

# Deep Exclusive Electroproduction of $\pi^0$ at High $Q^2$ in the Quark Valence Regime

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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 GeV<sup>2</sup>) obtained from Jefferson Lab Hall A experiment E12-06-014. The corresponding structure functions  $d\sigma_T/dt + \epsilon d\sigma_L/dt$ ,  $d\sigma_{TT}/dt$ ,  $d\sigma_{LT}/dt$ , 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.

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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  $\pi^0$  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

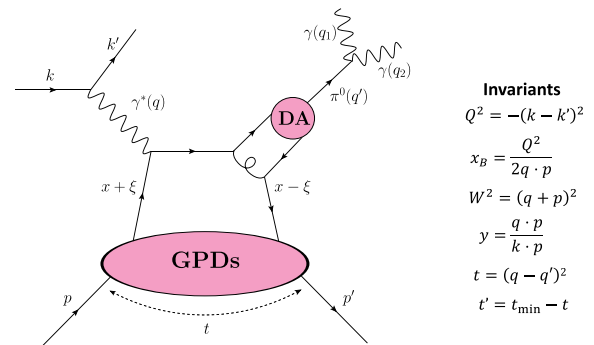


FIG. 1. Leading twist diagram representing the pseudoscalar DVMP to the  $\gamma\gamma$  channel. The net four-momentum transferred to the proton is  $t$ , whose minimum value  $t_{\min}$  occurs when the  $\pi^0$  meson is emitted parallel to the virtual photon. The average light cone momentum fraction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

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  $\pi^0$  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  $\pi^0$  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  $\pi^0$  electroproduction cross sections that extend to higher values of  $Q^2$  (from 3.1 to 8.4 GeV<sup>2</sup>) 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

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

where  $h(\pm 1)$  is the helicity of the initial lepton,  $E$  is the incident beam energy and  $\phi$  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  $\epsilon$  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  $\pi^0$  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  $2 \times 10^{-4}$  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  $13 \times 16$  array of PbF<sub>2</sub> 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,  $e'_{\text{Calo}}$   $p_{\text{HRS}}$ ) 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 PbF<sub>2</sub> 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  $\pi^0$  cross sections are reported. For each setting, cross sections are measured as a function of  $t' = t_{\min} - t$ , 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 <sup>2</sup> )	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31
$W^2$ (GeV <sup>2</sup> )	6.51	7.29	8.79	3.81	5.62	6.67	8.32	4.58	6.46
$-t_{\min}$ (GeV <sup>2</sup> )	0.16	0.17	0.17	0.33	0.35	0.35	0.36	0.67	0.71
$\epsilon$	0.61	0.62	0.63	0.51	0.71	0.55	0.52	0.66	0.50

reconstructed invariant mass of the detected  $\pi^0$  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  $\pi^0$  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  $12\phi$  bins by  $5t'$  bins. The different structure functions appearing in the  $\pi^0$  electroproduction cross section were extracted by exploiting their specific  $\phi$  dependencies, minimizing the  $\chi^2$  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  $12 \times 5$  bins for each  $(x_B, Q^2)$  setting.  $N_i^{\text{exp}}$  is the total number of events in bin  $i$  with corresponding statistical precision  $\sigma_i^{\text{exp}}$ . 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  $\chi^2$  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

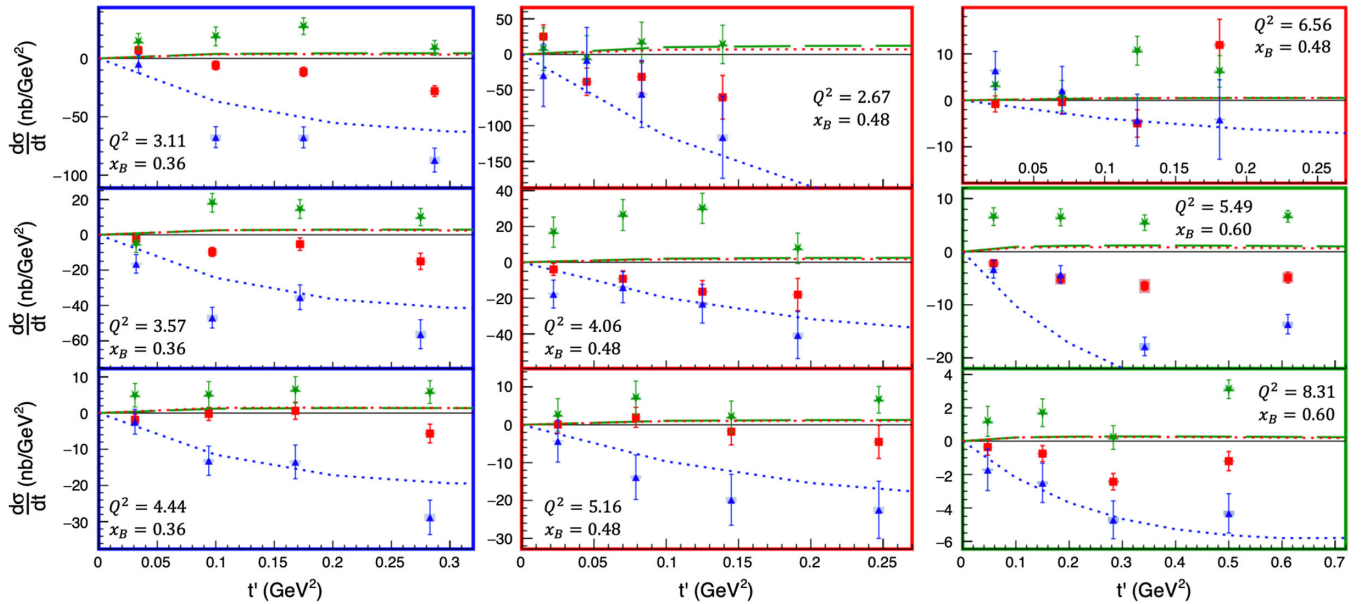


FIG. 2. Structure functions  $d\sigma_{TT}$  (blue triangles),  $d\sigma_{LT}$  (red squares), and  $d\sigma_{LT'}$  (green stars) for all kinematic setting as a function of  $t' = t_{\min} - t$ . The dashed curves are calculations based on transversity GPDs of the nucleon [15]. The gray boxes surrounding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

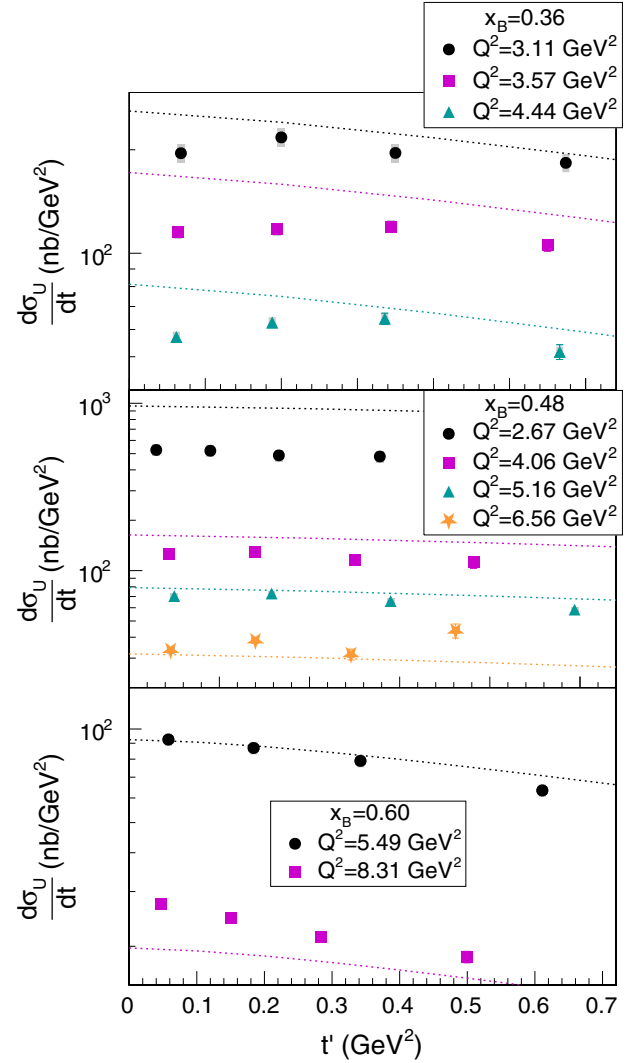


FIG. 3. Structure function  $d\sigma_U = d\sigma_T + \epsilon d\sigma_L$  as a function of  $t' = t_{\min} - t$  for all kinematic settings. The gray boxes surrounding the data points show the systematic uncertainty. The dashed curves are calculations which include (and are dominated by) transversity 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  $1.3 \text{ GeV}^2$ . 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

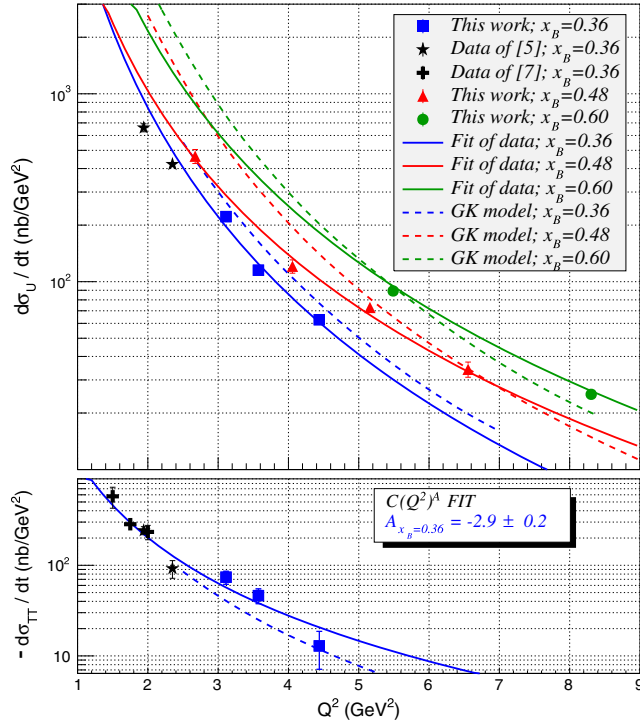


FIG. 4. The  $Q^2$  dependence of the structure functions  $d\sigma_U$  and  $-d\sigma_{TT}$  at  $\langle t' \rangle = 0.1 \text{ GeV}^2$ . The closed markers are the experimental results, the solid curves are the fitted functions, and the dotted curves are the predictions of [15]. The bars on the closed 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.

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

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

The longitudinal to transverse ratio  $R$  of exclusive  $\rho^0$  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  $\approx 1$  to  $\approx 5$  as  $Q^2$  increases. Thus even at  $Q^2 \sim 20 \text{ GeV}^2$  the transverse cross section in deep virtual exclusive  $\rho$  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  $\pi^0$  production for  $Q^2$  in the range of 1 to 3  $\text{GeV}^2$  [14–16]. Nonetheless we expect a gradual transition to dominance of  $\sigma_L$  in  $\pi^0$  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  $\pi^0$  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.

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