

Measurement of $d^2\sigma/d|\vec{q}|dE_{\text{avail}}$ in charged current ν_μ -nucleus interactions at $\langle E_\nu \rangle = 1.86$ GeV using the NOvA Near Detector

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(Dated: October 10, 2024)

Double- and single-differential cross sections for inclusive charged-current ν_μ -nucleus scattering are reported for the kinematic domain 0 to 2 GeV/c in three-momentum transfer and 0 to 2 GeV in available energy, at a mean ν_μ energy of 1.86 GeV. The measurements are based on an estimated 995,760 ν_μ CC interactions in the scintillator medium of the NOvA Near Detector. The subdomain populated by 2-particle-2-hole reactions is identified by the cross-section excess relative to predictions for ν_μ -nucleus scattering that are constrained by a data control sample. Models for 2-particle-2-hole processes are rated by χ^2 comparisons of the predicted-versus-measured ν_μ CC inclusive cross section over the full phase space and in the restricted subdomain. Shortfalls are observed in neutrino generator predictions obtained using the theory-based València and SuSAv2 2p2h models.

I. INTRODUCTION

A dedicated campaign is underway by the neutrino physics community to obtain a comprehensive picture of charged-current (CC) neutrino-nucleus interactions in the sub-GeV to few-GeV region of incident neutrino energies. Through the first decade of the present millennium, treatments of exclusive-channel neutrino scattering were largely based on hydrogen and deuterium bubble chamber data [1, 2]. The high-statistics neutrino-nucleus experiments of more recent times have resulted in refinements to the modeling of CC quasielastic scattering (CCQE) and of baryon-resonance production (RES) initiated by $\nu/\bar{\nu}$ -nucleus scattering [3, 4]. Shallow and deep inelastic CC scattering (DIS) have also received renewed scrutiny and modeling refinements [5]. Similarly, various aspects of neutrino CC coherent scattering (COH) and of kaon and hyperon production have been clarified [6]. The emerging theme from these developments is that neutrino-nucleus scattering involves much more than just neutrino-nucleon scattering in a relativistic Fermi gas. The presence of a nuclear medium introduces new phenomena whose observational effects must be understood to complete the picture of neutrino-

nucleus interactions.

Study of neutrino-nucleus scattering receives strong impetus from neutrino oscillation experiments as continued progress requires precise knowledge of differential cross sections. Neutrino oscillation measurements provide a window into the underlying physics and symmetries of neutrino states. At present, the ordering of neutrino mass eigenstates is unknown, the extent to which charge conjugation plus parity (CP) symmetry is violated in the lepton sector remains to be ascertained, and the octant assignment for the flavor mixing angle θ_{23} – if indeed it deviates from maximal mixing (45°) – needs to be resolved [7–9]. More precise knowledge of neutrino and antineutrino interactions in nuclear environments is required for experimental clarification of these fundamental questions.

A notable recent realization is that neutrino event rates in the sub- to few-GeV range of neutrino energy, E_ν , used by many of the oscillation experiments, receive contributions from multinucleon initial states. That interactions may involve two initial-state nucleons was known from electron-nucleus scattering [10]. However, the possibility that similar excitations occur in neutrino scattering, though mentioned in a 1985 paper by Delorme

and Ericson [11], was not generally recognized for some time. Initial hints in neutrino data came in the guise of unusually high values inferred for the axial mass parameter, M_A , of the axial-vector form factor, obtained with high-statistics samples of ν_μ -nucleus CC quasielastic-like scattering. In 2006–7, the K2K experiment reported M_A to be 1.20 ± 0.12 GeV from neutrinos on oxygen [12] and subsequently 1.14 ± 0.11 GeV for neutrinos on carbon [13]. At the time, the world-average axial-vector mass hovered around 1.00 GeV/ c^2 with uncertainty of $\sim 1\%$ [14, 15]. Thus it came as a shock during 2008–10 when MiniBooNE, presenting new studies of neutrino CCQE interactions in a carbon medium [16, 17], reported the “effective value” of quasielastic M_A to be 1.35 ± 0.17 GeV [17]. High values for M_A reflect the presence of an additional reaction rate above that expected from neutrino scattering on quasi-free nucleons. That the data exhibit this feature has been abundantly confirmed in measurements by MiniBooNE [18], MINOS [19], MINERvA [20–22], T2K [23, 24], MicroBooNE [25, 26], and NOvA [27]. The apparent high values for effective M_A in ν_μ -nucleus CCQE interactions were driven by the omission in the analyses of so-called 2-particle 2-hole (2p2h) processes:

$$\nu_\mu + \mathcal{A}_{(nN+\mathcal{A}')} \rightarrow \mu^- + p + N + \mathcal{A}', \quad (1)$$

where n , p , and N designate a neutron, proton, and nucleon (either a neutron or proton), respectively. Here, the incident neutrino interacts with nucleus \mathcal{A} to give a muon, proton, and nucleon in the final state. The remnant nucleus \mathcal{A}' with two holes in its Fermi sea subsequently undergoes deexcitation with possible nucleon ejection.

Theoretical calculations by the Lyon group were the first to explain the anomalous MiniBooNE CCQE result as originating with N-particle-N-hole interactions involving more than one nucleon, with N=2 giving the dominant contribution [28–30]. Soon thereafter the València group presented a detailed N-particle-N-hole model with 2p2h giving the dominant contribution [31–34]. Both of these microscopic models utilize the graphs and calculational methods of many-body quantum field theory. More recently, models of somewhat different construction have been presented. For example, the SuSAv2 model uses superscaling (SuSA), an approximation that invokes universal scaling functions for the electromagnetic and weak interactions, to describe single-body nuclear effects. In SuSAv2 this superscaling, together with microscopic calculations based on meson-exchange current (MEC) diagrams, are incorporated into a fully relativistic framework [35–37]. Additionally, semi-empirical approaches have been implemented in the GENIE [38] and GiBUU [39, 40] neutrino event generators. In paragraphs and figures to follow, the acronyms “2p2h-MEC” or just “2p2h” refer to the full suite of multinucleon processes.

In recent times, phenomenological predictions have

been probed at new levels of detail by detector-resolution-unfolded, double-differential (or even triple-differential) cross-section measurements. Initially this approach was applied to ν_μ and $\bar{\nu}_\mu$ quasielastic-like scattering [41–44]. More recently it has been used to characterize CC inclusive cross sections as well [45, 46]. The latter measurements are generally restricted to final-state muon kinematic variables, either to muon production angle and kinetic energy, or to muon transverse and longitudinal momenta. Exceptions to this were two MINERvA investigations of nuclear-medium effects for ν_μ -carbon and $\bar{\nu}_\mu$ -carbon scattering [47, 48] that reported double-differential cross sections using three-momentum transfer, $|\vec{q}|$, and available energy, E_{avail} . The E_{avail} variable represents final-state hadronic energy that is capable of producing ionization in the detector; it is the sum of electron, proton, charged pion, and kaon kinetic energy, plus neutral pion and photon total energy. For hyperons, E_{avail} is the total energy minus the nucleon mass; for antinucleons it is the total energy including rest mass. Available energy as used here excludes energies initiated by neutrons, as neutron scattering mostly does not register in detectors that rely on scintillation in hydrocarbons. Available energy is useful as a proxy for energy transfer, q_0 , in CC interactions because it minimizes detector-specific, model-dependent corrections that reconstruction of q_0 requires for unobserved energies.

The main motivation for choosing E_{avail} and reconstructed $|\vec{q}|$ is that they are experimental observables that closely resemble $(q_0, |\vec{q}|)$, the latter being the natural variables for the nuclear physics phenomenology associated with 2p2h [33, 39]. Assuming that the prevailing picture of 2p2h is roughly correct, ν_μ scattering on nucleon pairs results in energetic pp or pn pairs appearing in the final state. Then $|\vec{q}|$ of de Broglie wavelength ≤ 4 fm (corresponding to $|\vec{q}| > 0.3$ GeV/ c) is well-suited to probe the initial state, while E_{avail} measures the energy transfer to the target system.

This work uses data recorded by the NOvA Near Detector to measure the double-differential cross section in $|\vec{q}|$ and E_{avail} of ν_μ CC inclusive interactions

$$\nu_\mu(k) + \mathcal{A} \rightarrow \mu^-(k') + X. \quad (2)$$

Here, k and k' are the four-momenta of the incident neutrino and the outgoing muon. The NOvA data provide a high-statistics sample of neutrino CC interactions in the E_ν range from approximately 0.8 GeV to 3.2 GeV. This region lies above the sub-GeV E_ν range analyzed by T2K [23, 49], while being largely below the region $2 < E_\nu < 20$ GeV examined by MINERvA [20, 50]. Additionally, it covers the lower half of the high-flux plateau in the ν_μ energy spectrum planned for the DUNE experiment [51].

II. NEUTRINO BEAM, NEAR DETECTOR, AND DATA EXPOSURE

The NuMI neutrino beam at Fermilab [52] is produced by directing 120 GeV protons from the Main Injector accelerator onto a 1.2-m-long graphite target. Charged hadrons produced in the target traverse two magnetic focusing horns that are positioned immediately downstream. Operation of the horns in the forward horn-current mode results in focusing of positively charged pions and kaons. These positive mesons are then directed into a 675-m-long drift region where they decay to produce antimuons and muon neutrinos. The resulting ν_μ flux is calculated using a detailed simulation of beamline components and of the hadronic shower that emerges from the graphite target and evolves into mesons decaying to neutrinos. The simulation is based on Geant4 v9.2.p03 with the FTFP BERT hadron production model [53]. The PPFX package [54] is used to adjust the hadronic model to bring it into agreement with constraints provided by external hadron production data [55–72]. In the neutrino energy range relevant to this measurement (1.0–5.0 GeV) and at the NOvA off-axis angle of 14.6 mrad, 97.5% of the NuMI forward horn-current neutrino flux consists of ν_μ neutrinos. The remainder includes a 1.8% $\bar{\nu}_\mu$ component arising from decay of negatively charged mesons. There is also a contribution from ν_e and $\bar{\nu}_e$ neutrinos of 0.7% in this energy range [46, 73]. The ν_μ neutrino flux spectrum predicted at the ND is shown in Fig. 2 of Ref. [46].

The analyzed ν_μ -nucleus interactions occurred in the liquid scintillator tracking medium of the NOvA Near Detector (ND) [74]. The ND is a 193-ton active mass, segmented tracking calorimeter located 100 m underground. It is constructed from polyvinyl chloride cells of rectangular-prism shape (length = 3.9 m, width = 3.9 cm, 6.6 cm depth in beam direction) which are extruded together in units and joined along the long edges to form square planes of 96 cells per plane [75]. The cells are filled with organic liquid scintillator with trace concentrations of wavelength-shifting fluors [76]. The planes are aligned transverse to the beam direction in alternating horizontal and vertical orientations, enabling three-dimensional event reconstruction with ~ 4 cm granularity in the transverse dimensions. The active volume consists of 192 contiguous planes extending 12.7 m along the beam direction. It presents a target medium made of 63% active material with a radiation length of 38 cm, whose nuclear composition consists of carbon (66.7% by mass), chlorine (16.1%), hydrogen (10.8%), titanium (3.2%), oxygen (3.0%), and other nuclei ($< 0.3\%$) [46].

The downstream end of the ND is outfitted with a “muon catcher.” It consists of 10-cm-thick steel planes stacked along the beam direction, each of which is sandwiched between a pair of scintillator planes. Within the pair, one plane is vertically oriented and the other is horizontally oriented. The entire sequence contains ten steel planes and eleven pairs of scintillator planes. Including

the muon catcher and scintillator tracking volumes together, the ND is capable of stopping muons of kinetic energy up to 2.5 GeV.

Scintillation light produced by traversal of charged particles through a cell of the ND is collected via a loop of wavelength-shifting optical fiber and routed to an avalanche photodiode (APD) at the end of the cell. The APD signals are continuously digitized, and those that exceed a noise-vetoing threshold are sent to a data buffer. Receipt of a time stamp from the Fermilab accelerator prior to the delivery of the 10 μ s beam spill initiates the recording of a 550 μ s portion of data (that includes the beam spill), which is saved for analysis.

A detailed model of the ND, together with a combination of Geant4 v10.1.p03 [53] and custom software, is used to simulate the detector’s response to particles initiated by individual interactions. The simulation, which is tuned to reproduce measured scintillator response and fiber attenuation properties, models the development of scintillation and Cherenkov radiation in the active detector materials and simulates the light transport, collection, and digitization processes [77]. Test stand measurements have been used to adjust the Birks suppression of scintillation light used in the simulation, and to validate the simulated response of the readout electronics [78].

The ND is located off-axis in the NuMI beam where it is exposed to a narrow-band ν_μ flux with a mean energy of 1.86 GeV. The data were taken between August 2014 and February 2017 with the NuMI beam operating in the medium-energy, forward horn-current beam configuration. The results presented here are obtained from an exposure of 8.09×10^{20} protons on target (POT).

III. SIMULATION OF NEUTRINO INTERACTIONS

For this analysis, simulation of neutrino events in the ND is based on the GENIE v2.12.2 neutrino event generator [79, 80]. This GENIE-based reference Monte Carlo (MC) has been described in detail in a previous publication [27]. In brief, the target nucleus is modeled as a local relativistic Fermi gas [81] with addition of a high-momentum tail for the momentum distribution of single nucleons to account for short-range correlations [82]. CCQE interactions are simulated using weak interaction current–current phenomenology [83]. Neutrino-induced pion production arises from interactions with single nucleons and proceeds either by RES processes or by non-resonant shallow and DIS reactions. Pion production via RES is simulated using the Rein–Sehgal model [1] with incorporation of modern baryon-resonance properties [84]. Non-resonant inelastic scattering is modeled using the scaling formalism of Bodek–Yang [85] in conjunction with a custom hadronization model [86] and PYTHIA6 [87]. Parameters of DIS processes are adjusted to reproduce electron and neutrino scattering measurements over the invariant hadronic mass range

$W < 1.7$ GeV [88]. In particular, a 57% reduction in the nominal GENIE rate for ν_μ CC non-resonant pion production is imposed, as this yields better agreement with deuterium bubble chamber data [89, 90]. Neutrino-nucleus COH scattering resulting in single pion production is simulated using the Rein-Sehgal model [91, 92]. The reference simulation includes a treatment of final-state intranuclear interactions (FSI) of pions and nucleons that are created and propagate within the struck nucleus. An effective model for FSI is used in lieu of a full intranuclear cascade; each pion is allowed to have at most one rescattering interaction while traversing the nucleus [93]. This approximation enables event reweighting to be applied to the simulation.

Recent advances in neutrino phenomenology motivate additional augmentations to GENIE [27]. For CCQE reactions, kinematic distortions attributed to screening of electroweak couplings in a nuclear medium are included as a reweight based on the calculations of Nieves and collaborators using the random phase approximation (RPA) technique [81, 94]. For baryon-resonance pion production, experiments have reported a suppression effect at very low four-momentum transfer, Q^2 [19, 95–97]. To account for this suppression, a weight analogous to the RPA reweight but parametrized in terms of Q^2 instead of $(q_0, |\vec{q}|)$ is applied to CC RES events at low Q^2 , and a systematic uncertainty is assigned to the RES model. For $Q^2 \leq 0.2$ GeV/c, the fractional uncertainty on the cross section associated with RES suppression is $\leq 1.5\%$.

The analysis uses five different models that describe 2p2h reactions; all of the models are implemented in the GENIE framework. Three of the models are data-based and two are theoretically motivated. NOvA tune 2p2h (i) is a model that has been adjusted to match the NOvA ND data [27]. It was used in previous NOvA neutrino-oscillation investigations [9, 98, 99], and it is the 2p2h model used by the reference simulation for this work. The other 2p2h models include (ii) the GENIE Empirical model (or “Empirical MEC” or “Dytman MEC”) [38], (iii) a representation of 2p2h designed to match MINERvA inclusive ν_μ scattering data reported in [47], (iv) the SuSAv2 microscopic MEC model [35, 36, 100], and (v) the microscopic model developed by the València group (Nieves *et al.* [31, 33]). A main goal of this work is to rate the performance of these models in predicting differential cross sections measured using NOvA data.

For the purpose of delineating systematic uncertainty associated with 2p2h modeling, re-weighting was applied to the MINERvA tune [101] and to the SuSAv2 and València models that varied the relative abundances of final-state hadronic systems consisting of two protons versus a neutron-proton pair. In the figures and tables to follow, model predictions are displayed in the order enumerated above, which amounts to ranking from highest to lowest according to the magnitude of the estimated 2p2h cross section.

IV. EVENT RECONSTRUCTION AND SELECTION

Energy deposits (hits) in the detector resulting in APD responses above a noise-vetoing threshold are recorded with energy, time, and channel location information. Calibration of the absolute energy deposition of hits is established using intervals of ionization on cosmic ray muon trajectories that enter and range to a stop in the detector. Hits neighboring each other in space and time are assumed to be associated with a single neutrino interaction. The hits are grouped into candidate particle trajectories (tracks) via a Kalman filter-based algorithm [102–104] in both the horizontal and vertical two-dimensional detector views [105, 106]. Tracks from the two views that overlap are combined to form three-dimensional tracks. A separate algorithm scores the tracks according to a k -nearest neighbor classifier [108] and assigns the most muon-like track (if one is present) as the muon candidate, using criteria described in the paragraph below. The track reconstruction examines the most upstream hits of the candidate interaction and determines the interaction vertex plus emerging line segments that best describe those hits [105]. For the hits associated with the reconstructed vertex, a different algorithm is used to form particle trajectories (prongs) [107]. The latter algorithm allows hits to be more broadly distributed around the particle’s direction, and it is optimized for electromagnetic shower reconstruction.

Candidate ν_μ CC interactions are selected using procedures previously developed for the NOvA measurement of the CC inclusive double-differential cross section in muon kinetic energy, T_μ , and muon production angle, $\cos\theta_\mu$ [46]. Events that pass basic quality cuts in timing, containment, and contiguity are required to have a candidate muon track. Muon identification is based on a multivariate algorithm that examines hit-to-hit energy deposition and multiple scattering. Muons are distinguished from charged pions on the basis of (i) the difference between log-likelihood functions based on dE/dx of muons versus pions, (ii) average dE/dx in hits in the last 10 cm of tracks, (iii) average dE/dx in hits in the last 40 cm of tracks, and (iv) muon versus pion likelihood assigned according to average angular deflections as a function of distance traveled. These reconstructed variables are processed using a boosted decision tree algorithm [46]. The event vertex is placed at the beginning of the muon track, and it is required to lie within a fiducial volume of dimensions 2.7 m by 2.7 m by 9.0 m that is contained within the detector’s active volume. The fiducial volume begins one meter downstream from the front face of the active volume and is surrounded on all sides by at least 52 cm of active volume. To ensure reliable estimation of final-state hadronic energy, events having hit clusters that extend to the edges of the ND are rejected. Furthermore, events are rejected if any track or prong other than the muon enters the muon catcher. The energy of muons that stop in the detector, E_μ , is deter-

mined using track length. The energy resolution is 4% for muons that stop in the ND scintillator volume upstream of the muon catcher, while for muons that stop in the catcher it is typically 5% to 6% [46].

In order to use the tracking volume of the NOvA ND to carry out a ν_μ CC inclusive measurement in an optimal way, the analysis imposes requirements on final-state muon kinematics. These requirements, as described below, are the same as were used previously for the NOvA measurement of $d^2\sigma_{\text{incl}}/d\cos\theta_\mu dT_\mu$ [46]. The requirements are applied to the signal definition and to selection cuts on reconstructed events. They have an impact on the shape of the extracted cross section. For the signal definition the requirements are defined in terms of eight intervals in true T_μ , each of which is paired with an interval in $\cos\theta_\mu$. A summary of the allowed pairs of ranges is given in Table I where, for example, selected muons with T_μ between 0.5–1.1 GeV must have $\cos\theta_\mu$ values within 0.5–1.0, and similarly for the remaining pairs of ranges in the Table.

TABLE I. Muon kinematic requirements of the signal definition for this analysis. Selected muons have $(T_\mu, \cos\theta_\mu)$ values that fall within the eight pairs of intervals delimited by the vertical columns of the Table.

T_μ (GeV)	0.5 to: 1.1	1.2	1.3	1.4	1.8	1.9	2.2	2.5
$1.0 \geq \cos\theta_\mu \geq$:	0.5	0.56	0.62	0.68	0.85	0.88	0.91	0.94

Selected events are binned and unfolded using $|\vec{q}|$ and E_{avail} and no cuts are imposed using these variables. The analysis is restricted to the kinematic domain $0.0 \text{ GeV}/c \leq |\vec{q}| \leq 2.0 \text{ GeV}/c$ and $E_{\text{avail}} \leq 2.0 \text{ GeV}$. Regions with larger values of $|\vec{q}|$ and/or E_{avail} have negligible event statistics. For final results, bins that have very low efficiency are not reported.

V. VARIABLES, BINNING, AND CROSS SECTION

The observables used to construct other analysis variables are the muon energy, E_μ , the muon momentum, p_μ , the muon angle with respect to the neutrino beam direction, θ_μ , and the sum of the calibrated, observed (visible) hadronic energy deposited in the detector, E_{vis} . The fully reconstructed energy of the final state hadronic system, E_{had} , is obtained by applying correction weights to E_{vis} that account for unseen energy, such as that lost to inactive detector material or carried away by neutrons. The energy resolution for E_{had} in this analysis is 30% [109]. The reconstructed neutrino energy, E_ν , is calculated as the sum of E_{had} and E_μ . The four-momentum-transfer-squared, Q^2 , from the leptonic current to the hadronic system is calculated as

$$Q^2 = -(k - k')^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2. \quad (3)$$

As previously noted, theoretical treatments of 2p2h are often couched in terms of magnitudes of four-momentum-

transfer components, q_0 and $|\vec{q}|$. The two variables on which this analysis is based are ones that approximate these components; their construction is described below.

Three-momentum transfer: The magnitude of the three-momentum transfer, $|\vec{q}|$, from the leptonic current to the target nucleus is calculated as follows:

$$|\vec{q}| = \sqrt{Q^2 + (E_\nu - E_\mu)^2}. \quad (4)$$

The relationship between reconstructed and true $|\vec{q}|$ is established using selected events from the reference simulation. It is linear to good approximation, and the variance from linear is measured by the absolute resolution for reconstructed $|\vec{q}|$, defined as the standard deviation, σ , of the distribution of the absolute residual, $(|\vec{q}|_{\text{true}} - |\vec{q}|_{\text{reco}})$. The absolute resolution for $|\vec{q}|$ is 0.28 GeV/ c . The fractional $|\vec{q}|$ resolution is similarly defined as σ of the fractional $|\vec{q}|$ residual distribution; it is 21%. The distributions of absolute and fractional residuals broaden with increasing $|\vec{q}|$, however they remain centered very close to 0 [110].

Available energy: A second variable is needed to characterize the energy transfer received by the hadronic system. The variable E_{avail} (see Sec. I) is designed to be as close as possible to the energy that can be reliably observed in the detector with minimal model dependence. Available energy is constructed by correcting E_{vis} to the amount of visible energy that would be detected in a perfect detector.

Reconstruction of E_{avail} is based on a map from event visible energy, E_{vis} , to true E_{avail} , constructed using selected MC events. For each event, the sum of reconstructed non-leptonic energy deposited in the detector, E_{vis} , is matched with the true E_{avail} value. Then, for each bin (width = 20 MeV) of reconstructed E_{vis} , the mode of the true E_{avail} distribution is obtained. A profile of the modes is then fitted to a function that transforms reconstructed E_{vis} to true E_{avail} . A quadratic is sufficient to describe the relationship: $E_{\text{avail}} = a + b(E_{\text{vis}}) + c(E_{\text{vis}})^2$. The linear term has slope $b = 1.68$; it requires a quadratic correction ($c = 0.0235 \text{ GeV}^{-1}$) and a small offset ($a = -0.0051 \text{ GeV}$).

The absolute E_{avail} resolution, defined as σ of the absolute residual distribution, is 0.21 GeV. The fractional E_{avail} resolution is 32%. The E_{avail} residual distributions, when broken out into bins of increasing E_{avail} , remain centered near zero with approximately Gaussian shapes that broaden with bin energy [110].

Resolution binning: Bins of variable width are chosen for each of the two kinematic variables according to the experimental resolutions [110]. To cover the interval $0 \leq |\vec{q}| \leq 2.0 \text{ GeV}/c$, twelve bins are chosen whose widths become larger with increasing $|\vec{q}|$. An overflow bin is allotted for the few events that have $|\vec{q}| > 2.0 \text{ GeV}/c$. Similarly for E_{avail} , since the resolution worsens with increasing values in a linear way over the range from 0 to 2.0 GeV, nine bins with increasing widths are chosen to

span this interval (together with an overflow bin). The net result of these binning choices is the 2-D pixelation of the $|\vec{q}|$ - E_{avail} phase space that is apparent in figures to follow.

Double-differential cross section: The flux-integrated double-differential cross section is calculated as follows:

$$\left(\frac{d\sigma^2}{d|\vec{q}| dE_{\text{avail}}} \right)_{ij} = \frac{\sum_{\alpha\beta} U_{ij,\alpha\beta} (N_{\alpha\beta}^{\text{Sel}} - N_{\alpha\beta}^{\text{Bkgd}})}{\epsilon_{ij} \Phi_\nu T_N (\Delta|\vec{q}|)_i (\Delta E_{\text{avail}})_j}. \quad (5)$$

The array $N_{\alpha\beta}^{\text{Sel}}$ is the number of selected data events, and $N_{\alpha\beta}^{\text{Bkgd}}$ is the number of estimated background events that is subtracted from the data to get the estimated signal. The unfolding matrix, $U_{ij,\alpha\beta}$, converts event counts in reconstructed bins (α, β) to counts in unfolded bins (i, j) ; ϵ_{ij} is the efficiency correction in the $(|\vec{q}|, E_{\text{avail}})$ bin designated by (i, j) , Φ_ν is the integrated neutrino flux, T_N is the number of nucleons in the fiducial volume, and $(\Delta|\vec{q}|)_i$ and $(\Delta E_{\text{avail}})_j$ are the widths of the bin (i, j) .

VI. SELECTED SAMPLE

The selected data sample consists of events that reconstruction indicates have occurred in the kinematic domain $0 \leq |\vec{q}| \leq 2.0$ GeV/c and $0 \leq E_{\text{avail}} \leq 2.0$ GeV. The inclusive CC signal-event data sample is obtained by subtracting the estimated background from the selected data (see Sec.VIII). The signal-event sample consists of 995,760 events whose distribution over the $|\vec{q}|$ -versus- E_{avail} plane is shown in Fig. 1.

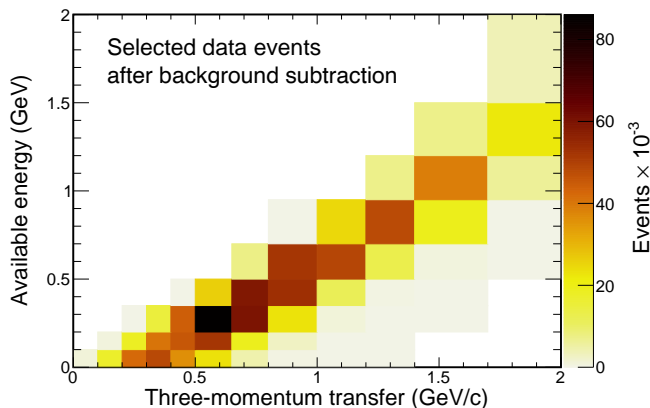


FIG. 1. Distribution of selected signal events of the data, after background subtraction.

The majority of the data events that populate Fig. 1 are predicted to arise from the known CC neutrino-nucleon interactions CCQE, RES, and DIS that occur within the NOvA nuclear medium. Plots (a), (b), and (c) of Fig. 2 display the separate event distributions predicted for the three CC channels, for the same POT exposure and with the same selections as applied to the data of Fig. 1. The three channels differ significantly in their absolute rates and in the locations of

their peak event rates. The CCQE interactions dominate the region of low $|\vec{q}|$ and low E_{avail} where the 2p2h process is also expected to have a sizable presence. The distribution for RES reactions overlaps portions of the CCQE region, however it is most abundant in regions with $|\vec{q}| \geq 0.5$ GeV/c with $E_{\text{avail}} \geq 0.2$ GeV. Above $|\vec{q}| \simeq 1.2$ GeV/c with $E_{\text{avail}} \geq 0.7$ GeV, the RES distribution drops off while the DIS distribution gains strength. The DIS contribution is largest in the vicinity of $|\vec{q}| \simeq 1.5$ GeV/c and $E_{\text{avail}} \simeq 1.0$ GeV.

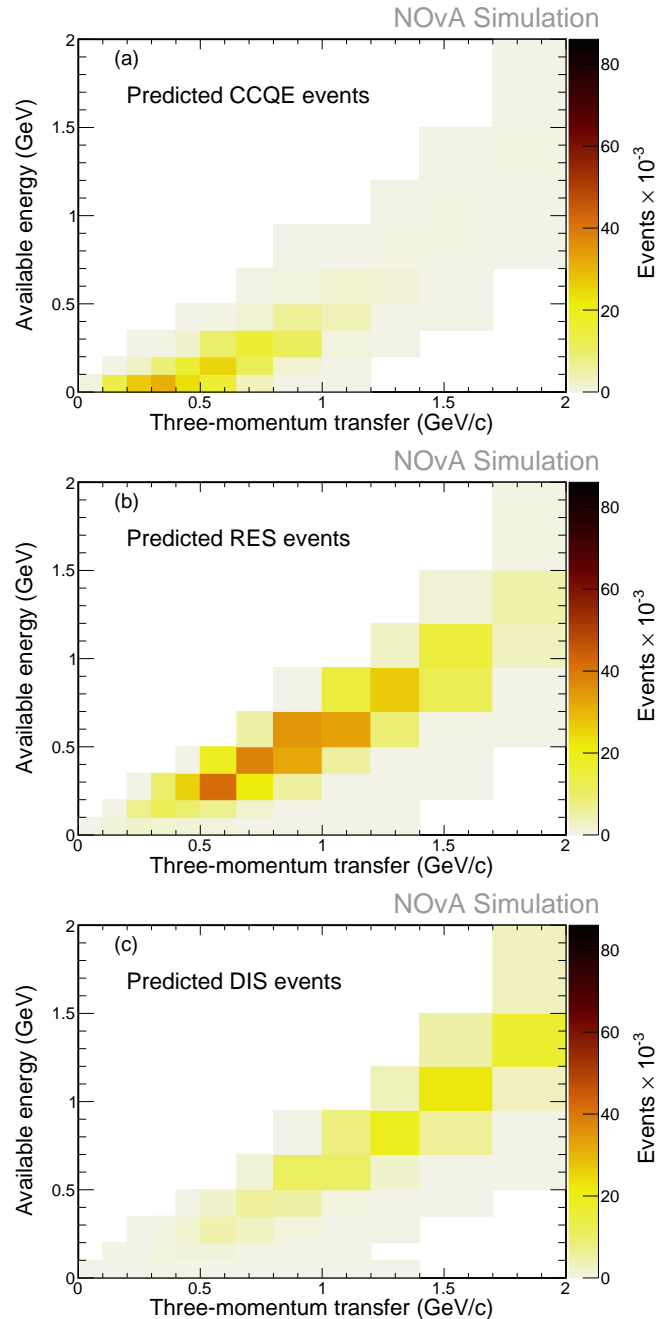


FIG. 2. Event distributions predicted for the data exposure from CC interactions on single nucleons of the NOvA nuclear medium from the reaction channels CCQE (a), RES (b), and DIS (c).

VII. SAMPLE EFFICIENCY AND PURITY

The cross section requires the correction factors, ϵ_{ij} , for sample selection efficiency, defined as the fraction of true signal events that are selected according to the signal definition of Sec. IV. Also required is bin-by-bin knowledge of the selected sample purity, i.e., the fraction of signal events among selected events, in order to implement the subtraction of background from the selected sample (Sec. VIII). Figures 3 and 4 show the selection efficiency and purity, respectively, over the $(|\vec{q}|, E_{\text{avail}})$ kinematic plane.

The requirements of full containment for muon tracks and for final-state hadrons have major impact on the selected sample. Figure 3 shows that regions of high three-momentum transfer with low to intermediate available energy have a relatively lower detection efficiency. The efficiency as a function of either kinematic variable is correlated with that of the other. The efficiency is highest (40% to nearly 100%) along the kinematic boundary where the final-state energy is roughly balanced between the leptonic and hadronic systems. In regions remote from the boundary, the CC interactions tend to have higher momentum (i.e., longer muon tracks) and these have a lower probability of stopping within the fiducial volume. Consequently the efficiency falls off smoothly and rather rapidly with increasing displacement from the kinematic edge. The region with $E_{\text{avail}} < 0.4$ GeV and $0.6 \leq |\vec{q}| \leq 1.2$ GeV/c has a slowly varying selection efficiency that averages around 20%. Quasielastic scattering and multi-nucleon scattering occur predominantly in lower regions of $|\vec{q}|$ and E_{avail} , while baryon-resonance production and deep inelastic scattering dominate higher $|\vec{q}|$ and E_{avail} .

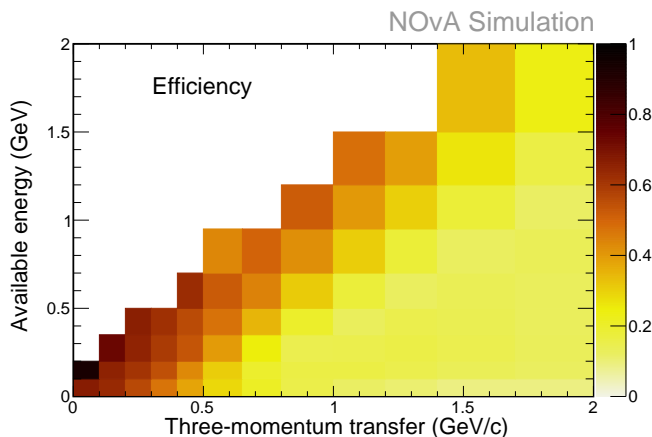


FIG. 3. Event selection efficiency plotted over the plane of reconstructed three-momentum transfer versus reconstructed available energy. The efficiency peaks along the kinematic boundary and diminishes smoothly with increasing displacement of bins from the boundary.

The average efficiency for the selected sample reflects the cost of the selection cuts that are required to minimize background contributions. Starting from a raw sample of selected CC events, the muon identification

cut gives an event reduction of nearly 15%, and muon containment plus vertex containment give an additional reduction of nearly 53%. Subsequent restrictions on the allowed muon phase space and on hadronic shower containment give an additional 4.5% reduction, resulting in a final average efficiency of 27.8%.

Figure 4 shows sample purity in bins of reconstructed available energy versus three-momentum transfer with binning determined by the resolution. The purity after all selections is fairly uniform across the analyzed phase space and it exceeds 75% in nearly all bins. The average purity over all bins is 92.9%. In contrast to efficiency, the purity exhibits relatively mild correlations between $|\vec{q}|$ and E_{avail} . The purity is highest in bins wherein E_{avail} in GeV is roughly equal to the value of $|\vec{q}|$ in GeV/c; it is diminished by 10% to 15% in regions where $|\vec{q}|$ is numerically larger than E_{avail} or where $|\vec{q}|$ exceeds 1.7 GeV/c. As described below, two of the four types of background reactions tend to appear in those regions.

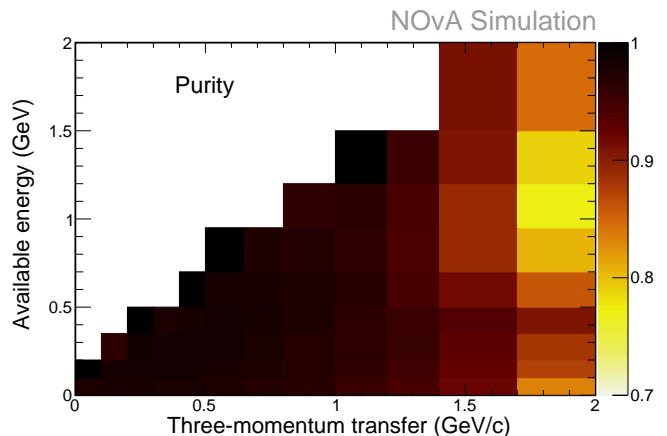


FIG. 4. The sample purity in bins of $(|\vec{q}|, E_{\text{avail}})$. The purity is fairly uniform over the analyzed phase space, with an average value of nearly 93%.

VIII. BACKGROUND PROCESSES AND DATA UNFOLDING

The selected data events include a 7.2% contribution from background events as estimated using the reference simulation. Nearly all background events fall into one of four categories: (i) $\bar{\nu}_\mu$ interactions arising from the defocused component of the NuMI beam (2.8%), (ii) ν_μ CC events whose true muon kinematics (but not their reconstructed kinematics) fail the T_μ and/or $\cos\theta_\mu$ selections (2.3%), (iii) NC interactions or ν_e -flavor CC events reconstructed as ν_μ CC interactions (1.2%), and (iv) ν_μ CC events with vertices originating outside the fiducial volume (including events with an interaction in the rock) (0.9%). The background processes distribute over the analyzed $(|\vec{q}|, E_{\text{avail}})$ phase space and their subtraction does not significantly change the shape of the signal distribution. There is however a mild tendency for processes

(ii) and (iii) to appear in regions with $|\vec{q}| > 1.0 \text{ GeV}/c$ and with $E_{\text{avail}} > 0.5 \text{ GeV}$.

The distribution of events in bins of reconstructed $|\vec{q}|$ and E_{avail} is subject to distortions induced by finite detector resolution. This detector-induced smearing is corrected by subjecting the event distribution to the D’Agostini iterative unfolding algorithm [111, 112] as implemented by the RooUnfold package in ROOT [113]. To determine the optimal number of iterations to use in unfolding the data, the algorithm’s performance was evaluated using 500 independent, systematically shifted simulation samples (referred to as “universes”). The evaluation was based on ensemble averages of the mean squared error [111]. The mean squared error per universe (MSE) is defined as

$$\text{MSE} = \sum_{j=1}^{\text{Bins}} \frac{(\sigma_{\text{Unfold}_j})^2 + (\text{Unfold}_j - \text{True}_j)^2}{(\text{True}_j)^2}. \quad (6)$$

Here, σ_{Unfold_j} is the error assigned by RooUnfold to the j th bin, Unfold_j is the event count in the j th bin of the unfolded distribution, and True_j is that in the j th bin in the truth distribution. The underlying truth of the data is unknown, so instead of optimizing the MSE to the data, it was optimized using 500 systematically independent simulated samples. The value averaged over the ensemble of universes, $\overline{\text{MSE}}$, was used to determine the best number of unfolding iterations. The $\overline{\text{MSE}}$ was observed to reduce dramatically with one iteration and to minimize with two iterations; with iterations beyond two it gradually and continuously climbed away from the minimum. The same behavior was observed using a χ^2 constructed as $\sum_{j=1}^{\text{Bins}} \frac{(\text{Unfold}_j - \text{True}_j)^2}{\sigma_{\text{Unfold}_j}}$, and so two iterations were chosen for the unfolding [110]. The verity of applying unfolding to reconstructed events was checked in fake data studies by examining the ratio of unfolded distributions to MC truth distributions over the analyzed $|\vec{q}|$ -vs.- E_{avail} plane.

IX. SYSTEMATIC UNCERTAINTIES

The cross-section measurement requires knowledge of neutrino-nucleus interactions including 2p2h, of the neutrino flux, of detector calibration and response, and of ionization and Cherenkov light initiated by final-state particles. There are uncertainties associated with each of these quantities. Most of the sources of uncertainty that affect the present work were encountered in the NOvA measurement of CC inclusive $d^2\sigma/d\cos\theta_\mu dT_\mu$ and details of their treatment are given in Ref. [46]. As in the previous work, this analysis uses the multi-universe method for determining the total systematic uncertainty. The method involves randomly varying parameters that characterize uncertainty sources to create a new prediction – a “universe.” In the new simulation the background estimate is altered, as are the unfolding matrix,

efficiency correction, and flux estimation for the cross-section calculation. Consequently the new simulation leads to a variant cross section for this particular universe. The ensemble of variant cross sections is then compared to the reference simulation used by the analysis. The error band is constructed by taking the root mean square of the bin-by-bin upward excursions and, separately, the downward excursions. The resulting error band may, in general, be asymmetric.

A. Sources of uncertainty

There are 96 individual parameters that characterize sources of uncertainty; however each of them can be assigned to one of the following four general categories:

Neutrino flux modeling: Sources of uncertainty associated with calculation of the forward horn-current neutrino flux (see Sec. II) include focusing of the primary proton beam, modeling of hadron production in the target and of secondary production in the horns, and modeling of the beam optics, including uncertainties in the locations of beamline elements [46]. The flux uncertainty acts predominantly as a normalization uncertainty that can introduce high correlations among data bins.

Neutrino-nucleus interaction modeling: The reference simulation is used to estimate backgrounds, correct for efficiency losses, and construct the unfolding matrix. Consequently uncertainties in the parameters of the GENIE-based cross-section modeling propagate to the error band of the measurement. The parameters are those associated with neutrino-nucleus cross sections, modeling of nuclear effects, hadronization in neutrino final states, and intranuclear propagation and scattering of mesons and nucleons [27, 80]. The modeling of 2p2h interactions receives special treatment, as detailed in Sec.IX B below.

Energy scale: The muon energy is measured from its range. Uncertainties in the muon energy scale arise from modeling the dE/dx energy loss in propagation through the active scintillator volume and in the muon catcher. The uncertainty on muon energy includes a component that is uncorrelated between these two regions of the detector. There are uncertainties in the energy scale for ionizations by protons and charged pions. Visible hadronic energy is used to estimate E_{avail} and the small energy depositions that arise from secondary neutron scattering affect the estimate. The detector’s response to neutrons is assigned an uncertainty based upon data versus MC comparisons of neutron-enriched samples induced by antineutrino QE-like scattering [46].

Detector response: There are uncertainties associated with the calibration of the visible hadronic energy scale and with modeling of the transport of light produced in the scintillator and wavelength-shifting fibers to the APDs. The calibrated energy response varies with distance from the readout, and there is uncertainty in the

modeling of its non-uniformity which is included as a calibration uncertainty. There are uncertainties in the amount of scintillator light expected from particles, including that associated with the parameter of Birks' empirical formula [114]. The latter uncertainties are constrained by measurements of the light yield from protons carried out using a test stand [115]. Light production in the scintillator includes Cherenkov light, for which there are modeling uncertainties as well. Light calibration uncertainties are estimated based on dedicated MC simulations. These uncertainties are not included in the multi-universe approach; instead, a covariance matrix is calculated for each calibration systematic, and these are added to the multi-universe covariances.

In the reference simulation, secondary interactions of produced hadrons with the detector medium are modeled using Geant4 and there are uncertainties associated with the hadron-nucleus cross sections that are utilized by the Geant4 code. The effect of uncertainties from secondary hadronic scattering was examined using simulations wherein the rate of secondary interactions in selected events was enhanced or diminished by up to 30%, with the total number of events held constant. These changes, when propagated to determinations of the differential cross sections in this work, generate fractional uncertainties at the sub-percent level for all bins.

The number of nucleons in the fiducial volume is $(5.689 \pm 0.014) \times 10^{31}$, which gives a negligible contribution to the total uncertainty budget.

Sources of uncertainty worthy of note as sizable but likely amenable to reductions in the future, are as follows: *(i)* modeling of the neutrino flux (as discussed in the first paragraph of this subsection), *(ii)* modeling of 2p2h processes (discussed in Sec. IX B), *(iii)* the mass parameter of the axial vector dipole form factor in CC baryon-resonance production, *(iv)* the mass parameter of the axial vector dipole form factor in CC quasielastic scattering, *(v)* the shape of RPA enhancements in $|\vec{q}|$ and q_0 distributions, and *(vi)* the mass parameter of the vector form factor in CC baryon-resonance production. A quantitative breakdown of the total systematic error budget is presented in Sec. IX C.

B. Systematic for 2p2h modeling

The analysis incurs uncertainties from the modeling of 2p2h, reflecting the current limited knowledge about these processes. To determine the cross-section variations that 2p2h uncertainties may introduce, the five 2p2h models identified in Sec. III were investigated [110]. All of the models have a similar cross-section dependence on E_ν , but they predict different absolute rates and distributions over the plane of $|\vec{q}|$ and E_{avail} . In general, the data tunes give higher event rates over much of the phase space. The València and SuSAv2 models predict peaks at slightly higher values of $|\vec{q}|$ (0.8 GeV/c versus 0.6 GeV/c) than do the data tunes (see the upper plot

of Fig. 9).

The shapes of the predicted 2p2h distributions are influenced by the initial state dinucleon fraction $R_N = (np \rightarrow pp)/(nn \rightarrow np)$ used by the models. The MINERvA data tune offers a base model in which $R_N = 2.8$, together with two companion tunes in which the final state dinucleon is only pp or np . The GENIE Empirical model uses $R_N = 4.0$. The València and the SuSAv2 models each use their own calculated prediction for the di-nucleon fraction. In the València model $R_N = 2.8$, while in the SuSAv2 model $R_N = 7.8$.

The MINERvA tune to València 2p2h, which is a data-driven construction, and the SuSAv2 model, as a developed theoretical model, offer predictions about 2p2h that are entirely free of tuning to NOvA data. Moreover the differences between their predictions roughly span the variability that occurs among all five of the models examined [110]. Consequently, on a bin-by-bin basis, the largest excursion from nominal (based on the NOvA tune) predicted by either the MINERvA tune with $R_N = 2.8$ or by SuSAv2 is taken as the estimate of the uncertainty. That is, the largest absolute deviation from the nominal, either positive or negative, is used to define an error that is symmetric about the nominal. This 2p2h modeling uncertainty is added in quadrature, bin-by-bin, with the other sources of systematic error to get the total systematic uncertainty.

C. Total systematic uncertainty

The fractional uncertainties on the cross section arising from all sources of systematic error are shown in Fig. 5 in bins of $|\vec{q}|$, and in Fig. 6 in bins of E_{avail} . In both figures, the flux (green dotted histogram) is the largest source of uncertainty in nearly all bins. The flux uncertainty is roughly uniform across the phase space, staying within the range 10 to 14%.

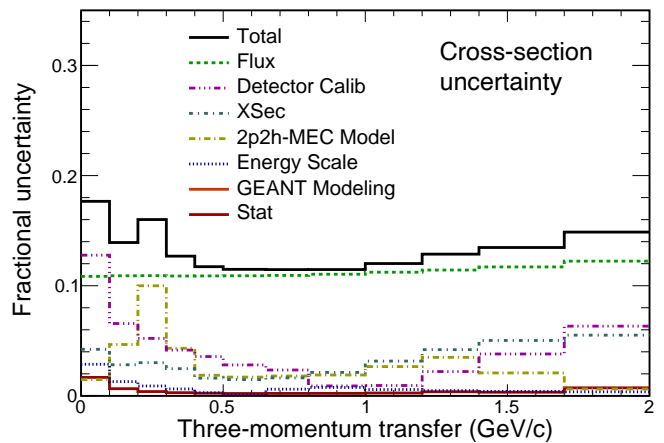


FIG. 5. Fractional uncertainties on the cross section from systematic error sources vs. $|\vec{q}|$. The histograms show the contributions of source categories to the total fractional uncertainty.

Detector calibration (purple, dot-dash) gives the next largest uncertainty in low and high bins of both $|\vec{q}|$ and E_{avail} . Uncertainties originating in modeling of neutrino-nucleon interactions (blue, dot-dash) and the 2p2h process (olive-green, dot-dash) have significant presence in some portions of the phase space. The total uncertainty (solid black) for projections onto bins in either variables is $< 19\%$ across the entire analysis domain.

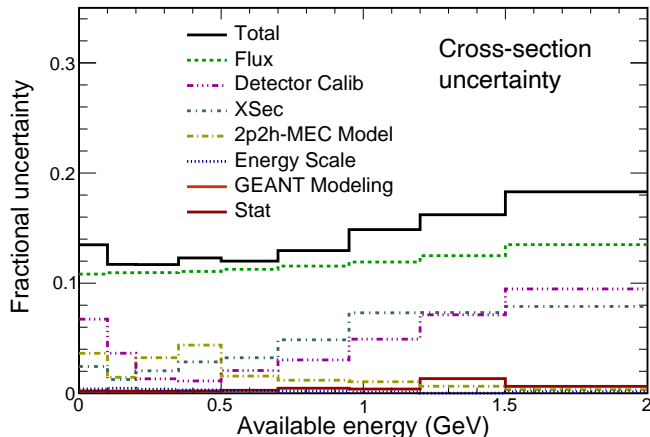


FIG. 6. Fractional uncertainties on the cross section from systematic error sources vs. E_{avail} .

Table II gives breakdowns of the weighted average fractional uncertainties and correlations for the CC inclusive cross-section measurement. For the fractional uncertainties, the contribution from each source category is averaged over all bins, with each bin weighted by its cross-section content. The bin-to-bin correlations from all sources of systematic uncertainty are based on the difference between systematically-shifted simulations and the reference simulation, which is used to calculate a total systematic uncertainty covariance matrix. The statistical covariance matrix is calculated separately and the total uncertainty covariance matrix is taken as the linear sum of the systematic and statistical covariance matrices. More specifically, the weighted average fractional uncertainty, $\langle \delta\sigma/\sigma \rangle$, is calculated as $(\sum_i \sqrt{V_{ii}}) / (\sum_i \sigma_i)$ where i is a measurement bin, V is the covariance matrix, and σ_i is the measured double-differential cross section.

The relative strength of correlations among the sources is indicated by the weighted average correlation, $\langle \text{corr} \rangle$, whose value approaches 1.0 or 0.0 for strong or for neutral correlations, respectively. The values in Table II are calculated as $\langle \text{corr} \rangle = (\sum_{i < j} C_{ij} \sigma_i \sigma_j) / (\sum_{i < j} \sigma_i \sigma_j)$ where C is the correlation matrix, and where the indices i and j refer to different measurement bins [46, 116].

The flux is the leading source and it contributes an average fractional uncertainty of 11%. The average correlation over all bins for the flux is 1.0, indicating that this is mainly a normalization uncertainty. The effect of the flux uncertainty can be alleviated in part by shape-only comparisons of the measured cross section with predictions, and comparisons of this type are provided in subsequent sections. Sizable correlations are also present for other

uncertainty sources; however, these are subdominant relative to correlation with the flux. The total systematic plus statistical uncertainty, calculated as a quadrature sum, is 17%.

TABLE II. Fractional uncertainties and correlations for the CC inclusive cross-section measurement, broken out by uncertainty source categories and averaged over all bins.

Source of uncertainty	Weighted avg fractional uncertainty	Weighted avg correlation
Flux	11 %	1.0
2p2h-MEC model	7.1 %	0.6
Cross section model	5.6 %	0.2
Detector calibration	3.7 %	0.6
Energy scale	0.9 %	0.6
Event statistics	0.5 %	0.4
Total	17 %	0.5

X. DOUBLE-DIFFERENTIAL CROSS SECTION

The distribution of signal events after unfolding and with correction for detection efficiency provides the foundation for the cross-section measurement. Calculation of the flux-integrated, CC inclusive double-differential cross section per nucleon was performed according to Eq. (5). The differential cross section thereby obtained is displayed in Fig. 7 over the plane of $|\vec{q}|$ and E_{avail} . The cross sections reported by this analysis are based on the contents of the 68 bins with lowest fractional uncertainty (from the 72 bins displayed in Figs 7 and 8).

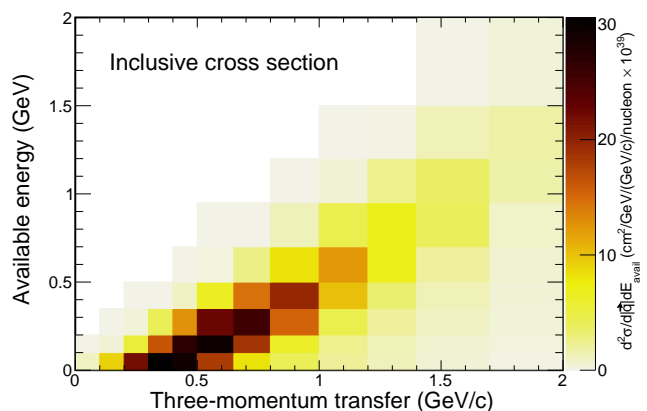


FIG. 7. The flux-integrated, CC inclusive double-differential cross section obtained by this analysis.

The cross section retains the ridge-like shape exhibited by the signal event distribution, with the cross-section strength falling off as boundary regions of the analyzed phase space are approached. The cross section peaks in the bin centered at 0.35 GeV/c in $|\vec{q}|$ and 0.05 GeV in E_{avail} with a value of $3.35 \times 10^{-38} \text{ cm}^2/(\text{GeV}/c)/\text{GeV}/\text{nucleon}$.

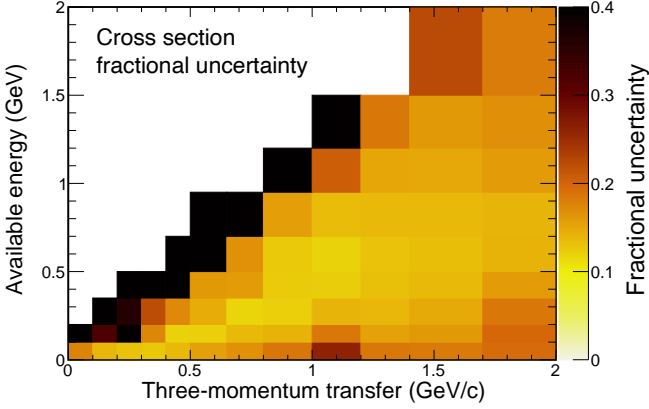


FIG. 8. Bin-by-bin fractional uncertainties for the double-differential cross section shown in Fig. 7.

The fractional uncertainty for cross-section bins of Fig. 7 is displayed in Fig. 8. The uncertainty falls within 15% to 20% for most of the phase space, but becomes larger at the kinematic boundaries. Tabular summaries of the bin-by-bin cross-section and uncertainty values are available in the Supplement [117].

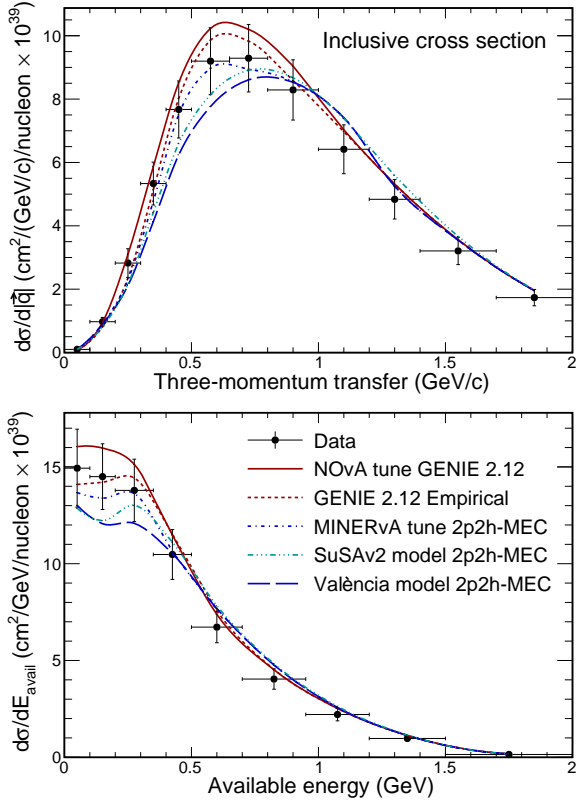


FIG. 9. Inclusive single-differential cross sections $d\sigma/d|\vec{q}|$ (top) and $d\sigma/dE_{\text{avail}}$ (bottom). The data (black crosses) are compared to MC predictions using the five 2p2h models described in the text.

Figure 9 shows the single-variable differential cross sections $d\sigma/d|\vec{q}|$ (upper plot) and $d\sigma/dE_{\text{avail}}$ (lower plot). Each of these is obtained by integrating the double-differential cross section over the other variable. The

differential cross section for $|\vec{q}|$ rises smoothly from 0 GeV/c, peaks at 0.65 GeV/c, and then decreases roughly linearly with increasing $|\vec{q}|$ beyond the peak. The differential cross section for E_{avail} is largest from 0 GeV to 0.3 GeV and subsequently falls off rapidly. The data (black crosses) are compared to simulations rendered using the GENIE v2.12.2 neutrino event generator, in which the 2p2h models described in Sec. III have been employed. The solid red curves show predictions based on the NOvA cross-section tune used by the reference simulation of this analysis. Also shown are the predictions obtained with four other GENIE-based simulations, each of which uses a different 2p2h model. The NOvA data tune gives a good representation of the data, while the GENIE Empirical and MINERvA data tunes under-predict the data through the peak regions. Notably, the theory-based models of SuSAv2 and València give even larger under-predictions, both in the vicinity of the cross-section peaks and along the rising slope of $d\sigma/d|\vec{q}|$ at low $|\vec{q}|$.

Figure 10 shows the differential cross section in bins of E_{avail} for six contiguous ranges of $|\vec{q}|$ wherein bins of Fig. 7 have been merged. The data (crosses) are compared with predictions obtained with the three neutrino-generator tunes and two theory-based models considered by the analysis. The predictions are in general agreement concerning the evolutionary trend for 2p2h excitation through the six regions, however, differences in the absolute rate for 2p2h reactions are apparent. As with the distributions of Fig. 9, the more-differential comparisons provided by Fig. 10 indicate shortfalls for predicted rates, especially those of the theory-based València and SuSAv2 models.

In Fig. 10 the 2p2h contribution and the model spread are especially prominent in the range $0.5 \leq |\vec{q}| \leq 1.0$ GeV/c. The measured cross section versus E_{avail} for this restricted range of $|\vec{q}|$ is displayed in Fig. 11. Here the data are compared to the contributions from CCQE, RES, and DIS, but without 2p2h. The excess in the data is observed to be largest in the region of E_{avail} that lies between the CCQE and RES contributions, where the latter arises predominantly from $\Delta(1232)$ resonance production. This situation is as expected, for the appearance of 2p2h in the kinematic region between elastic scattering and Δ production is well-established in electron-nucleus interactions [4]. The trends in the data relative to the simulations as shown in Figs. 10 and 11, are very similar to those reported by the MINERvA collaboration from CC interactions obtained using a wide-band neutrino flux with spectral peak at 3.0 GeV [20].

Table III shows the chi-square per degree of freedom (χ^2/DoF) computed using the 2p2h predictions and data shown in Fig. 7, and using the full covariance matrix described in Sec. IX C. Columns 2 and 3 give the χ^2 and χ^2/DoF for comparisons involving both the cross-section shape and absolute rate using 68 DoF, while column 4 gives the χ^2/DoF (67 DoF) for shape-only comparisons where the prediction is normalized to the measured cross section.

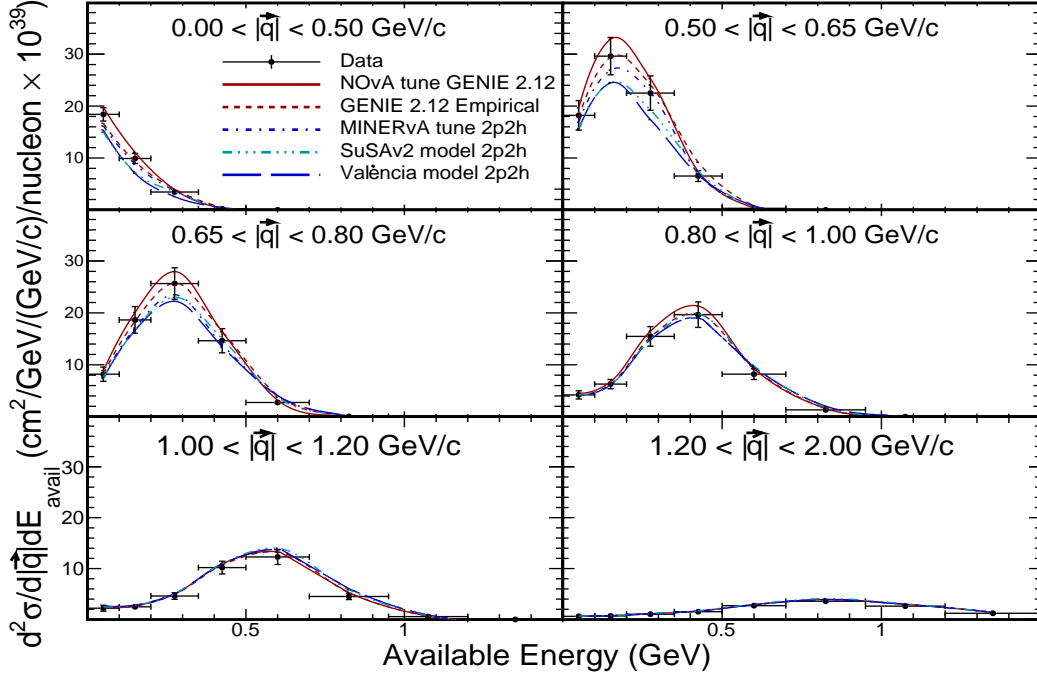


FIG. 10. The inclusive cross section in bins of E_{avail} , for six contiguous slices of $|\vec{q}|$. The data (crosses) are compared to predictions for ν_μ CC inclusive scattering that use five different modeling implementations for 2p2h.

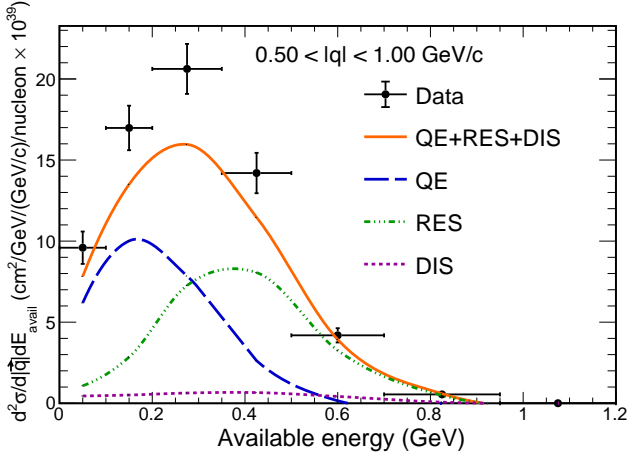


FIG. 11. Cross section versus E_{avail} for the inclusive cross section restricted to the range in three-momentum transfer where the 2p2h contribution is estimated to be large. The data (crosses) are compared to the sum of CCQE, RES, and DIS contributions as estimated by NOvA-tuned GENIE v2.12.2 (solid orange curve).

The lowest χ^2 is obtained with the NOvA-tune prediction. This outcome is not surprising since the tuning was done using neutrino data recorded by the NOvA Near Detector. The next lowest χ^2 is obtained with the GENIE Empirical model, with yet larger χ^2 values found for the other three models. Column 4 shows that the ranking by χ^2 indicated by columns 2 and 3 remains the same when the comparison is restricted to be shape-

only wherein the predictions are normalized to the observed cross section. Interestingly, the covariances in the χ^2 enable the SuSAv2 model to compare favorably with the MINERvA tune, an outcome that cannot be readily inferred from comparing the predicted distributions for the single-variable differential cross sections shown in Fig. 9. Note that for the two theory-based 2p2h models, the χ^2/DoF values worsen when the evaluations are restricted to shape-only. For the València model, restriction to shape-only doubles the χ^2 .

TABLE III. Chi-squares with full covariances for predictions of GENIE-based simulations that use different 2p2h models, compared to the measured CC inclusive double-differential cross section. Columns 2 and 3 give the χ^2 and $\chi^2/(68 \text{ DoF})$ for shape plus rate comparisons; column 4 gives the $\chi^2/(67 \text{ DoF})$ for shape-only comparisons.

2p2h-MEC Model	χ^2	χ^2/DoF	Shape Only
NOvA tune 2p2h	270	3.96	3.25
GENIE Empirical	550	8.08	7.36
MINERvA tune 2p2h	746	11.0	11.7
SuSAv2 2p2h	766	11.3	12.8
València 2p2h	1501	22.1	46.0

The behavior of the 2p2h models with respect to each of the kinematic variables individually can be probed by comparing predictions to the single-variable cross sections $d\sigma/d|\vec{q}|$ and $d\sigma/dE_{\text{avail}}$ displayed in Fig. 9. Table IV provides these comparisons using χ^2 with covariances. The χ^2/DoF values obtained with either of

the cross-section distributions give similar rankings for the 2p2h models as is found with fitting to the double-differential cross section (Table III). As previously, the χ^2/DoF are made larger for the theory-based models when the fitting is restricted to shape-only whereas the opposite trend is observed with the NOvA tune.

TABLE IV. Comparisons of 2p2h-model predictions using χ^2 with covariances, for the single-variable cross sections of Fig. 9. Columns 2 and 3 give χ^2/DoF for fits to the total and shape-only $d\sigma/d|\vec{q}|$ (with 12, 11 DoF respectively); columns 4 and 5 give χ^2/DoF for fits to $d\sigma/dE_{\text{avail}}$ (with 9, 8 DoF).

2p2h-MEC Model	$ \vec{q} $ Distribution		E_{avail} Distribution	
	χ^2/DoF	Shape Only	χ^2/DoF	Shape Only
NOvA tune	2.45	2.12	0.20	0.12
GENIE Emp	3.74	3.65	0.67	0.68
MINERvA	2.66	2.84	4.32	4.84
SuSAv2	4.29	4.90	5.72	6.78
València	5.34	6.48	7.61	9.50

Figure 11 indicates that 2p2h, together with CCQE, RES, and DIS, is a major component of the CC double-differential cross section. While the relative χ^2 values of Table III clearly favor the NOvA tune for 2p2h, they do not discriminate very strongly among the other 2p2h implementations. These comparisons may be rendered less sensitive by the inclusion of regions of the analysis phase space where 2p2h has a small or negligible presence. Identification of subregions of the $|\vec{q}|$ versus E_{avail} phase space wherein the 2p2h contribution has a discernible presence is therefore highly desirable. Indeed, according to the models examined by this work, the majority of 2p2h interactions occur in a single contiguous subregion of $(|\vec{q}|, E_{\text{avail}})$, the delineation of which is described in the next section. This delineation enables examination of the ν_μ CC inclusive cross section of Fig. 7 to be focused on those bins that fall within the 2p2h-enriched subregion, with the remaining bins treated using an overflow bin. With the comparison of 2p2h predictions to data being made more localized in this way, the testing of 2p2h models is different and perhaps more stringent than that provided by the full-phase-space comparisons of Table III.

XI. ESTIMATION OF 2P2H CONTRIBUTION

A set of templates for event distributions over the plane of $|\vec{q}|$ vs. E_{avail} is assembled using the GENIE-based reference simulation of this analysis. The templates are the predicted contributions from reaction categories that make up the total inclusive cross section. The set consists of the three major categories CCQE, RES, and DIS, plus an additional low-population template “Other” that accounts for CC coherent scattering and purely leptonic inverse muon decay events. If the

reference simulation were completely accurate, then subtraction of the cross-section contributions represented by the four templates from the measured double-differential cross section would isolate an excess in the data that arises from 2p2h processes.

Data-based constraints on the event rate normalizations of the RES and DIS templates are developed by defining a control sample which is nearly devoid of CCQE and 2p2h events. Events in the data control sample satisfy at least one of the following two criteria: (i) The event has, in addition to the muon track, a particle prong of length > 100 cm (see Sec. IV). (ii) The event has three or more reconstructed prongs (in addition to the muon track) that emerge from the primary vertex.

The capability to modify the distribution shapes predicted by the templates is introduced by dividing the analysis phase space and the templates into three regions of $|\vec{q}|$ denoted I, II, and III, wherein the RES and DIS template normalizations are matched to the control sample. The region boundaries are chosen as ones that make optimal use of the control sample. (i) Region I is $|\vec{q}| \leq 1.2$ GeV/c; this region constrains the RES normalization (see Fig. 2b). (ii) Region II is the intermediate region: $1.2 < |\vec{q}| < 1.4$ GeV/c. (iii) Region III is the outer region: $1.4 \text{ GeV}/c \leq |\vec{q}|$; it well-constrains the DIS normalization.

Simulation studies show that the NOvA detectors lack the resolution to distinguish between CCQE 1p1h scattering and the manifestations that 2p2h interactions may have. Consequently, the analysis bases its CCQE template and its normalization on the standard weak-interaction phenomenology used by GENIE v2.12.2 to model quasi-elastic scattering as related in Sec. III. Uncertainties are assigned to the parameters of this modeling as proposed by Refs. [80, 94], with one exception: For the uncertainty associated with the axial-vector mass, M_A , the reference simulation uses $M_A = 1.04 \pm 0.05$ GeV [118].

The approach adopted, after evaluating trial simulation runs, is to adjust the RES and DIS normalizations in Region I via fitting to the control sample distribution in that Region, while leaving the CCQE normalization at the nominal value assigned by the reference simulation. In the outer Region (III), the same procedure is used. In the intermediate Region (II), the RES and DIS normalizations are the average of the fit normalizations obtained in Regions I and III. In this way, a degree of continuity is assured for RES and DIS template predictions over the entire analysis phase space. The contribution from the “Other” template is quite small, and its normalization is also fixed at the nominal reference-simulation value. With the above-mentioned adjustments in place, each of the four templates (RES, DIS, CCQE, and Other) are defined over the entire analysis phase space.

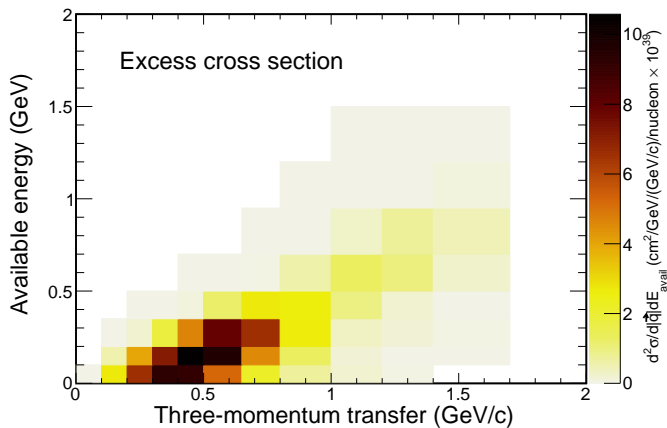


FIG. 12. Double-differential cross section of excess events relative to GENIE-based estimation of conventional CC neutrino-nucleon scattering. The cross section can be compared to the predictions of the 2p2h models and tunes.

Figure 12 shows the result of carrying out the subtraction of the sum over the four reaction templates from the distribution of selected signal events, and then converting the remaining event distribution into a cross section. As described above, the populated bins show the data cross-section excess relative to expectation derived from the GENIE-based reference simulation, with RES and DIS contributions constrained by the control sample, for CC neutrino-nucleon scattering within nuclei modeled as a local relativistic Fermi gas. The subtraction of templates from the data gives rise to small numbers of negative event counts appearing in bins that are remote from regions with sizable event populations. The ratio of total negative to total positive event counts for the entire phase space is 0.029, with 76% of the negative counts occurring in the region $1.4 \text{ GeV}/c \leq |\vec{q}| \leq 2.0 \text{ GeV}/c$ with $0.95 \text{ GeV} \leq E_{\text{avail}} \leq 2.0$. Figure 12 is prepared with the content of these negative bins set to zero. Assuming that the contiguous, excess cross section of Fig. 12 represents 2p2h interactions, then 2p2h is nearly 17% of the CC-inclusive cross section that occurs within the restricted phase space defined by Table I. The extracted cross section is largest between 0.40 and 0.50 GeV/c in $|\vec{q}|$ and between 0.10 and 0.20 GeV in available energy, with a value of $(1.1 \pm 0.3) \times 10^{-38} \text{ cm}^2/(\text{GeV}/c)/\text{GeV}/\text{nucleon}$. Smaller contributions are indicated at larger $|\vec{q}|$ and E_{avail} values. The bin-by-bin cross-section fractional uncertainty is 28% to 86% in the region $0.3 \leq |\vec{q}| \leq 0.8 \text{ GeV}/c$ and $0.0 \leq E_{\text{avail}} \leq 0.35 \text{ GeV}$.

The per-bin cross-section fractional uncertainties for the extracted 2p2h signal arise from the same source-of-error categories that characterize the CC-inclusive sample measurement, namely those described in Sec. IX and summarized in Figs. 5 and 6. The relative contributions, however, are somewhat different. For bins that contain the bulk of 2p2h rate, namely $0.3 \leq |\vec{q}| \leq 0.8 \text{ GeV}/c$ and $0 \leq E_{\text{avail}} \leq 0.35 \text{ GeV}$, uncertainties from the flux, CC cross-section modeling, and 2p2h modeling are comparable and fall in the range 10 to 40%. Uncertainty from de-

tector calibration generally falls below this range but becomes sizable (40 to 48%) for E_{avail} exceeding 0.35 GeV . These rather large uncertainties are inherent to subtracting a large and partially unconstrained background in order to estimate a signal which is roughly three times smaller.

Figure 13 shows the data of Fig. 12 plotted in bins of E_{avail} for six contiguous slices of $|\vec{q}|$. The excitation pattern as a function of increasing $|\vec{q}|$ follows the trend predicted for the 2p2h contribution to the CC inclusive data, as displayed in Fig. 10. The uncertainties on the data points are large throughout. Nevertheless, discrepancies can be seen with cross-section rate and shape between the data (crosses) and the predictions of the SuSAv2 model (teal, dot-dot-dash curve) and of the València model (blue, long-dash curve).

Figure 14 displays the single-differential cross sections in $|\vec{q}|$ and in E_{avail} for the 2p2h contribution, and compares them to predictions from the 2p2h tunes and models. In these projections, the predictions of the NOvA tune exceed the data points in many bins, while predictions from the other models sometimes or often fall below the data points. The two theory-based models give relatively broader and flatter distributions than do the data tunes. In particular, the València model predicts a two-component nature for 2p2h. The components are predicted to have distributions that are kinematically separated, with one being more CCQE-like and the other being more like a $\Delta(1232)$ excitation. The peaks of these distributions project onto adjacent but different points on the E_{avail} axis of the lower plot in Fig. 14, giving rise to a net distribution that is distinctly flatter than those predicted by the other models. The data do not favor this aspect of the València model.

Table V provides comparisons of the five implementations of 2p2h-MEC to the extracted 2p2h double-differential cross section. The comparisons use the full χ^2 including covariances, calculated over 18 bins for which the fractional uncertainty per bin is less than 100%. Once again, the NOvA tune for 2p2h gives the lowest χ^2 for the prediction to the overall cross section (columns 2 and 3), however respectable χ^2/DoF values are found for most of the models. Stronger distinctions are afforded by the shape-only comparisons displayed in column 4, wherein model predictions are normalized to the total extracted cross section. Restriction to shape-only fitting worsens the χ^2/DoF for all models except the NOvA tune. This outcome is consistent with the disparities between predicted shapes and the data that are discernible in Fig. 14.

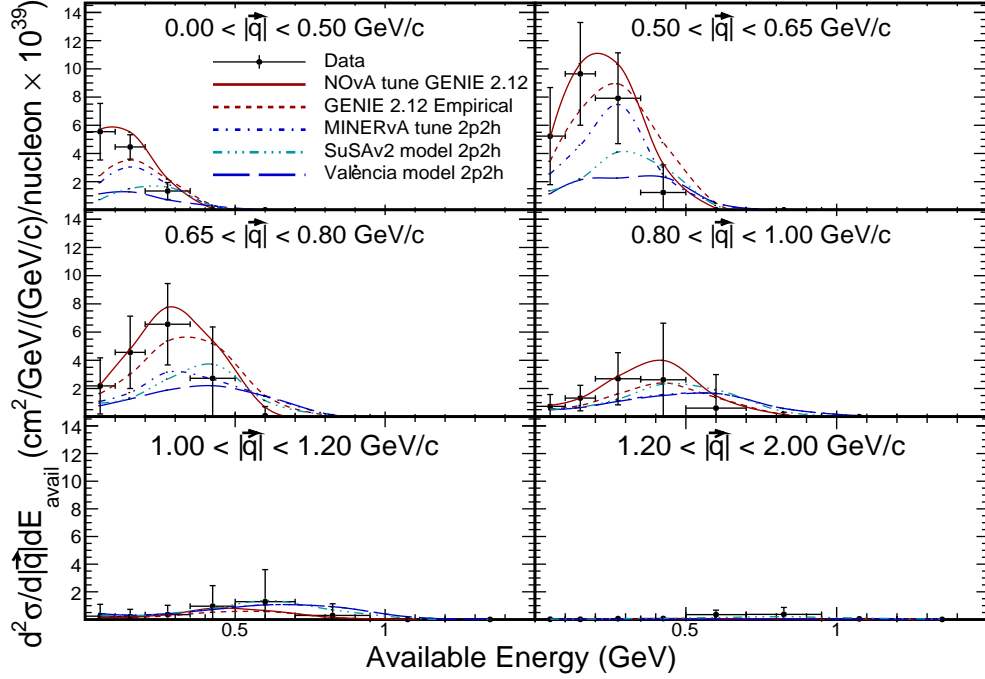


FIG. 13. The estimated 2p2h cross section of Fig. 12 displayed in bins of E_{avail} for six contiguous slices of $|\vec{q}|$.

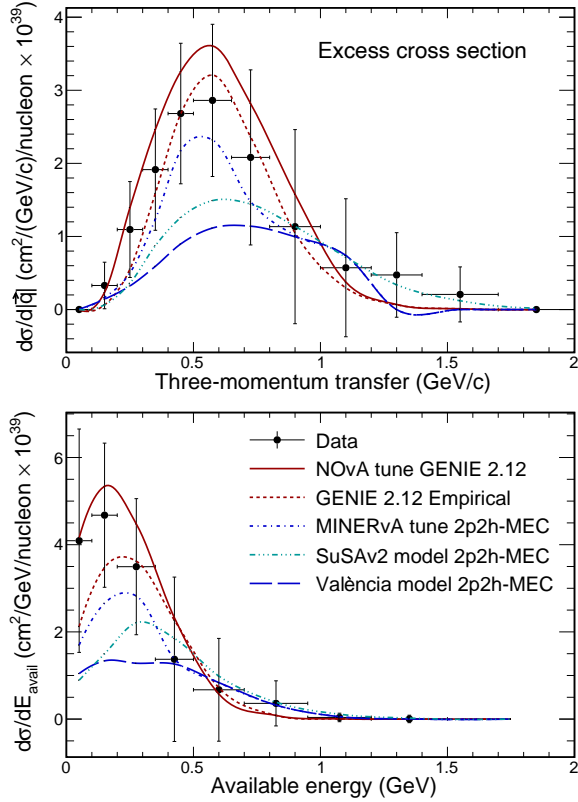


FIG. 14. Distribution of the excess cross section relative to non-2p2h CC neutrino-nucleon scattering, projected onto three-momentum transfer (top) and available energy (bottom), and compared to 2p2h-model predictions.

TABLE V. Comparisons based on χ^2 with covariances, of 2p2h models to the extracted 2p2h-MEC cross section over the plane of $(|\vec{q}|, E_{\text{avail}})$. Columns 2 and 3 give the χ^2 and $\chi^2/(18 \text{ DoF})$ for shape-plus-rate comparisons, while column 4 gives the $\chi^2/(17 \text{ DoF})$ for shape-only comparisons.

2p2h-MEC Model	χ^2	χ^2/DoF	Shape Only
NOvA tune 2p2h	15.8	0.88	0.72
GENIE Empirical	31.1	1.73	2.77
MINERvA tune 2p2h	31.0	1.72	4.58
SuSAv2 2p2h	54.2	3.01	4.10
València 2p2h	34.4	1.91	4.30

XII. PREDICTIONS FOR ν_μ CC SCATTERING IN 2P2H-ENRICHED REGION

Figure 12 identifies regions of the analysis phase space populated by 2p2h interactions and enables a contiguous, 2p2h-enriched subregion to be defined. For the purpose of model testing, the analysis defines such a region by restricting to bins that contain $>10\%$ of the cross-section value of the peak bin located at $(|\vec{q}|, E_{\text{avail}}) = (0.4\text{-}0.5 \text{ GeV}/c, 0.1\text{-}0.2 \text{ GeV})$. The selected bins form a contiguous region that extends from $(|\vec{q}|, E_{\text{avail}}) = (0.1 \text{ GeV}/c, 0.0 \text{ GeV})$ to $(1.2 \text{ GeV}/c, 0.7 \text{ GeV})$. The binning is indicated by Fig. 12 and Table VI. (Less restrictive choices, e.g., restriction to bins with $>1\%$ or $>5\%$ of the peak bin content, give similar results.)

As done previously for the comparisons of Table III, each of the five representations of 2p2h is used to pre-

dict the CC inclusive cross section, and each prediction is compared to the measured double-differential cross section (Fig. 7) in the 2p2h-enriched subregion. The resulting χ^2 values including covariances are displayed in Table VII. The χ^2 values displayed in columns 2 and 4 show that the MINERvA and NOvA data tunes provide better matches to the data in the 2p2h-enriched region than do the other three 2p2h implementations. Interestingly the MINERvA tune compares well with the NOvA tune, even though it was adjusted to match data having a higher mean E_ν (3.0 GeV versus 1.86 GeV) [47].

TABLE VI. Bin intervals of the 2p2h-enriched subregion. Each column gives the $|\vec{q}|$ interval in GeV/c (which is subdivided into bins) associated with a given E_{avail} bin in GeV.

E_{avail}	0.00-0.10	0.10-0.20	0.20-0.35	0.35-0.50	0.50-0.70
$ \vec{q} $	0.10-0.80	0.20-1.00	0.30-1.00	0.50-1.00	1.00-1.20

TABLE VII. Comparisons using χ^2 with covariances, of 2p2h models versus measured cross section over the $(|\vec{q}|, E_{\text{avail}})$ phase-space region enriched with 2p2h events. Columns 2 and 3 summarize the shape-plus-rate comparisons for 22 DoF, while column 4 gives the $\chi^2/(21 \text{ DoF})$ for shape-only comparisons.

2p2h-MEC Model	χ^2	χ^2/DoF	Shape Only
NOvA tune 2p2h	103	4.69	3.90
GENIE Empirical	185	8.40	7.99
MINERvA tune 2p2h	84.4	3.83	4.11
SuSAv2 2p2h	177	8.04	9.15
València 2p2h	347	15.8	18.6

The two theory-based models give relatively larger chi-squares; the values in column four show this trend to be more pronounced for the shape-only comparisons with the data. The scattering amplitudes invoked by the València and by the SuSAv2 models are quite numerous and involve virtual pions, nucleons, higher-mass mesons, and baryon resonances. The limited successes so far with this general approach suggest that important aspects of 2p2h still await an accurate theoretical characterization. That said, the theoretical descriptions are likely to improve in the near future, as further developments of the València and the SuSAv2 models are in progress [34, 37, 120] and other approaches are being explored [121].

XIII. CONCLUSIONS

This work reports a high-statistics measurement of the CC-inclusive double-differential cross section $d^2\sigma/d|\vec{q}|dE_{\text{avail}}$ for neutrino-nucleus interactions of mean energy 1.86 GeV in a detector medium that is predominantly carbon but includes heavier nuclei. Differential cross sections over the plane of $|\vec{q}|$ and E_{avail} are presented in Figs. 7, 9, and 10. The selected event sample

probes incident energies $0.8 \leq E_\nu \leq 3.2 \text{ GeV}$, a range of great importance to NOvA neutrino-oscillation measurements. This E_ν range lies above the sub-GeV region analyzed by T2K and MicroBooNE, while being mostly below the 2 to 6 GeV region examined by MINERvA using its on-axis NuMI beam exposures. It covers the lower half of the high-flux plateau in the ν_μ energy spectrum planned for the DUNE experiment [51]. This work extends [46] and complements [119] other NOvA investigations of ν_μ CC scattering in the above-stated E_ν range.

The CC-inclusive cross section receives contributions from 2p2h reactions wherein more than one nucleon of a struck nucleus is involved in the interaction. The inclusive cross section for 2p2h is estimated from the data by subtracting template distributions for scattering on single nucleons predicted by a tuned version of GENIE v2.12.2 with normalization constraints for RES and DIS provided by a control sample. The 2p2h cross section thereby inferred (Fig. 12) enables a restricted, contiguous region of phase space enriched in 2p2h reactions to be identified. Chi-square comparisons of GENIE-based predictions to ν_μ CC inclusive scattering data (*i*) using the full analyzed phase space (Table III), and (*ii*) restricting to the 2p2h-enriched region (Table VII), provide relative ratings for 2p2h models. Chi-squares for predictions that use the SuSAv2 and València 2p2h models, and for predictions based on three different ν_μ -generator data tunes, indicate shortfalls with these representations of 2p2h scattering. The measurements of this work will facilitate the development of more accurate descriptions of ν_μ CC inclusive scattering and of 2p2h reactions as is required by the long-baseline neutrino oscillation experiments.

ACKNOWLEDGMENTS

This document was prepared by the NOvA collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. This work was supported by the U.S. Department of Energy; the U.S. National Science Foundation; the Department of Science and Technology, India; the European Research Council; the MSMT CR, GA UK, Czech Republic; the RAS, MSHE, and RFBR, Russia; CNPq and FAPEG, Brazil; UKRI, STFC and the Royal Society, United Kingdom; and the state and University of Minnesota. We are grateful for the contributions of the staffs of the University of Minnesota at the Ash River Laboratory, and of Fermilab. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising.

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