

Deep Exclusive Electroproduction of π^0 at High Q^2 in the Quark Valence Regime

M. Dlamini,¹ B. Karki,¹ S. F. Ali,² P.-J. Lin,³ F. Georges,³ H.-S. Ko,^{3,4} N. Israel,¹ M. N. H. Rashad,⁵ A. Stefanko,⁶ D. Adikaram,⁷ Z. Ahmed,⁸ H. Albataineh,⁹ B. Aljawrneh,¹⁰ K. Allada,¹¹ S. Allison,⁵ S. Alsalmi,¹² D. Androic,¹³ K. Aniol,¹⁴ J. Annand,¹⁵ H. Atac,¹⁶ T. Averett,¹⁷ C. Ayerbe Gayoso,¹⁷ X. Bai,¹⁸ J. Bane,¹⁹ S. Barcus,¹⁷ K. Bartlett,¹⁷ V. Bellini,²⁰ R. Beminiwattha,²¹ J. Bericic,⁷ D. Biswas,²² E. Brash,²³ D. Bulumulla,⁵ J. Campbell,²⁴ A. Camsonne,⁷ M. Carmignotto,² J. Castellano,²⁵ C. Chen,²² J.-P. Chen,⁷ T. Chetry,¹ M. E. Christy,²² E. Cisbani,²⁶ B. Clary,²⁷ E. Cohen,²⁸ N. Compton,¹ J. C. Cornejo,^{17,6} S. Covrig Dusa,⁷ B. Crowe,²⁹ S. Danagoulian,¹⁰ T. Danley,¹ F. De Persio,²⁶ W. Deconinck,¹⁷ M. Defurne,³⁰ C. Desnault,³ D. Di,¹⁸ M. Duer,²⁸ B. Duran,¹⁶ R. Ent,⁷ C. Fanelli,¹¹ G. Franklin,⁶ E. Fuchey,²⁷ C. Gal,¹⁸ D. Gaskell,⁷ T. Gautam,²² O. Glamazdin,³¹ K. Gnanvo,¹⁸ V. M. Gray,¹⁷ C. Gu,¹⁸ T. Hague,¹² G. Hamad,¹ D. Hamilton,¹⁵ K. Hamilton,¹⁵ O. Hansen,⁷ F. Hauenstein,⁵ W. Henry,¹⁶ D. W. Higinbotham,⁷ T. Holmstrom,³² T. Horn,^{2,7} Y. Huang,¹⁸ G. M. Huber,⁸ C. Hyde,⁵ H. Ibrahim,³³ C.-M. Jen,³⁴ K. Jin,¹⁸ M. Jones,⁷ A. Kabir,¹² C. Keppel,⁷ V. Khachatryan,^{7,35,36} P. M. King,¹ S. Li,³⁷ W. Li,⁸ J. Liu,¹⁸ H. Liu,³⁸ A. Liyanage,²² J. Magee,¹⁷ S. Malace,⁷ J. Mammei,³⁹ P. Markowitz,²⁵ E. McClellan,⁷ F. Meddi,²⁶ D. Meekins,⁷ K. Mesik,⁴⁰ R. Michaels,⁷ A. Mkrtchyan,² R. Montgomery,¹⁵ C. Muñoz Camacho,³ L. S. Myers,⁷ P. Nadel-Turonski,⁷ S. J. Nazeer,²² V. Nelyubin,¹⁸ D. Nguyen,¹⁸ N. Nuruzzaman,²² M. Nycz,¹² O. F. Obretch,²⁷ L. Ou,¹¹ C. Palatchi,¹⁸ B. Pandey,²² S. Park,³⁵ K. Park,⁵ C. Peng,⁴¹ R. Pomatsalyuk,³¹ E. Pooser,⁷ A. J. R. Puckett,²⁷ V. Punjabi,⁴² B. Quinn,⁶ S. Rahman,³⁹ P. E. Reimer,⁴³ J. Roche,^{1,*} I. Sapkota,² A. Sarty,⁴⁴ B. Sawatzky,⁷ N. H. Saylor,⁴⁵ B. Schmookler,¹¹ M. H. Shabestari,⁴⁶ A. Shahinyan,⁴⁷ S. Sirca,⁴⁸ G. R. Smith,⁷ S. Sooriyaarachchilage,²² N. Sparveris,¹⁶ R. Spies,³⁹ T. Su,¹² A. Subedi,⁴⁶ V. Sulkosky,¹¹ A. Sun,⁶ L. Thorne,⁶ Y. Tian,⁴⁹ N. Ton,¹⁸ F. Tortorici,²⁰ R. Trotta,⁵⁰ G. M. Urciuoli,²⁶ E. Voutier,³ B. Waidyawansa,⁷ Y. Wang,¹⁷ B. Wojtsekhowski,⁷ S. Wood,⁷ X. Yan,⁵¹ L. Ye,⁴⁶ Z. Ye,¹⁸ C. Yero,²⁵ J. Zhang,¹⁸ Y. Zhao,³⁵ and P. Zhu⁵²

(Jefferson Lab Hall A Collaboration)

¹Ohio University, Athens, Ohio 45701, USA

²Catholic University of America, Washington, DC 20064, USA

³Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

⁴Seoul National University, 1 Gwanak-ro, Gwanak-gu, 08826 Seoul, Korea

⁵Old Dominion University, Norfolk, Virginia 23529, USA

⁶Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

⁷Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

⁸University of Regina, Regina, Saskatchewan S4S 0A2 Canada

⁹Texas A&M University-Kingsville, Kingsville, Texas 78363, USA

¹⁰North Carolina Ag. and Tech. State University, Greensboro, North Carolina 27411, USA

¹¹Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

¹²Kent State University, Kent, Ohio 44240, USA

¹³University of Zagreb, Trg Republike Hrvatske 14, 10000 Zagreb, Croatia

¹⁴California State University, Los Angeles, Los Angeles, California 90032, USA

¹⁵SUPA School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom

¹⁶Temple University, Philadelphia, Pennsylvania 19122, USA

¹⁷The College of William and Mary, Williamsburg, Virginia 23185, USA

¹⁸University of Virginia, Charlottesville, Virginia 22904, USA

¹⁹University of Tennessee, Knoxville, Tennessee 37996, USA

²⁰Istituto Nazionale di Fisica Nucleare, Dipt. Di Fisica delle Uni. di Catania, I-95123 Catania, Italy

²¹Syracuse University, Syracuse, New York 13244, USA

²²Hampton University, Hampton, Virginia 23669, USA

²³Christopher Newport University, Newport News, Virginia 23606, USA

²⁴Dalhousie University, Nova Scotia B3H 4R2, Canada

²⁵Florida International University, Miami, Florida 33199, USA

²⁶Istituto Nazionale di Fisica Nucleare—Sezione di Roma, P.le Aldo Moro, 2-00185 Roma, Italy

²⁷University of Connecticut, Storrs, Connecticut 06269, USA

²⁸Tel Aviv University, Tel Aviv 699780 1, Israel

²⁹North Carolina Central University, Durham, North Carolina 27707, USA

³⁰CEA Saclay, 91191 Gif-sur-Yvette, France

³¹*Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine*
³²*Randolph Macon College, Ashlan, Virginia 23005, USA*
³³*Cairo University, Cairo 121613, Egypt*
³⁴*Virginia Polytechnic Institute & State University, Blacksburg, Virginia 234061, USA*
³⁵*Stony Brook, State University of New York, New York 11794, USA*
³⁶*Cornell University, Ithaca, New York 14853, USA*
³⁷*University of New Hampshire, Durham, New Hampshire 03824, USA*
³⁸*Columbia University, New York, New York 10027, USA*
³⁹*University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
⁴⁰*Rutgers University, New Brunswick, New Jersey 08854, USA*
⁴¹*Duke University, Durham, North Carolina 27708, USA*
⁴²*Norfolk State University, Norfolk, Virginia 23504, USA*
⁴³*Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
⁴⁴*Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada*
⁴⁵*Rensselaer Polytechnic Institute, Troy, New York 12180, USA*
⁴⁶*Mississippi State University, Mississippi State, Mississippi 39762, USA*
⁴⁷*AANL, 2 Alikhanian Brothers Street, 0036 Yerevan, Armenia*
⁴⁸*Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia*
⁴⁹*Shandong University, Jinan, Shandong, 250100, China*
⁵⁰*Duquesne University, 600 Forbes Avenue, Pittsburgh, Pennsylvania 15282, USA*
⁵¹*Huangshan University, Huangshan, Anhui, 245041, China*
⁵²*University of Science and Technology of China, Hefei, Anhui 230026, China*
 (Received 2 December 2020; revised 7 June 2021; accepted 17 August 2021; published 5 October 2021)

We report measurements of the exclusive neutral pion electroproduction cross section off protons at large values of x_B (0.36, 0.48, and 0.60) and Q^2 (3.1 to 8.4 GeV²) obtained from Jefferson Lab Hall A experiment E12-06-014. The corresponding structure functions $d\sigma_T/dt + ed\sigma_L/dt$, $d\sigma_{TT}/dt$, $d\sigma_{LT}/dt$, and $d\sigma_{LT'}/dt$ are extracted as a function of the proton momentum transfer $t - t_{\min}$. The results suggest the amplitude for transversely polarized virtual photons continues to dominate the cross section throughout this kinematic range. The data are well described by calculations based on transversity generalized parton distributions coupled to a helicity flip distribution amplitude of the pion, thus providing a unique way to probe the structure of the nucleon.

DOI: 10.1103/PhysRevLett.127.152301

Generalized parton distributions (GPDs) [1–3] describe the three-dimensional structure of the nucleon by correlating the transverse position and the longitudinal momentum of the quarks and gluons inside of it. GPDs are accessible through deep exclusive processes, such as deeply virtual compton scattering (DVCS) and deeply virtual meson production (DVMP). For the latter, collinear factorization theorems [4] applied to longitudinally polarized virtual photons only (not to the transversely polarized ones) establish that the DVMP amplitude factorizes at large Q^2 into a hard perturbative part and a soft component described by the GPDs of the nucleon. Figure 1 shows the leading mechanism of the π^0 electroproduction reaction and defines the kinematic variables of the process. There

are four chiral-even GPDs ($H, E, \tilde{H}, \tilde{E}$) that define the quark helicity-conserving amplitudes and four chiral-odd (transversity) GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$) that define the quark

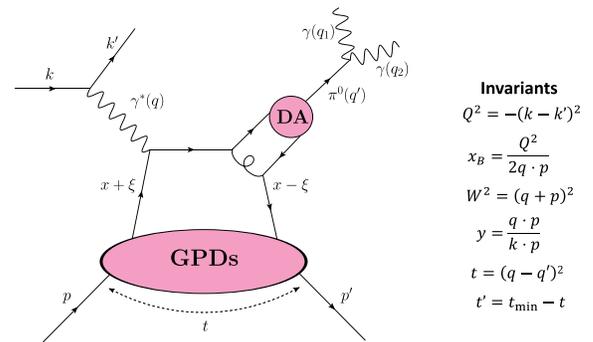


FIG. 1. Leading twist diagram representing the pseudoscalar DVMP to the $\gamma\gamma$ channel. The net four-momentum transferred to the proton is t , whose minimum value t_{\min} occurs when the π^0 meson is emitted parallel to the virtual photon. The average light cone momentum fraction carried by the struck parton is x with -2ξ the light cone momentum transfer.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

helicity-flip amplitudes. In the Bjorken limit where $Q^2 \rightarrow \infty$, the target rest-frame energy of the virtual photon $\nu \rightarrow \infty$ and $t/Q^2 \ll 1$, QCD predicts that the reaction cross section is dominated by the contribution of longitudinally polarized virtual photons. This longitudinal component depends on the momentum transfer as Q^{-6} , whereas the transverse component goes asymptotically as Q^{-8} . The longitudinal cross section of DVMP only depends on the convolution of chiral-even GPDs of the nucleon with the quark helicity-conserving distribution amplitude (DA) of the meson [5]. However, existing data [6–13] for neutral pseudoscalar meson production in the quark valence regime, with limited reach in Q^2 , show that transversely polarized virtual photons dominate the total cross section. In the collinear approximation, singularities occur for transversely polarized photons and mesons. To explain the large transverse contribution to the π^0 electroproduction cross sections, it has been suggested [14–16] to regularize these singularities by including transverse degrees of freedom of the quarks and antiquarks making up the meson. In this framework, the π^0 electroproduction cross section is described by the convolution of a higher order helicity-flip DA of the meson with the transversity GPDs of the nucleon. Calculations based on this approach [14,15] were able to reproduce reasonably well the existing neutral pseudoscalar meson production data cited above. This Letter reports measurements of π^0 electroproduction cross sections that extend to higher values of Q^2 (from 3.1 to 8.4 GeV²) and of x_B (0.36, 0.48, and 0.60), with a large coverage in t and center of mass energy s .

The exclusive meson electroproduction cross section can be written [17] in terms of contributions from longitudinally (L) and transversely (T) polarized photons and their interference as

$$\begin{aligned} \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = & \frac{1}{2\pi} \frac{d^2\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E) \left[\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right. \\ & + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) \\ & \left. + h\sqrt{2\epsilon(1-\epsilon)} \frac{d\sigma_{LT'}}{dt} \sin(\phi) \right], \quad (1) \end{aligned}$$

where $h(\pm 1)$ is the helicity of the initial lepton, E is the incident beam energy and ϕ is an angle between leptonic and hadronic planes defined according to the Trento convention [18]. The virtual photon flux [19] ($d^2\Gamma_\gamma/dQ^2 dx_B$) and the degree of longitudinal polarization ϵ are defined as

$$\frac{d^2\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E) = \frac{\alpha}{8\pi} \frac{1}{1-\epsilon} \frac{1-x_B}{x_B^3} \frac{Q^2}{M_p^2 E^2}, \quad (2)$$

$$\epsilon = \frac{1-y-\frac{Q^2}{4E^2}}{1-y+\frac{y^2}{2}+\frac{Q^2}{4E^2}}, \quad (3)$$

where M_p is the proton mass and $y = [q \cdot p]/[k \cdot p]$.

Experiment E12-06-114 took data between 2014 and 2016 in Jefferson Lab Hall A. The main goal of this experiment was to measure the DVCS cross section $ep \rightarrow e\pi\gamma$. The same experimental configuration also captured exclusive π^0 electroproduction events. The kinematics covered by the experiment are shown in Table I. The electron beam scattered off a 15-cm-long liquid hydrogen target with luminosities greater than $10^{38} \text{ cm}^{-2} \text{ s}^{-1}$. The beam polarization measured by the Hall A Møller polarimeter was $86 \pm 1\%$, with the uncertainty dominated by the systematic precision of the measurement. Scattered electrons were detected in a high-resolution spectrometer (HRS) with a relative momentum resolution of 2×10^{-4} and a horizontal angular resolution of 2 mr [20]. Photons from the DVCS and DVMP processes were measured in an electromagnetic calorimeter consisting of a 13×16 array of PbF₂ crystals. The analog signal of each channel was sampled by a 1 GHz analog ring sampler [21,22] and recorded over 128 ns. The calorimeter was calibrated multiple times during the experiment using coincident elastic H(e, e'_{Calo} p_{HRS}) events. The typical energy resolution of the calorimeter was 3% at 4.2 GeV with an angular resolution of 1.5 mr (when located 6 m from the target). Between two consecutive elastic calibrations, the output of the calorimeter for a given photon energy changed up to 10% due to the radiation damage of the PbF₂ crystals. The loss of signal was estimated and compensated for by adjusting the

TABLE I. Incident beam energy E and average values for scattering kinematic variables for each of the nine (E, Q^2, x_B) settings where the π^0 cross sections are reported. For each setting, cross sections are measured as a function of $t' = t_{\text{min}} - t$, with t_{min} calculated event by event.

x_B label	0.36			0.48			0.60		
$\langle x_B \rangle$	0.36	0.36	0.36	0.48	0.45	0.46	0.46	0.59	0.60
E (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV ²)	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31
W^2 (GeV ²)	6.51	7.29	8.79	3.81	5.62	6.67	8.32	4.58	6.46
$-t_{\text{min}}$ (GeV ²)	0.16	0.17	0.17	0.33	0.35	0.35	0.36	0.67	0.71
ϵ	0.61	0.62	0.63	0.51	0.71	0.55	0.52	0.66	0.50

reconstructed invariant mass of the detected π^0 events. Additional details are presented in [23].

Neutral pions were reconstructed by selecting two photons in the calorimeter above 500 MeV each, in coincidence with the detection of a scattered electron in the HRS. The HRS-calorimeter coincidence-time resolution was about 1 ns. The total contribution from accidental coincidences was below 2% and was subtracted from the experimental yield. The π^0 sample was cleanly identified by selecting events around the invariant mass $m_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$. The exclusivity of the reaction was ensured by reconstructing the missing-mass squared M_X^2 of the $H(e, e'\gamma\gamma)X$ reaction (see figure in the Supplemental Material [23]).

The acceptance and resolution of the experiment were computed by a Monte Carlo simulation based on the GEANT4 software [27]. The simulation and cross section extraction includes the real and virtual radiative effects, based on calculations of [24], see also Supplemental Material [23].

Data were binned into 12ϕ bins by $5t'$ bins. The different structure functions appearing in the π^0 electroproduction cross section were extracted by exploiting their specific ϕ dependencies, minimizing the χ^2 between the number of experimental and simulated events:

$$\chi^2 = \sum_{i=1}^{N=60} \left(\frac{N_i^{\text{exp}} - N_i^{\text{sim}}}{\sigma_i^{\text{exp}}} \right)^2 \quad (4)$$

where the sum runs over all 12×5 bins for each (x_B, Q^2) setting. N_i^{exp} is the total number of events in bin i with corresponding statistical precision σ_i^{exp} . The number of simulated events in bin i is computed by convoluting the acceptance and resolution of the experimental setup with the kinematic dependencies of each of the structure functions ($d\sigma_T/dt + \epsilon d\sigma_L/dt$, $d\sigma_{TT}/dt$, and $d\sigma_{LT}/dt$) that make up the cross section [see Eq. (1)]. These structure functions are the free parameters of the χ^2 minimization. An example of these fits and the numerical values of all the extracted structure functions are shown in the Supplemental Material [23]. The helicity-dependent structure function $d\sigma_{LT}$ is extracted by a similar fit to the difference in yield for events with opposite helicities. Bin migration effects from one kinematic bin to another due to resolution and radiative effects are incorporated into the simulation and are up to 10% depending upon the kinematic bin. Cross sections are only reported for the four lowest t' bins; the additional highest t' bin in the analysis is only used to evaluate bin migration to the lower t' bins. The systematic uncertainty associated with the bin migration is assessed by varying the selection cut on the missing mass squared, for each kinematic bin. The $d\sigma_T/dt + \epsilon d\sigma_L/dt$, $d\sigma_{TT}/dt$, and $d\sigma_{LT}/dt$ values extracted from the fit show a degree of correlation of around 10% at low t' , but this correlation reaches 90% at large t' due to the loss of full azimuthal acceptance in the detector.

The total systematic uncertainty of the results reported herein varies between 4% and 8% depending on the kinematic setting. The variation in the systematic uncertainty from one setting to another is due to the effect of the

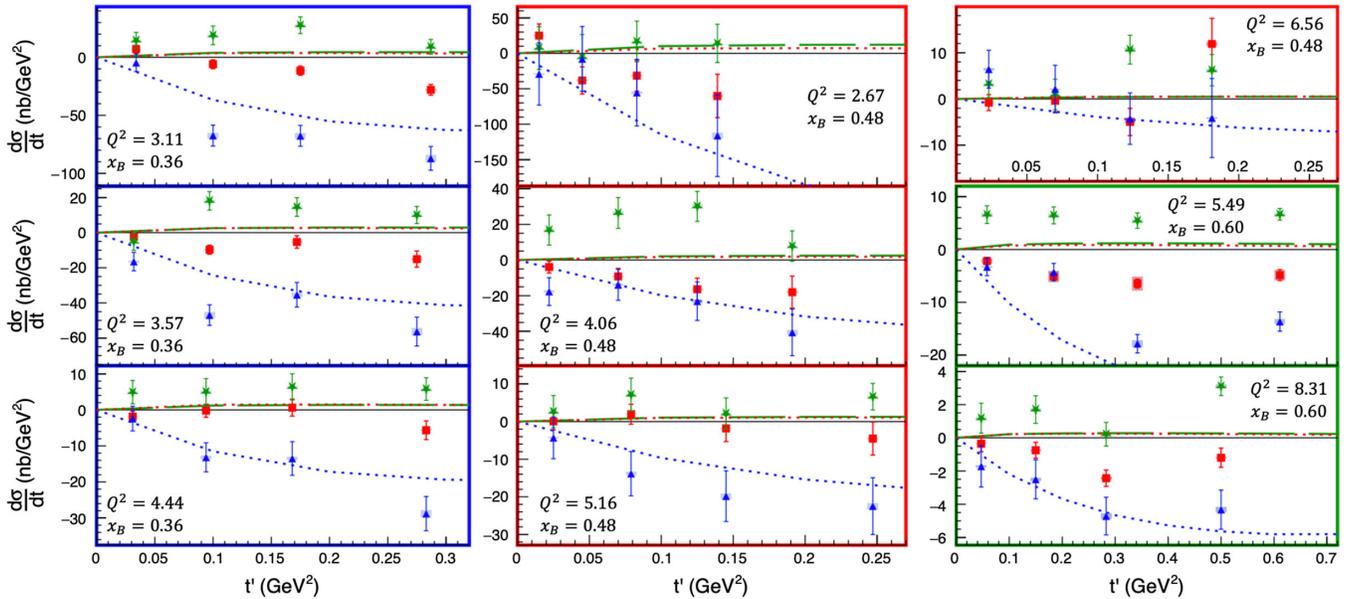


FIG. 2. Structure functions $d\sigma_{TT}$ (blue triangles), $d\sigma_{LT}$ (red squares), and $d\sigma_{LT'}$ (green stars) for all kinematic setting as a function of $t' = t_{\min} - t$. The dashed curves are calculations based on transversity GPDs of the nucleon [15]. The gray boxes surrounding the data points show the systematic uncertainty.

exclusivity cut, which is very sensitive to our ability to reproduce in the simulation the actual energy resolution of the photons as a function of their impact position onto the calorimeter.

Figure 2 shows the measurements of the structure functions $d\sigma_{TT}$, $d\sigma_{LT}$, and $d\sigma_{LT'}$ at the kinematics settings listed in Table I. In general $d\sigma_{TT}$ is larger than the interference terms involving the longitudinal amplitude ($d\sigma_{LT}$ and $d\sigma_{LT'}$). This hints at a dominance of the transverse amplitude in the reaction mechanism. Data are compared to calculations from the modified factorization approach first introduced in [14,15]. This model provides a large contribution to the transverse amplitude which arises from the convolution of chiral-odd (transversity) GPDs of the nucleon with a quark-helicity flip pion DA, whereas the longitudinal amplitude is extremely small, as illustrated by the calculations of $d\sigma_{LT}$ and $d\sigma_{LT'}$ in this framework. It is interesting to note that the data show a stronger longitudinal amplitude than in the model, which underestimate the values of both $d\sigma_{LT}$ and $d\sigma_{LT'}$, while providing a good agreement with $d\sigma_{TT}$. The underestimation of $d\sigma_{LT'}$ was already observed in [6,12]. The sign of the interference structure function $d\sigma_{LT}$ is measured to be systematically opposite to the theory calculations. In these model calculations of $d\sigma_{LT}$, the contributions from the real parts of H_T and \tilde{E} on one hand, and $\tilde{E}_T = 2\tilde{H}_T + E_T$ and \tilde{H} on the other hand enter with opposite sign. The latter term is small, and therefore these data for $d\sigma_{LT}$ will strongly constrain models of the currently poorly known GPD \tilde{E} .

Figure 3 shows the measurements of the unpolarized structure function $d\sigma_U = d\sigma_T + \epsilon d\sigma_L$. Calculations based on the modified factorization approach [15] are in reasonable agreement. This has been observed at lower values of Q^2 ($< 3 \text{ GeV}^2$) [8–10]. The fact that this is still true at these much higher values of the momentum transfer indicates that the asymptotic regime predicted by QCD, where the longitudinal amplitude must dominate, is not yet reached. On the other hand, at the highest value of Q^2 the transverse dominated calculations underestimate the data, thus providing some evidence of a sizeable longitudinal contribution, as also confirmed in Fig. 2 by the fact that $d\sigma_{LT}$ is becoming relatively larger compared to $d\sigma_{TT}$.

The Q^2 dependence of the structure functions is particularly interesting to study, as its asymptotic limit is the only feature that can be predicted from first principles (i.e., QCD) for different reaction mechanisms. Figure 4 (top) shows the Q^2 dependence of $d\sigma_U = d\sigma_T + \epsilon d\sigma_L$ at constant $t' = 0.1 \text{ GeV}^2$ and all three values of x_B . A broader perspective on the Q^2 and t dependence of these results is presented by the fits in Table II. At each x_B setting, we fit the data to a functional form $C(Q^2)^A \exp(-Bt')$. These fits, plotted in Fig. 4 at fixed t' demonstrate an approximately global $1/Q^6$ behavior of the cross section over the t' and x_B range. The calculations based on the modified factorization approach show a steeper variation with Q^2 (approximately

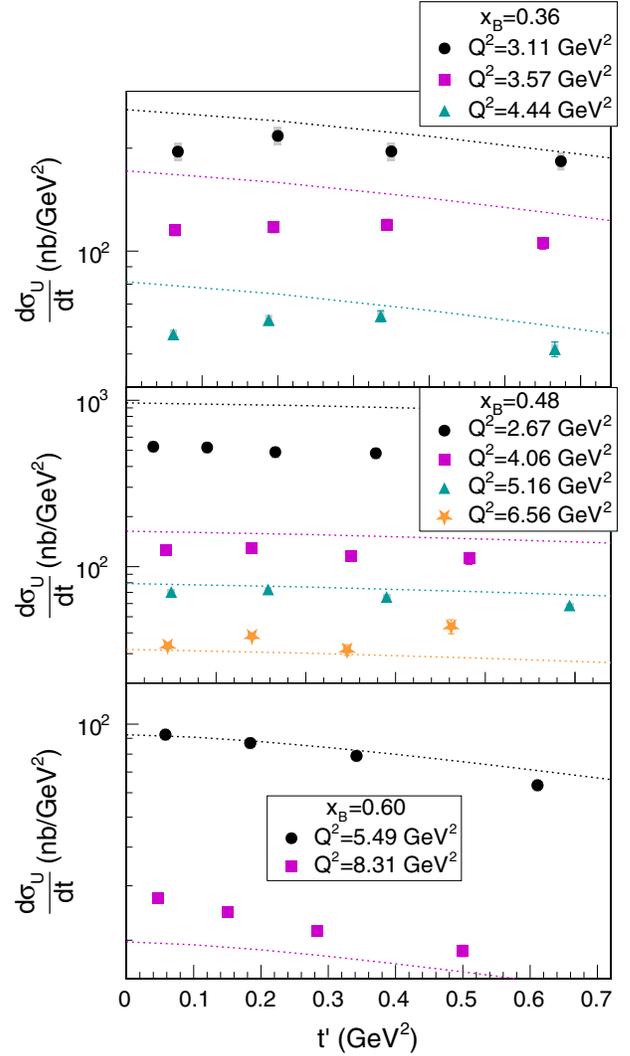


FIG. 3. Structure function $d\sigma_U = d\sigma_T + \epsilon d\sigma_L$ as a function of $t' = t_{\min} - t$ for all kinematic settings. The gray boxes surrounding the data points show the systematic uncertainty. The dashed curves are calculations which include (and are dominated by) transversity GPDs of the nucleon [15].

Q^{-7}) than the dependence observed in the data. This suggests a more significant longitudinal component in the data than in the model, which is also compatible with the significantly larger values $d\sigma_{LT}$ shown in Fig. 2. The bottom panel in Fig. 4 shows the Q^2 dependence of $d\sigma_{TT}$ which is also incompatible with the asymptotic limit $\sim Q^{-8}$.

Figure 4 also shows the comparison with the previous available data at lower Q^2 and illustrates the much higher reach of these new measurements to best constrain the Q^2 dependence of the cross section, and for different values of x_B . These data also reach large values of $t = t_{\min} - t'$, with the central value of $-t$ up to 1.3 GeV^2 . The t dependence of the cross section, often parametrized by Regge-like profile functions, is no longer valid at typical values of $-t > 1 \text{ GeV}^2$. This was realized in the GPD analysis of

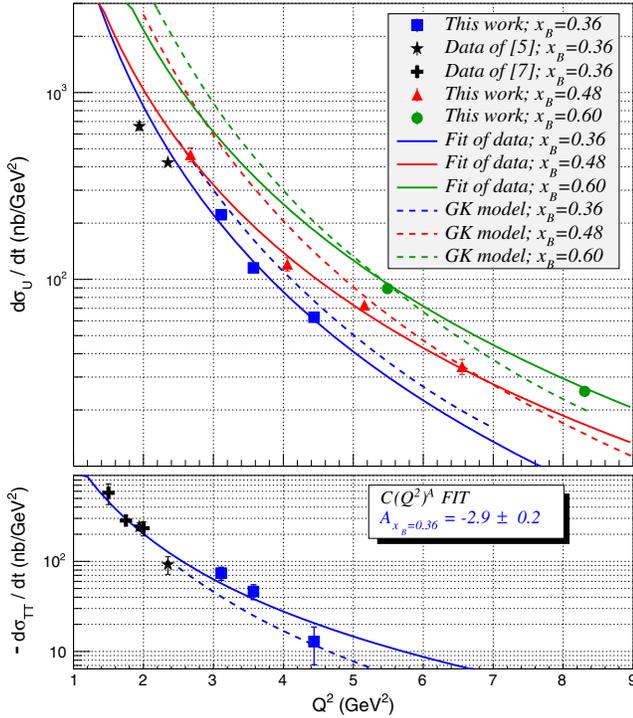


FIG. 4. The Q^2 dependence of the structure functions $d\sigma_U$ and $-d\sigma_{TT}$ at $\langle t' \rangle = 0.1 \text{ GeV}^2$. The closed markers are the experimental results, the solid curves are the fitted functions, and the dotted curves are the predictions of [15]. The bars on the closed markers show their statistical and systematic uncertainties added in quadrature. The $d\sigma_U$ and $-d\sigma_{TT}$ from this experiment and the corresponding curves at the settings $x_B = 0.36, 0.48$, and 0.60 are shown in blue, red, and green, respectively. The black stars and crosses show the results from [7] and [10] correspondingly, which are also included in the fit at $x_B = 0.36$.

nucleon form factors [28]. The theory calculations shown herein include a profile function with a strong $x \otimes t$ correlation [29], which also allows the proton radius to remain finite as $x \rightarrow 1$ and allows the proton form factors—the lowest moments of GPDs—to behave as powers of t at large $-t$. One must point out, though, that these calculations are obtained using some kinematic approximations, such as $\xi \approx x_B/(2 - x_B)$. Recent theory developments [30] have shown that power corrections of $\mathcal{O}(t/Q^2)$ and $\mathcal{O}(M_p/Q^2)$ should be included and recent

TABLE II. Combined (Q^2, t') fits $d\sigma_U = C(Q^2)^A \exp(-Bt')$ at each x_B setting. Only the data of this publication are included. The fits and error bars are based on the statistical and systematic uncertainties of the data, added in quadrature.

x_B	$C \mu\text{b}/\text{GeV}^2$	A	$B \text{ GeV}^{-2}$	χ^2 Total	$N_{\text{d.o.f.}}$
0.36	8.6 ± 1.4	-3.3 ± 0.1	0.34 ± 0.17	18.	9
0.48	8.3 ± 0.9	-2.9 ± 0.1	0.69 ± 0.3	27.	13
0.60	$20. \pm 4.$	-3.1 ± 0.1	0.75 ± 0.1	1.6	5

DVCS data [31] at similar kinematics have been proved sensitive to these effects.

The longitudinal to transverse ratio R of exclusive ρ^0 electroproduction was measured at HERA over the range of Q^2 from $\leq 1 \text{ GeV}^2$ to $\geq 20 \text{ GeV}^2$ [32,33]. Over this kinematic range, R rises from ≈ 1 to ≈ 5 as Q^2 increases. Thus even at $Q^2 \sim 20 \text{ GeV}^2$ the transverse cross section in deep virtual exclusive ρ production is not negligible. The role of the pion as the Goldstone boson of chiral symmetry breaking predicts a much smaller value of R for exclusive π^0 production for Q^2 in the range of 1 to 3 GeV^2 [14–16]. Nonetheless we expect a gradual transition to dominance of σ_L in π^0 electroproduction as Q^2 increases. Observing this transition is crucial to disentangling the contributions of quark helicity-flip and helicity-conserving amplitudes. The present data demonstrate slower than asymptotic Q^2 dependence and also provide initial evidence for the interference of quark helicity-flip and helicity-conserving amplitudes in $d\sigma_{LT}$. An L/T separation of the π^0 electroproduction cross section at these high values of x_B will provide a definite answer on the size of the longitudinal contribution. This is the goal of an upcoming experiment [34] in Hall C at Jefferson Lab which is expected to run within the next two years.

We thank P. Kroll and S. Liuti, for very fruitful discussions about these results. We acknowledge essential contributions by the Hall A collaboration and Accelerator and Physics Division staff at Jefferson Lab. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-AC05-06OR23177. This work was also supported a DOE Early Career Award to S. Covrig Dusa for the development of high power hydrogen target cells, the National Science Foundation (NSF), the French CNRS/IN2P3, ANR, and P2IO Laboratory of Excellence, and the Natural Sciences and Engineering Research Council of Canada (NSERC).

* rochej@ohio.edu

- [1] X. Ji, Gauge Invariant Decomposition of Nucleon Spin, *Phys. Rev. Lett.* **78**, 610 (1997).
- [2] D. Müller, D. Robaschik, B. Geyer, F. M. Dittes, and J. Horejsi, Wave functions, evolution equations and evolution kernels from light-ray operators of QCD, *Fortschr. Phys.* **42**, 101 (1994).
- [3] A. V. Radyushkin, Nonforward parton distributions, *Phys. Rev. D* **56**, 5524 (1997).
- [4] J. C. Collins, L. Frankfurt, and M. Strikman, Factorization for hard exclusive electroproduction of mesons in QCD, *Phys. Rev. D* **56**, 2982 (1997).
- [5] G. P. Lepage and S. J. Brodsky, Exclusive processes in perturbative quantum chromodynamics, *Phys. Rev. D* **22**, 2157 (1980).

- [6] R. Masi *et al.*, Measurement of $ep \rightarrow ep\pi^0$ beam spin asymmetries above the resonance region, *Phys. Rev. C* **77**, 042201 (2008).
- [7] E. Fuchey *et al.*, Exclusive neutral pion electroproduction in the deeply virtual regime, *Phys. Rev. C* **83**, 025201 (2011).
- [8] I. Bedlinskiy *et al.* (CLAS Collaboration), Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transversity GPDs, *Phys. Rev. Lett.* **109**, 112001 (2012).
- [9] I. Bedlinskiy *et al.* (CLAS Collaboration), Exclusive π^0 electroproduction at $W > 2$ GeV with CLAS, *Phys. Rev. C* **90**, 025205 (2014).
- [10] M. Defurne *et al.* (Jefferson Lab Hall A Collaboration), Rosenbluth Separation of the π^0 Electroproduction Cross Section, *Phys. Rev. Lett.* **117**, 262001 (2016).
- [11] M. Mazouz *et al.* (Jefferson Lab Hall A Collaboration), Rosenbluth Separation of the π^0 Electroproduction Cross Section off the Neutron, *Phys. Rev. Lett.* **118**, 222002 (2017).
- [12] A. Kim *et al.*, Target and double spin asymmetries of deeply virtual π^0 production with a longitudinally polarized proton target and CLAS, *Phys. Lett. B* **768**, 168 (2017).
- [13] M. Alexeev *et al.* (COMPASS Collaboration), Measurement of the cross section for hard exclusive π^0 muoproduction on the proton, *Phys. Lett. B* **805**, 135454 (2020).
- [14] S. Ahmad, G. R. Goldstein, and S. Liuti, Nucleon tensor charge from exclusive π^0 electroproduction, *Phys. Rev. D* **79**, 054014 (2009).
- [15] S. V. Goloskokov and P. Kroll, Transversity in hard exclusive electroproduction of pseudoscalar mesons, *Eur. Phys. J. A* **47**, 112 (2011), and private communication.
- [16] G. R. Goldstein, J. O. G. Hernandez, and S. Liuti, Easy as π^0 : On the interpretation of recent electroproduction results, *J. Phys. G* **39**, 115001 (2012).
- [17] D. Drechsel and L. Tiator, Threshold pion photoproduction on nucleons, *J. Phys. G* **18**, 449 (1992).
- [18] A. Bacchetta, U. D'Alesio, M. Diehl, and C. A. Miller, Single-spin asymmetries: The trento conventions, *Phys. Rev. D* **70**, 117504 (2004).
- [19] L. N. Hand, Experimental investigation of pion electroproduction, *Phys. Rev.* **129**, 1834 (1963).
- [20] J. Alcorn *et al.*, Basic Instrumentation for Hall A at Jefferson Lab, *Nucl. Instrum. Methods Phys. Res., Sect. A* **522**, 294 (2004).
- [21] F. Feinstein (ANTARES Collaboration), The analogue ring sampler: A front-end chip for ANTARES, *Nucl. Instrum. Methods Phys. Res., Sect. A* **504**, 258 (2003).
- [22] F. Druillolle, D. Lachartre, F. Feinstein, E. Delagnes, H. Lafoux, C. Hadamache, and J. Fopma (ANTARES Collaboration), The analog ring sampler: An ASIC for the front-end electronics of the ANTARES neutrino telescope, in *Nuclear Science. Proceedings, Symposium, NSS 2001, San Diego, USA, 2001*; *IEEE Trans. Nucl. Sci.* **49**, 1122 (2002).
- [23] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.127.152301> for a more detailed description of the practical aspects of this experiment, for an example of the comparison of the reconstructed $h(e, e'\pi^0)x$ missing mass with the simulation one, for a description of the radiative correction approach, and for an example of the fit of the data and for the numerical values of the extracted structure functions, which includes references to [7,20–22,24–26].
- [24] M. Vanderhaeghen, J. M. Friedrich, D. Lhuillier, D. Marchand, L. Van Hoorebeke, and J. Van de Wiele, QED radiative corrections to virtual Compton scattering, *Phys. Rev. C* **62**, 025501 (2000).
- [25] M. Defurne *et al.* (Jefferson Lab Hall A Collaboration), E00-110 experiment at Jefferson Lab Hall A: Deeply virtual Compton scattering off the proton at 6 GeV, *Phys. Rev. C* **92**, 055202 (2015).
- [26] M. E. Christy and P. E. Bosted, Empirical fit to precision inclusive electron-proton cross-sections in the resonance region, *Phys. Rev. C* **81**, 055213 (2010).
- [27] S. Agostinelli and others (GEANT4 Collaboration), GEANT4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [28] M. Diehl and P. Kroll, Nucleon form factors, generalized parton distributions and quark angular momentum, *Eur. Phys. J. C* **73**, 2397 (2013).
- [29] P. Kroll, The GPD \tilde{H} and spin correlations in wide-angle Compton scattering, *Eur. Phys. J. A* **53**, 130 (2017).
- [30] V. M. Braun, A. N. Manashov, D. Müller, and B. M. Pirnay, Deeply virtual Compton scattering to the twist-four accuracy: Impact of finite- t and target mass corrections, *Phys. Rev. D* **89**, 074022 (2014).
- [31] M. Defurne *et al.*, A glimpse of gluons through deeply virtual Compton scattering on the proton, *Nat. Commun.* **8**, 1408 (2017).
- [32] S. Chekanov *et al.* (ZEUS Collaboration), Exclusive rho0 production in deep inelastic scattering at HERA, *PMC Phys. A* **1**, 6 (2007).
- [33] F. D. Aaron *et al.* (H1 Collaboration), Inclusive photoproduction of ρ^0 , K^{*0} and ϕ mesons at HERA, *Phys. Lett. B* **673**, 119 (2009).
- [34] C. E. Hyde, C. Muñoz Camacho, J. Roche *et al.*, *Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C*, Proposal E12-13-010 (Jefferson Lab, 2013), https://www.jlab.org/exp_prog/proposals/13/PR12-13-010.pdf.