispersion to adjacent pads [6]. The performances of TPC prototypes have been determined at the DESY test beam facility [7, 8]. For all track angles relative to the pad geometry of the Micromegas modules and for all drift distances a spatial resolution of better than 800 μm was achieved, as shown in Figure 2. Furthermore, a dE/dx resolution of better than 10 % was demonstrated.

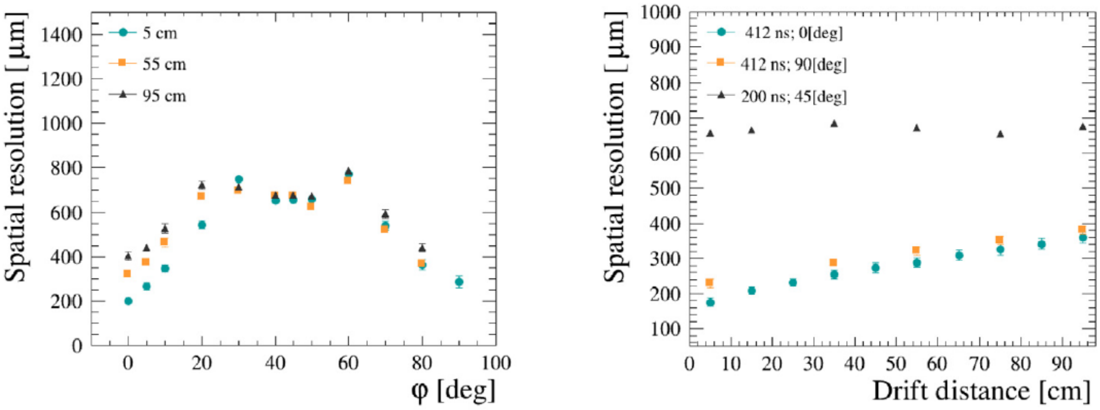

Figure 2: The measured spatial resolution of a TPC prototype shown as a function of the incident track angle (left) and of the drift distance (right) [8]

For the time-of-flight (ToF) detector six detector planes are arranged to a cube surface surrounding the SFGD and HATPC setup. The purpose of the ToF is to contribute to the particle identification and to veto particles that do not originate from the SFGD as the active neutrino target. Each of the six detector planes consists of 20 plastic scintillator bars stacked to an area of 2.4×2.2 m^2. On both ends of the scintillator bars arrays of large-area silicon photo-multipliers are attached. The time resolution of the ToF has been determined to 0.14 ns using cosmic muons [9].

3. Improvements and Conclusions

Up to now part of the unpredictabilities in neutrino nucleus interactions stems from the missing data on final state neutrons. Test beam data of the SFGD prototype showed that a reconstruction of the final state neutron is possible [10]. The neutrons were detected using the signal of the first recoil proton and their kinetic energy was measured from the time difference between the signals from the neutrino interaction and the recoil event.

In addition, a detailed study on the sensitivity of the upgraded detector on neutrino nucleus interactions was performed [11]. In this study it was shown that the resolution on the neutrino energy could be improved by replacing the well known reconstruction of the neutrino energy from variables of the muon kinematics, E_{QE}, alone. Instead, the energy sum of all particles in the final state, E_{vis}, can be exploited.

Using the upgraded ND280 detector, a full reconstruction of the final state of neutrino-nucleus interactions will be possible for the first time. This includes the measurement of low energy protons and the event-by-event reconstruction of final-state neutrons. With the new detector capabilities at hand also new methods of event reconstruction and analysis appear feasible. As an example, a detailed Monte-Carlo study has shown that based on an event-by-event measurement of the kinetic energy of the final state neutron the resolution of the antineutrino energy determination should improve from currently 15 % to 7 % [12].

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