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## Rosenbluth Separation of the $\pi^0$ Electroproduction Cross Section Off the Neutron

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We report the first longitudinal-transverse separation of the deeply virtual exclusive  $\pi^0$  electroproduction cross section off the neutron and coherent deuteron. The corresponding four structure functions  $d\sigma_L/dt$ ,  $d\sigma_T/dt$ ,  $d\sigma_{LT}/dt$ , and  $d\sigma_{TT}/dt$  are extracted as a function of the momentum transfer to the recoil system at  $Q^2 = 1.75 \text{ GeV}^2$  and  $x_B = 0.36$ . The  $ed \rightarrow ed\pi^0$  cross sections are found compatible with the small values expected from theoretical models. The  $en \rightarrow en\pi^0$  cross sections show a dominance from the response to transversely polarized photons, and are in good agreement with calculations based on the transversity generalized parton distributions of the nucleon. By combining these results with previous measurements of  $\pi^0$  electroproduction off the proton, we present a flavor decomposition of the  $u$  and  $d$  quark contributions to the cross section.

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Understanding the internal three-dimensional structure of nucleons in terms of quarks and gluons is a major challenge of modern hadronic physics. Two complementary approaches have been used in the past in order to achieve this goal. On the one hand, nucleon form factors (FFs) measured in elastic electron scattering provide information on the transverse charge and current distributions inside the nucleon [1]. On the other hand, parton distribution functions (PDFs) measured in deeply inelastic scattering (DIS) characterize the longitudinal momentum distribution of the underlying quarks and gluons [2]. Twenty years ago, FFs and PDFs were unified within the formalism of generalized parton distributions (GPDs) [3–5]. GPDs are universal functions encoding a wealth of information about the nucleon internal structure such as the correlation between the transverse position of quarks and gluons (partons) and their longitudinal momenta [6]. GPDs also provide access to the contribution of quark and gluon orbital angular momenta to the nucleon spin [4]. Eight GPDs for each quark flavor  $q$  describe nucleon structure at leading order in  $1/Q$  (twist-2). They correspond to each combination of nucleon and parton helicities. The four chiral-even GPDs ( $H^q$ ,  $E^q$ ,  $\tilde{H}^q$ , and  $\tilde{E}^q$ ) conserve the helicity of the parton whereas the four chiral-odd, or transversity GPDs ( $H_T^q$ ,  $E_T^q$ ,  $\tilde{H}_T^q$ , and  $\tilde{E}_T^q$ ), flip the parton helicity [7,8].

GPDs parametrize the structure of the target independently of the reaction [7]. Chiral-even GPDs can be accessed experimentally via hard exclusive processes such as deeply virtual Compton scattering (DVCS) and deeply virtual meson electroproduction (DVMP) in the Bjorken limit  $Q^2 \rightarrow \infty$  and  $t/Q^2 \ll 1$  at fixed  $x_B$ . Recent results on DVCS show the validity of this limit at values of  $Q^2$  as low as  $1.5 \text{ GeV}^2$  [9–11]. In the case of DVMP, the longitudinal scattering amplitude factorizes into a hard perturbative contribution and a soft convolution of the nucleon GPDs and the meson distribution amplitude (DA). The transverse virtual photo-production amplitude is proven to be

suppressed by a factor of  $1/Q^2$  at sufficiently high values of  $Q^2$  [12]. In the case of  $\pi^0$  electroproduction, it was suggested in Refs. [13,14] that a large contribution to the transverse amplitude could arise from the convolution of the transversity GPDs of the nucleon with a twist-3 quark-helicity flip pion DA. Model calculations including the transversity GPDs have successfully described recent  $\pi^0$  electroproduction data on a proton target, measured at Jefferson Lab (JLab) [15–18]. Measurements of  $\pi^0$  electroproduction on the neutron are extremely interesting as they provide the exciting possibility to separate the individual contributions of the  $u$  and  $d$  quarks to the cross sections, when combined with measurements from a proton target at the same kinematics.

The differential cross section of deeply virtual  $\pi^0$  production is given by [19]:

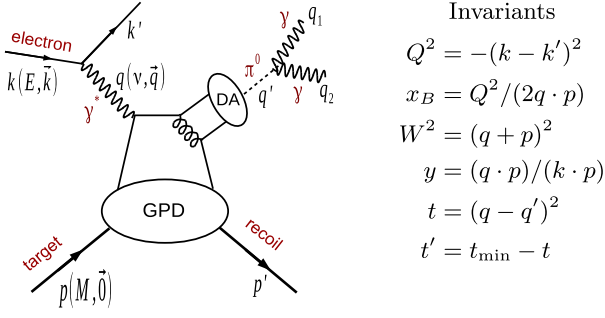
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi} \frac{d^2\Gamma_A}{dQ^2 dx_B} \left( \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \times \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi \right), \quad (1)$$

where  $\phi$  is the angle between the hadronic and leptonic planes following the Trento Convention [20]. The virtual photon flux factor  $d^2\Gamma_A$  and photon polarization  $\epsilon$  are defined by

$$\frac{d^2\Gamma_A}{dQ^2 dx_B} = \frac{\alpha}{2\pi} \frac{y^2(1-x_B)}{x_B Q^2} \frac{1}{1-\epsilon},$$

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

Figure 1 shows the lowest order Feynman diagram of the reaction and includes definitions of the kinematic variables. The  $\phi$  dependence in Eq. (1) allows the extraction of the



Invariants

$$Q^2 = -(k - k')^2$$

$$x_B = Q^2 / (2q \cdot p)$$

$$W^2 = (q + p)^2$$

$$y = (q \cdot p) / (k \cdot p)$$

$$t = (q - q')^2$$

$$t' = t_{\min} - t$$

FIG. 1. Diagram of the coherent  $\pi^0$  electroproduction reaction on the nucleon ( $M = M_N$ ,  $x_B = 0.36$ ) or deuteron ( $M = M_d$ ,  $x_B = 0.18$ ) with the dominant  $\pi^0 \rightarrow \gamma\gamma$  decay mode. The minimal  $|t|$  value is  $t_{\min} = (Q^2 + m_{\pi^0}^2)^2 / (4W^2) - (|\vec{q}^{\text{c.m.}}| - |\vec{q}'^{\text{c.m.}}|)^2$ , where  $m_{\pi^0}$  is the  $\pi^0$  mass,  $q' = q_1 + q_2$ , and the c.m. superscript refers to the target  $-\pi^0$  center-of-mass frame.

interference terms  $d\sigma_{TL}/dt$  and  $d\sigma_{TT}/dt$  while measurements of the total cross section at two incident beam energies and fixed  $Q^2$  and  $x_B$  separate  $d\sigma_T/dt$  and  $d\sigma_L/dt$ .

In JLab Hall A experiment E08-025, we measured the  $D(e, e'\pi^0)X$  reaction, with the primary goal of extracting the  $n(e, e'\pi^0)n$  cross section in the quasi-free approximation. We perform a Rosenbluth separation, based on data taken with incident beam energies  $E = 4.455$  ( $\epsilon = 0.65$ ) and  $5.550$  GeV ( $\epsilon = 0.79$ ). A 15-cm-long liquid deuterium (LD2) target was used as a quasifree neutron target. The quasifree  $\pi^0$  electroproduction events off the proton are subtracted using the data from experiment E07-007 [18], similarly to the analysis of DVCS off the neutron in Ref. [21]. These two experiments ran concurrently with liquid hydrogen (LH2) and LD2 targets interchanged daily to minimize systematic uncertainties. Scattered electrons were detected with  $10^{-4}$  momentum resolution in the left high resolution spectrometer (HRS) of Hall A [22], which determined accurately the electron scattering kinematics centered at  $x_B = 0.36$  and  $Q^2 = 1.75$  GeV<sup>2</sup>. The two photons from the  $\pi^0$  decay were detected in an electromagnetic calorimeter composed of a  $13 \times 16$  array of  $3 \times 3 \times 18.6$  cm<sup>3</sup> PbF<sub>2</sub> crystals, resulting in a  $[0, 2\pi]$  coverage in  $\phi$  and  $[0, 0.25]$  GeV<sup>2</sup> range in  $t' = t_{\min} - t$ . A 3.1% energy resolution at 3.16 GeV and a 0.6 ns  $\pi^0$ -electron coincidence time resolution was achieved by means of a 1 GHz flash ADC system in each calorimeter channel. The calibration of the calorimeter was performed with elastic  $H(e, e'_{\text{Calo}})p_{\text{HRS}}$  data from dedicated runs in which the scattered electrons were detected in the calorimeter, with energy predetermined by the kinematics of the elastic recoil proton in the HRS. The calorimeter calibration was monitored continuously *a posteriori* by tracking the 2-photon invariant mass  $m_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$  and the  $ep \rightarrow e\pi^0 X$  missing mass squared  $M_X^2 = (q + p - q_1 - q_2)^2$ . Exclusive  $\pi^0$  electroproduction events are selected for each  $(t', \phi)$  bin by applying a bidimensional cut:

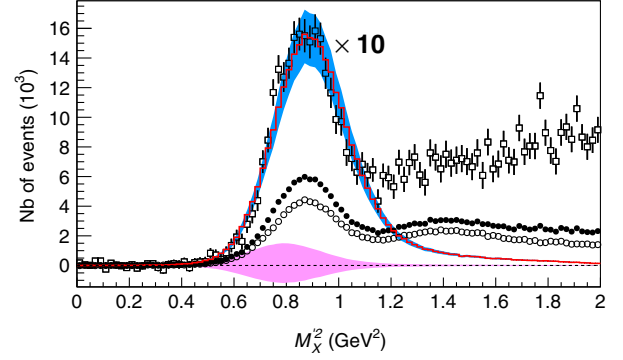


FIG. 2. Corrected missing mass squared  $M_X^2$  for  $D(e, e'\pi^0)X$  (solid circles) and normalized Fermi-smear  $H(e, e'\pi^0)X$  events (open circles). Bars show statistical uncertainties. The difference between the two distributions (squares) is scaled by a factor 10 for clarity. The blue and magenta bands (both scaled  $\times 10$ ), show the simulated  $n(e, e'\pi^0)n$  and  $d(e, e'\pi^0)d$  yields, respectively, fit to the data by minimizing Eq. (6). These bands include the statistical uncertainty of the fit. The total fit to the open squares distribution is shown by the solid (red) histogram.

$$|m_{\gamma\gamma} - m_{\pi^0}| < 4\sigma_{m_{\gamma\gamma}}; \quad (3)$$

$$M_X^2 = M_X^2 + C(m_{\gamma\gamma} - m_{\pi^0}) < 0.95 \text{ GeV}^2, \quad (4)$$

$$0.5 \text{ GeV}^2 < M_X^2,$$

where  $\sigma_{m_{\gamma\gamma}}$  is the resolution of the reconstructed  $\pi^0$  invariant mass, and the empirical factor  $C = 13$  GeV takes into account the natural correlation between the invariant mass and missing mass originating from energy fluctuations in the calorimeter. Figure 2 shows the corrected missing mass squared  $M_X^2$  obtained at  $E = 4.455$  GeV for LH2 and LD2 data sets where  $M_X^2$  is calculated with a target 4-vector  $p$  corresponding to a nucleon at rest. Accidentals were subtracted from these spectra and the LH2 data were normalized to the same integrated luminosity as the LD2 data.

The average momentum transfer to the target  $\langle |\vec{\Delta}| \rangle = \langle |\vec{q} - \vec{q}'| \rangle$  in the kinematics of this experiment is much larger than the average  $np$  relative momentum in the deuteron wave function  $\langle |\vec{p}_F| \rangle$ . Below the threshold for the production of a second pion, the impulse approximation is expected to accurately describe the exclusive  $D(e, e'\pi^0)X$  yield, with  $X = np \oplus d$ . Thus, we write the cross section as the sum of the coherent elastic channel  $d(e, e'\pi^0)d$  and two incoherent quasielastic contributions:

$$D(e, e'\pi^0)X = d(e, e'\pi^0)d + n(e, e'\pi^0)n + p(e, e'\pi^0)p. \quad (5)$$

We subtract the  $p(e, e'\pi^0)p$  yield from the deuterium data by normalizing our  $H(e, e'\pi^0)X$  data to the luminosity of

the LD2 data. The Fermi-momentum  $\vec{p}_F$  of bound protons inside the deuteron is statistically added to the LH2 data following the distribution given in Ref. [23] since this effect is intrinsically present in the  $M_X^2$  spectrum of the LD2 data. The Fermi-momentum smearing increases the width of the missing mass distribution by less than 1%. The result of the subtraction of the  $H(e, e'\pi^0)X$  data from the  $D(e, e'\pi^0)X$  yield is shown in Fig. 2. The  $d(e, e'\pi^0)d$  and  $n(e, e'\pi^0)n$  channels are, in principle, kinematically separated by  $\Delta M_X^2 = t(1 - M/M_d) \approx t/2$ , where  $M_d$  is the deuteron mass. This kinematic shift, due to the calculation of  $M_X^2$  using  $p(M_N, \vec{0})$ , is exploited in the procedure described below to separate the contributions of the quasifree neutron and coherent deuteron channels in the total  $\pi^0$  electroproduction cross section.

Figure 2 illustrates that the exclusive  $\pi^0$  electroproduction events are primarily localized below the production threshold for a second pion:  $M_X^2 < (M + m_{\pi^0})^2 \approx 1.15 \text{ GeV}^2$ . However, we apply a nominal cut of  $M_X^2 < 0.95 \text{ GeV}^2$  to minimize any contamination of inclusive events that might arise from resolution effects (see Fig. 2 in Ref. [18] for more details). The resulting events below this  $M_X^2$  cut are divided into  $12 \times 2 \times 5 \times 30$  bins in  $\phi$ ,  $E$ ,  $t'$ , and  $M_X^2$ , respectively. The first two variables allow the independent extraction of the four structure functions of the  $\pi^0$  electroproduction cross section while the binning in  $M_X^2$  enables the separation of the  $d(e, e'\pi^0)d$  and  $n(e, e'\pi^0)n$  contributions.

A Monte Carlo simulation of the experimental setup is based on the GEANT4 toolkit [24]. It includes both external and real internal radiative effects based on calculations described in Ref. [25]. A comparison with the radiative calculations of Ref. [26] at our central kinematics showed agreement within 2%. The virtual internal effects are applied as a global correction factor to the extracted cross sections. The HRS acceptance is modeled by an  $R$  function [27] defining correlated multidimensional boundaries. Only the overlapping ( $Q^2, x_B$ ) phase space between the two beam energy settings is considered. The calorimeter energy resolution in the  $p(e, e'\pi^0)p$  simulation is smeared to match the  $M_X^2$  distribution in each ( $E, t', \phi$ ) bin of the LH2 data. These bin-by-bin resolution smearing factors are also applied to the  $n(e, e'\pi^0)n$  and  $d(e, e'\pi^0)d$  simulated data. The Fermi smearing described above is also applied to the simulated  $n(e, e'\pi^0)n$  yields. The systematic uncertainty of this smearing procedure as well the asymmetric systematic uncertainty originated from the inclusive yield under the  $M_X^2$  cut are evaluated by varying the cut applied around its nominal value. They are found to be bin dependent and were added quadratically to the 3.1% normalization uncertainty listed in Ref. [18].

We fit the simulated yield to the experimental distributions for all bins in  $\phi$ ,  $E$ ,  $t'$ , and  $M_X^2$ . To wit, we minimize the  $\chi^2$ :

$$\chi^2 = \sum_{i=1}^{3600} \left( \frac{N_i^{\text{exp}} - N_i^{\text{sim}}}{\delta_i^{\text{exp}}} \right)^2, \quad (6)$$

where  $N_i^{\text{exp}}$  ( $N_i^{\text{sim}}$ ) is the number of experimental (simulated) events in bin  $i$  and  $\delta_i^{\text{exp}}$  is the corresponding uncertainty. The kinematic factors appearing in Eq. (1) are convoluted with the experimental acceptance and resolution in the computation of  $N_i^{\text{sim}}$ . The eight cross-section structure functions  $d\sigma_{\Lambda}^{n,d}(t')/dt$  ( $\Lambda = T, L, LT, TT$ ) that define  $N_i^{\text{sim}}$  are the free parameters of the fit for each  $t'$  bin. The minimization of Eq. (6) yields a value of  $\chi^2/ndf = 0.98$ .

Figure 3 shows the measured  $\phi$ -dependent photoabsorption cross section for both beam energies and for the lowest  $t'$  bin. The  $d^2\sigma^n/dtd\phi$  cross section is almost independent of the beam energy, indicating a dominance of the transverse response. The  $d^2\sigma^d/dtd\phi$  cross section is found negligible within uncertainties for all  $\phi$  bins. The fit to the  $M_X^2$  distribution is shown in Fig. 2, which also illustrates that the LD2–LH2 yield is dominated by the neutron contribution in the exclusive region. In Fig. 4, we display the  $\phi$ -independent cross section  $d\sigma_T + ed\sigma_L$  for the two beam energies, separated into the fitted quasifree neutron and coherent deuteron channels. The highest  $t'$  bin is used in the analysis to treat bin migration effects and is not shown herein. The figure again shows the clear separation of the neutron signal. The coherent deuteron cross sections are found to be very small and compatible with theoretical calculations based on chiral-even deuteron GPDs, which predict cross-section values smaller than 1 nb/GeV<sup>2</sup> in similar kinematics [28].

Figure 5 shows the four extracted structure functions for the neutron and the deuteron as functions of  $t'$ . The neutron

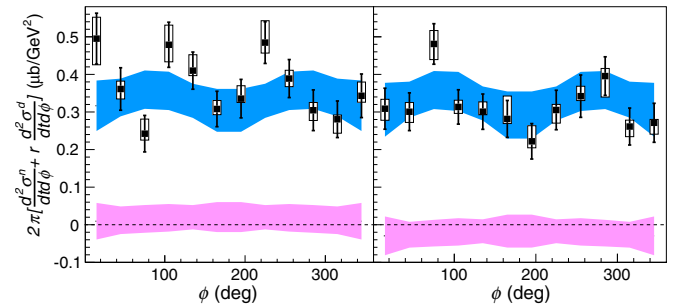


FIG. 3. Total cross section  $2\pi[d^2\sigma^n/dtd\phi + r(d^2\sigma^d/dtd\phi)]$  as a function of  $\phi$  at  $E = 4.45 \text{ GeV}$  (left) and  $E = 5.55 \text{ GeV}$  (right), in the bin  $\langle t' \rangle = 0.025 \text{ GeV}^2$  (neutron kinematics), equivalently  $\langle t' \rangle = 0.021 \text{ GeV}^2$  (deuteron kinematics), with  $r = 1.27$  (left) and  $r = 1.33$  (right) being the ratio deuteron-neutron of the virtual photon flux convoluted with the experimental acceptance. The error-bars show the statistical uncertainty. The boxes around the points show the total systematic uncertainties. The blue and magenta bands represent the contributions of  $2\pi(d^2\sigma^n/dtd\phi)$  and  $2\pi(d^2\sigma^d/dtd\phi)$ , respectively, including the statistical uncertainty of the fit.

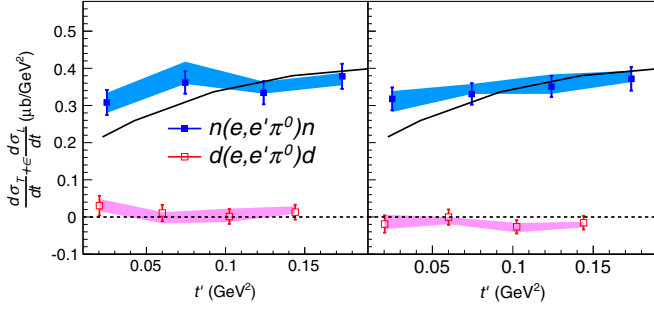


FIG. 4. The  $\phi$ -independent photoproduction cross sections extracted from the fit, as functions of  $t'$ , and separated into quasifree neutron and coherent deuteron contributions:  $d\sigma_T^n/dt + \epsilon(d\sigma_L^n/dt)$  and  $d\sigma_T^d/dt + \epsilon(d\sigma_L^d/dt)$ . The data in the left and right panels were obtained at  $E = 4.45$  and  $E = 5.55$  GeV, respectively. The error bars show the statistical uncertainty from the fit. The blue and magenta bands represent the systematic errors. The solid lines are theoretical calculations for the neutron from Ref. [14].

cross sections are dominated by  $d\sigma_T^n/dt$  and  $d\sigma_{TT}^n/dt$ , while the terms involving a longitudinal response are compatible with zero within uncertainties and are in good agreement with previous results off a proton target at the same kinematics [18]. The neutron measurements are compared to a calculation based on both quark helicity-conserving GPDs and quark helicity-flip (transversity) GPDs [14], and show good agreement for all structure functions, with a slight overestimation of  $|d\sigma_{TT}^n/dt|$ . The experimental  $d\sigma_L^n/dt$  term is also compatible with the VGG model [29] based on chiral-even GPDs, which predicts  $d\sigma_L^n/dt < 4$  nb/GeV<sup>2</sup> for all  $t'$  bins. Together with previous measurements of  $d\sigma_T/dt$  and  $d\sigma_{TT}/dt$  on the proton [18] and extensive unseparated measurements before [15–17], these new results provide strong support to the exciting idea that transversity GPDs can be accessed via neutral pion electroproduction in the high  $Q^2$  regime.

Within the modified factorization approach of [14],  $d\sigma_T/dt$  and  $d\sigma_{TT}/dt$  are functions of  $\langle H_T \rangle$  and  $\langle \bar{E}_T \rangle$ , which are convolutions of the elementary  $\gamma^*q \rightarrow q\pi^0$  amplitude with the transversity GPDs  $H_T$  and  $\bar{E}_T = 2\tilde{H}_T + E_T$ :

$$\frac{d\sigma_T}{dt} = \Lambda \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 \right], \quad (7)$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2. \quad (8)$$

In these equations  $\Lambda(Q^2, x_B)$  is a phase space factor [17] and  $\xi \simeq x_B/(2 - x_B)$  is the skewness variable. For a proton and a neutron target, the quark-flavor structures of  $|\langle H_T \rangle|^2$  (neglecting strange quarks) are

$$|\langle H_T^{p,n} \rangle|^2 = \frac{1}{2} \left| \frac{2}{3} \langle H_T^{u,d} \rangle + \frac{1}{3} \langle H_T^{d,u} \rangle \right|^2, \quad (9)$$

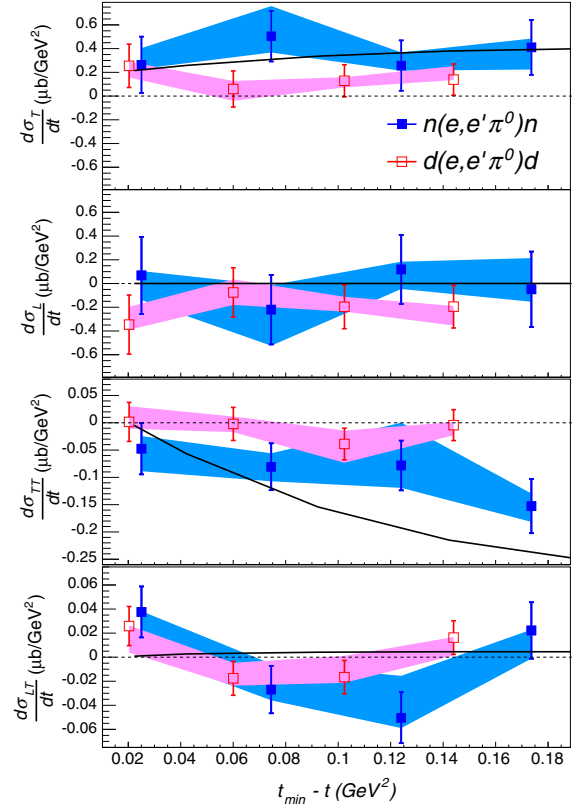


FIG. 5. Structure functions  $d\sigma_T/dt$ ,  $d\sigma_L/dt$ ,  $d\sigma_{TL}/dt$ , and  $d\sigma_{TT}/dt$  as a function of  $t' = t_{\min} - t$  for the neutron (blue) and the deuteron (red). The filled bands around the points show systematic uncertainties. The solid lines are theoretical calculations for the neutron from Ref. [14].

with similar equations for  $|\langle \bar{E}_T \rangle|^2$ . The different flavor weights of the proton and neutron targets allow us to separately determine  $|\langle H_T^u \rangle|$  and  $|\langle H_T^d \rangle|$  (similarly  $|\langle \bar{E}_T^u \rangle|$  and  $|\langle \bar{E}_T^d \rangle|$ ) by combining the data we report herein and  $\pi^0$  electroproduction cross sections on the proton measured at the same kinematics as in Ref. [18]. The unknown relative phase between the  $u$  and  $d$  convolutions is treated as a systematic uncertainty in the separation. The flavor-separated results assuming no relative phase between the  $u$  and  $d$  convolutions are presented in Fig. 6, with the bands indicating their variation when the phase takes all possible values between 0 and  $\pi$ . This phase could be resolved with exclusive  $p(\gamma^*, \eta p)$  data in the same kinematics [30]. Figure 6 shows that the magnitudes of the  $u$ -quark convolutions are larger than the  $d$ -quark convolutions for all  $t$  bins. The results in Fig. 6 also demonstrate that the  $u$ -quark nucleon helicity nonflip term  $|\langle \bar{E}_T^u \rangle|$  is larger than the nucleon helicity flip term  $|\langle H_T^u \rangle|$ . The comparison to the Goloskokov-Kroll model [14] shows good agreement for  $|\langle H_T \rangle|$  for both quark flavors but an underestimation for  $|\langle \bar{E}_T^u \rangle|$ . The GPD  $H_T$  parametrization is constrained in the forward limit by the transversity parton distributions. However, no similar experimental constraint is available

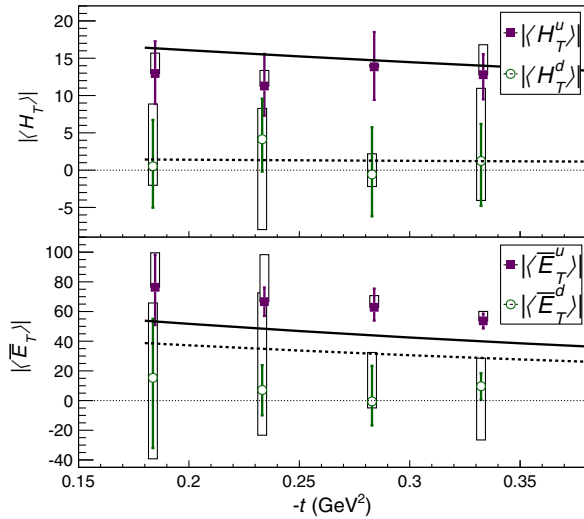


FIG. 6. Magnitude of the nucleon helicity-flip  $\langle H_T \rangle$  (top) and nonflip  $\langle \bar{E}_T \rangle$  (bottom) transversity terms for  $u$  (squares) and  $d$  (circles) quarks assuming no relative phase between them. The boxes around the points represent the variation of the results when their relative phase varies between 0 and  $\pi$ . Bars show the quadratic sum of the statistical and systematic uncertainties of the data. Solid (dashed) lines are calculations from the Goloskokov-Kroll model [14] for  $u$  ( $d$ ) quark.

for  $\bar{E}_T$ . The constraints on  $\bar{E}_T$  are mainly taken from lattice QCD calculations [31].

In conclusion, we have separated the four unpolarized structure functions of  $\pi^0$  electroproduction off the neutron at  $Q^2 = 1.75 \text{ GeV}^2$  and  $x_B = 0.36$  in the  $t'$  range  $[0, 0.2] \text{ GeV}^2$ . Similar measurements are obtained for coherent  $\pi^0$  electroproduction off the deuteron at  $x_B = 0.18$ . The latter are found to be very small and according to theoretical expectations. Neutron results show a dominance of the transverse response confirming the transversity GPD approach for the description of this process. By combining neutron and proton results, we have performed the first flavor decomposition of the  $u$  and  $d$  quark contributions to the cross section. Additional information from  $\eta$  meson electroproduction will soon help constraint the relative phase between the  $u$  and  $d$  quark contributions.

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