CLAS12 Run Group K Jeopardy PAC48

Quark-Gluon Confinement & Strong QCD

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1 Introduction

Run Group K encompasses the following three approved experiments, which share the same CLAS12 configuration and address complementary aspects of strong QCD:

- E12-16-010 - A Search for Hybrid Baryons in Hall B with CLAS12
- E12-16-010A - Nucleon Resonance Structure Studies Via Exclusive KY Electroproduction
- E12-16-010B - Deeply Virtual Compton Scattering with CLAS12 at 6.6 GeV and 8.8 GeV

RG-K was approved by PAC 44 to run for 100 PAC days using electron beam energies of 6.6 GeV and 8.8 GeV, with longitudinally polarized electrons ($P_e \geq 85\%$) impinging on a liquid-hydrogen target at the full nominal luminosity for CLAS12.

RG-K opportunistically ran from Nov. 28 to Dec. 20, 2018 for 11 calendar days at 7.5 GeV and 9 calendar days at 6.5 GeV, corresponding to 12 PAC days, considering the high beam availability obtained. The accumulated charge was ∼45 mC, equal to 7% of the expected 648 mC at full luminosity, as shown in Fig. 1, and a total of 15.6G events were collected.

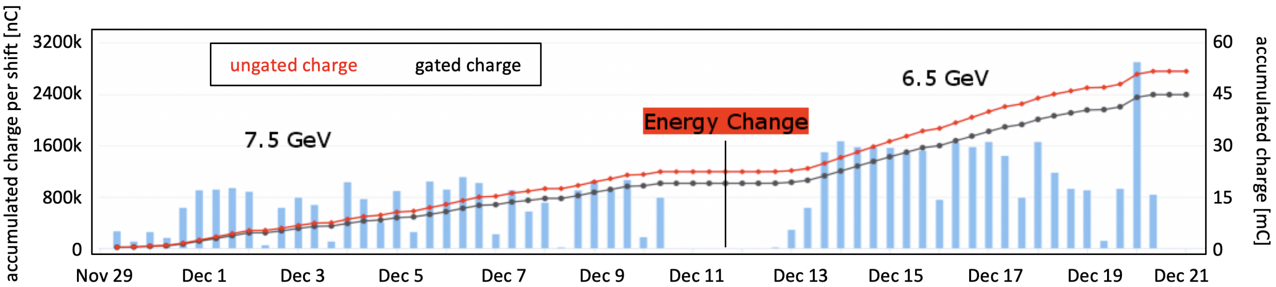


Figure 1: Accumulated charge during the RG-K Fall 2018 run. The blue bars show the beam charge accumulated during each shift.

The aim of this document is to show that the preliminary data analysis confirms the quality of the event reconstruction and the statistics expected in the proposals, to provide information on the latest developments in the field, proving that, since its approval, the physics program has maintained and possibly increased its scientific interest, and to confirm the commitment of the proponents. Based on this assessment, we formally request approval for the remaining 88 approved PAC days for RG-K.

2 Physics Program Highlights

This series of Run Group proposals aims at establishing a comprehensive research program to tackle some of the most intricate problems in hadron physics. They have also strong connections to proposals that have already been approved as part of the CLAS12 physics program and will very significantly extend the science reach of those experiments, while at the same time presenting new avenues towards clarifying the degrees of freedom active in the excitation of baryons and providing new insights into the so far unresolved problem of understanding the confinement of light quarks. The scope of this program covers three major research efforts:

- Establishing the nucleon excitation spectrum with emphasis on the high mass region and gluonic excitations;
- Quantifying the role of the active degrees of freedom in the nucleon spectrum and their evolution with distance scale;
- Making inroads towards understanding the confinement of light quarks, gluons, and the meson cloud, their emergence from the confinement regime, and the role they have in providing dynamical stability of the nucleon.

The tools available to meet these challenges and that are being employed in this Run Group proposal are threefold:

- Extending and completing our knowledge of the nucleon energy spectrum via measurements of a variety of processes and final states. This also includes use of modern analysis tools in multi-channel partial wave analysis extended for the description of exclusive electroproduction, as well as reaction models for specific channels such as $N\pi$, $N\pi\pi$, and KY that have been developed in the recent past.
- Determining the transition form factors and their Q^2 dependence in exclusive meson electroproduction, and their interpretation in terms of quark excitations, gluonic excitations, and the meson-baryon cloud. This involves the strong theory effort provided by the group of participating theorists. Several lower mass states have already been successfully interpreted in such categories. We seek to extend these measurements towards the higher resonance mass range.
- Providing new insight into the confinement of light quarks by measuring the shear forces and pressure acting upon quarks by employing the DVCS process to extract the chiral even Compton Form Factors (CFF) $\mathcal{H}(\xi, t)$ and $\mathcal{E}(\xi, t)$. This opportunity is afforded by the remarkable properties of the second Mellin moments of GPDs H and E that relate to the CFF $\mathcal{H}$ and the gravitational form factors (GFF) $d_1(t)$ and $M_2(t)$ of the nucleon matrix element of the energy-momentum tensor. Employing DVCS as a proxy for graviton scattering enables access to these mechanical properties.

Very significant progress has been made in recent years and is evident in many new entries of N^* and Δ^* states in the latest edition of the Review of Particle Properties [1] (PDG2018), as well as the inclusion of the transition form factor measurements for several excited states in the Review of Nucleon and Δ states in that edition. Most of the newly discovered states have masses in the range from 1.85 GeV to 2.2 GeV and were discovered in precise meson photoproduction data, especially high precision $K\Lambda$ and $K\Sigma$ cross section measurements, and measurements of single- and double-polarization observables. This includes precision measurements in $N\pi$ final states, and very recently the discovery of a new $N'(1720)3/2^+$ state [2] employing photo- and electroproduction measurements of the $p\pi^+\pi^-$ final state.

We can expect additional new states to be observed from the data sets that are currently still in the experiment analysis phase, and therefore have not been included in the available multi-channel analysis frameworks. The mass region above 2.1 GeV has hardly been studied. This is the region where gluonic excitations are expected to occur, and it is a major focus of this Run Group. Additionally, measuring concurrently a set of different final states at different photon virtualities Q^2, opens up new possibilities that were not available with the configuration available with the CLAS detector in the lower energy range or from the photoproduction studies only.

We remark that by employing the detailed CLAS DVCS data on beam spin asymmetries and on differential cross sections, the first extraction of the gravitational form factor $d_1(t)$ was achieved, leading to the first piece of information on a mechanical properties of the proton [3]: the radial dependence of its internal pressure distribution $p(r)$. The proposed program, together with the already collected data from RG-A will very significantly extend the precision and kinematic reach of the DVCS data and give access to a more detailed account of the shear forces acting on the quarks inside the proton. Figure 2 shows an extraction of the shear stress from a chiral quark soliton model.

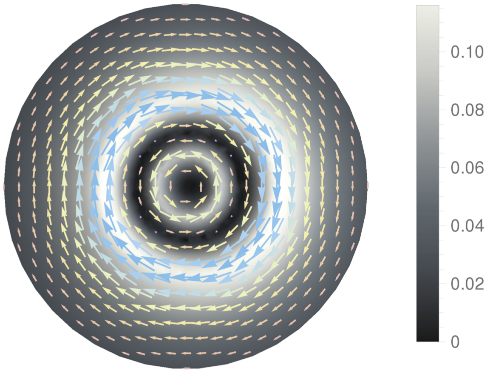


Figure 2: Distribution of shear forces in the proton extracted from a chiral quark soliton model. The shear stress changes direction at a radial value of 0.5 fm, which constrains the integrated torque to be equal 0. Figure taken from Ref. [4]. The radius of the disc in the figure is 1.5 fm and the color scale gives the absolute value of the tangential force in GeV/fm.

3 Hybrid Baryon Quest

Experiment: E12-06-010: A Search for Hybrid Baryons in Hall B with CLAS12
Spokespersons: V.D. Burkert, D.S. Carman, A. D'Angelo*, E. Golovatch, R.W. Gothe, V.I. Mokeev (*Contact Person)

3.1 Physics Motivation

Mapping out the nucleon spectrum and the excitation strengths of individual resonances is a powerful way to answer a central question of hadron physics: "What are the effective degrees of freedom as the excited states are probed at different distance scales?". The theory of the strong interaction, Quantum Chromodynamics (QCD), not only allows for the existence of baryons with dominant gluonic contributions (hybrid baryons), but Lattice QCD (LQCD) calculations have now also predicted several baryon states with a dominant gluonic admixture to the wave function, and with the lowest mass hybrids approximately 1.3 GeV above the nucleon ground state [5], i.e. in the range of $W = 2.2$ GeV to 2.5 GeV. These studies of exotic baryons are of current interest given the evidence of new pentaquarks state by the LHCb Collaboration that provides evidence for baryon degrees of freedom beyond the three constituent quarks [6].

In contrast to the meson sector, hybrid baryons have quantum numbers that are also populated by ordinary three-quark states. Hybrid baryons hence mix with these three-quark excited states or with dynamically generated states making the identification of gluonic baryons more difficult. However a distinctively different Q^2 evolution of the hybrid-baryon electrocouplings is expected considering the different color-multiplet assignments for the quark-core in a regular versus a hybrid baryon [7], i.e. color singlet versus octet, which also calls for low photon virtualities as the preferential regime for studies of the hybrid-baryon electrocouplings. The search for new hybrid baryon states with the glue as an extra constituent beyond the three constituent quarks will be performed by focusing on measurements at $Q^2 < 2.0$ GeV^2 where the expected magnitudes of the hybrid electroexcitation amplitudes are maximal.

Analyses of meson electroproduction from CLAS data have shown to be most effective in providing information on the internal structure several excited states including: $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $\Delta(1620)1/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$ [8, 9, 10]. Moreover a new $N'(1720)3/2^+$ resonance has been discovered by complementary analysis of photo- and electroproduction cross sections of the $p\pi^+\pi^-$ final state from a proton target [2].

The experimental program is meant to vastly improve upon the available information and to extend the reach of meson electroproduction to cover the nucleon resonance mass range up to 3 GeV and an extended low Q^2 range from 0.05 GeV^2 to 2 GeV^2, using electron beam energies of 6.6 GeV and 8.8 GeV. The unpolarized differential cross sections for the K^+Y and $\pi^+\pi^-p$ exclusive channels will be measured, complemented by measurements of the differential transverse-transverse and transverse-longitudinal interference cross sections, along with other polarization observables.

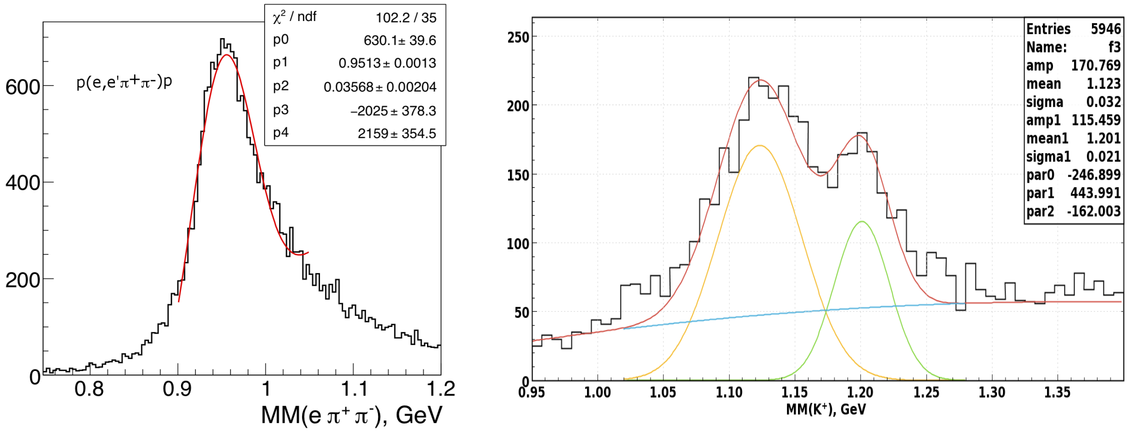


Figure 3: Left plot: Preliminary $e'\pi^+\pi^-$ missing mass distribution for the $\pi^+\pi^-p$ exclusive channel for electrons detected in the CLAS12 Forward Detector at 6.5 GeV. Right plot: Preliminary $e'K^+$ missing mass distribution for the $K^+\Lambda$ exclusive channel for electrons detected in the Forward Tagger. The analyzed data correspond to about 5% of the 7.5 GeV RG-K Fall 2018 data.

3.2 Status of Current Analysis Studies

Analysis of a small subset of the acquired RG-K data was performed to identify the $K^+\Lambda$, $K^+\Sigma^0$, and $p\pi^+\pi^-$ exclusive channels. The topology where the electron is detected in the CLAS12 Forward Detector provides events in the Q^2 range from 0.3 GeV^2 to 2 GeV^2, while events detected by the

Forward Tagger (FT) span the Q^2 range from 0.08 GeV^2 to 0.3 GeV^2 at 7.5 GeV electron beam energy. Figures 3 and 4 show the $e'K^+$ and the $e'\pi^+\pi^-$ missing mass distributions for the K^+Y and $p\pi^+\pi^-p$ exclusive channels. The KY and $p\pi^+\pi^-$ data are shown for beam energies of 6.5 GeV and 7.5 GeV. While the missing mass resolution is expected to improve after momentum corrections and detector alignment optimization are applied, it is already enough to identify the reactions events. Details of the analysis status may be found in Ref. [11].

The analyzed data correspond to about 6.5% of the available statistics at each of the electron beam energies. The projected number of $\pi^+\pi^-p$ reconstructed events for the RG-K data is already comparable with the e1-6 CLAS data set published in 2017. The full statistics from the remaining 88 PAC days for RG-K will exceed the existing world database by a factor 10 and will guarantee the high statistical precision and fine kinematical binning required to extract the complete set of polarization observables.

4 N* Structure Studies via KY Electroproduction

Experiment: E12-06-010A: Nucleon Resonance Structure Studies Via Exclusive KY
Electroproduction at 6.6 GeV and 8.8 GeV
Spokespersons: D.S. Carman*, V.I. Mokeev, R.W. Gothe (*Contact Person)

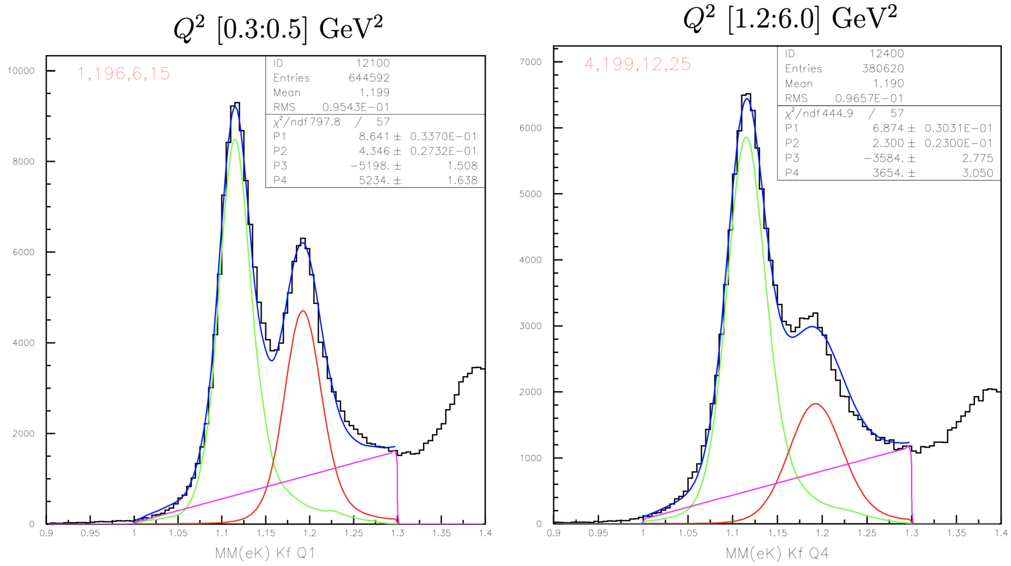
4.1 Physics Motivation

Studies of the structure of excited nucleon states in terms of the Q^2-evolution of their $\gamma_v pN^*$ electrocouplings represents the only source of information on many facets of the emergence of strong QCD underlying the generation of N^* states of different quantum numbers. Continuum QCD approaches and most available quark models reproduce the nucleon elastic form factors equally well, but predict different behaviors for the $\gamma_v pN^*$ electrocouplings. Confronting theory expectations with the data, will allow us to shed light on how resonances of distinctively different structure emerge from QCD [7]. The $\gamma_v pN^*$ electrocouplings are also of particular importance for gaining insight into the strong QCD dynamics responsible for the generation of hadron mass. Recent advances in continuum QCD approaches make it possible to connect the dressed quark mass function with the electrocouplings starting from the QCD Lagrangian [12].

This experiment, together with the approved experiments E12-09-003 and E12-06-108A from RG-A are the cornerstones of the CLAS12 N^* program and will allow us to probe the dressed quark mass function over a range of Q^2 overlapping the existing CLAS data and significantly extending the Q^2 coverage of the data up to 10-12 GeV^2. In this kinematic range, the reactions probe distances where the transition between the almost bare and massless QCD-quarks and the fully dressed constituent quarks of $\approx$300 MeV mass are expected, addressing the key open question of the Standard Model on the emergence of >98% of hadron mass from QCD. Consistent results on the $\gamma_v pN^*$ electrocouplings from the πN, ηN, $\pi\pi N$, and KY electroproduction channels with completely different non-resonant contributions will further validate the reliable and controlled extraction of these quantities.

The analyses of the CLAS results on the $\gamma_v pN^*$ electrocouplings within the continuum QCD approach and different quark models have revealed N^* structure for $Q^2 < 5.0$ GeV^2 as a complex interplay between an inner core of three dressed quarks and an external meson-baryon cloud. The relative contributions of the meson-baryon cloud depend strongly on the quantum numbers of the excited nucleon state. For all resonances studied using CLAS data, this contribution decreases with Q^2 in a gradual transition towards quark-core dominance for $Q^2 > 5.0$ GeV^2. Understanding the emergence of the meson-baryon cloud from the quark core represents an important avenue in the exploration of strong QCD. In order to address this problem, analyses of the data on the $\gamma_v p N^*$ electrocouplings at Q^2 where both the quark core and the meson-baryon cloud contribute is needed to bridge the efforts between the multi-channel amplitude analyses of meson photo-, electro-, and hadroproduction and the N^* quark models. The studies of the transition between the confined quarks in the quark core and the deconfined mesons and baryons in the external cloud are of particular interest for LQCD as it is the only approach with the potential to account for the effects of all relevant degrees of freedom in N^* structure.

E12-16-010A that is part of RG-K is particularly important to this effort as it is designed to span a range of Q^2 from 1 to 6 GeV^2 with statistics and binning over this range more than an order of magnitude above those already collected for the experiments carried out with CLAS. In this respect, studies of these electroproduction data will begin to rival those collected for photoproduction both in terms of statistics and in terms of binning. This experiment is specifically designed to bridge the above-mentioned transition region between low-energy and high-energy nucleon degrees of freedom.



Q^2 [0.3:0.5] GeV^2

Q^2 [1.2:6.0] GeV^2

Figure 4: Preliminary $e'K^+$ missing mass distributions (with the K^+ detected in the Forward Detector) from 9 runs of the 6.5 GeV RG-K data set before final calibrations and without momentum corrections for both the low Q^2 (left) and high Q^2 (right) range of the data showing the spectrum fits used for the yield extraction of the $K^+\Lambda$ (green lineshape) and $K^+\Sigma^0$ (red lineshape) final states.

4.2 Status of Current Analysis Studies

At this time RG-K has acquired data during a short run in the fall of 2018 at beam energies of 6.5 GeV and 7.5 GeV, amounting to 12 PAC days. To date the calibrations of this RG-K dataset have been completed and initial data processing is awaiting computing resources. However, based on a look at 10 processed data runs at each beam energy produced during the calibration phase, the performance of the CLAS12 Forward Detector has been shown to be reasonable with momentum measurements accurate to the ∼1% level. The existing data analysis has focused on optimizing the particle identification to allow isolation of the different final states in their different topologies as a function of kinematics, initial momentum corrections to optimize the signal isolation and enhance the signal to background ratio, and initial yield extractions. These studies have allowed for improved statistical estimates compared to what was included in the proposal and initial explorations of systematic uncertainties of the CLAS12 detector.

Due to the length restrictions for this PAC48 jeopardy submission document, the status of the ongoing analyses is described in preliminary analysis documents on our RG-K wikipage [11]. These documents highlight the particle identification scheme and exclusive analysis cuts used to isolate the signals of interest and to perform the preliminary yield extractions. These notes also include the results of lineshape fits vs. final state kinematics that are used to extract the yields and to provide estimates for the expected statistics for the full 100 days of RG-K, along with a direct comparison of these projected statistics to those in the original PAC44 proposal. Figure 4 highlights the quality of the available data in terms of $e'K^+$ missing mass spectra as a function of Q^2 with the lineshape fits to separate the KY signal from the background.

4.3 Projections for Remaining Data Collection

With the fall 2018 RG-K dataset for the $e'K^+$ final state, the statistics are already comparable to the available data from CLAS acquired from the e1f 6 GeV data set [13], which represent the lion's share of the available world data for K^+Y electroproduction in the resonance region. As such these data will be important to develop and optimize the analysis framework. In order to realize the full promise of the experiment, however, the approval of the remaining allocated beam time will be essential. With the full approved beam time, this experiment will be able to provide electroproduction data in the range up to $Q^2 \approx 6$ GeV^2 with more than a factor of 20 increase in statistics compared to the existing world data set for the $K^+\Lambda$ and $K^+\Sigma^0$ channels within the nucleon resonance region. For $Q^2 < 3$ GeV^2. the full RG-K statistics for this electroproduction experiment will provide for statistical uncertainties comparable to the available CLAS photoproduction dataset. Over this Q^2 range these data will allow for detailed studies of the emergence of the meson-baryon cloud from the quark core in N^* structure. This is an opportunity that JLab must capitalize on given the importance of these data to continue to advance our understanding of the spectrum and structure of nucleon excited states and to provide precision data that can be used to understand how these states of different quantum numbers emerge in QCD.

5 DVCS with CLAS12

Experiment: E12-06-010B: Deeply Virtual Compton Scattering with CLAS12 at 6.6 GeV and 8.8 GeV
Spokespersons: L. Elouadrhiri*, M. Defurne, F.-X. Girod, F. Sabatie (*Contact Person)

5.1 Physics Motivation Update

As outlined in our original proposal, we will be performing a Rosenbluth separation of the Bethe-Heitler and DVCS amplitudes, as well as the longitudinal and transverse parts of the neutral pion electroproduction cross sections. Achieving these goals simultaneously requires the longest possible lever arm in ϵ while remaining at high Q^2.

Since the approval of our original proposal, we performed a dispersive re-analysis of the published CLAS 6 GeV data to extract the D-term and the corresponding pressure distribution inside the nucleon [3]. This work has triggered some attention, including new theoretical estimations [14, 15, 16], lattice calculations [17], and is being incorporated in the program of future facilities such as the EIC [18]. The precise knowledge of the pressure distribution inside the nucleon also has consequences at hadron colliders [19], as well as astrophysical implications in the Equation of State of compact objects such as Neutron Stars [20, 21].

The most recent and sophisticated DVCS global analysis [22, 23] confirm that model assumptions are currently necessary to constrain the real part of the amplitude, and the D-term in particular. As laid out in detail in our original proposal, we will address these limitations by performing a model-independent separation of the interference and DVCS squared parts of the amplitude over the full range in x_B accessible with CLAS12.

5.2 Status of Current Analysis Studies

Preliminary results for the amplitudes of the DVCS beam spin asymmetries as a function of $-t$ are shown in Fig. 5 for seven (x_B, Q^2) bins. These data were obtained from the analysis of 18 runs at 6.5 and 7.5 GeV combined for illustration in this short document.

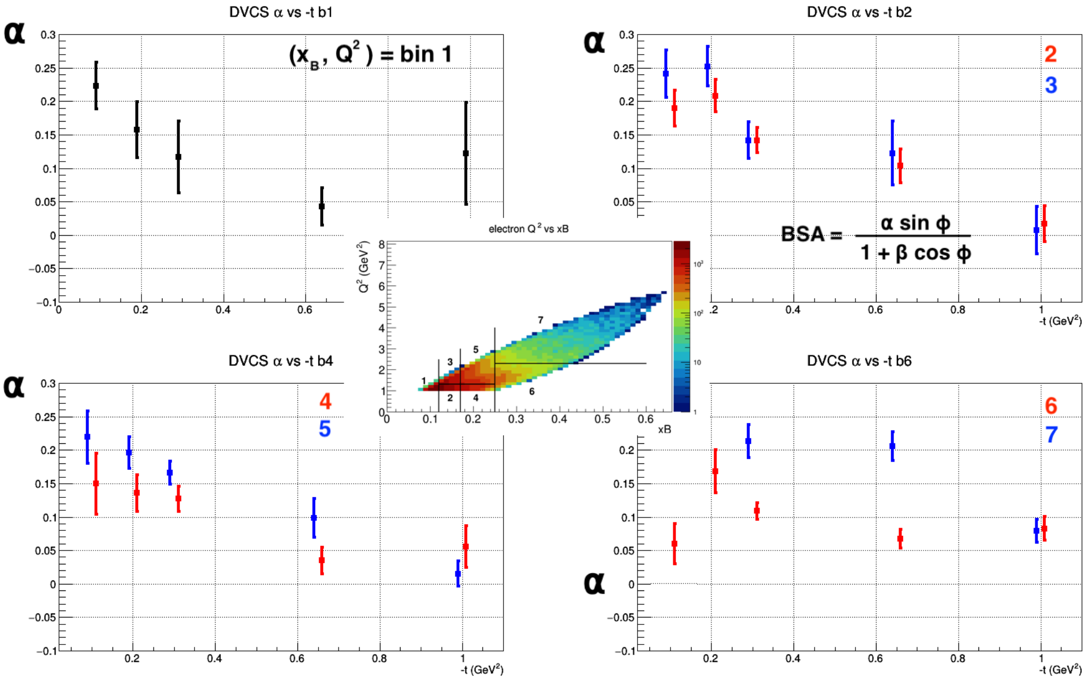


Figure 5: Preliminary DVCS beam spin asymmetry α amplitudes as a function of t for all (x_B, Q^2) bins as numbered on the Q^2 vs. x_B phase space inset for RG-K data at 6.5 GeV and 7.5 GeV.

The accumulated Faraday cup charges in these runs were respectively 1.64 and 2.27 mC for the two energies, and the numbers of exclusive events obtained are 92.7k and 65.8k, respectively. For comparison with the approved total PAC charge (75 nA for 100 days) of 648 mC we can extrapolate over 20M exclusive events under the assumption that the different experimental configurations will be scaled identically. This number is in good agreement with the original proposal projections.

Our preliminary results confirm the previous observations showing a flattening of the BSA t-slopes at large x_B. This can be interpreted as the shrinking of the nucleon in the reciprocal impact parameter space, as the active quark carries the full light cone momentum fraction and becomes the center of the system. The realization of the original physics goals of this experiment necessitates extracting both the real and imaginary parts of the amplitudes with a few percent accuracy, and over as large a range in $\xi \approx \frac{x_B}{2-x_B}$ as we can access to keep the systematic uncertainties of the dispersion relation analysis under control. These goals can only be achieved if the low energy data statistics matches the high energy data, as originally approved.

6 Summary

Since the approval of 100 PAC days by PAC44 in 2016, RG-K profited from the opportunity to take data for 12 PAC days at the end of 2018, when the CEBAF accelerator could not provide electrons in Hall B at the maximum energy of 10.6 GeV. 7.8 G events were accumulated at each of the available energies of 6.5 GeV and 7.5 GeV. The collected data are presently being calibrated for pass-1 cooking. Preliminary analysis of a small fraction of the data shows that the CLAS12 detector performance in the forward direction are already sufficient to identify the exclusive channels of interest for the RG-K physics program, even if further resolution optimizations are expected to be available in the future. The projected number of K^+Y, $\pi^+\pi^-p$, and DVCS final state events for the accumulated statistics already equals or exceeds the CLAS database, while reaching a wider range in Q^2, spanning from 0.05 GeV^2 to 6 GeV^2.

The scientists involved have continuously worked to maximize the impact of the RG-K physics program: new publications from CLAS data have proven the existence of a new baryon resonance [2] and have extracted for the first time the gravitational form factor $d_1(t)$ of the proton [3]. Access to the full RG-K approved statistics, which corresponds to remaining 88 PAC days, will surpass by more than one order of magnitude the present world data set and will guarantee the statistical and the systematic accuracy required to achieve the approved scientific goals.

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