RGC Jeopardy Update Document

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We summarize the case for renewing the PAC approval for Run Group C with the full allocated Beam time (185 PAC days) and overall rating of A.

I. INTRODUCTION

Run Group C (RGC) comprises six approved experiments with the CLAS12 spectrometer in Hall B, each scattering polarized electrons from longitudinally polarized protons or deuterons. The RGC experiments were approved for 185 PAC days (60 days on polarized deuterium/ND_3, 120 days on polarized hydrogen/NH_3, and 5 days of auxiliary data). They are:

E12-06-109: Longitudinal spin structure of the nucleon
(Contact: S. Kuhn; PAC rating: A)

E12-06-109a: DVCS on the neutron with a polarized deuterium target
(Contact: S. Niccolai; Run Group proposal, no separate rating)

E12-06-119b: DVCS on a longitudinally polarized proton target
(Contact: F. Sabatie; PAC rating: A)

E12-07-107: Spin-orbit correlations with a longitudinally polarized target
(Contact: H. Avakian; PAC rating: A-)

E12-09-009: Spin-orbit correlations in kaon electroproduction in DIS
(Contact: H. Avakian; PAC rating: B+)

E12-09-007b: Study of partonic distributions using SIDIS kaon production
(Contact: W. Armstrong; PAC rating A-)

The first of two anticipated Experimental Readiness Reviews for RGC was held at JLab on May 30, 2019. The ERR charge and agenda, various supporting documents, committee report, and collaboration response can be found on the review's wiki.[1] The collaboration officially passed the ERR, with relatively few and minor recommendations from the committee, all of which have been addressed. A request for beam scheduling was submitted in August 2019 for 182 calendar days (91 PAC days, or roughly 1/2 of the total approved beam time for RGC). This request was accepted with the sole proviso that running on *any* nuclear targets can be demonstrated not to harm the CLAS12 central silicon vertex detector. A beam test to address this question was conducted in February 2020, and the results appear to alleviate any concerns of running nuclear targets in CLAS12 [1]. A Scheduling Request for the remaining 94 PAC days will be made at a later time.

While no official CEBAF schedule beyond December 2020 has been released, all components of the experiment are on track to be ready by summer 2021, and the requested run time could fit into the Hall B schedule for a run beginning in Fall 2021 or Winter 2022. We formally request that PAC 48 renew the approval for RGC and the 185 total PAC days originally awarded to it. This document briefly summarizes the physics goals of Run Group C and provides updates on the work underway to ensure its success.

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[1] https://clasweb.jlab.org/wiki/index.php/RGC_ERR

II. PHYSICS GOALS

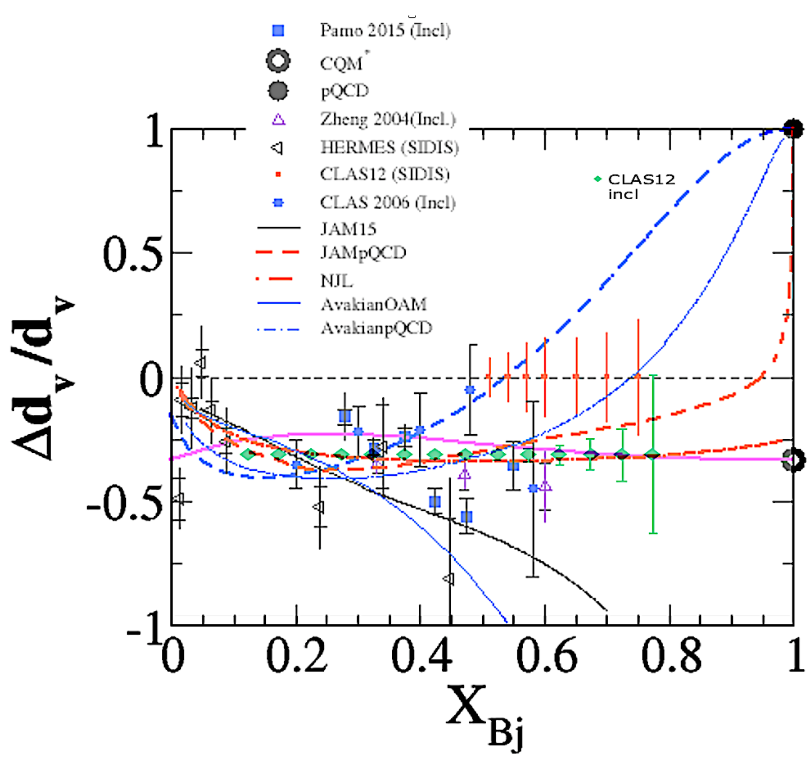

FIG. 1. Expected impact of inclusive and semi-inclusive RGC data on our knowledge of the d-quark polarization in the valence region.

The collective goal of the experiments in RGC is to elucidate the spin-dependent quark structure of the nucleon in the region of moderate to high Bjorken-x. Some of the highlights of the experimental program are:

- Determining the polarization of up and down quarks that carry most of the nucleon momentum (large $x_{Bjorken}$), see Fig. 1. This goal is part of the core program of Jefferson Lab at 12 GeV to map the longitudinal valence quark structure of the nucleon, and offers a stringent test of predictions from pQCD and other approaches to understand nucleon structure in the framework of QCD (Lattice QCD, Dyson-Schwinger approach, etc.). The continued interest in this physics has been reaffirmed by the 2015 NSAC Long range plan and is evidenced by recent publications [2] and conferences (Strong QCD From Hadron Structure Experiments, November 4-8, 2019, Newport News, VA). RGC will measure both inclusive double spin asymmetries on polarized protons and deuterons, and flavor-tagged asymmetries with pion and kaons in the final state. Together with the measurements on ^{3}He that have just concluded in Hall C, valence and sea quark polarizations over the full range in x from below 0.1 out to 0.8 can be extracted using state-of-the art global DGLAP analyses (see, e.g., the combined global fits by the JAM collaboration [3]).

- Constraining Generalized Parton Distributions of the nucleon through double-spin and target-spin observables in Deeply Virtual Compton Scattering on the proton and the neutron. Together with the corresponding program on unpolarized protons (RGA) and neutrons (RGB), these observables are crucial for an accurate extraction of the three-dimensional (longitudinal momentum and transverse position) quark structure of the nucleon, including a better understanding of the role played by orbital angular momentum in the decomposition of the total nucleon spin (see Fig. 2).

- Accessing new transverse-momentum dependent (TMD) parton distributions in the nucleon, in particular those that are correlated with the target spin (see Fig. 2). Single- and double-spin asymmetries in Semi-Inclusive DIS on polarized protons and deuterons, with detection of pions and kaons in the final state, will provide crucial information on the transverse motion of quarks inside the nucleon that is not accessible without polarized targets. These data are essential for the complete 3-dimensional picture of the nucleon that is a major goal of the energy-upgraded facility at Jefferson Lab.

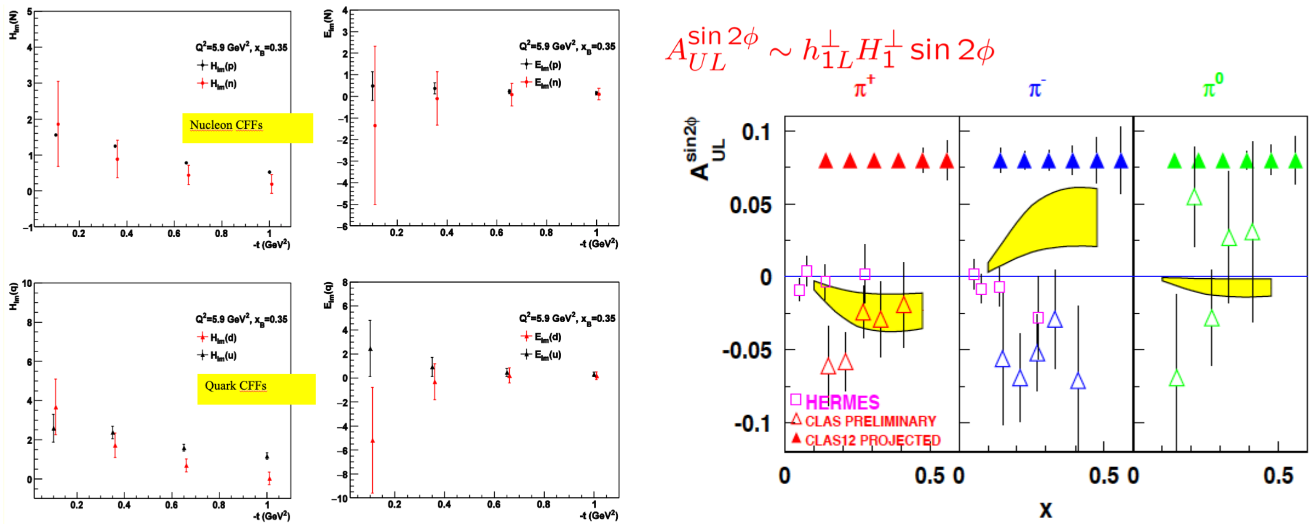

FIG. 2. Left: Expected precision on the extracted flavor-separated Compton Form Factors from a combined analysis of polarization observables in DVCS on proton and neutron. Right: Expected experimental uncertainties on the Kotzinian-Mulders TMD structure function of the proton.

III. STATUS OF EXPERIMENT PREPARATION

A. Longitudinally Polarized Target

Run Group C will be the first set of experiments to utilize a new longitudinally polarized target constructed by a collaboration of Christopher Newport University, the Jefferson Lab Target Group, Old Dominion University, and the University of Virginia. The target, designed specifically to operate within CLAS12, will dynamically polarize samples of frozen ammonia (NH_3 and ND_3) at a temperature of 1 K and magnetic field of 5 T. Almost all major components for the target system are in-house and tested, either in final or prototype form. This includes all electronics, microwave generators and waveguide components, 5 T magnet, and 1 K refrigerator and pumps. Preliminary versions of control and monitoring software, a combination of EPICS and LabView, have been written and utilized during target testing in the JLab Target Group laboratory.

Frozen, irradiated ammonia has become the *de facto* standard target material of polarized protons and deuterons for electron experiments at Jefferson Lab. Among its attributes are very high polarizations, high concentrations of protons and deuterons, and good resistance to ionizing radiation. Sufficient quantities of NH_3 and ND_3 to complete the Run Group C experiments are on hand at UVa.

The CLAS12 solenoid will provide the 5 T field for polarizing the target samples in the longitudinal direction [4]. For optimum dynamic nuclear polarization, the field should have a uniformity of about 10^{-4} (100 ppm) over the volume of the target sample. Field maps of the solenoid indicate that it is marginal in this respect, and so the polarized target is designed to incorporate thin, superconducting shim coils inside its 1 K refrigerator. Extensive modeling has been performed to validate the feasibility of this approach [5], and the JLab Target Group has considerable experience producing small superconducting coils of this nature [6].

The target samples will be cooled to 1 K using a bespoke, high cooling power ^{4}He evaporation refrigerator [7] currently undergoing tests in the Target Group's lab (Fig. 3). Three cool-downs have been performed to date, each highly successful. The refrigerator has a base temperature below 1 K, a cooling power of 1 W at 1.08 K, and a daily consumption of liquid helium under 50 liters. It features a number of innovative design elements, based on previous experience at JLab, that are intended to make it more reliable and more easily serviced, and to reduce the overhead of its operation. Most notable is a retractable helium bath for the target samples that will simplify and speed the routine operations of sample annealing and replacement.

Dynamic nuclear polarization of test samples of two-part epoxy doped with the paramagnetic radical TEMPO (chosen for convenient handling) has also been demonstrated using the new refrigerator, with the FROST 5 T warm-bore solenoid standing in for the CLAS12 solenoid. Proton polarizations during these tests were measured using protoyopes of a new Q-meter system designed and constructed at JLab [8]. The new system is intended to replace the decades-old Liverpool Q-meter [9], which is no longer in production.

A new target insertion cart for the Hall B rail system is now under construction that will permit precise alignment

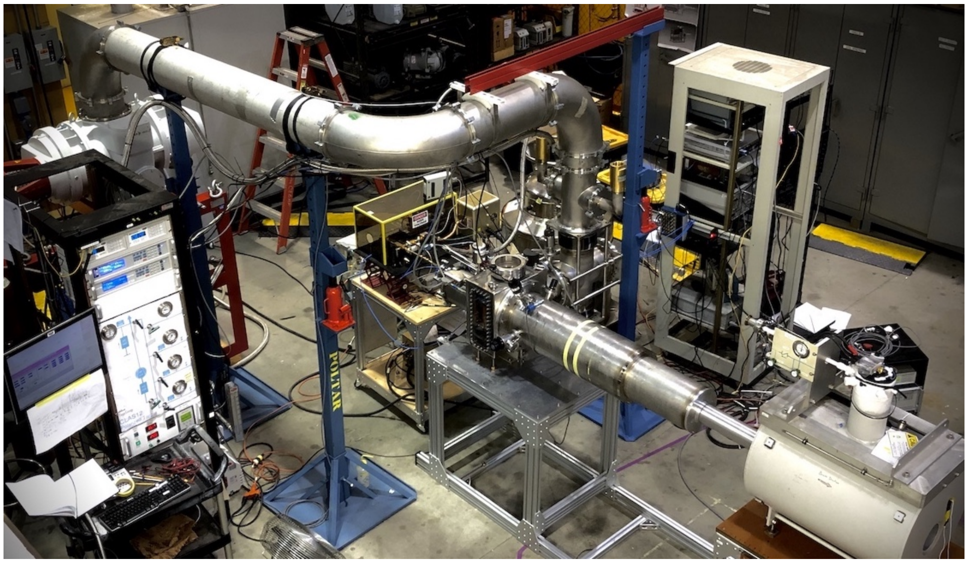

FIG. 3. Testing the longitudinally polarized target in the Target Group laboratory. The horizontal, 1 K refrigerator is partially inserted into the FROST 5 T solenoid in the lower right-hand corner.

of the system on the Hall B beam line. Furthermore, all essential electronic, vacuum, and piping components for the target will be mounted directly on the cart, reducing the time needed to install the system in the hall. Design is also underway of beam-ready replacements for certain prototype components of the refrigerator, such as the retractable helium bath and the thin, downstream portion of the vacuum chamber. These will be built in the near future, and the target system can be available for installation in Hall B in summer 2021.

B. Beam Raster

To maintain high polarization, the ionizing radiation dose to the target must be evenly distributed to its entire volume by rastering the electron beam over the sample's 1 cm radius. This is accomplished using two upstream sets of x-y dipole magnets synchronously driven by high-current, dipolar power supplies. The electron beam is deflected by the first set of magnets and then made parallel to the beam line by the second set. One power supply feeds both x magnets, arranged such that the magnetic fields are 180° out of phase; the y magnets operate in a similar fashion using a second power supply. RGC will be the first experiments to utilize a rastered beam in Hall B since the 12 GeV energy upgrade.

We have determined that the existing raster magnets from the 6 GeV program in Hall B are adequate for the RGC experiments, and appropriate locations on the beam line have been specified. A new spiral raster control module for the power supplies has been designed, constructed, and tested by the JLab Fast Electronics Group, and ±240 A power supplies from Danfysik are on hand. Together, they will raster the electron beam in a spiral pattern at constant linear speed, thus giving a uniform illumination over the face of the target sample. The period of a full spiral-in, spiral-out cycle will be about 1 s.

C. New Møller Shield and Drift Chamber Occupancies

Mølller scattering of the incident electrons represents the largest contribution to the background rate in CLAS12, which is quantified in terms of the number of drift chamber wires that record a signal during a time window of 250 ns. The number of DC wires in each of the three regions is normalized by the total number of wires in the region and referred to as the drift chamber (DC) occupancy. While the rule of thumb is to keep the DC occupancies near 3%, Run Groups A and B have successfully taken data at occupancies approaching 5-6%, and we take this to be maximum acceptable value for RGC.

However, we anticipate that moving the electron beam off axis, as is done when rastering the beam, will increase the DC occupancies, and so we have tried to quantify this effect using the Geant Monte Carlo (GEMC) simulation package. We bench marked our simulations against RGA and RGB data taken with one of the two available Mølller

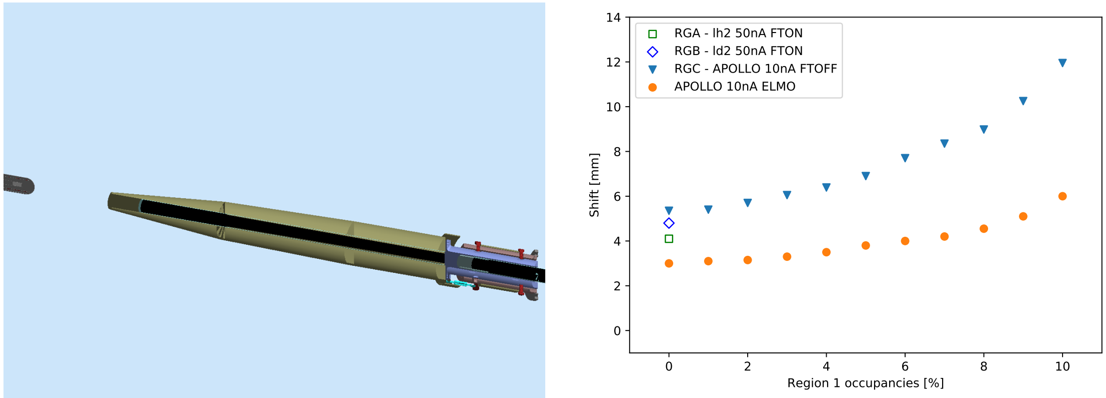

FIG. 4. Left: ELMO, the new Mølller shield design for RGC. Right: DC occupancies vs. raster size. The empty square and diamond points at 0 mm shift correspond to the observed DC occupancies for RGA and RGB groups in the FTon configuration. The triangles are for the ammonia target (APOLLO) with the existing FToff shielding, and the circles are for APOLLO with the new ELMO shield.

shields, FTon. This is the shield that is installed when the Forward Tracker (FT) is in use. When the larger FToff shield is used, the FT remains in place but is not utilized for data acquisition. Our simulations predict DC occupancies as high as 10% when the larger FTOFF shield was used in conjunction with a 10 nA beam rastered over a 1 cm radius impinging on the solid ammonia sample. To counter these high rates we have designed a new Mølller shield, again guided by GEMC, that will reduce the DC occupancies to about 5%, similar to those observed in RGA and RGB. The results are show in Fig. 4 alongside a 3D model of the new shield. As shown in the model, the new shield is comprised of three cones, one of which replaces the forward tracker. Compared to the existing FToff shield, the inner beam pipe diameter has been increased from 28.5 mm to 34.9 mm, and the upstream lead cone of the shield is expanded to stay within the 5° electron scattering angle for the in-bending torus setting. The new shield has been reviewed by the Hall B engineering staff, who are presently developing a detailed design.

D. Simulations

Simulations for the proton-DVCS final state were run in order to verify the feasibility of the measurements with the planned setup, test the data reconstruction chain, and prepare the analysis codes. The GENEPI event generator was used to generated $ep \to ep\gamma$ events, which were fed to the GEANT4 simulation of CLAS12 (GEMC). The output was processed with the CLAS12 recostruction (COATJAVA) and analyzed. The kinematics of the generated particles for the pDVCS channel are shown in Fig. 5. It can be noticed that the majority of generated events have protons at $\theta > 40°$, and photons at very low angles and high energy, coming mainly from the Bethe-Heitler (BH) process.

The corresponding reconstructed distributions after particle identification are in Fig. 6. While many of the very forward-going BH photons will be missed, the majority of the backwards-going protons will be collected by the CLAS12 Central Detector.

As was done in previous DVCS experiments at CLAS [10–12], exclusivity cuts will be used to extract the final state from background events such as scattering from nitrogen rather than hydrogen and π_0 decay with only one photon detected. Figure 7 shows the Q^2 versus x_B (left) and ϕ (right) distributions for the extracted $ep\gamma$ events after exclusivity selection cuts on $epgX$ and epX missing masses, missing energy of $ep\gamma$, and cone angle between reconstructed and expected photon.

Our simulations with the fully implemented target and beam line design show that the kinematic reach and reconstruction efficiency of the planned run will fulfill the experimental requirements. While we have presented only results for pDVCS here, the results for nDVCS are very similar and other channels also have similar acceptances (with exception of the inclusive channel which is not affected by our design choices).

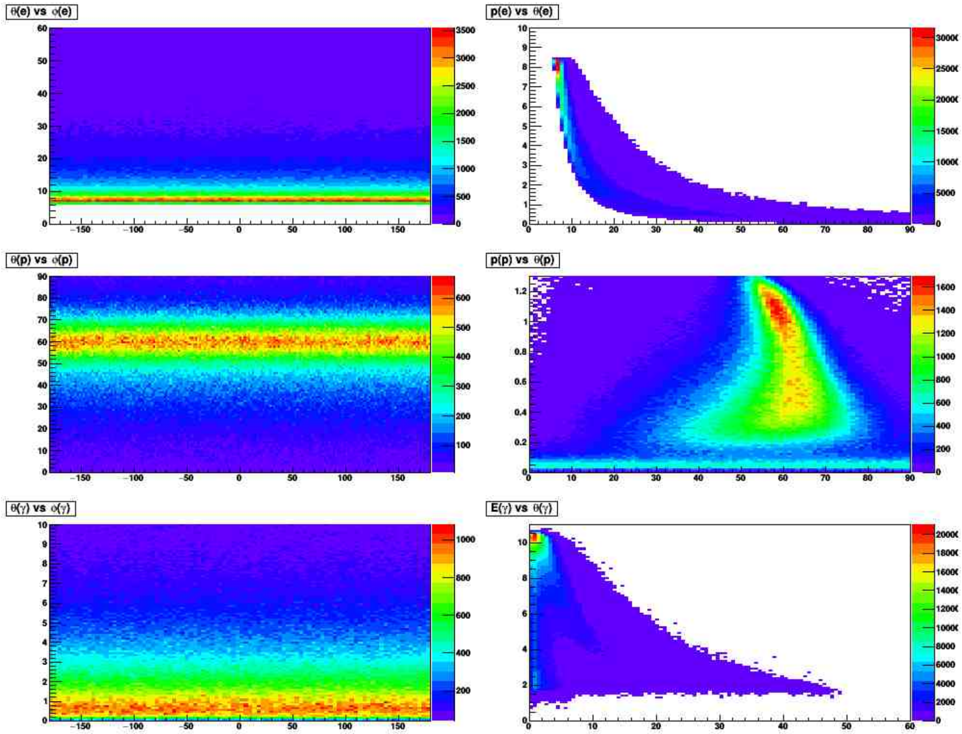

FIG. 5. Kinematics for the proton-DVCS final state, generated simulations. Left column: θ vs ϕ. Right column: momentum vs θ. From top to bottom: electrons, protons, photons.

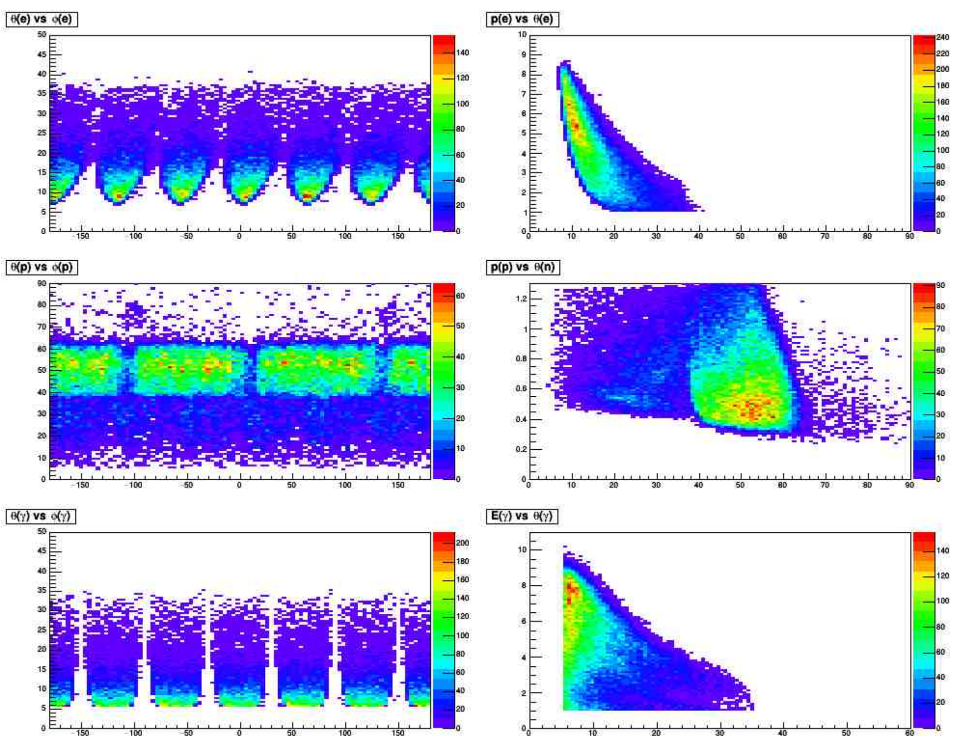

FIG. 6. Kinematics (in the FToff configuration) for the proton-DVCS final state, reconstructed simulations. Left column: θ vs ϕ. Right column: momentum vs θ. From top to bottom: electrons, protons, photons.

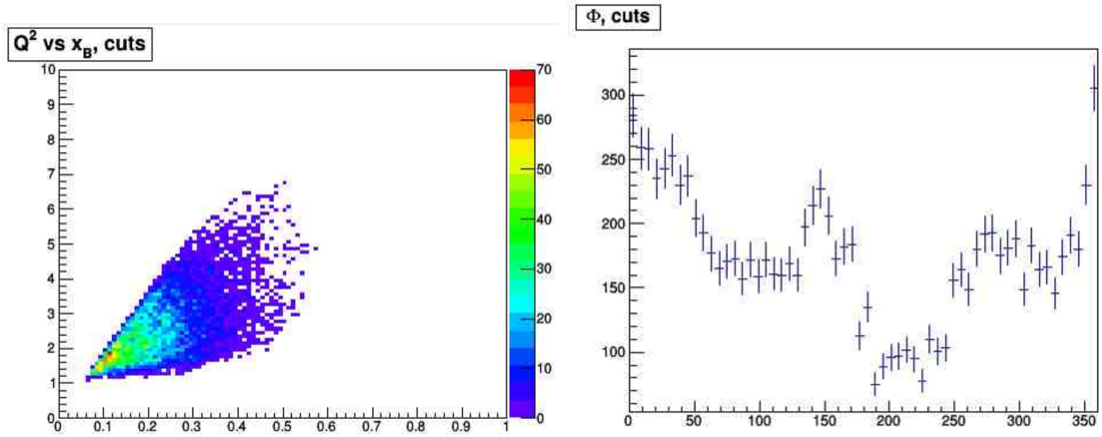

FIG. 7. Distribution of Q^2 as a function of x_B (left) and of the angle ϕ between the leptonic and hadronic plane (right), for proton-DVCS simulations in the RGC setup, after reconstruction and channel selection.

IV. SUMMARY

Since the various experiments comprising RGC have been approved, the community's interest in this program has only grown and the physics case remains compelling. No comparable data have been collected anywhere or are likely to be available in the foreseeable future. The collaboration and Jefferson Lab have made a major investment in the equipment needed for RGC, including substantial support by an NSF MRI awarded to a consortium of universities (CNU, ODU, and UVa). Members of the collaboration have invested significant time and effort into all aspects of the preparation of this experiment - from prototyping and building the polarized target to simulations and design of all necessary beam line equipment. The program to be carried out within RGC is a major part of the overall experimental program approved for CLAS12. The experiment will be ready to run anytime after summer 2021. We request that the PAC reaffirm the original approval of this run group, and give it the highest rating.

REFERENCES

[1] E. Pasyuk et al. Nuclear target test. `https://clasweb.jlab.org/group_meeting_minutes/Physics/talks_2020/NTT_report_05062020.pdf`, 2020.

[2] Tianbo Liu, Raza Sabbir Sufian, Guy F. de Téramond, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur. Unified description of polarized and unpolarized quark distributions in the proton. *Phys. Rev. Lett.*, 124(8):082003, 2020.

[3] J.J. Ethier, N. Sato, and W. Melnitchouk. First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis. *Phys. Rev. Lett.*, 119(13):132001, 2017.

[4] R. Fair *et al.* The clas12 superconducting magnets. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 962:163578, 2020.

[5] V. Lagerquist. Magnetic field requirements for the CLAS12 polarized arget. In *Proceedings of the 18th International Workshop on Polarized Sources, Targets, and Polarimetry (PSTP 2019)*, to be published.

[6] C.D. Keith, J. Brock, C. Carlin, S.A. Comer, D. Kashy, J. McAndrew, D.G. Meekins, E. Pasyuk, J.J. Pierce, and M.L. Seely. The jefferson lab frozen spin target. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 684:27 – 35, 2012.

[7] J. Brock. 1 K refrigerator for the CLAS12 polarized target. In *Proceedings of the 18th International Workshop on Polarized Sources, Targets, and Polarimetry (PSTP 2019)*, to be published.

[8] J. Maxwell. NMR polarization measurements for jefferson lab's solid polarized targets. In *Proceedings of the 17th International Workshop on Polarized Sources, Targets, and Polarimetry (PSTP 2017)*, 2017.

[9] G.R. Court, D.W. Gifford, P. Harrison, W.G. Heyes, and M.A. Houlden. A high precision q-meter for the measurement of proton polarization in polarised targets. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 324(3):433 – 440, 1993.

[10] S. Pisano et al. Single and double spin asymmetries for deeply virtual Compton scattering measured with CLAS and a longitudinally polarized proton target. *Phys. Rev. D*, 91(5):052014, 2015.

[11] F.X. Girod et al. Measurement of deeply virtual Compton scattering beam-spin asymmetries. *Phys. Rev. Lett.*, 100:162002, 2008.

[12] H.S. Jo et al. Cross sections for the exclusive photon electroproduction on the proton and generalized parton distributions. *Phys. Rev. Lett.*, 115(21):212003, 2015.