

Measurement of charged-current muon neutrino–argon interactions without pions in the final state using the MicroBooNE detector

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We report a new measurement of flux-integrated differential cross sections for charged-current (CC) muon neutrino interactions with argon nuclei that produce no final state pions ($\nu_\mu \text{CC}0\pi$). These interactions are of particular importance as a topologically defined signal dominated by quasielastic-like interactions. This measurement was performed with the MicroBooNE liquid argon time projection chamber detector located at the Fermilab Booster Neutrino Beam (BNB), and uses an exposure of 1.3×10^{21} protons on target collected between 2015 and 2020. The results are presented in terms of single and double-differential cross sections as a function of the final state muon momentum and angle. The data are compared with widely-used neutrino event generators. We find good agreement with the single-differential measurements, while only a subset of generators are also able to adequately describe the data in double-differential distributions. This work facilitates comparison with Cherenkov detector measurements, including those located at the BNB.

I. INTRODUCTION

Accelerator-based neutrino experiments enable precise measurements of oscillation parameters, aiming to conclusively determine the unknown neutrino mass ordering and establish the presence of charge-parity symmetry violation in the lepton sector [1, 2]. These future measurements require unprecedented precision in the characterization of neutrino-nucleus interactions for a variety of target nuclei and topological event signatures. Liquid argon TPC-based experiments such as the Fermilab Short-Baseline Neutrino (SBN) program [3, 4] and DUNE [5–8] take advantage of low-threshold proton reconstruction to define a charged-current quasielastic (CCQE)-like signal with one lepton and one proton in the final state ($1\ell 1p$). Water Cherenkov (WC) experiments such as the Super-Kamiokande far detector for T2K [9, 10] and Hyper-Kamiokande [11, 12] typically probe this channel using a single-ring $\text{CC}0\pi$ topology. Such measurements are not sensitive to the proton multiplicity due to the high Cherenkov threshold for protons. Hybrid scintillator detectors offer Cherenkov ring-based event reconstruction but with the addition of calorimetry for sub-threshold hadrons [13].

The present work aims to inform modeling and facilitate comparison across nuclear targets by selecting a high-statistics topological $\text{CC}0\pi$ semi-inclusive event sample within the MicroBooNE liquid argon time projection chamber (LArTPC), including events with no final state protons to probe the lepton kinematics associated with these interactions. This work also enables correlated multi-target cross section measurements using Cherenkov detectors in the same neutrino beam, in-

cluding ANNIE [14, 15]. This measurement builds on earlier MicroBooNE measurements of $\text{CC}0\pi Np$ interactions, which require at least one reconstructed proton in the final state. The previous measurements present detailed studies of the scattering kinematics with respect to the muon trajectory [16–18]. Relative to previous work, this measurement relaxes the final state proton requirement to expand the sample to include $\nu_\mu \text{CC}0\pi$ interactions with no associated protons. The muon momentum range is also expanded to include muons up to $2 \text{ GeV}/c$. Additionally, this work uses the full MicroBooNE dataset with an exposure of 1.3×10^{21} protons on target (POT), approximately double that of previous $\nu_\mu \text{CC}0\pi Np$ measurements [16–20].

The results are presented in terms of single and double-differential flux-integrated cross sections as a function of the final state muon momentum (p_μ) and the cosine of the scattering angle with respect to the incoming neutrino beam ($\cos \theta_\mu$). The absolute cross sections per argon nucleus are unfolded from reconstructed distributions into true regularized distributions using the Wiener-SVD unfolding technique [21], which enables hypothesis testing without loss of statistical power relative to the distributions of reconstructed quantities.

II. THE MICROBOONE EXPERIMENT

MicroBooNE is a LArTPC detector located at Fermi National Accelerator Laboratory (Fermilab) that collected data from 2015 to 2020 [22]. MicroBooNE contained approximately 85 tonnes of active liquid argon within a TPC with dimensions of 2.56 m horizontally (drift direction), 10.36 m along the beam direction, and 2.32 m vertically. A uniform 273 V/cm drift field was applied across the TPC active volume. The anode readout assembly features three sense wire planes with a 3 mm

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pitch, used to detect ionization charge. The sense wire waveforms provide measurements of energy deposition and particle trajectories, enabling 3D track reconstruction, momentum estimation, and particle identification. Located behind the anode plane are 32 photomultiplier tubes (PMTs) covered by acrylic disks coated with a wavelength shifter. The PMTs capture scintillation light from the interactions, providing nanosecond-level timing that associates reconstructed tracks with the neutrino beam spill. This timing information facilitates matching of TPC charge and prompt scintillation light signals, allows cosmic-ray activity to be identified and removed, and provides the location along the drift direction (transverse to the beam) for beam-related activity.

A. Booster Neutrino Beam

The MicroBooNE detector is positioned on-axis 463 m downstream of the Fermilab Booster Neutrino Beam (BNB) target and approximately 8° off-axis relative to the Neutrinos at the Main Injector (NuMI) beamline. Only BNB events are considered in this work. To produce the neutrino beam, protons accelerated to 8 GeV impinge on a beryllium target resulting in the production of hadrons, mainly pions. For the entirety of the MicroBooNE run period, the BNB hadron-focusing magnetic horn system operated in a mode where π^+ were focused. These hadrons decay in flight in a 50 m long decay pipe, leading to a neutrino flux of predominantly ν_μ (93.7%) and a smaller $\bar{\nu}_\mu$ contribution (5.8%), with the remainder of the flux comprising ν_e and $\bar{\nu}_e$. The average energy of muon neutrinos is approximately 0.8 GeV. The simulation and modeling of BNB flux and assessment of the associated systematic uncertainty follow the procedures previously developed by MiniBooNE [23].

B. Neutrino interaction modeling

To model and simulate neutrino–nucleus interactions, we use GENIE version 3.0.6 [24–26] using the Comprehensive Model Configuration (CMC) G18_10a.02.11a [27]. In this configuration, the nuclear ground state is modeled using a local Fermi gas (LFG) approach [28]. CCQE interactions producing a muon and a single proton ($1p1h$) are treated using the Valencia model [28–30]. This model also incorporates multi-nucleon interactions, dominated by two correlated nucleons, known as 2-particle-2-hole ($2p2h$) interactions, based on the Nieves-Simo-Vacas (NSV) $2p2h$ framework [28, 31]. Additionally, the model accounts for long-range correlations (LRC) in the nuclear medium using the random phase approximation (RPA) [30]. GENIE simulates single-pion production via heavy baryon decay, known as resonance production (RES), using the Feynman-Kislinger-Ravndal (FKR) formalism [32], a relativistic three-quark bound-state model. This approach uses the Berger and Sehgal (BS) [33, 34]

and Kuzmin-Lyubushkin-Naumov (KLN) [35, 36] models, which incorporate contributions from Rein and Sehgal (RS) [37]. Single-pion production involving the entire nucleus as a single entity, with no nucleon-level break-up or residual excitation, is defined as coherent pion production (COH) and is modeled using the formalism developed by Berger and Sehgal [38]. Deep inelastic scattering (DIS), which describes interactions with individual quarks, is simulated using the Bodek-Yang (BY) model [39–41]. The BY model is a phenomenological approach that incorporates tuned parton distribution functions (PDFs) extracted from global fits at high Q^2 . It extrapolates these PDFs to low Q^2 while accounting for target mass corrections, non-perturbative QCD effects, and higher-order QCD terms. Final-state interactions (FSI), which occur as hadrons exit the nucleus, are simulated using the hA2018 model [42]. Importantly, these FSI can lead to $CC0\pi$ final state topologies from several processes, including, for example, resonance production interactions where a charged pion is produced and absorbed in the nucleus.

The G18_10a.02.11a CMC is tuned to neutrino interaction data as described in Ref. [27]. MicroBooNE’s neutrino interaction model uses this tuned CMC as a starting point, then applies an additional model parameter tuning based on fits to T2K $CC0\pi$ data [43], used to obtain the central value and updated uncertainties [44]. This “MicroBooNE Tune” of the CC model parameters to an external dataset corrects for an under-prediction of the total CC cross section for $E_\nu \sim 1$ GeV observed relative to both T2K and MicroBooNE data.

C. Event Simulation

The propagation of simulated final-state particles through the MicroBooNE detector geometry is performed using Geant4 version 10.3.3 [45, 46]. The detector response is modeled with a custom simulation implemented within the LArSoft framework [47]. The simulation and data processing include detailed models of signal processing [48] and wire waveform induction effects [49], as well as data-driven calibrations and models for components such as electric field maps [50] and space charge effects [51]. Monte Carlo neutrino interactions are overlaid with cosmic ray data events taken from non-beam data to account for the cosmic ray background in an unbiased way and provide a data-driven model of detector noise [52]. Additionally, backgrounds due to cosmic-ray activity occurring in time with the beam, but where no neutrino interaction occurred, are estimated using data samples collected with the beam off (“EXT BNB”).

D. Event reconstruction

As with previous MicroBooNE $CC0\pi Np$ measurements [16–20], this work employs algorithms and tools

implemented within the Pandora multi-algorithm framework [53] to reconstruct cosmic-ray muon and neutrino events in the MicroBooNE detector. The algorithms include three-dimensional track reconstruction, which allows the determination of kinematic variables such as muon momentum and angle. Pandora begins by grouping charge hits on individual 2D readout planes, then matches these hits across planes to form an image of the ionization charge distribution in 3D. Clustering is applied to form tracks, which are used to identify and remove cosmic-ray activity. For the remaining neutrino interaction candidates, Pandora identifies and reconstructs particles produced in the neutrino interaction. These are characterized as track-like (e.g., muons, protons, and charged pions) or electromagnetic shower-like (e.g., electrons and photon-induced showers). These tracks and showers are then grouped into a particle flow hierarchy associated with a reconstructed neutrino vertex.

The energy and momentum of each final state particle object is computed using several approaches. For track-like particles, the momentum is estimated using the visible track length under the hypotheses that its energy loss profile is that of a muon or proton. A second momentum estimator uses multiple Coulomb scattering (MCS), assuming a muon track. This algorithm makes use of the fact that lower-momentum tracks tend to undergo more MCS, leading to a higher local curvature [54]. In this work, we consider only muon tracks that are fully contained within the detector (i.e., the full extent of the track is visible in the TPC) and use the total track length estimator for the momentum. For showers, energy is estimated using the total deposited charge, with corrections applied for known charge losses due to hit thresholding and clustering efficiencies.

In addition to the daughter track start and end points, lengths, and momenta, we also compute a variety of calorimetric quantities using the deposited charge distribution, which are used for particle identification. Specifically, the energy loss profile (dE/dx) as the track approaches its endpoint provides a powerful means to discriminate muon and pion tracks from highly-ionizing proton tracks. Two specific metrics used in this work are a χ^2 score for a track under the hypothesis that it is a proton (χ_p^2), and a ratio of likelihoods for a track's dE/dx profile under a muon or proton hypothesis (LLR PID) [55], which are among the inputs to the particle identification boosted decision tree (BDT) model described in Section III C.

III. EVENT SELECTION

A. Signal and background definitions

This measurement uses a topological $\text{CC}0\pi$ signal definition, which refers to any ν_μ CC scattering events with no charged or neutral pions in the final state. In practice, these events can only be identified when the muon

and charged pion have sufficient kinetic energy to be reliably reconstructed. Thus, the signal definition includes a muon and charged pion momentum threshold that is related to the reconstruction threshold. An upper threshold (2 GeV/c) is also applied to the muon momentum due to the requirement that muons be fully contained within the detector. This requirement reduces the efficiency significantly for high-momentum muon tracks that tend to exit the detector.

The signal is defined to include events where (1) a muon neutrino underwent a CC interaction with an ^{40}Ar nucleus, (2) the final state muon momentum is in the range $0.1 < p_\mu < 2.0 \text{ GeV}/c$, (3) there are no neutral pions in the final state, and (4) there are no charged pions with momentum $p_\pi > 70 \text{ MeV}/c$.

Simulated events that pass this signal definition and have a vertex within the fiducial volume (FV) are considered signal events. The FV is an inner rectangular volume within MicroBooNE's active volume, inset 21.5 cm from the TPC boundaries with the exception of the downstream end along the beam axis, where it is inset 70 cm from the downstream TPC boundary. For the purposes of presentation in the figures in later sections, signal events are further labeled by their true interaction types according to the GENIE generator: CC quasi-elastic (CCQE), CC meson exchange currents or $2p2h$ (CCMEC), CC resonance production (CCRES), and all other CC interaction processes that fall within the signal definition ('Signal (Other)'), a category dominated by DIS and CC coherent pion events.

All other events are considered background and grouped into categories: out of fiducial volume events ('Out FV') with a true neutrino-induced vertex position outside of the fiducial volume; neutral current events ('NC') where, for example, a proton or pion is misidentified as a muon; electron neutrino CC (' ν_e CC') events; other ν_μ CC interactions ('Other ν_μ CC') induced by a muon neutrino and having no final state pions but still failing to meet the signal definition, for example with a true muon momentum outside the signal range; CC events with pions above threshold (' $\text{CC}N\pi$ '); and cosmic-ray activity ('EXT BNB') misidentified as a neutrino interaction. A final category ('Other') includes any remaining backgrounds including, for example, antineutrino interactions.

The selection proceeds in three stages. First, the ν_μ CC pre-selection provides a sample of CC interaction candidates with reduced contamination from cosmic-ray activity and electromagnetic showers. Next, this sample is input to a particle identification algorithm that estimates the final state track content of each interaction. Finally, events meeting the topological criteria are subject to kinematic selections matching those in the signal definition to yield the final event sample.

B. Muon neutrino CC pre-selection

We apply a semi-inclusive pre-selection to the simulation and data to identify ν_μ CC events, reducing backgrounds related to cosmic-ray and electromagnetic shower activity prior to a more targeted signal selection. We require that Pandora has reconstructed a single neutrino vertex within the FV. To ensure high-quality reconstruction of particle types and momenta, all tracks resulting directly from that interaction must start within a particle containment volume (PCV) inset 10 cm from the TPC active volume boundary. To minimize cosmic-ray activity, the Pandora reconstruction provides a likelihood score that discriminates cosmic-like from neutrino-like event topologies. It is used to reject topologically cosmic-like events. Another discrimination algorithm provides a score (0–1) to differentiate between shower-like (closer to 0) or track-like (closer to 1) reconstructed final state objects based on the spatial distribution of associated clustered hits. A threshold of 0.5 is used to reject any event containing shower-like activity produced directly from the neutrino interaction. This suppresses many classes of background events, such as those with final state π^0 mesons.

In contrast to the $\text{CC}0\pi Np$ topology where a muon and at least one proton form a well-identified vertex, the more inclusive $\text{CC}0\pi$ channel includes interactions where the only reconstructed final state track is that of the muon. Using topological information alone (i.e., the distribution of ionization hits in 3D space) creates a 180° ambiguity in the track orientation, leading to an increased acceptance of cosmic-ray muon tracks that stop in the detector volume. To reduce this background contribution, additional calorimetric information is used in the muon candidate track selection. Specifically, tracks are excluded when there is a preference for a Bragg peak at the track endpoint closer to the reconstructed neutrino vertex and a poor goodness-of-fit for the dE/dx hypothesis corresponding to a forward-going muon.

C. Track identification BDT

The identification of the $\text{CC}0\pi$ signal topology is based on the classification of tracks associated with a reconstructed neutrino interaction. This classification is performed using an XGBoost [56] gradient boosted decision tree model trained on reconstructed simulated events that pass the pre-selection. The input parameters for the model include a set of reconstructed object parameters computed by the Pandora algorithms [53]. The objective of the model is to correctly classify final state particle objects as muons, charged pions, protons, or none of these types. The input parameters build on existing discriminants for protons and muons to construct an optimal classifier. Parameters must fall within a defined range, establishing loose cuts on the tracks to which the BDT is applied. The BDT input parameters and their ranges

are: distance from the neutrino vertex to the track start point (≤ 100 cm); a muon and proton likelihood ratio and χ^2 score for the track dE/dx evolution across the track length; range-based reconstructed track kinetic energy assuming a proton track (≤ 2.5 GeV); the fractional difference between the muon momentum as reconstructed using track range, p_μ^{range} , and an estimator p_μ^{MCS} based on multiple Coulomb scattering ($|(p_\mu^{\text{MCS}} - p_\mu^{\text{range}})/p_\mu^{\text{MCS}}| < 2.5$); track endpoint containment within the PCV; and multiplicity of associated track-like and shower-like secondary particles (≤ 10).

To validate the BDT model performance, statistical comparisons are performed to assess the agreement of simulation to a subset of the data corresponding to an exposure of 1.4×10^{20} POT. These comparisons include the track-level distributions of all model input parameters listed above, as well as the distributions of probability scores for each output class, for all track-like reconstructed objects associated with pre-selected events. Data and simulation are consistent in all cases, with agreement well within the 1σ model uncertainties (enumerated in Section IV).

For events passing the ν_μ CC pre-selection, the particle identification (PID) BDT model provides a probability score for each output class for each final state track in a neutrino interaction event. If any final state track's parameters fall outside the range of validity for the BDT model inputs, the event is rejected. The positive identification of a muon candidate track is an input to the ν_μ CC selection. Muons are correctly identified in 82% of cases. The primary source of muon misidentification is charged pions, which leave similar signatures in the LArTPC. According to simulations of particles identified as pions, 56% are true pions while 22% are true muons and 13% are protons. This nontrivial pion confusion is partly mitigated by the topological selection. Since each ν_μ CC candidate event must contain exactly one muon, the muon-like track with the highest muon BDT score is chosen as the primary muon candidate. Any remaining tracks that were initially classified as muons are reclassified as charged pions.

D. Signal selection criteria

The final selection criteria for the $\text{CC}0\pi$ sample are designed to coincide with the signal definition stated in Section III A, using reconstructed observables. Overall, we require that (1) events pass the pre-selection criteria defined in Section III B; (2) the BDT PID model has identified a muon candidate track that is fully contained within the PCV and has $0.1 < p_\mu^{\text{reco}} < 2.0$ GeV/c; (3) no charged pion tracks with momentum $p_\pi^{\text{reco}} > 70$ MeV/c have been identified by the BDT PID model; (4) all final state particles have been identified, and consist of one muon and any number of proton candidate tracks that all start and end within the PCV; (5) all final state activity has been classified by the BDT PID model. This selec-

TABLE I. Efficiency and purity for each stage in the CC0 π selection. The efficiency is shown as an absolute fraction and relative to the previous step (in parentheses).

Selection criterion	Efficiency (Rel.)	Purity
1 reconstructed ν	0.85 (85%)	0.11
Vertex in FV	0.78 (93%)	0.25
Neutrino-like topology	0.65 (82%)	0.39
No showers	0.53 (82%)	0.51
Daughters start in PCV	0.52 (99%)	0.52
ν_μ CC (BDT μ candidate)	0.49 (95%)	0.57
p_μ limits	0.49 (98%)	0.58
π^\pm threshold	0.44 (90%)	0.71
Complete BDT PID	0.37 (85%)	0.74
μ Contained	0.13 (34%)	0.71

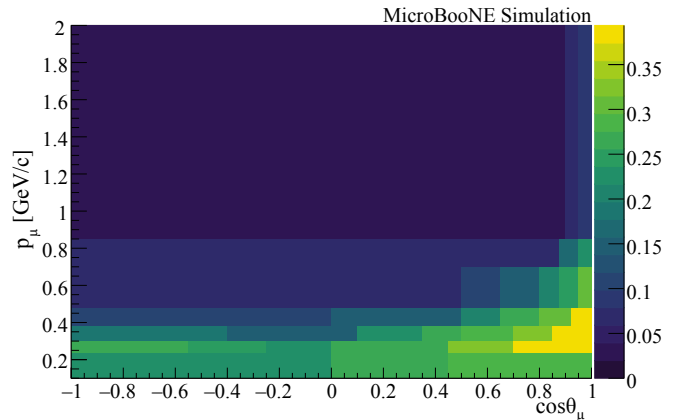
tion requires that all final state particles be positively identified by the BDT PID model and pass momentum requirements, improving the purity of the sample.

The CC0 π selection achieves an overall efficiency of 13% with a sample purity of 71% (Table I). The final requirement listed is containment of the full extent of the candidate muon within the PCV. This enables an accurate estimate of the muon momentum using the track's well-measured range and the known energy loss profile. It is also possible to measure the momentum of exiting muons using the deflection angles due to multiple Coulomb scatterings along the track [54]. This extension to higher muon momentum is not considered in this work. As seen when comparing the last two rows in Table I, containment has a sizable impact on the selection efficiency (37% \rightarrow 13%) which particularly impacts higher-momentum muons. Figure 1 illustrates the efficiency and purity as a function of muon momentum and angle, indicating the uniformly high purity. The efficiency is maximal for intermediate-momentum forward-going muons.

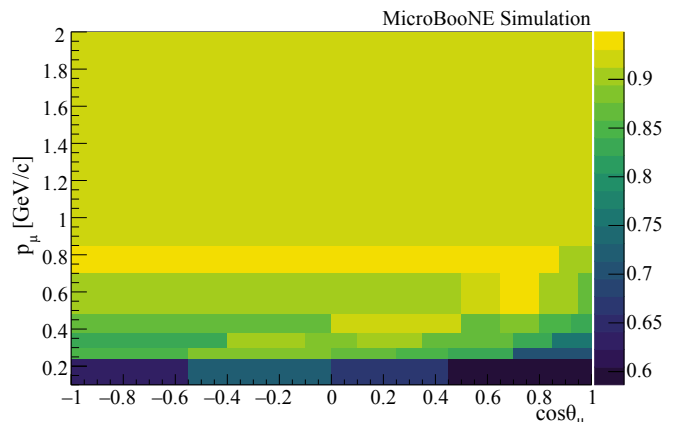
E. Binning of observables

The flux-integrated cross section is extracted as a function of final state muon momentum (p_μ) and the cosine of the muon angle with respect to the beam axis ($\cos\theta_\mu$). For each observable the binning choice has been optimized to ensure adequate event statistics. Each bin in the space of reconstructed observables is required to contain at least 50 selected signal events. To accurately reflect the measurement resolution, each reconstructed bin is required to contain $\geq 50\%$ of the events in the corresponding true bin. The diagonal elements of a normalized smearing matrix are therefore required to exceed 0.5. The total uncertainty within each reconstructed bin is less than 30%, and is approximately Gaussian. The optimal bin boundaries have been rounded to the nearest 5 MeV/ c and $\cos\theta = 0.005$.

Results are presented in two formats: (a) two uncorrelated 1D measurements in p_μ and $\cos\theta_\mu$, and (b) a single 2D measurement binned in the joint space of both



(a) Efficiency.



(b) Purity.

FIG. 1. Performance of the ν_μ CC0 π event selection, as a function of muon p_μ and $\cos\theta_\mu$, using the 2D binning.

observables. In the latter case, the bins are defined to enable a projection into 1D p_μ bins. In both cases, bin boundaries cover the range $0.1 < p_\mu < 2.0$ GeV/ c and $-1 < \cos\theta_\mu < 1$. The migration matrices and numerical values for all bin boundaries are given in the Supplemental Material [57].

IV. SYSTEMATIC UNCERTAINTIES

We consider systematic uncertainties from the simulation and modeling used to estimate efficiencies and backgrounds. The statistical uncertainties due to the finite sample size of data-driven background estimates are also treated as systematic uncertainties. This work follows the same approach as previous MicroBooNE neutrino cross section measurements [58]. To provide a sense of relative scale, we note throughout this discussion the approximate fractional uncertainty associated with each source of uncertainty near $p_\mu = 0.5$ GeV/ c . The total uncertainty in this 1D momentum bin is approximately

10%, including a 3% statistical contribution. The fractional uncertainty in each unfolded cross section bin can be found in the Supplementary Material [57].

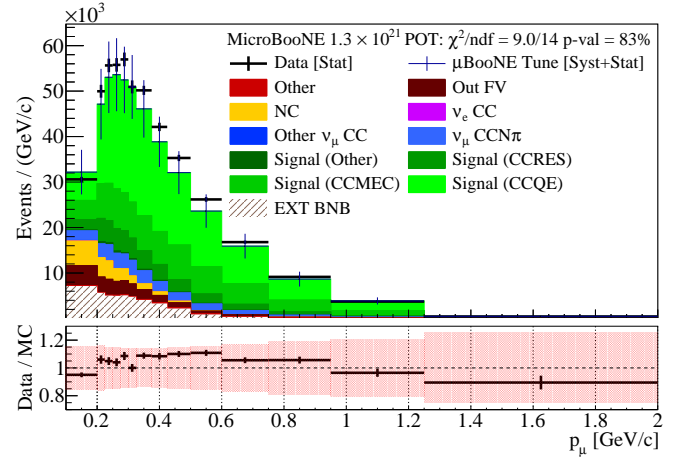
Uncertainties related to the BNB neutrino flux arise from underlying uncertainty in the beam simulation, details of the magnetic focusing horn, and hadron interaction cross sections. They impact the expected rate of neutrinos per POT and their energy distribution. These uncertainties are propagated by sampling 1000 randomly drawn parameter sets from the correlated distributions of the underlying simulation parameters to reweight events, following the approach developed by MiniBooNE [23]. Flux uncertainties vary within (5–20)% across the momentum range, with a minimum of 5% near 0.5 GeV/c. An additional small uncertainty of 2% accounts for limitations of the POT estimation.

The GENIE neutrino interaction model, as constrained in the MicroBooNE tune, includes 44 parameters. Similar to the flux, 500 randomly-drawn variations of these parameters constitute alternative “universes” used to estimate uncertainties and correlations by reweighting the nominal Monte Carlo events [18, 44]. Additional variations account for uncertainties on the vector and axial form factors used by the CCQE interaction models. The total neutrino interaction uncertainty varies from (4–23)% across the momentum range. At 0.5 GeV/c it is approximately 5%, comparable to flux uncertainties.

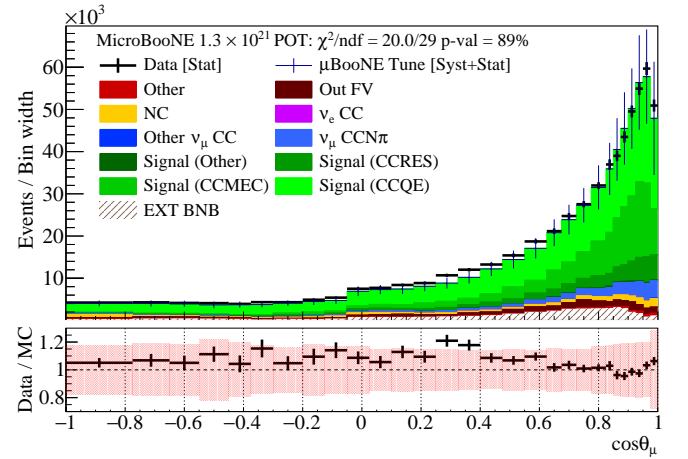
Uncertainties related to final state hadron reinteractions in the bulk argon (after leaving the nucleus) are implemented using the Geant4Reweight [59] package. This uncertainty is approximately 1% throughout the measured momentum range.

Detector response systematics quantify uncertainties arising from discrepancies between the detector response in simulation and measurements in calibration control regions [60]. These are estimated using alternative Monte Carlo samples with modified detector response models, including charge effects in the LArTPC [50, 51, 61], light propagation and detection, and modified wire signal formation [48, 49]. Most detector effects are captured through a data-driven approach of “wire modification” [61]. This technique uses data-simulation differences in deconvolved wire waveforms for well-characterized, time-tagged cosmic-ray muon samples to correct the detector’s ionization charge response as a function of position, and track angle and pitch. The correction carries an associated uncertainty driven by the sample statistics [61]. This method accounts for any source of ionization charge loss in the TPC. An additional small uncertainty is considered accounting for the temperature-dependent number of argon target nuclei contained in the active TPC volume. Detector response uncertainties vary across the momentum range, as the dominant contribution (32% of 46% total) in the lowest momentum bin. They are subdominant at intermediate and high momentum, with a minimum of 3% at 0.5 GeV/c.

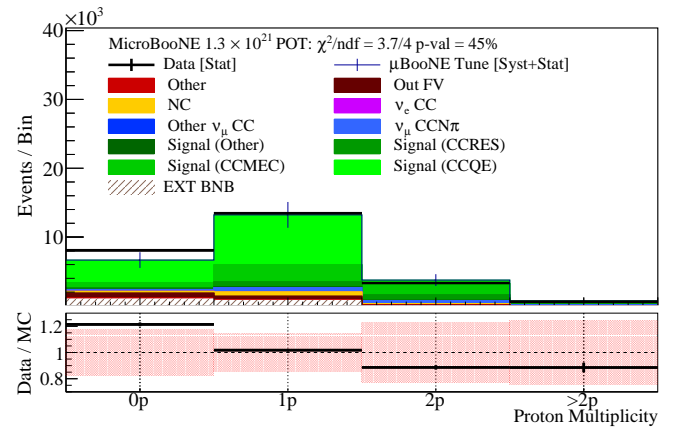
Finally, several statistical uncertainties are considered,



(a) Reconstructed p_μ .



(b) Reconstructed $\cos \theta_\mu$.



(c) Reconstructed proton multiplicity.

FIG. 2. Event rates for the CC0 π signal selection normalized by bin width, comparing data to simulation in 1D reconstructed observable bins. The data points indicate statistical errors, while the errors on the MC represent systematic uncertainties.

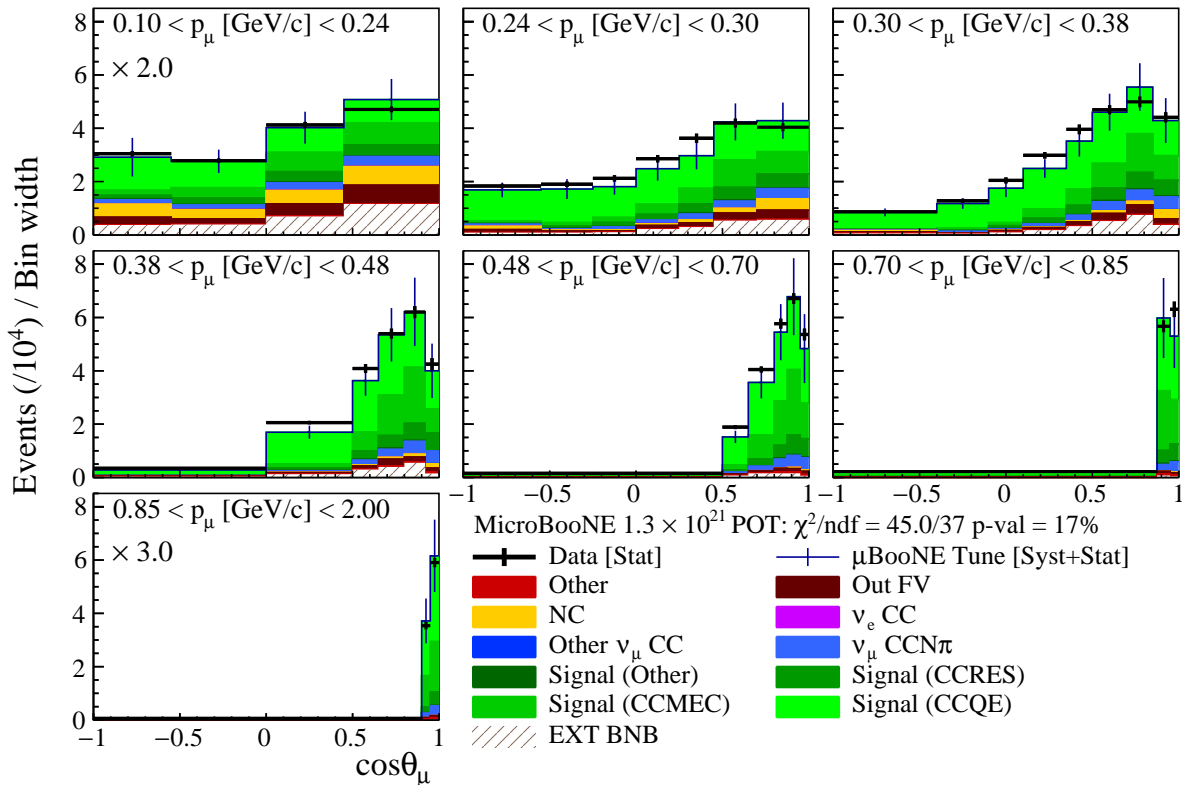


FIG. 3. Selected $CC0\pi$ events in the 2D reconstructed observable space, shown as a function of $\cos\theta_\mu$ in regions of p_μ . The data points indicate statistical errors, while the errors on the MC represent systematic uncertainties.

accounting for the finite sample sizes of the main neutrino interaction Monte Carlo, the beam-off data used to estimate backgrounds due to misidentified cosmic-ray activity in the absence of a neutrino interaction, and beam-off data samples overlaid with simulated neutrino interactions. These contributions are in the (1–3)% range at 0.5 GeV/c. Apart from a 9% contribution in the lowest momentum bin, the data statistical uncertainties vary from (3–6)% over the momentum range.

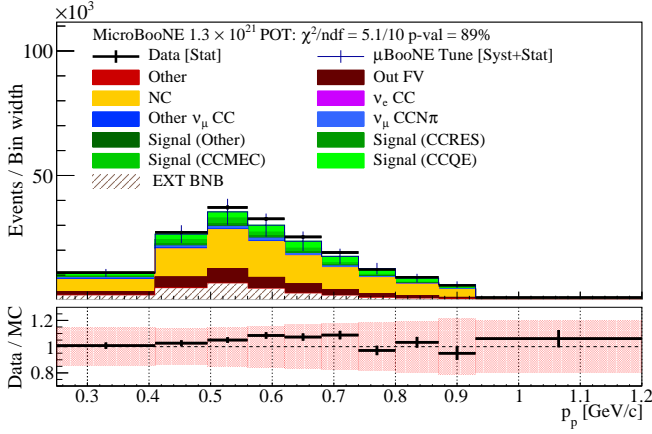
V. EVENT RATES

The measured event rates in 1D and 2D are shown in Figs. 2 and 3, respectively, comparing the full MicroBooNE BNB dataset to the central value Monte Carlo model (Sec. II) with the complete set of uncertainties (Sec. IV). Figure 2(c) also shows the reconstructed proton multiplicity distribution for the selected events. The dominant backgrounds vary across the kinematic space. Overall, the largest beam neutrino-induced background (5.5% of the overall selected event rate) is due to $\nu_\mu CCN\pi^\pm$ interactions, where the charged pion was mis-identified. At low p_μ , a larger fraction of background is due to NC events with final state protons. Cosmic ray-related backgrounds (EXT BNB) constitute 7.8% of selected events. This is due to the selection’s inclusion of

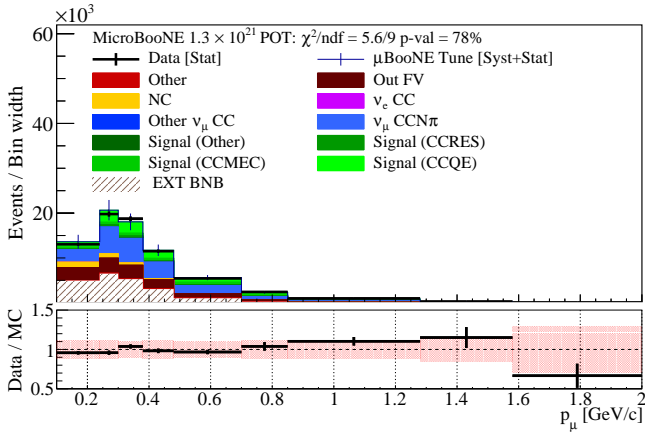
single track $1\mu 0p$ final states, as described in Section II D.

To validate the background modeling in the signal region, we consider a set of sideband control regions, defined by inverting selection criteria. The NC sideband selection requires that there are no muon-like particles in the final state. Here, events are selected having at least one proton-like rather than muon-like final state track. The BDT PID model must identify at least one proton in the final state, and all protons are required to have a momentum between (0.25 – 1.0) GeV/c. Figure 4(a) shows the event rate for the NC sideband as a function of the leading proton momentum. We obtain a sample with approximately 45% purity in NC events, the $CC0\pi$ signal being strongly suppressed, and find good agreement ($p = 89\%$) within uncertainties. The total uncertainty of about 25% is dominated by interaction modeling uncertainties.

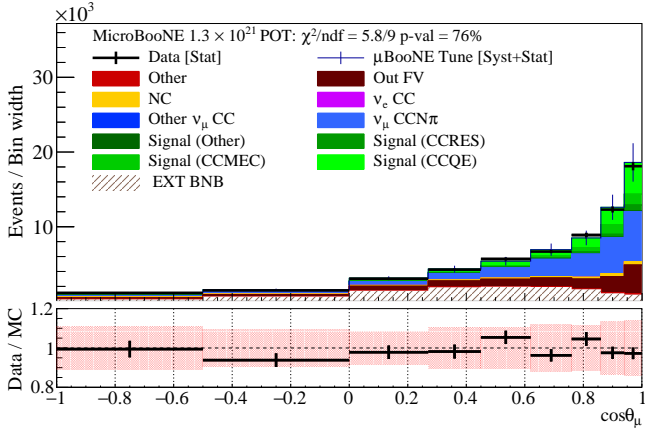
A $CCN\pi$ sideband provides a validation of the modeling of pion backgrounds in the $CC0\pi$ signal region. Here, events are initially classified as zero-shower $\nu_\mu CC$ -like and must satisfy the pre-selection cuts outlined in Section III B. From this sample, events are selected where the BDT PID model identifies one or more charged pion-like final state tracks. Candidate pion tracks must exceed a momentum threshold of 70 MeV/c, motivated by the track reconstruction efficiency. Figure 4(b) and 4(c) show the resulting $CCN\pi$ event distribution, measured



(a) Leading proton momentum distribution for the NC sideband selection.



(b) Distribution of p_μ for the $\text{CCN}\pi$ sideband selection.



(c) Distribution of $\cos \theta_\mu$ for the $\text{CCN}\pi$ sideband selection.

FIG. 4. Event rates for the validation sidebands, comparing data to simulation. The data points indicate statistical errors, while the errors on the MC represent systematic uncertainties.

as a function of the final state reconstructed p_μ and $\cos \theta_\mu$. Again in this selection, enhanced to 27.9% purity in $\nu_\mu \text{CCN}\pi$ events, we observed a high level of compatibility ($p > 75\%$) with the central value MicroBooNE GENIE tune simulation. A final sideband inverts the fiducial volume cut to measure the rates of events near the detector boundary, which contribute to the out-of-fiducial-volume (OOFV) backgrounds. This sample also shows agreement between data and simulation with $p = 85\%$ for the reconstructed muon momentum distribution. On the basis that the NC, $\text{CCN}\pi$, and OOFV backgrounds appear to be well-modeled within our uncertainties, we do not apply any additional tuning or corrections to the corresponding backgrounds in the signal region.

VI. CROSS SECTION EXTRACTION

We subtract estimated backgrounds from the event rates measured in data, scale according to the integrated neutrino flux and number of target nuclei, and apply efficiency and acceptance corrections to account for bin migrations between true and reconstructed observable bins. The full set of correlated systematic uncertainties as expressed in a covariance matrix are propagated. These corrections, which map the observed event rates from the space of reconstructed observables to a space of regularized true observables, are applied through an unfolding procedure. For this measurement, the unfolding is performed using the Wiener-SVD method [21] using the first derivative to define the regularization penalty term [58]. This technique provides a regularization that preserves the statistical power of goodness-of-fit tests relative to the directly-measured reconstructed distributions. This unfolding approach is described in further detail in Ref. [62].

The degree of regularization applied in unfolding using the Wiener-SVD method is represented in an output matrix referred to as the regularization matrix A_C . This matrix encodes the transformation between true observables and the regularized observables we use to express our measurement. Distributions expressed in terms of true observables (e.g., generator p_μ) must be transformed by the A_C matrix for statistical comparisons to this data.

Prior to analysis of the full dataset, a series of tests were conducted using Monte Carlo samples treated as data to validate the unfolding procedure and assess potential model dependence. The NuWro generator [63] provides an alternative neutrino interaction model. Additional samples were generated with extreme variations on the base GENIE model: one disabling the MicroBooNE GENIE tuning [44] (see Section II B) and another increasing the MEC ($2p2h$) cross section by a factor of two. In each case, we extract the unfolded cross section and assess the consistency with the true underlying cross section under the corresponding model variation hypothesis, determining the statistical consistency using

a χ^2 test. As the flux and detector simulation are identical, the only uncertainties included are those on the cross-section model, and additionally the Monte Carlo statistical uncertainties for the NuWro comparisons. The extracted cross sections are found to be well within the uncertainties in all cases, with $p > 73\%$ for the NuWro simulation and $p > 84\%$ for the alternative GENIE models. As an additional test of the uncertainties impacting momentum scale, a set of simulations are constructed by shifting the true and reconstructed muon momenta upward by 5% and 10%, about equal to and twice the muon momentum resolution, respectively. For these tests, the full set of uncertainties is used. With p values of 94% and 41% for the extracted cross sections relative to the true cross sections, we observe that the unfolding procedure is capable of recovering the true cross section even in the case of a significant mis-modeling of the muon momentum scale well beyond the relevant uncertainties.

VII. RESULTS

The unfolded single-differential cross sections in p_μ and $\cos\theta_\mu$ are shown in Figs. 5(a) and 5(b). The double-differential cross section is shown in Fig. 6 as a function of $\cos\theta_\mu$ in ranges of p_μ . For the double-differential cross section, the χ^2 values and p values in each momentum range are given in Table II. The fractional uncertainties on the extracted cross sections are available in the Supplemental Material [57]. We compare the extracted cross sections to predictions from a variety of neutrino event generators, transformed to the unfolded observable space via application of the A_C matrix. The corresponding χ^2 statistic and p value relative to the unfolded data are also shown.

The measurements are compared to models including: (1) GENIE version v3.2.0 [24] using the G18_10a_02_11a CMC (2) GiBUU 2025 [64]; (3) NEUT version 5.4.0.1 [65]; and (4) NuWro version 21.09.2 [63]. These generator predictions are processed using the NUISANCE framework [66]. Table III summarizes the resulting χ^2 and p values comparing the measured data with the models. A detailed comparison of the models represented in each generator configuration, as well as results for additional generator models, are available in the Supplemental Material [57].

We find that all models considered here describe the data in individual 1D distributions, while only a subset agree with the double-differential measurement. The latter provides a stricter test, assessing the extent to which models correctly describe the angular distribution as a function of momentum, and considering the correlations in this 2D space. Overall, GiBUU 2025 performs best for the measurement across the fully correlated 2D space, and the NEUT model also performs well. The success of up-to-date neutrino event generators is indicative of the significant modeling improvements in recent years and the value of multi-dimensional measurements to assess

models. Most generators under-predict the normalization. This effect is most pronounced for forward angles and intermediate muon momentum (0.5 – 0.7) GeV/c. These effects can be seen in Fig. 6, which indicates the goodness-of-fit for the angular distribution within each momentum range individually.

VIII. CONCLUSIONS

Neutrino interaction measurements using LArTPCs provide crucial input to inform the development and tuning of the models underpinning precision neutrino oscillation measurements and background estimation for beyond the Standard Model physics searches. Using the full 1.3×10^{21} POT exposure of the MicroBooNE LArTPC experiment in the Fermilab BNB, we have performed a high-statistics measurement of the flux-integrated single and double-differential cross sections in terms of final state muon kinematics for $\nu_\mu \text{CC}0\pi$ interactions on argon, i.e., interactions that have no final-state pions but may or may not have final state protons. This channel is of importance for neutrino oscillation searches as a topologically-defined proxy for well-modeled CCQE interactions, especially in detectors with a high threshold for hadronic activity (e.g., WC experiments), for which this measurement with an argon target provides a point of comparison.

The measurement, unfolding techniques, and background estimation are validated using a suite of fake data tests and targeted sideband selections isolating NC and $\text{CC}N\pi^\pm$ interactions. The observed event rates show good agreement with the central value GENIE model used in the efficiency and background estimation. Considering a suite of uncertainties concerning the data statistics, neutrino flux, interaction model, detector response, cosmic ray background normalization, and exposure and target mass estimation, we find an average total uncertainty below 20%.

The extracted 1D and 2D cross sections as a function of p_μ and $\cos\theta_\mu$ are quantitatively compared with a variety of neutrino event generators, representing an array of physics model sets and implementations. We find that all generator models considered provide a reasonable description of the p_μ and $\cos\theta_\mu$ distributions individually. The GiBUU 2025 and NEUT models also show agreement with the correlated joint distribution, while other models yield a poorer description with p values $< 5\%$. Additional tests using alternative GENIE models provide further guidance on the impact of specific model implementations in regions of the kinematic phase space. These data provide a high-statistics measurement of $\nu_\mu \text{CC}0\pi$ interactions in the correlated joint space of muon momentum and angle and offer a benchmark for further modeling improvements, looking ahead to increasingly precise measurements of neutrino oscillations and other accelerator-based measurements using both argon and other nuclei.

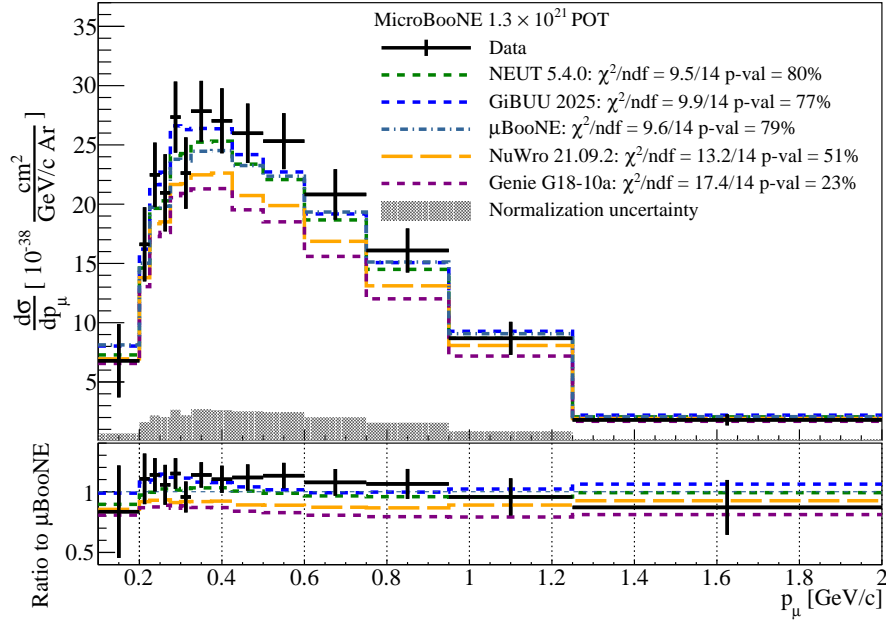
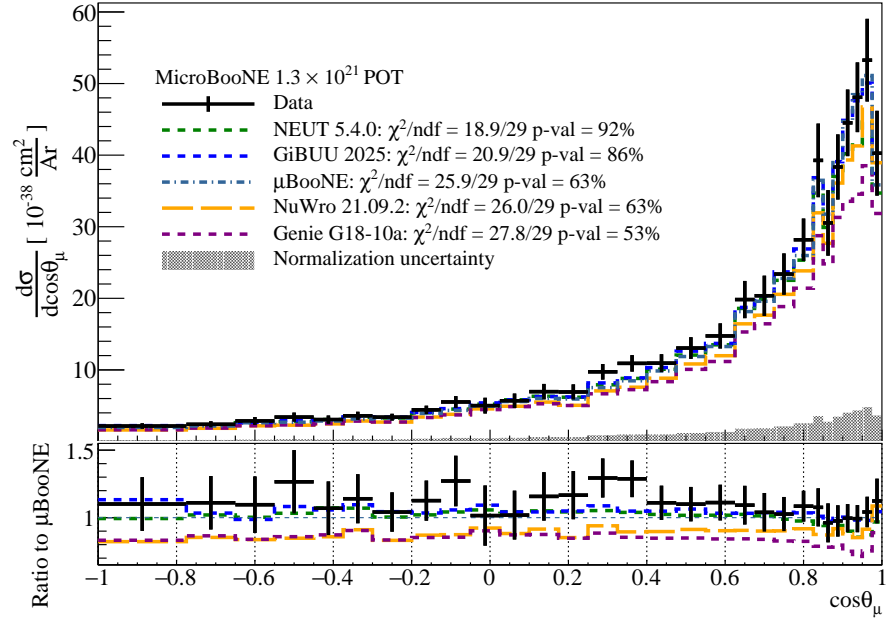
(a) p_μ differential cross section.(b) $\cos \theta_\mu$ differential cross section.

FIG. 5. Extracted flux-integrated differential cross sections for the $CC0\pi$ signal, in 1D p_μ and $\cos \theta_\mu$ bins. Errors on the data include both statistical and systematic uncertainties.

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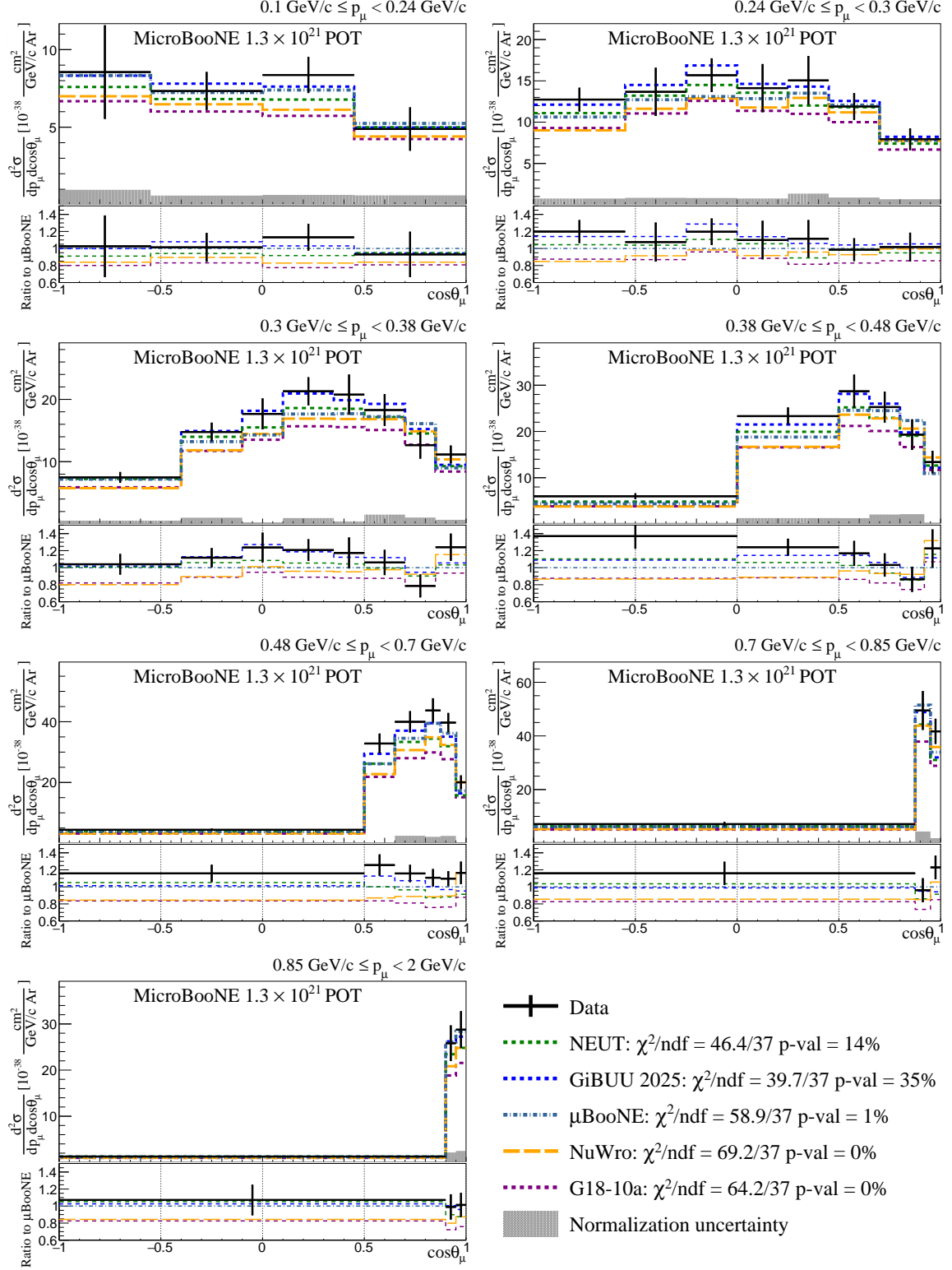


FIG. 6. Extracted flux-integrated double-differential cross sections for the CC0 π signal, shown as a function of $\cos\theta_\mu$ in ranges of p_μ . Errors on the data include both statistical and systematic uncertainties. The χ^2 and p values for individual momentum ranges are listed in Table II.

TABLE II. Generator model comparisons for individual momentum ranges in the double-differential cross section measurement, indicating the χ^2 and p values (p) for each generator in each range. Momentum ranges are in units of GeV/ c .

p_μ range	0.10 – 0.24		0.24 – 0.30		0.30 – 0.38		0.38 – 0.48		0.48 – 0.70		0.70 – 0.85		0.85 – 2.00	
Model	χ^2/ndf	p	χ^2/ndf	p	χ^2/ndf	p	χ^2/ndf	p	χ^2/ndf	p	χ^2/ndf	p	χ^2/ndf	p
μBooNE	1.1/4	89%	5.4/7	61%	14.0/8	8%	17.0/6	1%	6.7/6	35%	3.3/3	35%	0.4/3	95%
NEUT	2.5/4	65%	2.6/7	92%	5.8/8	67%	7.0/6	32%	11.2/6	8%	5.8/3	12%	2.4/3	49%
GiBUU 2025	1.3/4	85%	1.4/7	99%	4.6/8	80%	6.4/6	38%	4.1/6	67%	4.7/3	20%	0.2/3	98%
NuWro	4.3/4	37%	11.7/7	11%	18.4/8	2%	32.7/6	0%	16.4/6	1%	5.6/3	14%	2.6/3	46%
G18-10a	5.8/4	22%	8.0/7	21%	14.1/8	6%	24.6/6	0%	22.9/6	0%	12.3/3	1%	6.9/3	8%

TABLE III. Summary of generator model comparisons, indicating the χ^2 and p values for each model considered, in comparison to the 2D extracted cross section and the individual 1D single-differential distributions in p_μ and $\cos\theta_\mu$.

Model/Tune	2D $p_\mu/\cos\theta_\mu$		p_μ		$\cos\theta_\mu$	
	χ^2/ndf	p value	χ^2/ndf	p value	χ^2/ndf	p value
μBooNE	58.9/37	1%	9.6/14	79%	25.9/29	63%
NEUT	46.4/37	14%	9.5/14	80%	18.9/29	92%
GiBUU 2025	39.7/37	35%	9.9/14	77%	20.9/29	86%
NuWro	69.2/37	0%	13.2/14	51%	26.0/29	63%
G18-10a	64.2/37	0%	17.4/14	23%	27.8/29	53%

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- [1] G. C. Branco, R. G. Felipe, and F. R. Joaquim, Leptonic CP Violation, *Rev. Mod. Phys.* **84**, 515 (2012).
 - [2] P. F. De Salas, S. Gariazzo, O. Mena, C. A. Ternes, and M. Tórtola, Neutrino Mass Ordering from Oscillations and Beyond: 2018 Status and Future Prospects, *Front. Astron. Space Sci.* **5**, 36 (2018).
 - [3] R. Acciarri *et al.* (MicroBooNE, LArI-ND, ICARUS-WA104 Collaborations), A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam, (2015), arXiv:1503.01520 [physics.ins-det].
 - [4] P. A. Machado, O. Palamara, and D. W. Schmitz, The Short-Baseline Neutrino Program at Fermilab, *Ann. Rev. Nucl. Part. Sci.* **69**, 363 (2019).
 - [5] B. Abi *et al.* (DUNE Collaboration), Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics, (2020), arXiv:2002.03005 [hep-ex].
 - [6] B. Abi *et al.* (DUNE Collaboration), Long-baseline neutrino oscillation physics potential of the DUNE experiment, *Eur. Phys. J. C* **80**, 978 (2020).
 - [7] B. Abi *et al.* (DUNE Collaboration), Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment, *Eur. Phys. J. C* **81**, 322 (2021).
 - [8] B. Abi *et al.* (DUNE Collaboration), Supernova neutrino burst detection with the Deep Underground Neutrino Experiment, *Eur. Phys. J. C* **81**, 423 (2021).
 - [9] K. Abe *et al.* (T2K Collaboration), The T2K Experiment, *Nucl. Instrum. Meth. A* **659**, 106 (2011).
 - [10] K. Abe *et al.* (T2K Collaboration), Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations, *Nature* **580**, 339 (2020), [Erratum: *Nature* 583, E16 (2020)].
 - [11] K. Abe *et al.* (Hyper-Kamiokande Collaboration), Hyper-Kamiokande Design Report, (2018), arXiv:1805.04163 [physics.ins-det].
 - [12] K. Abe *et al.* (Hyper-Kamiokande Proto-Collaboration), Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande, *PTEP* **2015**, 053C02 (2015).
 - [13] M. Askins *et al.* (Theia Collaboration), THEIA: an advanced optical neutrino detector, *Eur. Phys. J. C* **80**, 416 (2020).
 - [14] I. Anghel *et al.* (ANNIE Collaboration), Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE), (2015), arXiv:1504.01480 [physics.ins-det].
 - [15] A. R. Back *et al.* (ANNIE Collaboration), Accelerator Neutrino Neutron Interaction Experiment (ANNIE): Preliminary Results and Physics Phase Proposal, (2017), arXiv:1707.08222 [physics.ins-det].
 - [16] P. Abratenko *et al.* (MicroBooNE Collaboration), Measurement of double-differential cross sections for mesonless charged-current muon neutrino interactions on argon with final-state protons using the MicroBooNE detector, (2024), arXiv:2403.19574 [hep-ex].
 - [17] P. Abratenko *et al.* (MicroBooNE Collaboration), Measurement of nuclear effects in neutrino-argon interactions using generalized kinematic imbalance variables with the MicroBooNE detector, *Phys. Rev. D* **109**, 092007 (2024).
 - [18] P. Abratenko *et al.* (MicroBooNE Collaboration), Multi-differential cross section measurements of ν_μ -argon quasi-elastic-like reactions with the MicroBooNE detector, *Phys. Rev. D* **108**, 053002 (2023).
 - [19] P. Abratenko *et al.* (MicroBooNE), Measurement of differential cross sections for ν_μ -Ar charged-current interactions with protons and no pions in the final state with the MicroBooNE detector, *Phys. Rev. D* **102**, 112013 (2020), arXiv:2010.02390 [hep-ex].
 - [20] P. Abratenko *et al.* (MicroBooNE), First Double-Differential Measurement of Kinematic Imbalance in Neutrino Interactions with the MicroBooNE Detector, *Phys. Rev. Lett.* **131**, 101802 (2023), arXiv:2301.03706 [hep-ex].
 - [21] W. Tang, X. Li, X. Qian, H. Wei, and C. Zhang, Data Unfolding with Wiener-SVD Method, *J. Instrum.* **12** (10), P10002.
 - [22] R. Acciarri *et al.* (MicroBooNE Collaboration), Design and Construction of the MicroBooNE Detector, *J. Instrum.* **12** (02), P02017.
 - [23] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), The Neutrino Flux Prediction at MiniBooNE, *Phys. Rev. D* **79**, 072002 (2009).
 - [24] L. Alvarez-Ruso *et al.* (GENIE Collaboration), Recent highlights from GENIE v3, *Eur. Phys. J. ST* **230**, 4449 (2021).
 - [25] C. Andreopoulos *et al.*, The GENIE Neutrino Monte Carlo Generator, *Nucl. Instrum. Meth. A* **614**, 87 (2010).
 - [26] C. Andreopoulos, C. Barry, S. Dytman, H. Gallagher, T. Golan, R. Hatcher, G. Perdue, and J. Yarba, The GENIE Neutrino Monte Carlo Generator: Physics and User Manual, (2015), arXiv:1510.05494 [hep-ph].
 - [27] J. Tena-Vidal *et al.* (GENIE Collaboration), Neutrino-nucleon cross-section model tuning in GENIE v3, *Phys. Rev. D* **104**, 072009 (2021).
 - [28] J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, Inclusive Charged-Current Neutrino-Nucleus Reactions, *Phys. Rev. C* **83**, 045501 (2011).
 - [29] J. Nieves, J. E. Amaro, and M. Valverde, Inclusive quasi-elastic neutrino reactions, *Phys. Rev. C* **70**, 055503 (2004), [Erratum: *Phys. Rev. C* **72**, 019902 (2005)].
 - [30] J. Nieves, F. Sanchez, I. Ruiz Simo, and M. J. Vicente Vacas, Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section, *Phys. Rev. D* **85**, 113008 (2012).

- [31] R. Gran, J. Nieves, F. Sanchez, and M. J. Vicente Vacas, Neutrino-nucleus quasi-elastic and 2p2h interactions up to 10 GeV, *Phys. Rev. D* **88**, 113007 (2013).
- [32] L. A. Copley, G. Karl, and E. Obryk, Electroproduction from nucleons in a relativistic quark model, *Phys. Rev. D* **4**, 2844 (1971).
- [33] C. Berger and L. M. Sehgal, Lepton mass effects in single pion production by neutrinos, *Phys. Rev. D* **76**, 113004 (2007).
- [34] K. M. Graczyk and J. T. Sobczyk, Form Factors in the Quark Resonance Model, *Phys. Rev. D* **77**, 053001 (2008), [Erratum: *Phys. Rev. D* **79**, 079903 (2009)].
- [35] J. A. Nowak (MiniBooNE Collaboration), Four Momentum Transfer Discrepancy in the Charged Current π^+ Production in the MiniBooNE: Data vs. Theory, *AIP Conf. Proc.* **1189**, 243 (2009).
- [36] K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Lepton polarization in neutrino nucleon interactions, *Mod. Phys. Lett. A* **19**, 2815 (2004).
- [37] D. Rein and L. M. Sehgal, Neutrino Excitation of Baryon Resonances and Single Pion Production, *Annals Phys.* **133**, 79 (1981).
- [38] C. Berger and L. M. Sehgal, PCAC and coherent pion production by low energy neutrinos, *Phys. Rev. D* **79**, 053003 (2009).
- [39] A. Bodek and U. k. Yang, Modeling neutrino and electron scattering cross-sections in the few GeV region with effective LO PDFs, *AIP Conf. Proc.* **670**, 110 (2003).
- [40] A. Bodek, I. Park, and U. k. Yang, Improved low Q^2 model for neutrino and electron nucleon cross sections in few GeV region, *Nucl. Phys. B Proc. Suppl.* **139**, 113 (2005).
- [41] A. Bodek and U. k. Yang, Nufact09 update to the Bodek-Yang unified model for electron- and neutrino- nucleon scattering cross sections, *AIP Conf. Proc.* **1222**, 233 (2010).
- [42] S. Dytman, Y. Hayato, R. Raboanary, J. T. Sobczyk, J. Tena Vidal, and N. Vololonina, Comparison of validation methods of simulations for final state interactions in hadron production experiments, *Phys. Rev. D* **104**, 053006 (2021).
- [43] K. Abe *et al.* (T2K Collaboration), Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam, *Phys. Rev. D* **93**, 112012 (2016).
- [44] P. Abratenko *et al.* (MicroBooNE Collaboration), New CC0 π GENIE model tune for MicroBooNE, *Phys. Rev. D* **105**, 072001 (2022).
- [45] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4 - A Simulation Toolkit, *Nucl. Instrum. Meth. A* **506**, 250 (2003).
- [46] J. Allison *et al.*, Recent developments in Geant4, *Nucl. Instrum. Meth. A* **835**, 186 (2016).
- [47] E. L. Snider and G. Petrillo, LArSoft: Toolkit for Simulation, Reconstruction and Analysis of Liquid Argon TPC Neutrino Detectors, *J. Phys. Conf. Ser.* **898**, 042057 (2017).
- [48] C. Adams *et al.* (MicroBooNE Collaboration), Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative evaluation with MicroBooNE simulation, *J. Instrum.* **13** (07), P07006.
- [49] C. Adams *et al.* (MicroBooNE Collaboration), Ionization electron signal processing in single phase LArTPCs. Part II. Data/simulation comparison and performance in MicroBooNE, *J. Instrum.* **13** (07), P07007.
- [50] C. Adams *et al.* (MicroBooNE Collaboration), A method to determine the electric field of liquid argon time projection chambers using a UV laser system and its application in MicroBooNE, *J. Instrum.* **15** (07), P07010.
- [51] P. Abratenko *et al.* (MicroBooNE Collaboration), Measurement of space charge effects in the MicroBooNE LArTPC using cosmic muons, *J. Instrum.* **15** (12), P12037.
- [52] C. Adams *et al.* (MicroBooNE Collaboration), Rejecting cosmic background for exclusive charged current quasi elastic neutrino interaction studies with Liquid Argon TPCs; a case study with the MicroBooNE detector, *Eur. Phys. J. C* **79**, 673 (2019).
- [53] R. Acciarri *et al.* (MicroBooNE Collaboration), The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector, *Eur. Phys. J. C* **78**, 82 (2018).
- [54] P. Abratenko *et al.* (MicroBooNE Collaboration), Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb scattering, *J. Instrum.* **12** (10), P10010.
- [55] P. Abratenko *et al.* (MicroBooNE Collaboration), Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data, *JHEP* **12**, 153.
- [56] T. Chen and C. Guestrin, XGBoost: A Scalable Tree Boosting System, (2016), arXiv:1603.02754 [cs.LG].
- [57] Supplemental Material, See Supplemental Material at [URL will be inserted by publisher] for details regarding the binning, bin migration, and smearing matrices, which includes Refs. [28, 42, 63, 65, 67–79].
- [58] S. Gardiner, Mathematical methods for neutrino cross-section extraction, (2024), arXiv:2401.04065 [hep-ex].
- [59] J. Calcutt, C. Thorpe, K. Mahn, and L. Fields, Geant4Reweight: a framework for evaluating and propagating hadronic interaction uncertainties in Geant4, *J. Instrum.* **16** (08), P08042.
- [60] C. Adams *et al.* (MicroBooNE Collaboration), Calibration of the charge and energy loss per unit length of the MicroBooNE liquid argon time projection chamber using muons and protons, *J. Instrum.* **15** (03), P03022.
- [61] P. Abratenko *et al.* (MicroBooNE Collaboration), Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data, *Eur. Phys. J. C* **82**, 454 (2022).
- [62] P. Abratenko *et al.* (MicroBooNE), Inclusive cross section measurements in final states with and without protons for charged-current ν_μ -Ar scattering in MicroBooNE, *Phys. Rev. D* **110**, 013006 (2024).
- [63] T. Golan, J. T. Sobczyk, and J. Zmuda, NuWro: the Wroclaw Monte Carlo Generator of Neutrino Interactions, *Nucl. Phys. B Proc. Suppl.* **229–232**, 499 (2012).
- [64] O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A. B. Larionov, T. Leitner, J. Weil, and U. Mosel, Transport-theoretical Description of Nuclear Reactions, *Phys. Rept.* **512**, 1 (2012).
- [65] Y. Hayato and L. Pickering, The NEUT neutrino interaction simulation program library, *Eur. Phys. J. ST* **230**, 4469 (2021).
- [66] P. Stowell *et al.*, NUISANCE: a neutrino cross-section generator tuning and comparison framework, *J. Instrum.* **12** (01), P01016.
- [67] R. Bradford, A. Bodek, H. S. Budd, and J. Arrington, A

- New parameterization of the nucleon elastic form-factors, Nucl. Phys. B Proc. Suppl. **159**, 127 (2006).
- [68] A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, Vector and Axial Nucleon Form Factors: A Duality Constrained Parameterization, Eur. Phys. J. C **53**, 349 (2008).
 - [69] O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Spectral function of finite nuclei and scattering of GeV electrons, Nucl. Phys. A **579**, 493 (1994).
 - [70] T. Golan, C. Juszczak, and J. T. Sobczyk, Final State Interactions Effects in Neutrino-Nucleus Interactions, Phys. Rev. C **86**, 015505 (2012).
 - [71] T. Leitner, L. Alvarez-Ruso, and U. Mosel, Charged current neutrino nucleus interactions at intermediate energies, Phys. Rev. C **73**, 065502 (2006).
 - [72] B. Blaettel, V. Koch, and U. Mosel, Transport theoretical analysis of relativistic heavy ion collisions, Rept. Prog. Phys. **56**, 1 (1993).
 - [73] T. Sjostrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP **05**, 026.
 - [74] U. Mosel and K. Gallmeister, Lepton-induced reactions on nuclei in a wide kinematical regime, Phys. Rev. D **109**, 033008 (2024).
 - [75] U. Mosel, Neutrino event generators: foundation, status and future, J. Phys. G **46**, 113001 (2019).
 - [76] A. S. Meyer, M. Betancourt, R. Gran, and R. J. Hill, Deuterium target data for precision neutrino-nucleus cross sections, Phys. Rev. D **93**, 113015 (2016).
 - [77] J. Schwehr, D. Cherdack, and R. Gran, GENIE implementation of IFIC Valencia model for QE-like 2p2h neutrino-nucleus cross section, (2016), arXiv:1601.02038 [hep-ph].
 - [78] J. Gonzalez-Rosa, G. D. Megias, J. A. Caballero, and M. B. Barbaro, SuSAv2 model for inelastic neutrino-nucleus scattering, Phys. Rev. D **105**, 093009 (2022).
 - [79] C. H. Llewellyn Smith, Neutrino Reactions at Accelerator Energies, Phys. Rept. **3**, 261 (1972).