

Measurement of single- and double-differential cross sections for mesonless charged-current muon neutrino interactions on argon with final-state protons using the MicroBooNE detector

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Charged-current neutrino interactions with final states containing zero mesons and at least one proton are of high interest for current and future accelerator-based neutrino oscillation experiments. Using the Booster Neutrino Beam and the MicroBooNE detector at Fermi National Accelerator Laboratory, we have obtained the first double-differential cross-section measurements of this channel for muon neutrino scattering on an argon target with a leading proton momentum threshold of 0.25 GeV/c. We also report a flux-averaged total cross section of $\sigma = (11.8 \pm 1.2) \times 10^{-38} \text{ cm}^2/\text{Ar}$ and several single-differential measurements which extend and improve upon previous results. Statistical and systematic uncertainties are quantified with a full treatment of correlations across 359 kinematic bins, including correlations between distributions describing different observables. The resulting dataset provides the most detailed information obtained to date for testing models of mesonless neutrino-argon scattering.

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I. INTRODUCTION

Accelerator-based measurements of neutrino oscillations will be critical for definitively answering key open questions in high-energy physics, including whether charge-parity (CP) violation [1] occurs in the lepton sector, whether *sterile* neutrino species [2] (which do not participate in the weak interaction) exist, and whether ν_3 is the heaviest or lightest of the known neutrino mass eigenstates [3]. In the coming years, the Fermilab-based Short Baseline Neutrino (SBN) program [4] and Deep Underground Neutrino Experiment (DUNE) [5] will both pursue high-precision neutrino oscillation analyses using liquid argon time projection

chambers (LArTPCs) as the primary detector technology. Maximizing the discovery potential of these large experimental efforts will require substantial improvements to the present understanding of GeV-scale neutrino-nucleus scattering physics [6]. An emerging literature of neutrino-argon cross-section measurements [7], pioneered by the ArgoNeuT [8] and MicroBooNE [9] LArTPC experiments, will provide the most direct constraints for refining interaction models to the precision needed for SBN and DUNE.

This article contributes to that effort by presenting measurements of differential cross sections for charged-current (CC) ν_μ scattering on argon leading to final states containing no mesons and one or more protons. This event topology (hereafter abbreviated as $\text{CC}0\pi Np$) is the dominant neutrino interaction channel for the SBN program, and its contribution is expected to remain important for DUNE oscillation analyses. The results presented herein build upon a previous MicroBooNE investigation [10] which measured single-differential neutrino-argon cross sections in the $\text{CC}0\pi Np$ channel for the first time. The

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present work leverages subsequent improvements to the MicroBooNE simulation [11], reconstruction [12], and systematic uncertainty quantification [13] to achieve more detailed measurements, including multiple double-differential distributions. The analysis also benefits from a significantly larger dataset, which was recorded by the MicroBooNE detector [9] with a total exposure of 6.79×10^{20} protons on target (POT) from the Fermilab Booster Neutrino Beam (BNB) [14].

Various kinematic distributions involving the three-momenta of the final-state muon and leading proton are measured and compared to simulations in this article. An innovative feature of the dataset is the strategy used for its presentation; covariances between all 359 kinematic bins studied in the analysis are reported and used to quantify an overall goodness-of-fit of theoretical predictions. The full group of cross-section measurements may thus be regarded as a single result with greater combined model discrimination power (due to the need to describe interdistribution correlations) than its constituent parts. Together with the inclusive cross-section measurements recently reported by MicroBooNE in Refs. [15,16], this analysis thus represents a first application of the “blockwise unfolding” technique proposed in Ref. [17].

The experimental setup and simulations used in the analysis are described in Sec. II. Section III presents the signal definition and the event selection criteria. Section IV discusses the strategy for reporting the results, including the observables measured and the general approach to corrections for imperfect event reconstruction. The procedures used to estimate uncertainties and convert measured event distributions to cross sections are documented in Secs. V and VI, respectively. Section VII reports the cross-section results and compares them to several model predictions. Finally, Sec. VIII contains a summary and conclusions.

II. MICROBOONE EXPERIMENT AND SIMULATION

The MicroBooNE detector [9] is a LArTPC that operated in the BNB from 2015–2021. The detector’s 85-tonne active mass of liquid argon was exposed to a 273 V/cm electric field and instrumented with 3 wire planes and 32 photomultiplier tubes (PMTs). Acrylic disks coated with tetraphenyl butadiene (TPB) were placed in front of the PMTs to convert the 128-nm argon scintillation light into visible wavelengths for efficient detection.

Neutrinos from the BNB are generated by bombarding a beryllium target with 8-GeV protons. Secondary particles produced by the proton collisions are focused by a magnetic horn and decay in flight. The decay products are directed toward a beam stop made of steel and concrete that absorbs particles other than neutrinos. During operation, the MicroBooNE detector was located 463 m downstream from the target along the beam axis. The BNB neutrino flux at this position is dominated by muon

neutrinos with a mean energy of 0.8 GeV. Minor contributions from $\bar{\nu}_\mu$ (5.8%) and a mixture of ν_e and $\bar{\nu}_e$ (0.5% combined) are also present.

Interpretation of the data obtained from the MicroBooNE detector is enabled by a suite of Monte Carlo simulations that provide comprehensive modeling of the entire experiment. Neutrino beam production is simulated using the Geant4 framework [18–20] and a detailed representation of the BNB apparatus developed by the MiniBooNE Collaboration [14].

A. Neutrino interaction model

Neutrino interactions are modeled in the MicroBooNE simulation chain using version 3.0.6 of the GENIE neutrino event generator [21–23] with the G18_10a_02_11a configuration. This configuration includes a local Fermi gas (LFG) representation of the nuclear ground state [24] and the Valencia model for quasielastic (QE) and two-particle two-hole (2p2h) interactions in the CC channel [25–29]. Resonance production (RES) is simulated with the model of Kuzmin-Lyubushkin-Naumov and Berger-Sehgal (KLN-BS) [30–33], deep inelastic scattering [34] (DIS) is described using the structure functions of Bodek and Yang [35,36], and coherent pion production (COH) follows the Berger-Sehgal approach [37]. Intranuclear hadronic final-state interactions (FSI) are simulated using the hA2018 model [38]. Several model parameters relevant for calculations of neutrino-nucleon cross sections were tuned by the GENIE Collaboration to datasets from bubble chamber experiments [39].

The GENIE v3.0.6 G18_10a_02_11a configuration described above was modified with MicroBooNE-specific tuning [11] of two CCQE and two CC2p2h model parameters to data from the T2K experiment reported in Ref. [40]. The resulting interaction model is referred to as the *MicroBooNE Tune* in the remainder of this article.

B. Detector simulation

Final-state particles produced in GENIE events are transported through the MicroBooNE detector geometry using version 10.3.3 of Geant4 [18–20]. The response of the detector electronics to these particles is modeled using a custom simulation implemented within the LArSoft framework [41]. This detector response model includes data-driven treatments of position dependence in the wire responses, distortion of the time projection chamber (TPC) electric field due to buildup of slow-moving positive ions (space-charge effects), and dynamically induced charge [42–46].

Backgrounds generated by cosmic rays and other sources unrelated to the neutrino beam are directly measured in the analysis using *beam-off* data samples collected at times when the BNB was not active. To ensure that these backgrounds are properly treated when reconstructing simulated neutrino interactions, an *overlay* technique is used; simulated TPC

wire and PMT waveforms induced by GENIE neutrino scattering events are superimposed on measured waveforms from beam-off data before analysis [47].

III. SIGNAL DEFINITION AND EVENT SELECTION

A neutrino scattering event is considered part of the signal for this analysis if it fulfills the following criteria:

- (1) A muon neutrino undergoes a CC interaction with an argon nucleus.
- (2) The final state contains at least one proton.
- (3) The momentum of the outgoing muon lies within the interval $[0.1, 1.2]$ GeV/ c .
- (4) The momentum of the leading final-state proton (i.e., the proton with the highest momentum) lies within the interval $[0.25, 1.0]$ GeV/ c .
- (5) The final state contains zero mesons and zero antimesons.

The momentum limits on the muon and leading proton in signal requirements (3) and (4) are motivated by considerations of efficiency, resolution, and systematic uncertainties. Apart from adjustments to these momentum limits, the signal definition given above is the same as the one adopted in the previous MicroBooNE $\text{CC}0\pi Np$ analysis [10].

A. Reconstruction workflow

Identification of candidate $\text{CC}0\pi Np$ signal events in this article relies upon an automated event reconstruction workflow implemented within the Pandora multi-algorithm pattern-recognition toolkit [48]. The individual hits reconstructed from the pulses recorded by each of the TPC wire planes are clustered in 2D and then correlated to produce 3D particle candidates. Collections of nearby particle candidates are grouped into *slices*, and information from both the TPC and PMTs is used to identify a maximum of one slice per event that contains a candidate neutrino interaction. Algorithms to calculate additional reconstructed quantities, such as the particle identification score described in Ref. [12] and the muon momentum estimator described in Ref. [49], are combined with this generic neutrino selection to perform the analysis.

B. Event categories

Plots of reconstructed event distributions in Figs. 1, 7–14 show the prediction of the MicroBooNE simulation as a stacked histogram that distinguishes between the following categories of events:

Signal: All events which satisfy signal requirements (1) to (5) and have a true neutrino vertex position that falls within the fiducial volume defined in selection requirement (I) from Sec. III C. Signal events are divided into subcategories based on whether the primary interaction mode is QE, 2p2h, or any other process. The last of these subcategories is dominated

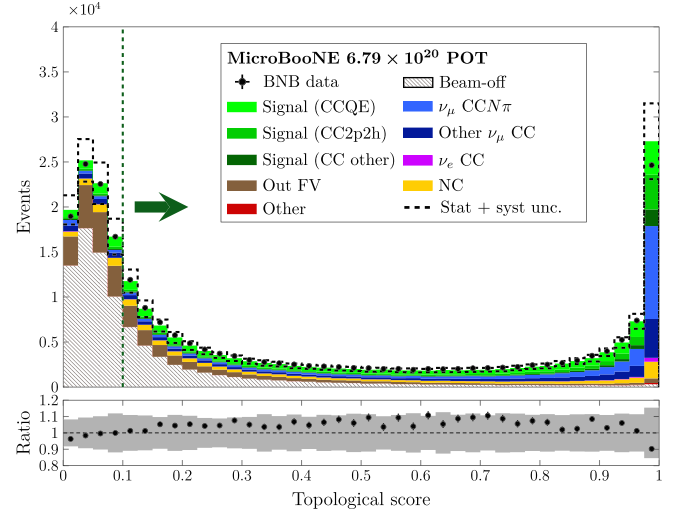


FIG. 1. Distribution of topological score values obtained when applying the ν_μ CC inclusive preselection. The portion near zero is dominated by beam-off events as expected. The green arrow points into the region in which events are accepted by selection requirement (III). The dashed lines indicate the total uncertainty on the simulation prediction evaluated according to the prescription given in Sec. V. The lower panel shows the ratio of the data to the simulation prediction. The same total uncertainty band is represented by the shaded gray region.

by resonant pion production followed by intranuclear pion absorption.

Out FV: Events in which the true neutrino vertex falls outside of the fiducial volume (FV). This category includes all final-state topologies since it is defined solely in terms of the true vertex location.

CCN π : Events containing a charged-current ν_μ interaction which produces one or more final-state pions of any charge. These fail to satisfy signal requirement (5). Note that ν_μ CC events containing final-state mesons other than pions fall into another event category.

CC0 π 0 p : Charged-current ν_μ events containing zero final-state pions of any momentum and zero protons within the true momentum limits imposed by signal requirement (4). Events with any number of mesons other than pions are allowed in this category.

Other CC: Charged-current ν_μ events which do not fall into any of the previous categories. Among these are events which would otherwise be signal but do not satisfy the muon momentum limits imposed by signal requirement (3). This category also includes events containing at least one proton within the momentum limits from signal requirement (4) together with one or more mesons other than pions.

ν_e CC: Events involving a charged-current ν_e interaction inside the fiducial volume. These fail to satisfy signal requirement (1).

NC: Events in which a neutrino or antineutrino of any flavor undergoes a neutral-current (NC) interaction

within the fiducial volume. These fail to satisfy signal requirement (1).

Beam-off: Cosmic-ray-induced backgrounds.

Other: All events which do not fall into one of the other categories defined above. This category is dominated by CC interactions of antineutrinos.

C. Inclusive ν_μ CC preselection

Following automated reconstruction using the Pandora framework, 12 event-selection criteria are applied to distinguish the $\text{CC}0\pi Np$ signal from other event topologies. These criteria are divided into a preselection that seeks to identify inclusive ν_μ CC events (described in the following paragraphs), quality checks to eliminate events with a poorly reconstructed final-state muon (Sec. III D), and additional requirements designed to isolate mesonless final states containing one or more protons (Sec. III E). Overall performance of the selection is then discussed in Sec. III F, including evolution of the efficiency and purity as each requirement is applied.

In order of application, the selection criteria used to identify ν_μ CC candidate events are as follows:

- (I) The position of the reconstructed neutrino vertex must lie within a fiducial volume representing a region in which the efficiency of the remainder of the selection is appreciable and the detector response is well understood. The fiducial volume chosen for this analysis is a rectangular prism with most boundaries parallel to and 21.5 cm inward from the edges of the active volume of the MicroBooNE detector. The only exception is the boundary that is perpendicular to the beam on the downstream side. This boundary is chosen to be 70 cm inward from the edge of the active volume to enable better acceptance of forward-going muons.
- (II) Starting points for all reconstructed primary particles (i.e., those labeled by the reconstruction as direct progeny of the neutrino) are required to lie within a looser containment volume offset inward from the active volume edges by 10 cm on all sides.
- (III) The topological score [50] assigned to the event must be greater than 0.1. This score represents the output of a support-vector machine designed to classify events as either neutrino-like (scores near 1) or cosmic-ray-like (scores near 0). Figure 1 shows the measured distribution of this variable, obtained at this stage of the selection, compared to the prediction from the MicroBooNE simulation chain. The topological score threshold of 0.1 is sufficient to remove a large fraction of beam-off and out-of-fiducial-volume backgrounds.
- (IV) The event must contain a muon candidate, which is defined as a reconstructed primary particle that satisfies the following criteria:

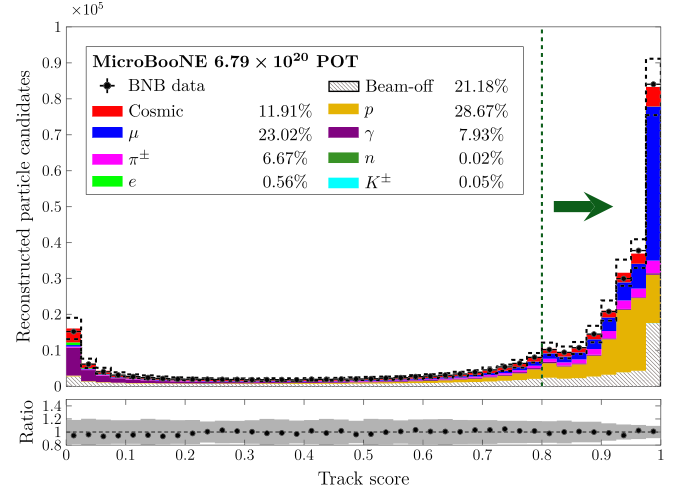


FIG. 2. Track score criterion applied to all reconstructed primary particles when searching for a muon candidate. The green arrow points into the region in which particle candidates are accepted. The percentages in the legend indicate the fraction of reconstructed particles of each type before the illustrated selection is applied. The lower panel shows the ratio of the data to the simulation prediction. The uncertainty on the simulation prediction is represented by the dashed lines in the top panel and the gray region in the bottom panel.

- (a) The track score [50,51] assigned to the particle by the reconstruction must be greater than 0.8. This score classifies reconstructed particles as shower-like (values near 0) and track-like (values near 1). This requirement slightly increases the muon purity (see Fig. 2). The “cosmic” (“beam-off”) category in the legend represents reconstructed particle candidates attributed to cosmic-ray activity in events that include (do not include) a simulated neutrino interaction. All other categories represent reconstructed particle candidates that correspond to a specific kind of true particle produced by a simulated neutrino interaction.
- (b) The Euclidean distance between the particle’s reconstructed starting position and the reconstructed neutrino vertex must be less than 4 cm (see Fig. 3). This is a minor quality check to ensure that the muon candidate is correctly associated with the reconstructed neutrino vertex.
- (c) The length of the particle track must be greater than 10 cm (see Fig. 4). Tracks below this length are overwhelmingly generated by protons and cosmic activity. The lower limit on the muon momentum applied in signal requirement (3) helps to mitigate the impact of this cut on the efficiency for very low-energy muons.
- (d) The log-likelihood ratio particle-identification (LLR PID) score assigned to the particle must exceed 0.2 (see Fig. 5). This score is calculated

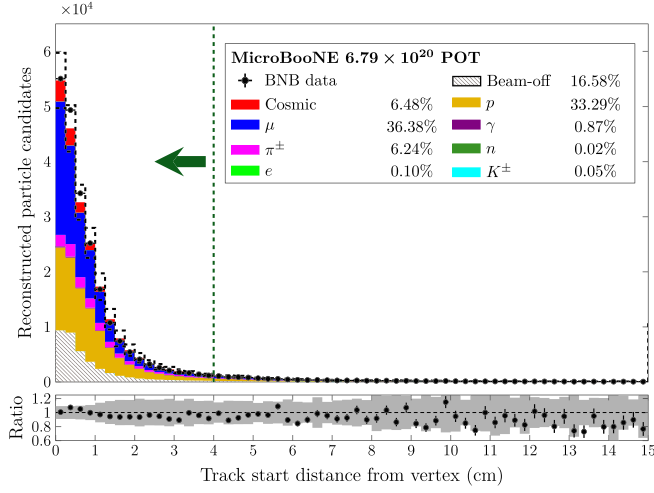


FIG. 3. Distribution of distances between the reconstructed neutrino vertex and reconstructed primary particles. The green arrow points into the region in which particles are accepted as possible muon candidates. The percentages in the legend indicate the fraction of reconstructed particles of each type before the illustrated selection is applied. The lower panel shows the ratio of the data to the simulation prediction. The uncertainty on the simulation prediction is represented by the dashed lines in the top panel and the gray region in the bottom panel.

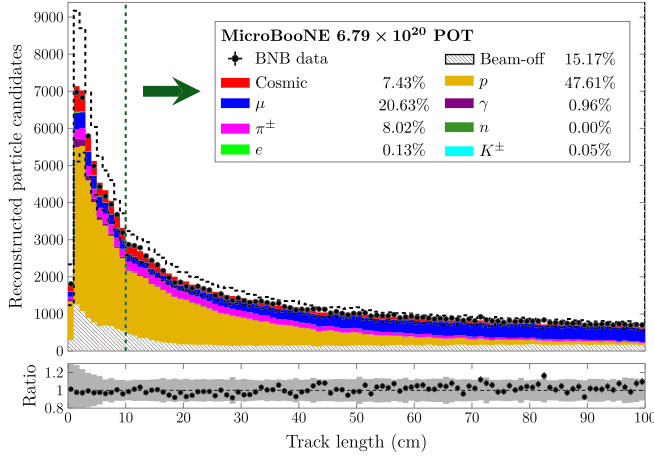


FIG. 4. Track length criterion applied to reconstructed primary particles when searching for a muon candidate. The green arrow points into the region in which particle candidates are accepted. The percentages in the legend indicate the fraction of reconstructed particles of each type before the illustrated selection is applied. The lower panel shows the ratio of the data to the simulation prediction. The uncertainty on the simulation prediction is represented by the dashed lines in the top panel and the gray region in the bottom panel.

by comparing track hit information from all three TPC wire planes to theoretical templates for muons and protons. The logarithm of a likelihood ratio for these two particle identification hypotheses is then converted to a score where -1

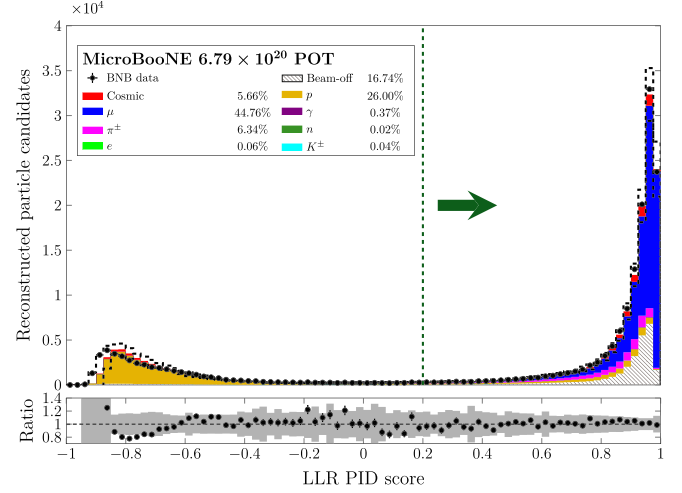


FIG. 5. Log-likelihood ratio particle ID score for reconstructed primary particles under consideration as possible muon candidates. The green arrow points into the region in which muon candidates are accepted by the selection. The percentages in the legend indicate the fraction of reconstructed particles of each type before the illustrated selection is applied. The lower panel shows the ratio of the data to the simulation prediction. The uncertainty on the simulation prediction is represented by the dashed lines in the top panel and the gray region in the bottom panel.

is most proton-like and 1 is most muon-like. Reference [12] describes this particle identification technique in greater detail.

In cases where two or more reconstructed primary particles satisfy these criteria, the one with the highest LLR PID score (most muon-like) is considered the muon candidate.

D. Muon momentum reconstruction quality checks

Three additional selection criteria are applied immediately after the ν_μ CC preselection to ensure adequate reconstruction of the outgoing muon momentum. In order of application, they are as follows:

- (V) The muon candidate track must have a reconstructed end point within the containment volume defined in selection requirement (II). Requiring containment allows for a reliable track-length-based estimate of the muon momentum. This criterion substantially improves the resolution when reconstructing the muon momentum and derived quantities (e.g., δp_T) at the cost of a notable drop in efficiency.
- (VI) Muon momentum estimators based on multiple Coulomb scattering [49] (p_μ^{MCS}) and based on track length [52] (p_μ^{range}) for the muon candidate track must agree with each other within 25%, i.e., they must satisfy the relation

$$\frac{|p_\mu^{\text{range}} - p_\mu^{\text{MCS}}|}{p_\mu^{\text{range}}} < 0.25. \quad (1)$$

This requirement removes events in which only a portion of the full muon track is successfully reconstructed.

- (VII) The track-length-based estimator for the reconstructed muon momentum p_μ^{range} must lie within the limits imposed by requirement (3) from the signal definition: $0.1 \text{ GeV}/c \leq p_\mu^{\text{range}} \leq 1.2 \text{ GeV}/c$.

E. $0\pi Np$ selection

The remaining five criteria from the full $CC0\pi Np$ selection are intended to isolate final states containing zero mesons and one or more protons. In order of application, they are

- (VIII) All reconstructed primary particles must have a track score higher than 0.5 (track-like). This requirement eliminates events containing electromagnetic showers, which are not expected for mesonless ν_μ interactions.
- (IX) At least one reconstructed primary particle that is not the muon candidate must be present in the event. All such particles are considered proton candidates.
- (X) All proton candidates must have reconstructed end points that lie within the containment volume defined in selection requirement (II). This is a quality requirement intended to ensure that a track-length-based estimator of the proton momentum will be valid. Containment of the end point for the muon candidate is already enforced by selection requirement (V).
- (XI) All proton candidates must have an LLR PID score less than 0.2 (see Fig. 6). The chosen cutoff value comes close to optimizing the product of efficiency and purity while maintaining good acceptance of low-momentum protons.
- (XII) The longest proton candidate track must have a length-based momentum estimator p_p^{range} that falls within the limits given in requirement (4) from the signal definition: $0.25 \text{ GeV}/c \leq p_p^{\text{range}} \leq 1.0 \text{ GeV}/c$.

F. Overall selection performance

Events that satisfy all 12 selection requirements described in the previous subsections are considered the $CC0\pi Np$ candidates of interest for this analysis. The full $CC0\pi Np$ selection achieves an estimated overall efficiency of 12.3% and a purity of 78.5%. The evolution of these quantities as each requirement is applied is shown in Table I, as well as the relative efficiency (“Rel. eff.”), which is defined as the ratio of the selection efficiency after the current requirement is applied to the efficiency before it is applied. Equivalently, it is the efficiency calculated considering only those signal events accepted after applying all previous criteria.

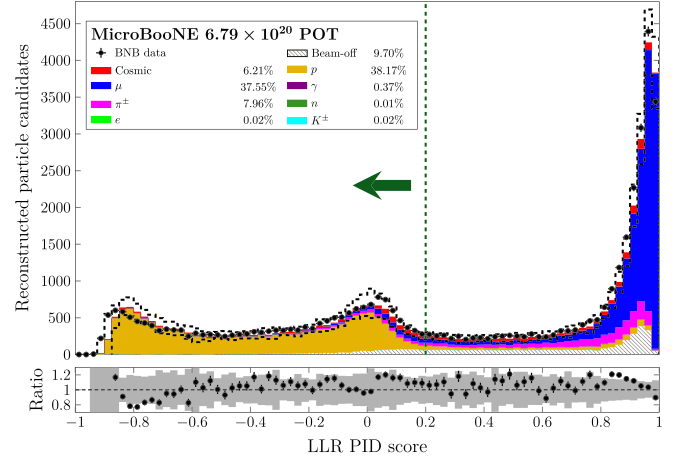


FIG. 6. Log-likelihood ratio particle ID requirement applied to proton candidates in selection requirement (XI). The green arrow points into the region in which proton candidates are accepted. The percentages in the legend indicate the fraction of reconstructed particles of each type before the illustrated selection is applied. The lower panel shows the ratio of the data to the simulation prediction. The uncertainty on the simulation prediction is represented by the dashed lines in the top panel and the gray region in the bottom panel.

IV. DATA PRESENTATION STRATEGY

The selection defined in the previous section is used in the remainder of this article to obtain single- and double-differential cross sections for a variety of kinematic variables. To maximize the usefulness of these measurements for the neutrino interaction modeling community, an innovative strategy for reporting the results has been developed.

TABLE I. Evolution of the selection efficiency, purity, and relative efficiency as the various requirements described in the text are applied.

Requirement	Index	Eff.	Purity	Rel. eff.
No cuts	...	1.0000	0.0230	...
In FV	(I)	0.7817	0.2084	0.7817
Starts contained	(II)	0.7258	0.2114	0.9284
Topological score	(III)	0.6418	0.2945	0.8843
CC incl.	(IV)	0.5720	0.3442	0.8913
μ contained	(V)	0.2381	0.3382	0.4162
μ quality	(VI)	0.1960	0.3967	0.8233
μ momentum limits	(VII)	0.1956	0.4044	0.9977
No showers	(VIII)	0.1716	0.4772	0.8775
Has p candidate	(IX)	0.1514	0.5300	0.8822
p contained	(X)	0.1435	0.5724	0.9482
p PID	(XI)	0.1249	0.7781	0.8700
p momentum limits	(XII)	0.1233	0.7851	0.9872

In previous MicroBooNE cross-section publications, and typically in the experimental neutrino scattering literature as a whole, individual kinematic distributions are treated as entirely separate entities. For example, in the article describing the previous MicroBooNE CC0 π N p analysis [10], single-differential cross sections are shown for both the muon momentum and scattering angle (among several other observables), but the covariance matrices used to report the measurement uncertainties consider only correlations between bins of the same variable. Readers are thus obliged to treat each reported differential cross section as if it were obtained in isolation from all others. This reduces the power of the full multivariable dataset since external users must either ignore correlations between the observables that are known to be important (e.g., those introduced by limited data statistics and systematic uncertainties on the neutrino flux prediction), invent *ad hoc* correlations that may be inaccurate, or consider only a single variable at a time when performing model comparisons. This problem has been encountered and discussed previously in the neutrino interaction literature [53], but standard practices for experimental data releases have not yet been adjusted to address it.

The present analysis overcomes this limitation by providing comprehensive uncertainties for all final results; cross sections are reported in a binning scheme that involves multiple variables, and an overall covariance matrix is computed that accounts for the measurement uncertainties and correlations between all pairs of bins. To avoid double-counting in the cross-section extraction procedure, bins describing the same kinematic distribution are grouped into distinct blocks. As described in the sections that follow, some mathematical operations are applied to each block independently, but the blockwise results are later merged together to form the final group of measurements.

A. Observables measured

Various observables related to the 3-momenta of the outgoing muon ($\mathbf{p}_\mu$) and leading proton ($\mathbf{p}_p$) are measured in this analysis. Studies of subleading protons in the CC0 π N p channel are reserved for later work. In addition to the magnitude of the momentum for the muon (p_μ) and leading proton (p_p) and their scattering angles (θ_μ and θ_p , defined with respect to the neutrino direction $+\hat{\mathbf{z}}$), differential cross sections in several other variables are reported. These include the opening angle $\theta_{\mu p}$ between the muon and leading proton

$$\theta_{\mu p} \equiv \arccos\left(\frac{\mathbf{p}_\mu \cdot \mathbf{p}_p}{p_\mu p_p}\right), \quad (2)$$

as well as the magnitude δp_T of the transverse missing momentum

$$\delta \mathbf{p}_T \equiv \mathbf{p}_\mu^T + \mathbf{p}_p^T. \quad (3)$$

Here, $\mathbf{p}_\mu^T$ is the vector projection of the muon momentum transverse to the neutrino beam direction and $\mathbf{p}_p^T$ is the same for the leading proton. These vectors have magnitudes p_μ^T and p_p^T respectively. One may also describe the angular orientation of $\delta \mathbf{p}_T$ with respect to $\mathbf{p}_\mu^T$ using the angle

$$\delta \alpha_T \equiv \arccos\left(\frac{-\mathbf{p}_\mu^T \cdot \delta \mathbf{p}_T}{p_\mu^T \delta p_T}\right) \quad (4)$$

as well as the vector components

$$\delta p_{T_x} \equiv \frac{(\hat{\mathbf{z}} \times \mathbf{p}_\mu^T) \cdot \delta \mathbf{p}_T}{p_\mu^T} = \delta p_T \cdot \sin \delta \alpha_T \quad (5)$$

and

$$\delta p_{T_y} \equiv \frac{-\mathbf{p}_\mu^T \cdot \delta \mathbf{p}_T}{p_\mu^T} = \delta p_T \cdot \cos \delta \alpha_T, \quad (6)$$

where the hat on $\hat{\mathbf{z}}$ indicates that it is a unit vector.

Measurements of the transverse kinematic imbalance (TKI) variables δp_T , $\delta \alpha_T$ were originally proposed [54] as a means of exploring nuclear effects in neutrino scattering with a reduced dependence on the neutrino energy. Cross sections as a function of these variables for a hydrocarbon target have been reported by the T2K [55] and MINERvA [56] collaborations, the latter also extending [57] the investigation to δp_{T_x} and δp_{T_y} . In response to community interest [58] in measuring these observables using a LArTPC, a recent MicroBooNE analysis reported first neutrino-argon differential cross sections in TKI variables for an exclusive one-proton final state [59], including the first double-differential TKI measurement for neutrino scattering on any nuclear target [60]. The present work reports similar measurements for the more inclusive CC0 π N p signal event topology.

Finally, this analysis measures an estimator p_n for the momentum of the initial struck neutron in the CC interaction. This estimator was proposed in Ref. [61] with similar phenomenological motivations as the TKI variables, but it is calculated using momentum components both transverse and longitudinal to the neutrino beam direction. Specifically, p_n is computed via the expression

$$p_n = \sqrt{\delta p_L^2 + \delta p_T^2} \quad (7)$$

where the reconstructed longitudinal missing momentum δp_L is given by

$$\delta p_L \equiv \frac{R}{2} - \frac{m_f^2 + \delta p_T^2}{2R}. \quad (8)$$

Here

$$m_f \equiv m_{\text{Ar40}} - m_n + B \quad (9)$$

and

$$R \equiv m_{\text{Ar40}} + p_\mu^z + p_p^z - E_\mu - E_p, \quad (10)$$

where $m_{\text{Ar40}} = 37.215526 \text{ GeV}/c^2$ is the mass of the ^{40}Ar nuclear target (not the atomic mass), $m_n = 0.93956541 \text{ GeV}/c^2$ is the mass of a neutron, and $B = 0.02478 \text{ GeV}$ is the assumed average binding energy for a neutron in ^{40}Ar . The longitudinal momentum components and total energies of the muon (p_μ^z, E_μ) and leading proton (p_p^z, E_p) are also used above.

The value of B chosen in the present work is a weighted average of the neutron separation energies E_α given in Table I of Ref. [61] with the shell occupancies n_α used as the weights. An equivalent prescription for carbon (using Table II from the same reference) was adopted to estimate B in a prior MINERvA analysis that studied p_n [56]. The first measured neutrino cross sections in this observable for an argon target were recently reported by MicroBooNE for a one-proton final state [62] assuming a different value $B = 0.0309 \text{ GeV}$ based on a study of electron scattering data [63].

B. Estimation of inefficiency and bin migrations

Corrections for imperfect detector and reconstruction performance in the analysis are applied using an unfolding procedure documented in Sec. VI. The implementation of this procedure requires a description of the relationship between reconstructed and true values of the observables of interest. This relationship is estimated quantitatively by assigning simulated $\text{CC}0\pi Np$ events to two duplicate sets of the bins defined in Table III of the Appendix. The *true bins* contain all simulated $\text{CC}0\pi Np$ events that have true values of the observables that fall within the relevant kinematic limits. The *reconstructed bins* contain those events that pass the full selection and have appropriate reconstructed values of the observables.

With these definitions, the connection between the reconstructed and true observables is described using a *response matrix* Δ , which transforms a prediction of signal event counts in true bins μ into a corresponding prediction in reconstructed bins j . Each element of the response matrix is computed from the MicroBooNE simulation results according to the relation

$$\Delta_{j\mu} \equiv \frac{\phi_{j\mu}}{\phi_\mu}, \quad (11)$$

where ϕ_μ is the total number of signal events in true bin μ and $\phi_{j\mu}$ is the number of signal events which fall

simultaneously into true bin μ and reconstructed bin j . Thus, the response matrix quantifies the effects of both inefficiency and smearing of the observables due to imperfect reconstruction. This matrix is employed in systematic uncertainty estimation and unfolding as described in Secs. V and VI respectively. It is plotted in Sec. IV of the Supplemental Material [64].

One may also quantify the effect of smearing separately from inefficiency by calculating the *migration matrix* M . Each element of this matrix is estimated from simulation via the expression

$$M_{j\mu} = \frac{\phi_{j\mu}}{\sum_{\ell} \phi_{\ell\mu}}, \quad (12)$$

where, to avoid double-counting, the sum over ℓ includes only those reconstructed bins in the block of interest. The migration matrix element $M_{j\mu}$ is thus an estimate of the probability that a selected signal event belonging to true bin μ will be assigned to reconstructed bin j . Plots of the migration matrices for each of the 14 blocks of bins defined in Table III are given in Sec. II of the Supplemental Material [64].

V. UNCERTAINTIES

Systematic uncertainties are estimated by modifying the nominal MicroBooNE simulation and calculating resultant variations in the expected number of selected events n_j in each reconstructed bin j . This expected event count includes contributions from both simulated neutrino interactions and measured constant-in-time backgrounds from beam-off data:

$$n_j = \phi_j + O_j + B_j. \quad (13)$$

Here the expected contents of the j -th reconstructed bin are divided into ϕ_j simulated signal $\text{CC}0\pi Np$ events, O_j measured beam-off background events, and B_j simulated beam-correlated background events.

Uncertainties are quantified using covariance matrices calculated according to a multiple-universe procedure. Under this approach, the covariance between the expected event counts n_a and n_b in the a -th and b -th reconstructed bins is represented by the matrix element

$$V_{ab}^{\text{reco}} = \frac{1}{N_{\text{univ}}} \sum_{u=1}^{N_{\text{univ}}} (n_a^{\text{CV}} - n_a^u)(n_b^{\text{CV}} - n_b^u). \quad (14)$$

Here n_a^{CV} is the total event count in reconstructed bin a predicted by the central-value MicroBooNE simulation. The variable n_a^u is a prediction of the same quantity computed based on an alternate simulation (i.e., in an alternate *universe*) in which some aspect of the models used to describe the neutrino beam, particle interactions, and the

detector response has been changed from the adopted central value. The total number of alternate universes N_{univ} included when computing the average in Eq. (14) depends on the systematic effect of interest. In some cases, only a single variation ($N_{\text{univ}} = 1$) is used. Covariance matrices V_{ab}^{reco} are calculated individually for each source of uncertainty. A total covariance matrix is then obtained by summing the individual contributions.

A. Sources of systematic uncertainty

Several classes of systematic uncertainties are considered in this analysis. Those related to the BNB flux prediction, which include variations related to the horn current and hadron production modeling, follow the treatment developed by the MiniBooNE Collaboration [14]. Flux shape uncertainties are handled in a way which allows the final cross-section results to be reported based upon the predicted BNB ν_μ flux (tabulated in the Supplemental Material [64]) rather than the unknown true flux [65].

The GENIE-based neutrino interaction model and associated uncertainties used by MicroBooNE are documented in a dedicated publication [11]. Following Ref. [59], an additional single-universe variation to the neutrino interaction model is adopted in which an alternative event generator (version 19.02.2 of NuWro [66]) replaces GENIE in the MicroBooNE simulation chain and is used to predict the reconstructed event counts.

Uncertainties related to propagation of the final-state particles emerging from the neutrino interaction are calculated using the Geant4Reweight [67] software package. Systematic variations of the Geant4 [18–20] total cross section model for positive pions, negative pions, and protons are considered. For protons, variations are applied to the elastic and reaction (i.e., total inelastic) channels separately. For pions, the elastic, quasielastic, absorption, single charge-exchange, double charge-exchange, and pion production channels are individually varied.

Systematic uncertainties on the detector response model are calculated for both the MicroBooNE photon detection system and the time projection chamber. For the former, three alternate universes are constructed in which the scintillation light yield, attenuation, and Rayleigh scattering length are individually varied. For the latter, space-charge effects, electron-ion recombination, and data-driven modifications to the simulated wire response [13] are considered.

Fully correlated fractional uncertainties are also applied to the beam-related portion of the reconstructed events ($\phi_j + B_j$) to account for limited precision in the counting of protons delivered to the beam target (2%) and the number of argon atoms in the fiducial volume (1%).

B. Signal model uncertainty

For most of the systematic uncertainties mentioned above, the simulated reconstructed event counts ϕ_j and

B_j are varied directly in each alternate universe. However, since uncertainties related to predicting the $\text{CC}0\pi Np$ signal will only affect the final results via their impact on estimating the detection efficiency and bin migrations, a different treatment is used for neutrino interaction model variations. In this case, the expected number of selected signal events ϕ_j is rewritten in the form

$$\phi_j = \sum_{\mu} \Delta_{j\mu} \phi_{\mu}^{\text{CV}}, \quad (15)$$

where $\Delta_{j\mu}$ is the response matrix element connecting true bin μ and reconstructed bin j . This quantity is varied in each alternate universe, while the expected signal event counts in the μ -th true bin ϕ_{μ}^{CV} are held constant at the central-value prediction (as indicated by the superscript). To avoid double-counting events, the sum over μ includes only those true bins that belong to the same block as the j -th reconstructed bin. Details about the binning scheme and response matrix definition are provided above in Sec. IV.

C. Statistical correlations

The data release strategy outlined in Sec. IV requires a slightly more complicated treatment of statistical uncertainties than has been typical for previous neutrino cross-section analyses. When every measured event belongs to exactly one bin, statistical fluctuations of the bin contents are described by independent Poisson distributions. In that case, the statistical covariance matrix is diagonal, and the variance of each bin is estimated by the number of observed counts.

However, reporting combined measurements over the multiple blocks of bins defined in Table III introduces correlations in the statistical uncertainties because the same event belongs to a unique bin in each block. Fortunately, the derivation of an estimator for the statistical covariance between two arbitrary bins is straightforward. As shown in Sec. III C 1 of Ref. [17], the statistical covariance between any pair of bins is estimated as simply the number of events that fall simultaneously into both of them. In the case of weighted Monte Carlo events, the sum of the squares of the event weights is used rather than the raw event count.

D. Impact on integrated cross section

The flux-averaged total $\text{CC}0\pi Np$ cross section obtained by this analysis is $\sigma = (11.8 \pm 1.2) \times 10^{-38} \text{ cm}^2/\text{Ar}$. The full fractional uncertainty of 9.8% includes contributions from the neutrino flux prediction (6.6%), neutrino interaction modeling (5.1%), detector response modeling (4.1%), beam exposure measurements (2.2%), data statistics (1.4%), estimation of the number of argon atoms in the

fiducial volume (1.1%), modeling of final-state particle propagation (0.9%), and Monte Carlo statistics (0.8%). The data statistical uncertainty includes a contribution from the beam-off measurements used to estimate cosmic-ray backgrounds. The Monte Carlo statistical uncertainty includes a contribution from simulated neutrino-induced backgrounds from the BNB.

For the total cross-section measurement, the additional neutrino interaction modeling uncertainty estimated by using NuWro as an alternative event generator (1.7%) is substantially smaller than the uncertainty arising from GENIE systematic variations (4.8%). However, for many of the differential measurements reported below, the NuWro-based systematic uncertainty is larger. Full covariance matrices giving the contributions of both of these classes of interaction model variations to the total measurement uncertainty are reported in the Supplemental Material [64]. For the detector response model, the uncertainty related to the simulation of electron recombination [68] has a dominant impact on the total cross section result (3.3%).

E. Reconstructed event distributions

As an intermediate step in the analysis, the event selection presented in Sec. III and the uncertainty treatment described above were applied to measure candidate $CC0\pi Np$ event rates in each of the 359 kinematic bins defined in Table III. The measured event rates and associated uncertainties were then used as input to the unfolding procedure defined in Sec. VI to obtain the final cross-section results.

The plots in Figs. 7–14 report the measured event rates (black data points) as a function of reconstructed observables for a total beam exposure of 6.79×10^{20} POT. The error bars on the data points show only the statistical uncertainty. The stacked histograms in the main panel of each plot show the central-value prediction from the MicroBooNE simulation chain. Individual contributions from the event categories defined in Sec. III are shown using the same color scheme as in Fig. 1. The total uncertainty (including statistical and systematic contributions) on the central-value prediction is indicated by the dashed lines. Below the main panel of each plot, the ratio of the data points to the central-value prediction is also shown, and the total uncertainty on the prediction is indicated by the gray band.

Fair agreement between the measured event rates and the MicroBooNE simulation prediction is seen across most of the phase space studied, yielding an overall χ^2 value of 584 for the 359 reconstructed bins. The areas of greatest tension are the muon angular distribution at moderate p_μ (see Fig. 7), as well as the individual and double-differential distributions of p_n and $\theta_{\mu p}$ (see Figs. 9 and 13).

F. Sideband-based validation of background model

Removal of the beam-correlated backgrounds in this analysis relies upon a simulation-based estimate B_j of their contribution to the measured event counts in each reconstructed bin j . A sideband study, described below, was performed to demonstrate that the background predictions from the MicroBooNE simulation are sufficiently precise to obtain the final measurements.

Three sets of alternative selection criteria were developed to enhance sensitivity to the three dominant backgrounds: events outside of the fiducial volume (Out FV, see Sec. III), NC events, and ν_μ charged-current events with one or more final-state pions ($CCN\pi$). In each case, the full $CC0\pi Np$ selection was used as a starting point, and minor adjustments were made to improve acceptance of the background category of interest. By construction, all events which pass at least one set of alternative selection criteria are rejected by the original $CC0\pi Np$ selection. The alternative selection criteria for each class of background are given below.

Out FV: The full $CC0\pi Np$ selection is unaltered except that the event must fail requirement (I) (i.e., the reconstructed neutrino vertex position must lie outside the fiducial volume).

NC: The event must fail requirement (IV) (there must not be a muon candidate). The additional requirements (V)–(VII) applied to the muon candidate are also removed. All other $CC0\pi Np$ selection criteria remain the same. The event must also contain at least two reconstructed primary particles. To allow all of the observables of interest to be defined for such events, the reconstructed primary particle with the longest track length is treated as the muon candidate, while the second-longest is treated as the leading proton candidate. Checks of the simulated NC events that passed the original $CC0\pi Np$ selection revealed that this ordering by track length occurred in a large majority (88%) of cases.

CCN π : The full $CC0\pi Np$ selection is unaltered except that requirement (XI) is reversed; at least one of the proton candidates must have an LLR PID score greater than 0.2 (muon-like).

To assess the adequacy of the background model for this analysis, the logical OR of these three alternative selections was applied to measure event rates. That is, an event was accepted by this combined sideband selection if it satisfied all of the criteria for at least one of the Out-FV-, NC-, or $CCN\pi$ -enhanced selections described above. Good agreement between the MicroBooNE simulation prediction and the sideband data, within the uncertainties defined above, was found across the full phase space defined in Table III. An overall χ^2 value of 304 was obtained for the full set of 359 bins. Based on this successful comparison with the sideband dataset, the background predictions of MicroBooNE's simulation

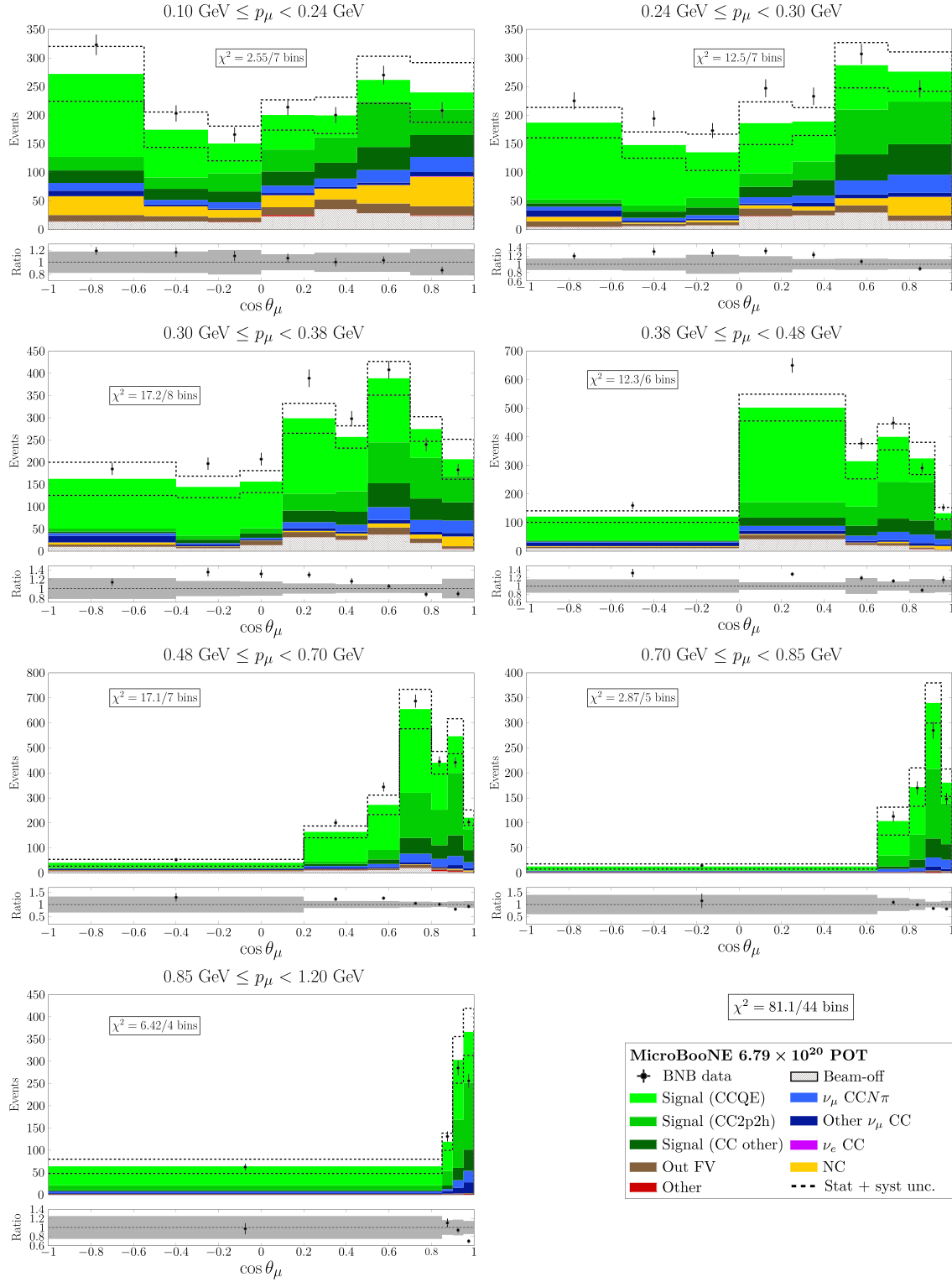


FIG. 7. Reconstructed event distributions for block #0 ($p_\mu, \cos \theta_\mu$). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

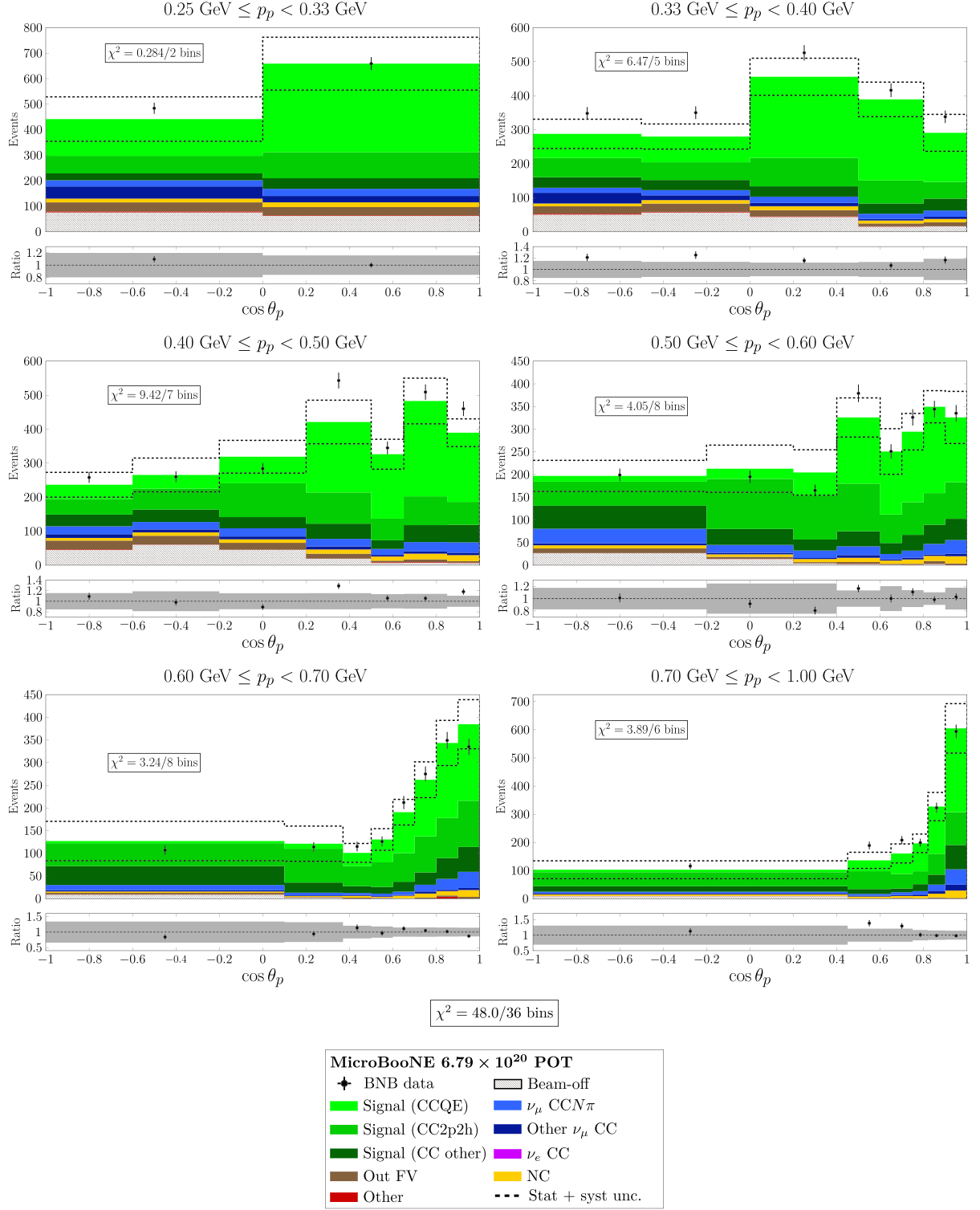


FIG. 8. Reconstructed event distributions for block #1 ($p_p, \cos \theta_p$). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

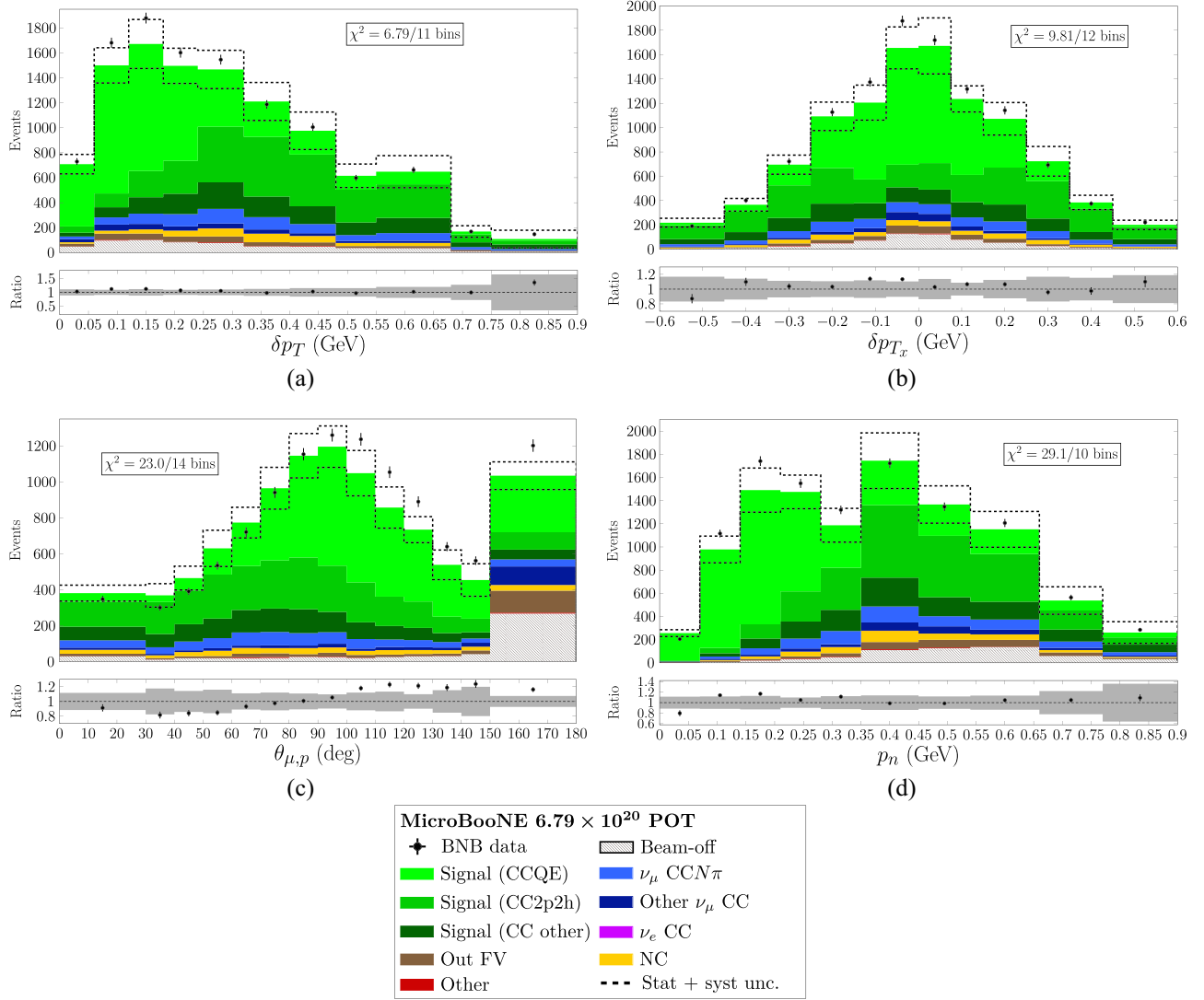


FIG. 9. Reconstructed event distributions for (a) block #2 (δp_T), (b) block #5 (δp_{T_x}), (c) block #7 ($\theta_{\mu,p}$), and (d) block #8 (p_n). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

are used unaltered to obtain the final cross-section results. Plots of the measured and predicted sideband event distributions are provided in Sec. III of the Supplemental Material [64].

VI. CROSS-SECTION EXTRACTION

A neutrino cross-section measurement is ultimately the result of a counting experiment: estimated backgrounds are subtracted from a measured number of events in each bin, and scaling factors are then applied to obtain a quantity with the appropriate units. Corrections to the measured event counts for detector inefficiency and bin migrations (due to imperfect reconstruction) must also be applied via a procedure called *unfolding*. Multiple standard methods for unfolding are described in terms of the matrix transformation

$$\hat{\phi}_\mu = \sum_j U_{\mu j} d_j, \quad (16)$$

where a vector of measured, background-subtracted event counts $\mathbf{d}$ is multiplied by an *unfolding matrix* U to obtain an estimator $\hat{\phi}$ for the vector of true signal event counts. The element of $\mathbf{d}$ corresponding to the j -th reconstructed bin is given by

$$d_j = D_j - O_j - B_j, \quad (17)$$

where D_j is the total number of measured events in the bin, and both O_j and B_j are defined as in Eq. (13). In this context, B_j is evaluated in the central-value universe. The covariance between the measured event counts in the a -th and b -th reconstructed bins is used to calculate the

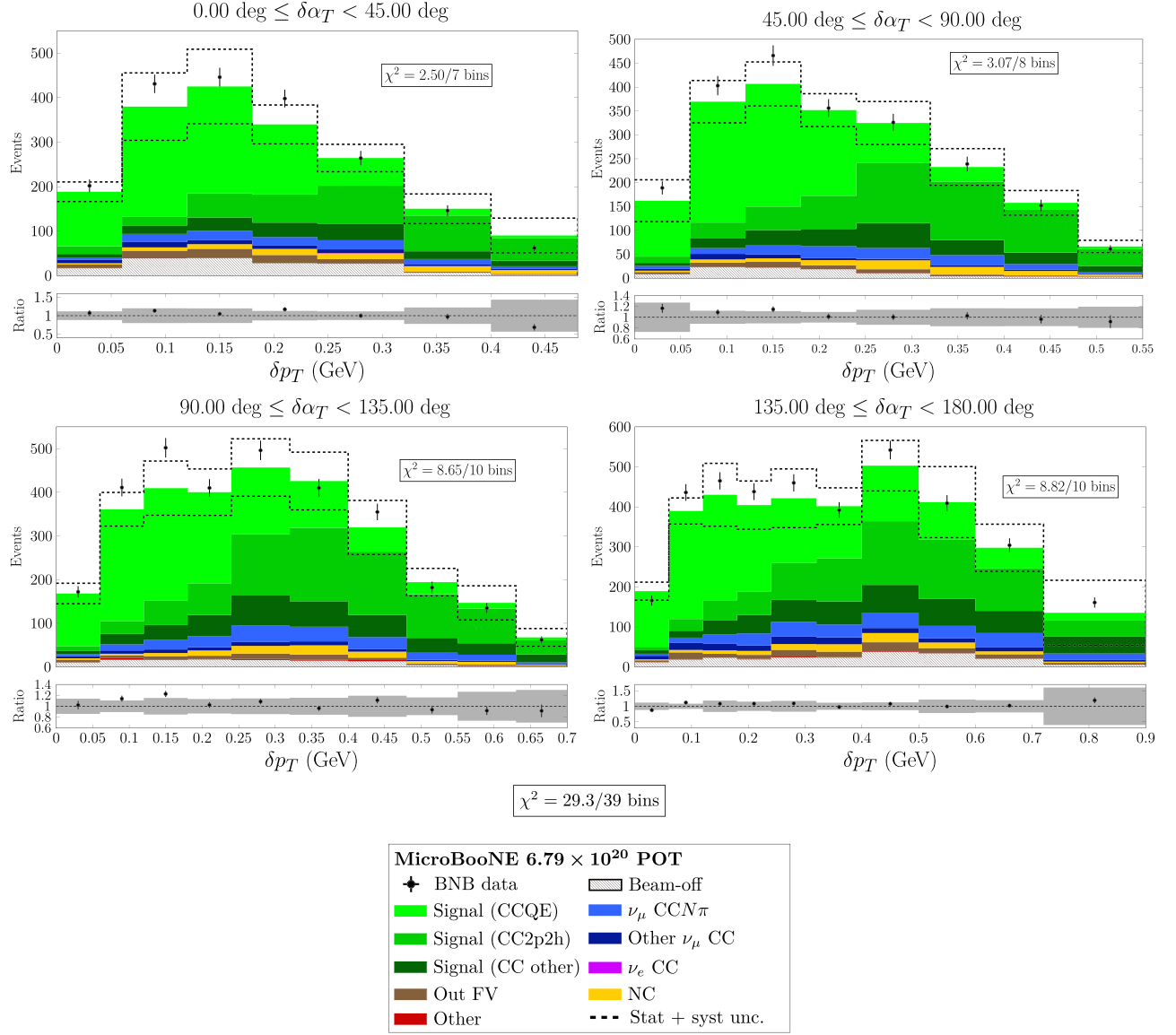


FIG. 10. Reconstructed event distributions for block #3 ($\delta\alpha_T, \delta p_T$). The overall χ^2 value includes contributions from four δp_T overflow bins that are not plotted. The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

covariance between the unfolded event counts in the μ -th and ν -th true bins according to the relation

$$V_{\mu\nu}^{\text{unf}} = \text{Cov}(\hat{\phi}_\mu, \hat{\phi}_\nu) = \sum_{a,b} U_{\mu a} \text{Cov}(d_a, d_b) U_{\nu b}^T. \quad (18)$$

The contribution of systematic uncertainties to the covariance on the background-subtracted measured event counts is estimated from the expected event counts:

$$\text{Cov}(d_a, d_b) \approx \text{Cov}(n_a, n_b) = V_{ab}^{\text{reco}}, \quad (19)$$

where V_{ab}^{reco} is calculated according to the prescription in Eq. (14).

A. The additional smearing matrix A_C

A simple method of unfolding is to directly invert the response matrix Δ via

$$U^{\text{direct}} = (\Delta^T \Delta)^{-1} \Delta^T. \quad (20)$$

However, in most cases of practical interest, this approach leads to strong anticorrelations between bins and large uncertainties. Overcoming these difficulties requires introducing new information (specifically, a prior prediction of the unfolded result) into the otherwise ill-posed unfolding problem. The process of adding this information is known as *regularization*. The various unfolding

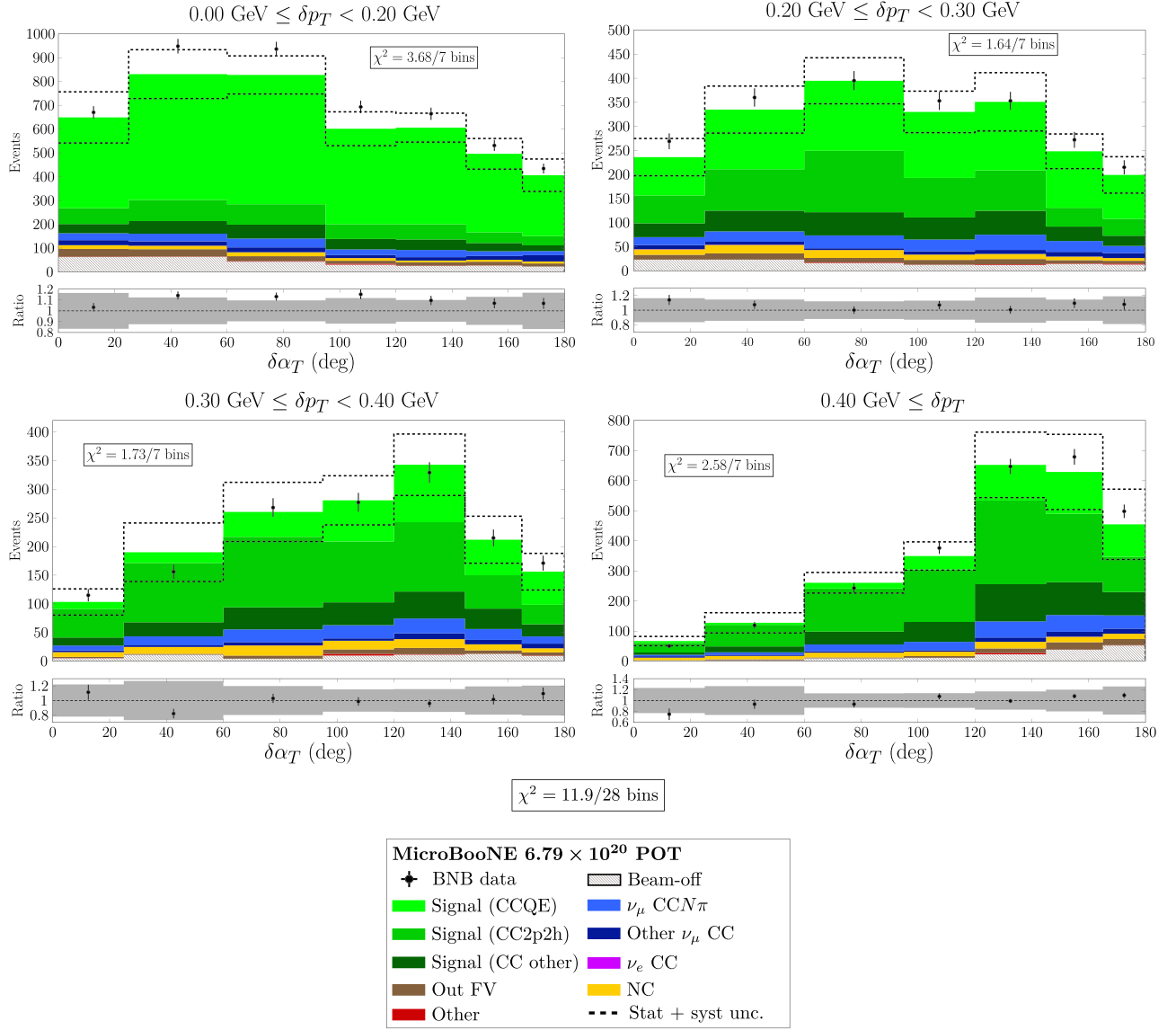


FIG. 11. Reconstructed event distributions for block #4 ($\delta p_T, \delta \alpha_T$). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

techniques defined in the literature differ in their prescriptions for how the regularization should be carried out.

Multiple recent MicroBooNE analyses [15,16,59,60,62,69,70] have used the Wiener-SVD [71] unfolding technique, which is based on an analogy with signal processing: regularization is applied using a “Wiener filter” matrix designed to mitigate “noise” arising from uncertainties on the measurement. The Wiener-SVD method involves explicit construction of an *additional smearing matrix* A_C which is related to the unfolding matrix U via

$$U = A_C \cdot U^{\text{direct}} = A_C \cdot (\Delta^T \Delta)^{-1} \Delta^T. \quad (21)$$

The additional smearing matrix thus encapsulates the effect of regularization on the unfolding procedure. While an expression for A_C specific to the Wiener-SVD method is given in Eq. (3.23) of the original publication [71], it follows from the definition in Eq. (21) that A_C may be calculated for an arbitrary unfolding method via

$$A_C = U \cdot \Delta. \quad (22)$$

Reference [71] also describes a method to avoid introducing new measurement uncertainties related to the unfolding procedure itself. By multiplying theoretical predictions by A_C before quantitative comparisons are made to the unfolded results, the effects of

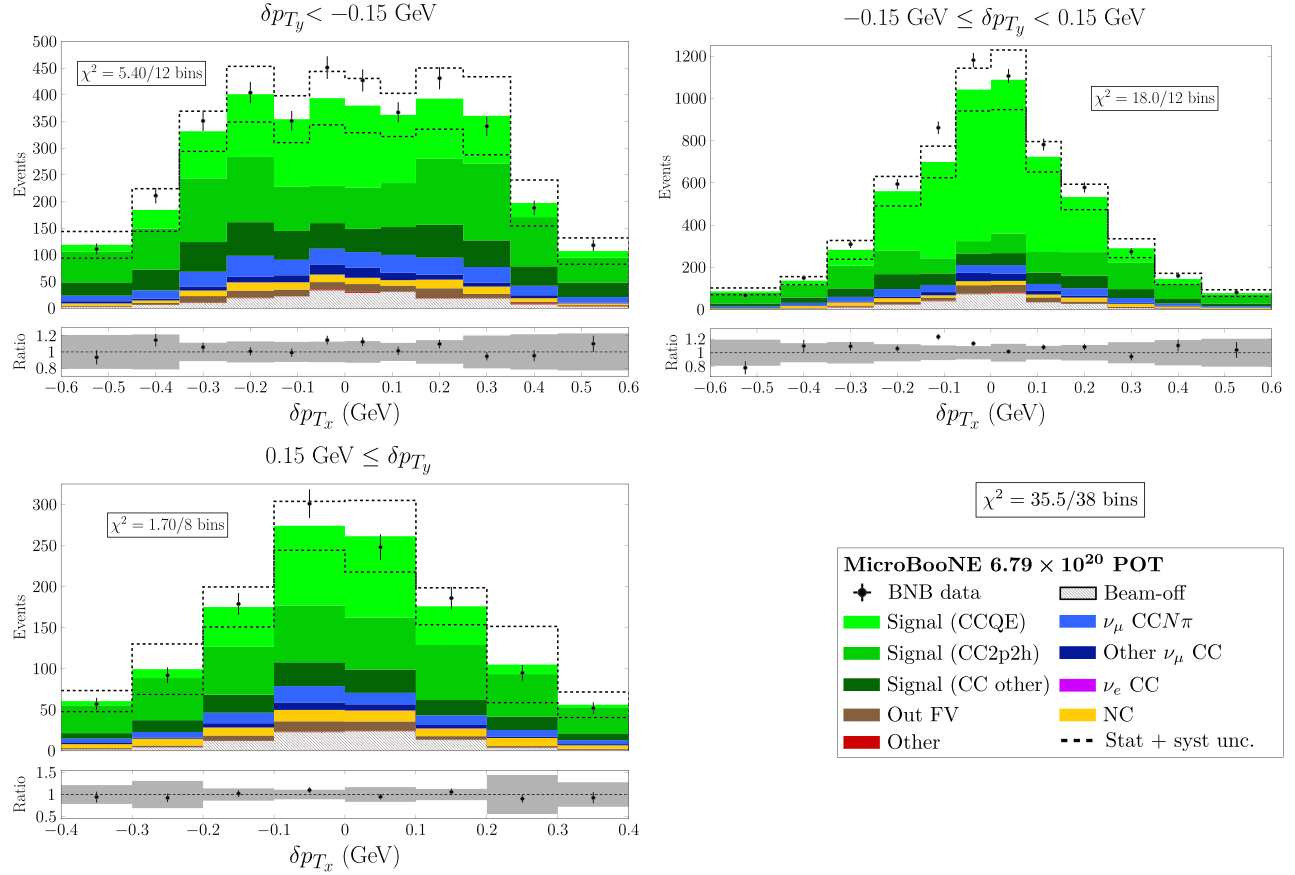


FIG. 12. Reconstructed event distributions for block #6 ($\delta p_{T_y}, \delta p_{T_x}$). The overall χ^2 value includes contributions from three underflow and three overflow δp_{T_x} bins that are not plotted. The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

regularization-related bias on the measurement are properly taken into account. This prescription is followed herein: all model predictions are multiplied by A_C when computing a χ^2 metric for goodness-of-fit with the unfolded data. The elements of the A_C matrix are provided in the Supplemental Material [64] to allow similar calculations for new theoretical predictions.

A helpful feature of the choice to use A_C is that the χ^2 statistic is consistent before and after unfolding. For a vector of predicted event counts ϕ , multiplying by A_C and comparing to the unfolded measurement $\hat{\phi}$ yields the same χ^2 value as applying Δ and comparing to the background-subtracted data $\mathbf{d}$ obtained before unfolding:

$$\chi^2 = (\hat{\phi} - A_C \cdot \phi)^T \cdot (V^{\text{unf}})^{-1} \cdot (\hat{\phi} - A_C \cdot \phi) \quad (23)$$

$$= (\mathbf{d} - \Delta \cdot \phi)^T \cdot (V^{\text{reco}})^{-1} \cdot (\mathbf{d} - \Delta \cdot \phi). \quad (24)$$

The equality of these two expressions for χ^2 follows from the definitions given above. The unfolding strategy used

in this article may therefore be viewed as an aid to data interpretation that preserves the model discrimination power achieved before it was applied.

While model predictions are always multiplied by A_C for all χ^2 calculations in this article, the predictions are shown unaltered in plots of the measured cross sections. This choice, which differs from some prior MicroBooNE publications but matches a recommendation from Ref. [72], is intended to facilitate qualitative interpretation of the results without the need to account for distortions arising from the use of A_C .

B. D'Agostini iterative unfolding

The present work adopts an iterative method of unfolding popularized in high-energy physics by D'Agostini [73]. An initial estimate for the unfolded event counts (iteration $i = 0$) is obtained from the central-value prediction of the MicroBooNE simulation in the true bins:

$$\hat{\phi}_\mu^0 = \phi_\mu^{\text{CV}}. \quad (25)$$

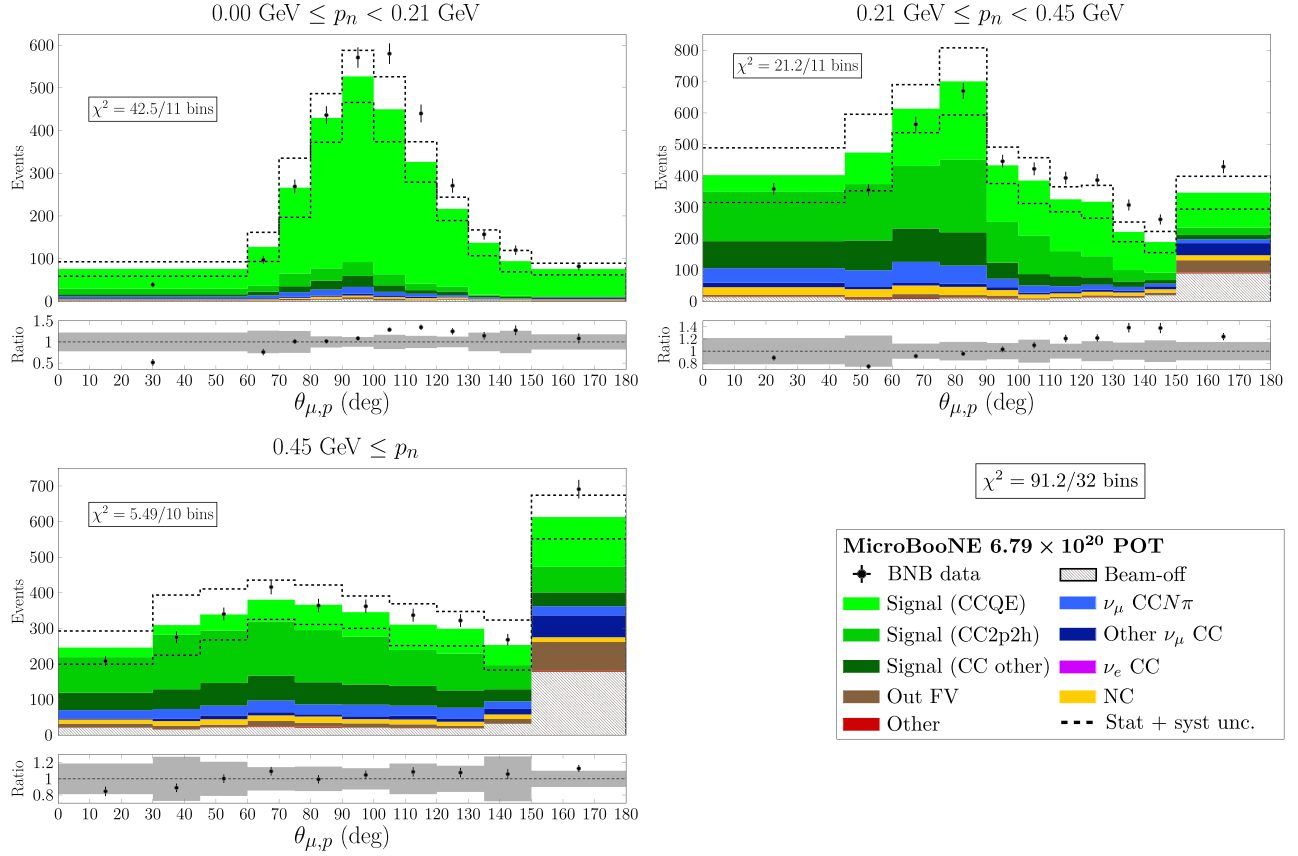


FIG. 13. Reconstructed event distributions for block #9 ($p_n, \theta_{\mu,p}$). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

Superscripts on $\hat{\phi}$ and related quantities are used to denote the number of iterations. Subsequent iterations of the method are used to refine the initial estimate using the measured event rates in each reconstructed bin. This is done via the formula

$$\hat{\phi}_\mu^{i+1} = \sum_j U_{\mu j}^i d_j, \quad (26)$$

where the unfolding matrix element

$$U_{\mu j}^i = \frac{P_{j\mu}^i}{\epsilon_\mu} \quad (27)$$

is defined in terms of the selection efficiency in the μ -th true bin

$$\epsilon_\mu = \sum_\ell \Delta_{\ell\mu} \quad (28)$$

and the conditional probability that a signal event which belongs to the μ -th true bin will be assigned to the j -th reconstructed bin

$$P_{j\mu}^i = \frac{\Delta_{j\mu} \hat{\phi}_\mu^i}{\sum_\nu \Delta_{j\nu} \hat{\phi}_\nu^i}. \quad (29)$$

Uncertainties are propagated through the unfolding procedure according to the expression

$$V_{\mu\nu}^{\text{unf}, i+1} = \text{Cov}(\hat{\phi}_\mu^{i+1}, \hat{\phi}_\nu^{i+1}) = \sum_{a,b} U_{\mu a}^i \text{Cov}(d_a, d_b) U_{\nu b}^i. \quad (30)$$

C. Convergence criterion for unfolding iterations

In the limit of many iterations, the D'Agostini approach converges to the direct inversion result discussed in Sec. VI A. Regularization is thus applied by stopping the method at a finite number of iterations.

Traditionally, the choice of the number of iterations to use in the D'Agostini unfolding method is a critical step of an analysis: one must iterate enough times to avoid a strong bias toward the initial estimate $\hat{\phi}_\mu^0$ for the true event distribution without approaching the direct inversion result too closely. These concerns are addressed in this article by multiplying theoretical predictions by the additional smearing matrix A_C before assessing goodness-of-fit with the unfolded data. The implicit regularization in the D'Agostini method is thus applied to the predictions in a consistent way, avoiding the need to introduce new unfolding-related

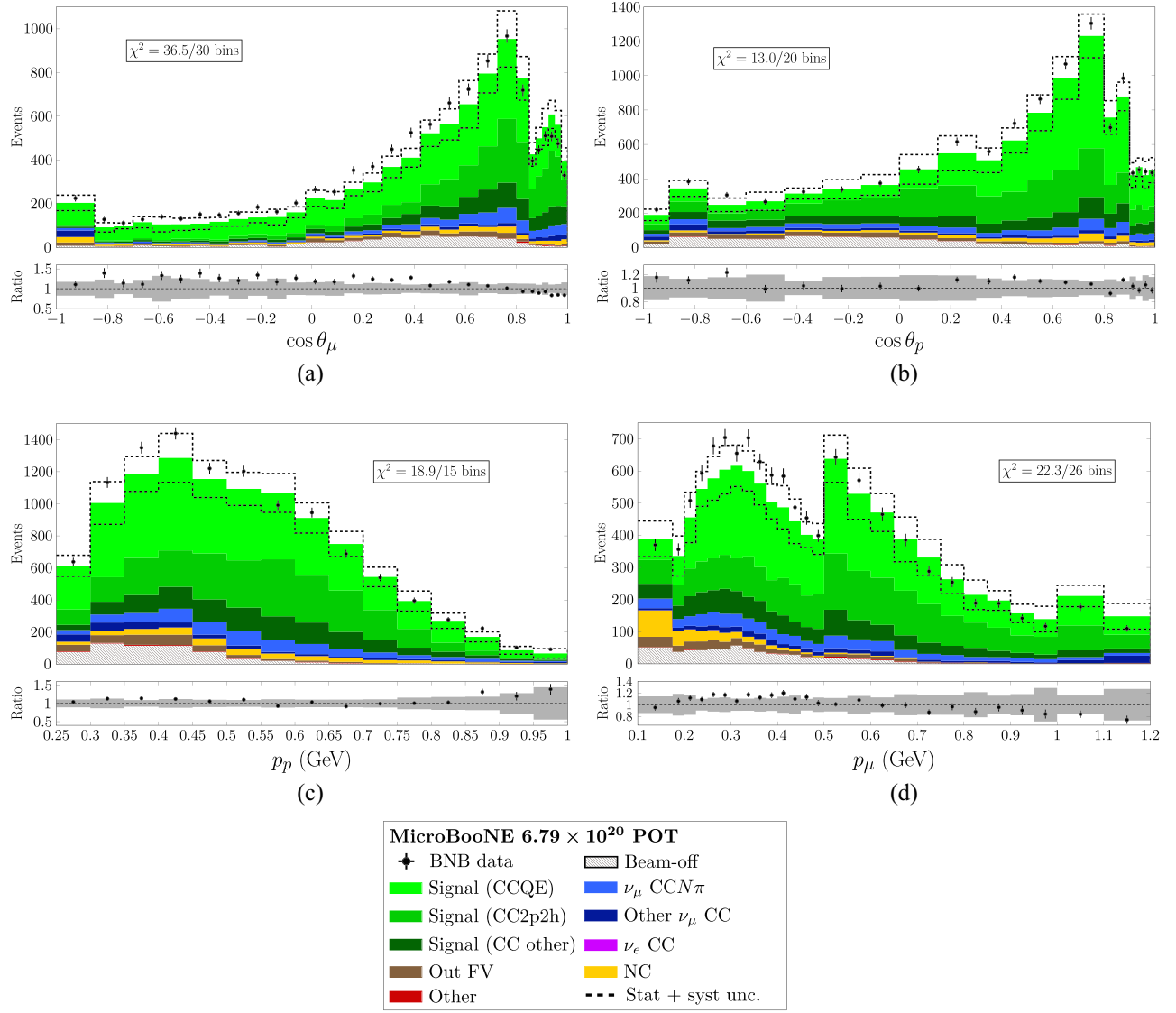


FIG. 14. Reconstructed event distributions for (a) block #10 ($\cos \theta_\mu$), (b) block #11 ($\cos \theta_p$), (c) block #12 (p_p), and (d) block #13 (p_μ). The bottom panel of each plot shows the ratio of the data to the MicroBooNE simulation prediction. The uncertainty on the prediction is represented by the dashed lines in each top panel and the gray region in each bottom panel.

systematic uncertainties. Notably, χ^2 scores calculated according to Eq. (23) are invariant with respect to the number of iterations used.

Nevertheless, even while using A_C , one must choose a definite number of iterations in order to unfold via the D'Agostini approach. In this analysis, the choice is made by continuing to iterate until the average fractional deviation $\mathfrak{F}$ in the T true bins

$$\mathfrak{F} \equiv \frac{1}{T} \sum_{\mu} \frac{|\hat{\phi}_{\mu}^{i+1} - \hat{\phi}_{\mu}^i|}{\hat{\phi}_{\mu}^{i+1}} \quad (31)$$

between neighboring iterations falls below 2.5%. This cutoff was chosen empirically based on the unfolding

performance in fake data studies and the observation that fluctuations of the bin counts at this level will be well covered by typical systematic uncertainties. The fake data studies used to validate the unfolding procedure treated the prediction in the NuWro alternate universe (see Sec. VA) as if it were real data. Recovery of the known true bin counts ϕ_μ predicted by NuWro was verified within the relevant subset of the uncertainties, i.e., only the Monte Carlo statistical and neutrino interaction model systematic uncertainties were included.

D. Blockwise unfolding

The convergence criterion discussed in Sec. VIC leads to between two and five iterations being used to unfold each individual block of bins.

To avoid the double-counting issues mentioned in Sec. IV (e.g., an incorrect calculation of the selection efficiency from the elements of the response matrix Δ), the sums in Eqs. (28), (29), and (31) should be understood to include only true and reconstructed bins within the same block. Also, since Eq. (31) is intended to be an average, T should be interpreted as the number of true bins in the block of interest.

An overall unfolding matrix U used according to Eq. (16) to obtain final results involving all bins is constructed as the direct sum of the blockwise unfolding matrices:

$$U = \bigoplus_b U_b = U_0 \oplus U_1 \oplus \dots$$

$$= \begin{pmatrix} U_0 & 0 & 0 & \dots \\ 0 & U_1 & 0 & \dots \\ 0 & 0 & \ddots & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}. \quad (32)$$

Here U_b is the unfolding matrix for the b -th block of true and reconstructed bins.

E. Decomposition of the blockwise covariance matrices

The covariance matrix $V_{\mu\nu}^{\text{unf}}$ describing the unfolded event counts $\hat{\phi}_\mu$ and $\hat{\phi}_\nu$ [see Eq. (18)] for an individual block of bins can be decomposed into components representing normalization-only, shape-only, and mixed uncertainties according to the relations [74]

$$V_{\mu\nu}^{\text{unf}} = V_{\mu\nu}^{\text{norm}} + V_{\mu\nu}^{\text{shape}} + V_{\mu\nu}^{\text{mixed}}, \quad (33)$$

$$V_{\mu\nu}^{\text{norm}} = \frac{\hat{\phi}_\mu \hat{\phi}_\nu}{\hat{\phi}_{\text{tot}}^2} \sum_{\alpha\beta} V_{\alpha\beta}, \quad (34)$$

$$V_{\mu\nu}^{\text{mixed}} = \frac{\hat{\phi}_\mu}{\hat{\phi}_{\text{tot}}} \sum_\alpha V_{\alpha\nu} + \frac{\hat{\phi}_\nu}{\hat{\phi}_{\text{tot}}} \sum_\alpha V_{\mu\alpha} - 2V_{\mu\nu}^{\text{norm}}, \quad (35)$$

where

$$\hat{\phi}_{\text{tot}} \equiv \sum_\alpha \hat{\phi}_\alpha, \quad (36)$$

and the sums are understood to include all true bins belonging to the block of interest and no others. Note that the same formulas cannot be meaningfully applied to the multiblock covariance matrix due to double-counting when computing the total number of events in Eq. (36). This decomposition of the covariance matrix is used when presenting cross-section results for individual blocks of bins in Sec. VII B.

F. Calculation of differential cross sections

The unfolded event counts $\hat{\phi}_\mu$ from the final iteration provide an estimator for the true number of signal events in the μ -th bin. They may be converted to a flux-averaged differential cross section according to the formula

$$\left\langle \frac{d^n \sigma}{d\mathbf{x}} \right\rangle_\mu = \frac{\hat{\phi}_\mu}{\Phi \mathcal{N}_{\text{Ar}} \Delta \mathbf{x}_\mu} \quad (37)$$

where $\Phi = 5.00846 \times 10^{11} \nu_\mu/\text{cm}^2$ is the integrated flux of muon neutrinos calculated for the beam exposure (6.79×10^{20} POT) used in the analysis, $\mathcal{N}_{\text{Ar}} = 7.99249 \times 10^{29}$ is the number of argon nuclei in the fiducial volume, and $\Delta \mathbf{x}_\mu$ is the product of the n widths of the μ -th bin of the n -dimensional measurement.

The covariance between the n - and m -dimensional differential cross sections in the μ -th and ν -th true bins is likewise given by

$$\text{Cov} \left(\left\langle \frac{d^n \sigma}{d\mathbf{x}} \right\rangle_\mu, \left\langle \frac{d^m \sigma}{d\mathbf{y}} \right\rangle_\nu \right) = \frac{\text{Cov}(\hat{\phi}_\mu, \hat{\phi}_\nu)}{\Phi^2 \mathcal{N}_{\text{Ar}}^2 \Delta \mathbf{x}_\mu \Delta \mathbf{y}_\nu}. \quad (38)$$

VII. RESULTS

The measurements shown in the remainder of this article are flux-averaged differential $\text{CC}0\pi Np$ cross sections obtained via the unfolding procedure presented above. Several event generator predictions are compared to the data using NUISANCE [75], and goodness-of-fit is quantified for the dataset as a whole and for the individual blocks of kinematic bins listed in Table III.

In Sec. I of the Supplemental Material [64], the full 359-bin dataset is presented in terms of flux-averaged total cross sections integrated over each bin (trivially obtainable by multiplying by the bin widths $\Delta \mathbf{x}_\mu$). This allows the measured cross sections and the covariance matrix elements for all observables to be expressed using consistent units.

A. Interaction models

In addition to the MicroBooNE Tune model described in Sec. II A and used to execute the analysis, the predictions of several other simulation-based neutrino interaction models are compared to the measured cross-section results. These models include multiple configurations of GENIE as well as three alternative neutrino event generators.

The GENIE-based prediction labeled *GENIE 3.0.6* is produced using the same code version and model set (G18_10a_02_11a) as the MicroBooNE Tune, but the custom MicroBooNE-specific modifications described in Ref. [11] are omitted. The *GENIE 2.12.10* prediction uses a near-default configuration of this older version of the code, which includes the Bodek-Ritchie Fermi gas description of the nuclear ground state [76], the Llewellyn Smith CCQE calculation [77], an empirical model for $2p2h$

interactions [78], the Rein-Sehgal treatment of RES and COH scattering [79], and the hA FSI model [80,81]. The modeling ingredients in *GENIE 3.2.0 G18_02a*, which uses the default configuration (*G18_02a_00_000*) of this recent GENIE release, are largely similar to GENIE 2.12.10. In addition to code updates, however, the KLN-BS RES model [30–33], Berger-Sehgal COH model [37], and hA2018 FSI model [38] replace their prior counterparts. The empirical 2p2h model was also adjusted between GENIE versions, leading to substantially reduced strength for this channel in GENIE 3.2.0 G18_02a relative to GENIE 2.12.10. A final configuration, *GENIE 3.2.0 G21_11b*, uses the more recently added *G21_11b_00_000* model set, which adopts the SuSAv2 calculation [82–85] of CCQE and 2p2h cross sections as well as the hN2018 FSI model [38]. The remaining components of the model set are similar to GENIE 3.0.6.

The first prediction of an alternate neutrino event generator, *NuWro 21.09.2*, uses the NuWro [66] implementations of the LFG nuclear ground state [24], the Llewellyn Smith CCQE model [77], a transverse enhancement treatment of 2p2h interactions [86], the Adler-Rarita-Schwinger treatment of Δ resonance production [33], the Berger-Sehgal COH model [37] and an intranuclear cascade approach to FSI. We also consider a variation of this model called *NuWro 21.09.2 SF*, in which a factorized spectral function [87] (SF) replaces the LFG for quasi-elastic events only. A more sophisticated spectral function model based on measurements by the Jefferson Lab Hall A Collaboration [88,89] has recently been implemented by the NuWro authors [90]. However, it is not yet available in a public NuWro release.

A comparison to *NEUT 5.6.0* is also provided, in which the NEUT event generator [91,92] is configured to use an LFG nuclear model [24], the Valencia model for CCQE and 2p2h [25–29], the KLN-BS RES calculation [30–33], the Berger-Sehgal COH model [37], and an FSI cascade treatment with nuclear medium corrections for pions [93].

Finally, a prediction from the GiBUU event generator [94] (labeled *GiBUU 2021.1*) is studied using the 2021 “patch 1” release of the code announced to users on 5 November 2021. Ingredients of the GiBUU physics model include an LFG representation of the nuclear ground state [24], a standard expression for the neutrino-nucleon CCQE cross section [95], an empirical 2p2h model, a treatment of RES based upon the MAID analysis [96], and a DIS model from PYTHIA [97]. A unique feature of the code is its dynamical model of intranuclear hadron transport based upon numerical solution of the Boltzmann-Uehling-Uhlenbeck equation. A consistent nuclear potential is used in both the description of the target nucleus and FSI.

The χ^2 metric used to assess goodness-of-fit when comparing these models to data accounts for the total covariance matrix associated with the measurements but neglects any theoretical uncertainties on the predictions

themselves. Documentation needed to enable new comparisons beyond those shown here is provided in Sec. I of the Supplemental Material [64]. The dataset from this article has also recently been incorporated into the NUISANCE [75] software framework for convenient use by the neutrino interaction modeling community.

B. Differential cross-section results

Figures 15–28 present the final results of the analysis as flux-averaged differential cross sections. The measurements are compared to the event generator models described above, each rendered in the plots as a distinct colored line. The legends accompanying each figure list the models together with their overall χ^2 scores describing the level of agreement with data. Each χ^2 score is separated from the number of bins for which it was calculated by a / character. A separate figure is included for each block of bins defined in Table III.

Following recent MicroBooNE publications that report cross sections for an exclusive single-proton final state [59,60,62], the covariance matrix decomposition described in Sec. VI E is applied when displaying the measurement uncertainties. For the data points shown in each plot, the inner error bars represent the statistical uncertainty only, while the outer error bars also include shape-only systematic uncertainties. The remaining portion of the total uncertainty, composed of both normalization and mixed terms, is shown by the gray band along the x -axis.

Table II presents the χ^2 scores quantifying goodness-of-fit with the full group of measurements for each of the event generator models studied. None of the simulation predictions provides a satisfactory treatment of the entire dataset ($\chi^2 \approx 1/\text{bin}$). The best χ^2 value is obtained by the GENIE 3.0.6 calculation, although poor agreement is seen between this model and the data in some of the individual blocks of bins, and its prediction is seen to be systematically low across the entire measured phase space. The modest preference for GENIE 3.0.6 may thus be attributed to a manifestation of Peelle’s pertinent puzzle [98] (in which

TABLE II. Overall χ^2 scores for each of the neutrino interaction models studied.

Model	$\chi^2/359$ bins
GENIE 3.0.6	576
MicroBooNE Tune	584
NEUT 5.6.0	1780
GENIE 3.2.0 G18_02a	3905
GiBUU 2021.1	4069
NuWro 21.09.2	4076
GENIE 3.2.0 G21_11b	4815
NuWro 21.09.2 SF	5515
GENIE 2.12.10	10327

implausibly low predictions are favored using a least-squares metric like χ^2) rather than a particularly high-quality description of the data. The notably larger χ^2 value seen for GENIE 2.12.10 compared to all other models may

be at least partially attributed to mismodeling of the elastic channel in the hA FSI model, which leads to strong distortions in the distributions of TKI variables [99]. As shown in the plots below, GiBUU 2021.1 has the best χ^2

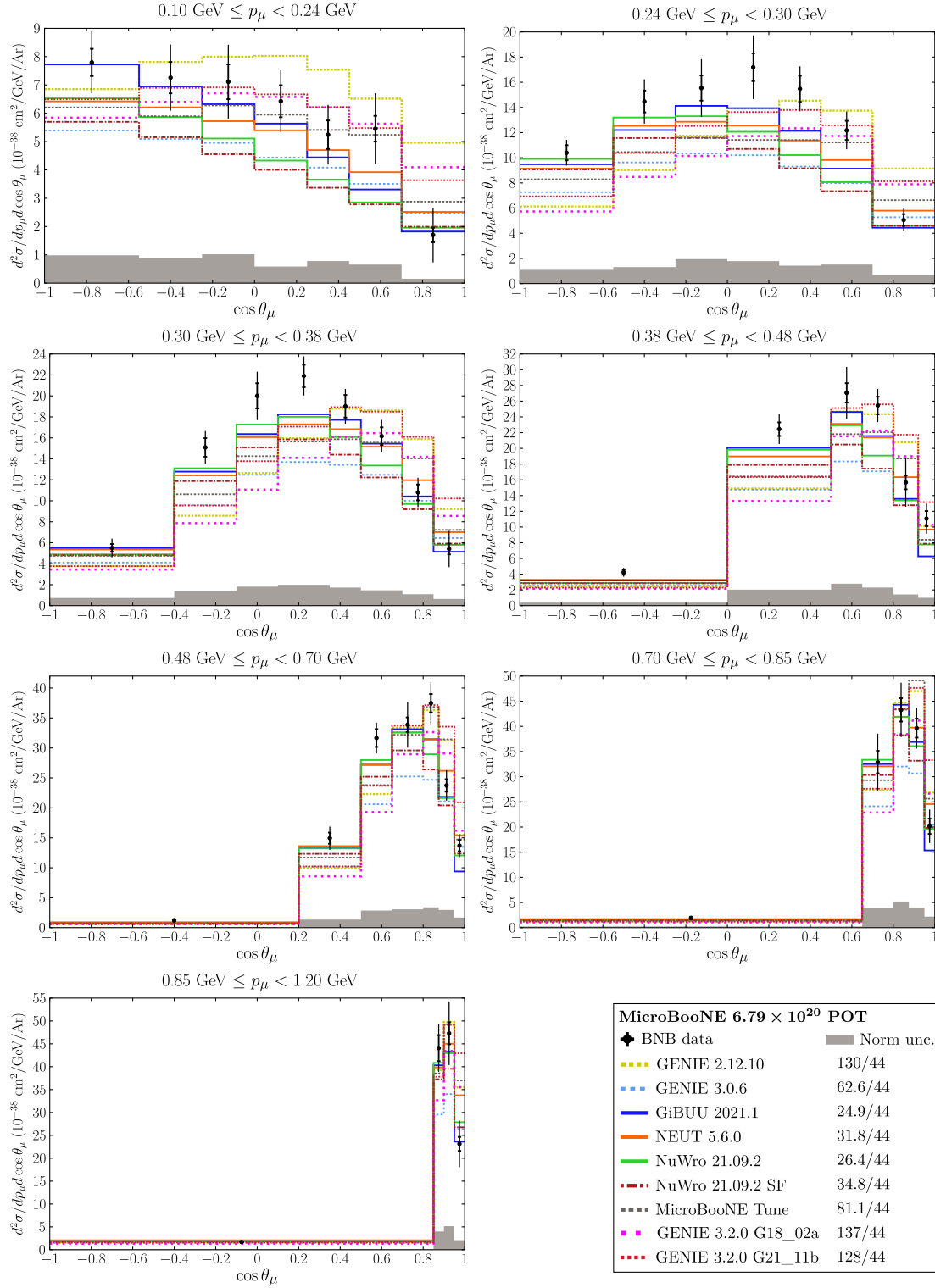


FIG. 15. Measured differential cross sections for block #0 ($p_\mu, \cos \theta_\mu$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

score for several of the individual blocks of bins despite performing more poorly when confronted with the combined results. Another notable pattern in the results is the relative performance of the NuWro prediction that includes

an SF nuclear model (NuWro 21.09.2 SF) compared to the default LFG (NuWro 21.09.2). While the LFG treatment achieves a somewhat lower χ^2 score for the measured cross sections that involve only the muon kinematics, the SF

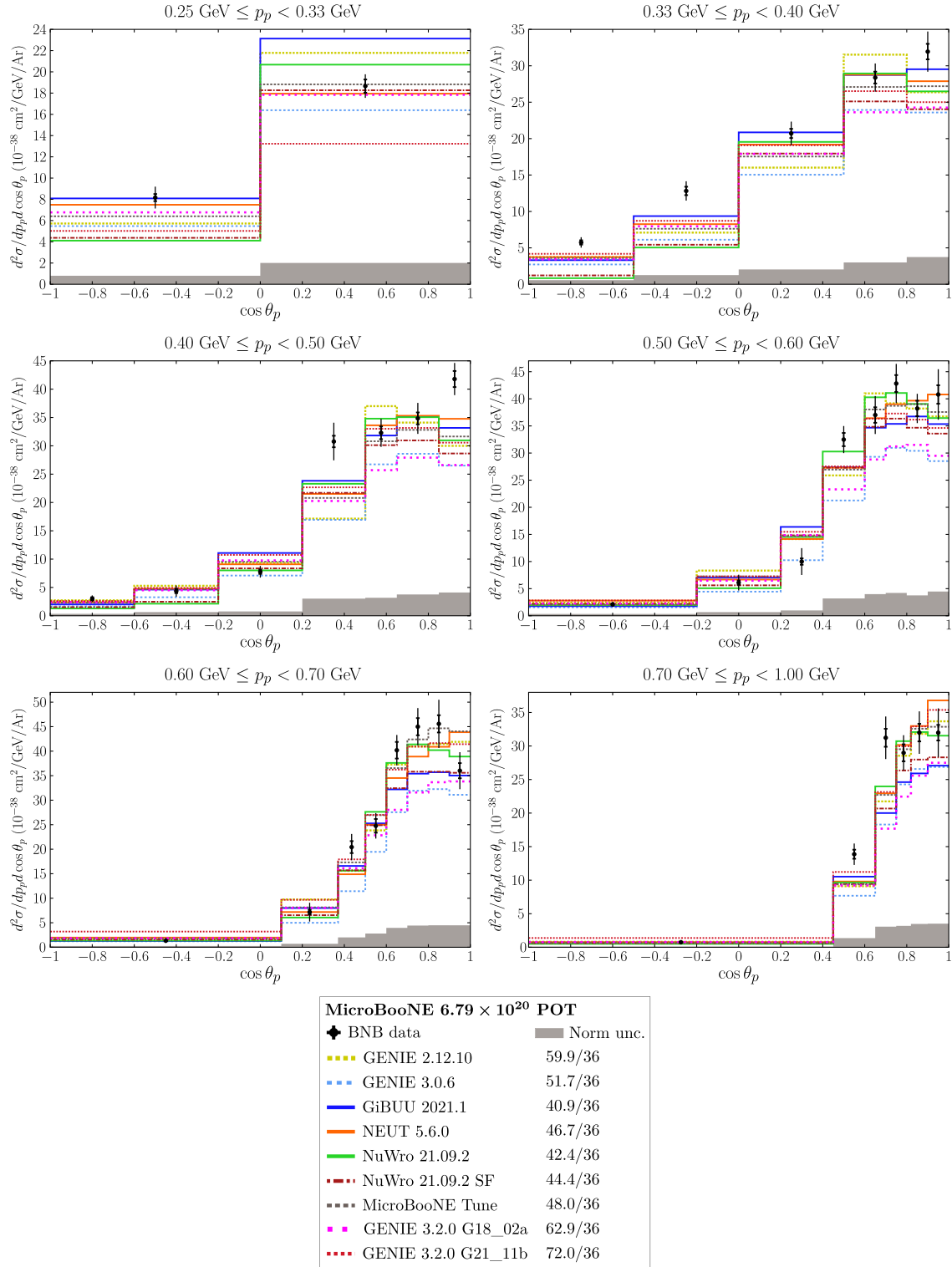


FIG. 16. Measured differential cross sections for block #1 (p_p , $\cos \theta_p$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

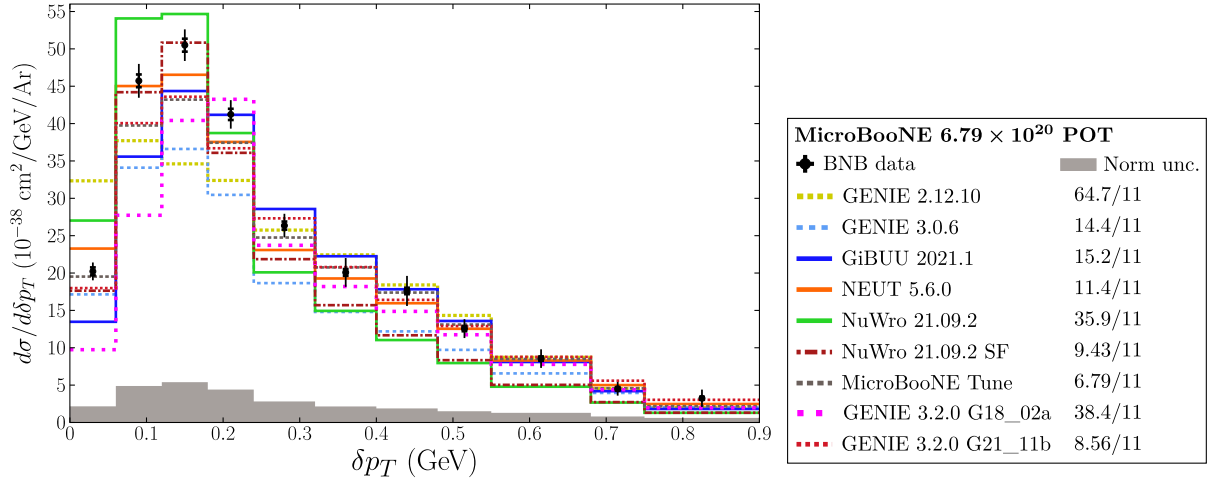


FIG. 17. Measured differential cross sections for block #2 (δp_T). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x-axis.

model has much better goodness-of-fit for all measurements of TKI variables and p_n .

Figure 15 presents the double-differential cross-section measurement in terms of muon momentum (p_μ) and scattering angle (θ_μ) obtained using the kinematic bins from block #0. All of the GENIE-based models studied fit this distribution more poorly than the alternative event generators, with the GiBUU 2021.1 and NuWro 21.09.2 models achieving the best agreement. A feature that partially explains the numerical results is the tendency for the non-GENIE event generators to have larger predictions in the region of moderate p_μ (especially between 0.3 and 0.38 GeV/c) and intermediate scattering angles. Interestingly, the data are compatible with an even larger cross section in this region, to the extent that all studied predictions lie noticeably below the measured central value in several relevant bins.

Figure 16 presents the double-differential cross-section measurement in terms of the leading proton momentum (p_p) and scattering angle (θ_p) obtained using the bins from block #1. Here the GENIE-based MicroBooNE Tune model has a χ^2 score that comes close to some of the alternative event generators, but there are still several bins where all models studied substantially underpredict the data. Significant model differences are seen in the shape of the forward-angle region at moderate and high p_p , but the systematic uncertainty of the present measurement allows for only limited sensitivity to these details.

Figure 17 shows the single-differential cross section in the transverse momentum imbalance δp_T as obtained from the analysis bins in block #2. While the two NuWro predictions at low- δp_T are substantially different, they become indistinguishable for high values of this observable. Because the low- δp_T region is dominated by CCQE

events without proton FSI, it is particularly sensitive to details of the nuclear ground state, and the data show a preference for the more sophisticated SF description (dot-dashed red) over the LFG (solid green) when controlling for other effects. Despite its use of an LFG nuclear model, however, the MicroBooNE Tune nevertheless achieves the best overall χ^2 score for this distribution. This is largely due to its good agreement with data in the high- δp_T tail, which contains CCQE events with FSI as well as more inelastic interaction modes. A possible explanation for the poorer NuWro performance in the tail is therefore an underestimation of FSI effects.

A double-differential result in which the δp_T measurement is subdivided into four $\delta \alpha_T$ bins (as defined in block #3) is plotted in Fig. 18. Here the same trend towards greater agreement between the two NuWro predictions as δp_T increases is seen in each $\delta \alpha_T$ region and has a similar interpretation. The deficit in the prediction of the GENIE 3.2.0 G18_02a model at low- δp_T , already present in the one-dimensional results from Fig. 17, is now seen to be roughly consistent across all bins of $\delta \alpha_T$, which is suggestive of missing CCQE strength. In the moderate δp_T region of the highest $\delta \alpha_T$ bin, a significant separation can be seen between the GiBUU 2021.1, MicroBooNE Tune, and NEUT 5.6.0 predictions, all of which have a relatively low χ^2 score for this distribution. These models differ in the relative contributions of QE and 2p2h that they predict in this portion of phase space (see Sec. VII of the Supplemental Material [64]), with GiBUU favoring an especially strong 2p2h component, NEUT preferring a high fraction of QE, and the GENIE-based MicroBooNE Tune falling between the two extremes. Although the potential for model discrimination using a measurement similar to this one has been noted in previous work [58] [Fig. 5(d)], the data points obtained from this analysis do not show a clear

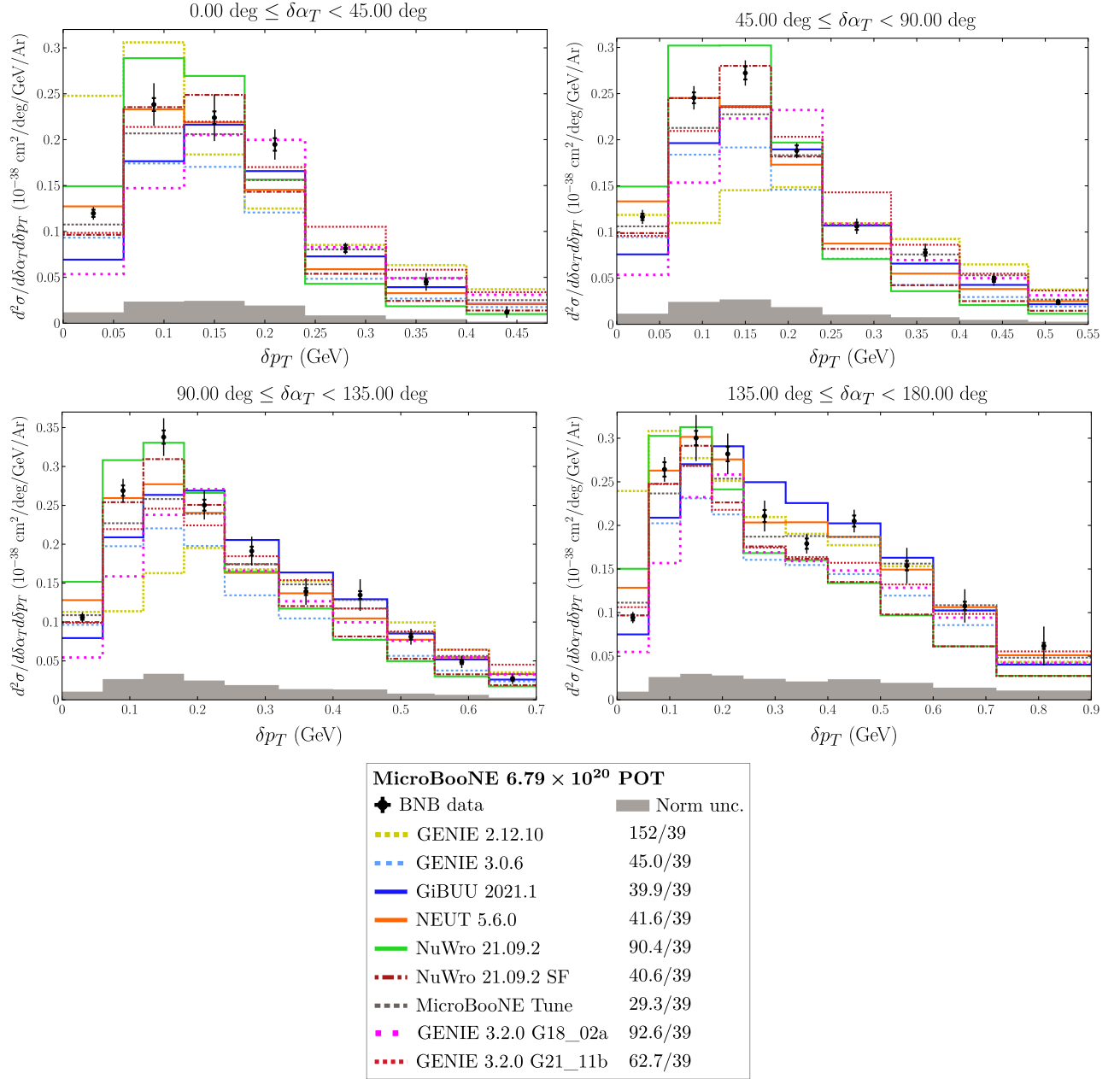


FIG. 18. Measured differential cross sections for block #3 ($\delta\alpha_T, \delta p_T$). The overall χ^2 value includes contributions from four δp_T overflow bins that are not plotted. Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

preference for any of these three models in the moderate δp_T bins at high $\delta\alpha_T$.

In Fig. 19, the bins from block #4 are used to report a measurement of double-differential $\delta\alpha_T$ distributions in four coarse bins of δp_T . Here the NuWro 21.09.2 SF model describes the data well at low- δp_T but substantially underestimates at high- δp_T . The poor χ^2 seen for GENIE 2.12.10 in the previous TKI measurements is especially simple to diagnose in this block of bins: the peaks seen at extreme $\delta\alpha_T$ values in the lowest δp_T bin

are symptomatic of a problem in the treatment of elastic FSI in the GENIE hA model [99]. The problem was resolved for the GENIE version 3 release series by removing the elastic channel from the newer hA2018 FSI model.

Figure 20 presents a single-differential cross-section measurement in δp_{T_x} , the component of $\delta \mathbf{p}_T$ that is orthogonal to the transverse projection of the outgoing muon momentum. The distribution of δp_{T_x} is nearly symmetric around zero, and the GiBUU 2021.1 model

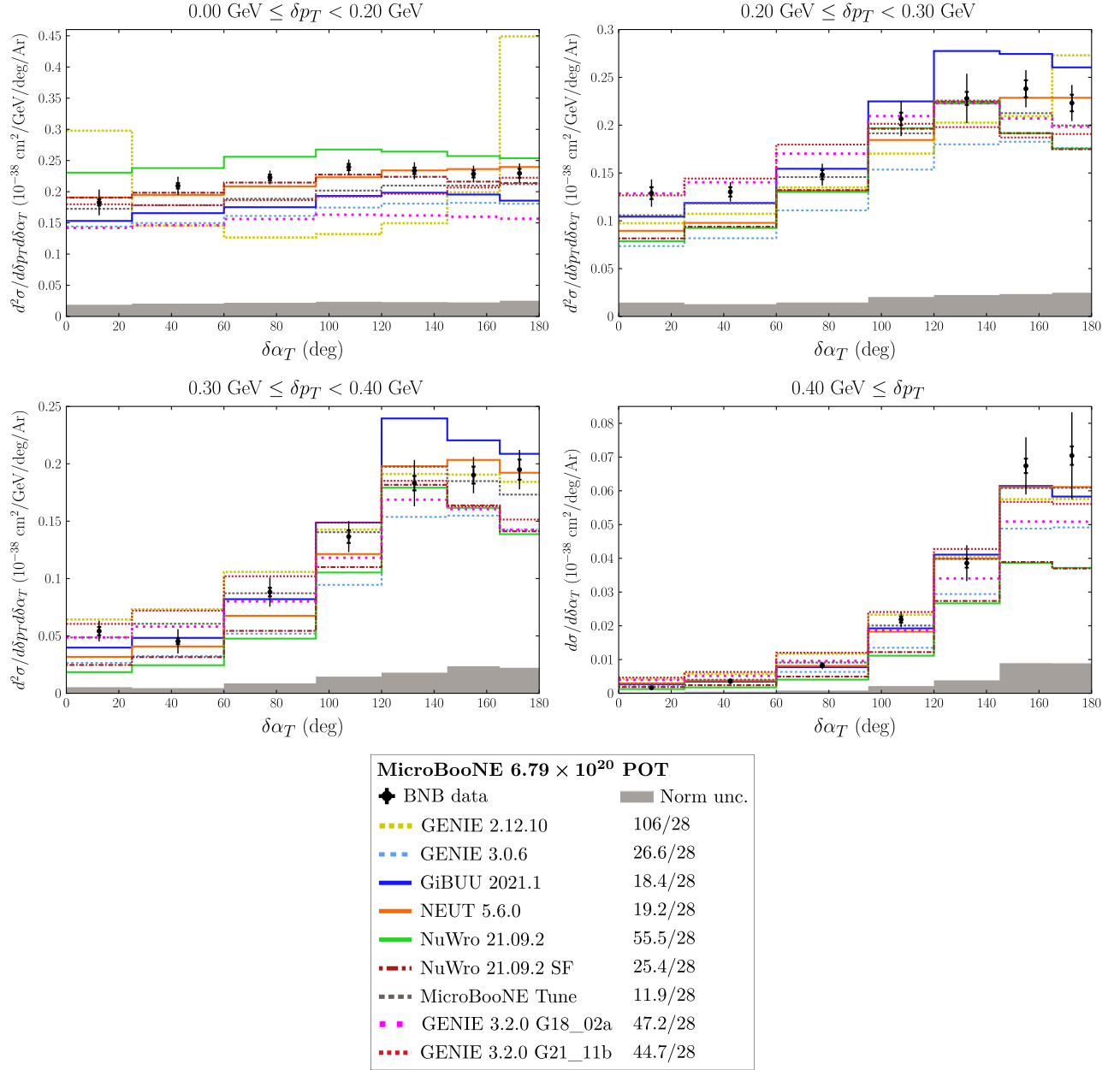


FIG. 19. Measured differential cross sections for block #4 ($\delta p_T, \delta \alpha_T$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

provides a particularly good description of this observable apart from a modest underestimation of the QE-rich peak. Figure 21 subdivides this measurement into three coarse bins of δp_{T_y} , the other component of $\delta \mathbf{p}_T$. Here the effects of FSI enhance the cross section in the region where δp_{T_y} is negative. Once again, a strong preference for the SF over the LFG is seen when comparing the two NuWro predictions, with the former achieving a χ^2 that is nearly a factor of two lower. In the FSI-enhanced low- δp_{T_y} bin, however, the choice of SF versus LFG makes almost no difference, and both NuWro

predictions fall noticeably below the data across the entire range of δp_{T_x} .

Figure 22 displays the measured single-differential $CC0\pi Np$ cross section in bins of $\theta_{\mu p}$, the opening angle between the outgoing muon and leading proton. Although all of the interaction models studied in this article agree on the rough shape of this angular distribution, the position of the peak is sensitive to the relative contributions of QE and 2p2h events, as seen in the lower-left panel of Fig. 9. The data points provide a peak location that is shifted slightly to the right of the bulk of the event generator predictions.

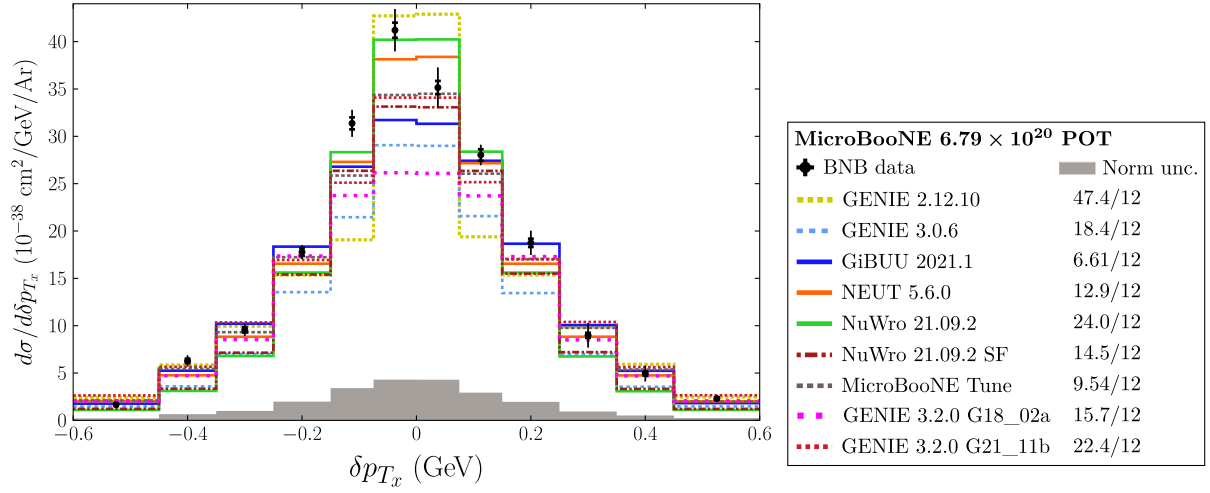


FIG. 20. Measured differential cross sections for block #5 (δp_{Tx}). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

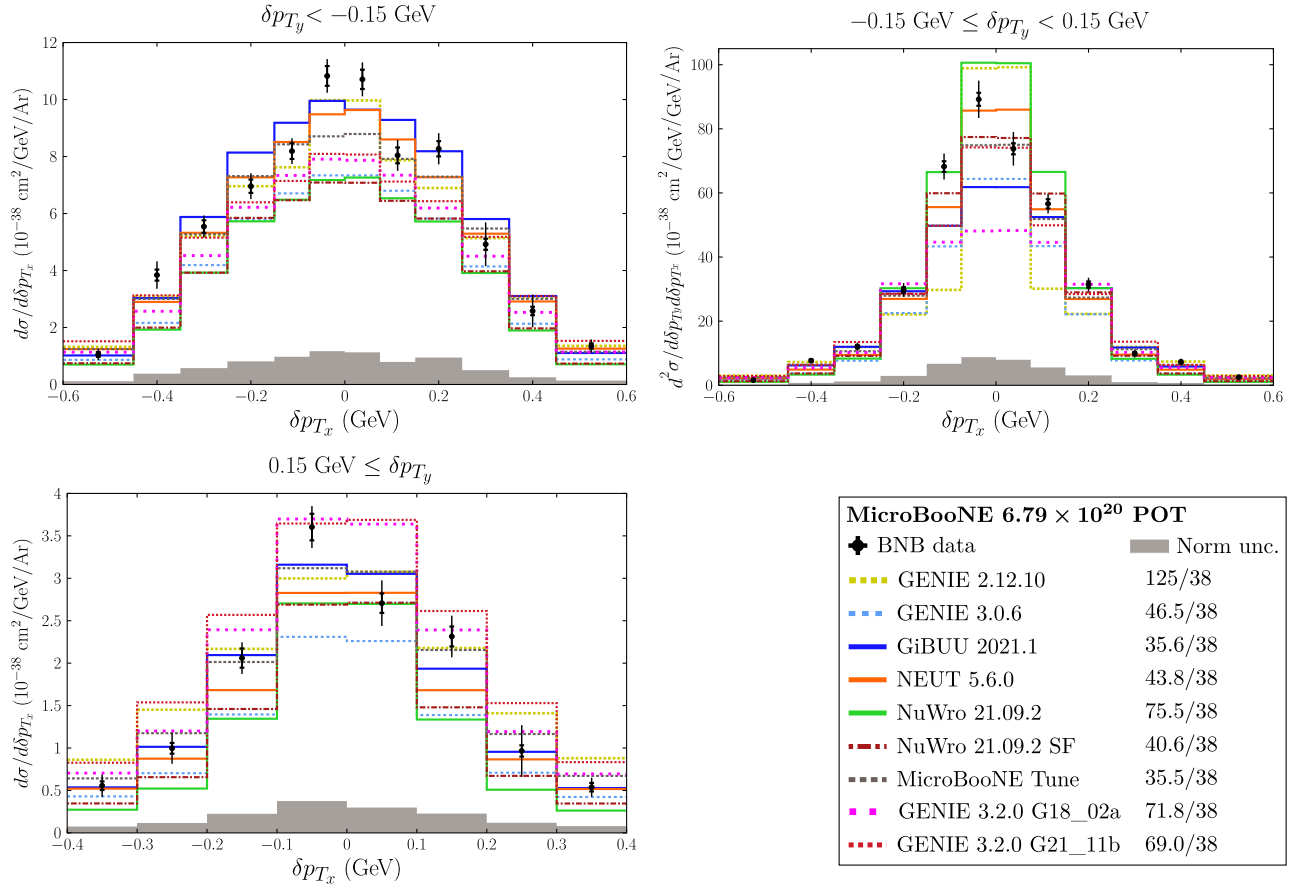


FIG. 21. Measured differential cross sections for block #6 ($\delta p_{Ty}, \delta p_{Tx}$). The overall χ^2 value includes contributions from three underflow and three overflow δp_{Tx} bins that are not plotted. Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

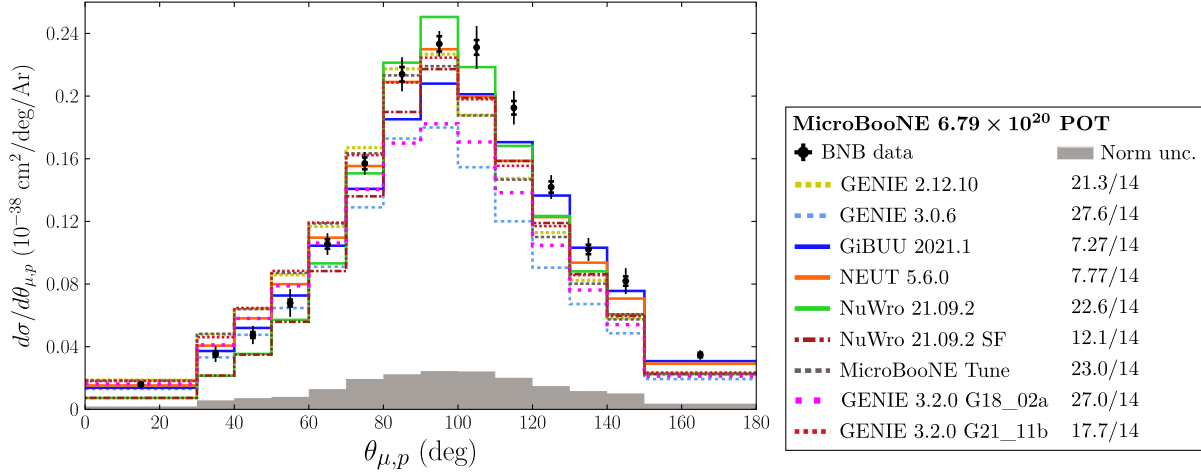


FIG. 22. Measured differential cross sections for block #7 ($\theta_{\mu,p}$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x-axis.

Interestingly, despite predicting very different 2p2h contributions to the distribution (see Sec. VII of the Supplemental Material [64]), GiBUU 2021.1 (strong 2p2h) and NEUT 5.6.0 (weak 2p2h) achieve the best goodness-of-fit with comparable χ^2 scores. This is partially explained by the highest three $\theta_{\mu,p}$ bins, in which the cross sections predicted by these two models are somewhat higher than all other event generators studied.

Figure 23 reports the measured distribution of p_n , a three-dimensional analog of δp_T which includes the component of missing momentum δp_L longitudinal to the neutrino beam. The addition of this new direction increases the χ^2/bin for all models studied. However, for the best-performing NuWro 21.09.2 SF prediction, the increase is modest (20%) compared to other models with similar quantitative agreement with the δp_T measurement in Fig. 17, including the MicroBooNE Tune (370%),

GENIE 3.2.0 G21_11b (170%), and NEUT 5.6.0 (340%). Because p_n is an estimator for the initial-state momentum of the struck nucleon in the primary neutrino interaction, superior agreement of a prediction based on the SF nuclear model versus LFG treatments might have been expected for this observable. However, it is noteworthy that better overall agreement with the SF is seen despite a clear underprediction of both NuWro models in the high p_n where FSI plays an important role.

Figure 24 presents double-differential cross sections as a function of $\theta_{\mu,p}$ in three bins of p_n . The NuWro 21.09.2 SF model again achieves the best goodness-of-fit, with the improvement over the LFG-based prediction especially noticeable in the lowest p_n bin. The GiBUU 2021.1 and NEUT 5.6.0 models are the only fairly close competitors in quantitative agreement, but all three of the best predictions show clear deficiencies in certain regions of phase space. At

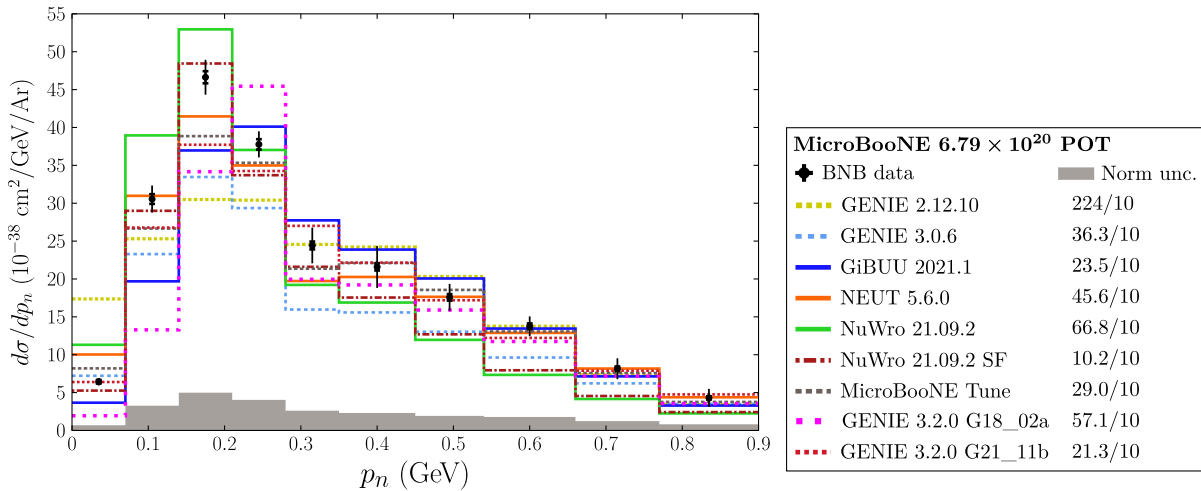


FIG. 23. Measured differential cross sections for block #8 (p_n). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x-axis.

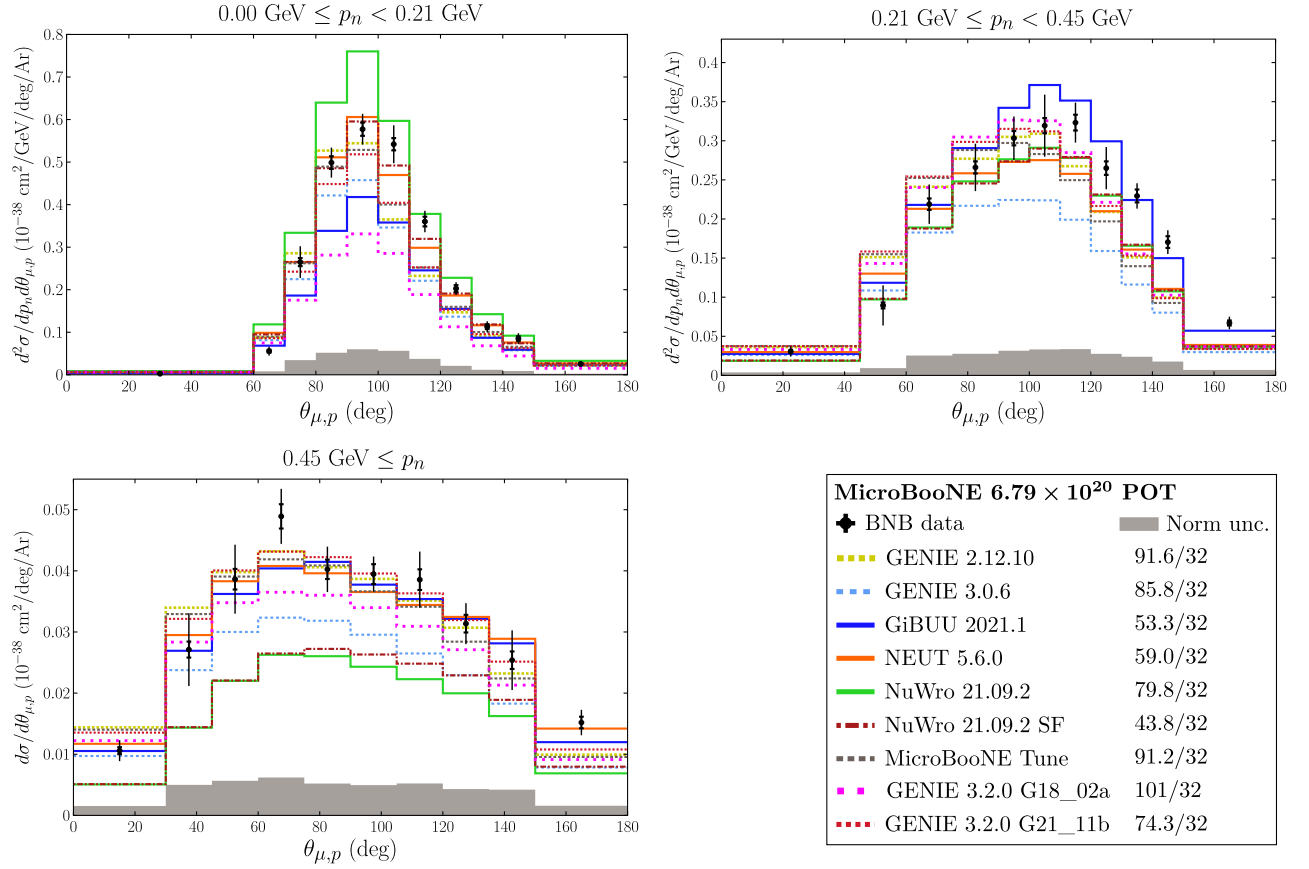


FIG. 24. Measured differential cross sections for block #9 ($p_n, \theta_{\mu,p}$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

low- p_n , GiBUU substantially underestimates the QE-rich peak, while NEUT and the NuWro SF model have similar predictions with better agreement. At high- p_n , GiBUU and NEUT are roughly consistent and NuWro is far below the data. In the middle p_n bin, the shapes of all three of these predictions are different, with GiBUU considerably larger than all other models studied at high values of $\theta_{\mu,p}$. The GiBUU prediction in the three highest $\theta_{\mu,p}$ bins at moderate p_n is clearly favored by the present measurement. While the plotted data points also seem to suggest an overestimation of the peak near $\theta_{\mu,p} = 100^\circ$ by the same model, the relatively large systematic uncertainties in this region limit firm conclusions.

Figure 25 shows the measured single-differential cross section as a function of the muon scattering angle θ_μ . The lowest χ^2 values obtained by GiBUU 2021.1, NuWro 21.09.2, and NEUT 5.6.0 can be attributed to two features of these model predictions. First, the data favor significantly more cross-section strength in the $\cos\theta_\mu \lesssim 0.6$ region than is predicted by the majority of the studied event generators. Here the best-fit predictions are noticeably higher than their counterparts. A similar tendency for models to underpredict data in this angular region has also been seen in recent MicroBooNE cross-section results for

quasielastic-like interactions [59] and inclusive charged-current ν_μ scattering with at least one proton in the final state [16]. Second, while there are significant differences between these models in the forward-angle region ($\cos\theta_\mu \gtrsim 0.8$), all of them provide a relatively good description of the data given the significant uncertainties. As experimental precision improves, future neutrino cross-section measurements with LArTPCs can thus be expected to provide additional model discrimination power using the forward portion of the muon angular distribution.

Finally, Figs. 26–28 present measured single-differential cross sections in terms of the leading proton scattering angle (θ_p), leading proton momentum (p_p), and muon momentum (p_μ), respectively. In the θ_p distribution, the limited precision in the forward direction does not allow clean discrimination between the differences seen in the competing predictions. However, the oscillatory pattern seen in the data points may hint towards a flatter shape than the clear forward peak expected from NEUT 5.6.0. In low bins of the p_p distribution, the measured cross section is larger than predicted by the bulk of the models studied. In the lowest p_p bin from 0.25–0.3 GeV/c, however, the GiBUU 2021.1 model overshoots the data. In the p_μ distribution,

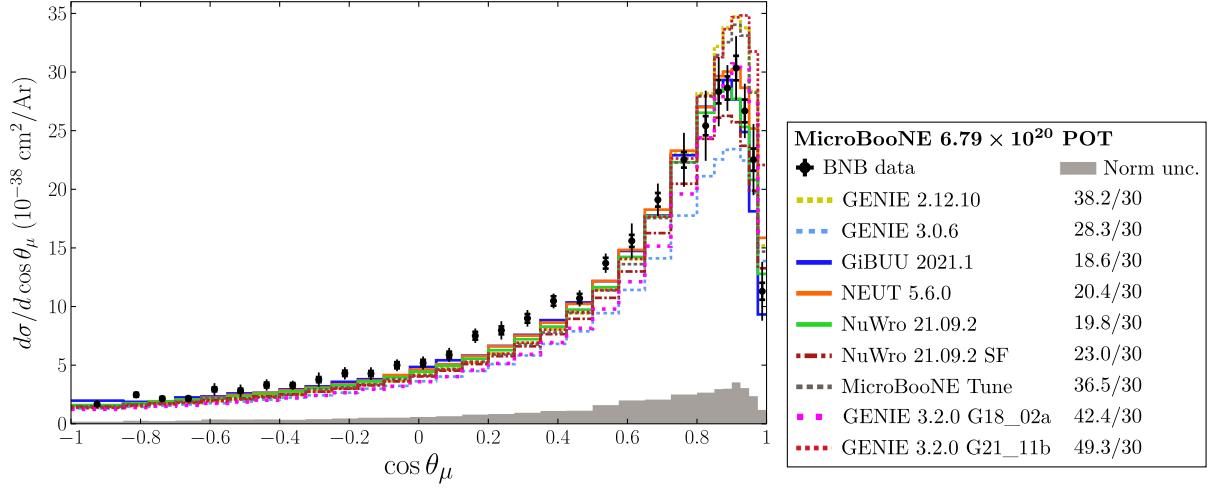


FIG. 25. Measured differential cross sections for block #10 ($\cos \theta_\mu$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

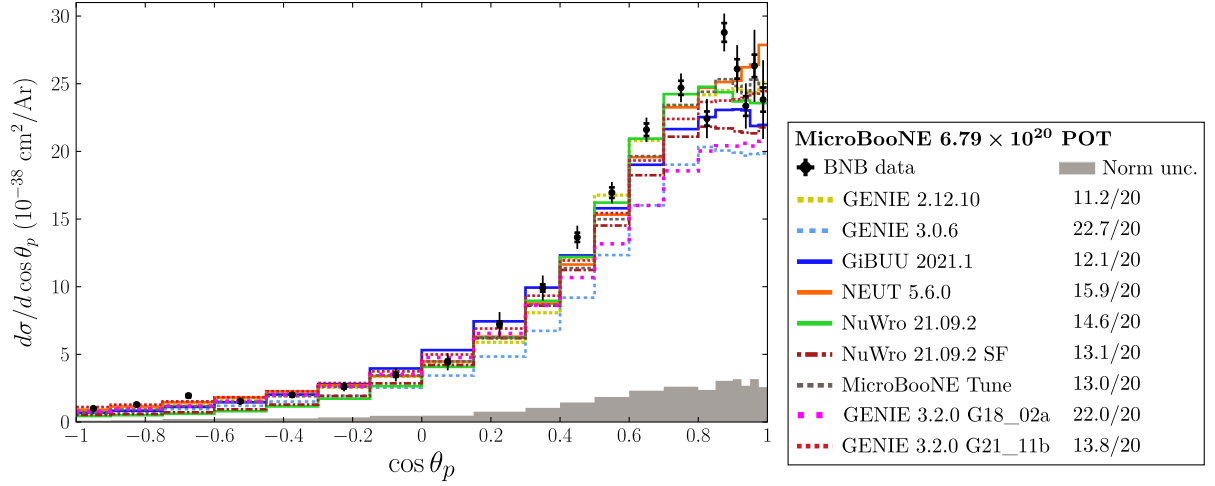


FIG. 26. Measured differential cross sections for block #11 ($\cos \theta_p$). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

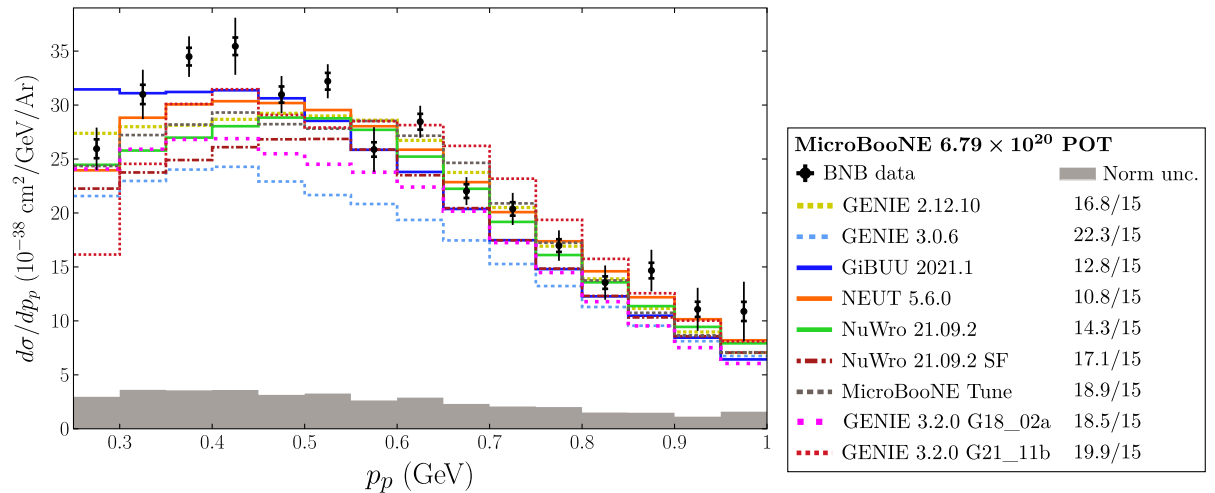


FIG. 27. Measured differential cross sections for block #12 (p_p). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x -axis.

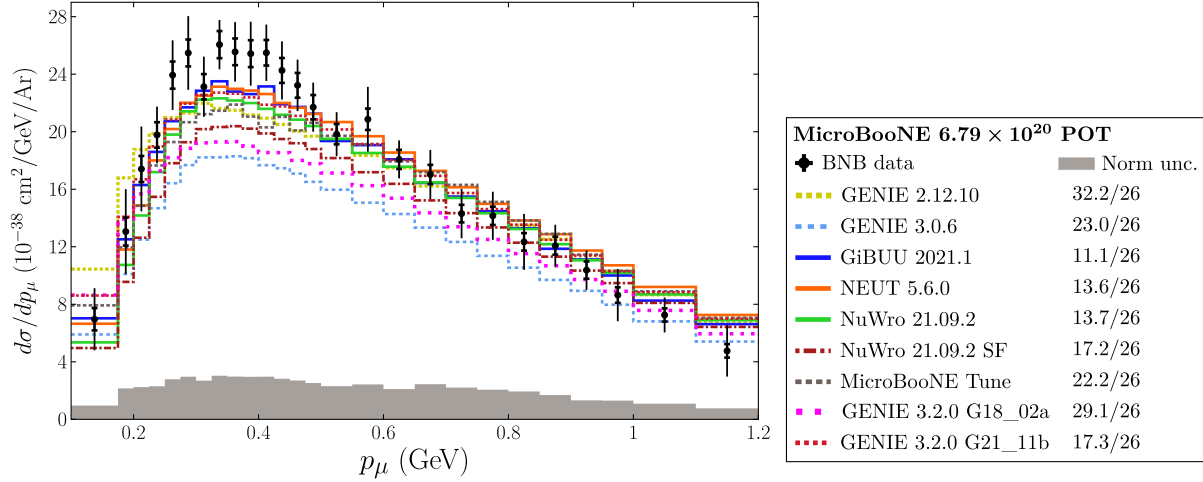


FIG. 28. Measured differential cross sections for block #13 (p_μ). Statistical (shape-only systematic) uncertainties are included in the inner (outer) error bars. The remainder of the total uncertainty is shown by the gray band along the x-axis.

all of the plotted event generator predictions underestimate the data near the peak ($p_\mu \in [0.25, 0.5]$ GeV/c), with GiBUU achieving the best goodness-of-fit. For both the CC0 $\pi N p$ cross sections shown here and a previous MicroBooNE measurement of inclusive CC ν_μ events with one or more final-state protons [[16], Fig. 18], data indicate a higher cross section near the peak of the p_μ distribution than is predicted by a variety of neutrino event generators.

VIII. SUMMARY AND CONCLUSIONS

This article presents a detailed study of charged-current muon-neutrino interactions with argon leading to mesonless final states containing one or more protons. Flux-averaged cross sections for this CC0 $\pi N p$ process were measured using the Fermilab Booster Neutrino Beam and MicroBooNE detector. The results are reported as a function of ten observables related to the three-momenta of the outgoing muon and leading proton. A larger dataset and significant improvements to MicroBooNE's software tools since the experiment's first CC0 $\pi N p$ cross-section analysis was reported [10] allow the present work to achieve higher precision and explore new kinematic distributions, including the first double-differential measurements in the CC0 $\pi N p$ channel for an argon target.

A covariance matrix describing correlated uncertainties between all 359 kinematic bins is provided in the Supplemental Material [64], allowing goodness-of-fit to be quantitatively assessed for theoretical predictions describing the entire dataset. This data release strategy represents an improvement over the typical procedure employed to date in the neutrino scattering literature, in which correlations between distinct kinematic distributions are not disclosed.

The predictions of several standard neutrino event generators are presented and compared to the MicroBooNE

data. The GiBUU 2021.1 model provides a relatively good description of all of the individual differential cross sections studied, but its poor agreement with the combined set of measurements (quantified with the χ^2 score given in Table II) suggests that the correlations between kinematic distributions are less well modeled. Overall agreement is likewise unsatisfactory for the other neutrino interaction models considered herein, with the GENIE 2.12.10 code obtaining a substantially higher χ^2 value than the others due to a less sophisticated treatment of some nuclear effects and a known problem in its FSI model [99]. The GENIE 3.0.6 prediction achieves the best overall goodness-of-fit of the models studied, but it is nevertheless seen to systematically underpredict the data across a large fraction of the measured phase space.

Some of the kinematic regions for which the present measurements give the greatest model discrimination power include moderate p_μ , low to moderate $\cos \theta_\mu$, and low p_p . As a general rule, the data show a clear preference for models that assign greater cross-section strength to these regions. The one exception is the lowest p_p bin studied (see Fig. 27) in which the measured cross section lies roughly in the middle of a wide spread of model predictions. The measured distribution of the muon-proton opening angle $\theta_{\mu p}$ also reveals a shape shifted toward slightly higher values compared to the bulk of the predictions studied.

The two NuWro configurations used in the data comparisons implement distinct treatments of the nuclear ground state when modeling CCQE interactions. While the default LFG achieves somewhat better agreement with the measured cross sections that depend only on muon kinematics, the more sophisticated SF model is consistently preferred by the measurements of kinematic imbalance variables. If one considers goodness-of-fit including correlations across the measurements of TKI variables (blocks

2–6) and p_n (block 8), then the NuWro 21.09.2 SF model ($\chi^2 = 383/142$ bins) provides a better fit to the data than the default NuWro configuration ($\chi^2 = 515$).

Especially when combined with recent MicroBooNE measurements examining more exclusive [59,60,100] and inclusive [70,101] final-state topologies in charged-current ν_μ -argon scattering, the present dataset provides a highly detailed benchmark for the ongoing effort to improve event generators to the precision needed for the future accelerator-based neutrino oscillation program.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: BIN DEFINITIONS

Table III presents the full set of 359 kinematic bins used to report the $\text{CC}0\pi Np$ cross section measurements. For an observable x , the bin with lower limit x^{low} and upper limit x^{high} will include events with $x^{\text{low}} \leq x < x^{\text{high}}$. The blocks of related bins (indicated in the table) are defined so that a selected event will belong to a unique bin within each block.

TABLE III. Bin definitions used in the analysis.

Block 0: $(p_\mu, \cos \theta_\mu)$				
Bin number	p_μ^{low} (GeV/ c)	p_μ^{high} (GeV/ c)	$\cos \theta_\mu^{\text{low}}$	$\cos \theta_\mu^{\text{high}}$
0	0.1	0.24	−1	−0.55
1			−0.55	−0.25
2			−0.25	0
3			0	0.25
4			0.25	0.45
5			0.45	0.7
6			0.7	1
7	0.24	0.3	−1	−0.55
8			−0.55	−0.25
9			−0.25	0
10			0	0.25
11			0.25	0.45
12			0.45	0.7
13			0.7	1
14	0.3	0.38	−1	−0.4
15			−0.4	−0.1
16			−0.1	0.1
17			0.1	0.35
18			0.35	0.5
19			0.5	0.7

(Table continued)

TABLE III. (*Continued*)

Block 0: $(p_\mu, \cos \theta_\mu)$				
Bin number	p_μ^{low} (GeV/ c)	p_μ^{high} (GeV/ c)	$\cos \theta_\mu^{\text{low}}$	$\cos \theta_\mu^{\text{high}}$
20			0.7	0.85
21			0.85	1
22	0.38	0.48	-1	0
23			0	0.5
24			0.5	0.65
25			0.65	0.8
26			0.8	0.92
27			0.92	1
28	0.48	0.7	-1	0.2
29			0.2	0.5
30			0.5	0.65
31			0.65	0.8
32			0.8	0.875
33			0.875	0.95
34			0.95	1
35	0.7	0.85	-1	0.65
36			0.65	0.8
37			0.8	0.875
38			0.875	0.95
39			0.95	1
40	0.85	1.2	-1	0.85
41			0.85	0.9
42			0.9	0.95
43			0.95	1
Block 1: $(p_p, \cos \theta_p)$				
Bin number	p_p^{low} (GeV/ c)	p_p^{high} (GeV/ c)	$\cos \theta_p^{\text{low}}$	$\cos \theta_p^{\text{high}}$
44	0.25	0.325	-1	0
45			0	1
46	0.325	0.4	-1	-0.5
47			-0.5	0
48			0	0.5
49			0.5	0.8
50			0.8	1
51	0.4	0.5	-1	-0.6
52			-0.6	-0.2
53			-0.2	0.2
54			0.2	0.5
55			0.5	0.65
56			0.65	0.85
57			0.85	1
58	0.5	0.6	-1	-0.2
59			-0.2	0.2
60			0.2	0.4
61			0.4	0.6
62			0.6	0.7
63			0.7	0.8

(*Table continued*)

TABLE III. (*Continued*)

Block 1: $(p_p, \cos \theta_p)$				
Bin number	p_p^{low} (GeV/ c)	p_p^{high} (GeV/ c)	$\cos \theta_p^{\text{low}}$	$\cos \theta_p^{\text{high}}$
64	0.6	0.7	0.8	0.9
65			0.9	1
66			-1	0.1
67			0.1	0.37
68			0.37	0.5
69			0.5	0.6
70			0.6	0.7
71			0.7	0.8
72			0.8	0.9
73			0.9	1
74	0.7	1	-1	0.45
75			0.45	0.65
76			0.65	0.75
77			0.75	0.82
78			0.82	0.9
79			0.9	1
Block 2: δp_T				
Bin number	δp_T^{low} (GeV/ c)	δp_T^{high} (GeV/ c)		
80	0	0.06		
81	0.06	0.12		
82	0.12	0.18		
83	0.18	0.24		
84	0.24	0.32		
85	0.32	0.40		
86	0.40	0.48		
87	0.48	0.55		
88	0.55	0.68		
89	0.68	0.75		
90	0.75	0.90		
91	0.90	∞		
Block 3: $(\delta \alpha_T, \delta p_T)$				
Bin number	$\delta \alpha_T^{\text{low}}$ ($^\circ$)	$\delta \alpha_T^{\text{high}}$ ($^\circ$)	δp_T^{low} (GeV/ c)	δp_T^{high} (GeV/ c)
92	0	45	0	0.06
93			0.06	0.12
94			0.12	0.18
95			0.18	0.24
96			0.24	0.32
97			0.32	0.40
98			0.40	0.48
99			0.48	∞
100			45	90
101	0.06	0.12		
102	0.12	0.18		
103	0.18	0.24		
104	0.24	0.32		
105	0.32	0.40		
106	0.40	0.48		

(Table continued)

TABLE III. (*Continued*)

Block 3: $(\delta\alpha_T, \delta p_T)$				
Bin number	$\delta\alpha_T^{\text{low}}$ ($^\circ$)	$\delta\alpha_T^{\text{high}}$ ($^\circ$)	δp_T^{low} (GeV/c)	δp_T^{high} (GeV/c)
107	90	135	0.48	0.55
108			0.55	∞
109			0	0.06
110			0.06	0.12
111			0.12	0.18
112			0.18	0.24
113			0.24	0.32
114			0.32	0.40
115			0.40	0.48
116			0.48	0.55
117			0.55	0.63
118			0.63	0.70
119			0.70	∞
120	135	180	0	0.06
121			0.06	0.12
122			0.12	0.18
123			0.18	0.24
124			0.24	0.32
125			0.32	0.40
126			0.40	0.50
127			0.50	0.60
128			0.60	0.72
129			0.72	0.90
130			0.90	∞
Block 4: $(\delta p_T, \delta\alpha_T)$				
Bin number	δp_T^{low} (GeV/c)	δp_T^{high} (GeV/c)	$\delta\alpha_T^{\text{low}}$ ($^\circ$)	$\delta\alpha_T^{\text{high}}$ ($^\circ$)
131	0	0.2	0	25
132			25	60
133			60	95
134			95	120
135			120	145
136			145	165
137			165	180
138	0.2	0.3	0	25
139			25	60
140			60	95
141			95	120
142			120	145
143			145	165
144			165	180
145	0.3	0.4	0	25
146			25	60
147			60	95
148			95	120
149			120	145
150			145	165
151			165	180
152	0.4	∞	0	25

(*Table continued*)

TABLE III. (*Continued*)

Block 4: $(\delta p_T, \delta \alpha_T)$				
Bin number	δp_T^{low} (GeV/c)	δp_T^{high} (GeV/c)	$\delta \alpha_T^{\text{low}}$ (°)	$\delta \alpha_T^{\text{high}}$ (°)
153			25	60
154			60	95
155			95	120
156			120	145
157			145	165
158			165	180
Block 5: δp_{T_x}				
Bin number	$\delta p_{T_x}^{\text{low}}$ (GeV/c)	$\delta p_{T_x}^{\text{high}}$ (GeV/c)		
159	$-\infty$	-0.60		
160	-0.60	-0.45		
161	-0.45	-0.35		
162	-0.35	-0.25		
163	-0.25	-0.15		
164	-0.15	-0.075		
165	-0.075	0		
166	0	0.075		
167	0.075	0.15		
168	0.15	0.25		
169	0.25	0.35		
170	0.35	0.45		
171	0.45	0.6		
172	0.60	∞		
Block 6: $(\delta p_{T_y}, \delta p_{T_x})$				
Bin number	$\delta p_{T_y}^{\text{low}}$ (GeV/c)	$\delta p_{T_y}^{\text{high}}$ (GeV/c)	$\delta p_{T_x}^{\text{low}}$ (GeV/c)	$\delta p_{T_x}^{\text{high}}$ (GeV/c)
173	$-\infty$	-0.15	$-\infty$	-0.6
174			-0.6	-0.45
175			-0.45	-0.35
176			-0.35	-0.25
177			-0.25	-0.15
178			-0.15	-0.075
179			-0.075	0
180			0	0.075
181			0.075	0.15
182			0.15	0.25
183			0.25	0.35
184			0.35	0.45
185			0.45	0.60
186			0.60	∞
187	-0.15	0.15	$-\infty$	-0.6
188			-0.6	-0.45
189			-0.45	-0.35
190			-0.35	-0.25
191			-0.25	-0.15
192			-0.15	-0.075
193			-0.075	0
194			0	0.075
195			0.075	0.15
196			0.15	0.25

(*Table continued*)

TABLE III. (Continued)

Block 6: $(\delta p_{T_y}, \delta p_{T_x})$				
Bin number	$\delta p_{T_y}^{\text{low}} (\text{GeV}/c)$	$\delta p_{T_y}^{\text{high}} (\text{GeV}/c)$	$\delta p_{T_x}^{\text{low}} (\text{GeV}/c)$	$\delta p_{T_x}^{\text{high}} (\text{GeV}/c)$
197			0.25	0.35
198			0.35	0.45
199			0.45	0.60
200			0.60	∞
201	0.15	∞	$-\infty$	-0.4
202			-0.4	-0.3
203			-0.3	-0.2
204			-0.2	-0.1
205			-0.1	0
206			0	0.1
207			0.1	0.2
208			0.2	0.3
209			0.3	0.4
210			0.4	∞
Block 7: $\theta_{\mu p}$				
Bin number	$\theta_{\mu p}^{\text{low}} (^{\circ})$	$\theta_{\mu p}^{\text{high}} (^{\circ})$		
211	0	30		
212	30	40		
213	40	50		
214	50	60		
215	60	70		
216	70	80		
217	80	90		
218	90	100		
219	100	110		
220	110	120		
221	120	130		
222	130	140		
223	140	150		
224	150	180		
Block 8: p_n				
Bin number	$p_n^{\text{low}} (\text{GeV}/c)$	$p_n^{\text{high}} (\text{GeV}/c)$		
225	0	0.07		
226	0.07	0.14		
227	0.14	0.21		
228	0.21	0.28		
229	0.28	0.35		
230	0.35	0.45		
231	0.45	0.54		
232	0.54	0.66		
233	0.66	0.77		
234	0.77	0.9		
235	0.9	∞		
Block 9: $(p_n, \theta_{\mu p})$				
Bin number	$p_n^{\text{low}} (\text{GeV}/c)$	$p_n^{\text{high}} (\text{GeV}/c)$	$\theta_{\mu p}^{\text{low}} (^{\circ})$	$\theta_{\mu p}^{\text{high}} (^{\circ})$
236	0	0.21	0	60

(Table continued)

TABLE III. (*Continued*)

Block 9: $(p_n, \theta_{\mu p})$				
Bin number	$p_n^{\text{low}}(\text{GeV}/c)$	$p_n^{\text{high}}(\text{GeV}/c)$	$\theta_{\mu p}^{\text{low}}\ (^{\circ})$	$\theta_{\mu p}^{\text{high}}\ (^{\circ})$
237	0.21	0.45	60	70
238			70	80
239			80	90
240			90	100
241			100	110
242			110	120
243			120	130
244			130	140
245			140	150
246			150	180
247	0.45	∞	0	45
248			45	60
249			60	75
250			75	90
251			90	100
252			100	110
253			110	120
254			120	130
255			130	140
256			140	150
257			150	180
258	0.45	∞	0	30
259			30	45
260			45	60
261			60	75
262			75	90
263			90	105
264			105	120
265			120	135
266			135	150
267			150	180
Block 10: $\cos \theta_{\mu}$				
Bin number	$\cos \theta_{\mu}^{\text{low}}$	$\cos \theta_{\mu}^{\text{high}}$		
268	-1	-0.85		
269	-0.85	-0.775		
270	-0.775	-0.7		
271	-0.7	-0.625		
272	-0.625	-0.55		
273	-0.55	-0.475		
274	-0.475	-0.4		
275	-0.4	-0.325		
276	-0.325	-0.25		
277	-0.25	-0.175		
278	-0.175	-0.1		
279	-0.1	-0.025		
280	-0.025	0.05		
281	0.05	0.125		
282	0.125	0.2		
283	0.2	0.275		
284	0.275	0.35		
285	0.35	0.425		

(*Table continued*)

TABLE III. (Continued)

Block 10: $\cos \theta_\mu$		
Bin number	$\cos \theta_\mu^{\text{low}}$	$\cos \theta_\mu^{\text{high}}$
286	0.425	0.5
287	0.5	0.575
288	0.575	0.65
289	0.65	0.725
290	0.725	0.8
291	0.8	0.85
292	0.85	0.875
293	0.875	0.9
294	0.9	0.925
295	0.925	0.95
296	0.95	0.975
297	0.975	1
Block 11: $\cos \theta_p$		
Bin number	$\cos \theta_p^{\text{low}}$	$\cos \theta_p^{\text{high}}$
298	-1	-0.9
299	-0.9	-0.75
300	-0.75	-0.6
301	-0.6	-0.45
302	-0.45	-0.3
303	-0.3	-0.15
304	-0.15	0
305	0	0.15
306	0.15	0.3
307	0.3	0.4
308	0.4	0.5
309	0.5	0.6
310	0.6	0.7
311	0.7	0.8
312	0.8	0.85
313	0.85	0.9
314	0.9	0.925
315	0.925	0.95
316	0.95	0.975
317	0.975	1
Block 12: p_p		
Bin number	$p_p^{\text{low}}(\text{GeV}/c)$	$p_p^{\text{high}}(\text{GeV}/c)$
318	0.25	0.3
319	0.3	0.35
320	0.35	0.4
321	0.4	0.45
322	0.45	0.5
323	0.5	0.55
324	0.55	0.6
325	0.6	0.65
326	0.65	0.7
327	0.7	0.75
328	0.75	0.8
329	0.8	0.85
330	0.85	0.9

(Table continued)

TABLE III. (*Continued*)

Block 12: p_p		
Bin number	$p_p^{\text{low}}(\text{GeV}/c)$	$p_p^{\text{high}}(\text{GeV}/c)$
331	0.9	0.95
332	0.95	1
Block 13: p_μ		
Bin number	$p_\mu^{\text{low}}(\text{GeV}/c)$	$p_\mu^{\text{high}}(\text{GeV}/c)$
333	0.1	0.175
334	0.175	0.2
335	0.2	0.225
336	0.225	0.25
337	0.25	0.275
338	0.275	0.3
339	0.3	0.325
340	0.325	0.35
341	0.35	0.375
342	0.375	0.4
343	0.4	0.425
344	0.425	0.45
345	0.45	0.475
346	0.475	0.5
347	0.5	0.55
348	0.55	0.6
349	0.6	0.65
350	0.65	0.7
351	0.7	0.75
352	0.75	0.8
353	0.8	0.85
354	0.85	0.9
355	0.9	0.95
356	0.95	1
357	1	1.1
358	1.1	1.2

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