PROCEEDINGS OF SCIENCE

Recent Neutrino Cross Section Measurements with the T2K Near Detectors

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Precise knowledge of how neutrinos interact with matter is essential for measuring neutrino oscillations in long-baseline experiments. At T2K, the near detector complex measures neutrino interactions to constrain cross section models for oscillation studies and to characterise the beam flux. The near detector complex provides a platform for performing neutrino-nucleon cross section measurements. The design of the ND280 near detector allows for a variety of cross section measurements on different targets to be performed. The additional WAGASCI near detector at a different off-axis angle features an increased water/carbon target ratio. Finally, the on-axis INGRID detector can be combined with ND280 and WAGASCI to measure the cross section at different neutrino energies and to further constrain the nuclear models for different targets.

Recent cross section measurements from the near detector complex will be presented. The latest measurements of pion production in ND280, including an improved analysis of coherent pion production making use of an anti-neutrino sample for the first time, will be shown. Additionally, a combined measurement of data from ND280 and INGRID allowing the first simultaneous measurement of cross section at different neutrino off-axis angles will also be presented.

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[*] Speaker

1. The T2K Experiment

The Tōkai to Kamioka (T2K) experiment is a long-baseline neutrino experiment with the primary goal of constraining the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix parameters by measuring neutrino oscillations [1]. The experiment consists of three principal sites: the neutrino beam line produced at J-PARC, the near detector complex which is situated 280 m downstream, and the Super-Kamiokande water Cherenkov tank at the far site in Kamioka 295 km to the west of the neutrino beam source [2]. Neutrino oscillations are studied by measuring the muon (anti-)neutrino disappearance and electron (anti-)neutrino appearance at the far detector compared to the initial neutrino beam which is primarily comprised of muon (anti-)neutrinos.

At J-PARC, 30 GeV protons are steered towards a graphite target, producing hadrons which are then focused into a decay volume. Muon (anti-)neutrinos are generated from charged pions decaying through $\pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$. The pion charge and therefore neutrino mode is selected by adjusting the electromagnetic horn current polarity between forward horn current (FHC) and reverse horn current (RHC). The beam is directed at a 2.5° off-axis angle with respect to Super-Kamiokande which allows for a high-intensity beam to be produced at the energy (0.6 GeV) corresponding to the first oscillation maximum. This also produces a narrow-band beam with which reduces the number of background events that would be present in a wide-band beam from the high energy region. Neutrino interactions are measured at the far site by studying the Cherenkov rings produced in the Super-Kamiokande water tank.

The near site has the purpose of constraining the main systematic uncertainties in the neutrino oscillation measurement, as well as measuring neutrino cross sections and characterising the near-initial beam flux. There are three near detectors: ND280, INGRID and WAGASCI, all of which are located at slightly different angles with respect to the neutrino beam. The INGRID detector is on-axis and is capable of measuring the neutrino beam direction and intensity using iron scintillator modules. ND280 is 2.5° off-axis and consists of several sub-detector modules surrounded by a 0.2 T UA1/NOMAD magnet. The ND280 sub-detector modules include a π^0 detector (P0D), followed by inter-weaved layers of fine grained detectors (FGDs) and time projection chambers (TPCs), as well as electromagnetic calorimeters (ECals). The FGDs are made of polystyrene and act as the primary target mass, while the TPCs measure the momentum and electric charge of charged particles passing through. The ECals measure neutral particles and facilitate supplementary particle identification (PID) by performing track and shower separation. As of November 2023, the P0D has been removed and replaced with a new 'super'-FGD and one (of two) high-angle TPCs which form part of the ND280 upgrade [3].

2. Cross section measurements at T2K

2.1 Neutrino oscillation measurements

For oscillation analyses at the T2K experiment, the expected number of signal neutrino oscillations events is modelled by the expression

$$N_{\text{pred}} = P_{\nu_\mu \rightarrow \nu_e}(E_\nu) \times \sigma(E_\nu) \times \Phi(E_\nu) \times \epsilon(E_\nu), \tag{1}$$

where $P_{\nu_\mu \to \nu_e}$ is the neutrino oscillation probability of muon neutrinos to electron neutrinos, σ is the interaction cross section, Φ is the neutrino flux, ϵ is the detector efficiency and E_ν is the neutrino energy. Neutrino interaction cross sections tend to be the leading source of systematic uncertainty in neutrino oscillation measurements.

2.2 Fit method

Each of the analyses presented use a binned log-likelihood template parameter fit as an unfolding method. This method iteratively adjusts the *template parameters*, which directly weight the number of signal events, as well as *nuisance parameters* which correspond to the detector, flux and cross section model systematic uncertainties. The total χ^2 statistic is minimised such that the best data-Monte Carlo (MC) agreement is obtained,

$$\chi^2 = \chi^2_{\text{stat}} + \chi^2_{\text{syst}} = -2 \ln \mathcal{L}_{\text{stat}} - 2 \ln \mathcal{L}_{\text{syst}}. \tag{2}$$

The statistical likelihood term χ^2_{stat} encapsulates the data-MC agreement as a Poissonian with Barlow-Beeston modifications [4]. The systematic likelihood term χ^2_{syst} is a Gaussian penalty term for the nuisance parameters moving away from their nominal values, and is constrained by a covariance matrix. The fitting process outputs a set of best-fit parameters and the correlations between these parameters. The best-fit parameters correspond to a best-fit number of signal events which is then used to calculate the cross section through

$$\frac{d\sigma}{dx_i} = \frac{N_i^{\text{signal}}}{\epsilon_i \Phi N_T} \frac{1}{\Delta x_i}. \tag{3}$$

Here, the index i denotes the bin index, x_i is one of the input kinematic variables, ϵ_i is the selection efficiency, N_i^{signal} is the best-fit number of signal events, N_T is the number of nucleon targets, Δx_i is the width of the bin and Φ is the total integrated flux.

3. Recent cross section results

3.1 ND280-INGRID ν_μCC0π joint fit

A recent analysis at T2K measures the muon neutrino charged-current pionless (ν_μCC0π) cross section on hydrocarbon using data from both ND280 and INGRID in a joint fit [5]. The ν_μCC0π channel has already been extensively studied at T2K due to its large relative presence in oscillation analyses. This measurement is the first time the channel has been studied at different, correlated fluxes from detectors at different off-axis angles as separate samples for a joint fit. The use of data from two detectors at different off-axis angles allows the flux uncertainties on the cross section measurements to be reduced.

The double-differential cross section is measured as a function of the primary outgoing muon momentum and angle with respect to the parent muon neutrino direction. The signal definition requires that a muon is detected as the primary outgoing lepton with neutrino vertex in the FGD1[1]

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[1] The sub-detector module numbers indicate the relative positions downstream from the P0D, so FGD1 and TPC1 are the most up-stream modules.

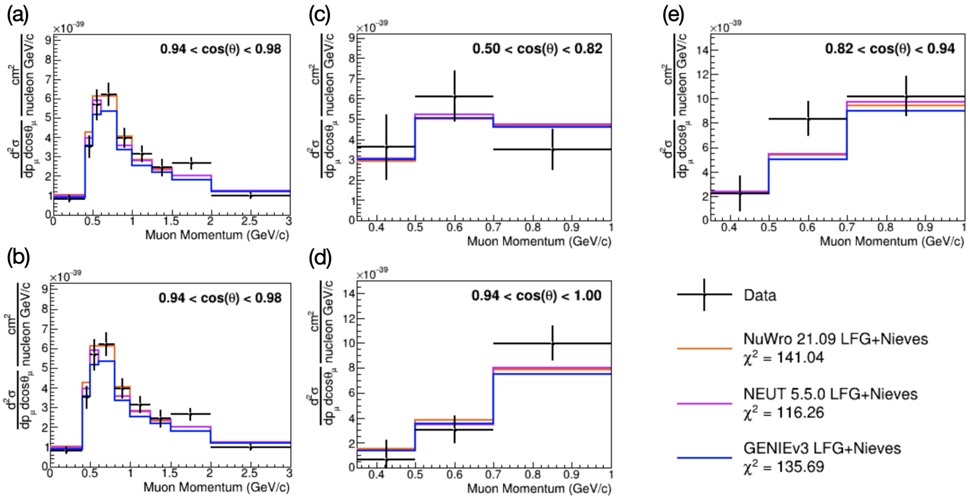

Figure 1: Selection of the extracted ND280 (a,b) and INGRID (c,d,e) cross sections as a function of muon kinematics compared to several different predictions from the GENIE [6], NEUT [7], Nieves [8] and NuWro [9] models. Note LFG stands for local Fermi gas. These plots are taken from [5].

fiducial volume of ND280 or the proton module of INGRID. Additionally, the final-state particles must include no pions any additional number of other hadrons.

The ND280 and INGRID selections use 11.53×10^{20} protons on target (POT) and 6.04×10^{20} POT respectively. Signal events in ND280 are categorised into five signal-enriched samples depending on the combination of final-state particles and the sub-detectors these particles enter. The samples are: (I) a single muon enters TPC2, (II) a muon enters TPC2 and at least one proton also enters TPC2, (III) a muon enters TPC2 and a proton enters FGD1, (IV) a muon enters FGD1 without crossing into TPC2 and a proton enters TPC2, (V) a muon remains in FGD1 or the ECal and no other particle tracks are produced. Three ND280 control samples are also used which constrain the largest backgrounds in the signal-enriched samples which tend to involve pion production. For the INGRID selection, there is one signal-enriched sample with a single muon track and zero or one proton tracks. The momentum is reconstructed in INGRID using the distance the muon traverses. There is also one INGRID control sample to constrain single pion-like events. A selection of the cross section results for particular muon momentum and angular bin permutations is shown in Fig. 1. Generally the MC predictions do not describe the data well. The χ^2 values significantly deviate from the expected number of degrees of freedom N which is 70, from 12 INGRID and 58 ND280 cross section bins. The reduced χ^2 values (χ^2/N) range between 1.5 and 2.1 which indicates poor data-MC agreement overall. Additional efforts in theoretical model development and further analysis are required to fully understand the discrepancies exhibited by this measurement.

3.2 Charged-current coherent $\overset{(-)}{\nu}_\mu$ pion production

The second analysis presented in these proceedings measures the muon neutrino and anti-neutrino charged-current coherent pion production (CC-COH) cross section [10]. Coherent interactions are relatively rare, but neutral-current coherent interactions (NC-COH) contribute to one of

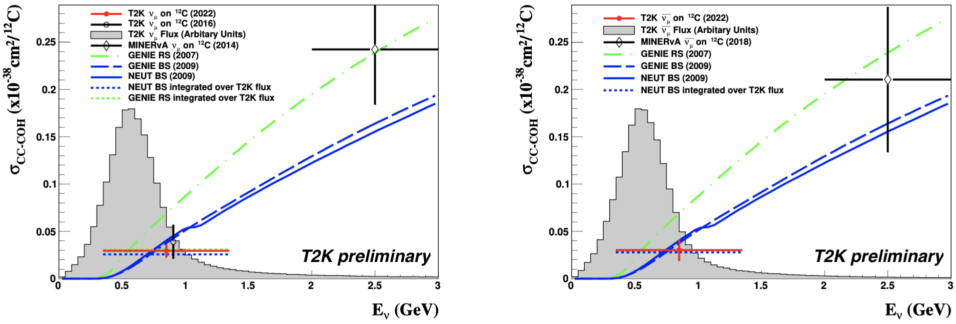

Figure 2: The total cross section results for the charged-current coherent analysis for neutrino (left) and anti-neutrino (right) modes compared to several Monte-Carlo model predictions using the Rein–Sehgal (RS) and Berger–Sehgal (BS) models. These plots are taken from [10].

the main backgrounds in oscillation analyses at T2K. NC-COH interactions are only identifiable by π^0 decay to two photons, which can mimic the electron neutrino appearance signal. A measurement of the CC-COH cross section allows for the NC-COH channel to be constrained. The CC-COH channel has previously been measured at T2K [11], but this analysis represents the first time an anti-neutrino sample has been included. Additionally, the POT from ND280 data-taking has more than doubled and the event selection has been re-optimised. The signal definition for this analysis requires an (anti-)muon to be detected as the primary outgoing lepton with neutrino vertex in the FGD1 fiducial volume of ND280. A negatively (positively) charged pion is also detected from the same vertex.

The total cross section for each mode is separately measured in a single neutrino energy bin. There are two signal-enriched samples corresponding to the neutrino and anti-neutrino modes; these use 11.54×10^{20} POT and 8.15×10^{20} POT respectively. In addition, there are two control samples which constrain the the resonance and deep inelastic scattering pion production processes which are the dominant backgrounds in the signal-enriched samples. The event selection process imposes cuts on the momentum transfer squared $|t|$ and vertex activity (VA), which is the energy deposited in the scintillator bars surrounding the neutrino interaction vertex. CC-COH signal events tend to have low $|t|$ and VA which allows them to be separated from the main backgrounds using selection cuts imposed on these observables. The observables used for the cross section are the muon and pion kinematics. The cross section results are shown in Fig. 2 and these agree well with the set of model predictions in each case. This analysis also halves the uncertainty on the previous ν_μ CC-COH cross section measurement in 2016 [11].

4. Conclusions

Two new cross section measurements have recently been produced at T2K. Those presented are two very different analyses performed using the T2K dataset, which encapsulates the diversity of cross section measurements being performed at T2K. Many more cross section analyses are in progress, and the upcoming ND280 upgrade broadens the scope for new studies and improving the precision on existing measurements.

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