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CLAS N^* Excitation Results from Pion and Kaon Electroproduction

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Abstract The study of the structure of excited nucleon N^* states employing the electroproduction of exclusive reactions is an important avenue for exploring the nature of the non-perturbative strong interaction. The electrocouplings of N^* states in the mass range below W=1.8 GeV have been determined from analyses of CLAS πN, ηN, and $\pi\pi N$ data at four-momentum transfers Q^2 up to 5 GeV^2. This work has made it clear that consistent results from independent analyses of several exclusive channels with different couplings and non-resonant backgrounds but the same N^* electroexcitation amplitudes, is essential to have confidence in the extracted results. In terms of hadronic couplings, many high-lying N^* states preferentially decay through the $\pi\pi N$ channel, while couplings to πN final states become rather small. The resonance parameters determined from πN and $\pi\pi N$ electroproduction can be checked in independent studies of the KY ($Y = \Lambda, \Sigma^0$) channels. Therefore, data from the KY channels already measured with CLAS will play an important role in N^* structure studies. These comparisons await the development of suitable reaction models. Starting in 2018, a program to study the structure of N^* states in various exclusive electroproduction channels using the new CLAS12 spectrometer will get underway. These studies will probe the structure of N^* states in the mass range up to W=3 GeV and Q^2 up to 12 GeV^2, thus providing a means to access N^* structure information spanning a broad regime encompassing both low- and high-energy degrees of freedom.

Keywords : Electromagnetic Interactions · Form Factors · Nucleon Structure · Excited Nucleon States

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1 Introduction

Intensive studies of the spectrum and structure of excited nucleon (N^*) states have played a crucial role in the development of our understanding of the strong interaction within the light quark sector. At the typical energy and distance scales found within the N^* states, the quark-gluon coupling is large. Therefore, we are confronted with the fact that quark-gluon confinement, hadron mass generation, and the dynamics that give rise to the N^* spectrum, cannot be understood within the framework of perturbative Quantum Chromodynamics (QCD). The need to understand QCD in this non-perturbative domain is a fundamental issue in nuclear physics, which the study of N^* structure can help to address. Such studies, in fact, represent a necessary step toward understanding how QCD in the regime of large quark-gluon couplings generates mass and how systems of confined quarks and gluons, i.e. mesons and baryons, are formed. These questions are among the most challenging open problems within the Standard Model of fundamental particles and interactions [1]. As a result of intense experimental and theoretical effort over the past 40 years, it is now apparent that the structure of N^* states is much more complex than what can be described in terms of models based on constituent quarks alone.

Electroproduction reactions $\gamma^* N \to N^* \to M + B$ provide a tool to probe the inner structure of the contributing N^* resonances through the extraction of the amplitudes that describe the transition between the virtual photon-nucleon initial state and the excited N^* state, i.e. the $\gamma_v NN^*$ electrocoupling amplitudes, which are directly related to the N^* structure. These electrocouplings can be represented by the so-called transition helicity amplitudes $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ that describe the N^* resonance electroexcitation for the two different helicity configurations of a transverse photon and the nucleon, and $S_{1/2}(Q^2)$ that describes the N^* resonance electroexcitation by longitudinal photons of zero helicity [2]. The Q^2 evolution of these electrocoupling amplitudes provides fundamental information on the relevant degrees of freedom that describe the structure of the nucleon as a function of distance scale. These fundamental quantities are now subject to computations starting from theoretical approaches based on the QCD Lagrangian.

Detailed comparisons of the theoretical predictions for these amplitudes against the experimental measurements form the basis of progress toward gauging our understanding of non-perturbative QCD. The measurement of the $\gamma_v NN^*$ electrocouplings is needed in order to gain access to the dynamical momentum-dependent mass and structure of the dressed quark in the non-perturbative domain where the quark-gluon coupling is large [3], through mapping of the dressed quark mass function [4] and extraction of the quark distribution amplitudes for N^* states of different quantum numbers [5]. This is critical in exploring the nature of quark-gluon confinement and dynamical chiral symmetry breaking (DCSB) in baryons.

Studies of low-lying nucleon excited states using electromagnetic probes at four-momentum transfers $Q^2 < 5$ GeV^2 have revealed that the structure of N^* states is a complex interplay between the internal core of three dressed quark and an external meson-baryon (M-B) cloud. N^* states of different quantum numbers have significantly different relative contributions from these two components, demonstrating distinctly different manifestations of the non-perturbative strong interaction in their generation. The relative contribution of the quark core increases with Q^2 in a gradual transition to a dominance of quark degrees of freedom for $Q^2 > 5$ GeV^2. This kinematics area still remains almost unexplored in exclusive reactions. Studies of the Q^2 evolution of N^* structure from low to high Q^2 offer access to the strong interaction between dressed quarks in the non-perturbative regime that is responsible for N^* formation.

Figure 1 illustrates the two contributions to the $\gamma_v NN^*$ electrocouplings. In Fig. 1(b) the virtual photon interacts directly with the constituent quark, an interaction that is sensitive to the quark current and depends on the quark-mass function. However, the full meson electroproduction amplitude in Fig. 1(a) requires contributions to the $\gamma_v NN^*$ vertex from both non-resonant meson electroproduction and the hadronic scattering amplitudes as shown in Fig. 1(c). These contributions incorporate all possible intermediate meson-baryon states and all possible meson-baryon scattering processes that eventually result in N^* formation in the intermediate state of the reaction. These two contributions can be separated from each another using, for example, a coupled-channel reaction model [6,7].

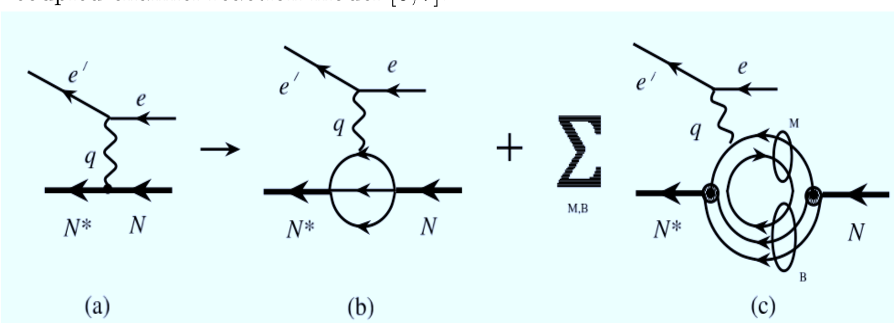

Fig. 1 Schematic representation of the $\gamma^* N \to N^*$ electroproduction process. (a) The fully dressed $\gamma_v NN^*$ electrocoupling that determines the N^* contribution to the resonant part of the meson electroproduction amplitude. (b) The contribution of the three-quark core. (c) The contribution from the meson-baryon cloud, where the sum is over all intermediate meson and baryon states. This figure was taken from Ref. [8].

Current theoretical approaches to understand N^* structure fall into two broad categories. In the first category are those that enable direct connection to the QCD Lagrangian, such as Lattice QCD (LQCD) and continuous QCD applications of the Dyson-Schwinger equations (DSE). In the second category are those that use models inspired by or derived from our knowledge of QCD, such as quark-hadron duality, light-front holographic QCD (AdS/QCD), light-cone sum rules (LCSR), and constituent quark models (CQMs). See Ref. [8] for an overview of each of these different approaches. It is important to realize that even those approaches that attempt to solve QCD directly can only do so approximately, and these approximations ultimately represent limitations that need careful consideration. As such, it is imperative that whenever possible, the results of these intensive and challenging calculations be compared directly to the data on resonance electrocouplings from electroproduction experiments over a broad range of Q^2 for N^* states with different quantum numbers.

2 CLAS N^* Program

Studies of the structure of the excited nucleon states, the so-called N^* program, is one of the key cornerstones of the physics program in Hall B at Jefferson Laboratory (JLab). The large acceptance spectrometer CLAS [9], which began data taking in 1997 and was decommissioned in 2012, was designed to measure photo- and electroproduction cross sections and polarization observables for beam energies up to 6 GeV over a broad kinematic range for a host of different exclusive reaction channels.

The photoproduction data sets from CLAS and other experiments have been used extensively in order to determine the resonance parameters from independent analyses of the πN, ηp, and $\pi\pi N$ exclusive channels, as well as from global multi-channel analyses within advanced coupled-channel approaches [6, 7]. However, data at Q^2=0 only allows for the identification of N^* states and the determination of their quantum numbers. In order to gain access to the structure of different N^* states, the determination of the Q^2 dependence of the $\gamma_v NN^*$ electrocouplings is necessary. In addition, electrocoupling data are promising for N^* studies and the search for new N^* states as the ratio of the resonant to non-resonant amplitudes increases with increasing Q^2 as seen in recent studies of CLAS πN and $\pi\pi p$ data [10].

The goal of the N^* program with CLAS is to study the spectrum of N^* states and their associated structure over a broad range of distance scales through studies of the Q^2 dependence of the $\gamma_v NN^*$ electrocouplings. An important constraint on the studies of electroproduction data is that the fit parameters for the N^* states must be described by Q^2-independent resonance masses and hadronic decay widths. The goal to extract the N^* resonance electrocouplings from the data is realized through two distinct phases. The first phase consists of the measurements of the cross sections and polarization observables in as fine a binning as the data support in the relevant kinematic variables Q^2, W, $d\tau_{hadrons}$ (where $d\tau_{hadrons}$ represents the phase space of the final state hadrons). The second phase consists of employing advanced reaction models that reasonably reproduce the data over its full phase space, in order to then extract the photo- and electrocoupling amplitudes and the hadronic decay widths for the dominant contributing N^* states in each different final state.

2.1 Non-Strange Final States

The electrocoupling amplitudes for most N^* states below 1.8 GeV have been extracted for the first time from analysis of CLAS data using electroproduction from a proton target in the exclusive $\pi^+ n$ and $\pi^0 p$ channels for Q^2 up to 5 GeV^2, in ηp for Q^2 up to 4 GeV^2, and for $\pi^+\pi^- p$ for Q^2 up to 1.5 GeV^2. These data include unpolarized differential cross sections, longitudinally polarized beam asymmetries, and longitudinal target and beam-target spin asymmetries. Resonance extractions from cross section and polarization data represent a complex exercise and involve a level of model and fit uncertainty. Therefore, it is highly desirable that the resonance transitions are determined from at least two different final states.

The available πN data from CLAS and other experiments have been analyzed within the framework of two conceptually different approaches based on a unitary isobar model (UIM) and a dispersion relation (DR) approach [11,12]. The UIM describes the N^* electroproduction amplitudes as a superposition of the N^* electroexcitations in the s-channel and the non-resonant Born terms. π, ρ, and ω exchanges in the t-channel were taken into account. In the DR approach, dispersion relations are employed that relate the real to the imaginary parts of the invariant amplitudes that describe the N^* electroproduction. Both approaches provide a good description of the πN data over the range of the available measurements. The $\pi^+\pi^- p$ electroproduction data from CLAS [10, 13,14] have been fit within the JM reaction model [15,16] with the goal of extracting resonance electrocouplings, as well as the $\pi\Delta$ and ρp hadronic decay widths. This model incorporates all relevant reaction mechanisms in the $\pi^+\pi^- p$ final state [17].

Figure 2 shows the $A_{1/2}$, $A_{3/2}$, and $S_{1/2}$ electrocouplings for the $\Delta(1232)\frac{3}{2}^+$ from analysis of $\pi^0 p$ data from CLAS [11], JLab Halls A and C [18,19], and MAMI [20]. This figure shows model predictions from the Light Cone Relativistic Quark Model (red curves) [21] and an estimate of the meson cloud contributions (blue curves) from the difference between the data and the quark model predictions. Fig. 3 shows representative CLAS data for the $A_{1/2}$ electrocouplings for the $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, and $N(1675)\frac{5}{2}^-$ from independent analysis of πN and $\pi\pi N$ data from CLAS [8,15,16,22]. Studies of the electrocouplings for N^* states of different quantum numbers at lower and intermediate Q^2 have revealed a very different interplay between the inner quark core and the meson-baryon cloud as a function of Q^2. In fact, structure studies of the low-lying N^* states have made significant progress in recent years due to the agreement of results from independent analyses of the CLAS πN and $\pi\pi N$ final states [15]. The good agreement of the extracted electrocouplings from both the πN and $\pi\pi N$ final states is non-trivial in that these channels have very different mechanisms for the non-resonant backgrounds. The agreement thus provides compelling evidence for the reliability of the results.

The size of the meson-baryon dressing amplitudes is maximal for $Q^2 <$ 1 GeV^2 (see Figs. 2 and 3). For increasing Q^2, there is a gradual transition

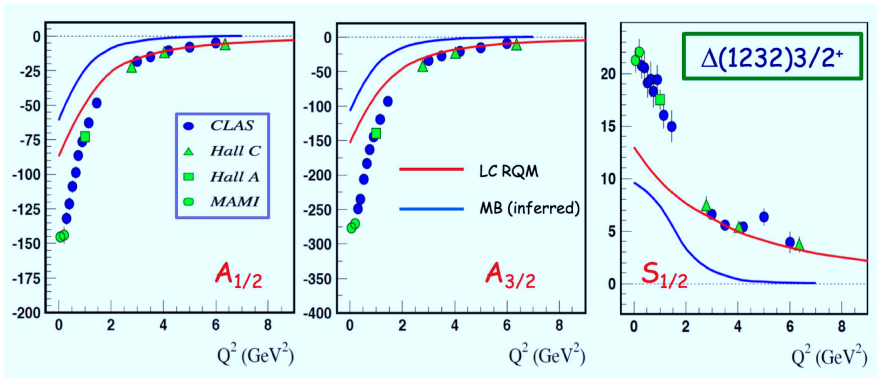

Fig. 2 The $A_{1/2}$, $A_{3/2}$, and $S_{1/2}$ electrocoupling amplitudes (in units of 10^{-3} GeV$^{-1/2}$) vs. Q^2 (GeV^2) for the $\Delta(1232)\frac{3}{2}^+$ from analyses of πN data from CLAS (blue circles) [11], JLab Hall A (green squares) [18], JLab Hall C (green triangles) [19], and MAMI (green circles) [20]. The calculations are from a non-relativistic light-front quark model with a running quark mass (red line) [21]. The inferred magnitude of the meson-baryon cloud contributions is shown by the blue line as the difference between the data and the quark model calculation.

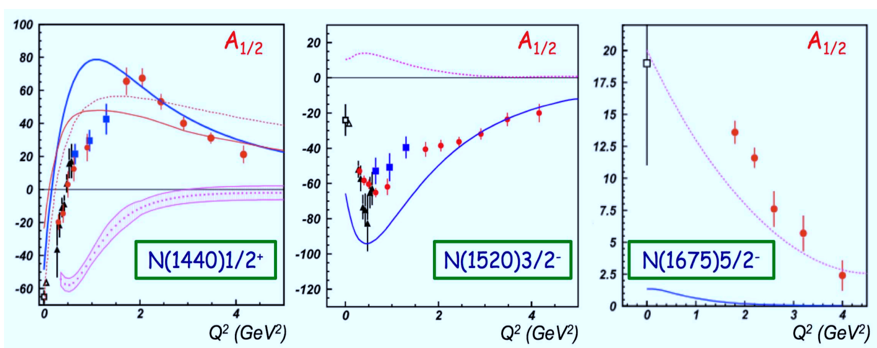

Fig. 3 The $A_{1/2}$ electrocoupling amplitudes (in units of 10^{-3} GeV$^{-1/2}$) vs. Q^2 (GeV^2) for the N^* states $N(1440)\frac{1}{2}^+$ (left), $N(1520)\frac{3}{2}^-$ (middle), and $N(1675)\frac{5}{2}^-$ (right) from analyses of the CLAS πN (circles) and $\pi\pi N$ (triangles, squares) data [8,12,15,16,22]. (Left) Calculation from a non-relativistic light-front quark model with a running quark mass (red line) [21] and from the quark core from the DSE approach (blue line) [3]. (Middle/Right) Calculations from the hypercentral constituent quark model (blue lines) [23]. An estimate of the meson-baryon cloud contributions is shown by the magenta line (or band) on each plot [24].

to the domain where the quark degrees of freedom begin to dominate, as seen by the improved description of the N^* electrocouplings obtained within the DSE approach (see Fig. 3), which accounts only for the quark core contributions. Note as well that studies of the electrocouplings for the $\Delta(1232)\frac{3}{2}^+$ and $N(1440)\frac{1}{2}^+$ states vs. Q^2 within the DSE approach [3] have explicitly demonstrated sensitivity to the momentum-dependent evolution of the dressed quark mass function. This mass function can now be explored in some detail as it influences and determines the electrocoupling amplitudes. This fundamental ingredient of QCD provides direct insight into the emergence of $> 98\%$ of the mass of the hadron. The quark core contribution can also be predicted within the hypercentral CQM [23]. For $Q^2 > 5$ GeV^2, the quark degrees of freedom are expected to fully dominate the N^* states [8]. Therefore, in the $\gamma_v NN^*$ electrocoupling studies for $Q^2 > 5$ GeV^2 that are part of the planned CLAS12 N^* program (see Section 3), the quark degrees of freedom will be probed more directly with only small contributions from the meson-baryon cloud.

Analysis of CLAS data for the $\pi\pi N$ channel has provided the only detailed structural information available regarding higher-lying nucleon excited states, e.g. $\Delta(1620)\frac{1}{2}^-$, $N(1650)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$, and $N(1720)\frac{3}{2}^+$. Fig. 4 shows a representative set of illustrative examples for $S_{1/2}$ for the $\Delta(1620)\frac{1}{2}^-$ [16], $A_{1/2}$ for the $\Delta(1700)\frac{3}{2}^-$, and $A_{3/2}$ for the $N(1720)\frac{3}{2}^+$ [22]. Here the analysis for each N^* state was carried out independently in different bins of W across the width of the resonance for Q^2 up to 1.5 GeV^2 with very good correspondence within each Q^2 bin. Note that many of the N^* states with masses above 1.6 GeV decay preferentially through the $\pi\pi N$ channel instead of the πN channel. An up-to-date list of the N^* photo- and electrocouplings extracted from the experimental data from CLAS and other experiments are available [25]. This webpage also includes all of the references to the data and to the determination of the amplitudes.

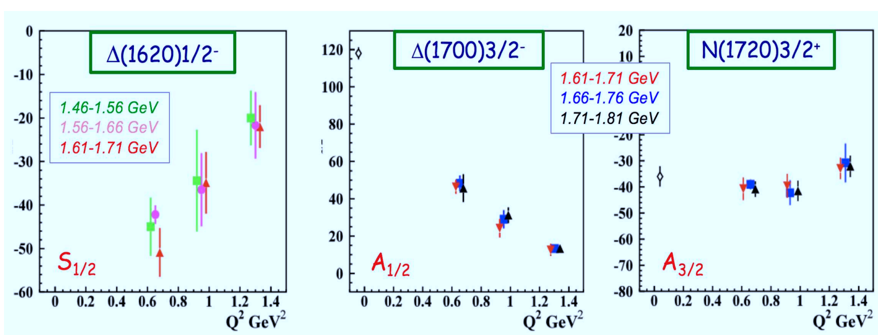

Fig. 4 CLAS results for the N^* electrocoupling amplitudes (in units of 10^{-3} GeV$^{-1/2}$) from analysis of the exclusive $\pi^+\pi^-p$ final state as a function of Q^2 (GeV^2). (Left) $S_{1/2}$ of the $\Delta(1620)\frac{1}{2}^-$ [16], (middle) preliminary extraction of $A_{1/2}$ for the $\Delta(1700)\frac{3}{2}^-$ [22], and (right) preliminary extraction of $A_{3/2}$ for the $N(1720)\frac{3}{2}^+$ [22]. Each electrocoupling amplitude was extracted in independent fits in different bins of W across the resonance peak width as shown for each Q^2 bin (points in each Q^2 bin offset for clarity).

Table 1 Listing of N^* states in the Review of Particle Properties (RPP) [28] with much improved evidence as observed in the Bonn-Gatchina partial wave analysis based on studies of the CLAS KY photoproduction data [29,30]. The last three columns show the importance of the $K^+\Lambda$, $K^+\Sigma^0$, and γN couplings in the observation of these states. This table was adapted from Ref. [31].

	RPP pre-2012	RPP 2014/2016	$K^+\Lambda$	$K^+\Sigma^0$	γN
$N(1710)\frac{1}{2}^+$	***	****	****	**	****
$N(1880)\frac{1}{2}^+$		**	**		**
$N(1895)\frac{1}{2}^-$		**	**	*	**
$N(1900)\frac{3}{2}^+$	**	***	***	**	***
$N(1875)\frac{3}{2}^-$		***	***	**	***
$N(2150)\frac{3}{2}^-$		**	**		**
$N(2000)\frac{5}{2}^+$	*	**	**	*	**
$N(2060)\frac{5}{2}^-$		**		**	**

2.2 Strange Final States

With a goal to have an independent determination of the electrocouplings for each N^* state from multiple exclusive reaction channels, a natural avenue to investigate for the higher-lying N^* states is the strangeness channels $K^+\Lambda$ and $K^+\Sigma^0$. In fact, data from the KY channels are critical to provide an independent extraction of the electrocoupling amplitudes for the higher-lying N^* states with small branching fractions for the πN decays. Studies of the strangeness channels represent a central part of the N^* program planned with CLAS12 [26] (see Section 3).

The relevance of the strangeness channels $K^+\Lambda$ and $K^+\Sigma^0$ has been recently demonstrated by the Bonn-Gatchina group in a multi-channel partial wave analysis [27]. Their analysis has provided much improved evidence for the existence of a set of eight N^* states (see Table 1). These states are included in the recent edition of the Review of Particle Properties [28]. These findings have critically relied upon the hyperon photoproduction data from CLAS [29, 30] and other experiments.

The CLAS program has yielded by far the most extensive and precise measurements of KY electroproduction data ever measured across the nucleon resonance region. These measurements have included the separated structure functions σ_T, σ_L, $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT}, σ_{TT}, and $\sigma_{LT'}$ for $K^+\Lambda$ and $K^+\Sigma^0$ [32–35], recoil polarization for $K^+\Lambda$ [36], and beam-recoil transferred polarization for $K^+\Lambda$ and $K^+\Sigma^0$ [37,38]. These measurements span Q^2 from 0.5 to 4.5 GeV^2, W from 1.6 to 3.0 GeV, and the full center-of-mass angular range of the K^+. The KY final states, due to the creation of an $s\bar{s}$ quark pair in the intermediate state, are naturally sensitive to coupling to higher-lying s-channel resonance states at $W > 1.6$ GeV, a region where our knowledge of the N^* spectrum is the most limited. Note also that although the two ground-state hyperons have the same valence quark structure (uds), they differ in isospin, such that intermediate N^* resonances can decay strongly to $K^+\Lambda$ final states, but intermediate Δ^* states cannot. Because $K^+\Sigma^0$ final states can have contributions from both N^* and Δ^* states, the hyperon final state selection constitutes an isospin filter. Shown in Figs. 5 and 6 is a small sample of the available data from CLAS in the form of the $K^+\Lambda$ and $K^+\Sigma^0$ structure functions σ_U, σ_{LT}, σ_{TT}, and $\sigma_{LT'}$ [35,39], illustrating its broad kinematic coverage and good statistical precision. Fig. 7 shows the Λ induced polarization from CLAS data for the reaction $ep \to e'K^+\Lambda$ at an average Q^2 of 1.9 GeV^2 for different angular ranges for $\cos\theta_K^{c.m.}$ taken with a 5.5 GeV electron beam [36].

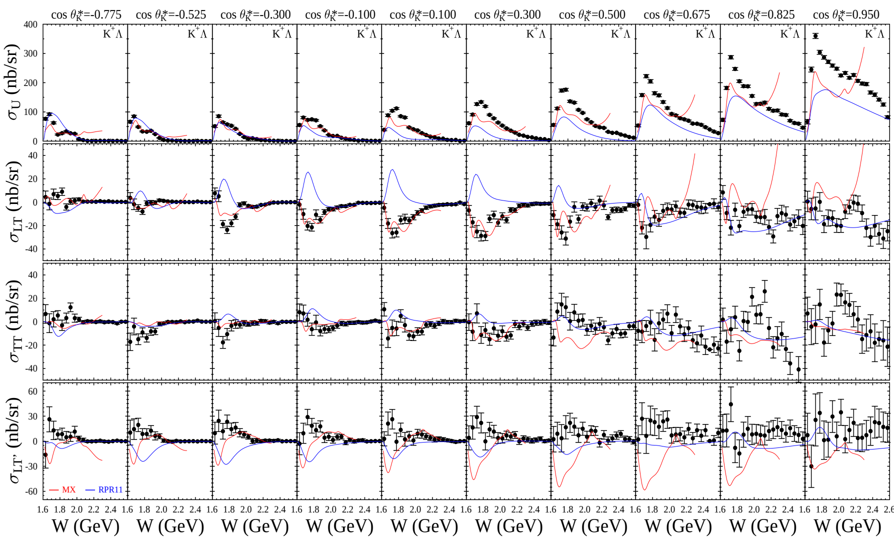

Fig. 5 Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT}, σ_{TT}, and $\sigma_{LT'}$ (nb/sr) from CLAS data for $K^+\Lambda$ production vs. W (GeV) for E_{beam}=5.5 GeV for Q^2=1.80 GeV^2 and $\cos\theta_K^*$ values as shown [35]. The error bars represent the statistical uncertainties only. The red curves are from the hadrodynamic KY model of Maxwell [40] and the blue curves are from the hybrid RPR-2011 KY model from Ghent [41].

Figs. 5, 6, and 7 include two of the more advanced single channel reaction models for the electromagnetic production of KY final states. The MX model is the isobar model from Maxwell [40] (red curves), and the RPR-2007 [42] and RPR-2011 [41] models are from the Ghent Regge plus Resonance (RPR) framework (blue curves). Both the MX and RPR models were developed based on fits to the extensive and precise photoproduction data from CLAS and other experiments, and describe those data reasonably well. However, they utterly fail to describe the electroproduction data in any of the kinematic phase space. Reliable information on the resonance electrocouplings from KY electroproduction off the proton as well as their hadronic decays is not yet available due to the lack of an adequate reaction model. However, after such a model is developed, the N^* electrocoupling amplitudes for states that couple to KY can be obtained from fits to the extensive existing CLAS KY electroproduc-

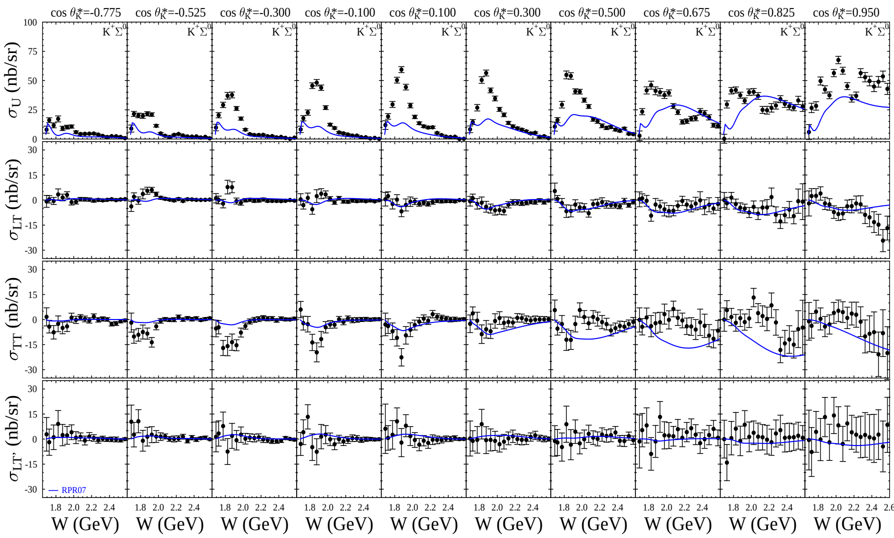

Fig. 6 Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT}, σ_{TT}, and $\sigma_{LT'}$ (nb/sr) from CLAS data for $K^+\Sigma^0$ production vs. W (GeV) for E_{beam}=5.5 GeV for Q^2=1.80 GeV^2 and $\cos\theta_K^*$ values as shown [35]. The error bars represent the statistical uncertainties only. The blue curves are from the hybrid RPR-2007 KY model from Ghent [42].

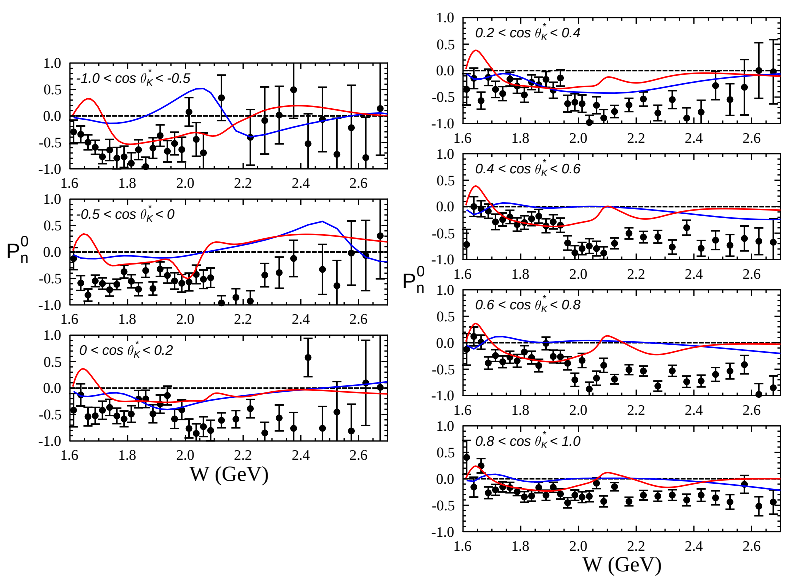

Fig. 7 Induced polarization of the final state hyperon in the reaction $ep \to e'K^+\Lambda$ from CLAS data at an average Q^2=1.9 GeV^2 for E_{beam}=5.5 GeV and $\cos\theta_K^*$ ranges as shown [36]. The error bars represent the statistical uncertainties only. The red curves are from the isobar model of Maxwell [40] and the blue curves are from the hybrid RPR-2011 KY model from Ghent [41].

tion data over the range $0.5 < Q^2 < 4.5$ GeV^2, which should be carried out independently in different bins of Q^2 with the same KY hadronic decays, extending the available information on these N^* states. The development of reaction models for the extraction of the $\gamma_v NN^*$ electrocouplings from the KY electroproduction channels is urgently needed.

Work is presently underway to further develop the existing single-channel Ghent RPR model [41] based on a combined refit of the γp and $\gamma^* p$ data from CLAS in the kinematic range W up to 2.6 GeV and Q^2 up to 4.5 GeV^2. This work should include an improved description of the non-resonant background contributions in the $K^+\Lambda$ and $K^+\Sigma^0$ final states. This development will then set the stage for further extension of this model into the kinematic range relevant for the planned studies with CLAS12 in kinematics with W up to 3 GeV and Q^2 up to 12 GeV^2. Ultimately, however, these electroproduction data need to be confronted within a global multi-channel model. Such efforts are getting underway by the ANL-Osaka [43], Bonn-Gatchina [44], and JPAC at JLab [45] groups.

It is also important to note that the πN and $\pi\pi N$ electroproduction channels represent the two dominant exclusive channels in the resonance region. The knowledge of the electroproduction mechanisms for these channels is critically important for N^* studies in channels with smaller cross sections such as $K^+\Lambda$ and $K^+\Sigma^0$ production, as they can be significantly affected in leading order by coupled-channel effects produced by their hadronic interactions in the pionic channels. Ultimately, such effects need to be properly included in the KY reaction models.

3 CLAS12 N^* Program

As part of the upgrade of the JLab accelerator from a maximum electron beam energy of 6 GeV to a maximum energy of 12 GeV, a new large acceptance spectrometer called CLAS12 was designed for experimental Hall B to replace the CLAS spectrometer. The new CLAS12 spectrometer [46] is designed for operation at beam energies up to 11 GeV (the maximum possible for delivery to Hall B) and will operate at a nominal beam-target luminosity of 1×10^{35} cm^{-2}s^{-1}, an order of magnitude increase over previous CLAS operation. This luminosity will allow for precision measurements of cross sections and polarization observables for almost all exclusive reaction channels relevant in the N^* excitation region for invariant energy W up to 3 GeV, the full decay particle phase space, and four-momentum transfer Q^2 from 0.05 GeV^2 up to 12 GeV^2. The full physics program for CLAS12 has focuses on measurements of the spatial and angular momentum structure of the nucleon, investigation of quark confinement and hadron excitations, and studies of the strong interaction in nuclei. The commissioning of the new CLAS12 spectrometer is scheduled to take place in the winter of 2017/2018, followed in the spring of 2018 by the first physics running period.

The N^* program with CLAS12 consists of three approved experiments. E12-09-003 [47] will focus on the non-strange final states (primarily πN, ηN, $\pi\pi N$) with an 11 GeV beam, and E12-06-108A [48] and E12-16-010A [49] will focus on the strange final states (primarily $K^+\Lambda$ and $K^+\Sigma^0$) with beam energies of 6.6 GeV, 8.8 GeV, and 11 GeV. These experiments will allow for the determination of the Q^2 evolution of the electrocoupling parameters for N^* states with masses in the range up to 3 GeV in the regime of Q^2 up to 12 GeV^2 and will be part of the first production physics running period with CLAS12 in 2018. The experiments will collect data simultaneously using a longitudinally polarized 11 GeV electron beam on an unpolarized liquid-hydrogen target.

The program of N^* studies with the CLAS12 detector has a number of important primary objectives. These include:

i) To study the higher-lying states in the N^* spectrum for $W > 1.8$ GeV, where spectroscopy information is limited and for which both constituent quark models [50,51] and LQCD calculations [52] show that the N^* spectrum is populated with a host of still unobserved missing baryon states. The data from KY electroproduction experiments will provide for important precision tests to confirm signals of new baryon states that have been observed based on KY photoproduction data [27]. Furthermore, the KY channels are sensitive to new states of baryonic matter with glue as an active structural component known as hybrid baryons [47,53].

ii) The extraction of electrocoupling amplitudes as a function of Q^2 for N^* states of different quantum numbers over the full nucleon resonance region is essential to understand the regime where the external meson-baryon cloud transitions to dynamics dominated by confined quarks and gluons. These data will shed light on the generation of the meson-baryon cloud from the confinement regime. Improved understanding of the affects of the meson-baryon cloud on the structure of N^* states was a critical step towards resolving the 50-year puzzle surrounding the $N^*(1440)\frac{1}{2}^-$ Roper resonance [54].

iii) To map out the quark structure of the dominant N^* and Δ^* states from the acquired electroproduction data through the exclusive final states including the non-strange channels $\pi^0 p$, $\pi^+ n$, ηp, $\pi^+\pi^- p$, as well as the dominant strangeness channels $K^+\Lambda$ and $K^+\Sigma^0$. This objective is motivated by results from existing analyses such as those shown in Fig. 3, where it is seen that the meson-baryon dressing contribution to the N^* structure decreases rapidly with increasing Q^2. The data can be described approximately in terms of dressed quarks already for Q^2 up to 3 GeV^2. It is therefore expected that the data at $Q^2 > 5$ GeV^2 can be used more directly to probe the quark substructure of the N^* and Δ^* states [8]. The comparison of the extracted resonance electrocoupling parameters from this new higher Q^2 regime to the predictions from LQCD and DSE calculations will allow for a much improved understanding of how the internal dressed quark core emerges from QCD and how the dynamics of the strong interaction are responsible for the formation of N^* and Δ^* states of different quantum numbers. Consistent results on the momentum-dependence of the dressed quark mass function from independent studies of difference resonance electrocouplings at $Q^2 > 5$ GeV^2 are critical in order to validate strong QCD [3,4,8].

iv) To access diquark correlations in N^* structure. These configurations of non-point-like diquarks are an important part of N^* structure and the $\gamma_v NN^*$ transition amplitudes. They are accessible from the results on the Q^2 evolution of the N^* electrocouplings. The amplitudes for diquark correlations are determined by the dressed quark mass function and offer another avenue with which to explore the momentum dependence of the dynamical mass of dressed quarks. These contributions depend on the quantum numbers of the N^* states. They are expected to be maximal for $Q^2 < 5$ GeV^2, and maximal sensitivity is expected in the range of Q^2 from 2 GeV^2 to 5 GeV^2 where contributions from meson-baryon cloud effects are substantially reduced.

v) To investigate the dynamics of dressed quark interactions and how they emerge from QCD to generate N^* states of different quantum numbers. This work is motivated by recent advances in the DSE approach [55,56] and LQCD [57], which have provided links between the dressed quark propagator, the dressed quark scattering amplitudes, and the QCD Lagrangian. These approaches also relate the momentum dependence of the dressed quark mass function to the $\gamma_v NN^*$ electrocouplings for N^* states of different quantum numbers. While the available electroproduction data from CLAS at 6 GeV beam energy provides only a glimpse of the evolution of the running quark mass function, future results on resonance electrocouplings from CLAS12 at beam energies up to 11 GeV will expand the kinematic range up to $Q^2 \leq 12$ GeV^2 [47–49]. These data will then allow for an exploration of the dressed quark mass function to distance scales where the transition from strong to perturbative QCD occurs. DSE analyses of the extracted N^* electrocoupling parameters have the potential to allow for investigation of the origin of quark-gluon confinement in baryons and the nature of more than 98% of the hadron mass generated non-perturbatively through DCSB, since both of these phenomena are rigorously incorporated into the DSE approach [3,4,8]. Efforts are currently underway to study the sensitivity of the proposed electromagnetic amplitude measurements to different parameterizations of the momentum dependence of the quark mass [58].

vi) To offer constraints from resonance electrocoupling amplitudes on the Generalized Parton Distributions (GPDs) describing $N \to N^*$ transitions. We note that a key aspect of the CLAS12 measurement program is the characterization of exclusive reactions at high Q^2 in terms of GPDs. The elastic and $\gamma_v NN^*$ transition form factors represent the first moments of the GPDs [59, 60], and they provide for unique constraints on the structure of nucleons and their excited states. Thus the N^* program at high Q^2 represents the initial step in a reliable parameterization of the transition $N \to N^*$ GPDs and is an important part of the larger overall CLAS12 program studying exclusive reactions.

4 Concluding Remarks

The study of the spectrum and structure of the excited nucleon states represents one of the key physics foundations for the measurement program in Hall B with the CLAS spectrometer. To date measurements with CLAS have provided a dominant amount of precision data (cross sections and polarization observables) for a number of different exclusive final states for Q^2 from 0 to 4.5 GeV^2 for W up to 2.5 GeV and the full center-of-mass angular range of the final state decay products. From the πN, ηN, and $\pi\pi N$ data, the electrocouplings of most N^* states up to $\sim$1.8 GeV have been extracted for the first time. A powerful cross-check of these findings is the good agreement of the extracted N^* electrocouplings from independent analyses of different final states. With the development and refinement of reaction models to describe the extensive CLAS $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction observables, the CLAS data from the strangeness channels are expected to provide an important complement to study the electrocoupling parameters for higher-lying N^* resonances with masses above 1.6 GeV and will serve as an important cross-check of the extracted electrocouplings from the $\pi\pi N$ channel.

The N^* program with the new CLAS12 spectrometer will extend these studies up to $Q^2 \sim 12$ GeV^2, the highest photon virtualities ever probed in exclusive reactions. This program will ultimately focus on the extraction of the $\gamma_v NN^*$ electrocoupling amplitudes for the *s*-channel resonances that couple strongly to the non-strange final states πN, ηN, and $\pi\pi N$, as well as the strange $K^+\Lambda$ and $K^+\Sigma^0$ final states. These studies in concert with theoretical developments will allow for insight into the strong interaction dynamics of dressed quarks and their confinement in baryons over a broad Q^2 range. The data will address the most challenging and open problems of the Standard Model on the nature of hadron mass, quark-gluon confinement, and the emergence of the N^* states of different quantum numbers from QCD.

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