PROCEEDINGS OF SCIENCE

Recent Neutrino Cross-section Measurements at T2K

D. R. Hadley on behalf of the T2K collaboration[a,*]

[a] *University of Warwick,*
Coventry, United Kingdom

E-mail: d.r.hadley@warwick.ac.uk

Precise knowledge of how neutrinos interact with matter is essential for measuring neutrino oscillations in long-baseline experiments. At the T2K experiment, the near detector complex measures neutrino interactions to constrain cross-section models for oscillation studies and characterise the beam flux. In addition, the near detector complex provides a separate platform for performing neutrino-nucleon cross-section measurements.

These proceedings report the latest cross-section measurements by T2K, including simultaneous measurement of the $CC0\pi$ cross-section averaged over multiple different neutrino energy spectra, and an improved analysis of the coherent pion production cross-section which makes use of an anti-neutrino sample for the first time.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

https://pos.sissa.it/

PoS(EPS-HEP2023)181

1. Introduction

The precise measurement of neutrino oscillations is one of the most important goals of contemporary experimental particle physics. A typical neutrino oscillation experiment consists of a neutrino beam source, a measurement at a near detector, before neutrinos have had a chance to oscillate, and a measurement at a far detector, after oscillations have occurred. By comparing the measurements at both near and far detectors, inferences can be made about the neutrino oscillation parameters. However, due to the neutrino flux distribution being different at the near and far detectors, systematic uncertainties between the two measurements do not exactly cancel.

Current and future planned accelerator-based experiments are aiming to make measurements with nuclear targets and beams that span 100s of MeV to a few GeV. In this energy regime, nuclear effects are important and must be well understood. Uncertainties in the neutrino-nucleus interaction model are the dominant source of systematic uncertainty in the oscillation measurements of currently operating experiments. These will need to be reduced to take full advantage of the high statistics datasets that will be collected by future experiments. Hence, measurements of neutrino-nucleus interactions are crucial for the success of neutrino oscillation experiments.

These proceedings report two new measurements of the neutrino-nucleus interaction cross-sections with the near detectors of the T2K experiment. First, a measurement of the $CC0\pi$ cross-section that combines the measurements of detectors exposed to different neutrino energy distributions [1]. Second, a measurement of the coherent charged current cross-section [2].

2. The T2K Experiment and Near Detectors

The T2K experiment[3] is a long baseline neutrino oscillation experiment. A beam of (anti) muon neutrinos is produced at the J-PARC accelerator in Tokai, Japan, and is fired towards the Super-Kamiokande detector, 295 km away. At 280 m from the beam source is the ND280 near detector complex. The complex consists of several detectors positioned at different angles with respect the to neutrino beam. The neutrino flux energy distribution depends on this angle. The on-axis detector, INGRID, is exposed to an $\langle E_\nu \rangle \sim 1.1$ GeV. The 2.5° off-axis detector, ND280, is exposed to an $\langle E_\nu \rangle \sim 0.6$ GeV [4]. The neutrino flux at each detector during neutrino-mode operation is shown in fig. 1.

The INGRID detector (fig. 2) consists of 14 standard modules in a cross formation whose primary purpose is to measure and monitor the neutrino beam shape, direction, and stability. A standard module is made of alternating layers of iron to provide target mass and plastic scintillator providing tracking and is used as a range detector in this analysis. In front of one of the standard modules is the Proton module. This is a fully active scintillator tracking detector that provides target mass and vertex and track reconstruction for the analysis presented here.

The ND280 detector (fig. 3) is a magnetized detector sitting inside the UA1 magnet. The sub-detectors used in the analyses presented here are the fine-grained detector (FGD1) which is an active plastic scintillator tracking detector that provides target mass and vertex reconstruction. This is surrounded by time projection chambers (TPCs) that provide track momentum measurements and particle identification.

3. Joint Measurements of $CC0\pi$ with multiple detectors exposed to different neutrino flux energy distributions

Neutrino oscillations are a function of the neutrino energy. It is critical to understand the interaction cross-section dependence on neutrino energy. The presence of detectors in the same beam but at different off-axis angles, exposed to different neutrino energy distributions provides a laboratory for studying the dependence of the neutrino interaction cross-section on the neutrino energy.

The signal topology, $CC0\pi$, is defined as a neutrino interaction with an outgoing muon, zero pions, and any number of other hadrons in the final state. Events in ND280 are selected with a muon-like track starting in FGD1 and entering a TPC. The samples are split based on the number of protons detected and which sub-detectors they enter. The dominant background is events containing pions where the pion was not reconstructed, for example a charged pion with too low momentum to produce a reconstructable track. These pion backgrounds are measured from the data with side-band samples where the pion is tagged. Examples of these samples are shown in fig. 4.

Events in INGRID are selected with a muon-like track starting inside the Proton module. If there is an additional track it is required to be proton-like. The muon must either stop in the Proton module or enter the standard module behind it. Momentum is measured for stopping muons from the range of the muon. A lower limit is set on the momentum of muons escaping from the standard module. The pion background is measured from the data with a side-band sample where the pion is tagged. Examples of these samples are shown in fig. 4.

From these samples, the flux averaged double differential $CC0\pi$ cross-section is measured as a function of muon momentum and angle. The cross-section averaged over the ND280 and INGRID flux is simultaneously measured and correlations between these measurements in different fluxes are provided. An example of some angular slices of these measurements is shown in fig. 5 and fig. 6.

Comparisons between these data and a range of MC models are shown in [1]. No model tested gives a good description across all kinematics and both fluxes, demonstrating the power of these data to test the neutrino interaction model and the need for model development going forward.

4. Coherent Charged Current cross-section Measurements

Charged current coherent pion production is a rare process where the neutrino interacts coherently with the entire nucleus producing an outgoing charged lepton and charged pion. There is no exchange of quantum numbers with the nucleus and the outgoing nucleus remains intact. T2K previously measured this process in neutrino mode [5]. These proceedings report an updated neutrino-mode measurement with higher statistics and a new measurement in anti-neutrino mode.

The selection selects events with a (anti) muon and charged pion in the final state. The coherent signal is distinguished from resonant and other pion production by two characteristics. First, there is zero momentum transfer, t to the nucleus. This can be reconstructed from the muon and pion kinematics. Second, the outgoing nucleus remains intact and there is no energy deposited in the vicinity of the interaction vertex, except that deposited by the outgoing muon and pion. Distributions of these variables are shown in fig. 7. In both distributions, a clear peak is seen at low $|t|$ and low vertex energy due to coherent pion production.

The measured ν_μ CC coherent pion production flux-averaged cross-section on ^{12}C is $(2.98 \pm 0.37(\text{stat.}) \pm 0.31(\text{syst.})\,^{+0.49}_{-0.00}\,(Q^2\text{ model})) \times 10^{-40}$ cm^2. The new measurement of the $\bar{\nu}_\mu$-induced cross-section on ^{12}C is $(3.05 \pm 0.71(\text{stat.}) \pm 0.39(\text{syst.})\,^{+0.74}_{-0.00}\,(Q^2\text{ model})) \times 10^{-40}$ cm^2 [2]. These results are shown in fig. 8. This is the first anti-neutrino measurement of this process at this energy. In the neutrino mode measurement, the uncertainty is reduced by a factor of ~2 from the previous results.

5. Summary

A summary of new measurements of $CC0\pi$ and charged current coherent pion production by T2K has been presented. Full details of these analyses and their associated data releases may be found in [1] and [2]. These measurements may be used to test interaction models, reduce uncertainties for future oscillation measurements, and improve our understanding of the physics of neutrino-nucleus interactions. T2K is in the process of upgrading its near detectors [6] and beam and will continue to collect data and produce cross-section measurements in the coming years.

References

[1] K. Abe et al. (T2K collaboration) arXiv:2303.14228 [hep-ex]

[2] K. Abe et al. (T2K collaboration) arXiv:2308.16606 [hep-ex]

[3] K. Abe et al. (T2K collaboration) Nucl. Instrum. Meth. A 659 (2011) 1, 106

[4] K. Abe et al. (T2K collaboration) Phys.Rev.D 87 (2013) 1, 012001

[5] K. Abe et al. (T2K collaboration) Phys.Rev.Lett. 117 (2016) 19, 192501

[6] K. Abe et al. (T2K collaboration) CERN-SPSC-2019-001 (SPSC-TDR-006)

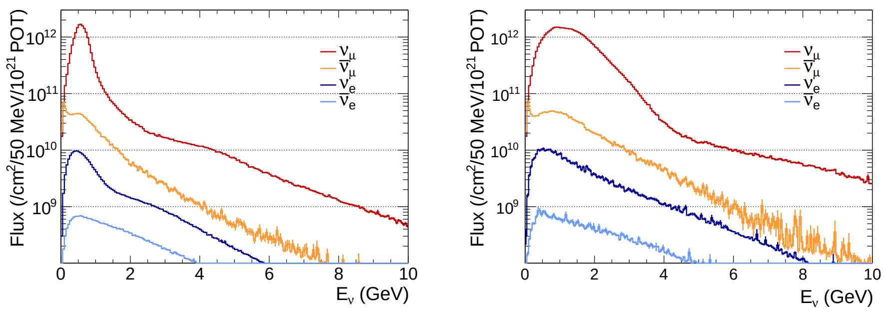

Figure 1: T2K neutrino mode flux prediction at ND280 (left) and INGRID (right) [1].

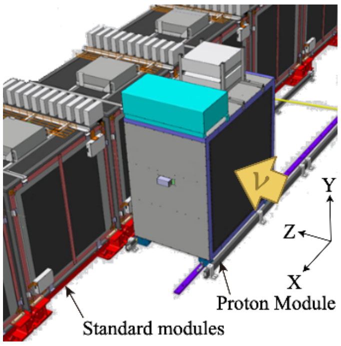

Figure 2: A schematic of the INGRID Proton module in front of the standard modules [1].

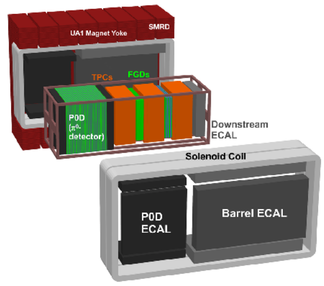

Figure 3: An schematic of the ND280 detector [1].

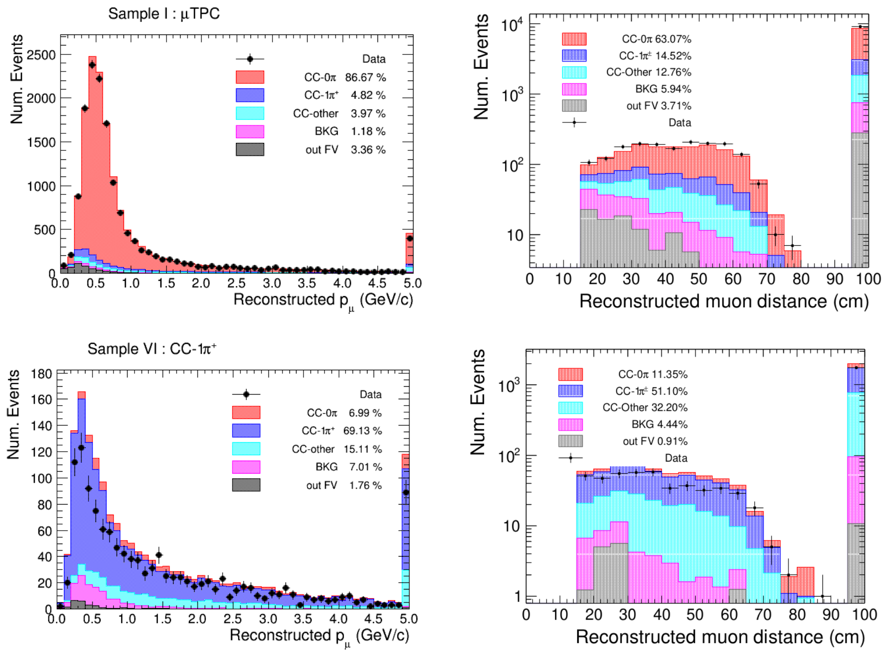

Figure 4: Reconstructed momentum and range distributions from some of the samples used in the $CC0\pi$ analysis. Left (right) shows an ND280 (INGRID) sample. Top (bottom) shows a signal (background) sample [1].

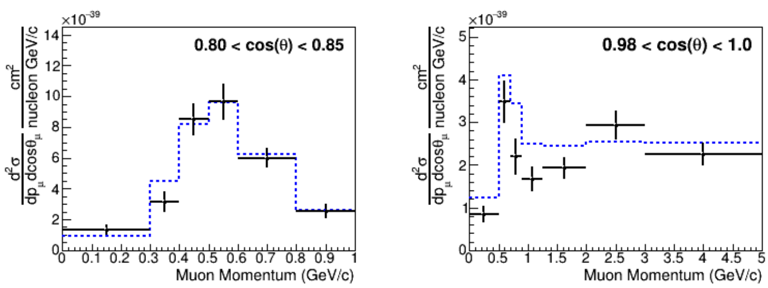

Figure 5: Some example angular slices of the extracted ND280 cross-section as a function of muon momentum in angle bins compared to the nominal NEUT MC prediction [1].

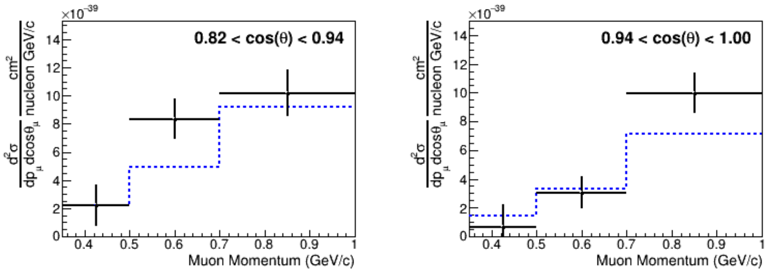

Figure 6: Some example angular slices of the extracted INGRID cross-section as a function of muon momentum in angle bins compared to the nominal NEUT MC prediction [1].

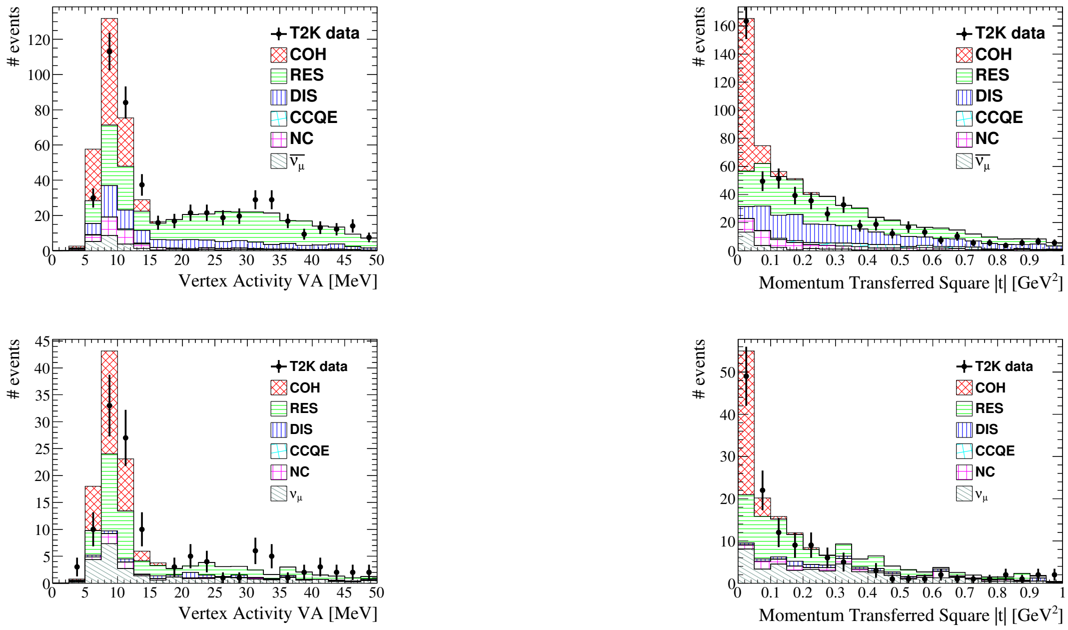

Figure 7: The vertex activity and reconstructed momentum transfer to the nucleus, $|t|$, for the neutrino sample (top) and anti-neutrino sample (bottom) [2].

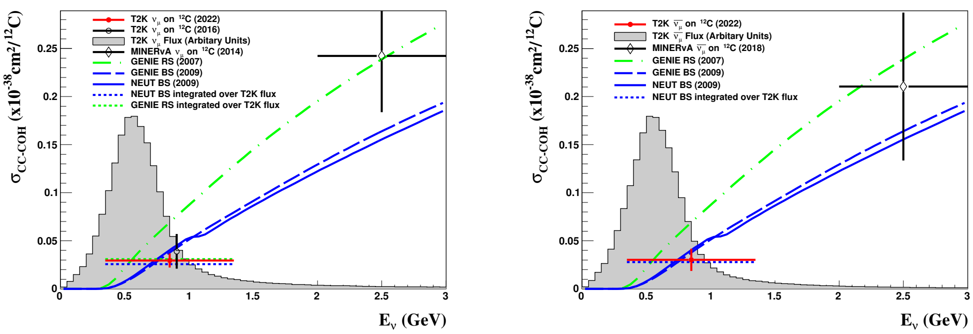

Figure 8: The T2K ν_μ (left) and $\bar{\nu}_\mu$ (right) CC coherent cross-section measurement on C [2].