Neutrons as probes of nuclear effects in muon neutrino CC0π at T2K's upgraded near detector

Liz Kneale and Patrick Stowell
on behalf of the T2K Collaboration

July 2024

Introduction

New neutron-tagging capabilities in the upgraded near detector at T2K (Tokai to Kamioka) will be key to reducing neutrino-nucleus interaction cross section uncertainties and improving neutrino and antineutrino energy reconstruction. In next-generation long-baseline oscillation experiments, neutrino interaction uncertainties will be one of the limiting factors [1] and precise knowledge of interaction cross sections and beam energy will be vital for future oscillation analyses. Neutrino kinematics can give insight into what is happening inside the nucleus in neutrino-nucleus interactions and the neutron is the missing piece in reconstructing muon (anti)neutrino energy from neutrino-nucleus interactions.

T2K is a long-baseline neutrino oscillation experiment [2] which measures oscillations of muon (anti)neutrinos from a beam at the J-PARC Neutrino Experimental Facility in Japan over a distance of 295 km to the Super-Kamiokande far detector. The neutrino beam flux and interaction cross sections uncertainties are constrained by the ND280 near detector 280 m from the beam source. The Super Fine-Grained Detector (SFGD) is part of the recent upgrade at ND280. The SFGD consists of over two million scintillator cubes with 3D tracking, sub-nanosecond time resolution [3], high light yield and 4π angular acceptance. As such, it is able to achieve particle identification and neutron tagging from muon (anti)neutrino interactions as well as more precise neutrino energy reconstruction by detecting and reconstructing kinematics of neutrons and lower-energy protons and pions.

The muon antineutrino charged-current CC0π-n topology, with at least one neutron and no observable pion, is a key observable signal topology with the beam in antineutrino mode. The principal contribution to this topology is the charged-current quasi-elastic (CCQE) interaction

$$\bar{\nu}_\mu p \rightarrow \mu^+ n$$

where a neutrino scatters off a single bound proton and produces a neutron which is also present in the final state. Other contributions to this topology include the 2p2h interaction, where a neutrino scatters off a correlated pair of nucleons and ejects both from the nucleus, and the charged-current resonant pion production interaction (CCRes), where the pion is absorbed before leaving the nucleus.

The equivalent muon neutrino CCQE interaction

$$\nu_\mu n \rightarrow \mu^- p$$

produces a proton. However, muon neutrinos can produce neutrons through Final State Interactions (FSI) in the nucleus and up to 10% of the CC0π-n topology in the antineutrino beam comes from muon neutrinos (Fig. 1). Muon neutrinos are an important background in the antineutrino beam and here we discuss the measurement of CC0π-n in the neutrino beam to discriminate between neutrino-nucleus interaction models and constrain muon neutrino backgrounds in the antineutrino beam.

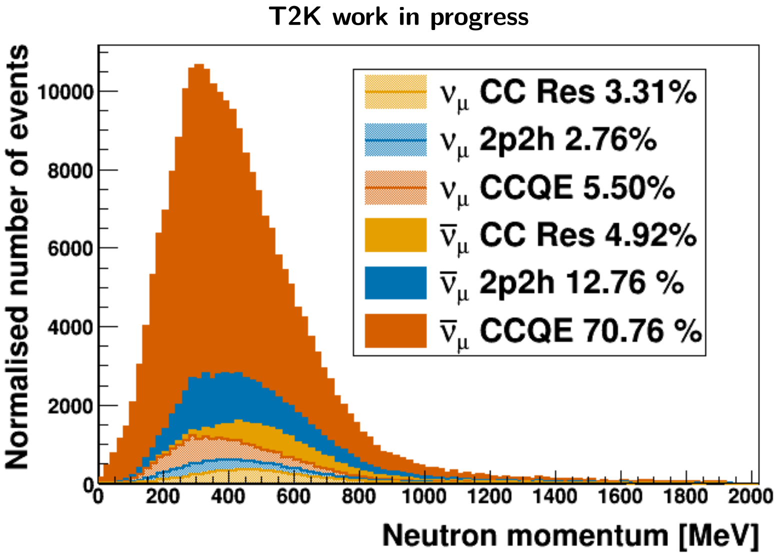

Figure 1: Simulated neutron momentum distribution for CC0π-n events broken down by reaction types (different colours). Up to 10% of the CC0π-n topology in the antineutrino beam mode comes from muon neutrinos.

Neutron tagging and energy in the SFGD

Charged particles leave tracks in the SFGD but neutrons are not directly detectable. However, the vertex and timing resolution are such that neutrons can be detected via secondary charged particles produced by neutron interactions with nuclei in the detector. A neutron signal in the SFGD is therefore characterised by the presence of a secondary vertex disconnected from the primary vertex. As shown in Fig. 2, almost 70% of the observable particles from the secondary vertex are expected to be protons, the remainder being charged pions and electrons (or positrons). The distance the neutron travels before it interacts to produce detectable secondaries is called the neutron lever arm.

The energy of the interacting muon (anti)neutrino can be reconstructed from the sum of the energies of the outgoing hadrons and leptons, whose energies are calculated from their charge deposits in the detector. The mean neutron energy can be over 15% of the neutrino energy [4] and yet since neutrons are neutral they do not deposit charge in the detector. Instead, the energy of the neutron can be calculated using its lever arm and time of flight from the primary (anti)neutrino interaction vertex to the secondary neutron interaction vertex [5].

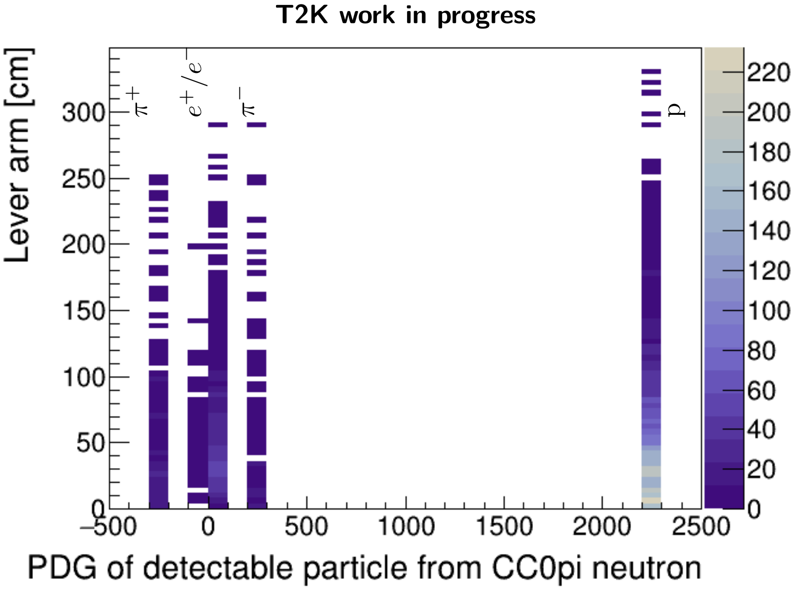

Figure 2: Plot of the neutron lever arm against the secondary outgoing particle type (PDG particle ID code) from simulation. 68% of the detectable particles produced are protons, 20% are electrons and positrons and the remaining are charged pions.

Neutrons for background and model discrimination

Since the neutron production mechanism differs between the muon neutrino and antineutrino interactions, it stands to reason that the neutron kinematics can also differ. The ability to discriminate between neutrinos and antineutrinos in ND280 can be exploited to identify discriminating kinematics for the far detector (Fig 3).

Final State Interactions (FSI) are complex processes which affect the hadrons produced by the primary scattering on a bound nucleon. They contribute significantly to the uncertainties in interaction cross section models and thus to systematic errors in neutrino oscillation measurements. Generators bring together different components of cross section models in an attempt to build a complete description of exclusive neutrino interaction final states and their likelihoods. FSI are subject to a number of effects and while the basic implementation of FSI in generators can be very similar, the precise treatment can vary, resulting in significant differences between generators, particularly at low hadron energies.

Neutron kinematics are particularly sensitive to FSI and can act as probes of the processes occurring inside the nucleus after the initial neutrino-nucleus interactions. Fig. 4 shows that the NEUT [6], NuWro [7] amd GENIE [8] differ significantly in their predictions for the neutron momentum spectrum, especially below 200 MeV (note that below around 120 MeV, neutron momentum becomes sensitive to binding energy effects). Measurements of low-energy neutron kinematics therefore have the potential to provide a test of the implementation of FSI in different generators, improving our understanding of neutrino-nucleus interactions.

A neutron analysis is underway to measure the ν_μCC0π topology with the beam in neutrino mode and probe the low-energy region for model discrimination.

Summary

High-resolution 3D tracking and excellent time resolution in the SFGD will improve understanding of outgoing neutron kinematics in neutrino-nucleus interactions. Neutron kinematics can in turn be used to improve neutrino energy reconstruction, constrain muon neutrino backgrounds in the antineutrino CC0π-n signal, and test FSI implementation in different cross section models and generators.

Neutron tagging and reconstruction to exploit the SFGD technology in the ND280 upgrade and beyond will push sensitivity to lower energies for enhanced physics capabilities including, but not limited to, reducing systematic uncertainties on cross section models for neutrino oscillation studies.

References

[1] Hyper-Kamiokande Proto-Collaboration et al. *Hyper-Kamiokande Design Report*. 2018. arXiv: `1805.04163 [physics.ins-det]`. URL: `https://arxiv.org/abs/1805.04163`.

[2] K. Abe et al. "The T2K experiment". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 659.1 (2011), pp. 106–135. ISSN: 0168-9002. DOI: `https://doi.org/10.1016/j.nima.2011.06.067`. URL: `https://www.sciencedirect.com/science/article/pii/S0168900211011910`.

[3] S Fedotov et al. "Scintillator cubes for 3D neutrino detector SuperFGD". In: *Journal of Physics: Conference Series* 2374.1 (Nov. 2022), p. 012106. DOI: `10.1088/1742-6596/2374/1/012106`. URL: `https://dx.doi.org/10.1088/1742-6596/2374/1/012106`.

[4] S. Gwon et al. "Neutron detection and application with a novel 3D-projection scintillator tracker in the future long-baseline neutrino oscillation experiments". In: *Phys. Rev. D* 107 (3 Feb. 2023), p. 032012. DOI: `10.1103/PhysRevD.107.032012`. URL: `https://link.aps.org/doi/10.1103/PhysRevD.107.032012`.

[5] L. Munteanu et al. "New method for an improved antineutrino energy reconstruction with charged-current interactions in next-generation detectors". In: *Phys. Rev. D* 101 (9 May 2020), p. 092003. DOI: `10.1103/PhysRevD.101.092003`. URL: `https://link.aps.org/doi/10.1103/PhysRevD.101.092003`.

[6] Yoshinari Hayato and Luke Pickering. "The NEUT neutrino interaction simulation program library". In: *The European Physical Journal Special Topics* 230.24 (Oct. 2021), pp. 4469–4481. ISSN: 1951-6401. DOI: `10.1140/epjs/s11734-021-00287-7`. URL: `http://dx.doi.org/10.1140/epjs/s11734-021-00287-7`.

[7] T. Golan, J.T. Sobczyk, and J. Żmuda. "NuWro: the Wrocław Monte Carlo Generator of Neutrino Interactions". In: *Nuclear Physics B - Proceedings Supplements* 229-232 (2012). Neutrino 2010, p. 499. ISSN: 0920-5632. DOI: `https://doi.org/10.1016/j.nuclphysbps.2012.09.136`. URL: `https://www.sciencedirect.com/science/article/pii/S0920563212003532`.

[8] C. Andreopoulos et al. "The GENIE neutrino Monte Carlo generator". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 614.1 (2010), pp. 87–104. ISSN: 0168-9002. DOI: `https://doi.org/10.1016/j.nima.2009.12.009`. URL: `https://www.sciencedirect.com/science/article/pii/S0168900209023043`.

[9] J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas. “Inclusive charged-current neutrino-nucleus reactions”. In: *Physical Review C* 83.4 (Apr. 2011). ISSN: 1089-490X. DOI: `10.1103/physrevc.83.045501`. URL: `http://dx.doi.org/10.1103/PhysRevC.83.045501`.

[10] O. Benhar et al. “Spectral function of finite nuclei and scattering of GeV electrons”. In: *Nuclear Physics A* 579.3 (1994), pp. 493–517. ISSN: 0375-9474. DOI: `https://doi.org/10.1016/0375-9474(94)90920-2`. URL: `https://www.sciencedirect.com/science/article/pii/0375947494909202`.

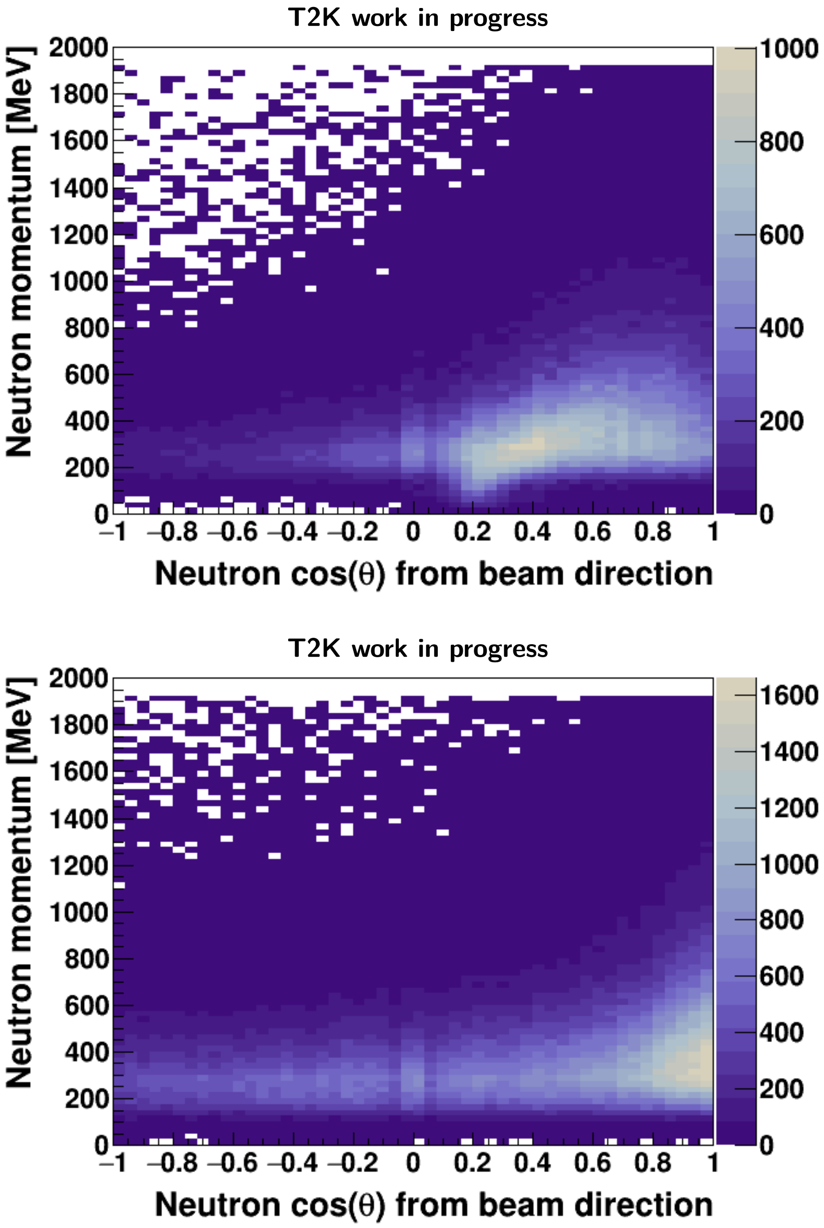

Figure 3: Plots of momentum against $\cos\theta$ with respect to beam direction for neutrons in the CC0π topology from antineutrino interactions (top) and neutrino interactions (bottom) show an example of kinematics that might be explored to identify discriminating kinematics for Super-Kamiokande.

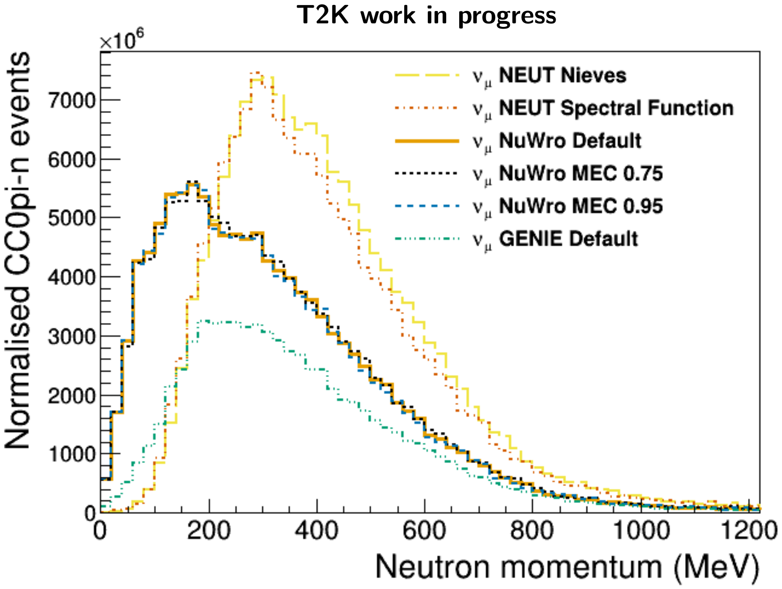

Figure 4: Neutron momentum for final-state neutrons in the CC0π-n topology from different models within NEUT, NuWro and GENIE generators. Models shown include the Nieves [9] and spectral function [10] models, and varying meson exchange current (MEC) fractions which can particularly impact 2p2h interactions.