First Measurement of the Muon Neutrino Charged Current Single Pion Production Cross Section on Water with the T2K Near Detector

(The T2K Collaboration)

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energies ∼ 4 GeV. The differential measurements are presented as a function of the muon and
pion kinematics, in the restricted phase-space defined by \( p_{\pi^+} > 200 \text{MeV/c}, \ p_\mu > 200 \text{MeV/c}, \) \( \cos(\theta_{\pi^+}) > 0.3 \) and \( \cos(\theta_\mu) > 0.3 \). The total flux integrated \( \nu_\mu \) charged current single positive pion production cross section on water in the restricted phase-space is measured to be \((\sigma)_{\phi} = 4.25 \pm 0.48 \) (stat) \( \pm 1.56 \) (syst) \( \times 10^{-40} \text{cm}^2/\text{nucleon} \). The total cross section is consistent with the NEUT prediction \( (5.03 \times 10^{-40} \text{cm}^2/\text{nucleon}) \) and 2\( \sigma \) lower than the GENIE prediction \( (7.68 \times 10^{-40} \text{cm}^2/\text{nucleon}) \). The differential cross sections are in good agreement with the NEUT generator. The GENIE simulation reproduces well the shapes of the distributions, but over-estimates the overall cross section normalization.

\[ \langle \phi \rangle = \frac{1}{2} \left( 1 + \frac{1}{3} \right) \left( 1 + \frac{1}{5} \right) \]

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PACS numbers: 14.60.Pq, 14.60.Lm, 25.30.Pt, 29.40.Ka, 29.40.Mc

I. INTRODUCTION

The T2K long baseline neutrino experiment \cite{1} has the primary goal to precisely measure neutrino oscillation parameters through measurements of \( \nu_e \) appearance and \( \nu_\mu \) disappearance from a \( \nu_\mu \) beam. As neutrinos are chargeless and colorless, neutrino oscillation experiments rely on the detection of charged particles coming from charged current (CC) and neutral current (NC) interactions to infer neutrino properties, e.g. CC quasi-elastic (QE) interactions allow the calculation of the neutrino energy from the lepton kinematics. The knowledge of \( \nu_\mu \) and \( \nu_e \) interaction cross sections is then fundamental to infer neutrino properties correctly. \( \nu_\mu \) CC resonant interactions are part of the signal and sometimes of the background of oscillation experiments, and a better understanding of this channel could be beneficial not only to T2K, but to the neutrino community in general, as there are discrepancies between models and experimental data.

Both the MiniBooNE \cite{2} and MINERvA \cite{3} collaborations provided measurements of the CC single positive pion production (CC1\( \pi^+ \)) cross sections in mineral oil and plastic scintillator, respectively. The CC1\( \pi^+ \) cross section is described by the particles leaving the nucleus, i.e. one muon, one positive pion and any number of nucleons. There are large discrepancies between the MiniBooNE and MINERvA experiments, and the historic ANL \cite{4} and BNL \cite{5} bubble chamber results, which could be due to nuclear effects that if not modelled correctly can modify the effective measured cross-section. The MiniBooNE and MINERvA results show also significant normalization and shape discrepancies between each other \cite{3}, and currently no theoretical model can explain all the pion production data available. Additional pion production data can help to constrain the pion production models and give valuable information on the nucleon-\( \Delta \) axial form factor \cite{6,7}.

We present the first CC1\( \pi^+ \) differential cross section measurements on water. A CC1\( \pi^+ \) measurement on water will have a strong impact on the T2K oscillation analysis, as current results suffer from large cross section systematic uncertainties related to the differences in targets between near and far detectors (carbon versus water) \cite{8}. These data will also be beneficial to future atmospheric and long-baseline experiments, that plan to use a water target, such as the Hyper-Kamiokande experiment \cite{9}.

II. T2K EXPERIMENT

The T2K long baseline neutrino experiment uses the J-PARC facility in Tokai, Japan, to produce 30 GeV protons, which produce charged pions by colliding with a graphite target and consequently result in a high purity \( \nu_\mu \) beam. The beam center axis is directed 2.5° off-axis towards Super-Kamiokande \cite{10} at 295 km from J-PARC. Two near detectors are located at 280 m from the target, the on-axis near detector (INGRID \cite{11}) and the off-axis near detector (ND280).

**Neutrino Beam Flux**—The predicted neutrino beam flux \cite{12} peaks at 0.6 GeV and its fractional composition is 92.6% \( \nu_\mu \), 6.2% \( \bar{\nu}_\mu \), 1.1% \( \nu_e \), 0.1% \( \bar{\nu}_e \). The proton interactions with the graphite target are simulated with the FLUKA2008 package \cite{13}. The propagation of secondary and tertiary pions and kaons and their decays to neutrinos is simulated with GEANT3 \cite{14}. The hadron interactions are modeled with GCALOR \cite{15} and tuned to hadron production data from external experiments, such as the CERN NA61/SHINE experiment \cite{16,17}.

**Neutrino Interaction Model**—Based on the prediction of the neutrino flux, the NEUT \cite{18} (version 5.1.4.2) event generator is used to simulate neutrino interactions in ND280.

For Charged Current Quasi Elastic (CCQE) and Neutral Current Quasi Elastic (NCQE) interactions, NEUT uses the Llewellyn Smith model \cite{18} integrated with the relativistic Fermi gas (RFG) model by Smith and Moniz to describe the nucleons within the nucleus \cite{20}. The outgoing nucleon is also required to have larger momentum than the Fermi surface momentum (Pauli blocking), which is 217 MeV/c for carbon and 225 MeV/c oxygen.

NEUT uses the Rein-Sehgal model for resonant interactions \cite{21}, considering 18 resonances with masses below 2 GeV/c \cite{2} and their interference terms. In addition 20%
of the \( \Delta \) resonances undergo pion-less \( \Delta \) decay, in which the \( \Delta \) is absorbed by the nuclear medium without emitting any pions: \( \Delta + N \rightarrow N' + N'' \). The NEUT pion production model is tuned using neutrino interaction data from the MiniBooNE experiments \cite{21,22} as explained in Ref \cite{8}. In particular, the axial mass for resonant CC1\( \pi^+ \) interactions is set to 1.41 GeV, and the overall CC1\( \pi^+ \) normalization for energies less than 2.5 GeV is further increased by 15\% compared to predictions when the axial mass is set to 1.41 GeV.

Coherent pion production is simulated for both NC and CC interactions using the Rein-Sehgal model \cite{23}, including the PCAC (Partially Conserved Axial vector Current) lepton mass correction for CC interactions \cite{24}.

DIS (deep inelastic scattering) processes are simulated using GRV98 parton distribution functions \cite{25} and corrections following the Bodek and Yang model \cite{26} to improve the agreement with experiments in the low-\( Q^2 \) region. To avoid double counting with the single pion resonant production, only multiple pion production processes are considered for the invariant mass of the recoiling hadron system \( W < 2 \text{GeV}/c^2 \). PYTHIA/JETSET \cite{27} is used for hadronisation at energies above 2 GeV, and an internal NEUT method is used at lower energies.

After the simulation of the initial neutrino-nucleon interaction, final state interactions are simulated with the cascade model \cite{28}. Each particle is propagated inside the nucleus with steps determined by the mean free path. The mean free path depends on the position inside the nucleus and the momentum of the particle. At each step, an interaction is generated according to the probability calculated from each cross section such as charge exchange, absorption or scattering. If an interaction occurs, the resulting particles are used for stepping through the rest of the nucleus. This process continues until all particles are either absorbed in the nucleus or escape it. Data from several pion scattering experiments are used to tune this model \cite{8}.

Additional information on the models used to simulate the neutrino interactions and the hadron transport in the nuclear medium can be found in references \cite{8,18}.

The results in this paper are also compared to the GENIE generator \cite{29}, as it provides a general framework valid over a large range of experiments, targets and neutrino energy. GENIE uses essentially the same models as NEUT for the neutrino interactions simulation, but they differ in the implementation and value of some of the parameters, such as \( M_A^{\text{RES}} \) which is set to 1.12 GeV. Single pion production (before final state interactions) comes from resonant and coherent processes in NEUT, whereas GENIE also considers DIS contributions to it. Although GENIE considers a lower value of \( M_A^{\text{RES}} \), the predicted single positive pion production cross-section is larger than in NEUT, because DIS processes are allowed to contribute to this state.

Near detector—ND280 is a complex of different subdetectors enclosed in the refurbished UA1/NOMAD magnet. The origin of the ND280 coordinate system is at the center of the magnet and the 0.2 T magnetic field is along the \( +z \) direction. The \( z \) axis is along the nominal neutrino beam axis, and \( x \) and \( y \) axes are horizontal and vertical, respectively.

The ND280 Tracker region contains two fine-grained detectors (FGDs \cite{30}) which are used as the neutrino interaction target, sandwiched between three gaseous time projection chambers (TPCs \cite{31}) which are used to track charged particles. The most upstream FGD (FGD1) primarily consists of polystyrene scintillator bars with layers oriented alternately in the \( x \) and \( y \) directions allowing 3D tracking of charged particles. The downstream FGD (FGD2) has a similar structure, but the polystyrene bars are interleaved with water layers, creating a modular structure of water layer + \( x \) layer + \( y \) layer + water layer, and so on (see Figure 1). The areal density of an \( xy \) module and a water module are respectively 2146.3 ± 14.4 mg/cm\(^2\) and 2792.6 ± 13.4 mg/cm\(^2\). This structure allows the measurement of neutrino interactions on water.

The electromagnetic calorimeters (ECals \cite{32}), made of layers of lead and scintillator bars, surround the Tracker region (Barrel-ECals) with one module downstream of it (Ds-ECal). Upstream of the Tracker there is a \( \pi^0 \) detector (P0D \cite{33}), consisting of scintillator, water and brass layers.

Magnet return yokes surround the entire detector to make the magnetic field uniform and contain it inside the detector. Plastic scintillators in the yoke form the side muon range detectors (SMRDS \cite{34}).

The analysis here presented uses FGD2 as the active interaction target, where in a signal event the neutrino interacts with a nucleus in the water layer, and the charged lepton coming from a CC interaction is tracked in the downstream scintillator layers. These results are based on data taken from November 2010 to May 2013. The good quality data collected during this period corresponds to \( 5.6 \times 10^{20} \) protons on target (p.o.t.).

III. SELECTION OF \( \nu_\mu \text{ CC1}\pi^+ \) INTERACTIONS IN WATER

Muon neutrino interactions are selected by using the highest momentum negative track starting in the fiducial volume (FV) of the FGD2. The FGD2 FV begins 58 mm inward from the lateral edges of the FGD2 and 7.5 mm inward from the upstream FGD2 edge (as shown in Figure 1). These tracks are required to enter the TPC3 (located immediately downstream of FGD2) and deposit energy compatible with a muon-like track. Additional tracks matched between the FDG and TPC associated with the same muon candidate vertex are tagged as either protons or positive, negative or neutral pions by looking at the trajectory and energy deposit in the TPCs, and at electromagnetic showers in the ECals. More details on the \( \nu_\mu \) CC inclusive and multi-pion selections can be found in References \cite{8,35}, respectively, where the only
The signal sample is selected with a purity of 39.9%.

Systematic uncertainties—The TPC and FGD detector systematic uncertainties are the same as the ones described in References [8, 35]. The ECal particle identification systematic uncertainties are evaluated with high

\[ E_{\nu}^{\text{rec}} = \frac{m_{\mu}^2 + m_{\pi}^2 - 2m_N E_f + 2(p_\mu \cdot p_\pi)}{(2E_f - P_\mu \cos(\theta_\mu) - P_\pi \cos(\theta_\pi) - m_N)} \]  

where \( m_{\mu}, m_{\pi}, \) and \( m_N \) are the masses of the muon, the pion and the nucleon respectively; \( E_f = E_\mu + E_\pi, p_\mu, p_\pi \) and \( \theta_\mu \) are the 4-momentum, 3-momentum and angle with the neutrino direction of the particle considered \((x = \mu, \pi)\). Distributions of the pion momentum in the external samples are found in Figure 3.
Ds-ECal. These efficiencies are used to correct the simulated and non-isolated ECal objects, due to the difficulty is evaluated with a control sample of both isolated-ECal and non-isolated-ECal objects. The FGD layer migration uncertainties have been evaluated with a control sample of both isolated-ECal and non-isolated-ECal objects. The last bin in the $p_\pi$, $p_\mu$, and $E_{\nu}^{rec}$ distributions contains the over-flow events.

The isolated ECAL reconstruction systematic uncertainties are evaluated with a control sample of both isolated-ECal and non-isolated-ECal objects. The efficiency is found to be $0.303 \pm 0.003$ in simulation and $0.315 \pm 0.009$ in data for the Barrel-ECal, and $0.826 \pm 0.002$ in simulation and $0.839 \pm 0.007$ for the Ds-ECal. These efficiencies are used to correct the simulation efficiency for tagging isolated-ECal objects only, which is $0.352$ for the Barrel-ECal and $0.163$ for the Ds-ECal.

The FGD water modules mass uncertainty is $0.55\%$. The FGD layer migration uncertainties have been evaluated in detail for this analysis. These migrations are divided into forward (i.e. when the reconstructed vertex is a layer downstream of the true vertex) and backward migrations (i.e. when the reconstructed vertex is a layer upstream of the true vertex). The forward migrations
Bayesian unfolding technique by d’Agostini has been successfully used by past T2K cross section measurements to extract the cross sections (see References [35, 38]). The first estimate of the true distribution is found by applying the unsmearing matrix $P(t_j|r_i)$ (found with Bayes’ theorem) to the data distribution:

$$\hat{N}_{t_j} = \frac{1}{\epsilon_j} \sum_{i} P(t_j|r_i)(N_{r_i} - \sum_k \alpha_k B_{r_i,k}),$$

where $t_j$ ($r_i$) indicates the true (reconstructed) bin for each observable, $N_{r_i}$ is the number of reconstructed events in bin $r_i$, $B_{r_i,k}$ is the number of predicted events in bin $r_i$ of background type $k$, $\alpha_k$ is a normalization constant derived from the external samples, and $\epsilon_j$ is the true efficiency in bin $t_j$.

Eq. 2 uses a background subtraction where the coefficients $\alpha_k$ are 1 if that part of the background is not constrained by any external sample, or otherwise calculated as:

$$\alpha_k = \frac{C_{\text{data},k}}{C_{\text{MC},k}},$$

where $C_{\text{data},k}$ is the total number of events in external sample $k$ in data and $C_{\text{MC},k}$ is the total number of events in external sample $k$ in MC. In this analysis the background is divided into 2 groups: the CC1$\pi^+$ interactions in scintillator or in the scintillator-like component of the water modules, that are constrained with the CC1$\pi^+$ scintillator sample; the non CC1$\pi^+$ background which is constrained with the CC1$\pi^+\pi$ water-enhanced sample.

The FGD2 water modules are composed of oxygen (73.83%), carbon (15.05%), hydrogen (10.48%), silicon (0.39%), and magnesium (0.25%). The carbon, silicon and magnesium come from the polycarbonate structure that enclose the liquid water. They compose the scintillator-like component of the water-modules and can be subtracted out with the $x$-layer as they have similar composition.

The effect of the systematic uncertainties on the cross section measurements is evaluated by using pseudo-experiments for each error source to calculate the covariance matrix:

$$V_{ij} = \frac{1}{N} \sum_{s,n=1}^{N} (\sigma_i^{s,n} - \sigma_{i,\text{nom}})(\sigma_j^{s,n} - \sigma_{j,\text{nom}}),$$

where $\sigma_i^{s,n}$ is the differential cross section in bin $i$ evaluated with throw $n$ of the uncertainty $s$, and $\sigma_{i,\text{nom}}$ is the nominal differential cross section in bin $i$. Statistical and systematic uncertainties are evaluated by varying the contents of each bin according to Poisson and Gaussian statistics, respectively.
FIG. 4. Unfolded $\nu_\mu$ CC1$\pi^+$ differential cross sections as a function of pion kinematics (top), muon kinematics (center), $\cos(\theta_{\mu,\pi^+})$ (bottom left) and $E_{\nu}^{\text{rec}}$ (bottom right) in the reduced phase-space of $p_{\mu^+} > 200$ MeV/$c$, $p_{\pi^+} > 200$ MeV/$c$, $\cos(\theta_{\pi^+}) > 0.3$ and $\cos(\theta_{\mu}) > 0.3$. For the $E_{\nu}^{\text{rec}}$, the $\sigma(E)$ is presented as a model dependent result. The inner (outer) error bars show the statistical (total) uncertainty on the data. The dashed (solid) line shows the NEUT, version 5.1.4.2, (GENIE, version 2.6.4) prediction.

V. CROSS-SECTION RESULTS

For a given variable $X$, the flux integrated differential cross section for bin $t_k$ is defined as:

$$\left\langle \frac{\partial \sigma}{\partial X} \right\rangle_{t_k} = \frac{N_{\text{unfolded}}}{T \Phi \Delta X_{t_k}},$$

where $N_{t_k}^{\text{unfolded}}$ is the estimated number of events in bin $t_k$ (as given by Eq. [2]), $T$ is the number of target nucleons, $\Phi$ is the $\nu_\mu$ flux per unit area and integrated over neutrino energy (as detailed in Reference [12]), and $\Delta X_{t_k}$ is the width of bin $t_k$. Even though single pion resonant production has a threshold at 480 MeV, no cut is applied to the $\nu_\mu$ flux, as the CC1$\pi^+$ signal definition includes processes with different thresholds as well.

The number of target nucleons is computed considering only the oxygen and hydrogen in the FGD2 water modules, as the carbon, silicium and magnesium components are removed by the Bayesian unfolding with background.
subtraction. The total number of target nucleons is found to be:

\[ \mathcal{T} = N_A \cdot V_{FV} \cdot \rho \sum_{a=\text{O,H}} f_a \frac{A_a}{M_a} = 2.55 \cdot 10^{29}, \]

where \( N_A = 6.022 \cdot 10^{23} \text{mol}^{-1} \) is the Avogadro number, \( V_{FV} \) is the volume of the modules considered inside the FV, \( \rho = \rho_{\text{area}}/\Delta z \) is the total density of the water modules of the FGD2 (\( \rho_{\text{area}} = 2798.7 \pm 5.4 \text{mg/cm}^2 \)) is the total areal density and \( \Delta z = 2.79 \text{cm} \) is the width of each water module; \( a \) runs over the elements present in the water modules; \( f_a \) is the mass fraction; \( A_a \) represents the averaged number of nucleons per nucleus; and \( M_a \) is the atomic mass.

Figure 4 shows the differential cross section as a function of pion kinematics (top), muon kinematics (center), \( \cos(\theta_{p(\mu,\pi)}^+) \) (bottom left), and \( E_{\nu}^{\text{CC}} \) (bottom right). For the \( E_{\nu}^{\text{CC}} \) the \( \sigma(E) \) is presented as a model dependent result, as the \( E_{\nu}^{\text{CC}} \) is unfolded to the true neutrino energy as predicted by NEUT. The NEUT and GENIE (version 2.6.4) predictions are also shown in the plots. The differential cross sections obtained are compatible with the NEUT prediction, but a small suppression is seen at \( 0.5 < p_{\pi^+} < 0.7 \text{GeV} \) and \( \cos(\theta_{\pi^+}) > 0.95 \). This might be linked to the model for CC coherent interactions used in NEUT: NEUT greatly over-estimates the amount of coherent interactions especially at low \( E_{\pi^+} \) [39]. The GENIE simulation reproduces well the shapes of the distributions, but over-estimates the overall cross section normalization.

The total flux integrated cross section is computed as:

\[ \langle \sigma \rangle_{\Phi} = \frac{N_{\text{total}}}{T \cdot \Phi}. \]

The total flux integrated \( \nu_\mu \) CC single positive pion production cross section on water in the restricted phase-space is measured to be \( \langle \sigma \rangle_{\Phi} = 4.25 \pm 0.48 \text{ (stat) } \pm 1.56 \text{ (syst) } \times 10^{-40} \text{ cm}^2/\text{nucleon} \). This result is compatible with the NEUT prediction of \( 5.08 \times 10^{-40} \text{ cm}^2/\text{nucleon} \), and about \( 2\sigma \) away from the GENIE prediction \( 7.68 \times 10^{-40} \text{ cm}^2/\text{nucleon} \). The dominant systematic uncertainties on this result are those related to the cross section model (23.9%) and flux parameters (25.5%). The flux uncertainties are larger than the initial uncertainty size because of the background subtraction procedure. Final state interactions and detector systematic uncertainties contribute with 5.3% and 10.8%, respectively. The data and MC statistical errors are estimated as 10.7% and 3.3%, respectively. Figure 5 shows the total \( \nu_\mu \) CC1π+ cross section on water in the reduced phase-space of \( p_{\pi^+} > 200 \text{MeV}/c, p_\mu > 200 \text{MeV}/c, \cos(\theta_{\pi^+}) > 0.3 \) and \( \cos(\theta_\mu) > 0.3 \), with the T2K \( \nu_\mu \) flux and the NEUT and GENIE predictions.

The data related to this measurement can be found together with the cross section results obtained when unfolding the muon kinematics and neutrino energy distributions in Reference [40].

**Conclusion**—The T2K off-axis near detector ND280 is used to extract the first \( \nu_\mu \) CC1π+ differential cross sections on water as a function of the pion kinematics and muon-pion angle. These results will be beneficial to the T2K experiment and the neutrino community in general, as a better understanding of neutrino induced pion production on water at energy below 2 GeV would result in a higher sensitivity to the measurement of oscillation parameters. The cross section is evaluated in the restricted phase-space defined by \( p_\mu > 200 \text{MeV}/c, p_{\pi^+} > 200 \text{MeV}/c, \cos(\theta_\mu) > 0.3 \) and \( \cos(\theta_{\pi^+}) > 0.3 \). The results are in good agreement with the NEUT generator and a general suppression is seen compared to the GENIE generator. The total \( \nu_\mu \) CC1π+ cross section on water is found to be \( \langle \sigma \rangle_{\Phi} = 4.25 \pm 0.48 \text{ (stat) } \pm 1.56 \text{ (syst) } \times 10^{-40} \text{ cm}^2/\text{nucleon} \), which is in good agreement with the NEUT prediction and is \( 2\sigma \) lower than the GENIE prediction.

**Acknowledgements**—We thank the J-PARC staff for superb accelerator performance and the CERN NA61 Collaboration for providing valuable particle production data. We acknowledge the support of MEXT, Japan; NSERC (Grant No. SAPPJ-2014-00031), NRC and CFI, Canada; CEA and CNRS/IN2P3, France; DFG, Germany; INFN, Italy; National Science Centre (NCN), Poland; RSF, RFBR and MES, Russia; MINECO and ERDF funds, Spain; SNSF and SERI, Switzerland; STFC, UK; and DOE, USA. We also thank CERN for the UA1/NOMAD magnet, DESY for the HERA-B magnet mover system, NI for SINET4, the WestGrid and SciNet consortia in Compute Canada, and GridPP in the United Kingdom. In addition, participation of individual
researchers and institutions has been further supported by funds from ERC (FP7), H2020 Grant No. RISE-GA644294-JENNIFER, EU; JSPS, Japan; Royal Society, UK; and the DOE Early Career program, USA.