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Nucleon Resonance Structure Studies Via Exclusive KY Electroproduction

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Abstract Studying the structure of excited nucleon 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 1.8 GeV have been determined from analyses of CLAS πN , ηN , and $\pi\pi N$ data. 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^* electro-excitation amplitudes, is essential to have confidence in the extracted results. In terms of hadronic coupling, many high-lying N^* states preferentially decay through the $\pi\pi N$ channel instead of πN . Data from the KY channels will therefore be critical to provide an independent analysis to compare the extracted electrocouplings for the high-lying N^* states against those determined from the πN and $\pi\pi N$ channels. A program to study excited N^* state structure in both non-strange and strange exclusive electroproduction channels using CLAS12 will measure differential cross sections and polarization observables to be used as input to extract the $\gamma_v NN^*$ electrocoupling amplitudes for the most prominent N^* states in the range of invariant energy W up to 3 GeV in the virtually unexplored domain of momentum transfers Q^2 up to 12 GeV².

Keywords : Electromagnetic Interactions · Form Factors · Hyperon Production

1 Introduction

Intensive spectroscopy of the nucleon excitation spectrum and detailed studies of the structure of these excited states has played a pivotal role in the development of our understanding of the strong interaction. The concept of quarks that emerged through such studies led to the development of the constituent quark model [1; 2] (CQM) in the 1980s. As a result of intense experimental and theoretical effort over the past 30 years, it is now apparent that the structure of the states in the nucleon excitation spectrum is much more complex than what can be described in terms of models based on constituent quarks alone. 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.

Studies of low-lying nucleon excited states using electromagnetic probes at four-momentum transfer $Q^2 < 5$ GeV² have revealed that the structure of these states is a complex interplay between the internal

core of three dressed quarks and an external meson-baryon 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 $Q^2 > 5 \text{ GeV}^2$. 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.

Electroproduction reactions $\gamma^* N \rightarrow N^* \rightarrow M + B$ provide a tool to probe the inner structure of the contributing N^* resonances through the extraction of the amplitudes for 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 helicity amplitudes [3], among which are $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$, which describe the N^* resonance electroexcitation for the two different helicity configurations of a transverse photon and the nucleon, as well as $S_{1/2}(Q^2)$, which describes the N^* resonance electroexcitation by longitudinal photons of zero helicity. Detailed comparisons of the theoretical predictions for these amplitudes with their 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 [4], through mapping of the dressed quark mass function [5] and extractions of the quark distribution amplitudes for N^* states of different quantum numbers [6]. This is critical in exploring the nature of quark-gluon confinement and dynamical chiral symmetry breaking (DCSB) in baryons.

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 the 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 [7].

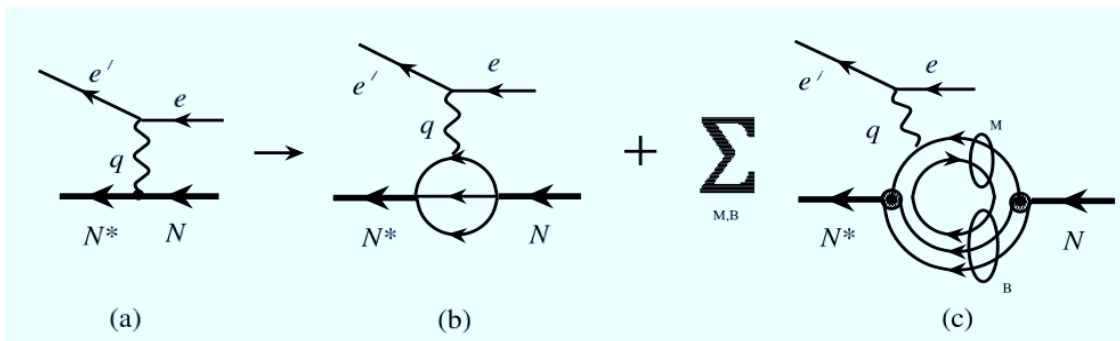


Fig. 1 Schematic representation of the $\gamma^* N \rightarrow N^*$ electroproduction process. (a) The fully dressed $\gamma_v NN^*$ electrocoupling that determines the N^* contribution to the resonant part of the meson electroproduction amplitude. (b) The contribution of the three-quark core. (c) The contribution from the meson-baryon cloud, where the sum is over all intermediate meson and baryon states. This figure is 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 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 CQMs. See Ref. [8] for an overview 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. Consistent determination of N^* properties from different exclusive channels with different couplings and non-resonant backgrounds offers model-independent support for the findings.

To date photoproduction data sets from CLAS and elsewhere have been used extensively to constrain coupled-channel fits and advanced single-channel models. However, data at $Q^2=0$ allows us to identify N^* states and determine their quantum numbers, but tell us very little about the structure of these states. It is the Q^2 dependence of the $\gamma_v NN^*$ electrocouplings that unravel and reveal these details. In addition, electrocoupling data are promising for studies of nucleon excited states as the ratio of resonant to non-resonant amplitudes increases with increasing Q^2 . Finally, the electroproduction data are an effective tool to confirm the existence of new N^* states as the data must be described by Q^2 -independent resonance masses and hadronic decay widths.

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. For each final state this goal 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 in the relevant kinematic variables Q^2 , W , $d\tau_{hadrons}$ (where $d\tau_{hadrons}$ represents the phase space of the final state hadrons) as the data support. The second phase consists of developing advanced reaction models that completely describe the data over its full phase space in order to then extract the electrocoupling amplitudes for the dominant contributing N^* states.

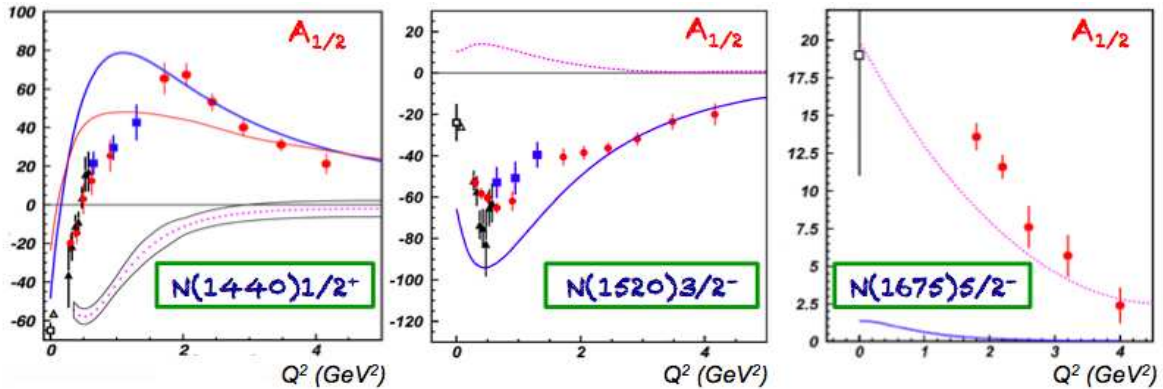


Fig. 2 The $A_{1/2}$ electrocoupling amplitudes (in units of $10^{-3} \text{ GeV}^{-1/2}$) vs. Q^2 (GeV^2) for the N^* states $N(1440)_{\frac{1}{2}}^+$ (left), $N(1520)_{\frac{3}{2}}^-$ (middle), and $N(1675)_{\frac{5}{2}}^-$ (right) from analyses of the CLAS πN (circles) and $\pi\pi N$ (triangles, squares) data. (Left) Calculation from a non-relativistic light-front quark model with a running quark mass (red line) and calculation of the quark core from the DSE approach (blue line). (Middle/Right) Calculations from the hypercentral constituent quark model (blue lines). The magnitude of the meson-baryon cloud contributions is shown by the magenta line (or band) on each plot. See Refs. [8; 10; 11; 12] for details on the data and the models.

Electrocoupling amplitudes for most N^* states below 1.8 GeV have been extracted for the first time from analysis of CLAS data in the exclusive π^+n and π^0p 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 . Figure 2 shows representative CLAS data for the $A_{1/2}$ electrocouplings for the $N(1440)_{\frac{1}{2}}^+$, $N(1520)_{\frac{3}{2}}^-$, and $N(1675)_{\frac{5}{2}}^-$ [8; 10; 11; 12]. Studies of the

electrocouplings for N^* states of different quantum numbers at lower Q^2 have revealed a very different interplay between the inner quark core and the meson-baryon cloud as a function of Q^2 . Structure studies of the low-lying N^* states, e.g. $\Delta(1232)_{\frac{3}{2}}^+$, $N(1440)_{\frac{1}{2}}^+$, $N(1520)_{\frac{3}{2}}^-$, and $N(1535)_{\frac{1}{2}}^-$, 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 [10]. The good agreement of the extracted electrocouplings from both the πN and $\pi\pi N$ exclusive channels 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 are maximal for $Q^2 < 1 \text{ GeV}^2$ (see Fig. 2). For increasing Q^2 , there is a gradual transition 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, which accounts only for the quark core contributions. For $Q^2 > 5 \text{ GeV}^2$, the quark degrees of freedom are expected to fully dominate the N^* states [8]. Therefore, in the $\gamma_v NN^*$ electrocoupling studies for $Q^2 > 5 \text{ GeV}^2$ expected with the future CLAS12 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 N^* states, e.g. $\Delta(1620)_{\frac{1}{2}}^-$, $N(1650)_{\frac{1}{2}}^-$, $N(1680)_{\frac{5}{2}}^+$, $\Delta(1700)_{\frac{3}{2}}^-$, and $N(1720)_{\frac{3}{2}}^+$. Fig. 3 shows a representative set of illustrative examples for $S_{1/2}$ for the $\Delta(1620)_{\frac{1}{2}}^-$ [11], as well as for $A_{1/2}$ for the $\Delta(1700)_{\frac{3}{2}}^-$ and $A_{3/2}$ for the $N(1720)_{\frac{3}{2}}^+$ [12]. 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 most of the N^* states with masses above 1.6 GeV decay preferentially through the $\pi\pi N$ channel instead of the πN channel.

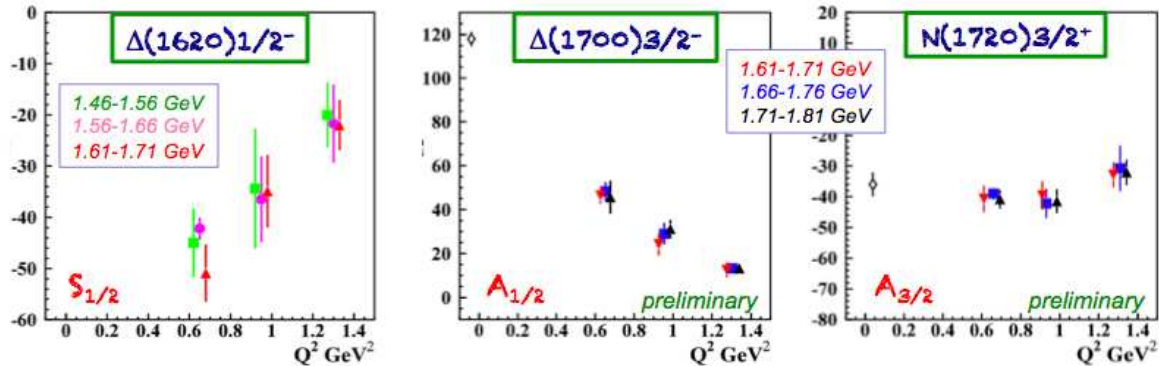


Fig. 3 CLAS results for the N^* electrocoupling amplitudes (in units of $10^{-3} \text{ GeV}^{-1/2}$) from analysis of the exclusive $\pi^+\pi^-p$ final state as a function of Q^2 (GeV^2). (Left) $S_{1/2}$ of the $\Delta(1620)_{\frac{1}{2}}^-$ [11], (middle) preliminary extraction of $A_{1/2}$ for the $\Delta(1700)_{\frac{3}{2}}^-$ [12], and (right) preliminary extraction of $A_{3/2}$ for the $N(1720)_{\frac{3}{2}}^+$ [12]. 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).

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. 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 $K^+\Sigma^0$ [13; 14; 15; 16], recoil polarization for $K^+\Lambda$ [17], and beam-recoil transferred polarization for $K^+\Lambda$ and $K^+\Sigma^0$ [18; 19]. For the hyperon polarization measurements, we have taken advantage of the self-analyzing nature of the weak decay of the Λ . 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 $W > 1.6 \text{ GeV}$, 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. 4 and 5 is a small sample of the available data in the form of the $K^+\Lambda$ and $K^+\Sigma^0$ structure functions σ_U , σ_{LT} , σ_{TT} , and $\sigma_{LT'}$ [16; 20], illustrating its broad kinematic coverage and statistical precision.

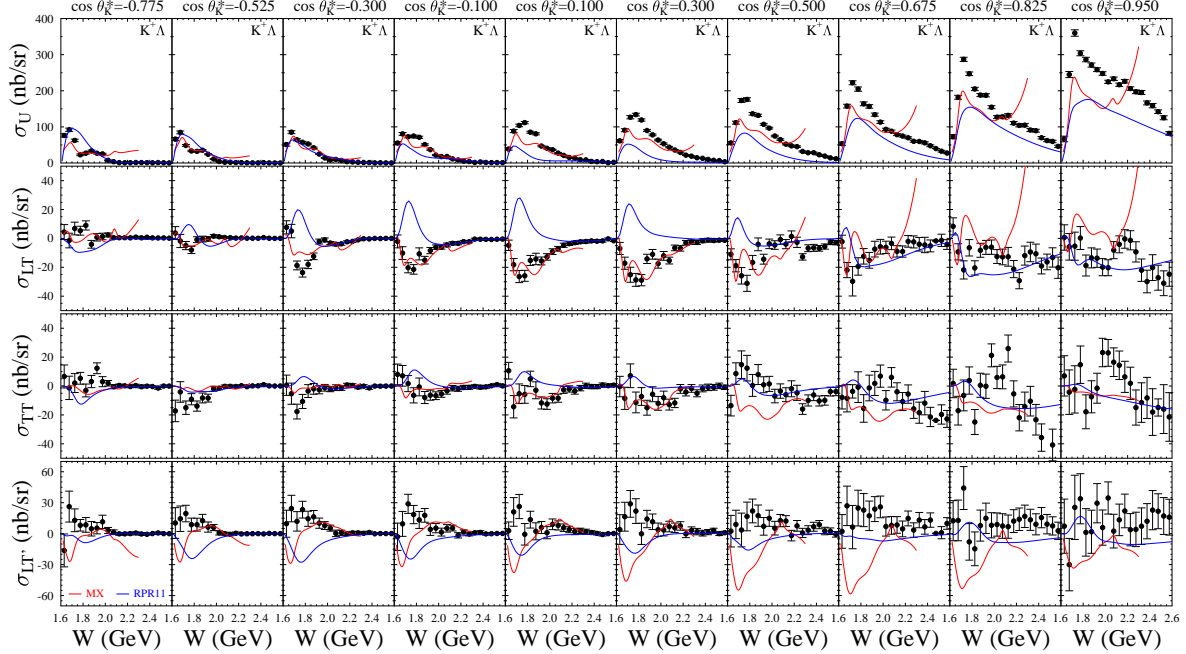


Fig. 4 Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT} , σ_{TT} , and $\sigma_{LT'}$ (nb/sr) for $K^+\Lambda$ production vs. W (GeV) for $E_{beam}=5.5$ GeV for $Q^2=1.80$ GeV² and $\cos\theta_K^*$ values as shown from CLAS data [16; 20]. The error bars represent the statistical uncertainties only. The red curves are from the hydrodynamic KY model of Maxwell [21] and the blue curves are from the hybrid RPR-2011 KY model from Ghent [22].

While there has been progress toward a better understanding of the low-lying N^* states in the region below 1.6 GeV, the vast majority of the predicted missing N^* and Δ^* states lie in the region from $1.6 < W < 3$ GeV. To date the PDG lists only four N^* states, $N(1650)\frac{1}{2}^-$, $N(1710)\frac{1}{2}^+$, $N(1720)\frac{3}{2}^+$, and $N(1900)\frac{3}{2}^+$, with known couplings to $K\Lambda$ and no N^* states are listed that couple to $K\Sigma$ [23]; only a single Δ^* state, $\Delta(1920)\frac{3}{2}^+$, is listed with coupling strength to $K\Sigma$. The branching ratios to KY provided for these states are typically less than 10% with uncertainties on the order of the measured coupling. While the relevance of this core set of N^* states in the $\gamma^{(*)}p \rightarrow K^+\Lambda$ reaction has long been considered a well-established fact, this set of states falls well short of reproducing the experimental results for $W < 2$ GeV.

Figs. 4 and 5 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 [21], and the RPR-2007 [24] and RPR-2011 [22] models are from the Ghent Regge plus Resonance (RPR) framework. Both the MX and RPR models were developed based on fits to the extensive and precise photoproduction data from CLAS and elsewhere 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 KY hadronic decays from N^* s 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 electroproduction data over the range $0.5 < Q^2 < 4.5$ GeV², 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.

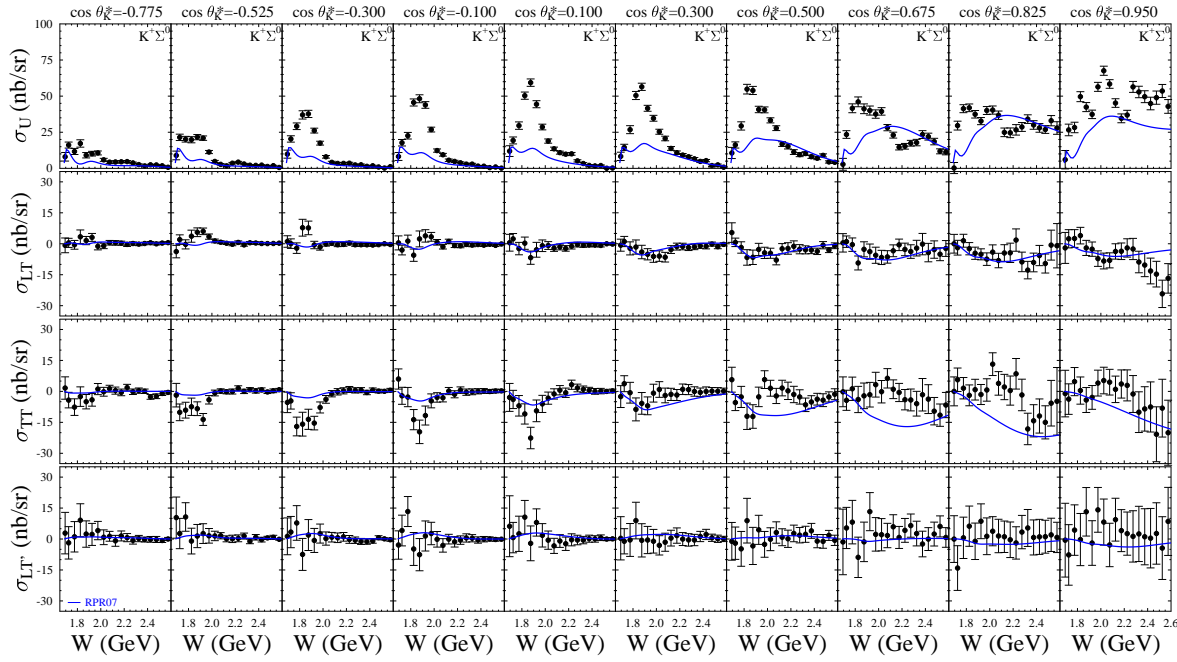


Fig. 5 Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT} , σ_{TT} , and $\sigma_{LT'}$ (nb/sr) for $K^+\Sigma^0$ production vs. W (GeV) for $E_{beam}=5.5$ GeV for $Q^2=1.80$ GeV² and $\cos\theta_K^*$ values as shown from CLAS data [16; 20]. The error bars represent the statistical uncertainties only. The blue curves are from the hybrid RPR-2007 KY model from Ghent [24].

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 [25] 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⁻²s⁻¹, an order of magnitude increase over previous CLAS operation. This luminosity will allow for precision measurements of cross sections and polarization observables for many exclusive reaction channels for invariant energy W up to 3 GeV, the full decay product phase space, and four-momentum transfer Q^2 up to 12 GeV². The 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 first part of 2017, followed shortly thereafter by the first physics running period.

The electrocoupling parameters determined for several low-lying N^* states from the data involving the pionic channels for Q^2 up to 5 GeV² have already provided valuable information. At these distance scales, the resonance structure is determined by both meson-baryon dressing and dressed quark contributions. The N^* program with the new CLAS12 spectrometer in Hall B is designed to study excited nucleon structure over a broad range of Q^2 , from $Q^2 = 3$ GeV² to allow for direct overlap with the data sets collected with the CLAS spectrometer, up to $Q^2=12$ GeV², the highest photon virtualities ever probed in exclusive electroproduction reactions. In the kinematic domain of Q^2 from 3 to 12 GeV², the

data can probe more directly the inner quark core and map out the transition from the confinement to the perturbative QCD domains.

The N^* program with CLAS12 consists of two approved experiments. E12-09-003 [26] will focus on the non-strange final states (primarily πN , ηN , $\pi\pi N$) and E12-06-108A [27] will focus on the strange final states (primarily $K^+\Lambda$ and $K^+\Sigma^0$). 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 GeV². These experiments will be part of the first production physics running period with CLAS12 in 2017. 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 objectives. These include:

i) 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. 2, 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 GeV². It is therefore expected that the data at $Q^2 > 5$ GeV² 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.

ii) 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 [28; 29] and LQCD [30], 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. 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 DSCB, since both of these phenomena are rigorously incorporated into the DSE approach [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 [31].

iii) To offer constraints from resonance electrocoupling amplitudes on the Generalized Parton Distributions (GPDs) describing $N \rightarrow N^*$ 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 [32; 33], 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 $N \rightarrow N^*$ 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 GeV². From the πN and $\pi\pi N$ data, the electrocouplings of most N^* states up to ~ 1.8 GeV have been extracted for the first time. With the development and refinement of reaction models to describe the extensive CLAS $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction data, the data from the strangeness channels is expected to provide an important complement to study the electrocoupling parameters for higher-lying N^* resonances with masses above 1.6 GeV.

The N^* program with the new CLAS12 spectrometer will extend these studies up to Q^2 of 12 GeV², 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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