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Charged current resonant and coherent single meson production results from T2K (on and off-axis)*

M. Nirkko†
AEC-LHEP, University of Bern
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Abstract

It is a truth universally acknowledged that a scientist in possession of a good neutrino oscillation experiment must be in want of a neutrino interaction model. In order to reduce systematic effects, understanding the way neutrinos interact with matter is crucial. Known cross-sections from various experiments show significant discrepancies with common theoretical models within the low energy region (∼1GeV). Data taken with the T2K near detectors will cover this critical region, as cross-section measurements for various interaction channels are on the way. This article focuses on the resonant and coherent contributions to neutrino-induced meson production, including proton decay backgrounds, for which various analyses are under way.

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INTRODUCTION

Recent cross-section measurements of single pion production (CC-1π^+) from MiniBooNE [1] and MINERvA [2] have been reported as differential cross-sections as a function of charged pion kinetic energy. While the data seemed to agree at higher energies, significant discrepancies were seen below 100MeV. More importantly, the Monte-Carlo (MC) models used did not agree well with data in either experiment [2].

Coherent pion production has so far only been measured in the intermediate energy range (1–10GeV) and above. Available data is sparse, and suggests that typical MC generators (GENIE [3], NEUT [4]) are not correctly predicting the cross-section at lower energies [5]. Extending the measurements below 1GeV will be beneficial to presently used models.

With neutrino energies similar to the BNB beam used for MiniBooNE and a more sharply peaked flux, T2K [6] will be able to provide complementary measurements of the various pion production channels at low energies, providing comparable results for MINERvA and others [7].

THE T2K EXPERIMENT

The Tokai-to-Kamioka (T2K) experiment is a long-baseline ($L/E \approx 500$km/GeV) muon-neutrino oscillation experiment located in Japan, shown in Fig. 1. Its main goals are to measure ν_e appearance (determines θ_{13}), ν_μ disappearance (determines θ_{23} and $|\Delta m^2_{32}|$) and CP violation (determines δ_{CP}). Further goals include a search for sterile components in ν_μ disappearance by observing NC events, and making world-leading contributions to neutrino-nucleus cross-section measurements. For more information on neutrino and antineutrino oscillation measurements at T2K, see references [8, 9].

T2K uses Super-Kamiokande [10] as the far detector, which measures neutrino rates at the first oscillation maximum. While the far detector already existed, the beamline and near detector complex were constructed for the T2K experiment. The proton synchotron located at J-PARC fires 30 GeV protons onto a graphite target, currently providing a beam

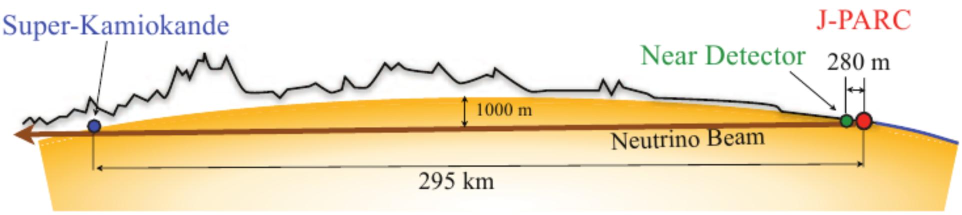

FIG. 1: Neutrinos are produced at J-PARC in Tokai, from which they travel 295km through the Earth before reaching the Super-Kamiokande detector in Kamioka. The near detector site located at J-PARC is used to monitor beam flux as well as measure neutrino interactions.

power up to 400kW. The target beam line is arranged at a 2.5° angle with respect to Super-Kamiokande; this off-axis method produces a narrow neutrino energy spectrum peaked at 0.6GeV.

Near detectors

The on-axis detector (INGRID, see Fig. 2) is constructed from an array of 16 iron/scintillator sandwich modules, and functions as a neutrino flux monitor. The identical modules are arranged in the shape of a plus sign, large enough to measure the beam flux at different off-axis angles. Each module is made from alternating planes of scintillator tracker and iron plates. A similar module consisting purely of scintillators called the proton module is placed upstream and is used for cross section measurements.

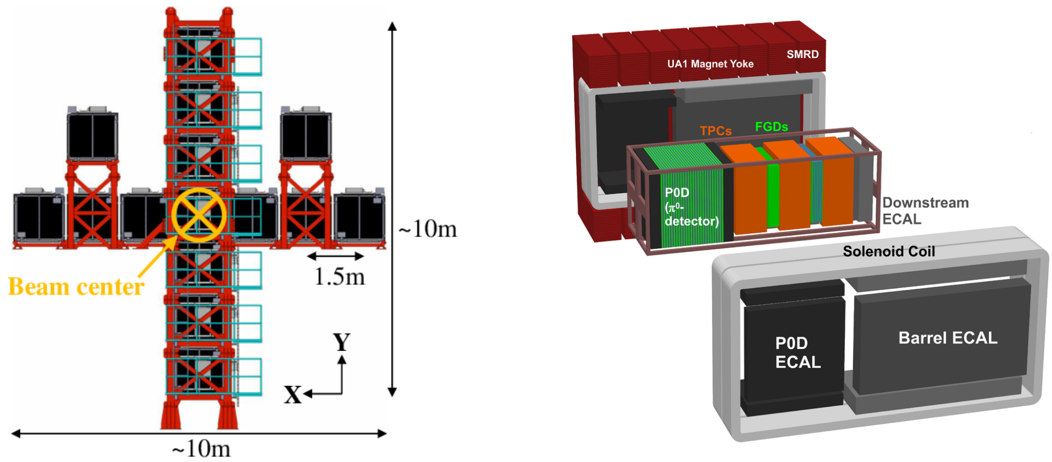

FIG. 2: Schematics of the on-axis (INGRID, left) and off-axis (ND280, right) detectors.

The off-axis detector (ND280, see Fig. 2) is located 280m downstream from the target and serves multiple purposes, from measuring the neutrino flux and energy spectrum as well as the intrinsic beam contamination from electron neutrinos to cross-sections for specific neutrino reactions. It is composed of various subdetectors: A water-scintillator detector optimised to detect π^0's (P0D) is placed at the upstream end. It consists of tracking planes of scintillator bars that alternate with water. Downstream of the P0D lies the tracker, optimised to study CC interactions. It consists of three time-projection chambers (TPCs) and two interspersed fine-grained detectors (FGDs). The TPCs contain an argon-based drift gas and a central cathode to produce a uniform electric field inside the active drift volume. Electrons produced by passing particles drift outward towards the central planes located on each side of the detector. The FGDs serve as massive targets for the neutrinos within the tracker. They consist of scintillator bars arranged in layers perpendicularly to each other. The first FGD consists purely of scintillator material, while the second FGD is interspersed with water layers. An electromagnetic calorimeter (ECal) surrounds both the P0D and the tracker. The entire detector is magnetised by a 0.2T homogenenous field, allowing the charge and momentum of reconstructed tracks to be determined.

Event topologies

There is no way to directly see what is going on inside the nucleus during a neutrino interaction, but nuclear effects such as Fermi momentum and final state interactions affect the particle composition and kinematics. For instance, one cannot say for certain whether an observed event containing a charged muon was caused by quasi-elastic scattering (CCQE), resonant production (CC-RES), deep inelastic scattering (CC-DIS). For this reason, it is usually preferred to define interactions by final state topology rather than reaction type. The T2K CC-Inclusive sample is split into three topologies (see Fig. 3) according to the number of charged pions exiting the nucleus.

The first sample (CC-0π) rejects pions altogether, and can be described by the reaction $\nu_\mu + N \rightarrow \mu^- + N'$. As one would expect, a large fraction of these events (64%) are "true" CCQE events. The rest is made up of other reactions such as CC-RES, where the outgoing meson is undetected due to reconstruction inefficiencies.

The second sample (CC-1π) includes all topologies with exactly one positive pion in the final state. Best described by the reaction $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N'$, the dominant reaction is CC-RES, weighing in at 40%. Events in which a pion is produced coherently (CC-COH), leaving the nucleus in exactly the same quantum state, would typically also be categorised as CC-1π. When specifically selecting CC-COH events, further cuts need to be applied to ensure no other particles are leaving the nucleus.

All other events are lumped into the third sample (CC-Other), this includes events where negative or neutral pions are produced: $\nu_\mu + N \rightarrow \mu^- + n\pi^{\pm,0} + N'$. Since this sample includes multiple pion events, 68% of events in this sample are CC-DIS.

CROSS-SECTION MEASUREMENTS

This article focuses on some of the more advanced CC-1π and CC-COH measurements at the T2K near detectors. For information about other cross section analyses, see Ref. [11, 12].

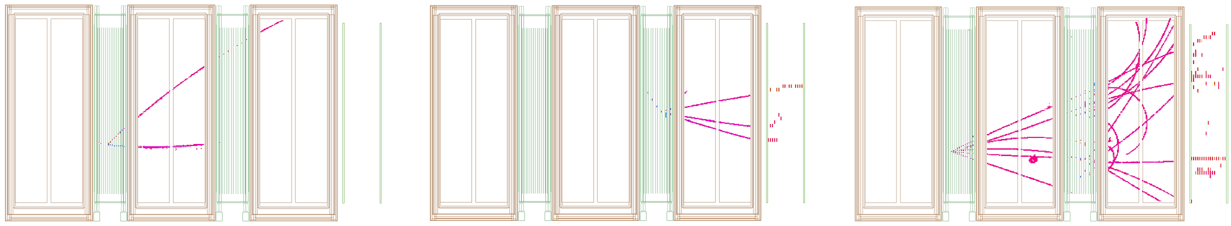

FIG. 3: ND280 tracker event displays for various topologies, from left: CC-0π, CC-1π, CC-Other.

Event selection

All analyses presented here involve charged-current interactions. It is therefore natural to begin any event selection by identifying the outgoing lepton track, in this case a muon. Following some basic data quality cuts, the highest momentum negative track with good quality is selected. It must start within the fiducial volume of the desired subdetector and is usually associated with the neutrino interaction point. Additionally, Particle Identification (PID) cuts require the track to behave like a Minimally Ionising Particle (MIP). This procedure selects events of which 90% are true CC interactions.

In the case of the ND280 tracker, PID is performed for tracks crossing a TPC. The momentum is obtained from the track curvature within the magnetic field, and the deposited charge inside the gas is related to the deposited energy per unit length dE/dx. Using the Bethe formula that describes the relation between these two variables for different particles, tracks are assigned a likelihood for each particle hypothesis by calculating the pull variables of the expected dE/dx distributions. These are optimised for muons in a specific momentum bin (400–500MeV/c) and perform less well for heavier particles such as kaons or protons.

CC-1π in water (P0D)

A search for CC-1π events in water is performed by selecting events with exactly two tracks inside the P0D fiducial volume. The events are split into two samples, depending on whether the muon track is fully contained within the P0D or not. The starting points of both selected tracks are required to be close to the reconstructed vertex. The dE/dx pull variables must match the muon/pion hypothesis. Furthermore, fully contained tracks are required to have a delayed Michel cluster[1] at the end.

An important feature of this measurement is that the water inside the P0D can easily be drained, allowing for different data runs with “water-in” and “water-out” configurations. The background from interactions within the surrounding material (such as scintillators, brass, and lead) is then reduced by subtracting the normalised event rates; one is left with the event rate in water.

[1] Electrons originating in the decay of stopped muons are called Michel electrons.

Regarding the cross-section, it is interesting to note that the T2K NEUT prediction before FSI agrees with the MiniBooNE data. Results using data are currently under internal review and will be published when approved. The result will be extended into a differential cross-section measurement in the near future. Further efforts will be made to include other topologies (e.g. events with > 2 tracks coming from the interaction vertex).

CC-1π in water (FGD2)

A similar analysis aims to measure the same quantity using events where the neutrino interacted inside FGD2. Starting with the CC-Inclusive selection (described above), a positive TPC-track with good quality is required. This track must be pion-like (the PID must match the pion hypothesis) and no other pion-like tracks are allowed in the event. Events containing π^0's are rejected by looking for showers in the ECAL. Since the water is not an active tracking material, the first hits are registered in the first downstream scintillator layer (in which the scintillator bars are arranged horizontally); an intrinsic background from carbon interactions is to be expected. Another important background contribution is from CC interactions other than CC-1π. In an attempt to constrain these backgrounds, two sidebands are used: A CC-1π scintillator sample using interactions within the second scintillator layers (bars arranged vertically) describes the intrinsic background from carbon interactions. For the CC non-1π interactions, a CC-Other water-enhanced sample is used. The MC-predicted background appears to be in good agreement with the data.

The flux-integrated differential cross-section is obtained using the Bayesian unfolding technique [13] to estimate the number of true signal events. Having estimated this number $N_k^{unfolded}$ for each bin k, the integrated neutrino flux Φ, the number of target nucleons $N_{targets}$ and the detection efficiency ϵ_k in a given bin of width ΔX_k, one can calculate the differential cross section for a variable X:

$$\langle \frac{\delta\sigma}{\delta X} \rangle_k = \frac{N_k^{unfolded}}{\epsilon_k N_{targets} \Phi \Delta X_k}. \tag{1}$$

The results are most interesting when discussed in terms of pion kinematics (Fig. 4): Both generators used (NEUT and GENIE) seem to slightly overestimate this channel. While the total cross section agrees with the NEUT prediction, GENIE overpredicts the cross section by 1.5σ.

CC-1π in carbon (FGD1)

A related analysis performs a similar selection on carbon, using the FGD1 as an active volume. Apart from investigating standard variables such as momentum p and angle $\cos(\theta)$, this study also attempts to reconstruct neutrino energy E_ν, momentum transfer Q^2, invariant mass W and angular variables $\theta_{\mu\pi}$, θ_{planar}, ϕ_{planar} that denote the angle between muon

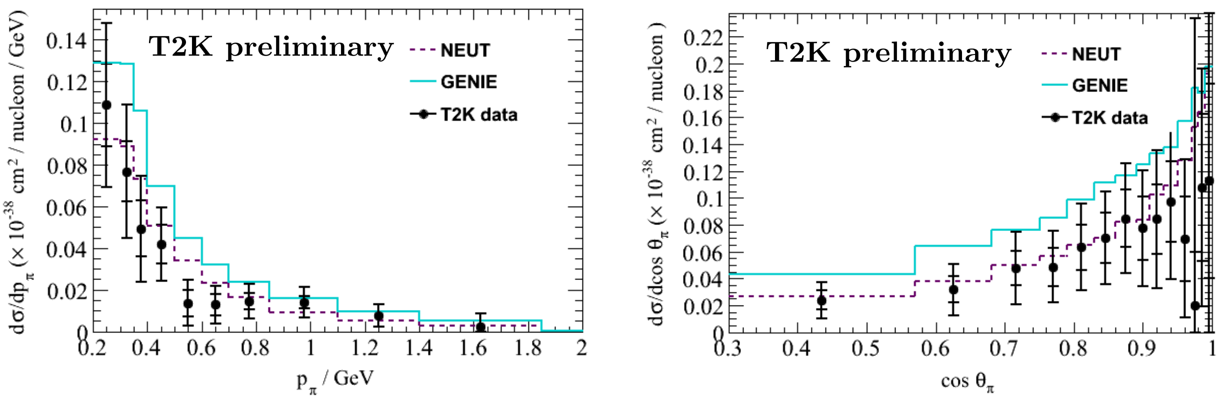

FIG. 4: Differential cross sections for CC-1π production in water, shown as function of reconstructed pion momentum (left) and angle (right). T2K preliminary results.

and muon candidates in the lab and the angles in the Adler system[2], respectively. These planar angles were studied by ANL [14], this study will provide a comparison at lower energies. Angular estimations for the pion candidates within the Rein-Sehgal model [15] were performed using NEUT MC: While the azimuthal angle ϕ_{planar} is presumed to have a flat distribution with a similar shape to ANL, differences are expected for the zenith angle $\cos(\theta_{planar})$. This is because the variable is highly sensitive to nuclear effects (e.g. low momentum pions) that were not an issue for ANL due to the deuterium target used.

CC-COH in carbon (FGD1)

To obtain a decent sample of CC-COH events, exactly one positive track is required after the standard CC-Inclusive cuts. It is required to have a pion-like, but not proton-like PID, and to be associated to the same vertex as the muon candidate. Additional variables are used to discriminate coherent interactions: The Vertex Activity (VA) measured in Photon Equivalent Units (PEU) is required to be low: VA < 300PEU. Also, the momentum transfer to the nucleus is required to be low: $|t| = \sqrt{(q - p_\pi)^2} < 0.15$GeV. To restrict the background, each of these two cuts are inverted separately to form two distinct background samples containing mainly CC-RES events. The background parameters and binned signal cross section are simultaneously fitted, yielding and excess of 55 ± 20 CC-COH events (2.7σ) with regard to the null hypothesis.

The cross section was calculated using two coherent production models in GENIE: the Rein-Seghal (RS) and the Alvarez-Ruso (AR) model [16, 17].

$$\langle \sigma_{CCcoh\pi,C} \rangle_{RS} = \left(3.8 \pm 1.0(stat)\ ^{+1.4}_{-1.3}(syst)\right) \times 10^{-40}\ \text{cm}^2/\text{nucleus}$$

$$\langle \sigma_{CCcoh\pi,C} \rangle_{AR} = \left(3.3 \pm 0.9(stat)\ ^{+1.3}_{-1.2}(syst)\right) \times 10^{-40}\ \text{cm}^2/\text{nucleus}$$

[2] The Adler system refers to the rest frame of the hadronic system, in this case the Δ^{++}.

Both models agree with the data obtained so far (see Fig. 5). Currently, this study lacks the statistical power to distinguish between them.

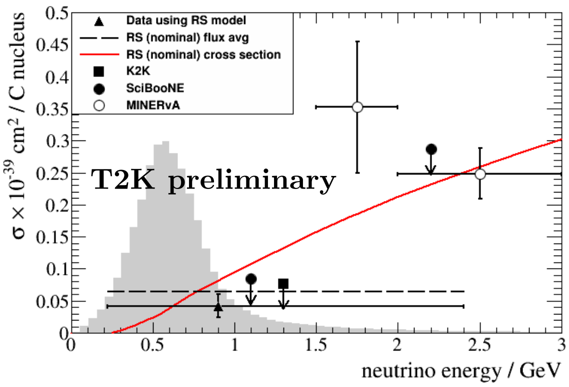

FIG. 5: Total cross section for CC-COH π^+ production in carbon, compared to Rein-Sehgal (left) and Alvarez-Ruso model (right). Previous measurements are shown for comparison. T2K preliminary results.

CC-COH in carbon (INGRID)

Another analysis attempting to measure neutrino-induced CC coherent production in carbon was conducted in the INGRID detector. A typical event is shown in Fig. 6. Exactly two tracks exiting the vertex and matching the muon/pion PID hypotheses are required. The muon must be forward going ($\theta_\mu < 15°$) due to the small Q^2 expected in CC-COH events. Furthermore, the vertex activity (VA), which is defined as the energy deposition around the vertex, must be low (VA $<$ 34MeV) to reject protons below the tracking threshold.

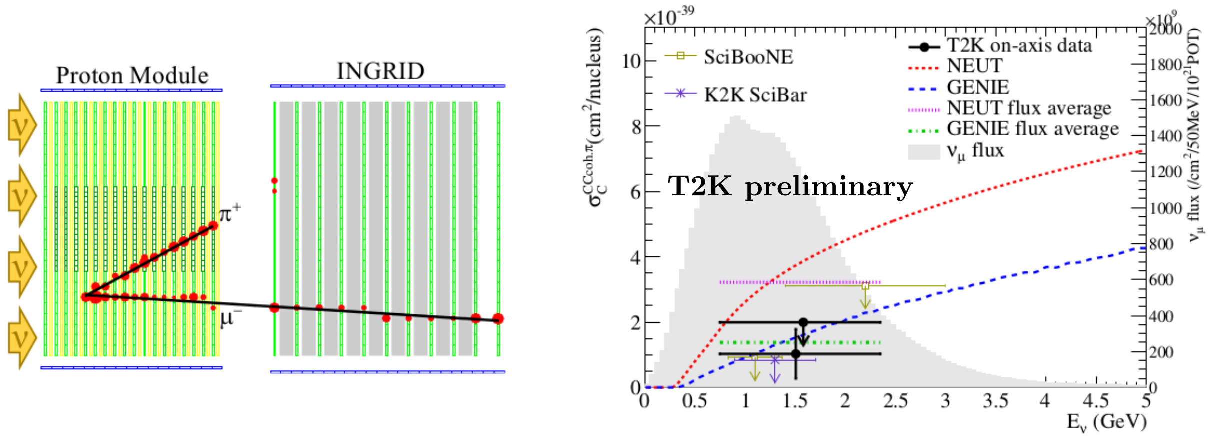

FIG. 6: INGRID search for coherent pion production. Left: Typical event display. Right: Total cross section for this interaction channel. T2K preliminary results.

The background for this selection is dominated by CC non-coherent interactions; a background subtraction technique is used to calculate the cross section:

$$\sigma_{CC-COH,\pi} = \frac{N_{sel} - N_{BG}}{\epsilon N_{targets}\Phi}, \tag{2}$$

where the number of signal events is estimated by subtracting the normalised number of background events N_{BG} from the number of selected events N_{sel}. The denominator contains the same variables as in equation 1, but without binning. This method is model-dependent due to the MC-based assumption on the signal purity: The total cross section thus measured is:

$$\sigma_{CCcoh\pi,C} = \left(1.0267 \pm 0.2455(stat)\ ^{+0.7028}_{-0.6769}(syst)\right) \times 10^{-39}\ \text{cm}^2/\text{nucleus}.$$

Due to the large systematic error, the null hypothesis cannot be excluded at this point in time. Therefore, an upper limit (90% C.L.) is calculated:

$$\sigma_{CCcoh\pi,C} < 1.9808 \times 10^{-39}\ \text{cm}^2/\text{nucleus}.$$

The result is consistent with the flux average calculated with GENIE, but about 40% below the NEUT prediction (see Fig. 6). The discrepancy is due to generator differences in pion-nucleon cross sections.

CC-$1K$ in carbon (FGD1)

As neutrino energy increases, so do the possibilities for meson production: various CC-$1K^+$ channels exist, where strangeness can be conserved (associated production) or violated (single kaon production). The latter is Cabibbo-surpressed, but nevertheless dominant in the energy region below the threshold for associated production. Very little data is available in the $\sim$1GeV region, with BNL contributing a single data point [18]. First analyses to measure kaon production in modern neutrino beams are on the way at MINERvA [19], with complementary measurements being performed at ND280. These channels represent an important background to proton decay[3]; future studies of the kaon kinematics may further the development of nuclear models.

The kaon analysis at ND280 uses GENIE with an additional model for single kaon production[4] [21]. Based on the inclusive CC selection previously described, it uses the TPC PID method within a restricted phase space to select kaons. With a total cross section $\sigma \sim 10^{-40}$ cm^2/nucleus and a rate of 7.2 events per 10^{20}POT predicted by GENIE MC, this analysis is expected to be statistics limited. A result will be reported in 2016.

[3] The proton decay mode $p \to K^+\bar{\nu}$ is favoured by some SUSY-GUT theories, with the current experimental limit for the proton lifetime set by Super-K at $\tau > 5.9 \times 10^{33}$y (90% C.L.) [20].

[4] The `SingleKaon` generator is included as optional model in recent versions of GENIE ($\geq$ 2.9.0) [21].

CONCLUSIONS

Cross section measurements provide both fundamental understanding of neutrino-nucleus interactions and valuable inputs to neutrino oscillation experiments. For future oscillation experiments, cross section uncertainties are expected to be among the dominant systematic uncertainties. To improve the various flaws currently present in nuclear models, it will be crucial to provide precision measurements of neutrino cross sections at various energies for different targets, interaction processes and neutrino types. When sufficient statistics are available, differential cross sections should be presented as function of kinematic variables, such as pion momentum. This allows for a better understanding of nuclear effects such as FSI, which distort the outgoing particle composition and kinematics. As the amount of data taken increases, more exotic cross section studies become of interest: Kaon production from neutrino interactions is one of the main backgrounds for proton decay modes predicted by SUSY-GUT theories, which have a fundamental impact on our understanding of the universe.

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† Speaker (for the T2K collaboration); `martti.nirkko@lhep.unibe.ch`

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