Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 011006 (2019)
https://doi.org/10.7566/JPSCP.26.011006

N* Physics with CLAS at Jefferson Lab

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(Received February 26, 2019)

Studies of the nucleon resonance electroexcitation amplitudes in a wide range of photon virtualities (Q^2) offer unique information on many facets of strong QCD behind the generation of all prominent excited nucleon states of distinctively different structure. As a part of a broad effort to determine the electrocouplings of the N^* and Δ resonances using both single and double pion electroproduction, the CLAS dataset is crucial for the reliable extraction of high-lying resonance electrocouplings from the combined isospin analysis of the $N\pi$ and $\pi^+\pi^-p$ channels. For several of the prominent excited states in the lower mass range the short distance behavior is described by a core of three dressed-quarks with running quark mass, and meson-baryon contributions make up significant parts of the excitation strength at large distances. Finally, an outlook of baryon resonance (N^*) physics at the 12 GeV CEBAF electron accelerator will be presented.

KEYWORDS: Electromagnetic Interactions, Form Factors, Nucleon Structure, Excited Nucleon States

1. Introduction

The excitation of nucleon resonances via the electromagnetic interaction is an important source of information on the structure of excited nucleon states and dynamics of the non-perturbative strong interaction behind the resonance formation [1,2]. The nucleon resonance electroexcitation amplitudes ($\gamma_v pN^*$ electrocouplings) are the primary source of information on many facets of non-perturbative strong interactions in the generation of the excited proton states from quarks and gluons. Detailed studies of resonance electroexcitation in exclusive meson electroproduction off nucleons became feasible only after dedicated experiments were carried out with the CLAS detector [3] in Hall B at Jefferson Lab (see Fig. 1). The CLAS detector has produced the dominant part of the available world data on all meson electroproduction channels off the nucleon relevant in the resonance region for Q^2 up to 5.0 GeV^2 available in the CLAS Physics Database [5]. Analyses of these data within the framework of phenomenological reaction models provided information on electrocouplings of most excited nucleon states in the mass range up to 1.8 GeV and at photon virtualities $Q^2 < 5.0$ GeV^2 [4]. The detailed information on the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings are available for the excited nucleon states in the resonance region. The $\gamma_v pN^*$ electrocouplings of these resonances were determined from independent studies of $N\pi$ [6, 7], $N\eta$ [8] and $\pi^+\pi^-p$ [9-11] electroproduction off protons. The results on $\gamma_v pN^*$ electrocouplings from the CLAS exclusive meson electroproduction data are stored in the web sites [12, 13].

The electrocoupling values obtained for the resonances from major $N\pi$ and $\pi^+\pi^-p$ exclusive channels with completely different non-resonant mechanisms are fully consistent offering a strong evidence for credible extraction of these fundamental quantities in a nearly model independent way. This success also demonstrates the capability of the reaction models developed for extraction of $\gamma_v pN^*$ electrocouplings to provide reliable information on the resonance parameters from independent studies of $N\pi$ and $\pi^+\pi^-p$ electroproduction off protons. $\gamma_v pN^*$ electrocouplings of several nucleon resonances determined from the CLAS data were published in the recent PDG edition [14]. The CLAS results on nucleon resonance electrocouplings already have a profound impact on the understanding of active degrees of freedom in the N^* structure at different distances and the strong QCD dynamics underlying the generation of excited nucleon states with different structural features. Analyses of the CLAS results on $\gamma_v pN^*$ electrocouplings within the framework of continuum QCD Dyson-Schwinger Equation approach and quark models revealed the N^* structure as a complex interplay between inner core of three dressed quarks and external meson-baryon cloud.

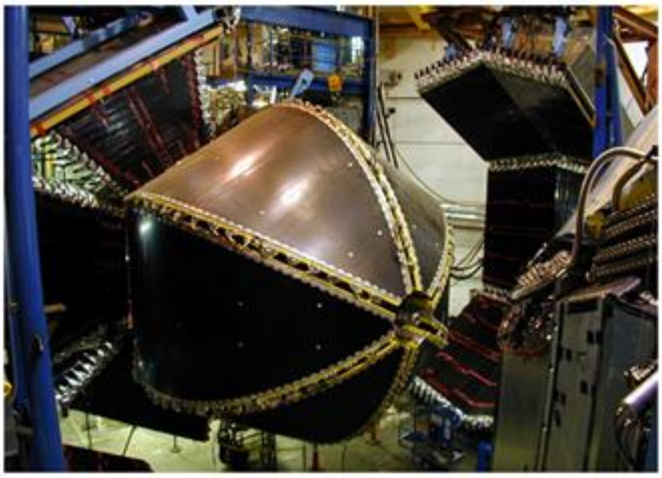

Fig. 1. The CLAS detector in an open maintenance position exposing the large drift chambers covering nearly the full polar angle range. The time-of-flight scintillator bars and the forward electromagnetic calorimeters are also visible.

The impressive success achieved in exploration of strong QCD regime from the results on electrocouplings of just several excited nucleon states strongly motivates further extension in studies of $\gamma_v pN^*$ electrocouplings over full spectrum of excited nucleon states and within the maximal range of photon virtualities covered by the CLAS detector of $Q^2 < 5.0$ GeV^2. These studies will address the key aspects in exploration of the strong QCD on universality or environmental sensitivity of the constituent quark running mass, elucidate complex dynamics underlying the generation of dressed quark-gluon vertex through the studies of electroexcitation amplitudes for the resonances with three quarks in the orbital-excited states. Exploration of all prominent resonances will offer further insight into diversity of qq-correlations in the structure of the excited nucleons of different quantum numbers as well as into dynamical chiral symmetry breaking through analyses of the results on the electroexcitation amplitudes of the pairs of resonances which are the chiral parity partners.

2. The current status of experimental measurements for the resonance parameter extraction

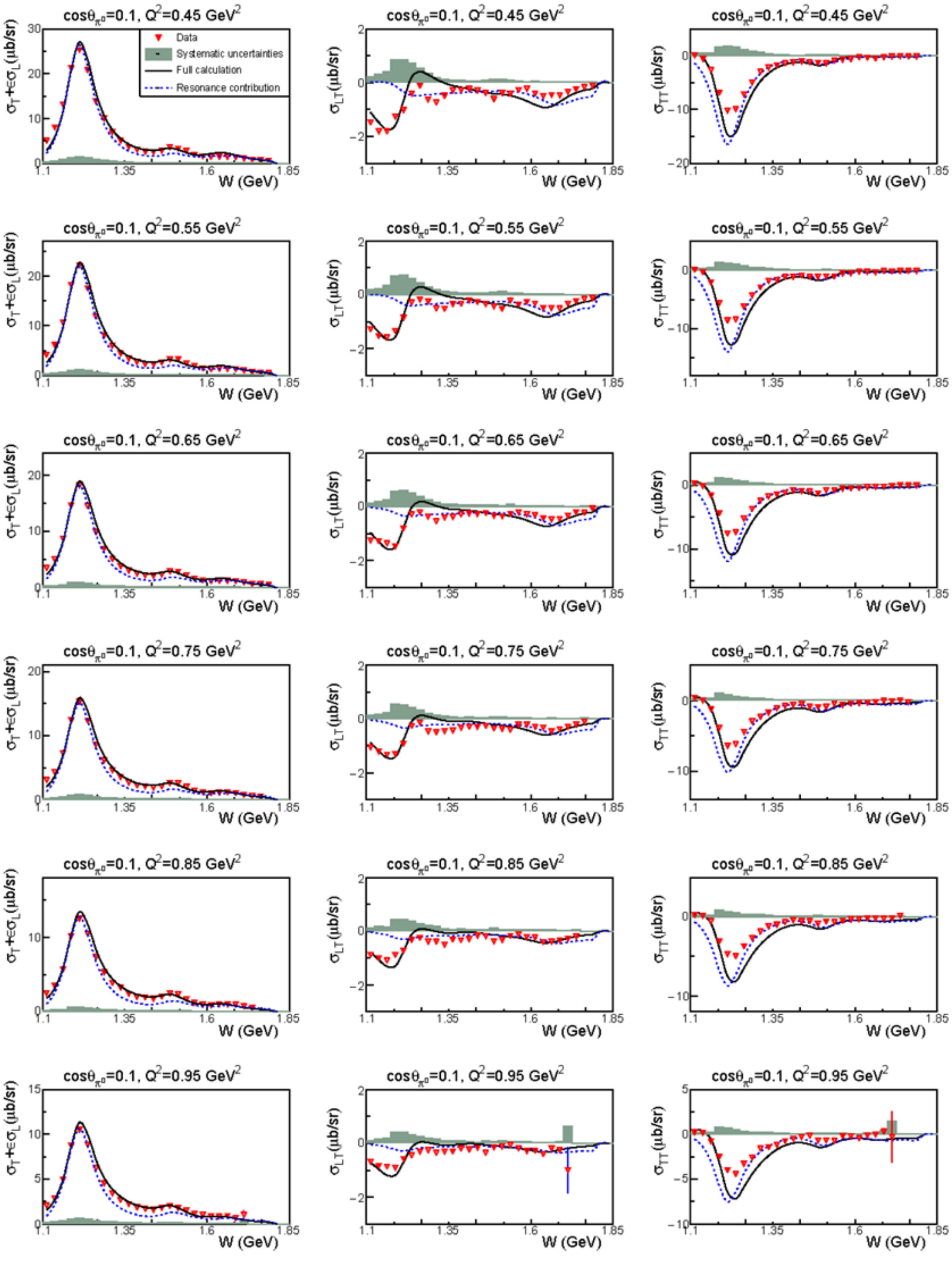

Fig. 2. W dependencies of the exclusive structure functions $\sigma_T + \varepsilon\sigma_L$, σ_{LT}, and σ_{TT} in different bins of the (cosθ, Q^2). Computation of the exclusive structure function within the framework of the JM model and with the resonance parameters determined from the CLAS exclusive meson electroproduction data [7, 10, 11] are shown by solid lines, while the blue dashed lines represents the resonant contributions.

The analysis of Nπ and $\pi^+\pi^-$p electroproductions off protons from CLAS has allowed us to develop the JLab-Moscow (JM) model with the goal to extract resonance electrocouplings as well as $\pi\Delta$ and ρp hadronic decay widths. Examples of the extracted structure functions of pπ^0 are shown in Fig. 2 and compared to predictions calculated using resonance electrocouplings and hadronic decay parameters from previous analyses of CLAS data [7, 10, 11]. Also shown are resonant contributions calculated from the JM model. The model incorporates all relevant reaction mechanisms in the final-state resonance region, including the $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρ^0p, π^+N(1520) $3/2^-$ and π^+N(1685) $5/2^+$ meson-baryon channels, as well as the direct production of the $\pi^+\pi^-$p final state without formation of intermediate unstable hadrons. The contributions from the well-established N* states in the mass range up to 2.0 GeV were included into the amplitudes of the $\pi\Delta$ and ρp meson-baryon channels by employing a unitarized version of the Breit-Wigner ansatz. The JM model provides a good description of the CLAS measurements at W < 2.0 GeV and 0.2 GeV^2 < Q^2 < 5.0 GeV^2 with χ^2/d.o.f. < 3.0 accounting for only the statistical uncertainties of the data. Descriptions of the fully integrated $\pi^+\pi^-$p electroproduction cross sections are shown in Fig. 3 together with the contributions from the meson-baryon mechanisms of the JM model inferred from the CLAS data. These results offer valuable input for the global multi-channel analyses in the resonance excitation region within advanced coupled channel approaches for their extensions towards the extraction of γ_vpN* electrocouplings from exclusive meson electroproduction off nucleon data. The determined resonant/non-resonant contributions are located within well-defined ranges (see Fig. 3 and 4). The uncertainties of the resonant/non-resonant contributions are comparable with the uncertainties of the measured cross sections, demonstrating unambiguous resonant/non-resonant separation of a good accuracy. The credible isolation of the resonant contributions makes it possible to determine the resonance photo-electrocouplings along with the $\pi\Delta$ and ρN decay widths by employing for the description of their amplitudes the unitarized Breit-Wigner ansatz [10] that fully accounts for the unitarity restrictions on the resonant amplitudes.

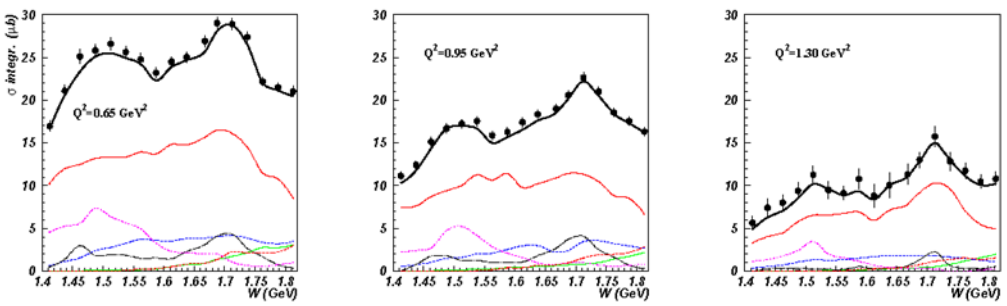

Fig. 3. Description of the fully integrated $\pi^+\pi^-$p electroproduction cross sections achieved within the framework of the JM model together with the cross sections for the various contributing mechanisms: full cross section (black solid), $\pi^-\Delta^{++}$ (red thin solid), ρ^0p (green thin solid), $\pi^+\Delta^0$ (blue thin dashed), π^+N(1520) $3/2^-$ (black dotted), direct 2π mechanisms (magenta thin dot-dashed), and π^+N(1685) $5/2^+$ (red thin dashed).

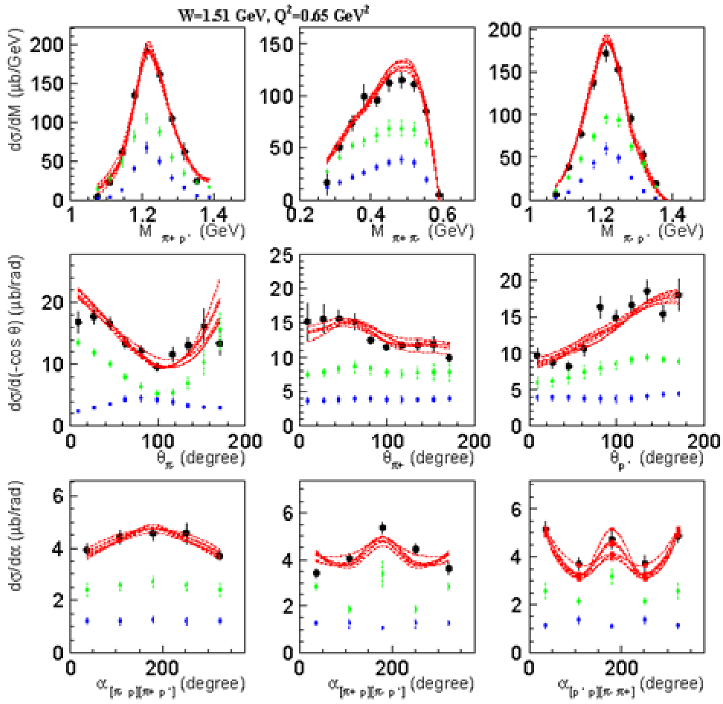

Fig. 4. Examples of fits to the CLAS data [4] on the nine one-fold differential $\pi^+\pi^-p$ electroproduction cross sections in bins of W and Q^2 within the framework of the JM model. The curves correspond to those fits with χ^2/d.o.f. less than the value determined so that the selected in the fit cross sections are spread within the data uncertainties for the dominant part of the data points. The resonant and non-resonant contributions determined from the data fit within the framework of the JM model [10] are shown by blue triangles and green squares, respectively.

3. The resonance parameters from the exclusive πN and $\pi^+\pi^-p$ channels

Consistent results for the $\gamma_v pN^*$ electrocouplings of the N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances, which have been determined in independent analyses of the dominant meson electroproduction channels πN and $\pi^+\pi^-p$, shown in Fig. 5 (left) and (middle), demonstrate that the extraction of these fundamental quantities is reliable. Studies of the exclusive electroproduction channels off protons πN and $\pi^+\pi^-p$ offer complementary information on the N^* electrocouplings. For low lying excited nucleon states in the mass range up to 1.6 GeV that decay preferentially to the πN final states, the data on single-pion exclusive electroproduction drive the extraction of these resonance electrocouplings. The CLAS data for the $\pi^+\pi^-p$ channel play a critical role in the extraction of the $\gamma_v pN^*$ electrocouplings of higher-lying nucleon excited states (M > 1.60 GeV), which decay preferentially to the πN final states, e.g. Δ(1620)1/2$^-$, Δ(1700)1/2$^-$, N(1720)3/2$^+$, and the N′(1720)3/2$^+$ candidate state. Right now, the electrocouplings of these states can only be determined from the data in the $\pi^+\pi^-p$ exclusive electroproduction channel off protons, while the πN channels do not have enough sensitivity to the electrocouplings of the aforementioned resonances.

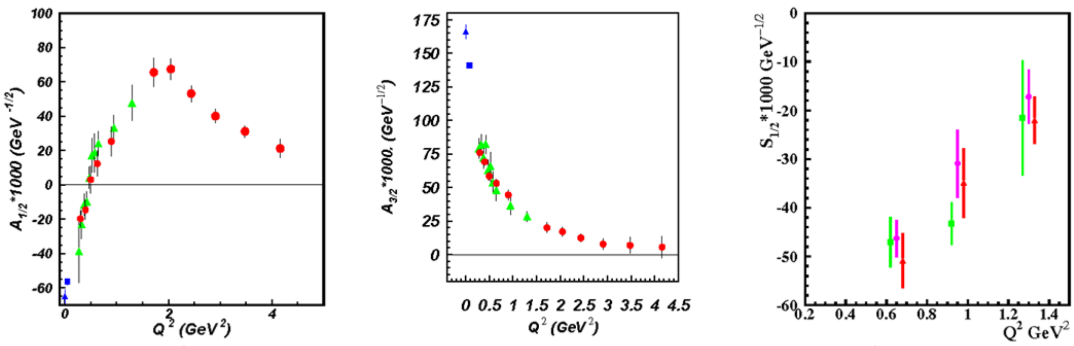

Fig. 5. $A_{1/2}$ $\gamma_v pN^*$ electrocouplings of the N(1440)1/2$^+$ (left), $A_{3/2}$ $\gamma_v pN^*$ electrocouplings of the N(1520)3/2$^-$ (middle), and $S_{1/2}$ $\gamma_v pN^*$ electrocouplings of the Δ(1620)1/2$^-$ (right) from analyses of the CLAS electroproduction data off protons in the πN (red circles in the left and middle panels) and $\pi^+\pi^-$p channels [10, 11] (green triangles in the left and middle panels). The right panel shows the Δ(1620)1/2$^-$ electrocouplings obtained from analyses of $\pi^+\pi^-$p electroproduction data off protons [11] carried out independently in three intervals of W: 1.51 GeV$\rightarrow$1.61 GeV (green squares), 1.56 GeV$\rightarrow$1.66 GeV (magenta circles), and 1.61 GeV$\rightarrow$1.71 GeV (red triangles). The photocouplings were taken from the RPP [15] (blue filled triangles) and the CLAS data analysis [16] of πN photoproduction (blue filled squares)

We have developed special procedures to test the reliability of the $\gamma_v pN^*$ resonance electrocouplings extracted from the charged double pion electroproduction data. In this case, we carried out the extraction of the resonance parameters, independently fitting the CLAS $\pi^+\pi^-$p electroproduction data in overlapping intervals of W. The non-resonant amplitudes in each of the W-intervals are different, while the resonance parameters should remain the same as they are determined from the data fit in different W-intervals, see Fig. 5 (right). The consistent results on these electrocouplings from the independent analyses in different W-intervals strongly support their reliable extraction. The tests described above demonstrated the capability of the models to provide reliable information on the $\gamma_v pN^*$ resonance electrocouplings from independent analyses of the data on exclusive πN and $\pi^+\pi^-$p electroproduction.

Recently the information on the excited nucleon state photocouplings was extended by the first results on the photocouplings of most nucleon resonances with masses above 1.6 GeV from the exclusive πN and $\pi^+\pi^-$p photoproduction off protons measured with CLAS. Many of them decay preferentially to the $\pi\pi$N final states. The cross sections of $\pi^+\pi^-$p photoproduction off protons are the biggest among $\pi\pi$N photoproduction off proton channels. Overall, 400 million $\pi^+\pi^-$p events were selected exceeding by a factor of ~50 the statistics previously collected in this channel. Good description of these new data with $1.15 < \chi^2/\text{d.o.f.} < 1.3$ was achieved within the framework of the meson-baryon reaction model JM. Credible isolation of the resonant contributions obtained in the data fit allowed us to determine the resonance parameters. The resonance photocouplings extracted from this work are listed in Table I and compared with the resonance photocoupling ranges and the results of the multichannel analysis included in the PDG2018. There is good agreement in the magnitude and sign of the photocouplings between our results and the photocoupling ranges in the PDG listings. On the other hand, for several resonances, the photocouplings determined from the multichannel analysis are different from ours. Implementation of our $\pi^+\pi^-p$ photoproduction data into the global multichannel analyses will improve essentially our knowledge on the photocouplings and hadronic decay parameters of the resonances in the mass range of W > 1.6 GeV. For successful description of the $\pi^+\pi^-p$ photo- and electroproduction CLAS data with Q^2-independent resonance hadronic decay parameters, the new baryon states N(1720)3/2$^+$ is needed. Evidences for the N(1720)3/2$^+$ new resonance will be published soon.

Resonances	$A_{1/2} \times 10^3$ From $\pi^+\pi^-p$ GeV$^{-1/2}$	$A_{1/2}\times 10^3$ PDG ranges GeV$^{-1/2}$	$A_{1/2} \times 10^3$ Multi-channel Analysis GeV$^{-1/2}$	$A_{3/2} \times 10^3$ From $\pi^+\pi^-p$ GeV$^{-1/2}$	$A_{3/2} \times 10^3$ PDG ranges GeV$^{-1/2}$	$A_{3/2} \times 10^3$ Multi-channel Analysis GeV$^{-1/2}$
Δ(1620)1/2$^-$	29.0±6.2	30–60	55±7			
N(1650)1/2$^-$	60.5±7.7	35–55	32±6			
N(1680)5/2$^+$	−27.8±3.6	−18–−5	−15±2	128±11	130–140	136±5
N(1720)3/2$^+$	80.9±11.5	80–120	115±45	−34.0±7.6	−48–135	135±40
Δ(1700)3/2$^-$	87.2±18.9	100–160	165±20	87.2±16.4	90 – 170	170±25
Δ(1905)5/2$^+$	19.0±7.6	17 – 27	25±5	−43.2±17.3	−55–−35	−50±5
Δ(1950)7/2$^+$	−69.8±14.1	−75–−65	−67±5	−118.1±19.3	−100−80	−94±4

Table I. Resonance photocouplings determined from analysis of the $\pi^+\pi^-p$ photoproduction data from this work in comparison with the previous results from the PDG average and from multichannel analysis.

4. Outlook

Exploration of the excited nucleon state structure in exclusive πN, KY, and $\pi^+\pi^-p$ electroproduction off protons at 5.0 GeV^2 < Q^2 < 12.0 GeV^2 is already started in run group A measurements with the CLAS12 detector. For the first time, the electrocouplings of all prominent nucleon resonances will become available at the highest photon virtualities (Q^2) ever achieved in the studies of exclusive electroproduction. These distance scales correspond to the still unexplored regime for N* electroexcitations where the resonance structure is dominated by the quark core with almost negligible meson-baryon cloud contributions. The foreseen experiments offer almost direct access to the properties of dressed quarks inside N* states of different quantum numbers. Consistent results on the dressed quark mass function derived from independent analyses of the data on the $\gamma_v pN^*$ electrocouplings of the resonances with distinctively different structure, such as radial excitations, spin-isospin flip, and orbital excitations, will validate the credible access to this fundamental ingredient of strong QCD from the experimental data. The expected data on the $\gamma_v pN^*$ electrocouplings will provide for the first-time access to the dressed quark mass function in the range of quark momenta up to 1.5 GeV, where the transition from the quark-gluon confinement to the pQCD regimes of the strong interaction takes full effect. Exploring the dressed quark mass function at these distances will allow us to address the most challenging open problems of the Standard Model on the nature of >98% of hadron mass and quark-gluon confinement.

Acknowledgment

I am grateful to V. I. Mokeev, I. G. Aznauryan, C. D. Roberts, E. Santopinto, and J. Segovia for helpful discussions. This work was supported in part by the U.S. Department of Energy (DE-FG-04ER41309).

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