

First Measurement of the Electron-Neutrino Charged-Current Pion Production Cross Section on Carbon with the T2K Near Detector

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The T2K Collaboration presents the first measurement of electron neutrino-induced charged-current pion production on a predominantly carbon target in a restricted kinematical phase space. This is performed using data from the 2.5° off-axis near detector, ND280. The differential cross sections with respect to the outgoing electron and pion kinematics, in addition to the total flux-integrated cross section, are obtained. Comparisons between the measured and predicted cross-section results using the Neut, Genie, and NuWro Monte Carlo event generators are presented. The measured total flux-integrated cross section is $[2.52 \pm 0.52(\text{stat}) \pm 0.30(\text{syst})] \times 10^{-39} \text{ cm}^2 \text{ nucleon}^{-1}$, which is lower than the event generator predictions.

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Introduction—Charged-current (CC) pion production from electron neutrinos scattering off nucleons ($\nu_e \text{CC}\pi^+$) is a subdominant interaction that contributes to the ν_e appearance signal in accelerator-based long-baseline

neutrino oscillation experiments such as T2K and NOvA [1,2]. This channel is sensitive to the parameters that favor $\nu_\mu \rightarrow \nu_e$ oscillations, including δ_{CP} and θ_{13} . The modeling of neutrino-nucleon interactions contributes $\sim 3\%$ to the

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total systematic uncertainty on the current best-fit oscillation parameters at T2K [3]. Improved constraints, particularly on ν_e cross sections, are necessary to determine oscillation parameters to better precision at T2K, as well as at next-generation experiments including Hyper-Kamiokande [4] and DUNE [5].

The $\nu_e \text{CC}\pi^+$ channel has been observed in several inclusive ν_e cross-section measurements [6–10], as well as in an exclusive measurement on argon [11]. Simulations with the Neut event generator [12] suggest single-pion production ($\text{CC}1\pi^+$) channels contribute $\sim 10\%$ to the ν_e appearance signal from the T2K flux given the current best-fit oscillation parameters [3]. Measuring pion production and ν_e cross sections at T2K presents unique challenges due to low statistics from the beam composition and numerous backgrounds, limiting the impact of these samples on constraining oscillation parameters. A recent measurement of $\nu_e \text{CC}1\pi^+$, which combined T2K data with Super-Kamiokande atmospheric data, revealed an event rate excess localized to low lepton momentum [13]. This Letter measured 225 events compared to a best-fit Monte Carlo (MC) prediction of 160 ± 19 under the near detector constraint. Similar excesses have also been reported using only T2K data, though with lower statistical significance [3,14]. This analysis directly leverages data from the T2K off-axis near detector, ND280, to constrain the $\nu_e \text{CC}\pi^+$ channel on carbon, improving our understanding of this crucial interaction.

The signal definition for this measurement is any CC interaction that produces an electron and at least one positively charged pion that escapes the nucleus. This is $\nu_e A \rightarrow e^- \pi^+ X$ where A is a target nucleus and X represents an arbitrary combination of hadrons, which, unlike the far detector samples, may include additional π^+ . Phase space constraints are chosen to ensure the e^- and π^+ can plausibly be detected and reliably reconstructed. The constraints are imposed on the e^- momentum (p_e) and angle with respect to the average neutrino direction (θ_e), as well as the pion momentum (p_π); these are $0.35 < p_e < 30 \text{ GeV}/c$, $\cos \theta_e > 0.7$, and $p_\pi < 1.5 \text{ GeV}/c$. Events outside of this region are retained for the fitting process but cross sections are not calculated here.

T2K experiment—Tōkai to Kamioka (T2K) is a long-baseline neutrino oscillation experiment in Japan [15]. The J-PARC facility houses both the neutrino beamline and the near detector complex, which is situated 280 m downstream from the neutrino beam line target. Super-Kamiokande (SK), a 50 kt water Cherenkov detector located 295 km to the west of J-PARC, serves as the far detector [16]. A neutrino beam with peak energy 0.6 GeV is produced by steering a beam of 30 GeV protons towards a graphite target [17]. This produces charged pions and kaons, which are then focused using magnetic horns towards a decay volume. Forward horn current (FHC) and reverse horn current (RHC) modes are used to select ν_μ

and $\bar{\nu}_\mu$ from decays of focused $\pi^\pm$ respectively. In FHC mode, the beam possesses an initial fractional composition of 92.6% ν_μ with 6.2% $\bar{\nu}_\mu$, 1.1% ν_e , and 0.1% $\bar{\nu}_e$ [18].

ND280 is a tracking detector used to measure the unoscillated neutrino beam at the same off-axis angle as SK (2.5°). The main target masses of ND280 are two fine-grained detectors (FGDs) [19]. These are comprised of modules made from polystyrene scintillator bars; each adjacent module has 192 bars oriented in alternating directions perpendicular to the neutrino beam. The upstream FGD (FGD1) has 15 modules and is predominantly carbon (86.1%) by mass, with smaller proportions of hydrogen (7.4%), oxygen (3.7%), titanium (1.7%), silicon (1.0%), and nitrogen (0.1%). Three time projection chambers (TPCs) adjacent to the FGDs are used to perform particle identification (PID) as well as for measuring the charge and momentum of traversing particles [20]. The TPCs and FGDs are surrounded by electromagnetic calorimeters (ECals) [21] which are used to detect neutral particles, perform track-shower separation and measure particle energy. The detector modules are enclosed by the 0.2 T UA1/NOMAD magnet, instrumented with the scintillator-based side muon range detector [22].

This analysis uses an exposure of 11.6×10^{20} protons on target (POT) collected by ND280 between 2010–2013 and 2016–2017 in the FHC mode. Neutrino interactions are primarily simulated using the Neut 5.4.0 [23] event generator. The Nuisance2 framework [24] is used to obtain additional predictions from the Genie 3.4.2 (“AR23” tune) [25] and NuWro 21.9.2 [26] generators. The beam line is simulated using FLUKA2011 [27,28], Geant4 [29], and GCALOR [30].

Event selection—Two signal-enriched samples with distinct pion detection methods are used to measure the $\nu_e \text{CC}\pi^+$ event rate. The $\text{TPC}-\pi^+$ sample selects events where the pion passes from FGD1 into the downstream TPC (TPC2). The $\text{FGD}-\pi^+$ sample selects FGD1-contained pions that decay to Michel electrons by $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$. The primary ν_e vertex is restricted to a fiducial volume (FV) within FGD1, excluding the five outermost scintillator bars in each layer where events tend to be misreconstructed, leaving a total target mass of 919.5 kg, or $(5.54 \pm 0.04) \times 10^{29}$ nucleons [8].

The event selection developed for an inclusive ν_e cross-section measurement [8] is used here, with the additional requirement that a pion is detected from the same vertex. In the $\text{TPC}-\pi^+$ sample, the leading positively charged track is subjected to PID cuts based on energy deposition (dE/dx) in the TPC gas mixture, identifying π^+ candidates; their momentum is estimated from track curvature in the B field. The $\text{FGD}-\pi^+$ sample tags Michel electrons from clusters of delayed hits that tend to indicate e^+ production from π^+ decays. Both signal samples use vetos to target events originating out-of-FV (OOFV) and events with upstream or high-angle tracker ECal activity to reduce background contamination.

FGD-contained pion tracks are typically short, making their curvature difficult to reconstruct accurately, so their momenta cannot be determined using the same method as TPC tracks. The momentum of a FGD-contained π^+ is instead inferred from the location of hits left by Michel electrons with respect to the ν_e interaction vertex as described in Ref. [31]. The relation between this distance d and the pion momentum is parametrized as $p_\pi = c_0 \times d^{c_1} + c_2$. The constants $c_{0,1,2}$ are determined from fitting the trend between p_π and d for MC. Recent ND280 cross-section measurements have been limited to a phase space of $p_\pi \gtrsim 200$ MeV/c where pions can be reliably reconstructed in the TPCs [32]; this technique removes this phase space limitation.

The largest background comes from π^0 s that originate from the hadronic recoil system in ν_μ CC and ν_μ NC (neutral-current) interactions in FGD1; in the CC case the muons are below the tracking threshold. The π^0 s decay into $\gamma\gamma$ pairs that convert to e^+e^- pairs, initiating electromagnetic showers. In cases where the two γ s convert promptly and produce spatially separated tracklike energy deposits above detection thresholds, they can be misidentified as a π^+ track and an electron shower emanating from a shared primary vertex. Around half of this background is removed by reconstructing the e^+e^- invariant mass from the two candidate particles. The e^+ track is taken as the π^+ candidate from the TPC- π^+ sample, or as the next highest momentum positively charged track which passes electron PID for the FGD- π^+ sample. Events with an invariant mass

clearly below the e^+e^- peak ($m_{\text{inv}} < 110$ MeV/ c^2) are removed. The γ background remains dominant at low p_e and high θ_e , necessitating the aforementioned phase space constraints. The largest non- γ background is from ν_e CC events where a low momentum proton ejected from a nucleus is misidentified as a π^+ ; the remaining phase space constraint of $p_\pi > 1.5$ GeV/c reflects this inability to reliably identify tracks in this region. The next largest background is ν_μ CC events where the μ^- is above the tracking threshold and is misidentified as a e^- . The remaining backgrounds are small ($< 5\%$) and are mostly those already discussed but with an OOFV primary vertex.

Events involving γ conversions consistent with the $\gamma \rightarrow e^+e^-$ hypothesis ($m_{\text{inv}} < 55$ MeV/ c^2) are assigned to a pair of γ control samples. These events must also pass one of the pion PID cuts used for the signal samples. The γ control samples also use sets of OOFV vetoes, ensuring the normalized invariant hadronic mass and momentum transfer distributions of the selected π^0 production modes generally match those of the targeted backgrounds.

The data and MC events selected by the merged signal and control samples are shown projected as distributions of electron kinematics and pion momentum in Fig. 1. A total of 115 events are selected by the signal samples in the targeted phase space, compared with 129 events predicted by Neut. The signal samples have a combined efficiency of $\sim 20\%$ that varies minimally across all in-phase space bins. The FGD- π^+ sample almost exclusively contributes to the lowest four p_π bins. The data and MC shape distributions

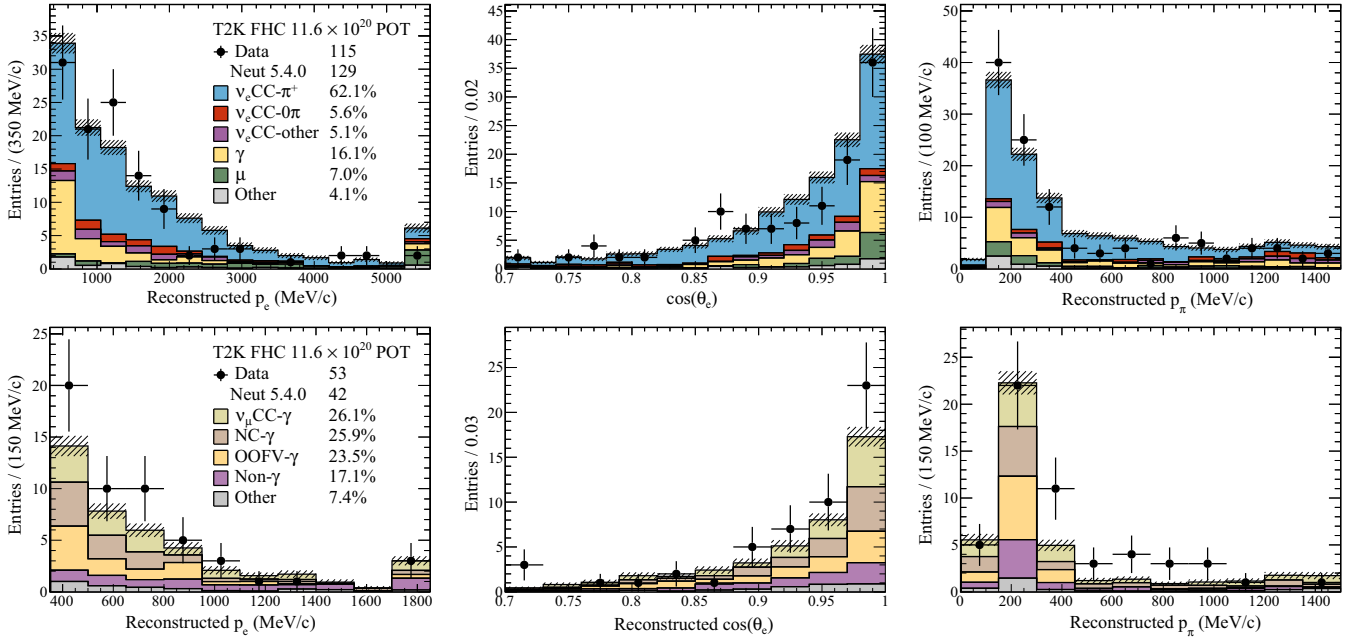


FIG. 1. Reconstructed electron and pion kinematics ($p_e, \cos \theta_e, p_\pi$) distributions for the signal samples (upper) and γ controls samples (lower) in the restricted phase space. These show the number of selected data and prefit Neut MC events with statistical uncertainties, distinguished by true event type.

generally match well in most bins for the signal samples; the γ control samples exhibit poorer agreement, but these are more statistically limited.

Fit and extraction—The unfolding method involves an unregularized binned template parameter likelihood fit used in several recent T2K cross-section analyses [33–35]. The binning scheme uses eight signal-region bins that enclose the target phase space. The intermediate bin edges are optimized to approximately distribute an equal amount of signal events between the bins along each kinematic observable. The fit uses template parameters that are proportional to the signal event rate in each true kinematic bin; nuisance parameters are assigned to scale combinations of MC events corresponding to different systematic uncertainties. The template and nuisance parameters are iteratively varied to minimize the data-MC difference, yielding a set of best-fit parameters. The four samples are fitted separately and the systematic uncertainties are supplied as covariance matrices that encode the initial uncertainties of and correlations between nuisance parameters. The template parameters have no initial uncertainty and are free to move without prior constraints. During the fitting process, the negative log-likelihood ratio $\chi^2 \simeq -2\log(\mathcal{L}_{\text{stat}}) - 2\log(\mathcal{L}_{\text{syst}})$ is minimized. The $\mathcal{L}_{\text{stat}}$ term is the likelihood ratio for the Poisson distribution with Barlow-Beeston modifications to account for finite MC statistics [36], and $\mathcal{L}_{\text{syst}}$ is the likelihood ratio for the set of parameter values at a specific fit point given their prior uncertainties divided by the maximum likelihood for those parameter values.

The differential cross-section values are calculated with respect to a kinematic variable x using $d\sigma/dx_i = \hat{N}_i/\epsilon_i\Phi N_T\Delta x_i$, where Δx is an interval in 3D of the kinematic space defined by the analysis bin edges, $\hat{N}$ is the background subtracted number of signal events, ϵ is the selection efficiency, and i denotes the bin index. This is normalized by the flux integral Φ (see data release [37]) and the number of nuclear targets N_T . The fitting process yields best-fit values and post-fit uncertainties for $\hat{N}_i$, ϵ_i , and Φ . The total cross section (σ) is calculated by summing the

TABLE I. The contributions of each source of uncertainty on the total flux-integrated cross section (σ).

Uncertainty source	Fractional error on σ [%]
Detector response	5.7
Flux model	6.8
Interaction and background modelling	7.8
Target mass	0.7
Total statistical	20.6
Total systematic	11.7

differential results multiplied by their bin widths. The uncertainties on the binned cross sections are evaluated by varying the fit parameters within their post-fit uncertainties and numerically propagating these changes to the cross-section results.

Sources of systematic uncertainty—The systematic uncertainties arise from the flux model, the detector response and the $\nu - A$ interaction model. The uncertainties on the ν_μ , $\bar{\nu}_\mu$, ν_e , and $\bar{\nu}_e$ flux modes are encoded in a covariance matrix that constrains the total shape and normalization uncertainties of the flux in the neutrino energy-flavor space [17]. The flux prediction is informed by replica target hadron production measurements by NA61/SHINE [38,39]. The uncertainties in the detector response are determined using separate dedicated control samples each corresponding to different aspects of event reconstruction in ND280. The difference in event rates between data and MC are then used to evaluate each source of uncertainty; these are also encapsulated by a single covariance matrix containing the reconstructed space bins of the four analysis samples. The dominant uncertainties in the detector response for the signal samples are from the TPC PID and matching between TPC-ECal tracks. For the γ control samples, the detector mass uncertainty effect on the photon mean free path is dominant. The $\nu - A$ interaction model uncertainties are theory-driven and correspond to parameters that model signal and background interactions as well as final-state interactions (FSI). A

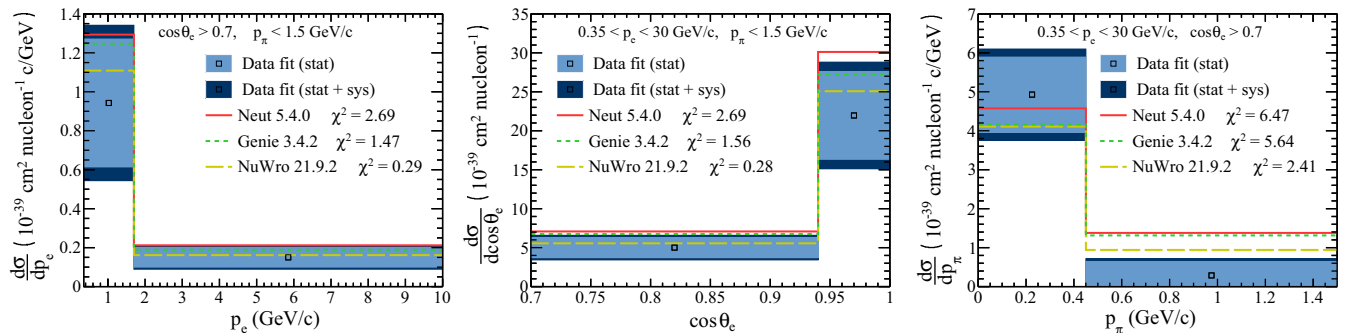


FIG. 2. The differential flux-integrated cross-section ($d\sigma$) results and predictions from Neut, Genie, and NuWro as a function of particle kinematics ($p_e, \cos\theta_e, p_\pi$). The upper p_e bin extends to 30 GeV/c and is normalized to account for the lower effective bin width.

description of each parameter and the prefit uncertainties assumed is available in Ref. [3]. For this analysis, the dominant interaction model uncertainties are those associated with FSI and normalizations to the multipion production channels. The fractional systematic and statistical uncertainties on the total cross section are shown in Table I.

Results—The total flux-integrated cross section is $[2.52 \pm 0.52(\text{stat}) \pm 0.30(\text{syst})] \times 10^{-39} \text{ cm}^2 \text{ nucleon}^{-1}$. The predicted total flux-integrated cross sections from event generators are listed alongside this in Table II. All of the neutrino event generators predict a larger cross section than this measurement, an effect which ranges from 0.5 - 1.6σ . The differential cross-section results are shown in Fig. 2; these results are also lower than the event generator predictions in the strongly forward going and high pion momentum regions of kinematic phase space. The cross-section result in the $0.45 < p_\pi < 1.5 \text{ GeV}/c$ region exhibits the largest discrepancy, with the Neut and Genie predictions overestimating this by 2.5σ and 2.4σ , respectively. The NuWro prediction is notably closer but still $> 1\sigma$ from the measured cross section. These results contrast with a $\nu_\mu \text{CC}1\pi^+$ measurement at T2K [18], where the data is overestimated by Neut and Genie below $0.2 \text{ GeV}/c$, while the region above this exhibits good agreement in most bins. From Fig. 1, this ND280 sample does not experience an event rate excess comparable to what is seen in the far detector analyses [13,14]. However, this analysis does not measure much of the phase space relevant to these samples ($p_e < 0.35 \text{ GeV}/c$). Below this limit it is too difficult to distinguish between signal events and the γ backgrounds; ascertaining whether any discrepancies in this region are a result of mismodeling the signal or background is not possible. The data release is hosted in Ref. [37].

Conclusions—The T2K collaboration has performed the first cross-section measurement of $\nu_e \text{CC}\pi^+$ on carbon in a restricted kinematic phase space. The total flux-integrated result is lower than predictions of the Neut, Genie, and NuWro MC event generators. The cross-section result for $0.45 < p_\pi < 1.5 \text{ GeV}/c$ exhibits a more substantial disagreement with Neut and Genie. This result represents an important first step in testing $\nu_e - A$ interaction models for the exclusive

π^+ production channel. Future studies should focus on enhancing $e^\pm\text{-}\gamma$ separation techniques to reduce the π^0 backgrounds in the low p_e region. The recent upgrades to ND280 may be capable of addressing this more effectively by making full use of its highly segmented FGD [40,41]. Larger datasets will also be necessary to reduce the statistical uncertainty and more precisely evaluate the performance of event generators in describing this interaction.

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TABLE II. The measured and predicted total flux-integrated cross sections (σ) per target nucleon (nucl) from Neut, Genie, and NuWro. The p value is calculated using the total χ^2 between the three-dimensionally binned data and Monte Carlo histograms for all eight in-phase space bins.

Generator	$\sigma(10^{-39} \text{ cm}^2 \text{ nucl}^{-1})$	p value
Neut 5.4.0	3.51	0.30
Genie 3.4.2	3.25	0.59
NuWro 21.9.2	2.84	0.89
Data	2.52 ± 0.60	...

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Data availability—The data that support the findings of this article are openly available [37].

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