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An improved muon neutrino charged-current single positive pion cross section on water using Michel electron reconstruction in the T2K near detector

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The T2K experiment is a long-baseline neutrino oscillation experiment, based in Japan, which measures the oscillation probability of muon neutrinos produced at the JPARC facility, and detected at Super-Kamiokande. A detailed understanding of neutrino-nucleus cross sections is essential to measuring neutrino oscillation parameters. The off-axis near detector ND280 is used to measure a variety of neutrino interaction rates in the unoscillated beam, in order to give a better understanding of the individual cross sections. T2K has been working to add single pion production events to the oscillation analysis samples, thus increasing the impact of pion production cross section uncertainties on oscillation results.
There is an ongoing effort on T2K to measure the cross section for charged current muon neutrino events on water, with one positively charged pion in the final state (ν_μCC1π^+) using the ND280 detector. The described measurement builds on a previous result, with significant changes to the particle kinematic ranges considered, including new reconstruction methods for accessing low energy pions using the signature of the decay chain to Michel electrons (the first instance of this technique being used in a T2K analysis). In addition, the analysis will benefit from an increase in statistics by a factor of two, an updated treatment for unfolding, and a new treatment for the evaluation and propagation of systematic uncertainties. This talk will focus on the updated analysis techniques and simulated results for a variety of potential data sets based on simulations and previous measurements of signal and background processes.
New or updated neutrino cross section measurements can be used to compare to our current interaction models, in order to reduce model-related systematics, which will be particularly important for next generation oscillation experiments.

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1. The T2K Experiment

T2K (Tokai-to-Kamioka) is a long baseline neutrino oscillation experiment based in Japan [1], which is designed to make precision measurements of neutrino oscillation parameters. A muon neutrino or antineutrino beam is generated at the J-PARC accelerator complex in Tokai, and interactions in the appearance and disappearance channels are studied at the Super-Kamiokande far detector. Super-K is a 22.5 kt fiducial volume water Cherenkov detector situated 295 km downstream from the beam production point, which also studies proton decay and neutrinos from other sources [2]. T2K uses an off-axis approach, directing the neutrino beam 2.5° away from Super-K. This results in a narrow band beam, with a flux peak at a neutrino energy of ~600 MeV.

In order to perform oscillation measurements, the rate of multiple interaction channels is observed. This rate, a function of reconstructed kinematics $\vec{x}$, can generally be expressed as

$$R(\vec{x}) = \int \phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_\alpha \to \nu_\beta) dE_\nu, \tag{1}$$

where ϕ is the initial neutrino flux, σ is the neutrino interaction cross section, ϵ is the efficiency of the detector, $P(\nu_\alpha \to \nu_\beta)$ is the probability of a neutrino of initial flavour α to later be observed as flavour β, and E_ν is the neutrino energy. In order to accurately measure the oscillation probability, precise knowledge of the underlying neutrino interaction cross sections is required. A recent T2K measurement [3] shows that the cross section error is currently one of the leading sources of systematic uncertainty, and as such T2K has a dedicated cross section program working to make measurements to lower these uncertainties. One such ongoing measurement is presented here.

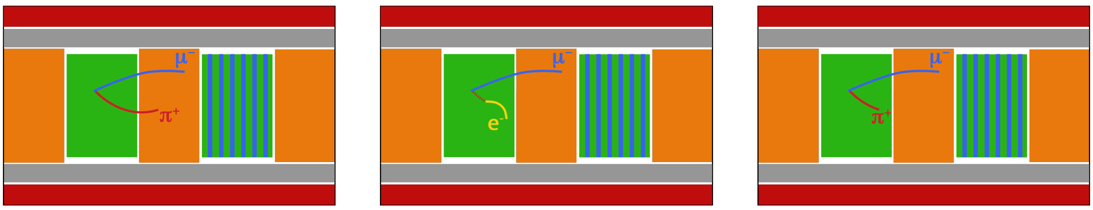
In the range of energies covered by T2K, most neutrino interactions proceed via charged current (CC) quasi-elastic (QE) scattering. As energies increase past the flux peak however, contributions from resonant (RES) interactions and deep inelastic scattering (DIS) begin to occur, along with interactions of a single neutrino with a bound state of multiple nucleons, often referred to as 2p2h interactions. After the initial interaction, the resultant particles must escape the nuclear medium before being detected. In doing so, many possible final state interactions (FSI) can take place, which can drastically alter the observed final state of the event. Further complications are also introduced due to the finite resolution of detectors, and the combination of these effects makes identifying the true neutrino interaction nearly impossible. Instead, we choose to measure and report cross section results in terms of the observed final state within the detector, referred to as the event topology. This reduces dependence on assumptions made by the underlying interaction generator models.

2. The ND280 Detector

T2K has a suite of near detectors 280 m downstream from the beam production point, which are used to monitor beam composition and provide constraints to oscillation analysis by measuring the beam prior to oscillation. The cross section measurement described uses the ND280 near detector [4], which sits at the same off-axis angle as Super-K and is formed from multiple sub-detectors, held inside the 0.2 T UA1 magnet. Of particular relevance to this analysis are the Fine Grained Detectors (FGDs) and Time Projection Chambers (TPCs), which form the inner tracker, with the FGDs interleaved between the TPCs. The two FGDs form the main target mass of ND280, and are made from alternately aligned bars of hydrocarbon scintillator. In addition, FGD2 features interleaved passive water layers, which make it possible to perform cross section measurements on water. The three TPCs are gaseous tracking detectors, which are used in event selections for charge discrimination and particle identification, along with measuring particle momentum. In 2022, an upgrade is planned to ND280, which will replace the π^0 detector with a greater resolution FGD, surrounded by high angle TPCs and dedicated time of flight detectors [5].

3. Sample Selection

In order to obtain an event sample for this analysis, a series of cuts are applied to Monte Carlo production. These search for events with a single negative muon, single positive pion, and no additional mesons in the final state (ν_μCC1π^+), with event vertices in either FGD1 or 2. No restrictions are placed on the presence of additional nucleons. This general CC1π^+ signal is split up into separate samples, based on how the pion is detected, as it is expected that these samples will cover largely different phase spaces. Higher energy pions which escape into the TPC and are identified via TPC PID methods, as shown in Figure 1a, form the TPC sample. The presence of lower energy pions which stop in the FGD and subsequently decay to muons and then Michel electrons can be inferred via the delayed signature left by Michel electrons, as in Figure 1b. These constitute the ME sample. Stopping pions whose decay electrons are not detected (Figure 1c) can be identified by applying FGD PID methods. These events form the FGD sample.



(a) TPC **(b)** ME **(c)** FGD

Figure 1: Topological view of the three CC1π^+ samples. TPCs are shown in orange, with FGD1 in light green and FGD2 in striped green and blue.

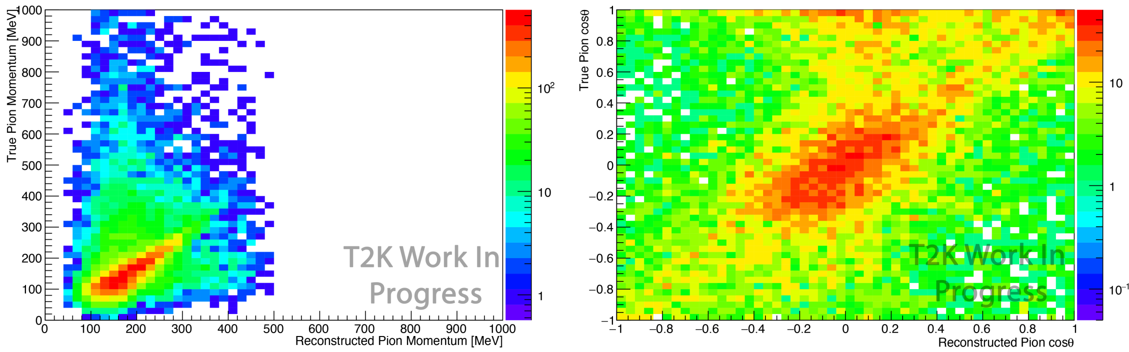
Along with the described signal samples, three control samples are formed to address the major backgrounds to the selected signal. The first two major backgrounds are events where multiple pions are observed in the final state, whether charged or neutral. The final one is formed to specifically deal with the CC0π background to the FGD signal sample, where protons are mistakenly reconstructed as pions. All signal and control samples are further sub-divided by which FGD layer the event vertex is reconstructed in: FGD1, FGD2x or FGD2y. Events in the FGD2x layers predominantly correspond to interactions on water, whereas FGD2y are mostly interactions on hydrocarbon.

4. Michel Electron Reconstruction

Of the total CC1π^+ sample, ~35% of events are inferred via the presence of Michel electrons. For these events, the analysis framework used currently provides no reconstructed pion kinematics.

This analysis seeks to use the geometry of the Michel electron decay to estimate the momentum and outgoing angle of the primary pion, so that the eventual cross section result can be made as a function of pion kinematics without a loss of statistics. In Monte Carlo generated events, strong correlation is observed between true primary pion momentum, and the separation between the event vertex and Michel electron initial position (hereafter referred to as the ME vertex). Comparison between the outgoing pion angle and the angle that the vector from the event vertex to the ME vertex forms with respect to the neutrino direction exhibits a similarly strong correlation.

To use these relationships the position of the ME vertex in the FGD has to be reconstructed. The accuracy of this is limited by the FGD structure, which consists of alternately aligned scintillator bars in the x and y directions; a single hit in a bar will record either an x or a y coordinate, rather than both. To obtain a full set of coordinates for the vertex, multiple FGD hits must be averaged over, which inherently biases the reconstructed vertex away from the truth.



(a) Momentum **(b)** $\cos\theta$

Figure 2: True vs reconstructed distributions in pion (a) momentum and (b) $\cos\theta$, reconstructed using the geometry of the Michel electron decay chain.

Figure 2 shows the comparison between true and reconstructed distributions using this method. It is clear from this that the momentum reconstruction is more accurate, displaying a clear linear correlation, albeit with some spread in the values. No events are reconstructed with momentum greater than ~500 MeV, as the separation required would allow the pion to escape the FGD and enter the TPC sample. The angular reconstruction is less accurate; despite some correlation, a lot of events are reconstructed incorrectly. This shows how the analysis is limited by the FGD design, which affects the reconstruction of the vector position (used to obtain the angle) more than that of the scalar momentum. However, the SuperFGD [6] coming as part of the ND280 upgrade [5] will have a cube-like scintillator structure, which will allow for full 3D tracking, and thus this technique should be more successful when applied there. This analysis serves as a proof of concept for the method, and binning of the ME sample is performed only in momentum.

5. Analysis Strategy

Extraction of the cross section is performed using a binned template likelihood fit, a technique used in many recent cross section analyses by T2K. In this analysis, a simultaneous extraction is performed for events occurring on both hydrocarbon and water, allowing measurement of both cross sections as well as the ratio between them to be made. The number of observed signal events in a true variable bin can be expressed as

$$N_i^{\alpha,\,\mathrm{sig}} = c_i^\alpha N_{i,\,\mathrm{MC}}^{\alpha,\,\mathrm{sig}}, \tag{2}$$

where i labels the true kinematic bin and α is the target material, CH or H_2O. This relates the number of observed signal events in the i^{th} true bin to the number predicted in Monte Carlo (MC) by a free template parameter, c_i^α. These template parameters are allowed to vary as MC is fit to data, and the unfolded result is taken as those which minimise the log likelihood. The unfolded number of events can then be used to calculate the differential cross section on target α in the i^{th} bin of kinematic variable x as

$$\left(\frac{d\sigma}{dx}\right)_i^\alpha = \frac{N_i^{\alpha,\,\mathrm{sig}}}{\epsilon \Phi T_\alpha \Delta x_i}, \tag{3}$$

where ϵ is the efficiency within the bin, Φ is the integrated flux, T_α the number of targets and Δx_i the bin width.

To perform efficiency corrections in the least model dependent way possible, a fine 4-dimensional binning scheme is used for extraction. This results in cross section measurements differential in both muon and pion momentum and cosine of θ. In theory this should give good model separation by giving access to both the leptonic and hadronic sides of the interaction, however the measurement will be statistically limited due to the fine binning scheme used. To provide a less statistically limited measurement, the muon kinematic bins can also be collapsed after extraction, to provide a double differential measurement in pion kinematics, which should still provide good model separation potential. A series of fake data studies have been performed to assess the robustness of the fit procedure used, with a fit to real data expected to be performed in the near future, which will be compared to various model predictions.

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