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# Exclusive $\eta$ electroproduction at $W > 2$ GeV with CLAS and Transversity GPDs

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The cross section of the exclusive  $\eta$  electroproduction reaction  $ep \rightarrow e'p'\eta$  was measured at Jefferson Lab with a 5.75-GeV electron beam and the CLAS detector. Differential cross sections  $d^4\sigma/dtdQ^2dx_Bd\phi_\eta$  and structure functions  $\sigma_U = \sigma_T + \epsilon\sigma_L, \sigma_{TT}$  and  $\sigma_{LT}$ , as functions of  $t$  were obtained over a wide range of  $Q^2$  and  $x_B$ . The  $\eta$  structure functions are compared with those of previously measured for  $\pi^0$  at the same kinematics. At low  $t$ , both  $\pi^0$  and  $\eta$  are described reasonably well by Generalized Parton Distributions (GPDs) in which chiral-odd transversity GPDs are dominant. The  $\pi^0$  and  $\eta$  data, when taken together, can facilitate the flavor decomposition of the transversity GPDs.

## I. INTRODUCTION

Understanding nucleon structure in terms of the fundamental degrees of freedom of Quantum Chromodynamics (QCD) is one of the main goals in the theory of strong interactions. Exclusive reactions may provide information about the quark and gluon distributions encoded in Generalized Parton Distributions (GPDs), which are accessed via application of the handbag mechanism [1, 2]. Deeply virtual meson electroproduction (DVMP), specifically for pseudoscalar meson production, e.g.  $\eta$  and  $\pi^0$ , is shown schematically in Fig. 1.

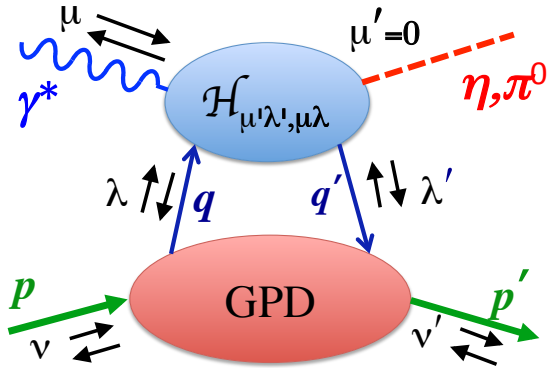


FIG. 1. The handbag diagram for deeply virtual  $\eta$  and  $\pi^0$  production. The helicities of the initial and final nucleons are denoted by  $\nu$  and  $\nu'$ , of the incident photon and produced meson by  $\mu$  and  $\mu'$  and of the active initial and final quark by  $\lambda$  and  $\lambda'$ . The arrows in the figure schematically represent the corresponding positive and negative helicities, respectively. For final-state pseudoscalar mesons  $\mu' = 0$ .

For each quark flavor there are eight leading-twist GPDs. Four correspond to parton helicity-conserving (chiral-even) processes, denoted by  $H^i, \tilde{H}^i, E^i$  and  $\tilde{E}^i$ , and four correspond to parton helicity-flip (chiral-odd) processes [3, 4],  $H_T^i, \tilde{H}_T^i, E_T^i$  and  $\tilde{E}_T^i$ , where  $i$  denotes quark flavor. The GPDs depend on three kinematic variables:  $x$ ,  $\xi$  and  $t$ , where  $x$  is the average longitudinal momentum fraction of the struck parton before and after the hard interaction and  $\xi$  (skewness) is half of the longitudinal momentum fraction transferred to the struck parton. Denoting  $q$  as the four-momentum transfer and  $Q^2 = -q^2$ , the skewness for light mesons of mass  $m$ , in which  $m^2/Q^2 \ll 1$ , can be expressed in terms of the Bjorken variable  $x_B$  as  $\xi \simeq x_B/(2-x_B)$ . Here  $x_B = Q^2/(2pq)$  and  $t = (p-p')^2$ , where  $p$  and  $p'$  are the initial and final four-momenta of the nucleon. Since the  $\pi^0$  and  $\eta$  have different combinations of quark flavors, it may be possible to approximately make a flavor decomposition of the GPDs for up and down quarks.

When the leading order chiral even theoretical calculations for longitudinal virtual photons were compared with the Jefferson Lab  $\pi^0$  data [5, 6] they were found to underestimate the measured cross sections by more than an order of magnitude in their accessible kinematic regions. The failure to describe the experimental results with quark helicity-conserving operators stimulated a consideration of the role of the chiral-odd quark helicity-flip processes. Pseudoscalar meson electroproduction was identified as especially sensitive to the quark helicity-flip subprocesses. During the past few years, two parallel theoretical approaches - [7, 8] (GK) and [9] (GL) - have been developed utilizing the chiral-odd GPDs in the calculation of pseudoscalar meson electroproduction. The GL and GK approaches, though employing different models of GPDs, lead to transverse photon amplitudes that are much larger than the longitudinal amplitudes. This has been recently confirmed

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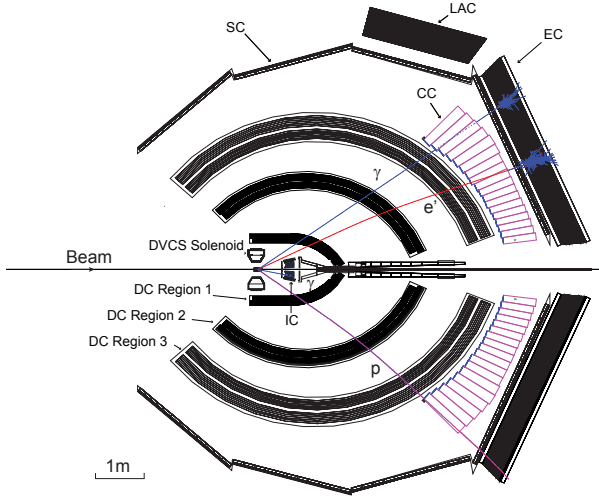


FIG. 2. (Color online) Schematic view of the CLAS detector in the plane of the beamline constructed by the Monte-Carlo simulation program GSIM. The notation is as follows: inner calorimeter (IC), electromagnetic calorimeter (EC), large angle electromagnetic calorimeter (LAC), Cherenkov counter (CC), scintillation hodoscope (SC), Drift Chambers (DC). The LAC was not used in this analysis. The tracks correspond, from top to bottom, to a photon (blue online), an electron (red online) curving toward the beam line, and a proton (purple online) curving away from the beam line.

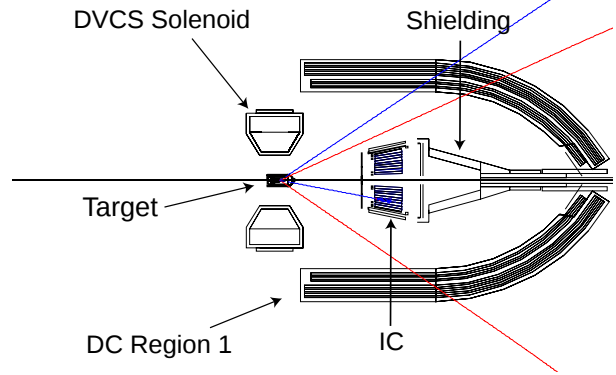


FIG. 3. (Color online) A blowup of Fig. 2 showing the CLAS target region in detail. IC is the inner calorimeter and DC Region 1 represents the drift chambers closest to the target.

1 experimentally for  $t$  near  $t_{min}$  [10].

## 2 II. EXPERIMENTAL SETUP

3 The measurements reported here were carried out 44  
4 with the CEBAF Large Acceptance Spectrometer 45  
5 (CLAS) [11] located in Hall B at Jefferson Lab. The 46  
6 data were obtained in 2005 in parallel with our pre- 47  
7 viously reported deeply virtual Compton scattering 48  
8 (DVCS) and  $\pi^0$  electroproduction experiments 49  
9 [5, 6, 12–14], sharing the same physical setup. The 50  
10 integrated luminosity corresponding to the data pre- 51  
11 sented here was  $20 \text{ fb}^{-1}$ . 52

12 The spectrometer consisted of a toroidal-like mag- 53  
13 netic field produced by six current coils symmet- 54  
14 rically arrayed around the beam axis that divided 55  
15 the detector into six sectors. The scheme of the 56  
16 CLAS detector array, as coded in the GEANT3- 57  
17 based CLAS simulation code GSIM [15], is shown 58  
18 in Fig. 2. 59

19 The data were taken using a 5.75 GeV incident 60  
20 electron beam impinging a 2.5 cm long liquid hy- 61  
21 drogen target. The electron beam was about 80% 62  
22 polarized. The sign of the beam polarization was 63  
23 changed during measurements at a frequency of 30 64  
24 Hz. We did not use beam polarization information 65  
25 in this analysis. Effectively, for this experiment the 66  
26 beam was unpolarized. The target was placed 67  
27 cm upstream of the nominal center of CLAS inside a 68

solenoid magnet to shield the detectors from Møller electrons.

Each sector was equipped with three regions of drift chambers (DC) [16] to determine the trajectory of charged particles, gas threshold Cherenkov counters (CC) [17] for electron identification, a scintillation hodoscope [18] for time-of-flight (TOF) measurements of charged particles, and an electromagnetic calorimeter (EC) [19] that was used for electron identification as well as detection of neutral particles. To detect photons at small polar angles (from  $4.5^\circ$  up to  $15^\circ$ ) an inner calorimeter (IC) was added to the standard CLAS configuration, 55 cm downstream from the target. The IC consisted of 424  $\text{PbWO}_4$  tapered crystals whose orientations were projected approximately toward the target. Figure 3 zooms in on the target area of Fig. 2 to better illustrate the deployment of the IC and solenoid relative to the target.

The toroidal magnet was operated at a current corresponding to an integral magnetic field of about 1.36 T-m in the forward direction. The magnet polarity was set such that negatively charged particles were bent inward towards the electron beam line. The scattered electrons were detected in the CC and EC, which extended from  $21^\circ$  to  $45^\circ$ . The lower angle limit was defined by the IC calorimeter, which was located just after the target.

A Faraday cup was used for the integrated charge measurement with 1% accuracy. It was composed of 4000 kg of lead, which corresponds to 75 radiation lengths, and was located 29 m downstream of the target.

In the experiment, all four final state particles of the reaction  $ep \rightarrow e'p'\eta$ ,  $\eta \rightarrow \gamma\gamma$  were detected. The kinematic coverage for this reaction is shown in Fig. 4, and for the individual kinematic variables in Fig. 5. For the purpose of physics analysis an additional cut on  $W > 2 \text{ GeV}$  was applied as well, where  $W$  is the  $\gamma^*p$  center-of-mass energy.

The basic configuration of the trigger included the

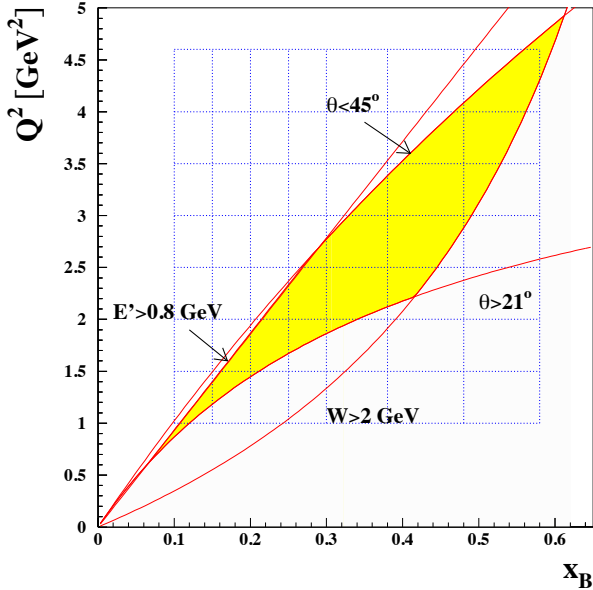


FIG. 4. (Color online) The kinematic coverage and binning as a function of  $Q^2$  and  $x_B$ . The accepted region (yellow online) is determined by the following cuts:  $W > 2$  GeV,  $E' > 0.8$  GeV,  $21^\circ < \theta < 45^\circ$ .  $W$  is the  $\gamma^*p$  center-of-mass energy,  $E'$  is the scattered electron energy and  $\theta$  is the electron's polar angle in the lab frame. The accepted yellow region within each grid boundary represents the kinematic regions for which the cross sections are calculated and presented.

1 coincidence between signals from the CC and the EC  
 2 in the same sector, with a threshold  $\sim 500$  MeV.  
 3 This was the general trigger for all experiments in  
 4 this run period. This threshold is far from the  
 5 kinematic limit of this experiment -  $E' > 0.8$  GeV  
 6 (see Fig.4). The accepted region (yellow online) for  
 7 this experiment is determined by the following cuts:  
 8  $W > 2$  GeV,  $E' > 0.8$  GeV,  $21^\circ < \theta < 45^\circ$ . Out  
 9 of a total of about  $7 \times 10^9$  recorded events, about  
 10  $20 \times 10^3$ , in 1200 kinematic bins in  $Q^2$ ,  $t$ ,  $x_B$  and  $\phi_\eta$ ,  
 11 for the reaction  $ep \rightarrow e'p'\eta$ , were finally retained.  
 12 The variable  $\phi_\eta$  is the azimuthal angle of the emit-  
 13 ted  $\eta$  relative to the electron scattering plane.

### 14 III. PARTICLE IDENTIFICATION

#### 15 A. Electron identification

16 An electron was identified by requiring the track  
 17 of a negatively charged particle in the DCs to be  
 18 matched in space with hits in the CC, the SC and  
 19 the EC. This electron selection effectively suppresses  
 20  $\pi^-$  contamination up to momenta  $\sim 2.5$  GeV, which  
 21 is approximately the threshold for Cherenkov radi-  
 22 ation of the  $\pi^-$  in the CC. Additional requirements  
 23 were used in the offline analysis to refine electron  
 24 identification and to suppress the remaining pions.

25 Energy deposition cuts on the electron signal in  
 26 the EC also play an important role in suppress-  
 27 ing the pion background. An electron propagat-  
 28 ing through the calorimeter produces an electromag-  
 29 netic shower and deposits a large fraction of its en-  
 30 ergy in the calorimeter proportional to its momen-  
 31 tum, while pions typically lose a smaller fraction of  
 32 their energy, primarily by ionization.

33 The distribution of the number of the photoelec-  
 34 trons in the CC after all selection criteria were ap-  
 35 plied is shown in Fig. 6. The residual small shoulder  
 36 around  $N_{phe} = 1$  represents the pion contamination,  
 37 which is seen to be negligibly small after applying  
 38 all selection criteria.

39 The charged particle tracks were reconstructed by  
 40 the drift chambers. The vertex location was calcul-  
 41 ated by the intersection of the track with the beam  
 42 line. A cut was applied on the  $z$ -component of the  
 43 electron vertex position to eliminate events originat-  
 44 ing outside the target. The vertex distribution and  
 45 cuts for one of the sectors are shown in Fig. 7. The  
 46 left plot shows the  $z$ -coordinate distribution before  
 47 the exclusivity cuts, which are described below in  
 48 Section IV B, and the right plot is the distribution  
 49 after the exclusivity cuts. The peak at  $z = -62.5$  cm  
 50 exhibits the interaction of the beam with an insulat-  
 51 ing foil, which is completely removed after the ap-  
 52 plication of the exclusivity cuts, demonstrating that  
 53 these cuts very effectively exclude the interactions  
 54 involving nuclei of the surrounding non-target ma-  
 55 terial.

#### 56 B. Proton identification

57 The proton was identified as a positively charged  
 58 particle with the correct time-of-flight. The quan-  
 59 tity of interest ( $\delta t = t_{SC} - t_{exp}$ ) is the difference  
 60 in the time between the measured flight time from  
 61 the event vertex to the SC system ( $t_{SC}$ ) and that  
 62 expected for the proton ( $t_{exp}$ ). The quantity  $t_{exp}$   
 63 was computed from the velocity of the particle and  
 64 the track length. The velocity was determined from  
 65 the momentum assuming the mass of the particle  
 66 equals that of a proton. A cut at the level of  $\pm 5\sigma_t$   
 67 was applied around  $\delta t = 0$ , where  $\sigma_t$  is the time-  
 68 of-flight resolution, which is momentum dependent.  
 69 This wide cut was possible because the exclusivity  
 70 cuts (see Section IV B below) very effectively sup-  
 71 pressed the remaining pion contamination.

#### 72 C. Photon identification

Photons were detected in both calorimeters, the  
 EC and IC. In the EC, photons were identified as  
 neutral particles with  $\beta > 0.8$  and  $E > 0.35$  GeV.  
 Fiducial cuts were applied to avoid the EC edges.  
 When a photon hits the boundary of the calorimeter,  
 the energy cannot be fully reconstructed due to the

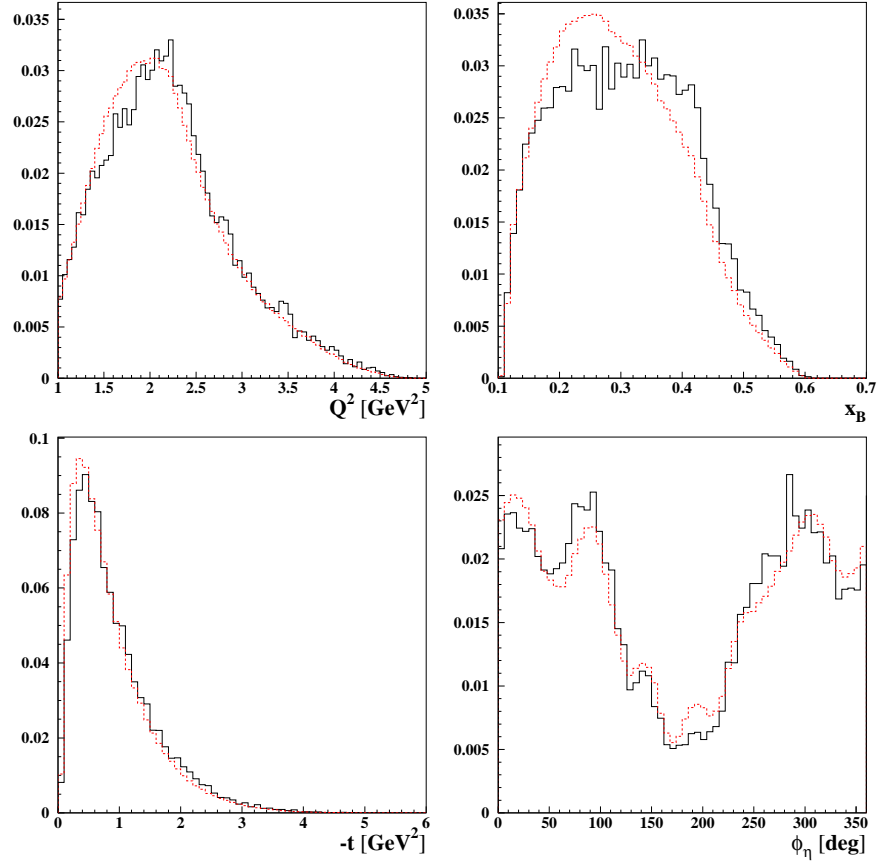


FIG. 5. (Color online) Yield distributions for kinematic variables  $Q^2$ ,  $x_B$ ,  $-t$  and  $\phi_\eta$  in arbitrary units. The data are in black (solid) and the results of Monte Carlo simulations (see Sec. VI) are in red (dotted). The areas under the curves are normalized to each other. The curves for both the data and Monte Carlo simulations are the final distributions obtained after tracking and include acceptances and efficiencies.

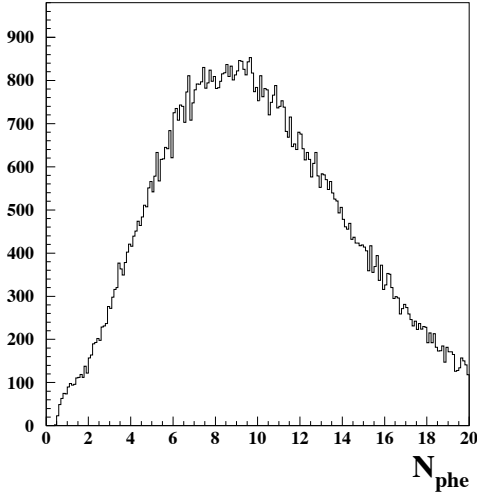


FIG. 6. The number of CC photoelectrons for events 20 that pass all cuts.

1 leakage of the shower out of the detector. Additional 23  
 2 fiducial cuts on the EC were applied to account for 24  
 3 the shadow of the IC (see Fig. 2). The calibration 25  
 4 of the EC was done using cosmic muons and the 26

5 photons from neutral pion decay ( $\pi^0 \rightarrow \gamma\gamma$ ).

6 In the IC, each detected cluster was considered a  
 7 photon. The assumption was made that this pho-  
 8 ton originated from the electron vertex. Additional  
 9 geometric cuts were applied to remove low-energy  
 10 clusters around the beam axis and photons near the  
 11 edges of the IC, where the energies of the photons  
 12 were incorrectly reconstructed due to the electro-  
 13 magnetic shower leakage. The photons from  $\eta \rightarrow \gamma\gamma$   
 14 decays were detected in the IC in an angular range  
 15 between  $5^\circ$  and  $17^\circ$  and in the EC for angles greater  
 16 than  $21^\circ$ . The reconstructed invariant mass of two-  
 17 photon events was then subjected to various cuts  
 18 to isolate exclusive  $\eta$  events, with a residual back-  
 19 ground, as discussed in Section IV B below.

#### D. Kinematic corrections

21 Ionization energy-loss corrections were applied to  
 22 protons and electrons in both data and Monte-  
 Carlo events. These corrections were estimated us-  
 ing the GSIM Monte Carlo program. Due to im-  
 perfect knowledge of the properties of the CLAS de-  
 tector, such as the magnetic field distribution and



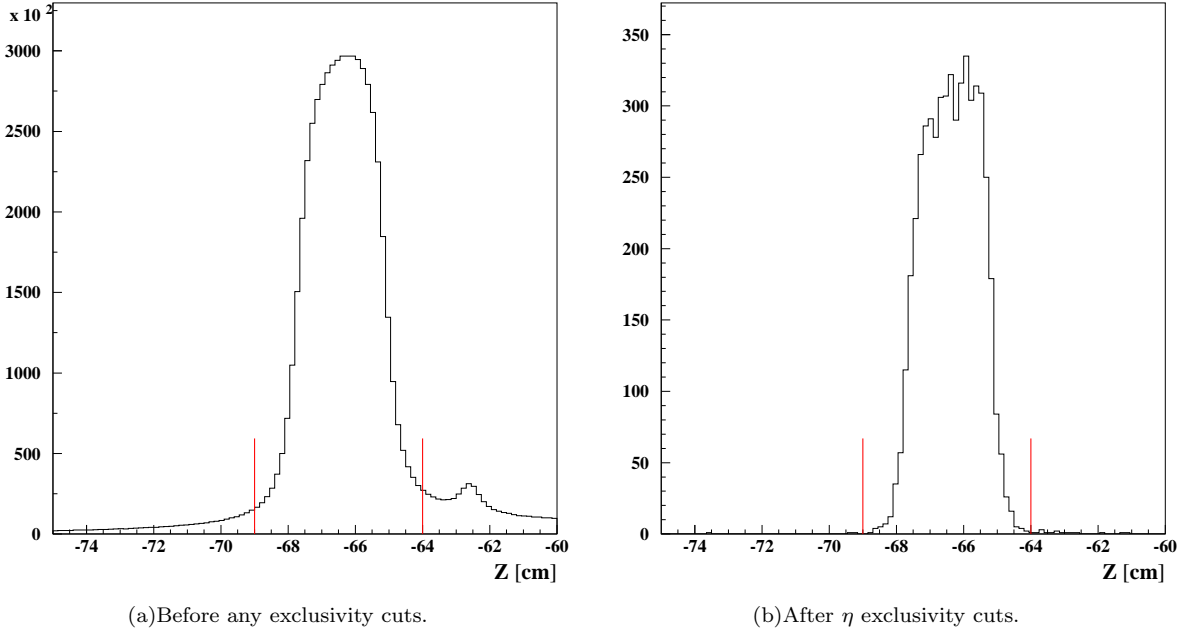


FIG. 7. The  $z$ -coordinate of the electron vertex. The vertical lines are the positions of the applied cuts. Note in (a) the small peak to the right of the target that is due to a foil placed at  $z = -62.5$  cm downstream of the target window. In (b) the peak due to the foil disappears after the selection of the exclusive reaction.

1 the precise placement of the components or detec- 28  
 2 tor materials, small empirical sector-dependent cor-  
 3 rections had to be made on the momenta and angles  
 4 of the detected electrons and protons. The cor-  
 5 rections were determined by systematically study-  
 6 ing the kinematics of the particles emitted from  
 7 well understood kinematically-complete processes,  
 8 e.g. elastic electron scattering. These corrections  
 9 were on the order of 1%.

#### 10 IV. EVENT SELECTION

##### 11 A. Fiducial cuts

12 Certain areas of the detector acceptance were not  
 13 efficient due to gaps in the DC, problematic SC  
 14 counters, and inefficient zones of the CC and the EC.  
 15 These areas were removed from the analysis as well  
 16 as from the simulation by means of geometrical cuts,  
 17 which were momentum, polar angle and azimuthal  
 18 angle dependent.

19 In addition, we excluded events, when a photon  
 20 from the  $\eta$ -decay or Bremsstrahlungs photon was  
 21 detected in the same sector as the electron. This  
 22 avoids additional photons which are close in space  
 23 to the scattered lepton leaving a signal in the EC  
 24 close to where the supposed lepton hits the EC. This  
 25 was done for both the experimental data as well as  
 26 the Monte Carlo data used for correcting experimental  
 27 yields.

##### B. Exclusivity cuts

To select the exclusive reaction  $ep \rightarrow e'p'\eta$ , each event was required to contain an electron, one proton and at least two photons in the final state. Then, so called *exclusivity cuts* were applied to all combinations of an electron, a proton and two photons to ensure energy and momentum conservation, thus eliminating events in which there were any additional undetected particles.

Four cuts were used for the exclusive event selection

- $\theta_X < 2^\circ$ , where  $\theta_X$  is the angle between the reconstructed  $\eta$  momentum vector and the missing momentum vector for the reaction  $ep \rightarrow e'p'X$ .
- the missing mass squared  $M_x^2(e'p')$  of the  $e'p'$  system ( $ep \rightarrow e'p'X$ ), with  $|M_x^2(e'p') - M_\eta^2| < 3\sigma$ ;
- the missing mass  $M_x(e'\gamma\gamma)$  of the  $e'\gamma\gamma$  system ( $ep \rightarrow e'\gamma\gamma X$ ), with  $|M_x(e'\gamma\gamma) - M_p| < 3\sigma$ ;
- the missing energy  $E_x(e'p'\eta)$  ( $ep \rightarrow e'p'\gamma\gamma X$ ), with  $|E_x(e'p'\eta) - 0| < 3\sigma$ ;

Here  $\sigma$  is the observed experimental resolution obtained as the standard deviation from the mean value of the distributions of each quantity. Three sets of resolutions were determined independently for each of the three photon-detection topologies (IC-IC, IC-EC, EC-EC). The invariant mass  $M_{\gamma\gamma}$  for the two detected photons, where both photons

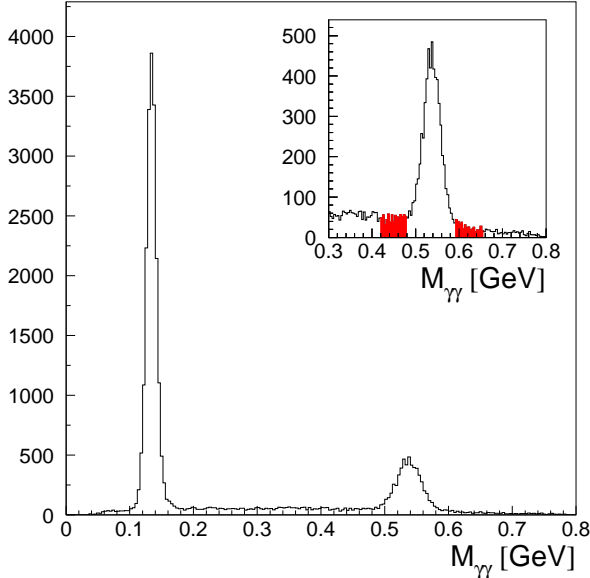


FIG. 8. (Color online) The two-photon invariant mass distribution,  $M_{\gamma\gamma}$ , after all exclusivity cuts have been applied, for the case where the two photons are detected by the IC. The large peak at lower  $M_{\gamma\gamma}$  is due to  $\pi^0$  electroproduction and the smaller peak at higher  $M_{\gamma\gamma}$  is due to  $\eta$  electroproduction. The inset shows the region around the  $\eta$  peak magnified. The filled regions above and below the peak (red online) are the sidebands that are used for background subtraction, as discussed in the text.

were detected in the IC, after these cuts is shown in Fig. 8. The two peaks correspond to  $\pi^0$  and  $\eta$  production, with the  $\pi^0$  production exhibiting a significantly larger cross section than  $\eta$  production. The distributions were generally broader than in the Monte Carlo simulations so that the cuts for the data were typically broader than those used for the Monte Carlo simulations. Similar results were obtained for the topology in which one photon was detected in the IC and one in the EC, as well as the case where both photons were detected in the EC.

### C. Background subtraction

The  $M_{\gamma\gamma}$  distribution contains background under the  $\eta$  peak even after the application of all exclusivity cuts shown in the insert of Fig. 8. The background under the  $\eta$  invariant mass peak was subtracted for each kinematic bin. It was found that most of the background comes from the production of  $\pi^0$  meson, together with the detection of only one decay photon with an accidental photon signal in the electromagnetic calorimeter. Thus, the background was subtracted using the following procedure. All  $\pi^0$  events which were in coincidence with accidental photons were identified. Then, the distributions of the invariant masses of one of the  $\pi^0$  de-

TABLE I.  $Q^2$  bins

Bin Number	Lower Limit (GeV <sup>2</sup> )	Upper limit (GeV <sup>2</sup> )
1	1.0	1.5
2	1.5	2.0
3	2.0	2.5
4	2.5	3.0
5	3.0	3.5
6	3.5	4.0
7	4.0	4.6

TABLE II.  $x_B$  bins

Bin Number	Lower Limit	Upper limit
1	0.10	0.15
2	0.15	0.20
3	0.20	0.25
4	0.25	0.30
5	0.30	0.38
6	0.38	0.48
7	0.48	0.58

TABLE III.  $|t|$  bins

Bin Number	Lower Limit (GeV <sup>2</sup> )	Upper limit (GeV <sup>2</sup> )
1	0.09	0.15
2	0.15	0.20
3	0.20	0.30
4	0.30	0.40
5	0.40	0.60
6	0.60	1.00
7	1.00	1.50
8	1.50	2.00

25 cay photons with the accidentals were obtained, and normalized with respect to the side bands around the  $\eta$  mass. The sidebands were determined as  $(-6\sigma, -3\sigma) \cup (3\sigma, 6\sigma)$  in the  $M_{\gamma\gamma}$  distributions, as shown in Fig. 8.

The resulting events in the region between side bands were then subtracted as the background contamination. The mean ratio of background to peak over all kinematic bins and all combinations of IC and EC is about 25%.

### D. Kinematic binning

The kinematics of the reaction are defined by four variables:  $Q^2$ ,  $x_B$ ,  $t$  and  $\phi_\eta$ . In order to obtain differential cross sections the data were divided into four-dimensional rectangular bins in these variables. There are 7 bins in  $x_B$ , 7 bins in  $Q^2$  as shown in Tables I–II and in Fig. 4. For each  $Q^2$ - $x_B$  bin there are nominally 8 bins in  $t$  (Table III), but the actual number is determined by the kinematic acceptance in  $t$  for each  $Q^2$ - $x_B$  bin, as well as the available statistics. Differential cross section distributions were obtained for 20 bins in  $\phi_\eta$  for each kinematic bin in  $Q^2$ ,  $x_B$  and  $t$ .

## V. CROSS SECTIONS FOR $\gamma^*p \rightarrow \eta p'$

The four-fold differential cross section as a function of the four variables ( $Q^2, x_B, t, \phi_\eta$ ) was obtained from the expression

$$\frac{d^4\sigma_{ep \rightarrow e'p'\eta}}{dQ^2 dx_B dt d\phi_\eta} = \frac{N(Q^2, x_B, t, \phi_\eta)}{\Delta Q^2 \Delta x_B \Delta t \Delta \phi_\eta} \times \frac{1}{\mathcal{L}_{int} \epsilon_{ACC} \delta_{RC} \delta_{Norm} Br(\eta \rightarrow \gamma\gamma)}. \quad (1)$$

The definitions of the quantities in Eq. 1 are:

- $N(Q^2, x_B, t, \phi_\eta)$  is the number of  $ep \rightarrow e'p'\eta$  events in a given ( $Q^2, x_B, t, \phi_\eta$ ) bin;
- $\Delta Q^2 \Delta x_B \Delta t \Delta \phi_\eta$  is the corresponding 4-dimensional bin volume. The accepted kinematic bin volumes in  $Q^2, x_B, t$ , and  $\phi_\eta$  are typically smaller than the product  $\Delta Q^2 \cdot \Delta x_B \cdot \Delta t \cdot \Delta \phi_\eta$  of the 4-dimensional grid because of cuts in  $\theta_e, W$  and  $E'$  (e.g. see Fig. 4). The reported  $Q^2, x_B$  and  $t$  value for each bin is the mean value of the accepted volume assuming a constant density of events.
- $\mathcal{L}_{int}$  is the integrated luminosity (which takes into account the correction for the data-acquisition dead time);
- $\epsilon_{ACC}$  is the acceptance calculated for each bin ( $Q^2, x_B, t, \phi_\eta$ ) (see Sec. VI);
- $\delta_{RC}$  is the correction factor due to the radiative effects calculated for each ( $Q^2, x_B, t, \phi_\eta$ ) bin (see Sec. VII);
- $\delta_{Norm}$  is the overall absolute normalization factor calculated from the elastic cross section measured in the same experiment (see Sec. VIII);
- $Br(\eta \rightarrow \gamma\gamma) = \frac{\Gamma(\eta \rightarrow \gamma\gamma)}{\Gamma_{total}} = 0.394$  [20] is the branching ratio for the  $\eta \rightarrow \gamma\gamma$  decay mode.

The reduced or “virtual photon” cross sections were extracted from the four-fold cross section (Eq. 1) through:

$$\frac{d^2\sigma_{\gamma^*p \rightarrow p'\eta}}{dt d\phi_\eta} = \frac{1}{\Gamma_V(Q^2, x_B, E)} \frac{d^4\sigma_{ep \rightarrow e'p'\eta}}{dQ^2 dx_B dt d\phi_\eta}. \quad (2)$$

The Hand convention [21] was adopted for the definition of the virtual photon flux  $\Gamma_V$ :

$$\Gamma_V(Q^2, x_B, E) = \frac{\alpha}{8\pi} \frac{Q^2}{m_p^2 E^2} \frac{1-x_B}{x_B^3} \frac{1}{1-\epsilon}, \quad (3)$$

where  $\alpha$  is the standard electromagnetic coupling constant. The variable  $\epsilon$  represents the ratio of

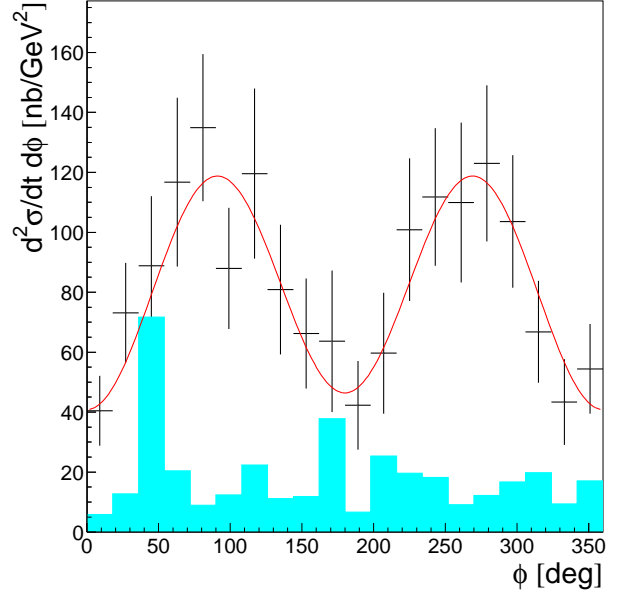


FIG. 9. (Color online) The differential cross section  $d^2\sigma/dtd\phi_\eta$  for the reaction  $\gamma^*p \rightarrow p'\eta$  for the kinematic interval at  $Q^2 = 1.75 \text{ GeV}^2$ ,  $x_B = 0.23$  and  $t = -0.8 \text{ GeV}^2$ . The error bars indicate statistical uncertainties. Systematic uncertainties are indicated by the cyan bars. The red curve is a fit in terms of the structure functions in Eq. 7.

fluxes of longitudinally and transversely polarized virtual photons and is given by

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

with  $y = p \cdot q / q \cdot k = \nu / E$ .

A table of the reduced cross sections can be obtained online in Ref. [22]. An example of the differential cross section as a function of  $\phi_\eta$  in a single kinematic interval in  $Q^2, t$  and  $x_B$  is shown in Fig. 9.

## VI. MONTE CARLO SIMULATION

The acceptance for each ( $Q^2, x_B, t, \phi_\eta$ ) bin of the CLAS detector with the present setup for the reaction  $ep \rightarrow e'p'\gamma\gamma$  was calculated using the Monte Carlo program GSIM. The event generator used an empirical parametrization of the cross section as a function of  $Q^2, x_B$  and  $t$ . The parameters were tuned using the MINUIT program to best match the simulated  $\eta$  cross section with the measured electroproduction cross section. Two iterations were found to be sufficient to describe the experimental cross section and distributions. The comparisons of the experimental and Monte Carlo simulated distributions are shown in Fig. 5 for the variables  $Q^2, x_B, -t$  and  $\phi_\eta$ .

Additional smearing factors for tracking and timing resolutions were included in the simulations to

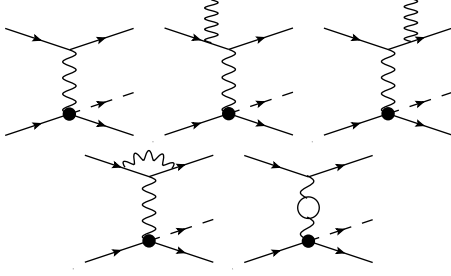


FIG. 10. Feynman diagrams contributing to the  $\eta$  electroproduction cross section. Left to right: Born process, Bremsstrahlung (by the initial and the final electron), vertex correction, and vacuum polarization.

57 provide more realistic resolutions for charged particles. The Monte Carlo events were analyzed by the  
 1 same code that was used to analyze the experimental  
 2 data, and with the additional smearing and some-  
 3 what different exclusivity cuts, to account for the  
 4 leftover discrepancies in calorimeter resolutions. Ul-  
 5 timately the number of reconstructed Monte Carlo  
 6 events was an order of magnitude higher than the  
 7 number of reconstructed experimental events. Thus,  
 8 the statistical uncertainty introduced by the accep-  
 9 tance calculation was typically much smaller than  
 10 the statistical uncertainty of the data.  
 11

12 The efficiency of the event reconstruction depends  
 13 on the level of noise in the detector, the greater the  
 14 noise the lower the efficiency. It was found that the  
 15 efficiency for reconstructing particles decreased lin-  
 16 early with increasing beam current. To take this  
 17 into account the background hits from random 3-  
 18 Hz-trigger events were mixed with the Monte Carlo  
 19 events for all detectors - DC, EC, IC, SC and CC.  
 20 The acceptance for a given bin was calculated as a  
 21 ratio of the number of reconstructed events to the  
 22 number of generated events as

$$\epsilon_{ACC}(Q^2, x_B, t, \phi_\eta) = \frac{N^{rec}(Q^2, x_B, t, \phi_\eta)}{N^{gen}(Q^2, x_B, t, \phi_\eta)}. \quad (5)$$

23 Only areas of the 4-dimensional space with an ac-  
 24 ceptance equal to or greater than 0.5% were used.  
 25 This cut was applied to avoid the regions where the  
 26 calculation of the acceptance was not reliable.

## VII. RADIATIVE CORRECTIONS

27 The QED processes include radiation of photons  
 28 that are not detected by the experimental set up, as  
 29 well as vacuum polarization and lepton-photon ver-  
 30 tex corrections (see Fig. 10). These processes can be  
 31 calculated from QED and the measured cross section  
 32 can be corrected for these effects [23]. The radiative  
 33 corrections,  $\delta_{RC}$ , for the experiment are give by

$$\sigma_\eta = \frac{\sigma_\eta^{meas}}{\delta_{RC}}. \quad (6)$$

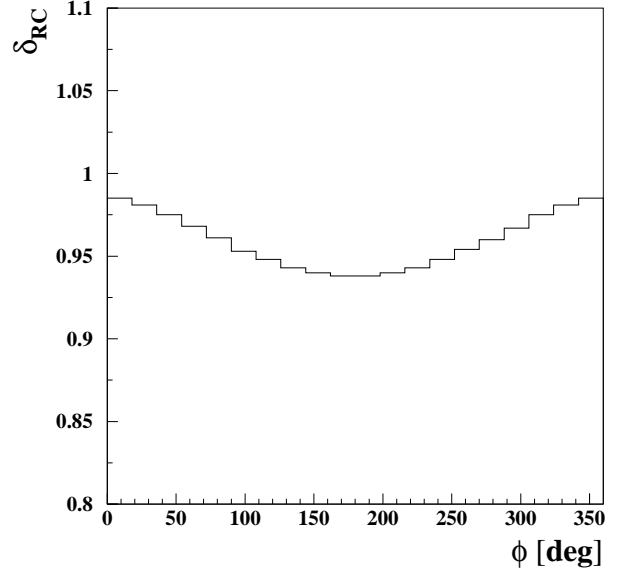


FIG. 11. Radiative corrections  $\delta_{RC}$  for  $\eta$  electroproduction as a function of  $\phi_\eta$  for the kinematic interval at  $Q^2 = 1.15 \text{ GeV}^2$ ,  $x_B = 0.13$  and  $t = -0.12 \text{ GeV}^2$ .

Here  $\sigma_\eta^{meas}$  is the observed cross section and  $\sigma_\eta$  is the  $\eta$  electroproduction cross section after corrections.

The radiative corrections were obtained using the software package EXCLURAD [24], which has been used for radiative corrections in previous CLAS experiments. The same analytical structure functions were implemented in the EXCLURAD package as were used to generate the  $\eta$  electroproduction events in the Monte Carlo simulation. The corrections were computed for each kinematic bin of  $Q^2$ ,  $x_B$ ,  $t$  and  $\phi_\eta$ . Fig. 11 shows the radiative corrections for the first kinematic bin ( $Q^2, x_B, t$ ) as a function of the  $\phi_\eta$ .

## VIII. NORMALIZATION CORRECTION

To check the overall absolute normalization, the cross section of elastic electron-proton scattering was measured using the same data set. The measured cross section was lower than the known elastic cross section [25, 26] by approximately 13% over most of the elastic kinematic range. Studies made using additional other reactions where the cross sections are well known, such as  $\pi^0$  production in the resonance region, and Monte Carlo simulations of the effects of random backgrounds, indicate that the measured cross sections were  $\sim 13\%$  lower than the available published cross sections over a wide kinematic range. Thus, a normalization factor  $\delta_{Norm} \sim 0.87$  was applied to the measured cross section. This value includes the efficiency of the SC counters, which was estimated to be around 95%, as well as other efficiency factors that are not accounted for in the analysis, such as trigger and CC efficiency effects.

## IX. SYSTEMATIC UNCERTAINTIES

61

1 There are various sources of systematic uncertain-  
 2 ties. Some are introduced in the analysis, while oth-  
 3 ers can be tracked back to uncertainties of measure-  
 4 ments such as target length or integrated luminos-  
 5 ity. Still others are related to an imperfect knowl-  
 6 edge of the response of the spectrometer. In most  
 7 cases uncertainties originating from the analysis it-  
 8 self can be estimated separately for each kinematic  
 9 bin  $(Q^2, x_B, t, \phi_\eta)$ . Where bin-by-bin estimates are  
 10 not possible, global values for all bins are estimated.

11 A source of systematic uncertainty is associated  
 12 with the numerous cuts which were applied in order  
 13 to isolate the reaction of interest, ie.  $ep \rightarrow e'p'\eta$   
 14 To estimate the systematic uncertainty of a cut, the  
 15 value of the cut was varied from the standard cut  
 16 position by a step on each side by  $\pm 0.5\sigma$ , where  $\sigma$  is  
 17 the resolution of the corresponding variable. Thus,  
 18 the resulting cross sections and structure functions  
 19 were obtained at each of 4 cut values in addition to  
 20 the standard cut of  $\pm 3\sigma$ .

21 All cuts were varied independently, such that at  
 22 each cut iteration, for each distribution, the en-  
 23 tire analysis, including calculation of acceptances,  
 24 cross sections, radiative corrections and structure  
 25 functions was performed. Then, for each kinematic  
 26 point, the cross sections and structure functions were  
 27 plotted as functions of cut variation and a linear fit  
 28 was performed. The slope parameter of the fit was  
 29 assumed to be the systematic uncertainty introduced  
 30 by the particular cut at a given kinematic point.  
 31 This procedure was performed for all sources of kine-  
 32 matic uncertainties where it was applicable. It was  
 33 shown that this method of systematic uncertainty  
 34 calculation overestimates the systematic uncertainty  
 35 for bins with low statistics, but was retained.

36 The systematic uncertainty associated with the  
 37 variation of the cross section within a kinematic bin  
 38 at  $Q^2$ ,  $x_B$  and  $t$  was estimated to be  $\pm 1.3\%$ , using  
 39 our cross section model.

40 To estimate the systematic uncertainty of the ab-  
 41 solute normalization procedure, the normalization  
 42 constant  $\delta_{Norm}$  was obtained separately for electrons  
 43 detected in each of the six sectors, resulting in a  
 44 mean value of 87%. The sector-by-sector rms vari-  
 45 ation from the mean value was used as an estimate  
 46 of the systematic uncertainty on the mean. The dis-  
 47 tribution of total systematic uncertainty, excluding  
 48 the uncertainty on absolute normalization is shown  
 49 in Fig. 12. Table IV contains a summary of the  
 50 information on all of the sources of systematic un-  
 51 certainty on the individual fourfold differential cross  
 52 sections -  $\frac{d^4\sigma_{ep \rightarrow e'p'\eta}}{dQ^2 dx_B dt d\phi_\eta}$  - that were studied.

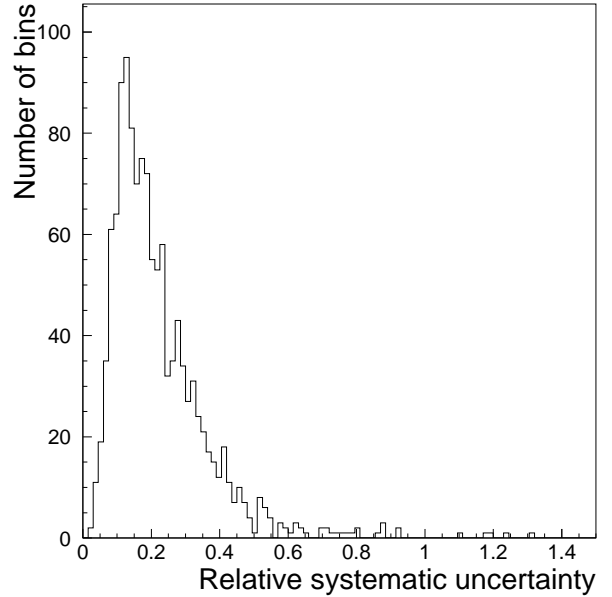


FIG. 12. The relative systematic uncertainties,  $\delta\sigma_{sys}/\sigma$  of the four-fold differential cross section (see Eq. 1) for all kinematic points. These do not include the overall normalization uncertainty,

## X. STRUCTURE FUNCTIONS

The reduced cross sections can be expanded in terms of structure functions as follows:

$$2\pi \frac{d^2\sigma}{dt d\phi_\eta} = \left( \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right) + \epsilon \cos 2\phi_\eta \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_\eta \frac{d\sigma_{LT}}{dt}, \quad (7)$$

from which the three combinations of structure functions,

$$\frac{d\sigma_U}{dt} \equiv \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}, \quad \frac{d\sigma_{TT}}{dt} \quad \text{and} \quad \frac{d\sigma_{LT}}{dt} \quad (8)$$

can be extracted by fitting the cross sections to the  $\phi_\eta$  distribution in each bin of  $(Q^2, x_B, t)$ . As an example, the curve in Fig. 9 is a fit to  $d^2\sigma/dtd\phi_\eta$  in terms of the coefficients of the  $\cos \phi_\eta$  and  $\cos 2\phi_\eta$  terms. The physical significance of the structure functions is as follows.

- $d\sigma_L/dt$  is the sum of structure functions initiated by a longitudinal virtual photon, both with and without nucleon helicity-flip, i.e. respectively  $\Delta\nu = \pm 1$  and  $\Delta\nu = 0$ ;
- $d\sigma_T/dt$  is the sum of structure functions initiated by transverse virtual photons of positive and negative helicity ( $\mu = \pm 1$ ), with and without nucleon helicity flip, respectively  $\Delta\nu = \pm 1$  and 0;

TABLE IV. Summary table of systematic uncertainties

Source	Varies by bin	Average uncertainty of the cross section	Average uncertainty of the structure function $\sigma_U$
Target length	No	0.2%	0.2%
Electron fiducial cut	Yes	$\sim 6.4\%$	$\sim 3.5\%$
Proton fiducial cut	Yes	$\sim 4.1\%$	$\sim 2.4\%$
Cut on missing mass of the $e\gamma\gamma$	Yes	$\sim 3.9\%$	$\sim 0.7\%$
Cut on invariant mass of 2 photons	Yes	$\sim 10.5\%$	$\sim 9.0\%$
Cut on missing energy of the $e\gamma\gamma$	Yes	$\sim 6.6\%$	$\sim 4.1\%$
Radiative corrections and cut on $M_X(ep)$	Yes	$\sim 8.0\%$	$\sim 6.0\%$
Absolute normalization	No	4.1%	4.1%
Luminosity calculation	No	$< 1\%$	$< 1\%$
Bin volume correction	Yes	$\sim 1.3\%$	$\sim 1.3\%$
Cut on energy of photon detected in the EC	Yes	$\sim 3.1\%$	$\sim 2.5\%$

- $d\sigma_{LT}/dt$  corresponds to interferences involving products of amplitudes for longitudinal and transverse photons;
- $d\sigma_{TT}/dt$  corresponds to interferences involving products of transverse positive and negative photon helicity amplitudes.

The structure functions for all kinematic bins are shown in Fig. 13 and listed in Appendix A. The quoted statistical uncertainties on the structure functions were obtained in the fitting procedure taking into account the statistical uncertainties on the individual cross section points. The quoted systematic uncertainties are the variations of the fitted structure functions due to variation of the cut parameters.

A number of observations can be made independently of the model predictions. The  $d\sigma_{TT}/dt$  structure function is negative and is smaller in magnitude than unpolarized structure function ( $d\sigma_U/dt \equiv d\sigma_T/dt + \epsilon d\sigma_L/dt$ ). However,  $d\sigma_{LT}/dt$  is significantly smaller than  $d\sigma_{TT}/dt$ . This reinforces the conclusion that the transverse photon amplitudes are dominant at the present values of  $Q^2$ .

The ratio  $R$  of the unpolarized cross sections for  $\eta$  and  $\pi^0$  for all kinematic bins is shown in Fig. 14. The ratio  $R$  is seen to be significantly less than 1, whereas the leading order handbag calculations [27] predict asymptotically  $R \sim 1$ . However, the observed value of  $R$ , typically about fifty percent, is greater than that predicted by the model of Ref. [8].

## XI. $t$ - SLOPES

After the structure functions were obtained, fits were made to extract the  $t$ -dependence of  $\sigma_U$  for different values  $x_B$  and  $Q^2$ . For each given  $x_B$  and  $Q^2$  we fit this structure function with an exponential function:

$$\frac{d\sigma_U}{dt} = Ae^{Bt}.$$

Fig. 15 shows the slope parameter  $B$  as a function of  $x_B$  for different values of  $Q^2$ . The data appear to exhibit a decrease in slope parameter with increasing

$x_B$ . However, the  $Q^2 - x_B$  correlation in the CLAS acceptance (see Fig. 4) does not permit one to make a definite conclusion about the  $Q^2$  dependences of the slope parameter for fixed  $x_B$ . What one can say is that at high  $Q^2$  and high  $x_B$  the slope parameter appears to be smaller than for the lowest values of these variables. The  $B$  parameter in the exponential determines the width of the transverse momentum distribution of the emerging protons, which, by a Fourier transform, is inversely related to the transverse size of the interaction region. From the point of view of the handbag picture, it is inversely related to the mean transverse radius of the separation between the active quark and the center of momentum of the spectators (see Ref. [28]). Thus the data implies that the separation is larger at the lowest  $x_B$  and  $Q^2$  and becomes smaller for increasing  $x_B$  and  $Q^2$ , as it must. This is consistent with the results for  $\pi^0$  electoproduction [6].

## XII. COMPARISONS WITH THEORETICAL HANDBAG MODELS

Fig. 13 shows the experimental structure functions for bins of  $Q^2$  and  $x_B$ . The results of the GPD-based model of Goloskokov and Kroll [8] are superimposed in Fig. 13. From these plots we conclude that the GPD-based theoretical model generally describes the CLAS data in the kinematical region of this experiment, although there are systematic discrepancies. For example, the theoretical model appears to underestimate  $d\sigma_U/dt$  in most kinematic bins.

According to GK, the primary contributing GPDs in meson production for transverse photons are  $H_T$ , which characterizes the quark distributions involved in nucleon helicity-flip, and  $\bar{E}_T (= 2\tilde{H}_T + E_T)$ , which characterizes the quark distributions involved in nucleon helicity-non-flip processes [29, 30]. As a reminder, in both cases the active quark undergoes a helicity-flip. The GPD  $\bar{E}_T$  is related to the spatial density of transversely polarized quarks in an unpolarized nucleon [30].

Ref. [8] obtains the following relations:

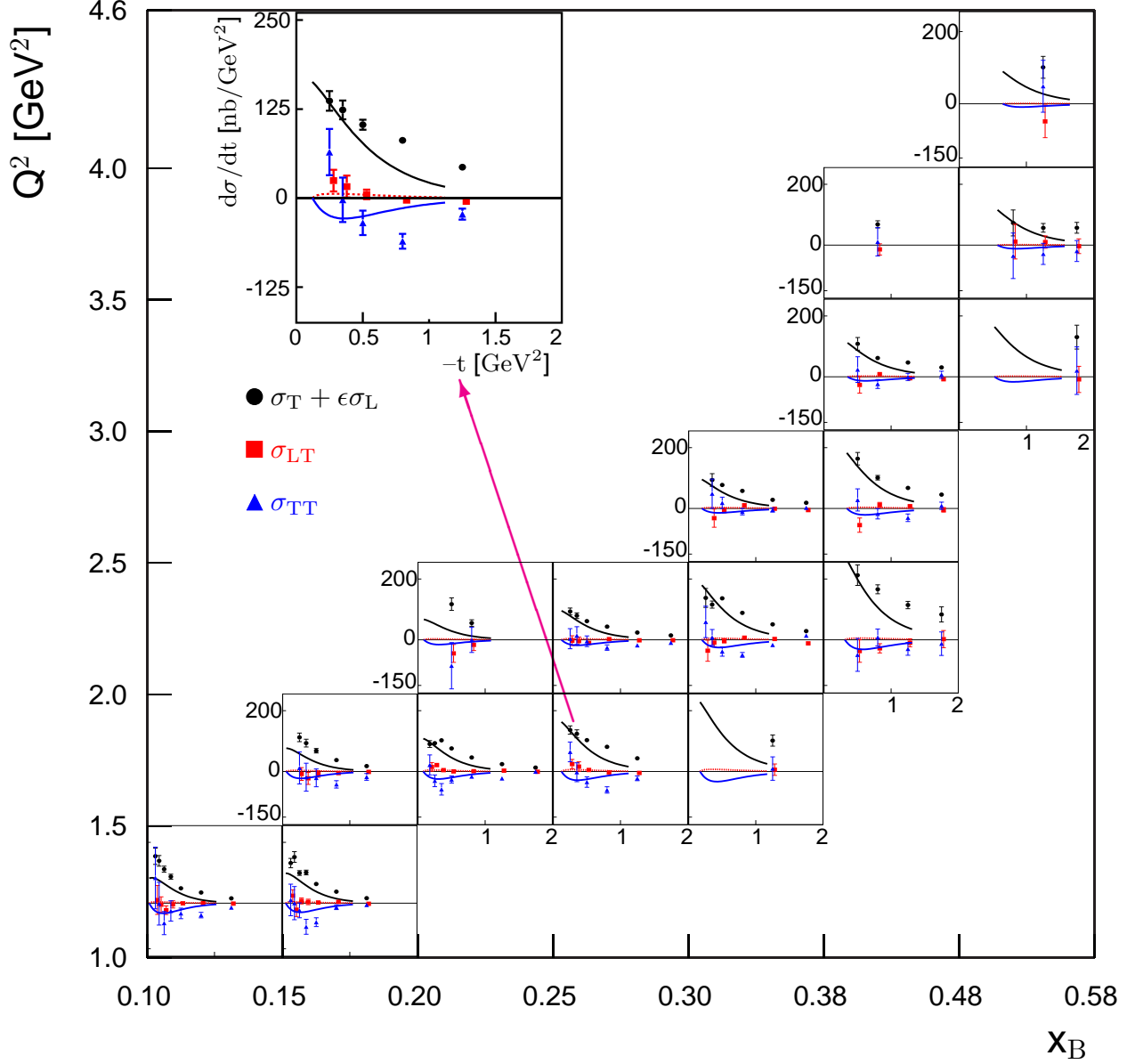


FIG. 13. The structure functions vs.  $t$  for the different  $(Q^2, x_B)$  bins, extracted from the present experiment. Black circles:  $d\sigma_U/dt$ . Red squares:  $d\sigma_{LT}/dt$ . Blue triangles:  $d\sigma_{TT}/dt$ . The black, red and blue curves are the corresponding results of the handbag based calculation of Ref. [8]. The inset is an enlarged view of the bin with  $x_B = 0.17$  and  $Q^2 = 1.87$  GeV<sup>2</sup>. The error bars are statistical only.

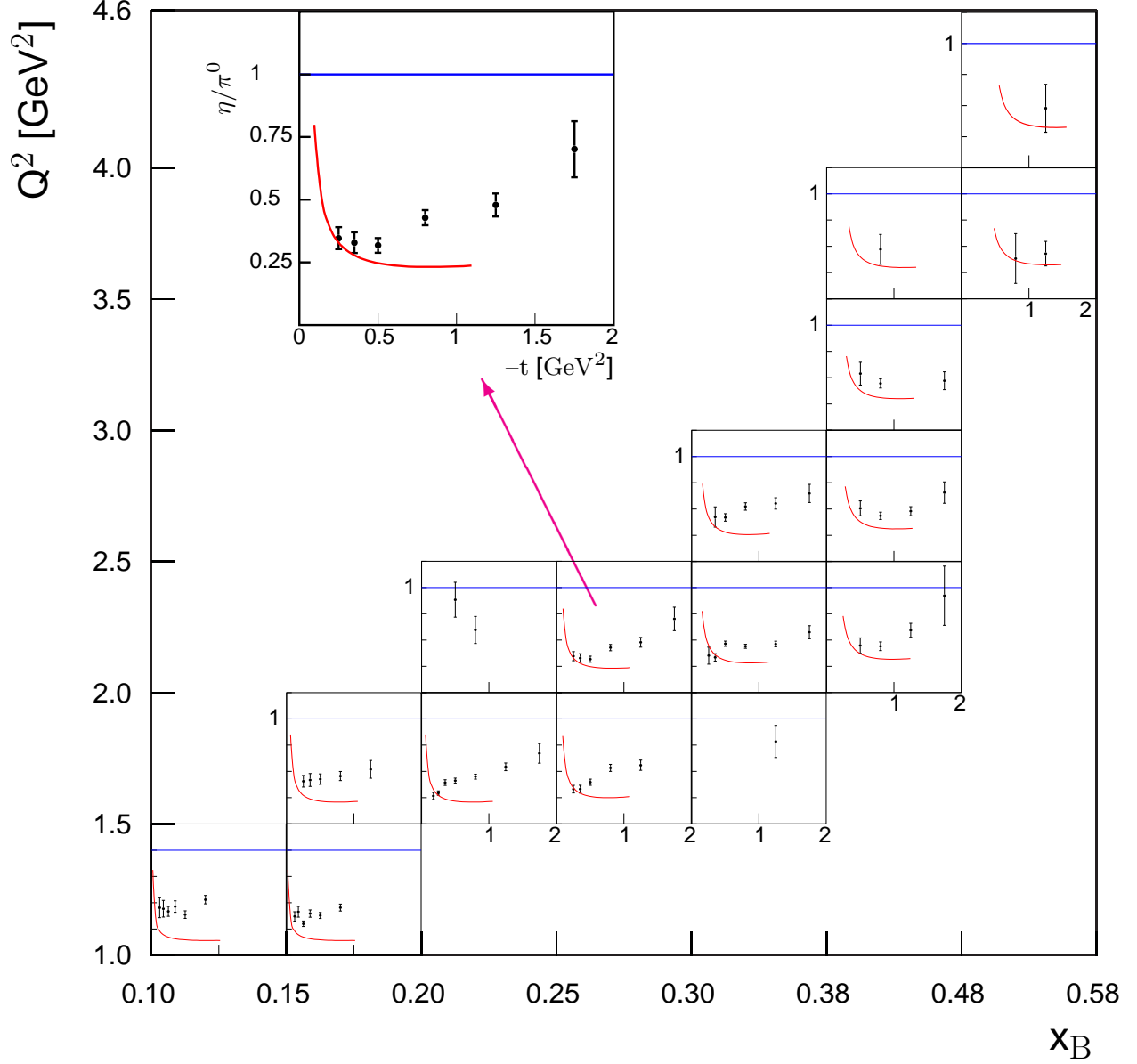


FIG. 14. The ratio  $R$  of the unpolarized structure functions for  $\eta$  and  $\pi^0$  extracted from the present experiment and Ref. [5], as functions of  $t$  for  $(Q^2, x_B)$  bins. The leading order handbag calculations [27] predict asymptotically  $R \sim 1$ . The curves are the result of a handbag based calculation of Ref. [8]. The inset is an enlarged view of the bin with  $x_B = 0.28$  and  $Q^2 = 2.2$  GeV<sup>2</sup>. The error bars are statistical only.



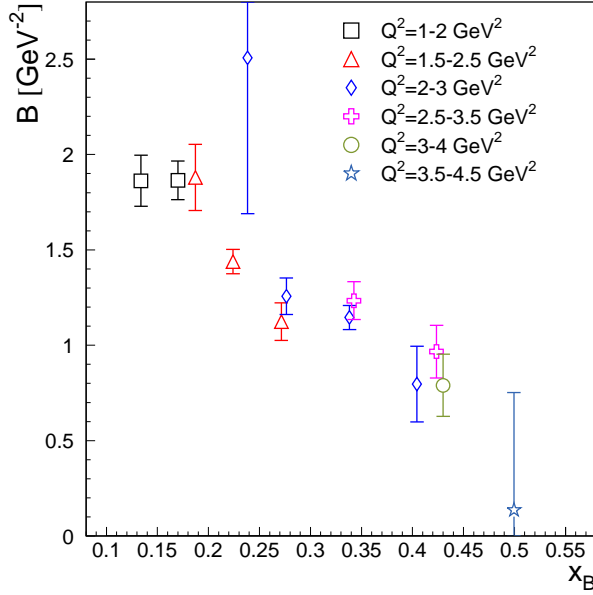


FIG. 15. Slope parameters  $B$  for different  $x_B$  and  $Q^2$  bins. The error bars are statistical only.

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu_\eta^2}{Q^8} \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle \bar{E}_T \rangle|^2 \right], \quad (9)$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'} \frac{\mu_\eta^2}{Q^8} \frac{t'}{16m^2} |\langle \bar{E}_T \rangle|^2. \quad (10)$$

Here  $\kappa'(Q^2, x_B)$  is a phase space factor,  $t' = t - t_{min}$ , and the brackets  $\langle H_T \rangle$  and  $\langle \bar{E}_T \rangle$  are the Generalized Form Factors (GFFs) that denote the convolution of the elementary process with the GPDs  $H_T$  and  $\bar{E}_T$  (see Fig. 1).

Note that for the case of nucleon helicity-non-flip, characterized by the GPD  $\bar{E}_T$ , overall helicity from the initial to the final state is not conserved. However, angular momentum is conserved - the difference being absorbed by the orbital motion of the scattered  $\eta - N$  pair. This accounts for the additional  $t'$  factor multiplying the  $\bar{E}_T$  terms in Eqs. 9 and 10.

As in the case of  $\pi^0$  electroproduction, the contribution of  $\sigma_L$  accounts for only a small fraction of the unseparated structure functions  $d\sigma_U/dt (\equiv d\sigma_T/dt + \epsilon d\sigma_L/dt)$  in the kinematic regime under investigation. This is because the contributions from  $\bar{H}$  and  $\bar{E}$  - the GPDs that are responsible for the leading-twist structure function  $\sigma_L$  - are relatively small compared with the contributions from  $\bar{E}_T$  and  $H_T$  (although not quite as small for  $\eta$  production as compared to  $\pi^0$  production), which contribute to  $d\sigma_T/dt$  and  $d\sigma_{TT}/dt$ . The extracted structure functions at selected values of  $Q^2$  and  $x_B$

for the  $\pi^0$  (left column) and  $\eta$  (right column) are shown in Fig. 16 side-by-side. The top row represents data for the kinematic point ( $Q^2 = 1.38 \text{ GeV}^2$ ,  $x_B = 0.17$ ) and the bottom row for the kinematic point ( $Q^2 = 2.21 \text{ GeV}^2$ ,  $x_B = 0.28$ ). The unpolarized structure function  $d\sigma_U/dt$  for  $\eta$  production is significantly smaller than that for  $\pi^0$  for all measured kinematic intervals of  $Q^2$ ,  $x_B$  and  $t$ . This is in contradiction to the leading order calculation [27] with  $d\sigma_L/dt$  dominance, where the ratio is expected to be on the order of unity. In the present case,  $\bar{E}_T$  is significantly larger than  $H_T$ . The curves in Fig. 13 and 16 are obtained by GK [8]. For the GPDs, their parameterization was guided by the lattice calculation results of Ref. [30].

The relative importance of  $\bar{E}_T$  and  $H_T$  can be understood by considering their composition in terms of their valence quark flavors and GPDs. Following GK, the  $\pi^0$  and  $\eta$  GPDs in terms of valence quark GPDs may be expressed as follows. For  $\pi^0$ :

$$\begin{aligned} H_T^{\pi^0} &= (e_u H_T^u - e_d H_T^d) / \sqrt{2}, \\ \bar{E}_T^{\pi^0} &= (e_u \bar{E}_T^u - e_d \bar{E}_T^d) / \sqrt{2}, \end{aligned} \quad (11)$$

where  $e_u = 1/3$  and  $e_d = -2/3$ .

For  $\eta$ , assuming the valence structure of the  $\eta$  is purely a member of the SU(3) octet, i.e.  $\eta = \eta_8$ , and there is no contribution from strange quarks is

$$\begin{aligned} H_T^\eta &= (e_u H_T^u + e_d H_T^d) / \sqrt{6}, \\ \bar{E}_T^\eta &= (e_u \bar{E}_T^u + e_d \bar{E}_T^d) / \sqrt{6}. \end{aligned} \quad (12)$$

In the model of GK, the sign of  $H_T^u$  is positive, while the sign of  $H_T^d$  is negative, but the signs of  $\bar{E}_T^u$  and  $\bar{E}_T^d$  are both positive. Thus, for  $\pi^0$ , taking into account the sign of  $e_u$  and  $e_d$ , the up and down quarks enhance  $\bar{E}_T^{\pi^0}$  and diminish  $H_T^{\pi^0}$ . The opposite effect occurs for  $\eta$  mesons. By combining the  $\eta$  and  $\pi^0$  data, and Eqs. 11 and 12 above, one can estimate the GPDs of the individual valence quark flavors in the framework of the dominance of the transversity GPDs. This is currently underway and will be published later.

We further note the following features: for  $\eta$  production the model of GK appears to underestimate the magnitude of  $d\sigma_U/dt$ , whereas for  $\pi^0$  electroproduction the theoretical calculation of  $d\sigma_U/dt$  more closely agrees with the data. Thus, one is led to the hypothesis that possibly  $H_T$  is underestimated for  $\eta$  electroproduction. Increasing  $H_T$  will increase  $d\sigma_T/dt$  and, therefore,  $d\sigma_U/dt$ , while not affecting  $d\sigma_{TT}/dt$ .

Referring again to Fig. 14, which shows the ratio of  $d\sigma_U/dt$  for  $\eta$  and  $\pi^0$ , the experimental value of this ratio is systematically higher than the theoretical prediction, which is related to the underestimation of the  $\eta$  cross section.

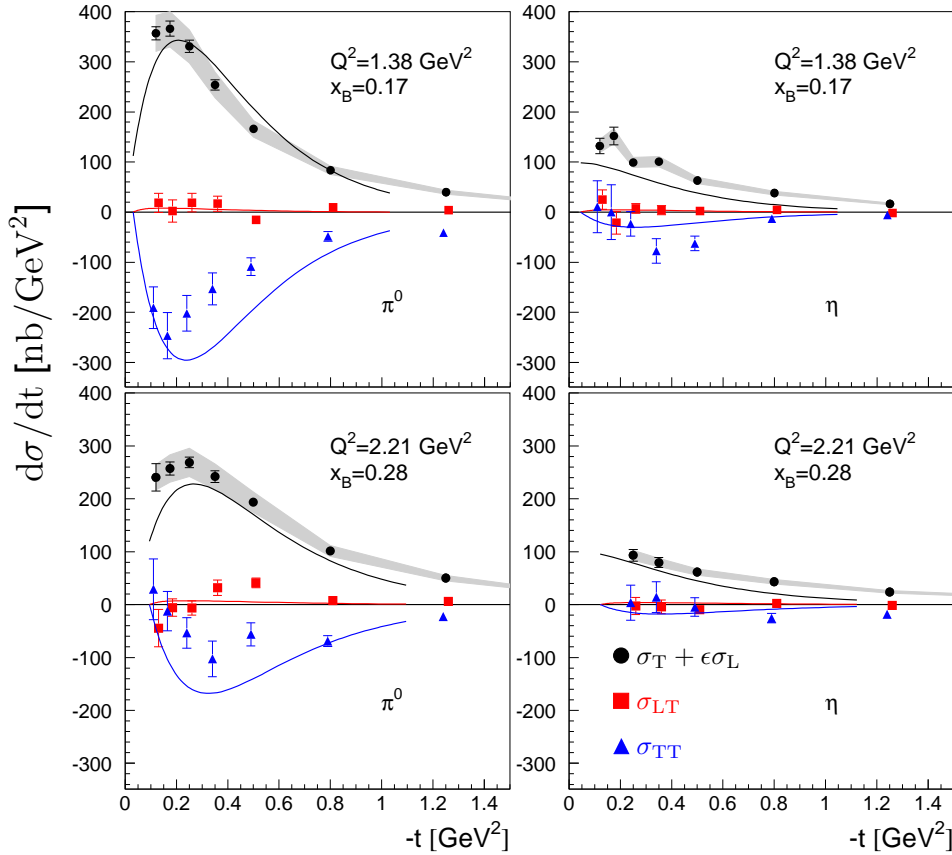


FIG. 16. (Color online) The extracted structure functions vs.  $t$  for the  $\pi^0$  (left column) [20] and  $\eta$  (right column). The top row presents data for the kinematic point ( $Q^2 = 1.38 \text{ GeV}^2, x_B = 0.17$ ) and bottom row for the kinematic point ( $Q^2 = 2.21 \text{ GeV}^2, x_B = 0.28$ ). The data for the  $\eta$  is identical to that shown in Fig. 13, with the vertical axis rescaled to highlight the difference in the magnitude of the cross sections for  $\pi^0$  and  $\eta$  electroproduction. The data and curves are as follows: black circles -  $d\sigma_U/dt = d\sigma_T/dt + \epsilon d\sigma_L/dt$ , blue triangles -  $d\sigma_{TT}/dt$ , red squares -  $d\sigma_{LT}/dt$ . The error bars are statistical only. The gray bands are our estimates of the absolute normalization systematic uncertainties on  $d\sigma_U/dt$ . The curves are theoretical predictions produced with the models of Ref. [8].

### XIII. CONCLUSION

Differential cross sections of exclusive  $\eta$  electroproduction were obtained in the few-GeV region in bins of  $Q^2, x_B, t$  and  $\phi_\eta$ . Virtual photon structure functions  $d\sigma_U/dt = d(\sigma_T + \epsilon\sigma_L)/dt$ ,  $d\sigma_{TT}/dt$  and  $d\sigma_{LT}/dt$  were extracted. It is found that  $d\sigma_U/dt$  is larger in magnitude than  $d\sigma_{TT}/dt$ , while  $d\sigma_{LT}/dt$  is significantly smaller than  $d\sigma_{TT}/dt$ . The exclusive cross sections and structure functions are typically more than a factor of two smaller than for previously measured  $\pi^0$  electroproduction for similar kinematic intervals. It appears that some of these differences can be roughly understood from GPD-models in terms of the quark composition of  $\pi^0$  and  $\eta$  mesons. The cross section ratios of  $\eta$  to  $\pi^0$  appear to agree with the handbag calculations at low  $|t|$ , but show significant deviations with increasing  $|t|$ .

Within the handbag interpretation, there are theoretical calculations [8], which were earlier found to describe  $\pi^0$  electroproduction [6] quite well. The result of the calculations confirmed that the mea-

sured unseparated cross sections are much larger than expected from leading-twist handbag calculations, which are dominated by longitudinal photons. For the present case, the same conclusion can be made in an almost model independent way by noting that the structure functions  $d\sigma_U/dt$  and  $d\sigma_{TT}/dt$  are significantly larger than  $d\sigma_{LT}/dt$ .

To make significant improvement in interpretation, higher statistical precision data, as well as  $L-T$  separation and polarization measurements over the entire range of kinematic variables are necessary. Such experiments are planned for the Jefferson Lab operations at 12 GeV.

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## Appendix A: Structure functions

17 The structure functions are presented in Table V. The first error is statistical uncertainty and the second  
 18 is the systematic uncertainty.

TABLE V: Structure Functions

$Q^2,$ $GeV^2$	$x_B$	$-t,$ $GeV^2$	$\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt},$ $nb/GeV^2$	$\frac{d\sigma_{LT}}{dt},$ $nb/GeV^2$	$\frac{d\sigma_{TT}}{dt},$ $nb/GeV^2$
1.17	0.134	0.12	159.3 ± 27.7 ± 22.3	8.2 ± 49.3 ± 33.2	88.4 ± 104.2 ± 126.4
1.17	0.134	0.17	144.7 ± 18.0 ± 16.2	2.2 ± 26.4 ± 20.2	-4.3 ± 73.1 ± 189.0
1.17	0.134	0.25	117.3 ± 10.3 ± 10.7	-22.0 ± 14.9 ± 9.9	-71.6 ± 40.2 ± 29.1
1.17	0.134	0.35	94.0 ± 8.8 ± 3.6	-1.3 ± 12.7 ± 4.2	-29.7 ± 35.7 ± 9.0
1.17	0.134	0.50	51.1 ± 4.3 ± 5.9	1.8 ± 6.0 ± 4.4	-34.1 ± 18.2 ± 10.0
1.17	0.134	0.80	36.3 ± 2.5 ± 1.6	1.1 ± 3.0 ± 5.6	-40.6 ± 9.5 ± 13.3
1.17	0.134	1.25	16.2 ± 1.7 ± 1.8	-1.2 ± 2.3 ± 3.0	-13.7 ± 6.2 ± 5.0
1.39	0.170	0.12	134.1 ± 15.5 ± 21.7	26.2 ± 19.8 ± 14.2	15.2 ± 52.7 ± 27.5
1.39	0.170	0.17	156.4 ± 18.2 ± 21.9	-18.1 ± 23.3 ± 28.7	-0.4 ± 56.5 ± 8.0
1.39	0.170	0.25	101.8 ± 8.0 ± 7.9	10.6 ± 10.0 ± 6.4	-22.9 ± 25.1 ± 26.2
1.39	0.170	0.35	104.6 ± 8.0 ± 6.3	7.6 ± 9.3 ± 9.2	-80.1 ± 25.3 ± 15.4
1.39	0.170	0.50	65.3 ± 4.5 ± 2.7	4.3 ± 5.0 ± 3.1	-64.3 ± 14.9 ± 16.7
1.39	0.170	0.80	39.0 ± 2.4 ± 2.6	5.7 ± 2.8 ± 3.3	-11.9 ± 8.0 ± 4.5
1.39	0.170	1.25	16.9 ± 1.5 ± 2.1	-1.7 ± 1.9 ± 1.1	-6.0 ± 5.2 ± 2.9
1.62	0.187	0.25	117.1 ± 14.6 ± 11.6	-6.0 ± 22.0 ± 13.4	11.3 ± 54.6 ± 32.0
1.62	0.187	0.35	98.4 ± 13.2 ± 9.0	-20.3 ± 20.4 ± 6.8	-22.0 ± 48.6 ± 49.5
1.62	0.187	0.50	71.0 ± 7.6 ± 3.6	-5.7 ± 10.7 ± 6.9	-22.7 ± 30.7 ± 37.5
1.62	0.187	0.80	38.5 ± 3.3 ± 1.7	-4.3 ± 4.4 ± 2.1	-43.0 ± 12.4 ± 8.7
1.62	0.187	1.25	18.3 ± 2.7 ± 2.2	-1.2 ± 3.8 ± 1.6	-15.9 ± 11.5 ± 5.8
1.77	0.224	0.18	93.3 ± 11.4 ± 12.0	16.9 ± 14.7 ± 11.9	22.1 ± 33.7 ± 29.9
1.77	0.224	0.25	96.4 ± 6.4 ± 6.7	23.9 ± 7.2 ± 6.1	-30.0 ± 20.0 ± 14.9
1.77	0.224	0.35	105.0 ± 6.6 ± 4.1	7.7 ± 7.0 ± 6.1	-60.1 ± 19.3 ± 13.5
1.77	0.224	0.50	77.9 ± 4.0 ± 4.2	2.8 ± 4.4 ± 3.3	-25.4 ± 11.7 ± 17.3
1.77	0.224	0.80	46.9 ± 2.2 ± 3.2	2.1 ± 2.4 ± 2.1	-15.5 ± 6.5 ± 6.6
1.77	0.224	1.25	24.5 ± 1.5 ± 1.8	3.0 ± 1.5 ± 1.8	-22.5 ± 4.2 ± 2.7
1.77	0.224	1.75	12.9 ± 1.7 ± 1.5	-0.9 ± 2.1 ± 1.8	-0.5 ± 4.9 ± 4.5
1.88	0.271	0.25	137.5 ± 13.8 ± 27.9	27.4 ± 15.4 ± 19.3	62.5 ± 33.0 ± 46.8
1.88	0.272	0.35	125.9 ± 13.3 ± 11.5	18.9 ± 15.3 ± 14.7	-1.1 ± 31.3 ± 78.2
1.88	0.271	0.50	104.0 ± 7.1 ± 3.7	6.5 ± 6.7 ± 6.4	-34.3 ± 17.2 ± 31.1
1.88	0.272	0.80	81.9 ± 4.7 ± 5.1	-2.3 ± 4.0 ± 3.0	-60.5 ± 10.5 ± 10.5
1.88	0.272	1.25	43.6 ± 3.4 ± 5.6	-4.0 ± 3.4 ± 4.4	-23.2 ± 7.8 ± 7.0
1.95	0.313	1.25	100.9 ± 18.2 ± 10.3	6.9 ± 18.6 ± 18.9	9.5 ± 38.4 ± 34.7
2.11	0.238	0.50	121.5 ± 21.1 ± 10.5	-42.3 ± 29.7 ± 8.6	-96.2 ± 78.9 ± 16.2
2.11	0.238	0.80	55.8 ± 10.6 ± 6.6	-14.2 ± 18.4 ± 4.0	-1.4 ± 41.5 ± 83.4
2.24	0.276	0.25	97.0 ± 11.6 ± 10.9	-1.0 ± 16.7 ± 20.1	2.0 ± 34.5 ± 24.7
2.24	0.276	0.35	80.8 ± 9.3 ± 5.8	-2.0 ± 12.9 ± 4.7	15.4 ± 29.5 ± 15.8
2.24	0.276	0.50	62.5 ± 5.3 ± 7.3	-7.8 ± 7.1 ± 5.3	-5.3 ± 18.0 ± 25.0
2.24	0.276	0.80	44.1 ± 2.8 ± 2.3	3.4 ± 3.3 ± 2.1	-25.0 ± 9.1 ± 4.7
2.24	0.276	1.25	24.2 ± 2.1 ± 2.4	-1.5 ± 2.8 ± 2.3	-17.4 ± 6.4 ± 4.3
2.24	0.276	1.75	14.7 ± 2.1 ± 2.4	-1.3 ± 2.5 ± 2.5	-9.8 ± 6.0 ± 5.7
2.26	0.335	0.25	142.4 ± 31.9 ± 41.2	-35.5 ± 35.4 ± 49.9	61.6 ± 53.2 ± 72.7
2.26	0.338	0.35	116.8 ± 11.7 ± 7.0	-7.9 ± 13.2 ± 12.2	6.4 ± 26.3 ± 40.2
2.26	0.338	0.50	137.8 ± 6.7 ± 7.7	-1.9 ± 7.1 ± 6.4	-38.1 ± 15.6 ± 4.2
2.26	0.338	0.80	88.8 ± 3.6 ± 3.8	8.1 ± 3.3 ± 3.8	-49.6 ± 7.9 ± 6.7
2.26	0.338	1.25	51.2 ± 2.7 ± 5.5	3.1 ± 2.8 ± 6.5	-16.4 ± 6.1 ± 10.6
2.26	0.338	1.75	28.5 ± 2.9 ± 4.4	-11.4 ± 3.1 ± 6.0	13.7 ± 5.1 ± 4.6
2.35	0.404	0.50	215.1 ± 34.0 ± 19.6	-38.8 ± 37.4 ± 28.9	-48.3 ± 54.3 ± 40.4
2.35	0.404	0.80	165.5 ± 14.6 ± 19.4	-26.8 ± 15.1 ± 16.1	6.5 ± 27.5 ± 16.3
2.35	0.404	1.25	114.4 ± 12.1 ± 20.4	-9.7 ± 12.9 ± 17.9	-29.9 ± 21.1 ± 24.1
2.35	0.404	1.75	84.0 ± 24.7 ± 55.2	1.4 ± 27.9 ± 76.6	-12.0 ± 38.4 ± 100.8
2.73	0.343	0.35	94.2 ± 20.7 ± 14.9	-28.5 ± 29.4 ± 16.0	46.0 ± 48.7 ± 29.3
2.73	0.343	0.50	79.1 ± 6.1 ± 3.2	-3.8 ± 8.3 ± 6.9	18.8 ± 19.3 ± 15.1
2.73	0.343	0.80	58.9 ± 3.4 ± 2.3	12.5 ± 4.3 ± 4.4	-8.5 ± 10.7 ± 5.5
2.73	0.343	1.25	28.6 ± 2.4 ± 2.9	-0.2 ± 3.2 ± 1.2	-4.2 ± 7.2 ± 9.8
2.73	0.343	1.75	18.7 ± 2.2 ± 2.7	-4.8 ± 3.0 ± 2.4	2.5 ± 6.0 ± 9.8
2.77	0.424	0.50	164.4 ± 20.7 ± 21.0	-53.5 ± 23.4 ± 25.3	26.9 ± 36.6 ± 33.4
2.77	0.424	0.80	100.9 ± 7.5 ± 11.5	12.2 ± 8.4 ± 13.3	-17.2 ± 16.9 ± 22.4
2.77	0.424	1.25	67.8 ± 5.5 ± 7.4	7.9 ± 6.4 ± 6.1	-29.8 ± 12.6 ± 13.7
2.77	0.424	1.75	45.3 ± 6.3 ± 6.9	-4.4 ± 7.6 ± 10.3	9.2 ± 11.8 ± 17.6

$Q^2,$ $GeV^2$	$x_B$	$-t,$ $GeV^2$	$\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt},$ $nb/GeV^2$	$\frac{d\sigma_{LT}}{dt},$ $nb/GeV^2$	$\frac{d\sigma_{TT}}{dt},$ $nb/GeV^2$
3.25	0.430	0.50	108.4 ± 20.7 ± 14.8	-22.2 ± 27.1 ± 17.5	21.1 ± 42.7 ± 23.3
3.25	0.431	0.80	62.2 ± 5.3 ± 4.7	9.8 ± 7.0 ± 4.7	-23.3 ± 14.8 ± 11.9
3.25	0.431	1.25	47.1 ± 4.2 ± 3.9	-3.6 ± 5.5 ± 8.6	-0.6 ± 11.8 ± 136.3
3.25	0.431	1.75	30.6 ± 4.9 ± 3.5	-7.3 ± 6.9 ± 4.5	6.3 ± 11.7 ± 13.2
3.30	0.497	1.75	128.6 ± 38.4 ± 35.0	-6.8 ± 42.0 ± 19.6	17.4 ± 77.0 ± 52.1
3.69	0.451	0.80	68.1 ± 11.7 ± 5.9	-12.1 ± 18.2 ± 5.5	6.9 ± 47.2 ± 25.2
3.77	0.513	0.80	71.4 ± 43.1 ± 10.8	15.2 ± 57.8 ± 25.4	-38.8 ± 76.2 ± 30.0
3.77	0.514	1.25	56.5 ± 14.3 ± 7.3	11.5 ± 20.2 ± 11.1	-29.6 ± 34.9 ± 22.9
3.77	0.513	1.75	57.2 ± 17.6 ± 9.1	-3.4 ± 23.9 ± 8.8	-17.4 ± 34.3 ± 16.0
4.24	0.540	1.25	100.7 ± 30.2 ± 12.7	-46.3 ± 44.9 ± 15.4	48.5 ± 72.4 ± 20.6

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