Update of the Proposal PR-09-003 “Nucleon Resonance Studies with CLAS12”

ABSTRACT

The proposal PR-09-003 *‘Nucleon Resonance Studies with CLAS12’* was approved by PAC34. By measuring the differential cross sections for the electroproduction of exclusive single-meson and double-pion off protons, we seek to extract the electromagnetic transition form factors (electrocouplings) for well-established excited nucleon states in the unexplored domain of $Q^2 > 5$ GeV^2. The expected data on resonance electrocouplings will allow us to systematically explore how in the strong interaction regime of QCD, bare quarks are dressed with gluons and how quark cores of the various N^* states emerge from QCD. This experiment is an essential part of the comprehensive program of exclusive electroproduction measurements with CLAS12, in which various channels such as deeply virtual Compton scattering and deeply virtual exclusive meson production will be measured as well. The close collaboration of experimentalists and theorists, as documented in the full proposal, will allow us to provide high-precision data and high-quality analyses, as well as state-of-the-art, QCD-based calculations of resonance electrocouplings.

I. INTRODUCTION

For the foreseeable future, the CLAS12 detector will be the sole facility worldwide capable of delivering comprehensive information on the $\gamma_v NN^*$ transition helicity amplitudes – and thereby the electrocouplings – at photon virtualities of $Q^2 > 5.0$ GeV^2 and in the mass range up to 2 GeV. Electrocouplings will be extracted from the electroproduction of the primary meson reaction channels, $n\pi^+$, $p\pi^0$, $p\eta$, and $p\pi^+\pi^-$. Through our recent work [1, 2] at $Q^2 < 5.0$ GeV^2, we have found consistent results on the $\gamma_v NN^*$ electrocouplings in both the single- and double-pion modes. In that these dominant meson-electroproduction channels possess completely different non-resonant contributions, consistent electrocouplings from these different reaction channels offer compelling evidence of the validity of this phenomenological result [3]. We expect such analysis of the dominant meson reaction channels at photon virtualities of $Q^2 > 5.0$ GeV^2 to similarly lend strong credence to the reliability of extracting the electrocoupling data. The final results on $\gamma_v NN^*$ electrocouplings will be determined from a simultaneous global analysis of all measured channels, within the framework of an advanced dynamical coupled-channel approach, based on the analytical continuation of the reaction amplitudes of multiple reaction channels. This approach is currently under development at the Excited Baryon Analysis Center (EBAC) and will be available shortly (2010/2011), which will allow for detailed tests with existing data collected in meson electroproduction at $Q^2 < 5$ GeV^2.

Investigating the evolution of the $\gamma_v NN^*$ electrocouplings for several prominent excited states at $Q^2 > 5.0$ GeV^2 will offer direct access to the quark structure of the nucleon. At these distance scales, meson-baryon cloud contributions are expected to be small or negligible. In conjunction with detailed information on the nucleon ground state structure from the other experiments at 12 GeV, a comprehensive dataset, allowing us to access quark contributions to the spectrum of nucleon states, will be available for the very first time. The results from our experiment will be used by EBAC and the Theory Support group for our proposal [4] to provide

- access to the dynamics of non-perturbative strong interactions among dressed quarks and to shed light on their emergence from QCD and the subsequent N* formation;
- information on how the constituent quark mass arises from a cloud of low-momentum gluons which constitute the dressing to the current quarks. This process of dynamical chiral-symmetry breaking accounts for over 97% of the nucleon mass;
- enhanced capabilities for exploring the behavior of the universal QCD β-function in the infrared regime.

We have strong theoretical support for our research program. In fact, the “Workshop on Electromagnetic Transition Form Factors,” which was held at JLab, October 13-15, 2008 [5], owes its genesis to this close collaboration between experimentalists and theorists on our experimental proposal. As new theoretical developments emerge, we shall certainly follow up on them as we did in documenting the detailed plan on theory support for our proposal in the 62-page White Paper entitled, “Theory Support for the Excited Baryon Program at the JLab 12 GeV Upgrade,” which appeared as a preprint [3]. We shall continue to disseminate the research activities on the electroproduction of baryon resonances at high Q^2 in dedicated sessions such as “Light Baryons at High Photon Virtualities” which convened within the “Third Workshop of the APS Topical Group in Hadron Physics,” April 29 - May 1, 2009, Denver, Colorado [6] and the upcoming workshop, “Exclusive Reaction at High Momentum Transfer IV,” May 18-21, 2010, which will take place at Jefferson Lab and where updates on the studies of $\gamma_v NN^*$ electrocouplings will be presented.

To keep abreast of the latest theoretical developments in extracting the $\gamma_v NN^*$ electrocouplings, – which incorporate quark degrees of freedom into the description of the non-resonant mechanisms that become relevant at high Q^2 – we hold monthly joint Hall B & EBAC Meetings at Jefferson Lab and organize informal seminars and meetings like the "N*-GPD Meeting" at JLab, September 11, 2009 [7].

Since our proposal was just approved in January, 2009, we shall focus on our achievements over this past year as described in the following three sections. Starting with Section II, we present several recent theoretical approaches that relate phenomenological information on the Q^2 evolution of the $\gamma_v NN^*$ electrocouplings to the mechanisms that are responsible for N^* formation and thereby shed light on their emergence from QCD. Updates on approaches for extracting $\gamma_v NN^*$ electrocouplings are reported in Section III and a brief update on the development of the experiment is delineated in section IV.

II. THEORETICAL DEVELOPMENTS IN INTERPRETING THE $\gamma_v NN^*$ ELECTROCOUPLINGS

Through the theoretical interpretation of $\gamma_v NN^*$ electrocouplings, we seek to establish an unambiguous relation between the information extracted phenomenologically and the non-perturbative strong interaction mechanisms that are responsible for baryon formation. Moreover, from our analysis of the available CLAS data on the Q^2-evolution of the $\gamma_v NN^*$ electrocouplings, we are able to describe the resonance structures in terms of an internal quark core and a surrounding meson baryon cloud, which can be viewed as originating from the reaction mechanisms as indicated in Fig. 1. Most of the data, upon which these analyses were based, were in the range $Q^2 < 5.0$ GeV^2 [3, 6, 8–11]. Analysis of these data indicate that the quark degrees of freedom already appear to become dominant for $Q^2 > 5.0$ GeV^2. The first datasets at Q^2 up to 7.0 GeV^2 obtained at Jefferson Lab [12, 13] are completely consistent with these expectations.

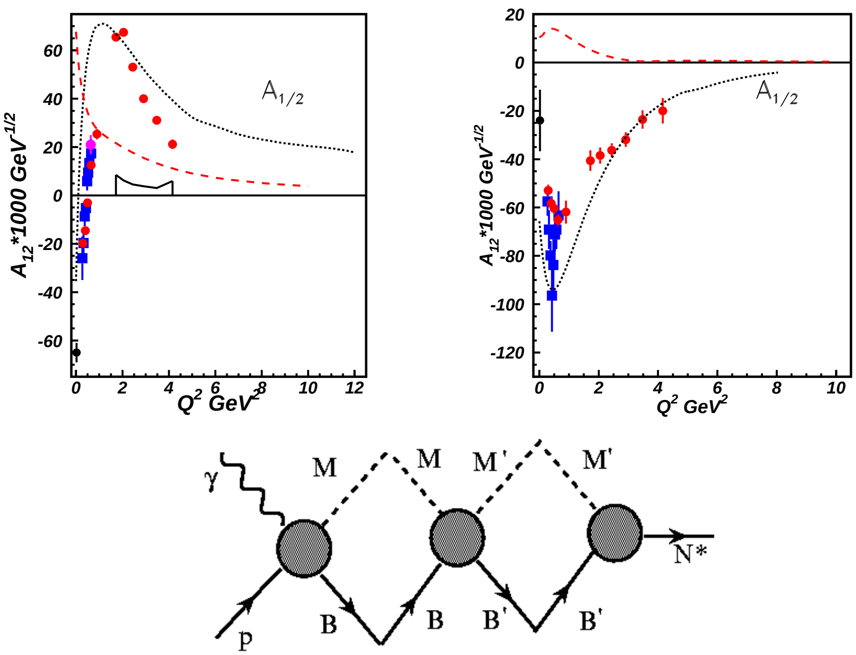

FIG. 1: The contributions from quark degrees of freedom and meson-baryon dressing to the $A_{1/2}$ electrocouplings of the $P_{11}(1440)$ (left) and $D_{13}(1520)$ (right) states. The CLAS data from analyses of $N\pi$ [1] and $\pi^+\pi^-p$ [2] electroproduction are shown in red and blue, respectively. The contributions from the quark core, estimated within the framework of relativistic quark models [14, 15], are given by the dotted lines, and the contributions from meson-baryon dressing, obtained within the framework of the EBAC-DCC approach [16], are represented by the red (dashed) lines. The diagram, beneath the plots, depicts the effects of the meson-baryon dressing.

A. The need for data at high Q^2

Figure 1 shows the CLAS helicity amplitude data for both single- and double-pion reactions for the two excited-baryon states. Superimposed are the contributions to the electrocouplings of the $P_{11}(1440)$ and $D_{13}(1520)$ states from the quark degrees of freedom, estimated within the framework of quark models [14, 15], and from meson baryon dressing, estimated within the framework of the Dynamical Coupled Channel (DCC) analysis from EBAC or EBAC-DCC [16]. These models find that the meson-baryon dressing contributions are substantial, particularly at $Q^2 < 1.0$ GeV^2, and are quite complex, thus making it difficult to access unambiguously the quark degrees of freedom at low Q^2.

A recent EBAC-DCC analysis of the world's $N\pi$ scattering data [17] indicates that a common quark core may create multiple resonance poles in the scattering amplitudes. For the P_{11} wave they find two poles in a complex energy plane near the corresponding PDG values for the $P_{11}(1440)$ state and a third one at (1820,−248) GeV; all three originate from a common quark core at a mass of 1.76 GeV. The combined analysis of the elastic πN scattering data and the recent single-pion electroproduction data, as performed within the framework of the extended analytical continuation method [18], has revealed significant imaginary parts in $\gamma_v NN^*$ transition helicity amplitudes, where two of the three poles lie close to the $P_{11}(1440)$ state. Earlier approaches for quark core contribution predicted electrocouplings that have no imaginary components. Such complications make it difficult for a direct comparison between $\gamma_v NN^*$ electrocouplings and predictions of models, that take into account only the contributions from quark degrees of freedom.

On the other hand, the EBAC results (cf. Fig. 1) have shown that absolute and relative contributions from the meson-baryon cloud decrease with increasing Q^2 and meson-baryon dressing becomes negligible at $Q^2 > 5.0$ GeV^2. It is at these distance scales where quark degrees of freedom are expected to dominate. The data on $\gamma_v NN^*$ electrocouplings at $Q^2 > 5$ GeV^2, are expected to afford direct access to the quark degrees of freedom, thereby allowing us to avoid the aforementioned complications caused by the meson-baryon dressing at lower photon virtualities.

We shall make use of several theoretical approaches towards the goal of understanding the strong-interaction mechanisms that create N^*s from the underlying quarks and gluons based on the phenomenological information on the Q^2 evolution of $\gamma_v NN^*$ electrocouplings. Among the approaches we will employ are: Lattice QCD, Light-cone sum rules, a formalism based on the Dyson-Schwinger equations of QCD, and quark models; the last being the only currently available tool for the analysis of electrocouplings of the majority of the excited proton states. Accounting for the meson-baryon dressing is still beyond the scope of any of these approaches. Therefore, they can only be efficiently applied in the analysis of $\gamma_v NN^*$ electrocouplings at $Q^2 > 5.0$ GeV^2, which is exactly within the expected kinematic reach of this experiment.

B. Lattice QCD

During this past year (2009) the first LQCD calculations of the highly excited state spectra of the nucleon and Δ were made with three flavors of dynamical fermions. A significant step in these calculations is the determination of the spin content of the states [19, 20]. The number of states that are well determined is far beyond any previous LQCD calculations. However, a full study will need to include multi-particle operator constructions which will couple to decaying states, for example the $P_{11}(1440)$. Already, though, some information as to the content of the states can be gleaned from wavefunction overlaps, such as mixing angles. The decay of these states via radiative transitions determines the $\gamma_v NN^*$ electrocouplings. The first LQCD predictions [21, 22] of the $N - P_{11}(1440)$ electromagnetic transition form factors F_1 and F_2 were obtained for several pion masses as shown in Fig. 2. The LQCD calculations were carried out for relatively large pion masses, with three flavors of dynamical fermions, utilizing a very simple basis of projection operators. Nonetheless, despite all these simplifications, the calculation reproduces major features of the form factor behavior at $Q^2 > 1.0$ GeV^2.

By the time of the 12 GeV Upgrade, the Theory Division at JLab [3] plans to have ready the excited proton states of minimal masses in each partial wave for the $\gamma_v NN^*$ electrocouplings at Q^2 up to 10 GeV^2, which will be evaluated at the physical pion mass and will employ a full basis of nucleon operators.

C. Light-cone sum rule approach

The University of Regensburg group is collaborating with us in the theoretical interpretation of $\gamma_v NN^*$ electrocouplings, where they are developing a combined approach by incorporating LQCD and light-cone sum rules (LCSR). In this approach several moments of quark distribution amplitudes (DAs) are derived from a QCD Lagrangian within

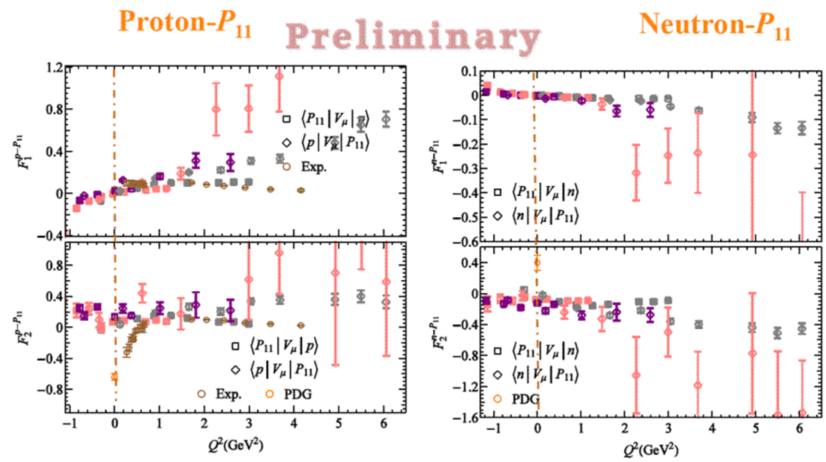

FIG. 2: The transition $N - P_{11}(1440)$ electromagnetic form factors F_1 (upper), F_2 (lower). CLAS data are shown in gold. JLab Theory Center LQCD results [22] for various pion masses are shown in magenta ($m_\pi = 743$ MeV), in gray ($m_\pi = 580$ MeV) and in red ($m_\pi = 450$ MeV).

the framework of LQCD. In the second step $\gamma_v NN^*$ electrocouplings are determined from quark-distribution amplitudes using light-cone sum rules [3, 23]. The crucial advantage of such a hybrid approach is that the form factors are calculated in terms of well-defined DAs that correspond to hadron (N or N^*) wave functions at small transverse separations. This approach has already provided results on the Q^2 evolution of $S_{11}(1535)$ electrocouplings within the entire range of photon virtualities covered by our approved experiment as shown in Fig. 3.

This past year (2009) a new computer code was developed that is somewhat more general and has been used on new lattices of size 24^3 and 32^3 at a pion mass of 275 MeV, which is significantly closer to the physical pion mass as compared to previous calculations. An improved projection operator was implemented in order to obtain a cleaner separation of the states with opposite parities. The analysis of the data at $m_\pi = 0.275\,\mathrm{GeV}$ is not yet finished and it is to be expected that the $N^*(1535)$ results will profit at least as much from the various improvements as the nucleon data [24]. These new results will be used to update the previous calculation of the $\gamma_v NN^*$ electrocouplings shown in Fig. 3. By the time of the 12 GeV Upgrade, the combined LQCD & LCSR approach will provide predictions on the Q^2 evolution of electrocouplings for several parity doublet pairs [3]. The LQCD calculations will be carried out at the physical pion mass and the LCSR approach used to obtain predictions in the entire Q^2 range covered by the proposed experiment. Moreover, the LCSR approach will be advanced to next-to-leading order. Employing the improved LCSR will allow one to obtain the information on quark DAs in N* quark cores from the $\gamma_v NN^*$ electrocoupling data and to explore the differences in the distribution amplitudes in the ground and excited nucleon states of various spins and parities.

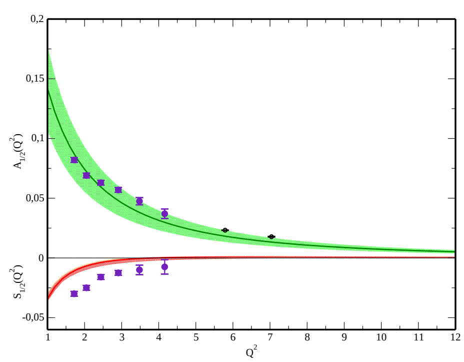

FIG. 3: Prediction on Q^2 evolution of $S_{11}(1535)$ electrocouplings obtained within the framework of combined LQCD & LCSR approach [3, 23] (shadowed areas) in comparison with the CLAS data [1] (points with error bars) and Hall C data.

D. Dyson-Schwinger equations

In addition to the LQCD calculations delineated above, the Dyson-Schwinger equations of QCD (DSEs) provide a powerful alternative approach. Formulated in the continuum and providing direct access to properties of hadrons constituted from QCD's lightest quarks, the DSEs enable observable information on $\gamma_v NN^*$ electrocouplings to be related to QCD itself. In this approach, dressed-quark propagators and scattering amplitudes are computed from QCD via a systematic and symmetry-preserving truncation scheme, and one obtains gauge-invariant observables expressed as contractions of gauge-covariant Schwinger functions. In particular, the $\gamma_v NN^*$ electrocouplings can be obtained by combining results from the gap-, Bethe-Salpeter-, and Faddeev-equations of QCD, to arrive at a Poincaré-invariant description of baryons, which are constituted from dressed-quarks and -gluons bound by interactions that are systematically connected with QCD [3, 25, 26]. The DSE framework is especially useful in elucidating non-perturbative manifestations of strong interaction physics, such as dynamical chiral-symmetry breaking and quark confinement. This is emphasized in Fig. 4, which depicts LQCD and DSE results on the momentum-dependence of the dynamically-generated dressed-quark mass function.

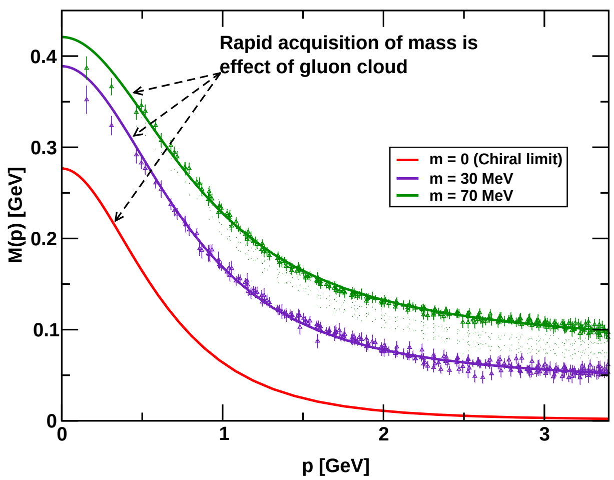

FIG. 4: Dressed quark mass function, M(p), for light-quarks, obtained in Landau gauge: solid curves are the DSE results, including the chiral-limit [27, 28]; points with error bars are the results from unquenched LQCD [29]. The data from our experiment will, for the first time, allow one to study the kinematic regime for absolute value of momenta running over the quark propagator $p < 1.1$ GeV, which spans the transition from almost-completely dressed constituent quarks to the almost-completely undressed current quarks. It is important to bear in mind that the dressed-quark propagator is gauge-covariant and hence the features evident in this figure have a genuinely measurable impact on observables.

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It is apparent in Fig. 4 that for momenta larger than 2 GeV, the mass function describes a current-quark, propagating almost like a single parton. However, for momenta less than this, the mass function rises sharply, reaching the constituent-quark mass-scale in the infrared. In this domain, the dressed-quark is far from a single parton: the effect evident in this figure is due to a cloud of low-momentum gluons attaching themselves to the current-quark. This is the phenomenon of dynamical chiral symmetry breaking. It is essentially non-perturbative and, even were the Standard Model Lagrangian to possess massless quarks, this effect would make them massive. Dynamical chiral symmetry breaking is responsible for more than 97% of the nucleon's mass. Contemporary theory suggests that dynamical chiral symmetry breaking is an unavoidable consequence of confinement but that remains to be conclusively proven. It is certain, however, that the momentum-dependence of the mass function is directly tied to the behavior of the QCD's β-function, and that this momentum-dependence produces effects that are unambiguously observable in experiment. For example, and of immediate relevance to this experiment, the transition from current-quark to non-perturbative dressed-quark can be observed in the Q^2 evolution of hadron elastic and transition form factors. This fact has recently been demonstrated very forcefully in connection with the pion's electromagnetic form factor [30]. In Fig. 5 we present a comparison between experimental data on the pion electromagnetic form factor and calculations conducted under two different assumptions for the dressed-quark propagator: the *solid-curve* is obtained with a momentum independent constituent-quark mass, generated by a contact interaction; whereas the *dashed-curve* is the DSE result obtained with a momentum-dependent mass-function of the type generated by QCD [31]. It is plain that only by accounting fully and correctly for the behavior of $M(p^2)$ can one hope to explain and understand extant and forthcoming data on the pion electromagnetic form factor. Studies are currently underway, aimed at identifying analogous signals for the running of the dressed quark in the Q^2-evolution of proton elastic form factors and the $N - P_{33}(1232)$ and $N - P_{11}(1440)$ transition electromagnetic form factors.

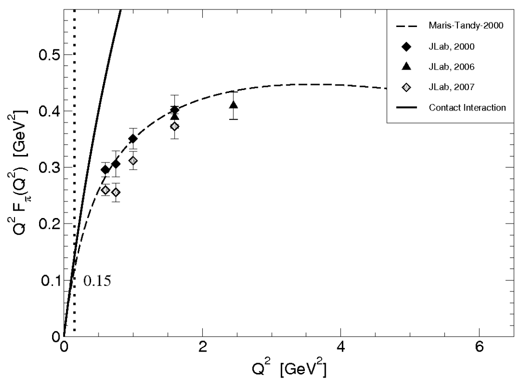

FIG. 5: Description of experimental data on the pion electromagnetic form factor with momentum independent quark mass (solid line) and full DSE prediction (dashed line) [30, 32] with a dynamical quark mass shown in Fig. 4.

The 12 GeV Upgrade will, for the first time, provide beams capable of generating momentum transfers in a domain that will enable experiment to be sensitive to the evolution of the mass function on $0 < p < 1.2$ GeV; namely, to probe the mass function in the domain within which the transition from non-perturbative to perturbative behavior takes place (see Fig. 4). Therefore, analysis of the data on $\gamma_v NN^*$ electrocouplings obtained in this experiment within the framework of QCD's DSEs will uniquely enable us to verify experimentally that dynamical chiral symmetry breaking in QCD is the origin of the vast bulk of the mass of observable matter in the universe. Moreover, the feedback between experiment and theory that must naturally follow, will provide the means to chart the behavior of QCD's β-function at infrared momenta. There is no greater challenge in the Standard Model, and few in physics, than learning to understand the truly non-perturbative long-range behavior of the strong interaction. In this connection, studies of excited states of the nucleon are especially useful because their properties are determined by the interactions between dressed-quarks at distances larger than those most important to the structure of ground states [3].

E. Quark models

Finally we mention several developments in quark models. The $q\bar{q}$ pair production and the quark form factors presumably will both play a key role in the description of the baryon excitation in the Q^2 range accessible with 12-GeV electrons. The presence of $q\bar{q}$ effects points towards the need of unquenching the quark models [33]. This problem has been addressed recently for the baryon sector [34]. With the availability of unquenched Constituent Quark Models (CQMs) both the electromagnetic and strong decay of the resonances will be described in a consistent way. With increasing momentum transfer the excitation of resonances will also allow the testing the short-distance behavior of the $q\bar{q}$ production mechanism and, in particular, of the meson production. The phenomenological quark form factors, which have been introduced up to now, contain the mixed contributions from both the structure of the effective (constituent) quarks and from the dynamics not explicitly included in the CQM, such as the $q\bar{q}$ pair creation or meson production effects. By unquenching the CQM, it will be possible to disentangle the quark form factors and test the onset of the transition to the asymptotic QCD current quarks.

F. Closing statement

In closing this section, we must emphasize that our proposed experiment will – for the foreseeable future – be the only experiment in the entire world that can provide data on $\gamma_v NN^*$ electrocouplings for a number of excited states at $Q^2 > 5.0$ GeV^2. These data will be vital in reaching an understanding of two truly novel phenomena in the Standard Model; namely, the essentially non-perturbative physics of confinement in baryons and the mechanism for dynamical chiral-symmetry breaking in QCD.

III. DEVELOPMENTS IN REACTION MODELS FOR DATA ANALYSIS

For the evaluation of $\gamma_v NN^*$ electrocouplings from this experiment a number of approaches have been developed in the past years that have already been tested with data taken at electron energies below 6 GeV, and $Q^2 < 5$ GeV^2. We briefly describe these approaches and discuss their applications in the data analysis.

A. Phenomenological analysis methods

For the analysis of the $N\pi$ channels two approaches have been developed. One approach is based on the fixed-t dispersion relations, the other on the unitary isobar model [1, 35]. The main difference between the two approaches is the way the non-resonant contributions are derived. Applying two different methods in the analysis of the same data sets will allow us to evaluate the validity of the resulting resonant electrocouplings, and the uncertainty coming from the specific assumptions made about the non-resonant contributions.

For the two-pion channel $p\pi^+\pi^-$ a phenomenological meson-baryon approach was developed [2, 36], that by fitting the model to nine independent differential cross sections of invariant masses and angular distributions from the CLAS data, allowed us to determine all essential contributions to the reaction. The model incorporates six relevant isobar channels and direct 2π production mechanisms, when the final $p\pi^+\pi^-$ state is created without formation of intermediate unstable hadrons.

As the resonance couplings must be independent of the specific decay channel, the comparison of the electrocouplings obtained from the $N\pi$ and $N\pi\pi$ channels, which have very different non-resonant contributions, will allow important cross checks of the results.

Finally, a combined analysis of the two major channels $N\pi$ and $N\pi\pi$ within the framework of EBAC-DCC approach [3, 4] will allow us to account explicitly for the hadronic final state interactions, which may play a substantial role for the $N\pi$ and $p\pi^+\pi^-$ final states. This approach rigorously maintains the constraints imposed by unitarity, and will allow us to determine $\gamma_v NN^*$ electrocouplings from residues at the poles in the complex energy plane, utilizing the analytical continuation method [18]. As the initial step to analyze the data of electromagnetic production of $N\pi$, $N\pi\pi$, $N\eta$, ΛK, ΣK, and $N\omega$ channels, the hadronic parameters of the EBAC-DCC model should be determined by analyzing the available $N\pi$ reaction data. This was completed [37] with accurate descriptions of *all* available $N\pi$ elastic-scattering data. Employing the analytical continuation method, resonance pole positions for 14 well-established N*s were extracted.

EBAC has developed the full machinery needed for determining the $\gamma_v NN^*$ electrocouplings through a coupled-channel analysis of $N\pi, \gamma^* N \to N\pi, N\eta$ reactions. The highest priority for the next three years is to complete a *combined* simultaneous coupled-channel analysis of all the world's data on $N\pi, \gamma^* N \to N\pi, N\eta$, and $N\pi\pi$ reactions [4]. Through this effort, information on the cross sections and amplitudes of contributing processes derived from analysis of the CLAS data within the framework of the aforementioned phenomenological reaction model will be helpful, and in particular, in the implementation of the complex $p\pi^+\pi^-$ electroproduction channel.

B. Progress in experimental analysis

In 2009 we made substantial progress in extracting the $\gamma_v NN^*$ electrocouplings through independent analyses of $N\pi$ and $p\pi^+\pi^-$ electroproduction within the framework described above. The CLAS data significantly extended the available information on $N\pi$ electroproduction observables. For the first time, data on differential cross sections, longitudinally polarized beam asymmetries, and longitudinal target and beam-target asymmetries for $N\pi$ electroproduction off protons became available from CLAS with nearly full 4π coverage in a wide kinematical area with $W < 1.7$ GeV and $0.15 < Q^2 < 6.0$ GeV^2. The combined analysis of a total of 120,000 data points was completed in 2009 and was recently published in [1]. We put significant effort into accounting for model and systematic uncertainties. All transverse and longitudinal $\gamma_v NN^*$ electrocouplings were determined for the $P_{33}(1232)$ state at $0.16 < Q^2 < 6.0$ GeV^2 and for the $P_{11}(1440)$ $D_{13}(1520)$, $S_{11}(1535)$ at $0.3 < Q^2 < 4.5$ GeV^2. For first time, these data further enabled the determination of the longitudinal electrocouplings of $P_{11}(1440)$ $D_{13}(1520)$, and $S_{11}(1535)$. Examples of extracted electrocouplings are shown in Figs. 6 and 7.

As mentioned earlier, the CLAS data on $p\pi^+\pi^-$ electroproduction [8, 9] for the first time provided information on nine independent single differential cross sections in each bin of W and Q^2 obtained in measurements in a mass range $1.4 < W < 2.1$ GeV with photon virtualities in the range of $0.25 < Q^2 < 1.5$ GeV^2. The recent results were published in 2009 [9]. A good description of the CLAS $p\pi^+\pi^-$ electroproduction data [8, 9], achieved within the framework of phenomenological reaction model [2, 36] allowed us to isolate resonant contributions to differential cross sections and for the first time to determine $\gamma_v NN^*$ electrocouplings for almost all excited proton states for masses less than

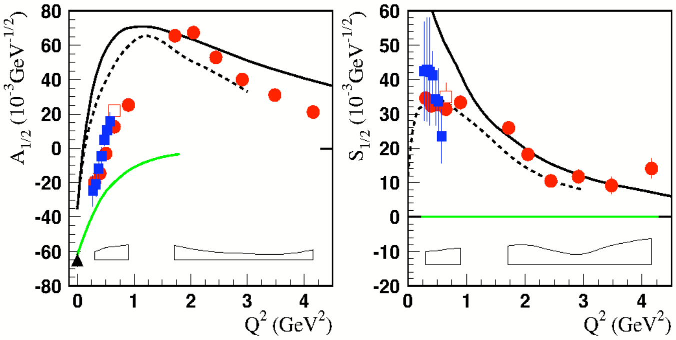

FIG. 6: Electrocouplings for the $P_{11}(1440)$ state determined from the CLAS data on $N\pi$ electroproduction [1] (filled red circles), from $N\pi$ / $N\pi\pi$ combined analysis [38] (open red squares) and preliminary results from the CLAS data on $p\pi^+\pi^-$ channel [2] (filled blue squares). The black solid and dashed lines represent light front quark model calculation [14, 39] for the $P_{11}(1440)$ as first radial excitation of three quarks in the ground state. The green lines correspond to electrocouplings calculated with the assumption that the $P_{11}(1440)$ is a hybrid 3qG state [40]. The open boxes at the bottom are the model uncertainty of circle symbols.

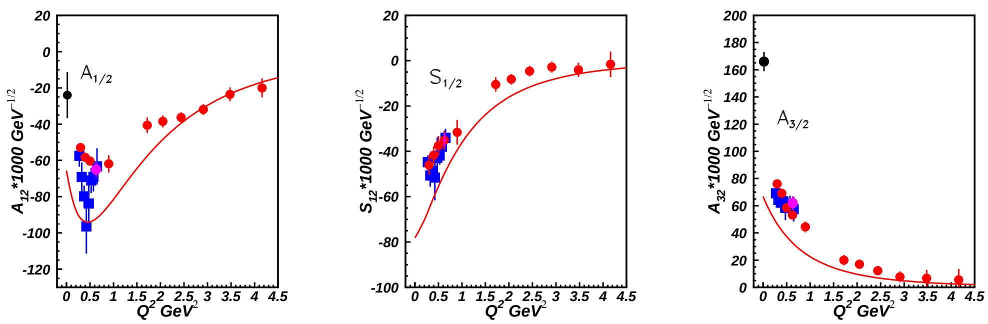

FIG. 7: Electrocouplings for $D_{13}(1520)$ state determined from the CLAS data on $N\pi$ electroproduction [1] (red points), from $N\pi$ / $N\pi\pi$ combined analysis [38] (magenta points) and preliminary results from the CLAS data on $p\pi^+\pi^-$ channel (blue points) [2]. Differences between the data and quark model [15] calculations at $Q^2 < 1.0$ GeV^2 indicate for possible contributions from meson-baryon dressing.

1.8 GeV at photon virtualities $Q^2 < 1.5$ GeV^2. The comparison of electrocouplings of $P_{11}(1440)$ and $D_{13}(1520)$ states obtained from analyses of the single and double pion production channels are shown in Fig. 6 and Fig. 7, respectively. Consistent results were obtained from these two major exclusive electroproduction channels with entirely different non-resonant amplitudes.

The EBAC-DCC approach was used to fit the CLAS $p\pi^0$ electroproduction data at lower Q^2. Using the hadronic parameters determined in the analysis of the $N\pi$ reactions, a fit of the CLAS and world $N\pi$ electroproduction data was carried out [18]. In fitting these data the only free parameters are the bare $\gamma_v NN^*$ electrocouplings. It was found [17, 18, 42] that the fit offers a good description of the available data at $W \leq \sim 1.65$ GeV. In Fig. 8 we show one of the results in fitting the CLAS structure function data for the $p(e, e'\pi^0)p$ process.

C. Non-resonant contributions at high Q^2

In 2009 we initiated an effort to implement quark degrees of freedom in the description of non-resonant mechanisms of $N\pi$ and $p\pi^+\pi^-$ electroproduction channels. The research efforts at the Universität Wuppertal and JINR at Dubna are in progress and will employ the hand-bag approach as developed and described in Ref. [41]. The extension of this approach to the nucleon resonance excitation region requires GPD modeling at $x_B > 0.6$. This is a new step in the

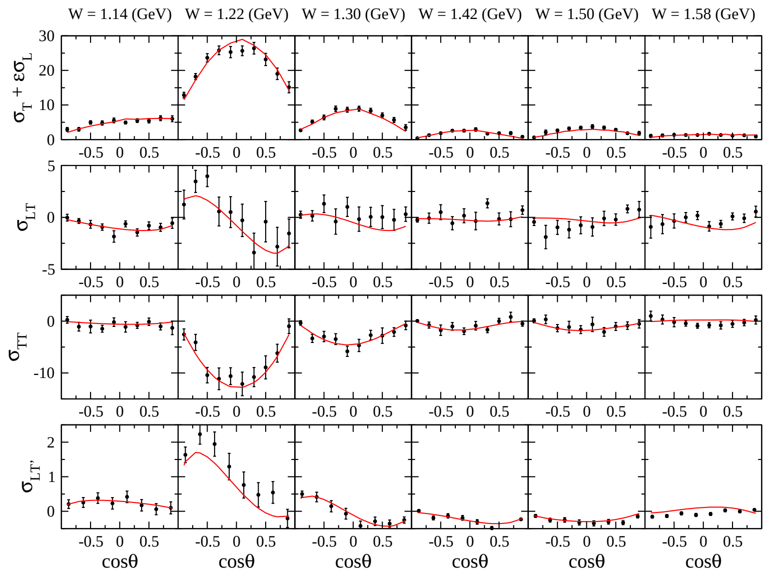

FIG. 8: Structure functions of $p(e, e'\pi^0)p$ ($Q^2 = 0.4$ GeV^2 and $W \leq 1.65$ GeV) with overlaid curves from the EBAC-DCC analysis [42].

GPD studies. The first results are expected by the end of 2010. The next step will be the implementation of quark degrees of freedom to the $\pi\Delta$ isobar channel in $p\pi^+\pi^-$ electroproduction. This further underscores the importance of our experiment; the approval of this experiment has initiated further GPD studies.

IV. DEVELOPMENT OF EXPERIMENTAL EQUIPMENT AND BEAMTIME REQUEST

Several of the spokespersons are also PIs for the development and construction of key elements of the CLAS12 baseline equipment: Forward Time-of-Flight Detector (University of South Carolina), Silicon Vertex Tracker (Moscow State University), High Threshold Čerenkov Detector (Rensselaer Polytechnic Institute and University of Connecticut), and Region 1 Drift Chambers (Idaho State University). All these design and construction efforts have now been successfully reviewed by technical committees of leading experts in their fields and all detector developments that we push fulfill or surpass the design requirements. The overall development of the CLAS12 baseline equipment needed to run our proposed experiment is on track. There are no updates to be reported beyond the recent full simulation that demonstrates the feasibility of the experiment, as documented in our proposal PR-09-003.

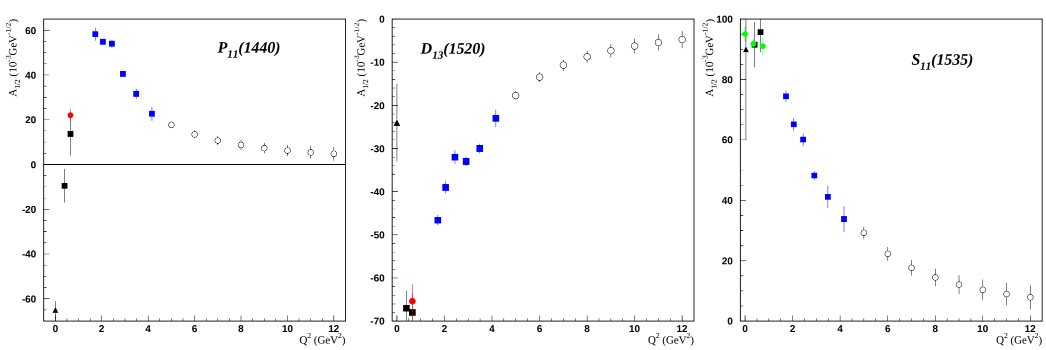

FIG. 9: Samples of expected results for three prominent excited states of the proton (open circles with error bars). Also shown are the corresponding electrocouplings, as extracted from the available CLAS data on $N\pi$ electroproduction [1, 11] (black filled squares), data from the analysis of e1-6 run [10] (blue filled squares), and the results from a combined analysis of the $N\pi$ and $N\pi\pi$ electroproduction channels [38] (red circles). Similar results are expected for many other resonances at higher masses, e.g. F15(1680), S11(1650), D33(1700), P13(1720), and others.

Within the total requested beam time of 60 days at 11 GeV electron beam energy with the highest possible electron beam polarization, the estimated collected statistics in most of the Q^2 and W bins will be higher and for the highest Q^2 bins comparable to the statistics accumulated in the previous e1 and e1-6 run periods. Furthermore the new results show that with the exception of the $P_{33}(1232)$ the overall resonance to background ratio remains approximately constant or in some cases, even increases with increasing Q^2. Therefore we are confident that we will be able to extract $\gamma_v NN^*$ electrocouplings up to Q^2=12 GeV^2 with an equivalent or better accuracy than currently extracted up to Q^2=4 GeV^2 (see Fig. 9). In applying the same approaches as described by the models above to the same measured observables, we will certainly have ample statistics for the analysis (see Sec. III).

Beam Time Request	Beam	Beam Energy	Luminosity	Target	Detector
60 *days*	*polarized* e^-	11 *GeV*	$10^{35}\ cm^{-2}s^{-1}$	LH_2	*CLAS12 base equipment*

[1] I.G. Aznauryan, V.D. Burkert *et al.* (CLAS Collaboration), Phys. Rev. **C80**, 055203 (2009).
[2] V.I. Mokeev, V.D. Burkert *et al.*, arXiv:0906.4081.
[3] Theory Support for the Excited Baryon Program at the Jlab 12 GeV Upgrade, JLAB-PHY-09-993, arXiv:0907.1901.
[4] T-S.H. Lee and the EBAC Collaboration, Status and Future of EBAC, http://ebac-theory.jlab.org/research.htm.
[5] The Workshop on Electromagnetic Transition Form Factors, October 13-15 2008, Newport News, JLab http://conferences.jlab.org/EmNN/.
[6] The Third Workshop of the APS Topical Group in Hadron Physics April 29 - May 1, 2009, Denver, Colorado http://www.fz-juelich.de/ikp/ghp2009Program.shtml.
[7] Informal N*-GPD Meeting at JLab, Sept. 11, 2009 http://www.jlab.org/∼mokeev/react/models/highq2/highq2.html.
[8] M. Ripani *et al.* (CLAS Collaboration), Phys. Rev. Lett. **91**, 022002 (2003).
[9] G.V. Fedotov *et al.*, (CLAS Collaboration), Phys. Rev. **C79**, 015204 (2009).
[10] K. Park *et al.*, Phys. Rev. **C77**, 015208 (2008).
[11] I.G. Aznauryan, V.D. Burkert, and H. Egiyan *et al.*, Phys. Rev. **C71**, 015201 (2005).
[12] M. Ungaro *et al.*, (CLAS Collaboration), Phys. Rev. Lett., **97**, 112003 (2006).
[13] A.N. Villano *et al.*, arXiv:0906.2839 [nucl-ex].
[14] I.G. Aznauryan, Phys. Rev. **C76**, 025212 (2007).
[15] E. De Sanctis, *et al.*, Phys. Rev. **C76**, 062201 (2007).
[16] B. Julia-Diaz, T.-S.H. Lee *et al.*, Phys. Rev. **C77**, 045205 (2008).
[17] N. Suzuki, *et al.*, arXiv:0909.1356.
[18] N. Suzuki, T. Sato, and T.-S.H. Lee, arXiv:0910.1742.
[19] J.J. Dudek, R.G. Edwards, M.J. Peardon, D.G. Richards, and C.E. Thomas, arXiv:0909.0200 [hep-ph], to be published in Phys. Rev. Lett.
[20] R.G. Edwards, to be published in proceedings of Hadron 2009.
[21] H.W. Lin *et al.*, Phys. Rev. **D79**, 034502 (2009).
[22] H.W. Lin *et al.*, arXiv:0810.5141.
[23] V.M. Braun, *et al.*, Phys. Rev. Lett. **103**, 072001 (2009).
[24] V.M. Braun *et al.* [QCDSF Collaboration], Phys. Rev. **D79**, 034504 (2009) [arXiv:0811.2712 [hep-lat]].
[25] C.D. Roberts, Prog. Part. Nucl. Phys. **61**, 50 (2008).
[26] C.D. Roberts *et al.*, Eur. Phys. J. ST **140**, 53 (2007).
[27] M.S. Bhagwat *et al.*, Phys. Rev. **C68**, 015203 (2003).
[28] M.S. Bhagwat and P.C. Tandy, AIP Conf. Proc. **842**, 225 (2006).
[29] P.O. Bowman *et al.*, Phys. Rev. **D71**, 015203 (2005).
[30] C.D. Roberts, *private communication*.
[31] P. Maris and P.C. Tandy, Phys. Rev. **C62**, 055204 (2000) [arXiv:nucl-th/0005015].
[32] P. Maris and P.C. Tandy, Phys. Rev. **C62**, 015203 (2000).
[33] S. Capstick *et al.*, Eur. Phys. J. **A35**, 253 (2008).
[34] R. Bijker and E. Santopinto, AIP Conf. Proc. **1116**, 93 (2009); Few-Body Syst. **44**,95 (2008); AIP Conf. Proc. **1056**, 95 (2008); arXiv:0809.4424; NSTAR2007: arXiv:0809.2299 and arXiv:0809.2296; MENU2007: arXiv:0806.3028; AIP Conf. Proc. **947**, 168 (2007).
[35] I.G. Aznauryan, Phys. Rev. **C67**, 015209 (2003).
[36] V.I. Mokeev, V.D. Burkert *et al.*, Phys. Rev. **C80**, 045212 (2009).
[37] B. Julia-Diaz, T.-S.H. Lee, A. Matsuyama, and T. Sato, Phys. Rev. **C76**, 065201 (2007).
[38] I.G. Aznauryan, V.D. Burkert *et al.*, Phys. Rev. **C72**, 045201 (2005).
[39] S. Capstick and B.D. Keister, Phys. Rev. **D51**, 3598 (1995).
[40] Z.P. Li, V.D .Burkert, and Zh. Li, Phys. Rev. **D46**, 70 (1992).
[41] S.V. Goloskokov and P. Kroll, arXiv:0906.0460.
[42] B. Julia-Diaz, T.-S.H. Lee, A. Matsuyama, T. Sato, and L.C. Smith, Phys. Rev. **C77**, 045205 (2008).