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E. L. Isupov et al. (CLAS Collaboration)

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Polarized Structure Function $\sigma_{LT'}$ from $\pi^0 p$ Electroproduction Data in the Resonance Region at $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$

E.L. Isupov,^{36,7} V.D. Burkert,³⁹ A.A. Golubenko,³⁶ K. Joo,⁷ N.S. Markov,^{39,7} V.I. Mokeev,³⁹ L.C. Smith,⁴⁶ W.R. Armstrong,¹ H. Atac,³⁸ H. Avakian,³⁹ N.A. Baltzell,³⁹ L. Barion,¹⁴ M. Battaglieri,^{39,16} I. Bedlinskiy,²⁶ F. Benmokhtar,⁸ A. Bianconi,^{41,20} L. Biondo,^{16,19,42} A.S. Biselli,^{9,3} M. Bondi,¹⁶ F. Bossù,⁵ W.J. Briscoe,¹³ W.K. Brooks,^{40,39} D. Bulumulla,³¹ R.A. Capobianco,⁷ D.S. Carman,³⁹ J.C. Carvajal,¹¹ P. Chatagnon,²¹ V. Chesnokov,³⁶ G. Ciullo,^{14,10} P.L. Cole,^{24,39} B.A. Clary,^{51,7} M. Contalbrigo,¹⁴ G. Costantini,^{41,20} A. D'Angelo,^{17,35} N. Dashyan,⁴⁸ R. De Vita,¹⁶ M. Defurne,⁵ A. Deur,³⁹ S. Diehl,^{32,7} C. Djalali,^{30,37} R. Dupre,²¹ H. Egiyan,³⁹ A. El Alaoui,⁴⁰ L. El Fassi,²⁵ L. Elouadrhiri,³⁹ P. Eugenio,¹² S. Fegan,⁴⁴ A. Filippi,¹⁸ G. Gavalian,^{39,27} G.P. Gilfoyle,³⁴ D.I. Glazier,⁴³ R.W. Gothe,³⁷ K.A. Griffioen,⁴⁷ M. Guidal,²¹ L. Guo,¹¹ K. Hafidi,¹ H. Hakobyan,^{40,48} M. Hattawy,³¹ T.B. Hayward,⁷ D. Heddle,^{6,39} K. Hicks,³⁰ A. Hobart,²¹ M. Holtrop,²⁷ I. Illari,¹³ D.G. Ireland,⁴³ D. Jenkins,⁴⁵ H.S. Jo,²³ D. Keller,⁴⁶ A. Khanal,¹¹ M. Khandaker,^{29,*} A. Kim,⁷ W. Kim,²³ F.J. Klein,⁴ V. Klimenko,⁷ A. Kripko,³² V. Kubarovsky,^{39,33} V. Lagerquist,³¹ L. Lanza,¹⁷ M. Leali,^{41,20} P. Lenisa,^{14,10} K. Livingston,⁴³ I. J. D. MacGregor,⁴³ D. Marchand,²¹ L. Marsicano,¹⁶ V. Mascagna,^{41,20} B. McKinnon,⁴³ Z.E. Meziani,¹ S. Migliorati,^{41,20} T. Mineeva,⁴⁰ M. Mirazita,¹⁵ C. Munoz Camacho,²¹ P. Nadel-Turonski,³⁹ K. Neupane,³⁷ S. Niccolai,^{21,13} T. O'Connell,⁷ M. Osipenko,¹⁶ P. Pandey,³¹ M. Paolone,²⁸ L.L. Pappalardo,^{14,10} R. Parenduzyan,³⁹ E. Pasyuk,³⁹ S.J. Paul,⁴⁹ W. Phelps,⁶ N. Pilleux,²¹ O. Pogorelko,²⁶ J. Poudel,³¹ J.W. Price,² Y. Prok,^{31,46} B.A. Raue,¹¹ T. Reed,¹¹ M. Ripani,¹⁶ J. Ritman,²² J. Rowley,³⁰ F. Sabatié,⁵ C. Salgado,²⁹ A. Schmidt,¹³ R.A. Schumacher,³ Y.G. Sharabian,³⁹ E.V. Shirokov,³⁶ U. Shrestha,⁷ P. Simmerling,⁷ D. Sokhan,^{5,43} N. Sparveris,³⁸ S. Stepanyan,³⁹ I.I. Strakovsky,¹³ S. Strauch,^{37,13} J.A. Tan,²³ R. Tyson,⁴³ M. Ungaro,^{39,33} S. Vallarino,¹⁴ L. Venturelli,^{41,20} H. Voskanyan,⁴⁸ E. Voutier,²¹ D. Watts,⁴⁴ K. Wei,⁷ X. Wei,³⁹ M.H. Wood,⁵⁰ B. Yale,⁴⁷ N. Zachariou,⁴⁴ J. Zhang,⁴⁶ and V. Ziegler³⁹

(The CLAS Collaboration)

¹Argonne National Laboratory, Argonne, Illinois 60439

²California State University, Dominguez Hills, Carson, CA 90747

³Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

⁴Catholic University of America, Washington, D.C. 20064

⁵IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

⁶Christopher Newport University, Newport News, Virginia 23606

⁷University of Connecticut, Storrs, Connecticut 06269

⁸Duquesne University, 600 Forbes Avenue, Pittsburgh, PA 15282

⁹Fairfield University, Fairfield CT 06824

¹⁰Università di Ferrara, 44121 Ferrara, Italy

¹¹Florida International University, Miami, Florida 33199

¹²Florida State University, Tallahassee, Florida 32306

¹³The George Washington University, Washington, DC 20052

¹⁴INFN, Sezione di Ferrara, 44100 Ferrara, Italy

¹⁵INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy

¹⁶INFN, Sezione di Genova, 16146 Genova, Italy

¹⁷INFN, Sezione di Roma Tor Vergata, 00133 Rome, Italy

¹⁸INFN, Sezione di Torino, 10125 Torino, Italy

¹⁹INFN, Sezione di Catania, 95123 Catania, Italy

²⁰INFN, Sezione di Pavia, 27100 Pavia, Italy

²¹Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

²²Institute für Kernphysik (Juelich), Juelich, Germany

²³Kyungpook National University, Daegu 41566, Republic of Korea

²⁴Lamar University, 4400 MLK Blvd, PO Box 10046, Beaumont, Texas 77710

²⁵Mississippi State University, Mississippi State, MS 39762-5167

²⁶National Research Centre Kurchatov Institute - ITEP, Moscow, 117259, Russia

²⁷University of New Hampshire, Durham, New Hampshire 03824-3568

²⁸New Mexico State University, PO Box 30001, Las Cruces, NM 88003, USA

²⁹Norfolk State University, Norfolk, Virginia 23504

³⁰Ohio University, Athens, Ohio 45701

³¹Old Dominion University, Norfolk, Virginia 23529

³²II Physikalisches Institut der Universität Giessen, 35392 Giessen, Germany

³³Rensselaer Polytechnic Institute, Troy, New York 12180-3590

³⁴University of Richmond, Richmond, Virginia 23173

³⁵ *Universita' di Roma Tor Vergata, 00133 Rome Italy*

³⁶ *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119234 Moscow, Russia*

³⁷ *University of South Carolina, Columbia, South Carolina 29208*

³⁸ *Temple University, Philadelphia, PA 19122*

³⁹ *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*

⁴⁰ *Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile*

⁴¹ *Università degli Studi di Brescia, 25123 Brescia, Italy*

⁴² *Università degli Studi di Messina, 98166 Messina, Italy*

⁴³ *University of Glasgow, Glasgow G12 8QQ, United Kingdom*

⁴⁴ *University of York, York YO10 5DD, United Kingdom*

⁴⁵ *Virginia Tech, Blacksburg, Virginia 24061-0435*

⁴⁶ *University of Virginia, Charlottesville, Virginia 22901*

⁴⁷ *College of William and Mary, Williamsburg, Virginia 23187-8795*

⁴⁸ *Yerevan Physics Institute, 375036 Yerevan, Armenia*

⁴⁹ *University of California, Riverside, California, 92521, USA*

⁵⁰ *Canisius College, Buffalo, NY*

⁵¹ *Lawrence Livermore National Laboratory, Livermore, CA, 94550*

The first results on the $\sigma_{LT'}$ structure function in exclusive $\pi^0 p$ electroproduction at invariant masses of the final state of $1.5 \text{ GeV} < W < 1.8 \text{ GeV}$ and in the range of photon virtualities $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$ were obtained from data on beam spin asymmetries and differential cross sections measured with the CLAS detector at Jefferson Lab. The Legendre moments determined from the $\sigma_{LT'}$ structure function have demonstrated sensitivity to the contributions from the nucleon resonances in the second and third resonance regions. These new data on the beam spin asymmetries in $\pi^0 p$ electroproduction extend the opportunities for the extraction of the nucleon resonance electroexcitation amplitudes in the mass range above 1.6 GeV.

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Studies of πN electroproduction are an effective tool for the exploration of nucleon resonance structure [1–5]. The CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab has provided most of the available information on these electroproduction channels at invariant masses of the final state hadrons $W < 1.8 \text{ GeV}$ and at photon virtualities $Q^2 < 5.0 \text{ GeV}^2$ [6–10]. The available data allow us to determine the nucleon resonance electroexcitation amplitudes (*i.e.* the $\gamma_v p N^*$ electrocouplings) for most resonances over this kinematic range [1, 2, 5, 9]. These results allow us to evaluate the resonant contribution to inclusive electron scattering with the $\gamma_v p N^*$ electrocouplings available from the experimental data, thereby paving the way to gain insight into the parton distributions in the ground state nucleon within the resonance excitation region [11, 12]. High-level analyses of the results on the $\gamma_v p N^*$ electrocouplings have revealed the structure of nucleon resonances as a complex interplay between the inner core of three dressed quarks and an external meson baryon cloud [1–3], shed light on the emergence of hadron mass [1, 4, 13, 14], and allow for the modeling of N^* structure within different quark models [15–20].

CLAS studies of $\pi^+ n$ electroproduction [9] have provided the $\gamma_v p N^*$ electrocouplings for the $N(1675)5/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$ resonances [15]. For a complete isospin analysis, it is important to explore both the $\pi^+ n$ and $\pi^0 p$ channels. Recently, new CLAS results on the differential $\pi^0 p$ electroproduction cross sections have become available for $W < 1.8 \text{ GeV}$ and $0.4 \text{ GeV}^2 <$

$Q^2 < 1.0 \text{ GeV}^2$ [10]. However, the data on πN electroproduction at $W > 1.6 \text{ GeV}$ and $Q^2 < 1.0 \text{ GeV}^2$ consist mostly of measurements with an unpolarized electron beam and an unpolarized proton target.

Measurement of the beam spin asymmetry (BSA) and the related $\sigma_{LT'}$ structure function can provide important constraints on the extraction of the $\gamma_v p N^*$ electrocouplings when combined with the differential cross sections. The $\sigma_{LT'}$ structure function determines the imaginary part of bilinear products between longitudinal and transverse amplitudes. Small contributions from the imaginary part of the longitudinal resonance amplitudes are amplified in their interference with the real part of the non-resonant contributions, making the BSAs an important observable for extraction of the longitudinal $S_{1/2}$ $\gamma_v p N^*$ electrocouplings. Previous studies of BSAs in both the $\pi^+ n$ and $\pi^0 p$ channels [21–24] were focused in the range of $W < 1.5 \text{ GeV}$. They demonstrated a substantial impact of the BSA data on the extraction of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ $S_{1/2}$ electrocouplings published in Ref. [5].

In this Letter, we present new measurements of the BSAs and $\sigma_{LT'}$ structure function from the CLAS $\pi^0 p$ electroproduction data with a major focus on the exploration of the second and third resonance regions. The data reported here cover the kinematic area of $1.5 \text{ GeV} < W < 1.8 \text{ GeV}$ and $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$ with the full angular range in the center-of-mass (CM) frame.

The data were taken during the e1e run period with the CLAS detector [25]. A longitudinally polarized electron

beam of 2.036-GeV energy and 10-nA nominal current was incident on a 2-cm-long liquid-hydrogen (LH_2) target. The beam polarization determined from Møller polarimeter measurements was $78.9 \pm 2.8(\text{stat}) \pm 3.0(\text{syst})\%$. All details on particle identification, event selection, and the related systematic uncertainties are available in our previous publication on $\pi^0 p$ cross sections and exclusive structure functions [10].

The kinematics of the $ep \rightarrow e'\pi^0 p$ reaction can be fully described by Q^2 , W and the final-state pion polar θ_π and azimuthal ϕ_π emission angles in the CM frame, where ϕ_π is defined relative to the electron scattering plane. The exclusive $\pi^0 p$ events were identified from the missing mass squared M_X^2 distributions in the reaction $ep \rightarrow e'pX$ after application of kinematic cuts to eliminate Bethe-Heitler backgrounds [10]. The exclusivity cuts over M_X^2 were applied in 3-dimensional bins of $(Q^2, W, \cos\theta_\pi)$. The selected $\pi^0 p$ events were binned using a $(Q^2, W, \cos\theta_\pi, \phi_\pi)$ grid consisting of 2 bins over Q^2 : from 0.4 GeV² to 0.6 GeV² and from 0.6 GeV² to 1.0 GeV², 28 bins over W , 10 bins over $\cos\theta_\pi$, and 12 bins over ϕ_π of equal sizes.

The measured asymmetry $A_{LT'}$ ($Q^2, W, \cos\theta_\pi, \phi_\pi$) was obtained from the event yields produced by the incoming electrons of positive and negative helicities, $N_\pi^+(Q^2, W, \cos\theta_\pi, \phi_\pi)$ and $N_\pi^-(Q^2, W, \cos\theta_\pi, \phi_\pi)$:

$$A_{LT'} = \frac{1}{P_e} \frac{(N_\pi^+ - N_\pi^-)}{(N_\pi^+ + N_\pi^-)}, \quad (1)$$

where P_e is the electron beam polarization. Representative examples of the BSA in the $ep \rightarrow e'\pi^0 p$ reaction at W values in the second and third resonance regions are shown in Fig. 1. The full set of BSA data from our measurement is available in the CLAS Physics Database [26]. The data in Fig. 1 are compared with the MAID model [27] predictions for the BSA computed with the $\gamma_v p N^*$ electrocouplings from CLAS analyses of πN and $\pi^+ \pi^- p$ data [5, 11, 15, 28, 29] and MAID analyses [30] of the πN electroproduction data. The BSAs predicted with the resonance electrocouplings from both the CLAS and MAID analyses are consistent in the second resonance region and reasonably reproduce the BSA data (see Fig. 1 (top)), demonstrating consistency of the MAID and CLAS analysis results on resonance electroexcitation in the second resonance region. In the third resonance region the BSAs computed with the CLAS and MAID results on the $\gamma_v p N^*$ electrocouplings are substantially different. Our results will be essential to improve the knowledge on the $\gamma_v p N^*$ electrocouplings of the resonances in the third resonance region.

The $\gamma_v p \rightarrow \pi^0 p$ virtual photon differential cross sections $\frac{d\sigma}{d\Omega_\pi}(Q^2, W, \cos\theta_\pi, \phi_\pi)$ for an electron beam of helicity h ($h = \pm 1$) off unpolarized protons depends on five structure functions. The transverse $\sigma_T(Q^2, W, \cos\theta_\pi)$, the longitudinal $\sigma_L(Q^2, W, \cos\theta_\pi)$, the transverse-transverse $\sigma_{TT}(Q^2, W, \cos\theta_\pi)$, and the longitudinal-

transverse $\sigma_{LT}(Q^2, W, \cos\theta_\pi)$ structure functions describe the helicity-independent part of the differential cross section, while the part proportional to the electron beam helicity h is described by the $\sigma_{LT'}(Q^2, W, \cos\theta_\pi)$ structure function [27]:

$$\begin{aligned} \frac{d\sigma}{d\Omega_\pi} &= \frac{p_\pi^*}{k_\gamma^*} (\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)} \sigma_{LT'} \sin\theta_\pi \sin\phi_\pi), \\ \sigma_0 &= \sigma_T + \epsilon_L \sigma_L + \epsilon \sigma_{TT} \sin^2\theta_\pi \cos 2\phi_\pi \\ &\quad + \sqrt{2\epsilon_L(1+\epsilon)} \sigma_{LT} \sin\theta_\pi \cos\phi_\pi, \end{aligned} \quad (2)$$

where p_π^* is the magnitude of the π^0 momentum in the CM frame. The commonly used real photon equivalent energy k_γ^* and the virtual photon polarization parameters ϵ and ϵ_L are described in Ref. [27].

Determination of $\sigma_{LT'}$ was made through the BSA $A_{LT'}$ and a parameterization of the σ_0 cross sections from the previous measurement [10]:

$$A_{LT'} = \frac{\sqrt{2\epsilon_L(1-\epsilon)} \sigma_{LT'} \sin\theta_\pi \sin\phi_\pi}{\sigma_0}. \quad (3)$$

The $A_{LT'}$ values are multiplied by σ_0 and the structure function $\sigma_{LT'}$ was then extracted using Eq.(3) through fitting the ϕ_π distributions in each bin of $(Q^2, W, \cos\theta_\pi)$. The systematic uncertainties of $\sigma_{LT'}$ are less than 10% and arise mainly from the uncertainties of the beam polarization P_e and the uncertainties of σ_0 from the available measurements [10]. The contributions from the systematic uncertainties for the BSAs are much smaller and were not included in the evaluation of the systematic uncertainties for $\sigma_{LT'}$. Representative examples of the structure functions $\sigma_{LT'}$ at $W > 1.6$ GeV are shown in Fig. 2. The full set of our results for $\sigma_{LT'}$ can be found in Ref. [26].

Results on the $\sigma_{LT'}$ structure function for $\pi^0 p$ electroproduction in the third resonance region are presented here for the first time. In Fig. 2 we also show the comparison between the data on $\sigma_{LT'}$ from our measurements and the expectations from MAID [27]. This unitarized reaction model incorporates all well-established resonances parameterized using Breit-Wigner amplitudes and with backgrounds calculated from t -channel vector-meson exchange and other Born diagrams. The $\sigma_{LT'}$ are computed with the $\gamma_v p N^*$ resonance electrocouplings obtained from the analyses of the πN electroproduction channels only [30] and from the CLAS πN and $\pi^+ \pi^- p$ electroproduction data [11, 28, 29].

In order to explore the sensitivity of $\sigma_{LT'}$ to the contributions from nucleon resonances (N^*), we decomposed this structure function using a Legendre polynomial expansion for each bin of (Q^2, W) to determine the Legendre moments $D_\ell(Q^2, W)$:

$$\sigma_{LT'} = \sum_{\ell=0}^{\ell_{\max}} D_\ell P_\ell(\cos\theta_\pi), \quad (4)$$

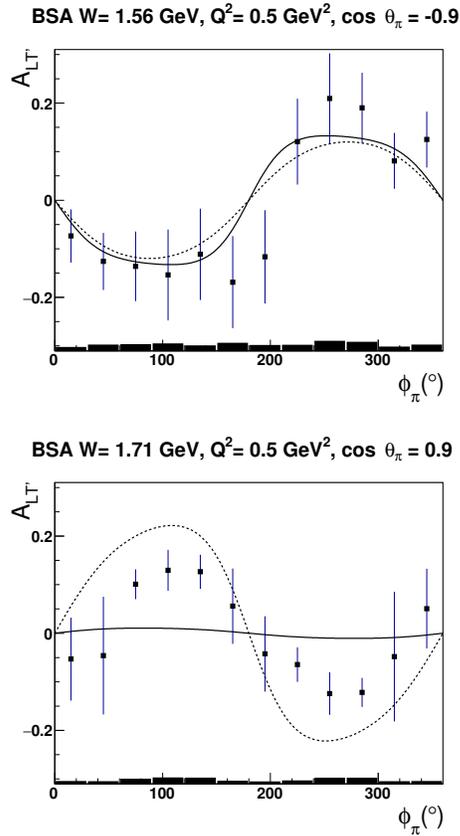


FIG. 1. BSA as a function of the CM pion azimuthal angle ϕ_π for the $ep \rightarrow e'\pi^0p$ reaction at $W=1.56 \text{ GeV}, Q^2 = 0.5 \text{ GeV}^2, \cos \theta_\pi = -0.9$ (top) and at $W=1.71 \text{ GeV}, Q^2 = 0.5 \text{ GeV}^2, \cos \theta_\pi = 0.9$ (bottom). The MAID model [27] expectation with the $\gamma_\nu pN^*$ electrocouplings from MAID [30] and the CLAS analyses [11, 28, 29] are shown by the solid and dotted lines, respectively.

with l from 0 to 3. The expansion of Eq.(4) is truncated at $l_{max} = 3$ to provide a stable description of the $\cos \theta_\pi$ dependence of $\sigma_{LT'}$. The results on the W dependence of the Legendre moments D_l are shown in Fig. 3. The full set of extracted Legendre moments is available in Ref. [26]. In order to relate the Legendre moments D_l to the bilinear products of the π^0p multipole electroproduction amplitudes, the formalism developed in Ref. [31] is used. The $\sigma_{LT'}$ structure function is expressed in terms of bilinear combinations of the F_i CGLN amplitudes, as described in Appendix C of Ref. [31]. Eqs. (23-28) in that paper allow us to relate the CGLN amplitudes F_i ($i=1,\dots,6$) to the bilinear products of the multipole amplitudes that enter into the D_l Legendre moments. Since the bilinear product of multipoles in the Legendre moments D_l of different l -values contain the contributions from resonances of different spins and parities, the Legendre moments D_l are suitable for disentangling the electroexcitation of different nucleon resonances.

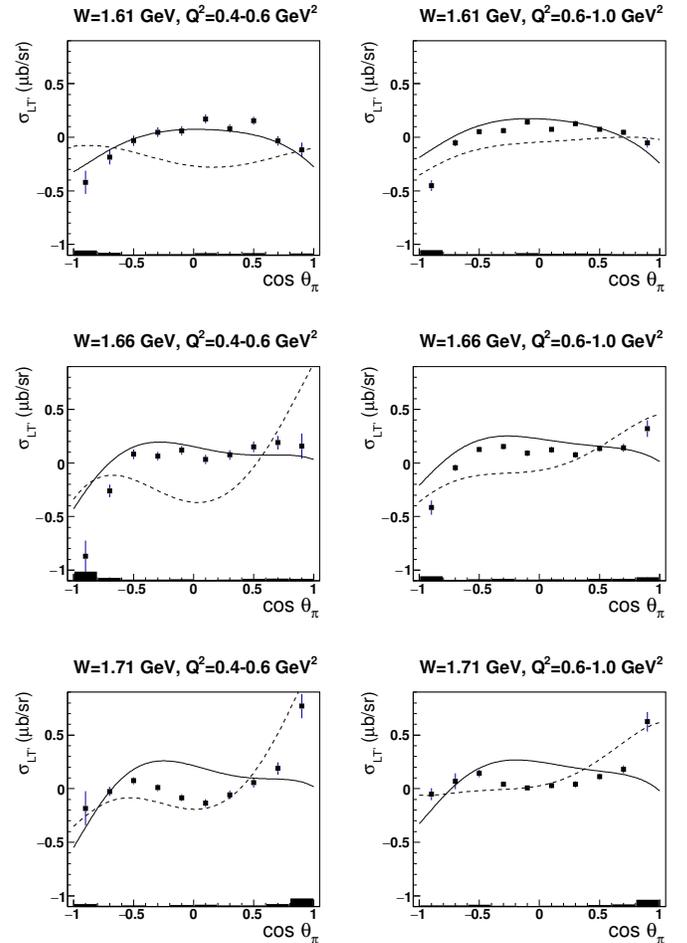


FIG. 2. The structure function $\sigma_{LT'}$ for π^0p electroproduction off protons at $W > 1.6 \text{ GeV}, Q^2$ from 0.4 GeV^2 to 0.6 GeV^2 (left panel) and from 0.6 GeV^2 to 1.0 GeV^2 (right panel). The lines represent the evaluations within the MAID reaction model [27] with the $\gamma_\nu pN^*$ electrocouplings from the πN electroproduction analysis [30] (solid line) and from the CLAS exclusive meson electroproduction data analyses (dashed line) [11, 28, 29]. The systematic uncertainties on the data are shown by the shadowed areas at the bottom of each plot.

We explored the sensitivity of the D_l Legendre moments to the variation of the $\gamma_\nu pN^*$ electrocouplings of all pronounced resonances in the second and third resonance regions and, in particular, to the $\Delta(1620)1/2^-, \Delta(1700)3/2^-,$ and $N(1720)3/2^+$ electrocouplings that currently have been established from solely the $\pi^+\pi^-p$ electroproduction data. The sensitivity of the D_l moments to the variation of the electrocouplings of all prominent resonances can be demonstrated by computing them within the MAID model [27] with the $\gamma_\nu pN^*$ electrocouplings from only the πN electroproduction data [30] and from the CLAS results [11, 28, 29] on the $\gamma_\nu pN^*$ electrocouplings determined from both πN and $\pi^+\pi^-p$ electroproduction as shown by the thick solid and

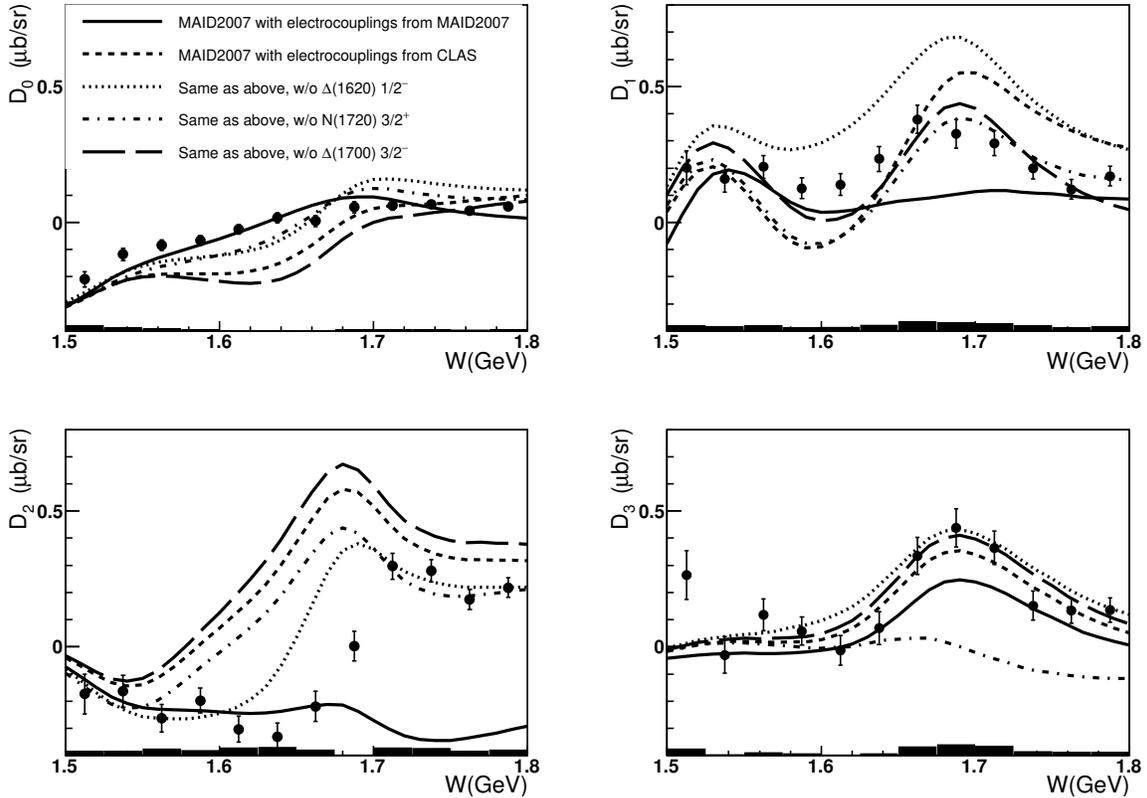


FIG. 3. Legendre moments $D_l(Q^2, W)$ ($l=0,1,2,3$) of the $\sigma_{LT'}$ structure function from the $\pi^0 p$ electroproduction data at $Q^2=0.4-0.6$ GeV 2 : $D_0(Q^2, W)$ (top left), $D_1(Q^2, W)$ (top right), $D_2(Q^2, W)$ (bottom left), $D_3(Q^2, W)$ (bottom right). The experimental results are shown by the filled circles with error bars accounting for the statistical uncertainties. The systematic data uncertainties are shown in the bottom part of each plot. The computed D_l moments within the MAID model [27] with the $\gamma_v p N^*$ electrocouplings from Ref. [30] and from Refs. [11, 28, 29] are shown by the thick solid and dashed lines, respectively. We also show the computed D_l values within the MAID model [27] with the $\gamma_v p N^*$ electrocouplings from Refs. [11, 28, 29] when the contributions from particular resonances are taken out: $\Delta(1620)1/2^-$ (thin dotted lines), $\Delta(1700)3/2^-$ (thick long-dashed lines), $N(1720)3/2^+$ (thin dash-dotted lines).

dashed lines in Fig. 3, respectively. The sensitivity of the D_l moments to the contribution from each of the states $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$ and $N(1720)3/2^+$ was studied by turning off each in turn while taking the $\gamma_v p N^*$ electrocouplings of the other resonances from the CLAS results [11, 28, 29]. The sensitivity to the particular resonance contributions can be seen in Fig. 3 as the difference between the computed D_l moments when the contributions from all resonances are taken into account (thick dashed lines) and when the contribution from a particular resonance is turned off. All D_l moments demonstrate variations outside the data uncertainties when the $\gamma_v p N^*$ electrocouplings from πN electroproduction [30] are replaced by the CLAS results [11, 28, 29], suggesting sensitivity of the $\sigma_{LT'}$ data to the resonance contributions in these kinematics.

The D_0 moment demonstrates sensitivity to the $\Delta(1620)1/2^-$ resonance (see Fig. 3 top left). This sensitivity is due to the multipole contributions of the D_0

decomposition:

$$D_0 \sim (5E_{3+}^* - 2E_{3-}^* + M_{1-}^* + M_{1+}^*)S_{0+} + E_{0+}^*(S_{3-} - S_{3+}). \quad (5)$$

We are using the well-known notations for the multipoles explained in Ref. [31]. The impact from the $\Delta(1620)1/2^-$ on the D_0 moment emerges from the interference between the S_{0+} resonance multipole with the transverse multipoles from the non-resonant contributions, as well as from interference between the resonance E_{0+} transverse and longitudinal multipoles with the non-resonant contributions.

From the D_1 multipole decomposition, we found that D_1 should be sensitive, in particular, to the contributions from the $\Delta(1700)3/2^-$ and $N(1720)3/2^+$ resonances since the D_1 moment contains the products:

$$D_1 \sim -6E_{2-}^*S_{2-} - 6M_{2-}^*S_{2-} + 6E_{1+}^*S_{1+} - 6M_{1+}^*S_{1+}, \quad (6)$$

where the multipole and the multipole conjugated products in the first two terms contain contributions from the $\Delta(1700)3/2^-$ and in the second two terms from the $N(1720)3/2^+$. The expected sensitivities are supported by the data on the D_1 moment (see Fig. 3 top right).

At W from 1.65 GeV to 1.70 GeV, the D_2 moment evolves rapidly and changes sign (see Fig. 3 bottom left). Making use of the CLAS results on the $\gamma_n p N^*$ electrocouplings [11, 28, 29] allows us to reproduce this trend even when the contributions from either the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, or $N(1720)3/2^+$ are turned off.

The D_2 moment is sensitive to the $\Delta(1620)1/2^-$ and $N(1720)3/2^+$ resonances. This sensitivity emerges from the following terms in the D_2 multipole decomposition:

$$\begin{aligned} D_2 \sim & 12(M_{2+}^* - E_{2-}^*)S_{1+} \quad (7) \\ & + 6(3E_{2+}^* + 2M_{2+}^*)S_{1+} - 15M_{1+}^*S_{2-} \\ & + 5(5E_{3+}^* - 2E_{3-}^* + M_{3-}^* - M_{3+}^*)S_{0+} \\ & + 5E_{0+}^*(3S_{3-} - 4S_{3+}). \end{aligned}$$

The $N(1720)3/2^+$ resonance impacts the D_2 moments owing to the interference between its longitudinal S_{1+} multipole and the transverse multipoles from the non-resonant contributions, as well as from the interference of the M_{1+} transverse resonance multipole and the longitudinal part of the non-resonant contributions. The $\Delta(1620)1/2^-$ impacts the D_2 moment because of the interference between its S_{0+} multipole and transverse non-resonant contributions, as well as due to the interference between the transverse E_{0+} multipole of the resonance and the longitudinal parts of the non-resonant contributions.

The D_3 moment is strongly affected by the $N(1720)3/2^+$ resonance (see Fig. 3 bottom right) due to the interference between the S_{1+} multipole for the resonance and the transverse part of the non-resonant processes, as well as because of the interference between the transverse M_{1+} resonance multipole and the longitudinal part of the non-resonant contribution seen in the multipole decomposition of D_3 :

$$\begin{aligned} D_3 \sim & 18(M_{3-}^* - E_{3+}^*)S_{1+} \quad (8) \\ & + (34E_{3+}^* - 36E_{3-}^*)S_{1+} - 28M_{1+}^*S_{3+}. \end{aligned}$$

Studies of the Legendre moment sensitivities to the resonant contributions at $0.6 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$ revealed similar features as those observed for the data at $0.4 \text{ GeV}^2 < Q^2 < 0.6 \text{ GeV}^2$ and discussed above.

In summary, the beam spin asymmetries and the $\sigma_{LT'}$ structure functions have become available from the CLAS data on exclusive $\pi^0 p$ electroproduction at 1.5 GeV $< W < 1.8$ GeV and photon virtualities $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$. These observables for $\pi^0 p$ electroproduction off protons were obtained for the first time at the invariant masses of the final state hadrons $W > 1.6$ GeV. The Legendre moments D_l ($l=0,1,2,3$) were determined from fits of the angular dependencies of $\sigma_{LT'}$ in each

bin of W and Q^2 covered by the measurements. The D_0 and D_1 Legendre moments demonstrate sensitivity to the electroexcitation amplitudes of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances. Previously, the information on the electroexcitation amplitudes of these excited states was obtained in the studies of $\pi^+ \pi^- p$ electroproduction off protons with CLAS [1, 29, 32]. Combined studies of the exclusive $\pi^+ n$ and $\pi^0 p$ electroproduction channels will provide independent results on the electroexcitation amplitudes of the nucleon resonances in the mass range of $W > 1.6$ GeV. Comparison of the results on the resonance electroexcitation amplitudes from the studies of both πN and $\pi^+ \pi^- p$ electroproduction will allow us to shed light on the systematic uncertainties in their extraction.

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* Current address: Idaho State University, Pocatello, Idaho 83209

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