Nucleon Resonance Electrocouplings from the CLAS Meson Electroproduction Data

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Abstract. Transition helicity amplitudes $\gamma_v NN^*$ (electrocouplings) were determined for prominent excited proton states with masses below 1.8 GeV in independent analyses of major meson electroproduction channels: $\pi^+ n$, $\pi^0 p$ and $\pi^+\pi^- p$. Consistent results on resonance electrocouplings obtained from analyses of these exclusive reactions with different non-resonant contributions demonstrate reliable extraction of these fundamental quantities for states that have significant decays for either $N\pi$ or $N\pi\pi$ channels. Preliminary results on electrocouplings of N^* states with masses above 1.6 GeV have become available from the CLAS data on $\pi^+\pi^- p$ electroproduction off protons for the first time. Comparison with quark models and coupled-channel approaches strongly suggest that N^* structure is determined by contributions from an internal core of three constituent quarks and an external meson-baryon cloud at the distances covered in these measurements with the CLAS detector.

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INTRODUCTION

Studies of nucleon resonance structure in exclusive meson electroproduction off protons represent an important direction in the N^* program with the CLAS detector [1], with the primary objective of determining electrocouplings, of most excited proton states at photon virtualities Q^2 up to 5.0 GeV^2. This information allows us to pin down active degrees of freedom in resonance structure at various distances, and eventually to access strong interaction mechanisms that are responsible for N^* formation from quarks and gluons [1, 2, 3]. In this paper we report the results on the studies of $\gamma_v NN^*$ electrocouplings of prominent excited proton states in the mass range up to 1.8 GeV from independent analyses of major meson electroproduction channels: $\pi^+ n$, $\pi^0 p$ and $\pi^+\pi^- p$. These channels are sensitive to resonance contributions, and they have different non-resonant mechanisms. Successful description of a large body of observables measured in $\pi^+ n$, $\pi^0 p$ and $\pi^+\pi^- p$ electroproduction reactions, achieved with consistent values of $\gamma_v NN^*$ electrocouplings, demonstrates the reliable extraction of these fundamental quantities. Analysis of the results on the $\gamma_v NN^*$ electrocouplings open access to active degrees of freedom in N^* structure at distances that correspond to the confinement regime at large values of the running quark-gluon coupling.

THE CLAS DATA ON PION ELECTROPRODUCTION OFF PROTONS AND ANALYSIS TOOLS

The CLAS data considerably extended information available on $\pi^+ n$, $\pi^0 p$ electroproduction off protons. A total of nearly 120000 data points on unpolarized differential cross sections, longitudinally polarized beam asymmetries, and longitudinal target and beam-target asymmetries were obtained with almost complete coverage of the accessible phase space [4]. The data were analyzed within the framework of two conceptually different approaches: a) the unitary isobar model (UIM), and b) a model, employing dispersion relations [5, 6]. All well established N^* states in the mass range $M_{N^*} < 1.8$ GeV were incorporated into the $N\pi$ channel analyses.

The UIM follows the approach of ref. [7]. The $N\pi$ electroproduction amplitudes are described as a superposition of N^* electroexcitation in s-channel and non-resonant Born terms. A Breit-Wigner ansatz with energy-dependent hadronic decay widths is employed for the resonant amplitudes. Non-resonant amplitudes are described by a gauge invariant superposition of nucleon s- and u-channel exchanges, and π, ρ, and ω t-channel exchanges. The latter are reggeized in order to better describe the data in the second and the third resonance regions. The final state interactions are treated as πN rescattering in the K-matrix approximation.

In another approach, the real and imaginary parts of invariant amplitudes, that describe $N\pi$ electroproduction, are related in a model-independent way by dispersion relations [5]. The analysis showed that the imaginary parts of amplitudes are dominated by resonant contributions at $W > 1.3$ GeV. In this kinematical region, they are described by resonant contributions only. At smaller W values, both resonant and non-resonant contributions to the imaginary part of amplitudes are taken into account.

The two approaches provide good description of the $N\pi$ data in the entire range covered by the CLAS measurements: $W < 1.7$ GeV and $Q^2 < 5.0$ GeV^2, resulting in χ^2/d.p. < 2.0 [4]. This good description of a large body of different observables allowed us to obtain reliable information on $\gamma_v NN^*$ resonance electrocouplings from the analysis of $\pi^+ n$ and $\pi^0 p$ electroproduction off protons.

The $\pi^+\pi^- p$ electroproduction data [8, 9] provide information on nine independent one-fold-differential and fully-integrated cross sections in each bin of W and Q^2 in a mass range $W < 2.0$ GeV, and with photon virtualities of $0.25 < Q^2 < 1.5$ GeV^2. Analysis of these data within framework of the JM reaction model [10, 11] allowed us to establish all essential contributing mechanisms from their manifestation in the measured cross sections. The $\pi^+\pi^- p$ electroproduction amplitudes are described in the JM model as a superposition of $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρp, $\pi^+ D^0_{13}(1520)$, $\pi^+ F^0_{15}(1685)$, $\pi^- P^{++}_{33}(1600)$ channels , and additional direct 2π production mechanisms, where the final $\pi^+\pi^- p$ state is created without formation of unstable hadrons in the intermediate state. The latter mechanisms are beyond the isobar approximation. They are required by unitarity of the $\pi^+\pi^- p$ amplitudes [12]. Direct 2π production amplitudes established in the analysis the CLAS data are presented in Ref. [10].

The JM model incorporates contributions from all well established N^* states to $\pi\Delta$ and ρp isobar channels. We also included the $3/2^+(1720)$ candidate state, suggested in the analysis [8] of the CLAS $\pi^+\pi^- p$ electroproduction data. In the current analysis,

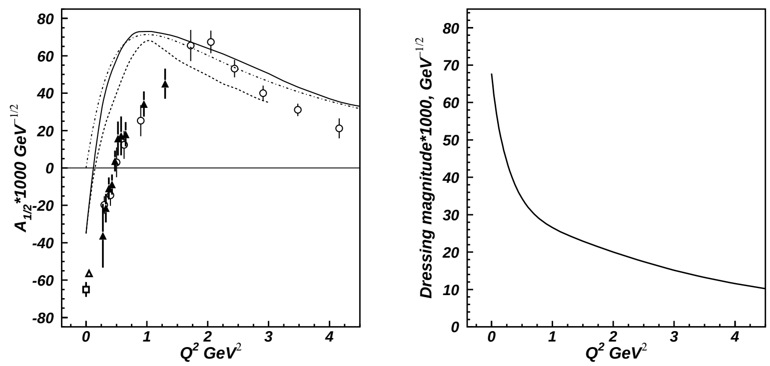

FIGURE 1. Left: Electrocouplings of the $P_{11}(1440)$ resonance determined in independent analyses of the CLAS data on $N\pi$ (circles) and $\pi^+\pi^-p$ (triangles) electroproduction off protons. Square and triangle at Q^2=0 correspond to RPP [16] and the CLAS $N\pi$ [17] photoproduction results, respectively. The results of relativistic light-front quark models [18, 19] are shown by solid and dashed lines, respectively. Results of the covariant valence quark-spectator diquark model [20] are shown by the dashed dotted line. Right: Estimate for absolute values of meson baryon dressing amplitude contributing to $A_{1/2}$ electrocoupling obtained within the framework of coupled-channel model [22] from a global fit of the data on $N\pi$ photo-, electro-, and hadroproduction.

resonant amplitudes are described using a unitarized Breit-Wigner ansatz proposed in Ref. [14], and modified to make it consistent with the resonant amplitude parametrization employed in the JM model. This ansatz accounts for transition between the same and different N^* states in the dressed-resonant propagator, making resonant amplitudes consistent with unitarity condition. We took into account for transitions between $D_{13}(1520)/D_{13}(1700)$, $S_{11}(1535)/S_{11}(1650)$ and $3/2^+(1720)/P_{13}(1720)$ pairs of N^* states, and found that use of the unitarized Breit-Wigner ansatz had a minor influence on the $\gamma_v NN^*$ electrocouplings, but may affect substantially the N^* hadronic decay widths. Non-resonant contributions to $\pi\Delta$ and ρp isobar channels are described in [10] and [13], respectively. Other isobar channels are described by non-resonant amplitudes presented in Refs. [11, 15].

The JM model provided reasonable description of $\pi^+\pi^-p$ differential cross sections at $W < 1.8$ GeV and $Q^2 < 1.5$ GeV^2 with χ^2/d.p. < 3.0.The successful description of $\pi^+\pi^-p$ electroproduction cross sections allows us to isolate the resonant parts and to determine $\gamma_v NN^*$ electrocouplings, as well as the $\pi\Delta$ and ρp decay widths.

RESULTS ON THE $\gamma_v NN^*$ ELECTROCOUPLINGS AND IMPACT ON THE STUDIES OF N^* STRUCTURE

Electrocouplings of $P_{11}(1440)$, $D_{13}(1520)$ and $F_{15}(1885)$ excited proton states are shown in Figs. 1 and 2. The results from $N\pi$ and $\pi^+\pi^-p$ channels are consistent within their uncertainties. Consistent results on $\gamma_v NN^*$ electrocouplings for several excited proton states determined in independent analyses of major meson electroproduction channels with different backgrounds demonstrate that the reaction models described above provide reliable evaluation of these fundamental quantities. It makes possible to determine electrocouplings of all resonances that decay preferentially to the either $N\pi$ or $N\pi\pi$ final states analyzing independently the $N\pi$ or $\pi^+\pi^- p$ electroproduction channels, respectively. The studies of $N\pi$ exclusive channels are the primary source of information on electrocouplings of the N^* states with masses below 1.6 GeV [4]. The $\pi^+\pi^- p$ electroproduction off protons allowed us to check the results from $N\pi$ data analyses for the resonances that have substantial decays to both $N\pi$ and $N\pi\pi$ channels. Furthermore, they are of particular importance for the evaluation of high-lying resonance electrocouplings, since most N^*'s with masses above 1.6 GeV decay preferentially via two pion emission.

Preliminary results on electrocouplings of $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$ and $P_{13}(1720)$ states were obtained from the CLAS $\pi^+\pi^- p$ electroproduction data [8]. Electrocouplings of the $D_{33}(1700)$ state determined from $N\pi$ (previously available world data [23]) and $\pi^+\pi^- p$ (the CLAS results) electroproduction channels are shown in Fig. 3. The CLAS results improved considerably our knowledge of the $D_{33}(1700)$ electrocouplings. They provided accurate data on the Q^2-evolution of the transverse electrocouplings and the first information on the longitudinal electrocouplings of all the above mentioned excited proton states.

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Analysis of the CLAS results on $P_{11}(1440)$ electrocouplings revealed major features of this state structure that remained a mystery for decades. Two light-front quark models [18, 19] and conceptually different covariant valence quark-spectator diquark model [20] provided reasonable descriptions of $P_{11}(1440)$ electrocouplings at $Q^2 > 1.5$ GeV^2. In these models, the $P_{11}(1440)$ structure is described as the first radial excitation of three-quark ($3q$) ground state. The CLAS results showed that at $Q^2 > 1.5$ GeV^2 the $P_{11}(1440)$ structure is determined mostly by a core of three constituent quarks. However, at $Q^2 <$ 1.0 GeV^2, quark models fail to describe the $A_{1/2}$ electrocoupling. This is an indication of additional contributions beyond those from a quark core. A general unitarity condition requires the contribution to $\gamma_v NN^*$ electrocouplings from meson-baryon dressing when the N^* state is excited through a sequence of the following processes: a) non-resonant meson-baryon production by a virtual photon and b) resonance formation in subsequent meson-baryon scattering [21]. The absolute value of meson-baryon dressing amplitudes determined from the data on $N\pi$ photo-, electro- and hadroproduction [22] is shown in Fig 1. It is maximal at small photon virtualities and may, in part, be responsible for the differences between quark model expectations and the CLAS results on $P_{11}(1440)$ electrocouplings.

Electrocouplings of the $D_{13}(1520)$ state, shown in Fig. 2, are well described at Q^2 $>$ 2.0 GeV^2 within the framework of quark model [24], which assumes the contributions from three constituent quarks in the first orbital excitation with L=1. This model underestimates the $A_{3/2}$ electrocoupling at $Q^2 <$ 2.0 GeV^2. At these photon virtualities absolute values of meson-baryon dressing contributions to this electrocoupling are maximal [22]. Differences between the CLAS results on $D_{13}(1520)$ electrocouplings and expectations of quark model [24] may be related to the meson-baryon cloud.

We conclude that the structure of excited proton states with masses below 1.6 GeV determined by combined contributions from the internal core of three constituent quarks and the external meson-baryon cloud.

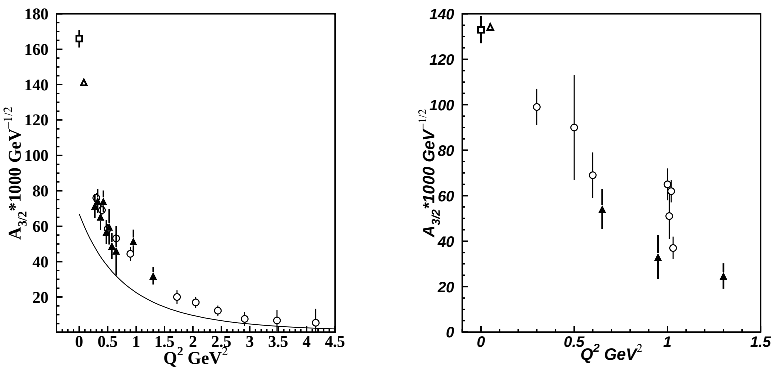

FIGURE 2. Electrocouplings of $D_{13}(1520)$ (left) and $F_{15}(1685)$ (right) resonances determined in independent analyses of the CLAS [4] and world [23] data on $N\pi$, and the CLAS data on $\pi^+\pi^-p$ [8, 9] electroproduction off protons. Symbols are the same as in Fig. 1. The results of quark model [24] are shown by solid line.

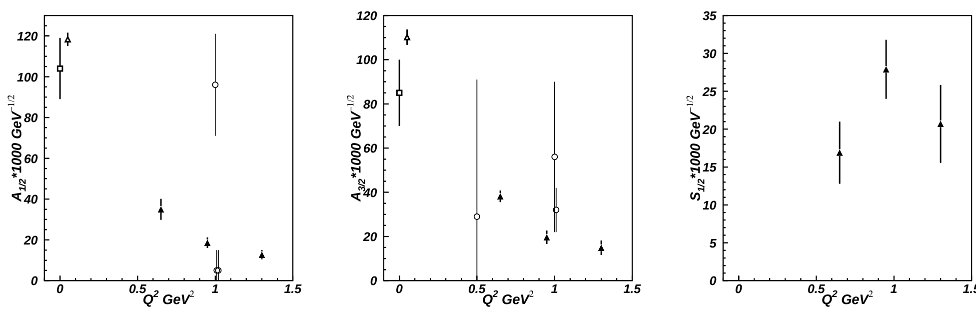

FIGURE 3. Electrocouplings of $D_{33}(1700)$ resonance $A_{1/2}$ (left), $A_{3/2}$ (middle) and $S_{1/2}$ (right) determined in independent analyses the CLAS data on $\pi^+\pi^-p$ [8, 9] and world data [23] on $N\pi$ electroproduction off protons. Symbols are the same as in Fig. 1.

CONCLUSION

The information on Q^2 evolution of $\gamma_v NN^*$ electrocouplings of many excited proton states in the mass range up to 1.8 GeV has become available from the analyses of exclusive $N\pi$ and $\pi^+\pi^-p$ electroproduction off protons measured with CLAS detector. Consistent results obtained from independent analyses of major meson electroproduction channels demonstrate reliable extraction of these fundamental quantities. They open up new opportunities for studies of the non-perturbative strong interaction that is responsible for the formation of excited proton states of different quantum numbers. In particular, they stimulated the development of N^* structure models presented, in part, at this workshop [20, 25, 26, 27, 28]. Furthermore, two conceptually different approaches of QCD-Lattice QCD [29, 30, 31, 32, 33, 34] and Dyson-Schwinger equations [3, 35]- are making progress toward the description of $\gamma_v NN^*$ electrocouplings from the first principles of QCD.

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