

# First Measurement of the Charged Current $\bar{\nu}_\mu$ Double Differential Cross Section on a Water Target without Pions in the final state

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This paper reports the first differential measurement of the charged-current  $\bar{\nu}_\mu$  interaction cross section on water with no pions in the final state. The unfolded flux-averaged measurement using the T2K off-axis near detector is given in double differential bins of  $\mu^+$  momentum and angle. The

integrated cross section in a restricted phase space is  $\sigma = (1.11 \pm 0.18) \times 10^{-38}$  cm<sup>2</sup> per water molecule. Comparisons with several nuclear models are also presented.

## I. INTRODUCTION

Long baseline neutrino experiments [1, 2] are now measuring both neutrino ( $\nu_\mu \rightarrow \nu_e$ ) and antineutrino ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) appearance oscillations to determine fundamental neutrino mixing parameters and to search for charge-parity (CP) violation in the lepton sector. Testing this symmetry may answer one of the most fundamental physics questions, the mystery of the matter-antimatter imbalance in our Universe.

Neutrino oscillation measurements are performed by measuring neutrino interactions on nuclei. The present uncertainties on models describing the (anti)neutrino-nucleus scattering are the main source of systematic error in currently operating experiments, such as T2K [3] and NOvA [4], and will affect future projects, DUNE [5] and HyperKamiokande [6]. The main difficulty in the description of (anti)neutrino-nucleus interactions derives from the intrinsic nature of the nucleus, where nucleons are bound together and nuclear effects must be taken into account. Many models are currently available, describing different pieces of this complex scenario such as relativistic Fermi gas [7], Spectral Function [8, 9], the random phase approximation [10–13], and the multinucleon [14–24] models. Thus a key component required by present and future [5, 25] experiments are the precise measurements and tests of theoretical models of both neutrino and antineutrino cross sections on detector target materials such as scintillator, water, and liquid Argon. In charged current interactions without pions in the final state, detailed measurements of the outgoing muon will help to test different theoretical models. In this paper, using the off-axis near detector of the T2K experiment, we present the first double differential antineutrino cross section measurement on water and compare it to various model predictions.

Measurements by T2K probe the completeness of the interaction model by comparing neutrinos and antineutrinos [26], by using different target materials [27], [28], and different energy spectra [29–31], and through leptonic-hadronic state correlations[32]. The published T2K measurements used unfolding techniques such as

the D’Agostini iterative unfolding [28] or the maximum binned likelihood [27, 32].

The analysis in this paper determines the kinematics of the outgoing  $\mu^+$  produced in  $\bar{\nu}_\mu$  CC0 $\pi$  interactions on water. The differential cross sections are extracted by following a similar analysis procedure performed in a previous T2K publication [32].

In the following sections, we describe the T2K anti-neutrino beam and near detector (ND280), the Monte Carlo simulation and data samples, the event selection, the cross section extraction method, the results and model comparisons.

## II. T2K EXPERIMENT

The Tokai to Kamioka (T2K) experiment [3] is a long baseline neutrino experiment located in Japan. It is composed of a neutrino beamline and a near detector at the Japan Proton Accelerator Research Complex (J-PARC) laboratory in Tokai, and a far detector, Super Kamiokande (SK), that is situated 295 km away in the Mozumi Mine in the Kamioka area of Hida City. The J-PARC synchrotron produces a 30 GeV energy proton beam that strikes a graphite target to produce pions and kaons that are focused by three horn magnets into a 96 m long decay volume. The horn magnet polarity can be set to select either positively or negatively charged pions and kaons to produce a predominately neutrino or antineutrino beam. The magnet setting for positively charged tracks is denoted as Forward Horn Current (FHC) and for negatively charged tracks, Reverse Horn Current (RHC). The near detector complex, 280 m downstream of the target, consists of an on-axis detector (INGRID) and an off-axis detector (ND280). The ND280 and SK detectors are positioned 2.5° away from the neutrino beam axis. At this angle, neutrino and antineutrino beams energies peak near 0.6 GeV. The following subsections describe the  $\bar{\nu}_\mu$  beam, the ND280 detector, and the Monte Carlo simulation programs.

### A. T2K BEAM

The neutrino and antineutrino fluxes for the RHC configuration in the ND280 detector were determined by simulating the T2K neutrino beamline [33] using FLUKA2011 [34, 35], GEANT3 [36], and GCALOR [37] software packages. The simulated hadronic yields have been reweighted using the NA61/SHINE [38–40] thin-target measurements and this reduced the flux uncertainties to be less than 10% around the flux peak. The  $\bar{\nu}_\mu$  fluxes are plotted in Fig. 1 along with the three background neutrino flavors,  $\nu_\mu$ ,  $\nu_e$ , and  $\bar{\nu}_e$ . In the peak

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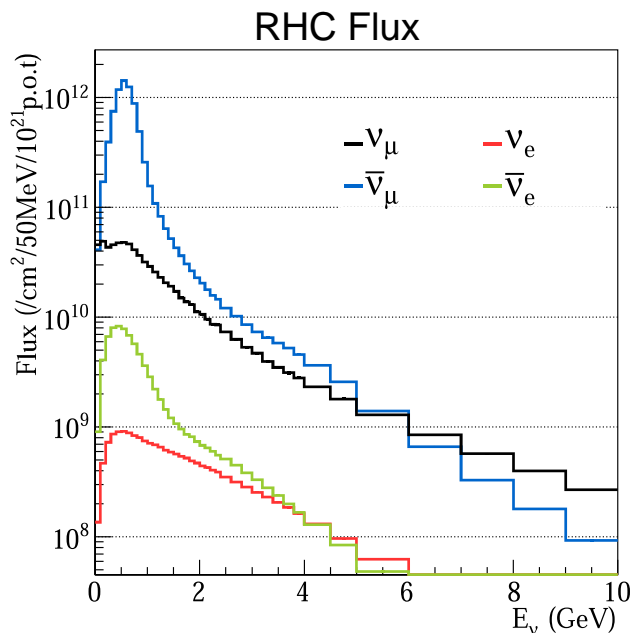


FIG. 1. The RHC flux given per cm<sup>2</sup>/50 MeV/10<sup>21</sup> Protons on Target (PoT) as a function of energy at the ND280 detector for the different neutrino components ( $\bar{\nu}_\mu$ ,  $\nu_\mu$ ,  $\bar{\nu}_e$ ,  $\nu_e$ ).

region ( $\sim 0.6$  GeV) the  $\nu_\mu$  contamination in the antineutrino flux is  $\sim 2.5\%$ . Details on the antineutrino beam and comparisons to the neutrino beam have been discussed in a previous T2K publication [41].

## B. ND280 DETECTOR.

The ND280 detector consists of sub-detectors inside the refurbished UA1/NOMAD magnet that operates at a 0.2 T magnetic field, that is normal to the neutrino beam and the vertical direction. The ND280 sub-detectors include the  $\pi^0$  detector [42] (P0D), three tracking time projection chambers [43] (TPC1-3), two fine-grained detectors (FGD1-2) interleaved with TPC1-3, and an electromagnetic calorimeter (ECAL), that encloses the P0D, TPC1-3, and FGD1-2 sub-detectors. For the analysis reported in this paper, the P0D and the TPC tracking detector in the ND280 detector complex are used. We define the +Z direction parallel to the neutrino beam direction, and +Y direction pointing vertically upwards.

We describe detector details relevant for the analysis. The P0D detector that reconstructs the neutrino interaction vertex is shown in Fig. 2. It contains 40 scintillator module planes (called P0Dules), each built of two perpendicular arrays of triangular scintillator bars, 134 horizontal (X) and 126 vertical (Y) bars. Each bar has a wavelength shifting fiber centered in the bar that is read out by a Hamamatsu Multi-pixel photon counter. P0Dules are formed into 3 major groups. The center

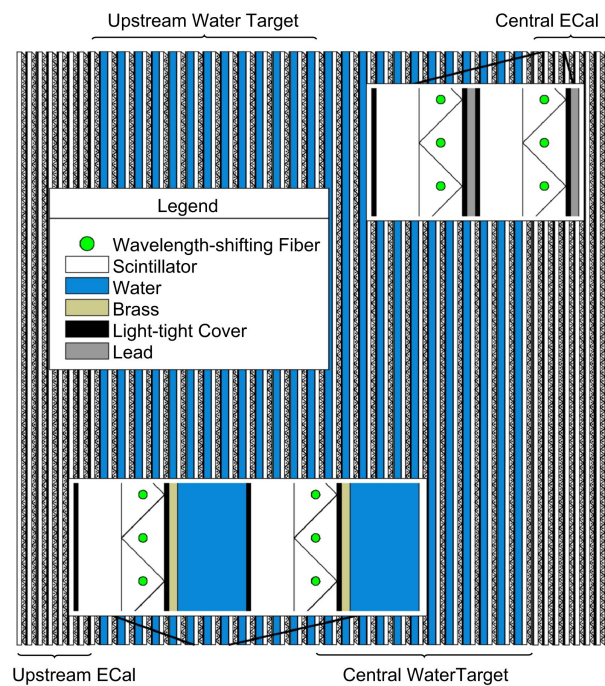


FIG. 2. Side view schematic diagram of the P0D detector. The white, zig-zag, and blue strip regions represent the vertical scintillator bars, the horizontal scintillator bars, and the water bag regions, respectively. The vertical and horizontal bars represent an x-y module or P0Dule. The first and last groups of seven P0Dules form the upstream and the central ECAL “super” modules and the middle 26 P0Dules interleaved with the water bags are the water target region. In this drawing, the beam direction (+Z) is to the right, the +Y direction is up, and +X direction is into the drawing.

group, called the water target, is the primary target for this analysis. It has 26 P0Dules interleaved with 2.8 cm thick water bags and 1.3 mm thick brass sheets. The water target region is drainable and data can be taken with or without water. The fiducial volume mass is 1900 kg of water and 3570 kg of other materials. The two other regions (called upstream and central ECALs) are the upstream and downstream groups that each contain 7 P0Dules sandwiched with lead sheets clad with steel. These two groups form a veto region to isolate neutrino interactions that occur in the water target. The size of the entire active P0D volume is  $2103 \times 2239 \times 2400$  mm<sup>3</sup> (XYZ) and its mass with and without water is 15,800 kg and 12,900 kg respectively. The two other regions (called upstream and central ECALs) are the upstream and downstream groups that each contain 7 P0Dules and steel sheets clad with lead. These two groups form a veto region to isolate neutrino interactions that occur in the water target.

The charged current neutrino interaction in the P0D, creates a muon that exits the P0D and enters the TPC1-3 detectors. The TPC1-3 detectors measure the  $\mu^+$  momentum and its dE/dx energy loss which is used for muon particle identification.

P $\emptyset$ D Target Mode	Data sample	MC sample
water-in	$2.87 \times 10^{20}$	$20.8 \times 10^{20}$
water-out	$3.43 \times 10^{20}$	$20.9 \times 10^{20}$

TABLE I. Protons on Target (PoT) for data and equivalent MC samples for RHC antineutrino beam running split for P $\emptyset$ D water-in/water-out modes.

### III. DATA AND MONTE CARLO SAMPLES

The studies reported here used the RHC  $\bar{\nu}_\mu$  beam running mode. The runs utilized detector configurations where the P $\emptyset$ D water bags were filled (water-in) or empty (water-out). Roughly equal amounts of exposure in each configuration was allowed in each running period so that the detector operations, efficiencies, and beam conditions were similar for both the water-in and water-out data samples.

#### A. Data Samples

The total Proton on Target (PoT) exposure for RHC antineutrino beam data running is shown in Table I. This sample required all data quality cuts to be satisfied and corresponded to  $2.87 \times 10^{20}$  PoT for the water-in and  $3.43 \times 10^{20}$  PoT for the water-out modes.

#### B. Monte Carlo Simulation

The analysis utilized simulated Monte Carlo (MC) samples with different beam and detector configurations for each data run. The total MC combined water-in and out samples were equivalent to  $20.8 \times 10^{20}$  and  $20.9 \times 10^{20}$  PoT, respectively. The simulation includes:

1. Primary  $\bar{\nu}_\mu$  and background  $\nu_\mu$ ,  $\nu_e$ , and  $\bar{\nu}_e$  beam production in the graphite target and propagation through the following horns and decay volume. The hadronic rates from the beam target were generated by FLUKA2011 which was tuned to the NA61/SHINE measurements and the GEANT3 simulation software predicted the flux and energy spectrum for the different neutrino flavors.
2. The antineutrino and neutrino interactions in the ND280 detector, where the NEUT [44] MC generator (version 5.3.3) is used to calculate the interaction cross sections and the final state particle kinematics.
3. The detector response, which used the GEANT4 [45] simulation package to transport the final state particles through the ND280 detector complex.

### IV. EVENT AND KINEMATIC SELECTION

The event selection for antineutrino interactions is optimized to identify the observable charged current events with no charged or neutral pions in the final state. This is nominally denoted as the CC-0 $\pi$  final state. This mainly includes charged current quasi-elastic (CCQE) events and the case where pions are created in the primary resonant antineutrino interaction, but reabsorbed before exiting the nucleus. The  $\bar{\nu}_\mu$  interactions with a multi-nucleon state such as 2 particle-2 hole (2p2h) can produce a final state without mesons. Non-CCQE neutrino interactions that produce a CC-0 $\pi$  final state will have antineutrino kinematics that are different from those created in CCQE interactions. This will be important to understand and to carefully model since this can change the antineutrino energy reconstruction which can affect current and future neutrino oscillation analyses.

We first consider three antineutrino mode selections (CC-inc, CC-0 $\pi$ , and CC-1 $\pi$ ). The event selection is similar to a previous T2K analysis [28] of a neutrino differential cross section measurement on water in the P $\emptyset$ D detector. The selection requires:

1. Overall ND280 data quality flags are good such that the detector was operational and stable during taking data.
2. There is a reconstructed track in the P $\emptyset$ D matching a track in the TPC with the start of the track reconstructed in the fiducial volume of the P $\emptyset$ D water target.
3. There is at least one track reconstructed in TPC1
4. There is a muon track candidate that is the highest momentum positively charged track, the highest momentum track in the event, and has a TPC dE/dx track measurement consistent with a muon energy loss. These first four requirements define the CC-Inc event selection.
5. There are no reconstructed P $\emptyset$ D showers in the event. This cut removes charged current events with a  $\pi^0$ .
6. Remaining events are then separated into 3 categories based on the number of  $\mu$ -like P $\emptyset$ D tracks in the event.
  - (a) Events with only a muon track candidate define the CC-0 $\pi$  selection.
  - (b) Events with a muon track candidate and one  $\mu$ -like track define the CC-1 $\pi$  selection.
  - (c) All other remaining events are not selected.

If there are other tracks, besides the muon track candidate, they are defined as  $\mu$ -like if the average energy loss per P $\emptyset$ D layer near the middle of the track is less



than 1.5 times that of the muon track candidate in the same event. The  $\mu^+$  track candidate is a minimum ionizing particle track which should have nearly the same measured energy loss per unit length of the pion track as measured in between the interaction vertex and before it decays in the detector. Comparing the average energy losses between the muon track candidate and different P $\emptyset$ D tracks in the same event, ensures that the tracks use the same detector gain calibrations. Using this cut, proton and pion tracks can be differentiated, allowing for any number of protons to be present in CC-0 $\pi$  events.

In Table II, the purity and the efficiency of the three selections (columns 2-4) are given in terms of five true MC final states (column 1). The true final states are CC-0 $\pi$ , CC-1 $\pi$ , CC-other (all other CC states excluding CC-0 $\pi$  and CC-1 $\pi$ ), BKGD (neutral current and non- $\bar{\nu}_\mu$  interactions) and OOFV (out of fiducial volume events). The OOFV events have interactions that occur outside the selected P $\emptyset$ D target region. This table shows that the CC-0 $\pi$  selection has very good purity ( $\sim 80\%$ ) and very high efficiency ( $\sim 95\%$ ) relative to the CC-Inc sample.

In Fig. 3 are shown the plots of the CC-0 $\pi$  and CC-1 $\pi$  selections of data superimposed over the NEUT simulations. This is presented in pairs of water-in/out samples for the CC-0 $\pi$  momentum, the CC-0 $\pi$   $\cos\theta$ , the CC-1 $\pi$  momentum, and the CC-1 $\pi$   $\cos\theta$ . The Monte Carlo color bands correspond to the true CC-0 $\pi$ , CC-1 $\pi$ , CC-Other, BKGD, and OOFV events. Overall there is reasonable agreement between data and Monte Carlo.

In Table II and Fig. 3 (a-d), the dominant backgrounds for the CC-0 $\pi$  selection are caused by misidentified CC events with one emitted pion (CC-1 $\pi$ ) or CC-other events, with CC-1 $\pi$  being the largest of the two. In order to constrain the CC-1 $\pi$  background, a control sample of CC-1 $\pi$  selected events will be included in the analysis fitting described in the next section. This allows a data constraint on the background estimation which leads to smaller background modeling uncertainties.

## V. DOUBLE DIFFERENTIAL CROSS SECTION FITTING METHOD

In this section we first describe the fitting and unfolding technique to extract the differential cross section in true  $p - \cos\theta$  bins of the  $\mu^+$  track. Then the binning choice is explained followed by descriptions of the fit parameters and checks and validation on the fitting method. Finally, the regularization choice and overall checks are discussed.

### A. Fitting

In an idealized experiment with no backgrounds and perfect detector resolutions, the differential cross section

Water-in mode:		% in Selected Sample		
	CC-Inc	CC-0 $\pi$	CC-1 $\pi$	
CC-0 $\pi$	60	80	10	
CC-1 $\pi$	17	13	57	
CC-Other	13	3	15	
BKGD	7	1	15	
OOFV	4	2	3	
$\epsilon_{relative}$		96	14	
Water-out mode:		% in Selected Sample		
	CC-Inc	CC-0 $\pi$	CC-1 $\pi$	
CC-0 $\pi$	58	82	11	
CC-1 $\pi$	16	12	57	
CC-other	12	2	14	
BKGD	8	1	14	
OOFV	5	2	4	
$\epsilon_{relative}$		95	15	

TABLE II. Purity and efficiency tables for the different selections for water-in and water-out samples. The true final states are given in the first column and the three selections (CC-Inc, CC-0 $\pi$ , and CC-1 $\pi$ ) are given in the rows below the double lines. An example in this table is that the water-out mode CC-0 $\pi$  selected sample will have 82% of its event originate from the true CC-0 $\pi$  final state. The  $\epsilon_{relative}$  is the fraction of relevant events (CC-0 $\pi$  or CC-1 $\pi$ ) present in the CC-Inc sample retained by the number of  $\mu$ -like tracks requirement. For example, 96% of the CC-0 $\pi$  events present in the water-in CC-Inc sample are retained in the water-in CC-0 $\pi$  sample. See text for final state descriptions.

as a function of kinematic variable  $x$  in a particular bin  $\Delta x_j$  is given as:

$$\frac{d\sigma}{dx_j} = \frac{N_j}{\epsilon_j \Phi T \Delta x_j} \quad (1)$$

where  $N_j$  is the number of measured events in bin  $j$ ,  $T$  is the number of target nuclei,  $\Phi$  is the neutrino flux per unit area and  $\epsilon_j$  is the efficiency to reconstruct a signal event in bin  $j$ . In this analysis, the  $\Delta x_j$  is the  $p - \cos\theta$  bin of the  $\mu^+$  track in the lab frame. We define  $N_j^{sig}$  as the number signal events and  $N_j^{sig,MC}$  as the number of predicted MC events in  $p - \cos\theta$  bin  $j$ . We introduce a scale parameter,  $c_j$ , to be fitted, where:

$$N_j^{sig} = c_j N_j^{sig,MC} \quad (2)$$

If we include different background types  $k$  in the reconstructed data,  $\sum_k^{bgd \ types} N_j^{bgd \ k,MC}$  should be added to the above equation. In addition, if the background event rates depend on different model parameters, the backgrounds can be reweighted by a product term,  $\prod_a^{model} \omega(\vec{a})_j^k$  which depends on a vector  $\vec{a}$  of background model parameters. Then the expression becomes:

$$N_j = c_j N_j^{sig,MC} + \sum_k^{bgd \ types} \left( \prod_a^{model} \omega(\vec{a})_j^k \right) N_j^{bgd \ k,MC} \quad (3)$$

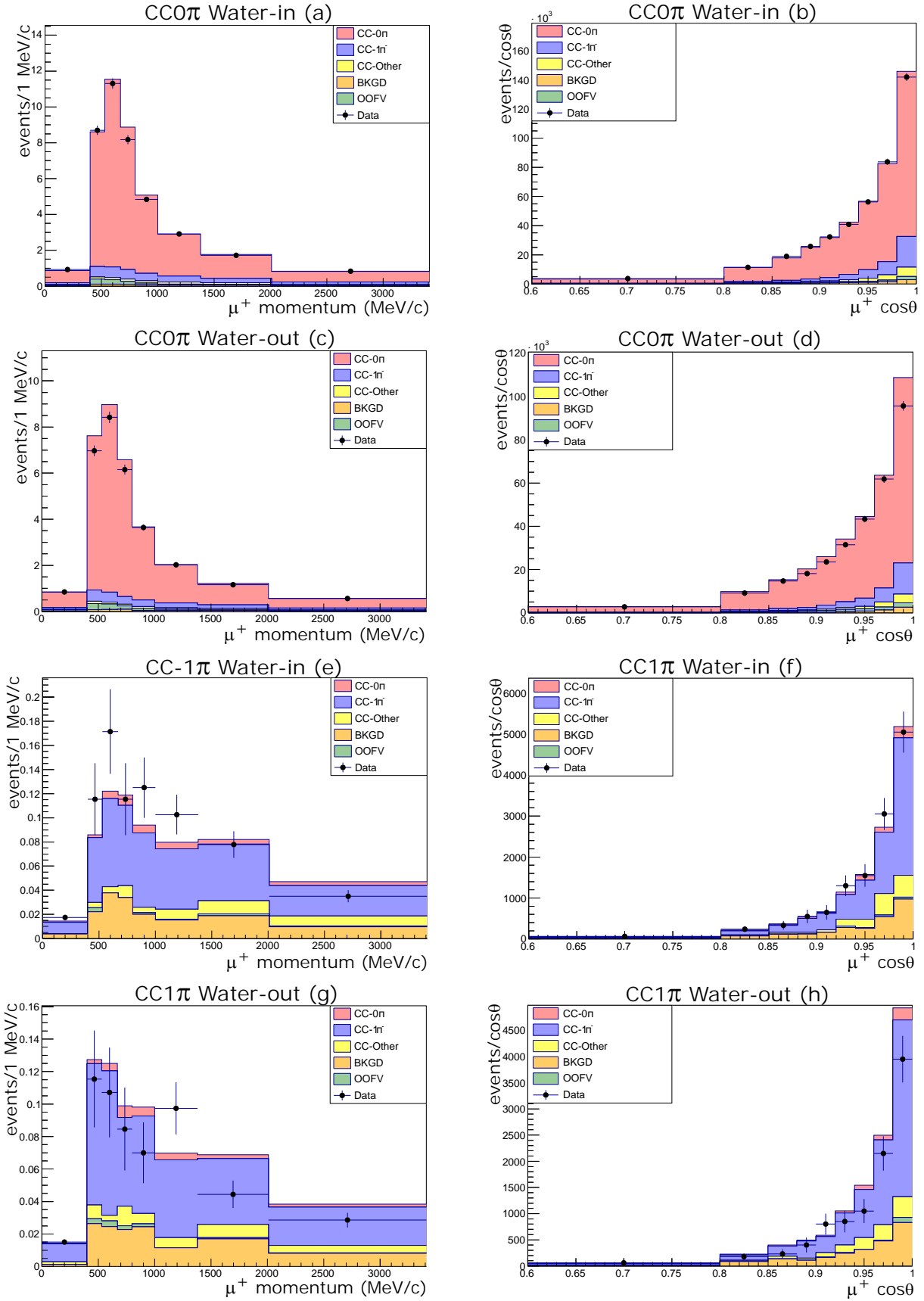


FIG. 3. The comparisons of lab frame momentum (left column) and  $\cos\theta$  (right column) distributions between data (black dots with error bars) and NEUT simulation predictions before fitting (stacked color bands). The CC-0 $\pi$  selections have been applied on the water-in samples (top row, (a) and (b)) and water-out samples (second row, (c) and (d)). The CC-1 $\pi$  selections have been applied on the water-in samples (third row, (e) and (f)) and water-out samples (fourth row, (g) and (h)).

where  $N_j$  is the predicted number of measured events (signal+background) in bin  $j$ , fitted parameters are  $c_j$  and vector parameter  $\vec{a}$ .

In real experiments the reconstruction is not perfect and we need to allow for smearing where events from a particular true  $p - \cos\theta$  bin  $j$  were smeared over several different reconstructed  $p - \cos\theta$  bins. If we consider events in some true kinematic bin  $j$  that are reconstructed with kinematics across bins indexed by  $i$ , a ‘‘smearing matrix’’  $S_{ij}$  can be constructed:

$$S_{ij} = \frac{N_{reco\ in\ i}^{true\ in\ j}}{N_{true\ in\ j}} \quad (4)$$

where  $N_{reco\ in\ i}^{true\ in\ j}$  is the number of events reconstructed in bin  $i$  that had true kinematics corresponding to bin  $j$ , and  $N_{true\ in\ j}$  is the number of events with true kinematics corresponding to bin  $j$ . The equation for the predicted observed number of events,  $N_i$ , in terms of the events in true kinematic bin  $j$  becomes:

$$N_i = \sum_j^{N_{bin}} S_{ij} \left\{ c_j N_j^{sig,MC} + \sum_k^{bkgd\ types} \left( \prod_a^{model} \omega(\vec{a})_j^k \right) N_j^{bkgd\ k,MC} \right\} \quad (5)$$

The above Eq.(5) forms a mapping between true bin  $j$  and reconstructed bin  $i$ . This approach [32] after fitting the parameters, will *unfold* the true number of events  $c_j N_j^{sig,MC}$  in bin  $j$  from the observed data. Using the histogram of observed reconstructed events  $N_i^{obs}$  and the predicted number of observed events  $N_i(\vec{c}, \vec{a})$  from Eq.(5), which depends on the fit parameters  $c_j$  and model parameters  $\vec{a}$ , we can form the binned likelihood of a histogram [46] as:

$$-2 \ln(L)_{stat} = \sum_i^{bins} 2 \left\{ N_i(\vec{c}, \vec{a}) - N_i^{obs} + N_i^{obs} \ln \left( \frac{N_i^{obs}}{N_i(\vec{c}, \vec{a})} \right) \right\} \quad (6)$$

which will be minimized.

In addition, three penalty terms are added to Eq.(6). The first is:

$$-2 \ln(L)_{bkgd} = (\vec{a} - \vec{a}_{prior})^T [V_{cov}^{model}]^{-1} \times (\vec{a} - \vec{a}_{prior}) \quad (7)$$

where  $V_{cov}^{model}$  is a covariance matrix containing the uncertainties and correlated errors on the background model parameters  $\vec{a}$  and the initial parameter value is given as  $\vec{a}_{prior}$  which has been discussed in [41].

The number of observed events includes a flux term that is the number of  $\bar{\nu}_\mu$  per unit area. This has been mod-

eled for the different neutrino energies as:

$$\sum_n^{E_\nu} f_n^i \quad (8)$$

where  $f_n^i$  is the fraction of antineutrinos in flux energy bin  $n$  for reconstructed bin  $i$ . This nominally sums to unity. The flux uncertainty is given in a covariance matrix  $V_{cov}^{flux}$  and this adds to Eq.(6) the flux penalty term:

$$-2 \ln(L)_{flux} = (\vec{f} - \vec{f}_{prior})^T [V_{cov}^{flux}]^{-1} \times (\vec{f} - \vec{f}_{prior}) \quad (9)$$

Finally the detector systematic uncertainties are given in a third covariance matrix,  $V_{cov}^{det}$ , with  $\vec{r}$  parameters which vary the reconstructed event rate  $r_i$  in bin  $i$ . This adds the last penalty term given as:

$$-2 \ln(L)_{det} = (\vec{r} - \vec{r}_{prior})^T [V_{cov}^{det}]^{-1} \times (\vec{r} - \vec{r}_{prior}) \quad (10)$$

The measurement described here is concerned with events that occur specifically on water targets. The number of signal events occurring on water and non-water targets are allowed to vary independently in the fit so that the interaction rate on only water targets can be extracted. We introduce a second set of scaling parameters,  $d_j$  for events that occur on non-water targets:

$$N_i = r_i \left( \sum_n^{E_\nu} f_n^i \right) \sum_j^{N_{bin}} S_{ij} \left\{ c_j N_j^{sig,water,MC} + d_j N_j^{sig,non-water,MC} + \sum_k^{bkgd.types} \left( \prod_a^{model} \omega(\vec{a})_j^k \right) N_j^{bkgd.k,MC} \right\} \quad (11)$$

Data samples where there was no water in the P $\emptyset$ D bags serve to constrain the  $d_j$  parameters so that while simultaneously fitting water-in and water-out data, the unfolded CC-0 $\pi$  event rate on water is extracted from the data as the  $c_j N_j^{sig,water,MC}$  term.

The final log likelihood equation of all terms that will be minimized to fit the data is:

$$-2 \ln(L)_{tot} = -2 \ln(L) \left[ \vec{c}, \vec{d}, \vec{a}, \vec{f}, \vec{r} \right]_{stat} - 2 \ln(L) [\vec{a}]_{bkgd} - 2 \ln(L) [\vec{f}]_{flux} - 2 \ln(L) ([\vec{r}])_{det} \quad (12)$$

Bin Index	True Momentum MeV/c	True $\cos\theta$ Bin edge
1	0-400	-1,1
2-4	400-530	-1,0.84,.94,1
5-8	530-670	-1,0.85,0.92,0.96,1
9-12	670-800	-1,0.88,0.93,0.97,1
13-16	800-1000	-1,0.90,0.94,0.97,1
17-20	1000-1380	-1,0.91,0.95,0.97,1
21-24	1380-2010	-1,0.92,0.96,0.98,1
25-27	2010-3410	-1,0.95,.98,1
28	3410-50000	-1,1

TABLE III.  $p$ - $\cos\theta$  bins over all kinematic phase space

where the fit parameters dependence of each likelihood term is made explicit. Note that ultimately, we are interested in the  $\vec{c}$  fit parameters that will be used to extract the unfolded true differential water cross section. This method differs from the D'Agostini iterative unfolding method used in [28], which did a single iteration and did not compare results with and without regularization.

### B. Binning Choice

The choice of the 2 dimensional  $\mu^+$  track  $p$ - $\cos\theta$  binning was determined by the following considerations:

1. The number of events in each 2-D bin should have reasonable statistics,  $\sim 100$  events. This improves the stability of the fit results.
2. The selection efficiency should be relatively high to minimize model dependence of the efficiency correction, and event populations should not differ very much between adjacent bins which also improves the stability of the fit results.
3. The bin sizes should be fine enough so local detector resolution effects are well represented and the detector resolutions do not change too much from bin to bin, however not too fine such that there are too few events in the bin.

We expect these choices should reduce regularization complications, which are discussed in later sections, or possibly even the need for regularization. The 28 bins over the entire kinematic phase space are specified in Table III. The 2-D plot in Fig. 4 contains the efficiencies of the water-in (a) and water-out (b) data sets.

Among the 28 bins covering the entire kinematic region, there are bins that have very few events due to the phase space or due to the low detector efficiency. These include the first ( $p < 400$  MeV/c) and last ( $p > 3410$  MeV/c) bins and lowest lying  $\cos\theta$  bins in each of the seven given momentum slices in the middle momentum ( $400 < p < 3410$  MeV/c) bins. Although we will fit in all 28 bins, we do not use these nine bins in the final differential cross

Bin Index	Momentum MeV/c	$\cos\theta$ Bin edge
1,2	400-530	.84,.94,1
3,4,5	530-670	.85,.92,.96,1
6,7,8	670-800	.88,.93,.97,1
9,10,11	800-1000	.90,.94,.97,1
12,13,14	1000-1380	.91,.95,.97,1
15,16,17	1380-2010	.92,.96,.98,1
18,19	2010-3410	.95,.98,1

TABLE IV.  $p$ - $\cos\theta$  bins used for the unfolded cross sections and indexed as cross section bin numbers.

section determinations. Instead we use the other 19 bins for the final differential cross section measurements. These 19 cross section bins are given in Table IV and their index number is called a cross section bin.

### C. Fit Parameters, Systematic Errors, and Checks

The parameters used in the likelihood fit in Eq.(12) include the signal interactions on water targets coefficients  $\vec{c}$ , the signal interactions on non-water targets coefficients  $\vec{d}$ , the fractional flux parameters  $\vec{f}$ , the background model parameters  $\vec{a}$ , and the reconstructed event rate scale factor  $\vec{r}$ . All types of parameters are listed with their numbers in Table V. We describe each parameter type in the following paragraphs.

There are two sets of 28 scale factors for the  $p - \cos\theta$  bins, one set  $\vec{c}$  for interaction on water and another  $\vec{d}$  for non-water interactions. The water parameters,  $\vec{c}$ , contain the subset of 19 parameters that are used to extract the final unfolded cross section.

There are 11 flux parameters representing the fraction of the  $\bar{\nu}_\mu$  flux in varying energy bin widths with energy boundaries at 0, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 2.5, 3.5, 5.0, 7.0, and 30.0 GeV. The pre-fit flux uncertainties are on the order of  $\sim 10\%$  in the matrix  $V_{cov}^{flux}$ .

There are 9 background model parameters and 6 pion final state interaction (FSI) parameters. The first three background model parameters, the axial mass, the axial form factor, and the fraction of non-resonant background, describe the main background, which is the charged current resonant background. The charged current deep inelastic background is described using a scaling parameter on a normalization function of the cross-section, which depends on the neutrino energy. The other background model parameters are normalization rates for the charged current coherent interactions on Carbon and Oxygen, neutral current, and coherent neutral current backgrounds. More details about those parameters can be found in [47].

The 6 pion FSI parameters include effects for absorption, inelastic scattering, charge exchange, and quasielastic scattering inside the nucleus. For descriptions of these FSI parameters see Table IV in a previous T2K publication [48].

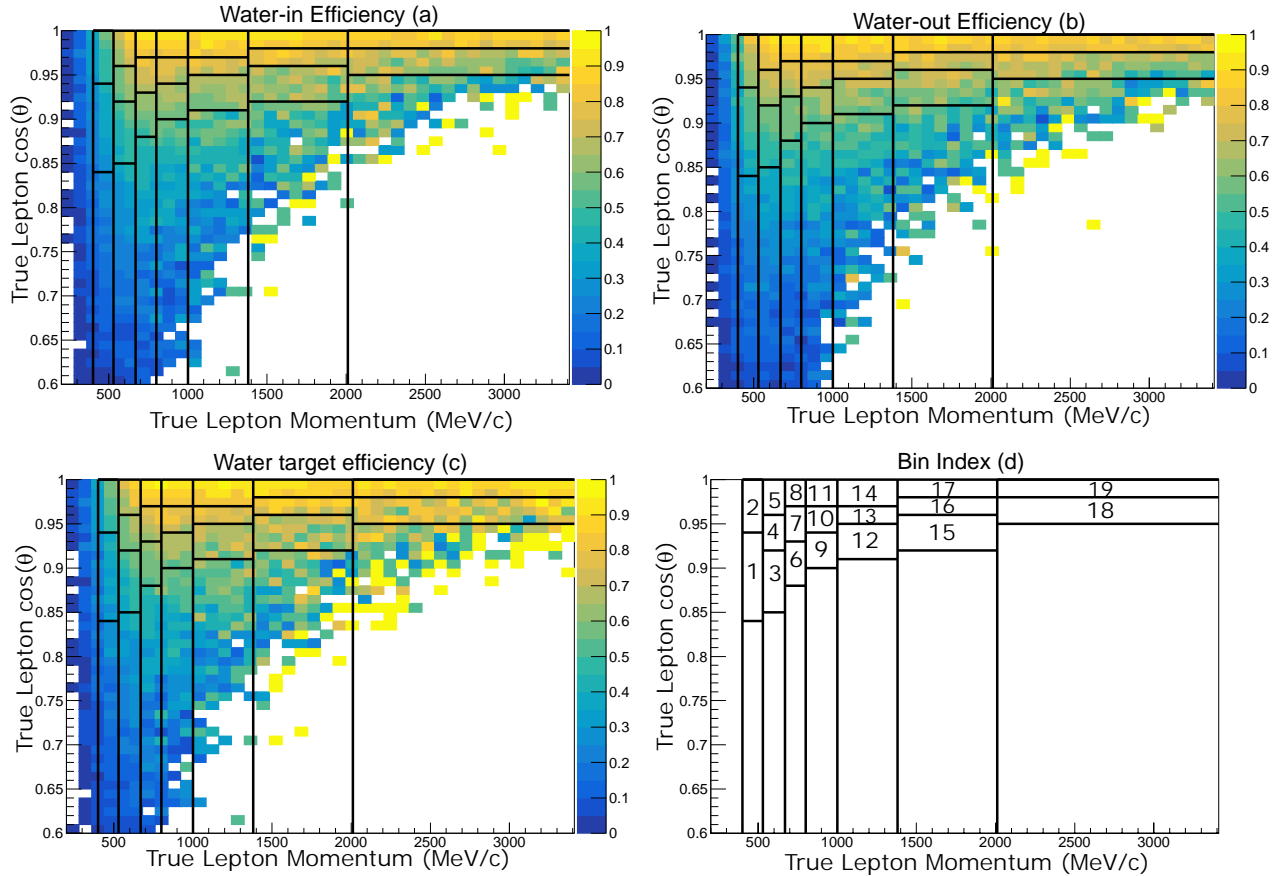


FIG. 4. The CC- $0\pi$  selection efficiency plots in 2-D  $p$  vs.  $\cos\theta$  bins for water-in (a), water-out (b) and water target only (c). There are 28 bins whose edges are drawn with vertical and horizontal lines. The efficiencies are given in color bands and it is noted that the efficiencies are very similar. The last plot (d) is the bin index given in Table IV. Note that the 28th bin in Table III is outside the plot boundary. The fit results in Section VI.A. use these 19 bins which are a subset of the 28 bins.

The detector parameters  $\vec{r}$  scale the predicted number of reconstructed events in Eq.(11) in each bin  $i$  of reconstructed  $\mu^+$  kinematics. These parameters also are included in the penalty terms in Eq.(10) and, being scale factors, they are nominally set to 1.0. There is one parameter for each of the 19 cross section bins for each water-in/water-out samples of the CC- $0\pi$  and CC- $1\pi$  selections. This totals to 76 detector parameters. The uncertainties of these parameters are determined from detector uncertainties in the TPC and the P $\emptyset$ D detectors. The TPC and P $\emptyset$ D momentum resolution and scale errors and the B-field distortions are estimated by varying their scales resulting in their combined errors of roughly 6%. The TPC charge mis-identification, track reconstruction efficiency, shower reconstruction efficiency, and TPC-P $\emptyset$ D matching errors are obtained by reweighting the parameters, resulting in their combined error of roughly 2.5%. The efficiency dependence on the signal CC- $0\pi$  model parameters was checked by varying the CCQE axial mass and Carbon and Oxygen antineutrino interaction signal model parameters. The remaining errors are due to the uncertainty on the mass of the non-water material in the P $\emptyset$ D detector [28]

Symbol	Parameter	Number
$\vec{c}$	signal on water coefficients	28
$\vec{d}$	signal on non-water coefficients	28
$\vec{f}$	flux parameters	11
$\vec{r}$	detector parameters	76
$\vec{a}$	background and FSI parameters	15

TABLE V. Table of parameters in the fit.

which was estimated to be 1.5% and the mass of water of the filled water target bags. The uncertainty of the water mass in each P $\emptyset$ D water-bag was modeled by an uncorrelated normal distribution with a 10% standard deviation. The typical initial errors on the parameters representing the CC- $0\pi$  samples are 5-10% whereas the errors on the CC- $1\pi$  samples are 10-20%.

Basic validation checks, that the fit behaves properly under the conditions that the MC matches the data with well defined conditions, were performed. The first check consisted of fitting the NEUT MC model to verify that all the fitted water coefficients,  $c_j$ , and non-water coefficients,  $d_j$ , are exactly reproduced. The next check was

to decrease/increase the water/non-water target masses by  $\pm 50\%$  and check that the  $c_j$  and  $d_j$  parameters decrease/increase by the correct amount.

The systematic errors on the flux, background parameters and detector systematics, which appear in the penalty terms in Eqs. (7), (9) and (10), were checked by removing 2 of the 3 groups of nuisance parameters and checking the values of the refit water-in coefficients. When each of these groups are turned on and off one by one, we find that water-in coefficients have errors in the range of 2-6%, 2-6%, and 6-14% due to uncertainties on the flux, background models, and detector systematics, respectively.

Finally, five different samples of the NEUT MC model, with the same number of events as the expected data sample, were generated and fitted. The resulting water coefficients  $c_j$  were all consistent between all five samples. To evaluate how well the post-fit results agree with a certain prediction, we define the  $\chi^2$  between some prediction with label A and the post-fit results to be:

$$\chi_A^2 = (\vec{\sigma}_A - \vec{\sigma}_{\text{post-fit}})^T [V_{\text{cov}}^{\text{post-fit}}]^{-1} (\vec{\sigma}_A - \vec{\sigma}_{\text{post-fit}}) \quad (13)$$

The resulting  $\chi^2$ s between the MC true event rates and the fitted ones from the five different samples had similar values.

#### D. Regularization

The aim of the analysis is to extract the parameters  $c_j$  which are proportional to the number of CC-0 $\pi$  events on water in the  $p - \cos\theta$  bins for  $i=1, \dots, 28$ . This is obtained by fitting the parameters  $c_j$  in Eq.(11) which determines the predicted  $N_i$  that is used in the binned likelihood in Eq.(6) and Eq.(12). This forms an inverse problem where small statistical fluctuations in the reconstructed event rates,  $N_i$ , can cause large variations of the fitted parameters  $c_j$ . The Fig.5(a) shows the covariance matrix of the fitted parameters  $c_j$  using a MC simulation test sample. There are some moderate bin to bin correlations seen in this covariance matrix. Specifically, there are off-diagonal anti-correlations between neighboring momentum bins for equivalent  $\cos\theta$  bins. These are caused by the fit being able to adjust the event rates in neighboring true bins in an anti-correlated way and getting similar predictions in the reconstructed bins.

These bin to bin variations can be reduced by applying data-driven regularization methods as discussed and applied in Section IV.D in a previous T2K analysis [32]. The regularization technique [49], consists of adding to Eq.(12) an additional penalty term:

$$-2\log(L[\vec{c}, p_{\text{reg}}])_{\text{reg}} = p_{\text{reg}} \sum_i^{N_{\text{bin}}-1} (c_i - c_{\hat{i}})^2 \quad (14)$$

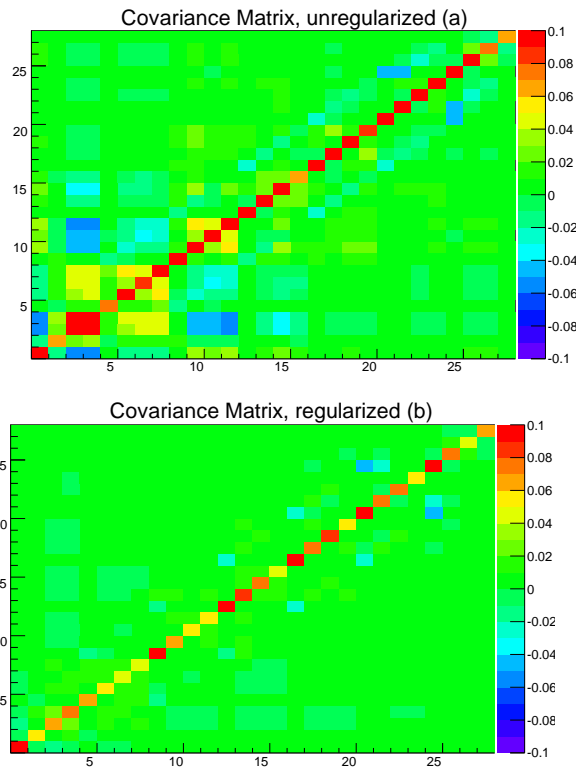


FIG. 5. Covariance Matrix of water-in coefficients before (a) and after (b) regularization was applied to a test MC sample. The regularization reduces off-diagonal correlations.

where  $\hat{i}$  is the index of bin corresponding to a neighboring momentum bin  $i$  for equivalent  $\cos\theta$  bins. Eq.(14) includes a parameter  $p_{\text{reg}}$  that controls the regularization strength between momentum bin boundaries. When Eq.(14) is added to Eq.(12) and the sum is minimized, this will clearly reduce variations between adjacent momentum bins depending on the size of  $p_{\text{reg}}$ . The L-curve regularization [50] is obtained when the ratio  $-2\log(L[\vec{c}, p_{\text{reg}}])_{\text{reg}}/p_{\text{reg}}$  has the largest curvature as a function of  $p_{\text{reg}}$ [50]. The  $p_{\text{reg}}$  values of 1 – 2 were found to have the largest curvature in this test sample shown in Fig.5(a). When regularization with  $p_{\text{reg}} = 1$  is applied to the test sample, the off-diagonal covariances and the bin to bin correlations are reduced as shown in Fig.5(b).

Both unregularized and regularized results will be shown. They are expected to be totally equivalent in terms of physics results but regularized results will minimize unphysical large bin-to-bin fluctuations. The purpose here is to provide at the same time fully correct and model independent results (unregularized) which are properly interpreted together with a full covariance matrix provided in a data release.

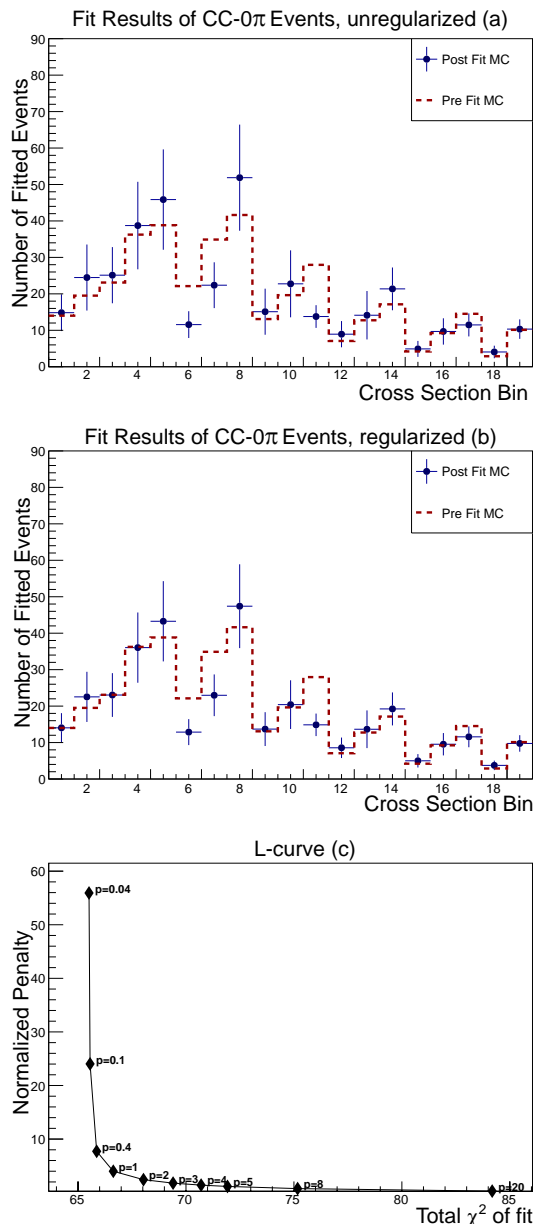


FIG. 6. Fit results of CC- $0\pi$  events rates in 19 cross section bins for unregularized (a) and regularized (b) for water events and the regularization L-curve of data (c).

## VI. DATA RESULTS AND COMPARISON TO MODELS

### A. Fit Results

The unregularized and regularized fit results of event rates with errors for the 19 bins of the water CC- $0\pi$  cross section by cross section bin number are shown in Fig. 6 (a) and (b), respectively. The L-curve of the regularized fits is shown in Fig. 6 (c). The largest L-curvature occurs in data at 1, and we choose  $p_{reg} = 1$  for the regularization.

Generator	data $\chi^2$ (regularized)	data $\chi^2$ (unregularized)
NEUT	29.2	33.1
GENIE	26.0	28.4
NuWro	16.8	18.4

TABLE VI. Comparisons of the data result in both the regularized and unregularized cases to NEUT, GENIE, and NuWro using the absolute  $\chi^2$  from Eq.(13).

The resulting fitted or post-fit results for the 28 water  $c_j$  and 28 non-water  $d_j$  parameters are shown in Fig. 7 (a) and (b) respectively. The unregularized fit is in green and the regularized fit is in blue. The nominal initial values are set to 1.0, so the shifts or deviations from initial to post-fit values can be readily inspected. The post-fit  $c_j$  are centered on  $\sim 1$  except for three (6th, 7th, and 11th) bins. We note the non-water  $d_j$  parameters are centered  $\sim 0.9$ , however, those same 3 bins in the post-fit non-water parameters do not have dips relative to their adjacent bins.

The covariance matrix of the fit results of the water  $c_j$  parameters are shown in Figs. 8 (a) and (b) for unregularized and regularized fits, respectively. We observe in the unregularized covariance slight positive (red bins) covariance correlations at low momentum ( $p < .67$  GeV/c) and a negative (blue bins) correlation in bin 25 which is a high momentum ( $p > 2.01$  GeV/c) bin.

### B. Cross Section Comparisons to NEUT and other Models

The regularized and the unregularized fit results of unfolded  $p$  vs  $\cos\theta$  bins of data (black crosses) with comparisons to cross section predictions from NEUT (ver.5.41), GENIE (ver.2.12.10), and NuWro (ver.18.02.1) models are shown in Fig. 9 and Fig. 10, respectively.

The NEUT and NuWro models both include Local Fermi Gas (LFG) with 2p2h and the GENIE model includes the Bodeck-Ritchie modifications to the Relativistic Fermi gas effects. These models have been described in a previous T2K publication[32] and the models were implemented using the NUISANCE framework[51]. The results are presented in seven plots of  $\cos\theta$  bins in seven different momentum ranges from 0.4 GeV/c to 3.41 GeV/c. The data mostly agrees within 1 standard deviation of all three predictions except for the 6th, 7th, and 11th data bins that are  $\sim 2$  standard deviations below the NEUT prediction. These correspond to the 3 low bins numbers 6,7, and 11 in Fig. 6, numbers 10,11, and 16 in Fig. 7, and the  $670 < p < 800$  MeV/c (1st and 2nd bin) and  $800 < p < 1000$  MeV/c (3rd bin) in Figs 9 and 10.

The number of differential cross section bins, 19, is the number of degrees of freedom in the  $\chi^2$  comparisons in Table VI. We see generally good agreement with all

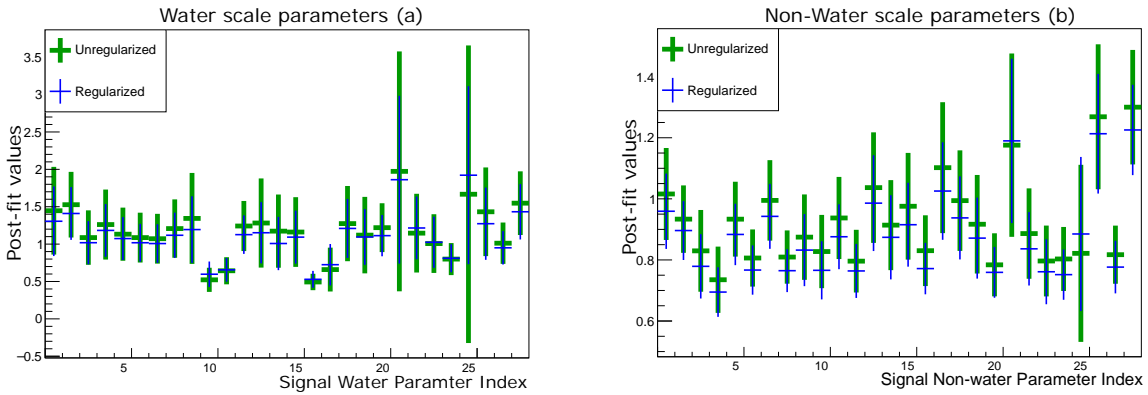


FIG. 7. Post-fit results of water (a) and non-water (b) events which correspond to the 28 scale parameters  $c_j$  and  $d_j$ , respectively

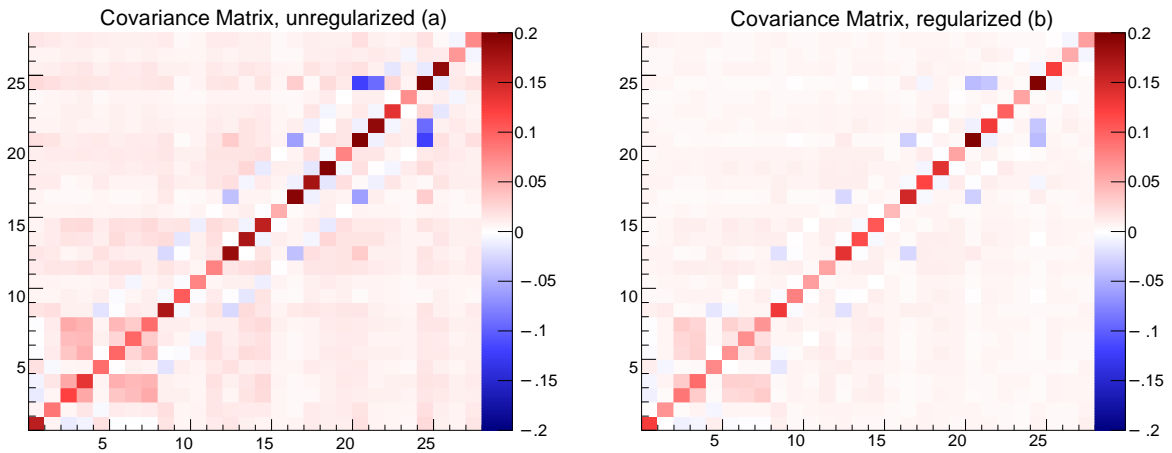


FIG. 8. Covariance Matrix of water parameters for unregularized fits (a) and regularized fits (b).

three models, but a slight preference for the NuWro prediction that has a lower  $\chi^2 = 18.4$  for 19 degrees of freedom. In addition, the  $\chi^2$ 's between the regularized and unregularized cases are seen to be consistent.

The total cross section integrated over all 19 bins, can be determined from the data and compared to NEUT, GENIE, and NuWro predictions. The T2K flux averaged cross sections, in the kinematic phase space in Table IV, are given in units of  $10^{-38} \frac{\text{cm}^2}{\text{water molecule}}$  as,

$$\begin{aligned}
 \sigma_{DATA}^{\text{regularized}} &= 1.11 \pm 0.18 \\
 \sigma_{DATA}^{\text{unregularized}} &= 1.17 \pm 0.22 \\
 \sigma_{NEUT} &= 1.05 \\
 \sigma_{GENIE} &= .954 \\
 \sigma_{NuWro} &= .911
 \end{aligned}
 \tag{15}$$

A data release has been provided[52] that contains the double-differential cross section central values and associated relative covariance matrix for both the regular-

ized and unregularized fits.

### C. Comparisons to Models.

## VII. DISCUSSION AND SUMMARY

We have performed a measurement of the  $\bar{\nu}_\mu$  CC double differential cross section on water without pions in the final state averaged over the T2K antineutrino beam flux. The measurement method in momentum- $\cos\theta$  bins included a likelihood fit with unfolding to correct for bin to bin smearing. The data was fit without regularization and with regularization to reduce bin to bin fluctuations that are possible when using unfolding methods. The regularized and unregularized results were nearly identical. The comparisons with the NEUT, GENIE, and NuWro models find a lowest  $\chi^2$  for NuWro where nearly all of the 19 measured data bins agreed within 1 standard deviation of the NuWro predictions.



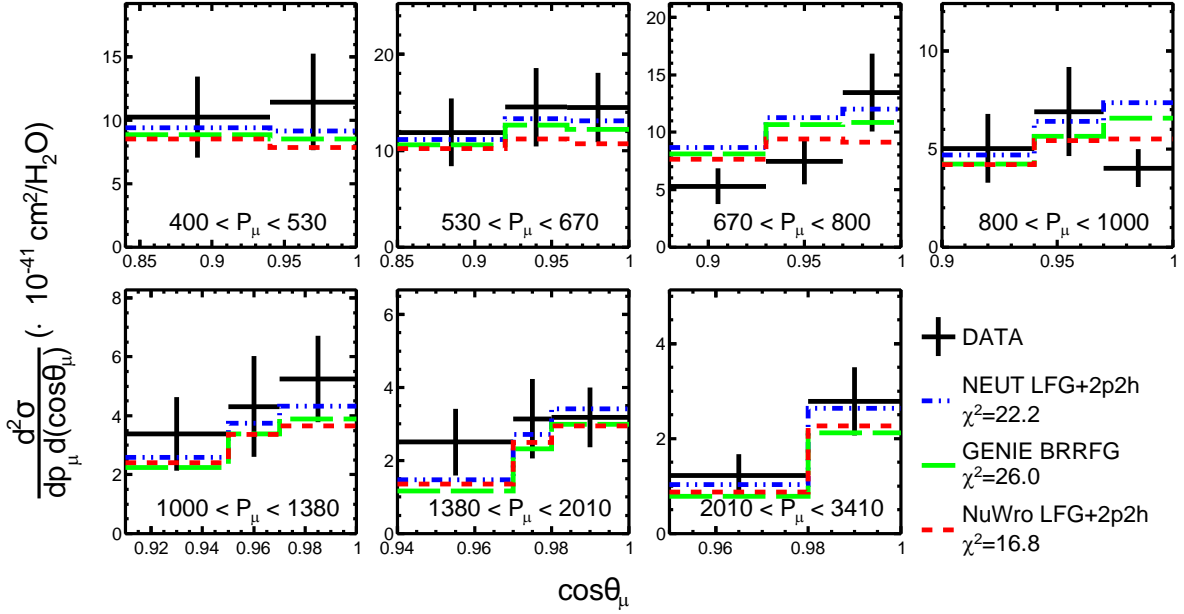


FIG. 9. Regularized fit results of data as a function of 19  $\cos \theta$  bins in seven different momentum ranges with comparisons to NEUT(ver.5.41), GENIE(ver.2.12.10), and NuWro(ver.18.02.1) predictions. The fit  $\chi^2$ 's of each model is defined by Eqn. 13.

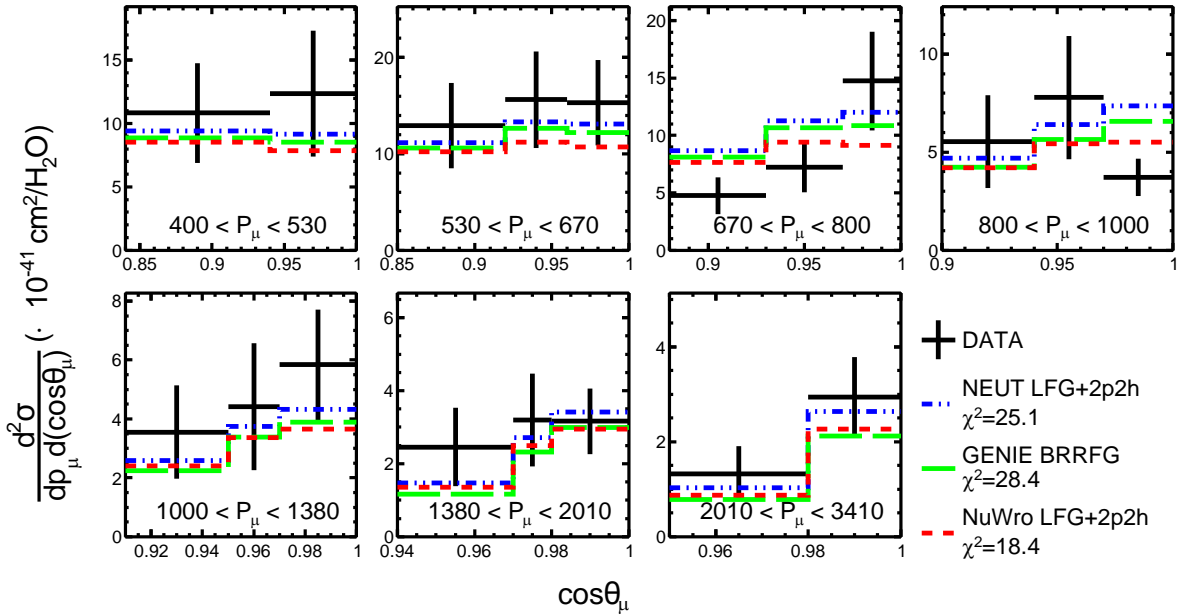


FIG. 10. Unregularized fit results on data as a function of 19  $\cos \theta$  bins in seven different momentum ranges with comparisons to NEUT(ver.5.41), GENIE(ver.2.12.10), and NuWro(ver.18.02.1) predictions. The fit  $\chi^2$ 's of each model is defined by Eqn. 13.

In summary, the first measurements of antineutrino cross sections on water were presented and are found to be in agreement with several MC model predictions including NEUT, which is extensively used in the T2K measurements of antineutrino interactions at the SuperK far detector. These antineutrino measurements and comparisons to Monte Carlo predictions are ex-

tremely important for the measurements of the antineutrino oscillation rates and the search for CP violation by T2K and for the development of future long baseline neutrino experiments.

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