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Latest T2K results on neutrino-nucleus cross section

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Cross section measurements are important for long-baseline oscillation experiments to reach their final sensitivity. The T2K near detector complex, designed to constrain the T2K flux and cross section models, also provides a complementary program of neutrino interaction cross section measurements. Through the use of various target materials (carbon, water, argon, iron, lead) and with on- and off-axis detectors which probe the neutrino spectra at different energies, T2K is able to explore different aspects of neutrino interactions modelling. These proceedings give an overview of the recent T2K neutrino cross section results.

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1. Introduction

T2K (Tokai to Kamioka) is a long-baseline experiment in Japan that studies (anti-)neutrino interactions using a high intensity muon (anti-)neutrino beam from J-PARC accelerator complex [1]. The beam production starts with ~30GeV protons that scatter off a carbon target producing charged mesons which subsequently decay in flight to muon neutrinos (ν_μ) or muon anti-neutrinos ($\bar{\nu}_\mu$) depending on the charge of the meson parent that is being focused. The beam travels then towards the near detectors and the far detector Super-Kamiokande (SK) situated about 295 km from the beam production point.

The main goal of T2K is to measure the oscillation probability of $\nu_\mu(\bar{\nu}_\mu)$ at the SK far detector. In these measurements, the neutrino event rate at the far detector is constrained by the cross section and the neutrino flux measured in the near detectors for the unoscillated beam. The neutrino interaction model tuned from the near detector measurement is used to predict the neutrino event distributions at the far detector. Resulting uncertainties associated with the modeling of neutrino–nucleus interactions are a leading source of the systematic errors in the oscillation analysis. Therefore, cross section measurements at the near detectors with different target materials and neutrino energies are necessary to test the interaction models in order for T2K to reach the final precision for its oscillation analysis.

In T2K the neutrino beam is directed 2.5° off-axis with respect to the SK direction to ensure a narrow beam with a peak energy at ~0.6 GeV/c, which maximizes the oscillation probability. At this energies, most neutrino interactions are charged-current (CC) quasi elastic (QE). In the tail of neutrino energy distribution, the CC resonant interaction (RES) with a pion production is the second important process. There is also a non-negligible contribution of "two-particle two-hole" (2p2h) process where a neutrino interacts with multiple nucleons at the same time.

Experimentally, the cross section is measured in terms of the topology of final-state particles observed in a detector and corresponds usually to a few different true neutrino interaction modes. This is due to the presence of nuclear effects and final state interactions (FSI) which can alter the observed particle types and kinematics. The CC0π topology for example refers to the final state that contains a charged lepton and no meson; while the CC1π^+ topology contains a charged lepton, one π^+ and no other meson. Both topologies allow any number of nucleons. By using the topology to define the signal, the model dependence of the measured cross section can be significantly reduced.

2. The near detectors of T2K experiment

The near detectors are located onsite J-PARC facility, on the east coast of Japan, close to the neutrino beam production point and are situated at different angles with respect to the beam. The INGRID detector is placed on-axis while WAGASCI and ND280 are both off-axis at 1.5° and 2.5°, respectively. Within a single experiment, a joint on- and off-axis measurements can be used to investigate the energy dependence of the neutrino interactions.

The ND280 detector is composed of the upstream π^0 detector (POD) and the downstream tracker region with two fine grained detectors (FGD) and three time projection chambers (TPC) surrounded by an electromagnetic calorimeter (ECal) and a 0.2T magnet. FGDs consist of layers of plastic scintillator and are used as tracking detectors and targets for neutrino interactions. FGD1 is purely made of hydrocarbon while FGD2 contains in addition water layers. FGDs are sandwiched between TPCs which provide particle identification based on dE/dx and momentum measurement from a track curvature in the magnetic field.

WAGASCI is the newest near detector, built as a 3D scintillator grid with a high angle acceptance. It is filled in 80% with 0.6 tons of water. Measurements in WAGASCI are performed together with other detectors: Proton Module and the INGRID detector. Proton Module is a fully active tracking detector that is also a hydrocarbon target. INGRID contains iron plates and scintillator bars, and is used as a muon range detector. Unlike ND280, there is no separation of neutrino and anti-neutrino interactions for measurements with WAGASCI.

3. Recent cross section results

T2K recently performed a cross section measurement in the $\nu_\mu CC1\pi^+$ channel with at least one additional proton in the final state (ν_μ**CC1**π^+**Np**) as a function of three **transverse kinematic imbalance (TKI)** variables [2, 3] : double transverse momentum (δp_{TT}), initial nucleon momentum (p_N) and transverse boosting angle ($\delta\alpha_T$). These variables are built from transverse momentum (with respect to the incoming neutrino direction) of the final state particles, namely μ^-, π^+ and the highest momentum proton.

The TKI variables are sensitive to the nuclear effects relevant to oscillation experiments: the initial nuclear state, the Fermi motion of initial state nucleon, and the FSI of outgoing hadrons.

Without nuclear effects, it is expected that $\delta p_{TT} = 0$ due to momentum conservation. The initial state of the bound nucleon and FSI experienced by the outgoing π^+ and proton can affect the peak position as well as cause a long tail in the region of large imbalance. The presence of FSI leads to the similar behavior for p_N that probes the Fermi motion inside the nucleus. The last variable, $\delta\alpha_T$ provides information whether the hadronic system is accelerated or decelerated by nuclear effects. In the absence of nuclear effects, the flat distribution of $\delta\alpha_T$ is expected because of the isotropic Fermi motion of the initial-state nucleon. The nuclear effects usually slow down the outgoing hadrons which results in $\delta\alpha_T > 90^0$.

The cross sections as a function of the TKI variables are measured [4] in the off-axis ND280 detector on the hydrocarbon target using the selected sample of events with vertex within FGD1 and μ^-, π^+ and proton(s) reaching TPC to be identified there. The phase-space constraints are applied for all signal particle. The selection purity is above 60%.

Fig. 1 shows the measured cross sections for the TKI variables compared to model predictions. Simple Fermi gas models (RFG and LFG) show disagreement with data (mainly for δp_{TT} and p_N) which indicates the nucleon Fermi motion is not well modelled. The sensitivity to FSI for $\delta\alpha_T$ is limited by the tight phase-space limits. Data compared to models show slight preference for GIBUU which uses a more realistic nuclear ground state to handle all interactions consistently and FSI modelling is more complete.

Another interesting result using the off-axis ND280 detector is the measurement of the **inclusive** $\nu_\mathbf{e}$**CC** and $\bar{\nu}_\mathbf{e}$**CC cross-sections** on the hydrocarbon target (FGD1) [5]. The intrinsic $\nu_e(\bar{\nu}_e)$ contribution (up to 2%) to the T2K beam flux provides the single largest background in the measurement of electron neutrino appearance at the far detector. The small fraction of $\nu_e(\bar{\nu}_e)$ and

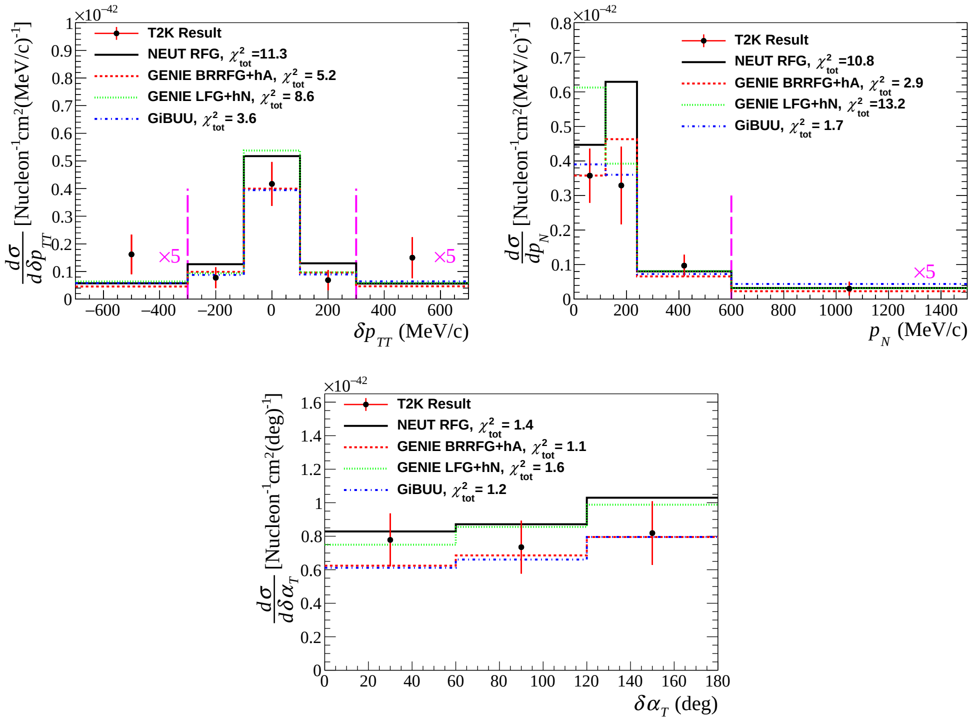

Figure 1: Measured differential cross sections per nucleon as a function of δp_{TT}, p_N and $\delta\alpha_T$ compared to model predictions. In the tails of δp_{TT} and p_N (beyond the magenta lines), the cross sections are scaled by a factor of 5 for better visualization [4].

the large backgrounds introduced by $\nu_\mu(\bar{\nu}_\mu)$ interactions make the selection of $\nu_e CC(\bar{\nu}_e CC)$ events challenging.

The measurement is based on data collected in the neutrino mode (forward horn current (FHC)) and anti-neutrino mode (reverse horn current mode (RHC)). There are in total three samples used in the analysis: FHC $\nu_e CC$, RHC $\bar{\nu}_e CC$ and RHC $\nu_e CC$. The last one is due to a relatively large contribution of ν_e component in the T2K $\bar{\nu}_\mu$ flux. TPC and ECal PID are used to select electrons and reject other particle types. The largest background in the selections comes from γ (mainly from π^0 decays) at low electron momentum as shown in Fig. 2.

The flux integrated cross section is extracted in a limited phase-space. Fig. 2 shows a comparison of cross section results to different models for all signal samples as a function of the electron momentum and a good agreement between data and models is found.

Recently T2K published $\bar{\nu}_\mu$**CC0**π**0p** cross section measured at the **off-axis angle of 1.5**° on water and hydrocarbon targets with WAGASCI, Proton Module and the INGRID detector [6]. These detectors are exposed to neutrinos with a higher energy than the ND280 detector. The mean neutrino energy is ~0.86 GeV/c at the off-axis angle of 1.5°. The signal is defined as the charged-current interaction with only single muon and without detected charged π or protons. Similar to other analyses, the cross section is calculated in the limited phase-space restricted to the high-detection efficiency region. The differential $\bar{\nu}_\mu$ cross section and $\bar{\nu}_\mu + \nu_\mu$ cross section are extracted. Results for the sum are presented in Fig. 3. To extract the cross section on water in WAGASCI, the correction

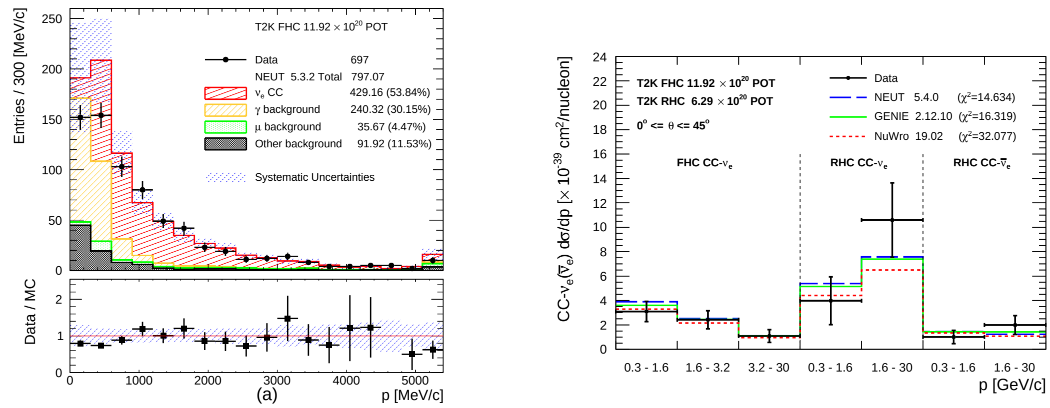

Figure 2: The momentum distribution of the selected $\nu_e CC$ sample (left). Flux integrated $\nu_e CC(\bar{\nu}_e CC)$ inclusive cross section results as a function of the electron momentum compared to models (right) [5].

for the number of interactions on plastic scintillator is calculated using the selected events in the Proton Module. The cross sections on hydrocarbon and water agree well within errors with the NEUT predictions.

The advantage of the joint ν_μ**CC0**π + ν_μ**CC1**π cross section measurement reported recently, is the use of correlations between different samples where the migrations between them give information about the FSI effects. The first such measurement is using the T2K neutrino data from the on-axis Water Module and Proton Module together with the INGRID detector. The selected samples include muons stopping in INGRID and through going. Fig. 4 shows the angular distributions of the μ candidate for selected $\nu_\mu CC0\pi$ sample with interactions on water and hydrocarbon, the purity of selection is 60-70% and differs between Water and Proton modules. The lower purity (40-50%) is observed for $\nu_\mu CC1\pi$ sample.

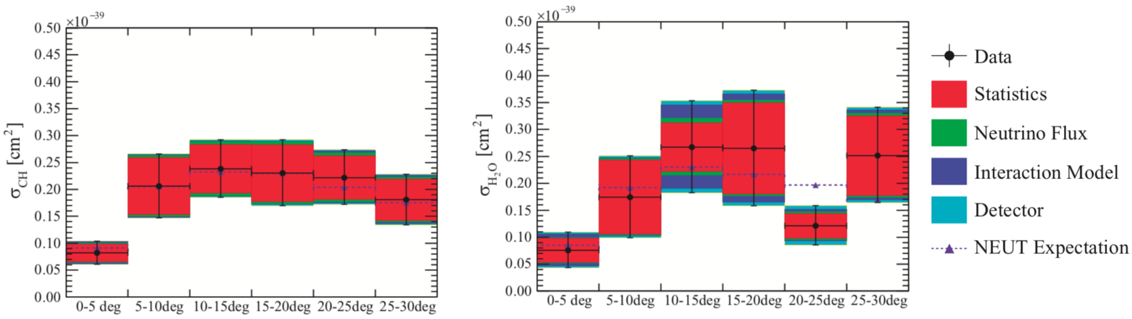

Figure 3: The measured $\nu_\mu + \bar{\nu}_\mu$ cross section on hydrocarbon (left) and on water (right) at the 1.5° off-axis angle [6].

The analysis is being finalized and results include the double differential cross section on water and hydrocarbon as a function of the muon kinematics as well as their ratio calculated for $\nu_\mu CC0\pi$ and $\nu_\mu CC1\pi$ samples to enhance the sensitivity to the nuclear effects.

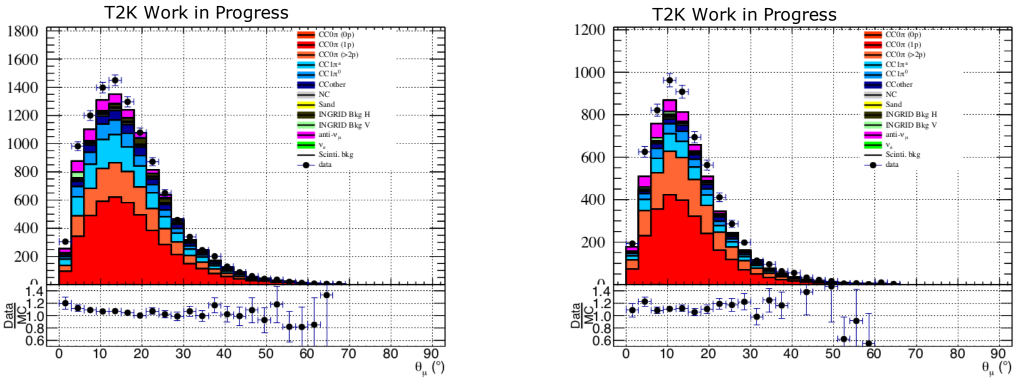

Figure 4: Angular distributions of the μ candidate for selected $\nu_\mu CC0\pi$ sample in Proton Module (left) and the Water Module (right) [T2K work in progress].

4. Summary

T2K has the capabilities to make a wide range of cross section measurements and keeps on exploring possibilities to deepen our knowledge of neutrino interactions. In addition to the studies described above, the T2K Collaboration is in the process of upgrading the near detector which will lead to a large increase in the sensitivity to models due to the extension of the phase-space at low energy and high angle regions. A further reduction of backgrounds is also expected (for example γ background in the $\nu_e(\bar{\nu}_e)$ selections) and a significant improvement of the statistical precision.

References

[1] K. Abe *et al.* [T2K], Nucl. Instrum. Meth. A **659** (2011), 106-135.

[2] X. G. Lu, D. Coplowe, R. Shah, G. Barr, D. Wark and A. Weber, Phys. Rev. D **92** (2015) no.5, 051302.

[3] X. Lu and J. T. Sobczyk, Phys. Rev. C **99** (2019) no.5, 055504.

[4] K. Abe *et al.* [T2K], Phys. Rev. D **103** (2021) no.11, 112009.

[5] K. Abe *et al.* [T2K], JHEP **10** (2020), 114.

[6] K. Abe *et al.* [T2K], PTEP **2021** (2021) no.4, 043C01, [arXiv:2004.13989 [hep-ex]].