Measurement of the $\nu_e$-Nucleus Charged-Current Double-Differential Cross Section at $\langle E_\nu \rangle = 2.4$ GeV Using NOvA

M. A. Acero,² P. Adamson,¹² L. Aliaga,¹² N. Anfimov,²⁵ A. Antoshkin,²⁵ E. Arrieta-Diaz,²⁷ L. Asquith,³⁹ A. Aurisano,⁵ A. Back,¹⁹,²³ M. Baird,¹⁹,³⁹,⁴⁴ N. Balashov,²⁵ P. Baldi,²⁴ B. A. Bambah,¹⁶ S. Bashar,²⁴ K. Bays,²⁴,¹⁸ R. Bernstein,¹² V. Bhatnagar,³³ D. Bhattarai,³¹, B. Bhuyan,³³ J. Bian,²⁴,³⁰ A. C. Booth,²⁵ R. Bowles,²⁵ B. Brahma,¹⁷ C. Bromberg,²⁸ B. C. Choudhary,¹⁰ A. Christensen,⁸ T. E. Coan,³⁸ M. Colo,⁴⁶ L. Cremonesi,³⁵ G. S. Davies,³¹,¹⁹ P. F. Derwent,¹² P. Ding,¹² Z. Djuric,¹ M. Dolce,² D. Doyle,⁸ D. Dueñas Tonguino,⁶, E. C. Dukes,⁴⁴ R. Ehrlich,⁴⁴ M. Elkins,²³ A. Girì,¹² R. A. Gomes,¹⁵ M. C. Goodman,¹ V. Grichine,²¹ M. Groh,⁸,¹⁹ R. Group,⁴⁴ B. Guo,³⁷ A. Habig,²⁹ F. Hakl,²⁰ A. Hall,⁴⁴ J. Hartnell,⁹ R. Hatcher,¹² H. Hausner,⁴⁷ M. He,¹⁵ K. Heller,³⁰ V. Hewes,⁶ A. Himmel,¹² B. Jargowsky,²⁴ J. Jarosz,⁸ F. Jediny,⁹ C. Johnson,⁸ M. Judah,³⁴ I. Kakorin,²⁵ D. M. Kaplan,¹⁸ A. Kalitkina,²⁵ R. Keloth,⁷ K. Kullenberg,²⁵ M. Kubu,⁹ A. Kumar,³³ C. D. Kuruppu,³⁷ V. Kus,⁹ T. Lackey,¹²,¹⁹ K. Lang,⁴¹ P. Lasorak,³⁹ J. Lesmeister,¹⁵ S. Lin,⁸ A. Lister,⁴⁷ J. Liu,²⁴ M. Lokajíček,²² J. M. C. Lopez,⁴³ R. Mahji,¹⁶ S. Magill,¹ M. Manrique Plata,¹⁹ W. A. Mann,⁴² M. T. Manoharan,⁷ M. L. Marshak,³⁰ M. Martinez-Casales,²³ V. Matveev,²² B. Mayes,³⁹ M. D. Messier,¹⁹ H. Meyer,⁴⁵ T. Miao,²⁵ V. Mikola,⁴⁸ W. H. Miller,⁴⁵ S. Mishra,³ S. R. Mishra,³⁷ R. Mohanta,¹⁶ A. Moren,²⁹ A. Morozova,²⁵ W. Mu,¹² L. Mualem,⁴ M. Muether,⁴⁵ K. Mulder,⁴³ D. Naples,³⁴ A. Nath,¹⁴ N. Nayak,²⁴ S. Nelleri,⁷ J. K. Nelson,⁴⁶ R. Nichol,⁴³ E. Niner,¹² A. Norman,¹² A. Norrick,¹² T. Nosek,¹² H. Oh,⁴ A. Olshevskiy,²¹ T. Olson,⁴² J. Ott,²⁴ A. Pal,³² J. Paley,¹² L. Panda,³² R. B. Patterson,⁴ G. Pawloski,³⁰ O. Petrova,²⁵ R. Petti,³⁷ D. D. Phan,¹² R. K. Plunkett,¹² A. Pobedimov,²⁵ J. C. C. Porter,³⁹ A. Rafique,¹ L. R. Prais,²¹ V. Raj,² M. Rajaialaisia,² B. Ramson,¹² B. Rebel,¹²,²⁴ P. Rojas,⁸ P. Roy,²⁵ V. Ryabov,²⁶ O. Samoylov,²⁵ M. C. Sanchez,²³ S. Sánchez Falero,²³ P. Shanahan,¹² S. Shukla,³ A. Sheshukov,²³ I. Singh,¹⁰ P. Singh,³⁵,¹⁰ V. Singh,⁵ E. Smith,¹⁹ J. Smolik,⁹ P. Snopok,¹⁸ N. Solomey,⁴⁵ A. Sousa,⁶ K. Soustruznik,⁵ M. Strait,³⁰ L. Suter,¹² A. Sutton,⁴ S. Swain,³² C. Sweeney,⁴³ A. Szuc,⁴³ R. L. Talaga,¹ B. Tapia Oregui,⁴³ P. Tas,⁵ B. N. Temizel,¹⁸ T. Thakore,⁶ R. B. Thayyullathil,¹ J. Thomas,³⁷ E. Tiras,¹¹,²³ J. Tripathi,²³ J. Trokan-Tenorio,²³ Y. Torun,¹⁸ J. Urheim,¹⁹ P. Vahle,⁴⁶ Z. Vallari,⁴ J. Vasel,¹¹ V. Vašek,¹² M. Wallbank,⁵ T. K. Warburton,²³ M. Wettstein,²³ D. Whittington,³⁰,¹² D. A. Wickremasinghe,¹² T. Wieber,¹³ J. Wolcott,⁴² W. Wu,²⁴ Y. Xiao,²⁴ B. Yaeggy,⁶ A. Yallappa Dombra,⁴⁰ A. Yankelevich,²⁴ K. Yonehara,¹² S. Yu,¹,¹⁸ Y. Yu,¹² S. Zadorozhnyy,²¹ J. Zalesak,²² Y. Zhang,³⁹ and R. Zwaska¹²

(NOvA Collaboration)

¹Argonne National Laboratory, Argonne, Illinois 60439, USA
²Universidad del Atlantico, Carrera 30 No. 8-49, Puerto Colombia, Atlantico, Colombia
³Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221 005, India
⁴California Institute of Technology, Pasadena, California 91125, USA
⁵Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
⁶Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA
⁷Department of Physics, Cochin University of Science and Technology, Kochi 682 022, India
⁸Department of Physics, Colorado State University, Fort Collins, Colorado 80523-1875, USA
⁹Czech Technical University in Prague, Břehova 7, 115 19 Prague 1, Czech Republic
¹⁰Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India
¹¹Department of Physics, Erciyes University, Kayseri 38030, Turkey
¹²Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
¹³Instituto de Física, Universidade Federal de Goiás, Goiânia, Goiás 74690-900, Brazil
¹⁴Department of Physics, IIT Guwahati, Guwahati 781 039, India
¹⁵Department of Physics, IIT Guwahati, Guwahati 781 039, India
¹⁶School of Physics, University of Hyderabad, Hyderabad 500 046, India
¹⁷Department of Physics, IIT Hyderabad, Hyderabad 502 205, India
¹⁸Illinois Institute of Technology, Chicago Illinois 60616, USA
¹⁹Indiana University, Bloomington, Indiana 47405, USA
²⁰Institute for Computer Science, The American Academy of Sciences, 182 07 Prague, Czech Republic
²¹Institute for Nuclear Research of Russia, Academy of Sciences 7a, 60th October Anniversary prospect, Moscow 117312, Russia

Published by the American Physical Society
The inclusive electron neutrino charged-current cross section is measured in the NOvA near detector using \(8.02 \times 10^{20}\) protons-on-target in the NuMI beam. The sample of GeV electron neutrino interactions is the largest analyzed to date and is limited by \(\approx 17\%\) systematic rather than the \(\approx 7.4\%\) statistical uncertainties. The double-differential cross section in final-state electron energy and angle is presented for the first time, together with the single-differential dependence on \(Q^2\) (squared four-momentum transfer) and energy, in the range \(1\text{ GeV} \leq E_e < 6\text{ GeV}\). Detailed comparisons are made to the predictions of the GENIE, GiBUU, NEUT, and NuWro neutrino event generators. The data do not strongly favor a model over the others consistently across all three cross sections measured, though some models have especially good or poor agreement in the single differential cross section vs \(Q^2\).

DOI: 10.1103/PhysRevLett.130.051802

Precision measurements of neutrino oscillation parameters \([1-4]\) such as \(\delta_{\text{CP}}\) and the neutrino mass ordering use \(\nu_e\) (\(\bar{\nu}_e\)) appearance in predominantly \(\nu_\mu\) (\(\bar{\nu}_\mu\)) beams and depend on detailed understanding of neutrino interaction models. Despite the two-detector technique that largely mitigates the impact of cross-section uncertainties, oscillation measurements still require model predictions to estimate the energy spectrum and selection efficiencies of \(\nu_e\) interactions via accurate modeling of interaction rate and outgoing-particle kinematics.

Lepton universality suggests that \(\nu_\mu\) and \(\nu_e\) interactions are largely similar, but differences in final-state lepton mass, tree-level radiative corrections, and imprecisely known form factors of the nucleon lead to differences in the predicted cross sections and their uncertainties \([5]\). There are few direct \(\nu_e\) cross-section measurements at the GeV energy scale as \(\nu_e\) comprise \(\lesssim 1\%\) of the neutrino beams produced at accelerators. The dominant \(\nu_\mu\) component produces significant backgrounds. Previous measurements in this energy range have been performed by Gargamelle \([6]\) and T2K \([7,8]\), both of which reported the total integrated cross section as a function of energy. MINERvA has reported single-differential cross sections...
for the quasielastic component of the $\nu_e$—carbon cross section [9]. The measurement presented here uses the largest GeV sample of electron neutrino-initiated interactions to date, with which the simultaneous differential dependence on electron energy $E_e$ and angle $\theta_e$ is extracted for the first time. The cross sections as functions of squared four-momentum transfer $Q^2$ and neutrino energy $E_\nu$ are also presented.

Generators, such as [10–13], group predictions of neutrino-nucleus interaction cross sections into three processes in this energy range: quasielastic (QE), baryon resonance production (RES), and deep inelastic scattering (DIS). The modeling of these processes must be altered in the nuclear medium. A fourth process due to meson exchange current (MEC) occurs only inside the nuclei. These nuclear effects are not completely understood and the implementation of existing models in generators is currently incomplete [14–17]. Measured differential dependencies using $\nu_e$ can be used to constrain the underlying interaction channels, elucidate nuclear effects, and probe key aspects of neutrino-nucleus interaction models used to calculate oscillation-experiment acceptances.

The NOvA experiment is designed to measure neutrino flavor oscillations [1] using two detectors separated by 809 km, placed 14.6 mrad off axis from the central beam direction of Fermilab’s NuMI beam [18]. Magnetic focusing horns in the beamline charge-select neutrino parents giving 96% $\nu_\mu$ flux between 1 and 6 GeV. The energy spectrum peak at 1.8 GeV at the near detector (ND) as shown in Fig. 1. The largest contamination is $\bar{\nu}_e$; the $<1\%$ $\nu_e + \bar{\nu}_e$ arises mostly from muon decays below 3 GeV neutrino energy and kaon decays above.

The ND is a tracking calorimeter composed of liquid scintillator-filled PVC cells. The portion of the detector relevant to this measurement is $3.9 \times 3.9 \times 12.8$ m (long dimension along beam direction) in size and is segmented into cells $3.9$ m long with a rectangular cross section of 6.6 cm (0.15 radiation length) in the beam direction and 3.9 cm (0.45 Molière radius) transverse to the beam, spanning the height and width of the detector in planes of alternating vertical and horizontal orientation. Each cell is filled with a blend of 95% mineral oil and 5% pseudocumene with trace concentrations of wavelength shifting fluoros [19]. The resulting composition by mass is 67% carbon, 16% chlorine, 11% hydrogen, 3% titanium, and 3% oxygen with other trace elements. When a particle traverses the detector, a wavelength-shifting fiber in the cell collects and delivers scintillation light to an avalanche photodiode. The result is digitized by custom front-end electronics. All signals above a noise-vetoing threshold are sent to a data buffer.

This Letter presents data corresponding to $8.02 \times 10^{20}$ protons delivered to the NuMI production target (POT) between November 2014 and February 2017.

This analysis relies on simulation to calculate the flux, optimize event selection criteria, estimate selection efficiency, and assess the effects of detector resolution, acceptance, and systematic uncertainties. The simulation proceeds in several steps: first neutrinos are generated from simulated mesons in the NuMI beam, then those neutrinos interact with nuclei in the detector, after which the final-state particles are transported through the detector.

The NuMI flux is predicted using GEANT4 v9.03 [20] with the FTFP BERT hadronic model. The hadron production model is adjusted and constrained using external measurements by the PPFX package [21]. Neutrino interactions are simulated using the GENIE v2.12.2 [10] event generator, hereinafter referred to as GENIE v2. The neutrino-interaction model output is adjusted to incorporate advances in theory and external data to better match a sample of $\nu_\mu$ charged-current (CC) interactions from NOvA ND data as detailed in Ref. [22]. In this dedicated tune, hereinafter referred to as the NOvA tune, there are three substantial adjustments to the GENIE v2 prediction: (1) the QE axial mass ($M_A$ CCQE) is changed from 0.99 to 1.04 GeV/$c^2$ [23]; (2) soft nonresonant single pion production events from neutrinos are reduced by 57%; (3) the empirical MEC model [24] is tuned to ND data using a two-dimensional fit in hadronic energy and momentum transfer. This procedure changes the shape of the MEC prediction and increases its cross section by 50%. The NOvA-tune is applied to all simulated CC interactions.

GEANT4(v10.1.p3) is used to simulate energy deposited in the NOvA ND from the particles generated by neutrino interactions. Photon generation and propagation are modeled separately as follows: (1) the modeling and transfer of scintillation light uses NOvA measurements of scintillator response and fiber attenuation properties [25]; (2) the Birks suppression of the scintillation light is tuned using test-stand measurements and validated using a custom simulated response of the readout electronics [26].

The signature of $\nu_e$ CC interactions is an electron in the final state that produces an electromagnetic cascade within
FIG. 2. Simulated ElectronID distributions of $\nu_e + \bar{\nu}_e$ CC (blue), $\nu_\mu + \bar{\nu}_\mu$ CC (orange), and NC (green), compared to data integrated over the reported electron kinematic phase space. The dashed (solid) line shows the total prediction from simulation (after extracted fit normalization corrections). Statistical uncertainties on data are too small to be seen. The vertical errors represent the $\pm 1\sigma$ systematic range. All spectra are normalized to the data exposure.

the detector. The major backgrounds are neutral current (NC) and $\nu_\mu$ CC interactions with final-state $n$’s that decay into two photons. These can mimic electron energy depositions if the showers overlap or one photon is low energy.

Candidate neutrino interactions (events) are reconstructed by forming collections of observed energy deposits (hits) from final-state charged particles correlated in space and time [27]. Events are assigned a vertex by minimizing the angular spread of hits relative to candidate vertices [28]. Using a fuzzy K-means algorithm, hits within the event are clustered in regions of space emanating from the vertex into reconstructed particle trajectories (prongs) [29]. Primary event vertices are required to be contained in a 49 t fiducial volume spanning 2.8 m in both width and height and 6.5 m in length. All prongs are required to stop at least 30 cm from any edge of the detector to ensure containment. Events containing between 20 and 200 hits and at least one prong are selected for analysis. Events outside this range are generally low visible energy NC events or high-multiplicity events in which the electromagnetic cascade is difficult to isolate.

Prongs are identified as candidate electrons using a boosted decision tree (BDT) algorithm [30]. One input to the BDT is the output of a convolutional neural network trained using simulated samples of single particles labeling prongs as muonic, electromagnetic, or hadronic in origin. Other inputs include the energy-weighted transverse width of the prong and the distance from the vertex to the prong start aiding the separation of photon- from electron-induced showers. BDT performance was validated against a sideband of data enriched with EM showers in $\nu_\mu$CC$^{0}_{D}$ events. Candidate events are assigned an ElectronID score equal to the most electron-like BDT score of their constituent protons. Figure 2 shows the ElectronID distribution in data and simulation after selection criteria (and kinematic restrictions, defined below) are applied.

The selected sample is binned according to the candidate electron shower’s calorimetric energy $E_e$ and angle $\cos \theta_e$. Within each electron kinematic bin, the simulated ElectronID distribution is used to generate signal and background predictions, or templates. Each bin’s templates are broken further into three components, whose three independent normalization parameters are constrained in a simultaneous fit to the data: $\nu_e + \bar{\nu}_e$, $\nu_\mu + \bar{\nu}_\mu$, and NC. Neutrinos and antineutrinos are not separated due to similarities in the shapes of their templates.

Electron-kinematic bins that satisfy two criteria are included in the fit: at least 100 predicted signal events and an estimated signal-to-background ratio $> 0.4$ in the ElectronID $> 0.2$ region. These requirements remove regions (e.g., $\cos \theta_e > 0.94, 1 \leq E_e < 1.5$ GeV) that do not have adequate discrimination between signal and photon-induced backgrounds and limit the measurement to the kinematic ranges:

$$
0.85 \leq \cos \theta_e < 0.90 \cap 1.0 \leq E_e (\text{GeV}) < 1.65,
0.90 \leq \cos \theta_e < 0.94 \cap 1.0 \leq E_e (\text{GeV}) < 2.0,
0.94 \leq \cos \theta_e < 0.97 \cap 1.4 \leq E_e (\text{GeV}) < 3.0,
0.97 \leq \cos \theta_e \leq 1.00 \cap 1.4 \leq E_e (\text{GeV}) < 6.0. \quad (1)
$$

A $\chi^2$ minimization procedure [31] fits the normalizations of the signal and two background templates. A covariance matrix encodes the correlations between templates across all kinematic and template bins using systematic uncertainties which affect the shape of ElectronID and reconstructed electron kinematics within the fit. The fit produces a $\chi^2$ of 131 for 141 degrees of freedom and normalization parameters ranging between 0.9 to 1.1 with outliers in low-statistics, high-uncertainty bins. A sample purity of $13 \pm 1.3\%$ is predicted by extracting signal and background as the integral of the corresponding post-fit templates. Uncertainties on purity rise to 1.5% in kinematic regions where the $\nu_\mu + \bar{\nu}_\mu$ and NC normalization parameters are highly correlated due to similarities in template shape. The contribution of $\nu_e$ CC background is removed from the renormalized signal template using the 5% contribution from simulation. The resulting sample is estimated to contain $9200 \pm 1000$ $\nu_e$ CC interaction candidates. The selection efficiency is approximately 40% at 2 GeV, $\cos \theta_e \geq 0.97$ and reduces linearly to 13% at the edges of the phase space with an average of 23%. The signal sample is estimated to be 28% QE, 20% MEC, 31% RES, 20% DIS, and 1% CC coherent pion production.

The flux-averaged double-differential $\nu_e$ CC cross section in final state electron kinematic variables is constructed using
TABLE I. Fractional uncertainties and correlations, broken down by source. Averages are taken across all reported bins, weighted by the measured cross section.

| Source                | Average uncertainty (%) | Average correlation |
|-----------------------|-------------------------|---------------------|
| Flux                  | 10.3                    | 0.90                |
| ν-A model             | 9.8                     | 0.64                |
| Calibration           | 5.9                     | 0.05                |
| Detector model        | 5.6                     | 0.21                |
| Other                 | 2.8                     | 0.03                |
| Statistical           | 7.4                     | 0.02                |
| Total                 | 18.2                    | 0.59                |

\[
\left( \frac{d^2\sigma}{d\cos\theta dE} \right)_i = \frac{\sum_j U_{ij}^{-1} N_i \delta_i(\cos\theta, E) j}{N_i \phi_i(\cos\theta, E) j \Delta \cos\theta \Delta E_i}, \tag{2}
\]

where \( N_i \) is the estimated \( \nu_e \) CC events from the template fit. \( U_{ij} \) is an unfolding matrix used to relate the reconstructed value in bin \( j \) to the true value in bin \( i \). The data are iteratively unfolded using d’Agostini’s method [32] with two iterations as implemented in RooUnfold [33]. The optimal number was found by minimizing the average mean square error [34] calculated across simulated samples with random variations of systematic uncertainties. \( N_i \) is the number of nuclear targets in the fiducial volume, \( \phi \) the integrated neutrino flux, \( \epsilon \) the selection efficiency correction factor, and \( \Delta E \) and \( \Delta \cos\theta \) are the bin widths used for the electron kinematic variables. Bin widths are chosen small enough to match the detector resolution and large enough to include a statistically significant event sample. The average \( E_\nu \) resolution is 350 MeV, and the angular resolution ranges from 2° for forward-going electrons to 11° for less forward-going electrons.

Table I summarizes the effects of sources of uncertainty on the measurements. Systematic uncertainties are evaluated by varying the parameters used to model neutrino flux, neutrino-nucleus interactions (ν-A), detector response, and re-extracting the differential cross section. The difference between the cross section extracted using the nominal simulation and that extracted using the simulation with a varied parameter is taken as the uncertainty due to each parameter. The procedure accounts for changes in the compositions of backgrounds, selection efficiency, and event reconstruction due to the variations considered.

Dominant sources of systematic uncertainty are from the neutrino flux and ν-A predictions. Uncertainties on the flux arise from hadron production uncertainties (9%) [21] and beam optics modeling (4%). ν-A modeling uncertainties are assessed through reweightable parameters from the GENIE generator [10] and a custom set of NOvA-specific uncertainties [22]. At \( E_\nu < 3 \) GeV, parameters affecting the RES signal and backgrounds (CC/NC\( \pi^0 \)) and the MEC signal prediction are dominant. DIS related multipion production uncertainties dominate at \( E_\nu > 3 \) GeV.

Nonleading sources of uncertainty come from detector calibration and modeling. These sources become dominant at \( \cos\theta_e < 0.94 \) and \( E_e < 1.5 \) GeV. Minor sources of uncertainty, which include detector mass, integrated beam exposure, beam intensity modeling, and the modeling of diffractive (DFR) \( \pi^0 \) production, are combined in the “other” category of Table I. DFR modeling uncertainties are evaluated by reweighting the default ν-H NC interactions producing a \( \pi^0 \) prediction from GENIE to an estimate based on the Kopeliovich model et al. [35,36] as a function of \( E_\nu \) and the Bjorken scaling variables. The average uncertainty on DFR modeling is 2.6%.

Table I shows the weighted average bin-to-bin correlations [37] calculated as

\[
\langle \text{corr} \rangle = \frac{\sum_{i<j} C_{ij} \times \sigma_i \times \sigma_j}{\sum_{i<j} \sigma_i \times \sigma_j}, \tag{3}
\]

where \( C_{ij} \) is the correlation between bins \( i \) and \( j \) and \( \sigma_i \) is the double-differential cross section measured in bin \( i \) for each source of systematic uncertainty. Large average correlation from the flux uncertainty indicate that it mainly impacts normalization. Interaction modeling also exhibits strong correlations across all bins, due to a combination of the template fitting procedure and model parameters, such as the axial mass from the RES model and DIS pion production uncertainties, that impact selection efficiency.

Three results are presented: the flux-integrated double-differential cross section vs electron energy and angle shown in Fig. 3, the cross section vs \( E_\nu \) shown in Fig. 4,
and the differential cross section vs $Q^2$ shown in Fig. 5. All results are calculated from data using unfolding and efficiency corrections derived from the NOvA tune. The one-dimensional results apply the phase space restrictions in (1), without any restriction on the derived quantities of $E_e$ or $Q^2\{= 2E_e[E_e - (P_e \cos \theta_e)] - m^2_e\}$. $E_e$ is reconstructed using a quadratic function determined from a 2D fit to the simulated electron and hadronic calorimetric energy [38]. The result is extracted with unfolding and efficiency corrections in $E_e$ or $Q^2$.

The extracted cross sections are compared to predictions from several generators: GENIE (NOvA-tune, v2.12.2, and v3.00.06 with a global configuration N18_10j_02_11a), NuWro 2019 [13], GiBUU 2019 [11], and NEUT 5.4.0 [12]. Table II summarizes $\chi^2$ values for each model compared to data with a full treatment of bin-to-bin correlations. The values show no model is consistently favored across the ensemble of measurements.

Though the GiBUU and NuWro predictions have normalizations systematically lower than the data in Figs. 3–5 (15% and 10%, respectively) their $\chi^2$'s in Table II are comparable to other models’ due to the phenomenon of Peelle’s Pertinent Puzzle (PPP) [39,40]. PPP arises when the dominant uncertainty of a result is from highly correlated normalization uncertainties, like the flux uncertainty in Table I. Under these circumstances, the best-fitting model as reckoned by $\chi^2$ can be well outside the data points. Disagreements with the GENIE predictions are dominated by the discrepancy in the $E_e > 4.75$ GeV bin and its correlations with other bins. When this bin is excluded from the calculation, the $\chi^2$'s for the GENIE predictions approach those of the NuWro and GiBUU predictions. NEUT shows slight disagreement throughout that angular slice, predicting a softer energy spectrum than is observed in data.

In $E_e$ comparisons NuWro and GiBUU plateau at a lower total cross section than the data as described above. The differential cross section vs $Q^2$ shows preference toward the NOvA-tune and GENIE v3 predictions. NEUT predicts a softer $Q^2$ distribution than seen in data, while GiBUU and NuWro accurately predict the low $Q^2$ behavior but tension is seen at high $Q^2$. The gray band in Fig. 5 shows the size of the flux-related normalization uncertainties, which illustrates that differences seen between data and the generators are not consistent with an overall change in the cross-section normalization.

This Letter presents the first measurement of the inclusive charged-current double-differential electron-neutrino cross section vs electron energy and angle, using the NOvA ND. This provides new information concerning directly observable final-state electron kinematics necessary for neutrino energy estimation and efficiency correction in $\nu_e$ appearance measurements. Measured cross sections are shown compared to multiple versions of GENIE, and to GiBUU, NEUT, and NuWro event generators, in the neutrino energy range from 1 to 6 GeV. The models show general agreement

**TABLE II.** $\chi^2$ calculated for each model presented in Figs. 3–5 compared to data. Degrees of freedom are 17, 12, and 9 for the double-differential, $E_e$, and $Q^2$ results, respectively.

| Generator   | $d^2\sigma/dQ^2 dE_e$ | $\sigma(E_e)$ | $d\sigma/dQ^2$ |
|------------|----------------------|----------------|----------------|
| GENIE v2—NOvA-tune | 24.1 | 13.4 | 1.3 |
| GENIE v2.12.2 | 24.3 | 14.3 | 19.6 |
| GENIE v3.00.06 | 27.4 | 21.6 | 3.4 |
| GiBUU 2019 | 17.5 | 16.0 | 14.7 |
| NEUT 5.4.0 | 25.1 | 16.9 | 45.0 |
| NuWro 2019 | 18.7 | 15.3 | 10.0 |
with the data in the two-dimensional phase space as well as various levels of success in the neutrino energy and $Q^2$ measurements. Disagreements are seen in both overall normalization across all reported measurements and with certain shape differences, primarily seen in $Q^2$. The data related to this measurement and systematic covariance matrices can be found at [41].

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 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.

[1] M. A. Acero et al. (NOvA Collaboration), Phys. Rev. Lett. 123, 151803 (2019).
[2] K. Abe et al. (The T2K Collaboration), Phys. Rev. D 103, L011101 (2021).
[3] B. Abi et al. (DUNE Collaboration), J. Instrum. 15, T08008 (2020).
[4] M. Yokoyama (Hyper-Kamiokande Proto Collaboration), in Prospects in Neutrino Physics (2017), arXiv:1705.00306.
[5] M. Day and K. S. McFarland, Phys. Rev. D 86, 053003 (2012).
[6] J. Blietschau et al. (Gargamelle Collaboration), Nucl. Phys. B133, 205 (1978).
[7] K. Abe et al. (T2K Collaboration), Phys. Rev. Lett. 113, 241803 (2014).
[8] Tomohiro Abe, Motoko Fujiwara, Junji Hisano, and Yutaro Shoji (T2K Collaboration), J. High Energy Phys. 10 (2020) 114.
[9] J. Wolcott et al. (MINERvA Collaboration), Phys. Rev. Lett. 116, 081802 (2016).
[10] C. Andreopoulos et al., Nucl. Instrum. Methods Phys. Res., Sect. A 614, 87 (2010).
[11] O. Lalakulich, K. Gallmeister, and U. Mosel, J. Phys. Conf. Ser. 408, 012053 (2013).
[12] Y. Hayato, Acta Phys. Pol. B 40, 2477 (2009), https://inspirehep.net/literature/844435.
[13] T. Golan, J. Sobczyk, and J. Zmuda, Nucl. Phys. B, Proc. Suppl. 229–232, 499 (2012).
[14] M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C 80, 065501 (2009).
[15] J. Nieves, I. R. Simo, and M. J. VicenteVacas, Phys. Rev. C 83, 045501 (2011).
[16] G. D. Megias, J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly, and I. R. Simo, Phys. Rev. D 94, 093004 (2016).
[17] T. Van Cuyck, N. Jachowicz, R. Gonzalez-Jimenez, J. Ryckebusch, and N. VanDessel, Phys. Rev. C 95, 054611 (2017).
[18] P. Adamson et al., Nucl. Instrum. Methods Phys. Res., Sect. A 806, 279 (2016).
[19] S. Muñoz, B. Baugh, C. Bower, T. E. Coan, J. Cooper, L. Corwin, J. A. Karty, P. Mason, M. D. Messier, A. Pla-Dalmau, and M. Proudfoot, Nucl. Instrum. Methods Phys. Res., Sect. A 799, 1 (2015).
[20] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[21] L. Aliaga et al. (MINERvA Collaboration), Phys. Rev. D 94, 092005 (2016); 95, 039903 (2017).
[22] M. Acero et al. (NOvA Collaboration), Eur. Phys. J. C 80, 1119 (2020).
[23] A. S. Meyer, M. Betancourt, R. Gran, and R. J. Hill, Phys. Rev. D 93, 113015 (2016).
[24] T. Katori, AIP Conf. Proc. 1663, 030001 (2015).
[25] A. Aurisano, C. Backhouse, R. Hatcher, N. Mayer, J. Musser, R. Patterson, R. Schroeter, and A. Sousa, J. Phys. Conf. Ser. 664, 072002 (2015).
[26] N. Anfimov, A. Antoshkin, A. Aurisano, O. Samoylov, and A. Sotnikov, J. Instrum. 15, C06066 (2020).
[27] M. Ester et al., in Proceedings of the Second International Conference on Knowledge Discovery and Data Mining, KDD’96 (AAAI Press, USA, 1996), pp. 226–231.
[28] M. Baird, J. Bian, M. Messier, E. Niner, D. Rocco, and K. Sachdev, J. Phys. Conf. Ser. 664, 072035 (2015).
[29] J. C. Dunn, J. Cybern. 3, 32 (1973).
[30] A. Hoecker et al., arXiv:physics/0703039.
[31] S. Mufson, B. Baugh, C. Bower, T. E. Coan, J. Cooper, L. Corwin, J. A. Karty, P. Mason, M. D. Messier, A. Pla-Dalmau, and M. Proudfoot, Nucl. Instrum. Methods Phys. Res., Sect. A 799, 1 (2015).
[32] J. C. Dunn, J. Cybern. 3, 32 (1973).
[33] A. Hoecker et al., arXiv:physics/0703039.
[34] W. T. Eadie et al., in Proceedings of the PHYSTAT 2011 Workshop (CERN, Geneva, 2011), pp. 313–318.
[35] B. Z. Kopeliovich, I. Schmidt, and M. Siddikov, Phys. Rev. D 85, 073003 (2012).
[36] M. Horvatic, M. Kuncich, and M. R. Boesing, Phys. Rev. D 85, 073003 (2012).
[37] F. Psihas, Measurement of long baseline neutrino oscillations and improvements from deep learning, Ph.D. thesis, Indiana University, 2018, https://wwwosti.gov/biblio/1437288.
[38] D. L. Smith, Probability, Statistics, and Data Uncertainties in Nuclear Science and Technology (American Nuclear Society, La Grange Park, 1991).
[39] R. Frühwirth, D. Neudecker, and H. Leeb, EPJ Web Conf. 27, 00008 (2012).
[40] M. Acero et al. (NOvA Collaboration), NOvA Data Release Webpage, https://novaexperiment.fnal.gov/data-releases/2022.