Run Group C Jeopardy Update Document

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(Dated: April 22, 2024)

I. INTRODUCTION

The CLAS12 Run Group C (RG-C) comprises 8 experiments, 5 approved and rated by the PAC and 3 run-group addition proposals, sharing the same target types (dynamically polarized NH_3 and ND_3) and beam (11 GeV polarized electrons). They are listed in Table I.

Experiment number	Title	Contact person	PAC days (rating)
E12-06-109	Longitudinal Spin Structure of the Nucleon	S. Kuhn	80 (A)
E12-06-109A	DVCS on the neutron with polarized deuterium target	S. Niccolai	RG Addition
E12-06-119(b)	DVCS on longitudinally polarized proton target	M. Defurne	120 (A)
E12-07-107	Spin-Orbit Correlations with longitudinally polarized target	H. Avakian	103 (A-)
E12-09-007(b)	Study of partonic distributions using SIDIS K production	W. Armstrong	80 (A-)
E12-09-009	Spin-Orbit Correlations in K production with polarized targets	H. Avakian	103 (B+)
E12-09-007A	Dihadron Electroproduction in DIS with Long. Polarized Targets	C. Dilks	RG Addition
E12-07-107A	Baryon Production in the Target Fragmentation Region with Pol. Targets	T. Hayward	RG Addition

TABLE I. The experiments of Run Group C.

The physics objectives of Run-Group C are manifold:

- PDFs: Extend measurements of quark helicity distributions to the highest x possible to test predictions for valence quark distributions; provide high precision data over a wide range in Q^2 for DGLAP extractions of sea quark and gluon helicity distributions.
- GPDs: Measure Deeply Virtual Compton Scattering (DVCS) target and beam-target spin asymmetries on the proton and the neutron to extract Generalized Parton Distribution Functions (GPDs).
- TMDs: Study single- and dihadron production in SIDIS, both in the current and target fragmentation regions, to unravel the three-dimensional spin and momentum structure of quark distributions in the nucleon.

The beam time originally allocated for RG-C was 185 PAC days, corresponding to the minimum time required to complete all PAC-approved experiments within the run group. After the PAC48 Jeopardy Review in September 2020, this beam time was reduced to 120 PAC days, with an emphasis on the DVCS program within RG-C. The Run Group was scheduled for a total of 244 calendar days (plus 6 commissioning days and 7 reconfiguration days) during the time period June 2022 - March 2023, corresponding to 122 PAC days. During the run of RG-C, several major down-times of the accelerator and the equipment in Hall B (including a meltdown of the power supply for the Central Detector Solenoid) led to a significant reduction of the actually available beam time, corresponding to an effective run of 80 out of the 120 awarded PAC days. In order to optimize the science impact of the world-wide unique capabilities of Jefferson Lab, taking polarized target data for the full approved beam time is crucial. Scheduling the remaining

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time of 40 PAC days is essential to reach the optimal accuracy of the various observables proposed for RG-C, in particular for DVCS. By scheduling the remaining run time for RG-C in conjunction with the polarized EMC effect measurement, RG-G (also under jeopardy review at this PAC), the significant investment of time, effort and resources in the construction of the polarized target and its re-installation in Hall B will be utilized to its full potential.

II. EXPERIMENTAL SETUP

Run group C uses the CLAS12 spectrometer in its baseline configuration, plus the Forward Tagger (FT), both modules of the RICH, and the Central Neutron Detector. Additional elements specific to RG-C are a set of $x-y$ raster magnets, a bespoke large Møller cone "ELMO" which can be swapped out for the FT, and the longitudinally polarized H/D target, discussed in the next section.

A. Polarized Target

A new longitudinally polarized target, APOLLO (Ammonia POLarized LOngitunally), was developed and operated specifically for the Run Group C experiments. In APOLLO, protons and deuterons in 5 cm long samples of pre-irradiated NH_3 and ND_3 are dynamically polarized in the 5 T field of the CLAS12 solenoid at a temperature of 1 K. Irradiation of the ammonia samples prior to the experiment is necessary to produce the paramagnetic radicals in the solid lattice that are needed for dynamic nuclear polarization. As has been the case for all polarized ammonia experiments at Jefferson Lab, the irradiation was performed with 12 MeV electron beam on the campus of the National Institute of Standards in Gaithersburg, MD. APOLLO comprised many innovative features and improvements on previous polarized targets, including a new NMR system electronics and software, superconducting magnetic field correction coils, and a novel target sample transport system ("trolley") that enabled rapid swaps of target material in spite of the very long target insert which had to be concentric with the beam line (due to space constraints).

Overall, the performance of the target was very good during Run Group C. Only 88 hours (less than 4% of the overall in-beam time) were lost due to unscheduled target repairs or maintenance. Maximum polarizations for protons and deuterons of 90% and 55%, respectively, were achieved with APOLLO. The deuteron polarization is believed to be a record for electron beam experiments.

However, these results were only obtained after additional radiation from the CEBAF beam was applied to the target samples. The initial polarizations at the beginning of RG-C were significantly lower, indicating that the NH_3 and ND_3 samples had not received the optimal radiation dose for dynamic polarization. To improve the performance of this and future polarized solid targets at Jefferson Lab, the JLab Target Group is establishing a program to irradiate and test target samples on site. This program is slated to be operational by approximately June 2025.

The target was removed from Hall B at the end of Run Group C and placed in climate-controlled storage. Vacuum integrity and other system tests should be performed several weeks prior to re-installing it in Hall B, but we do not anticipate any major repairs will be needed. Approximately 3–4 weeks are necessary to install the target system and make it operational in Hall B. The same target system will be utilized with dynamically polarized samples of ^{7}LiD for the Run Group G experiment, and we anticipate that the two experiments may run consecutively or even interleaved with each other.

III. OVERVIEW OF THE THREE RUN PERIODS

RG-C took data during three periods of roughly two calendar months each, between mid June 2022 and March 2023, for a total of about 80 PAC days. The average beam polarization was about 83%, with variations of a couple of percent during the different run periods.

A. Summer 2022

The experiment ran from June 12 to August 26 in "FTon" configuration (optimized for very forward photon detection). The data collected during that time amounted to a total of 28 PAC days. With a total integrated beam charge of 10 mC, roughly 16 B triggers were collected, with the CLAS12 torus in inbending configuration.

B. Fall 2022

The experiment ran from September 3 to November 11, 2022, in “FTout” configuration. During this time, the Forward Tagger (FT) was replaced with the larger Møller shield, allowing us to run with double the luminosity and a larger raster pattern, to maximize the statistics at larger Q^2 and larger photon angles. This run corresponded to 30 PAC days. With an integrated beam charge of 18 mC, roughly 20 B triggers were collected, with the CLAS12 torus in inbending configuration, and the solenoid with two opposite polarities. This part of the run ended prematurely due to the meltdown of the CLAS12 solenoid power supply.

C. Winter 2023

The experiment resumed after the repair of the CLAS12 solenoid power supply and ran from January 31 to March 20, 2023, back in the “FTon” configuration. This run corresponded to 22 PAC days. With an integrated beam charge of 7 mC, roughly 11 B triggers were collected, with the CLAS12 torus in both inbending and outbending configuration.

In the following, we report some preliminary results, primarily from the first of these three sections of RG-C. Our preliminary data show the high quality and statistical precision that can be achieved with the experimental setup of RG-C, and the desirability for additional statistical accuracy in some “statistic-poor” channels and regions of phase space.

IV. PRELIMINARY RESULTS

Currently only the Summer 2022 period is fully calibrated, and the ”cooking” (i.e. the data processing) of this dataset has begun recently. The data shown in the following are based on a small subset of the data collected during that first period, and an even smaller subset of the overall data taken so far. The alignment and calibration of the other two periods are ongoing.

A. Proton DVCS

Measuring Deeply Virtual Compton Scattering (DVCS) on a polarised target is crucial for the study of Generalized Parton Distributions (GPDs). The process can be described by four GPDs: H, $\widetilde{H}$ E, $\widetilde{E}$. GPDs are not fully accessible in DVCS: the DVCS observables are sensitive to the Compton Form Factors (CFFs) $\mathcal{H}$, $\widetilde{\mathcal{H}}$ $\mathcal{E}$, $\widetilde{\mathcal{E}}$, which are integrals over the variable x of the corresponding GPDs. Depending on the target and beam polarization, and on the measured observable, different combinations of CFFs can be extracted. The RGC polarized proton target allows for the measurement of the target-spin asymmetry (TSA) which is most sensitive to the imaginary part of CFFs $\mathcal{H}$ and $\widetilde{\mathcal{H}}$. The beam-spin asymmetry is also sensitive to these CFFs but in different combinations; measuring both on the same kinematic range is necessary to separate the two. Therefore RGC data provides important complementary measurements to the results obtained by RGA [1] that are essential to further our understanding of nucleon GPDs in the valence region. The RG-C TSA measurements follow what was done with the polarised target experiment at CLAS in the 6 GeV era [2]. RG-C aims to expand the kinematic range covered with high statistics data, which is of the utmost importance to the extraction of GPDs.

The preliminary results shown here (see Figs. 1–2) were produced using 4 runs taken with the NH3 target. In addition, data were taken on a Carbon target, which is essential to quantify the nuclear background coming from the Nitrogen in polarised targets. The background reduces the amplitude of measured asymmetries, therefore it needs to be accounted for by scaling the asymmetries with the dilution factor. In this preliminary analysis, this is computed by taking the ratio of the number of Carbon events over NH3 events normalised by beam charge in each kinematic bin. The analysis selects $ep \to ep\gamma$ DVCS candidates picking the highest momenta electron, proton, and photon in an event and requiring $P_\gamma > 2GeV$. Then strict exclusivity cuts are applied, which are tuned to improve the dilution factor. In Fig 1 a few of the exclusivity variables are shown, it is important to note that the NH3 data has been reconstructed with the latest calibrations, whereas the Carbon data is not calibrated.

The calibrated dataset does not contain enough statistic to build an asymmetry, therefore we compute it from runs from the so-far un-calibrated data set. Figure 2 shows the TSA and dilution factor. This very preliminary asymmetry obtained with $\sim 1\%$ of the collected statistics matches the expected shape, but any physics conclusion would be

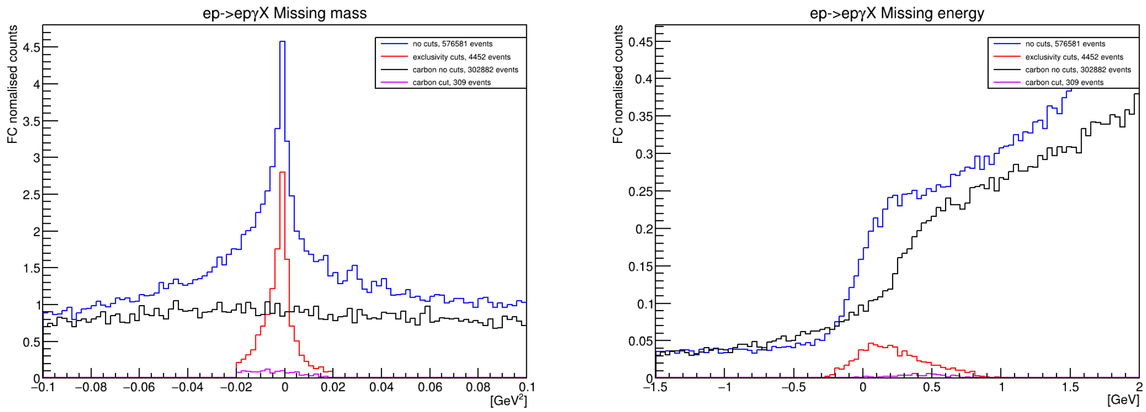

FIG. 1. pDVCS exclusivity variables, histograms are scaled to the beam charge collected.

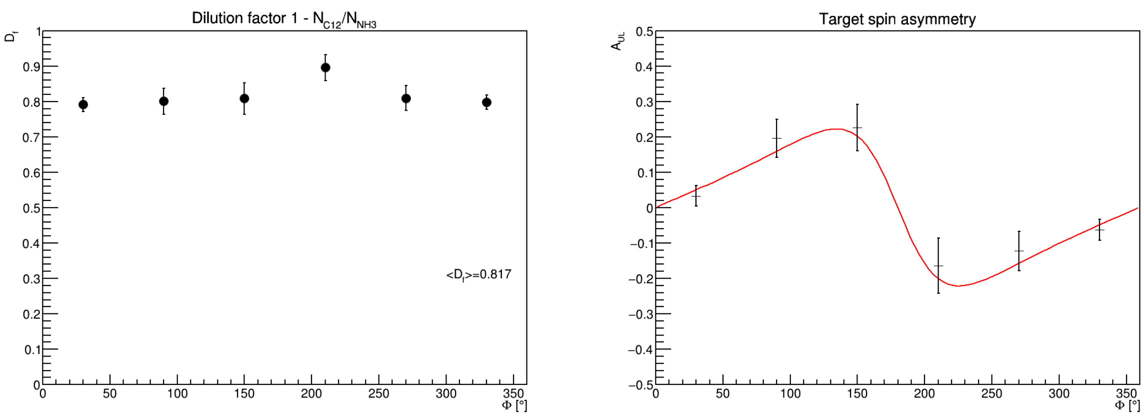

FIG. 2. pDVCS target spin asymmetry measured with roughly 1% of the collected data.

premature. In parallel an $ep \to ep\pi^0 \to ep\gamma\gamma$ analysis is ongoing to estimate the π^0 contamination in the DVCS sample, which is a significant background that tends to dilute the asymmetry.

B. Neutron DVCS

As detailed in Section IV A, the RG-C experiment will allow us to access different combinations of GPDs by measuring the DVCS beam-spin, target-spin and double-spin asymmetries. The latter two will be measured for the first time on the neutron, giving access to the real and imaginary parts of the $\mathcal{H}$ CFF. Comparing data on the proton and the neutron will allow us to understand the flavor dependence of CFFs, and eventually access GPDs for the u and d quark.

The nDVCS measurement is challenging: the cross-section is an order of magnitude lower than the pDVCS one, and the statistics are reduced due to the low efficiency of neutron detection. The limited availability of cooked data does not allow to extract preliminary observables for nDVCS. In Fig. 3, several exclusivity variables for the $en \to e'n'\gamma$ reaction are shown, comparing data on an ND3 or a C target. The events have been loosely selected around the D peak. An important source of background comes from protons misidentified as neutrons: they show in the shoulder of the $\Delta\Phi$ distribution and in the bump for $p_\perp > 0.2$GeV/c in particular. Studies of this background with MC simulations and RGA data is ongoing. Data and simulations will also be used to treat the π^0 background.

In parallel to the nDVCS analysis on ND3, pDVCS is studied using the same target. Comparison between the free proton in H and the bound proton in D will allow us to understand the impact of the medium on the DVCS asymmetries. This is crucial to interpret the neutron DVCS result, as free neutron target are experimentally impossible to achieve. pDVCS data on an ND3 target is presented in Fig. 4. The BSA shows the expected $\frac{A\sin(\Phi)}{1+B\cos(\Phi)}$ shape. As only limited data has been cooked, not enough data is available on a negatively polarized target to extract the

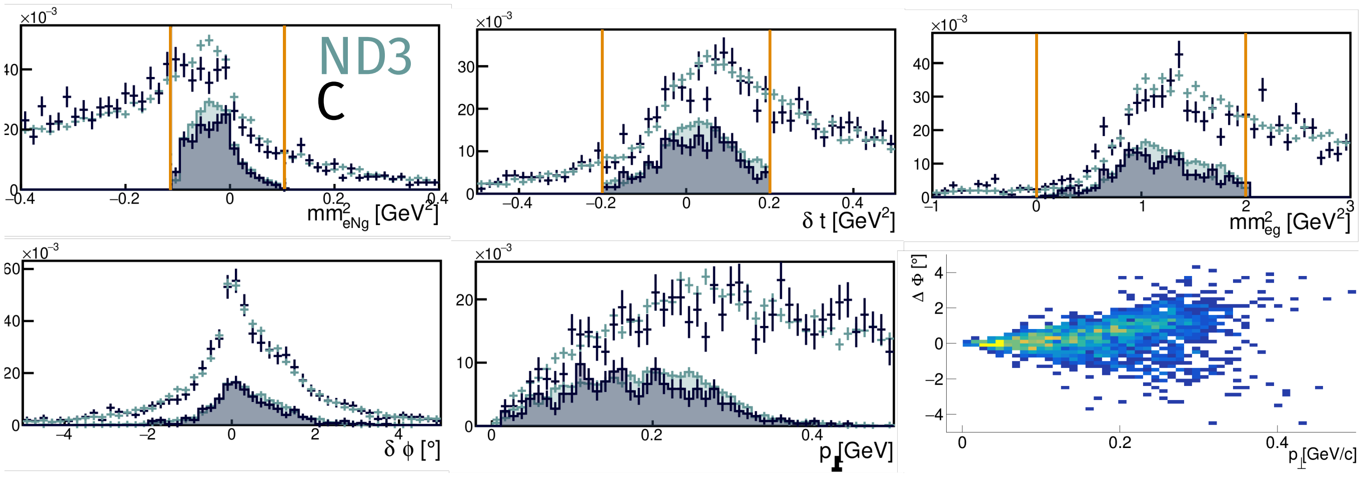

FIG. 3. Some exclusivity variables for the nDVCS reaction. From left to right, the first row shows the total missing mass of the system, the difference between two ways of computing the momentum tranfer t Δt and the missing mass of X in $en \to enX$. The second row shows the difference between two ways of computing the angle between the leptonic and hadronic planes of the DVCS reaction $\Delta\Phi$ and the total perpendicular missing momentum of the reaction. Data on an ND3 and a C targets are compared, they are normalized to one another by using the accumulated charge in the Faraday cups.

TSA or DSA for now. However, it is clear that the full originally approved statistics on the deuteron is required for significant results on both the neutron and the (bound) proton channel.

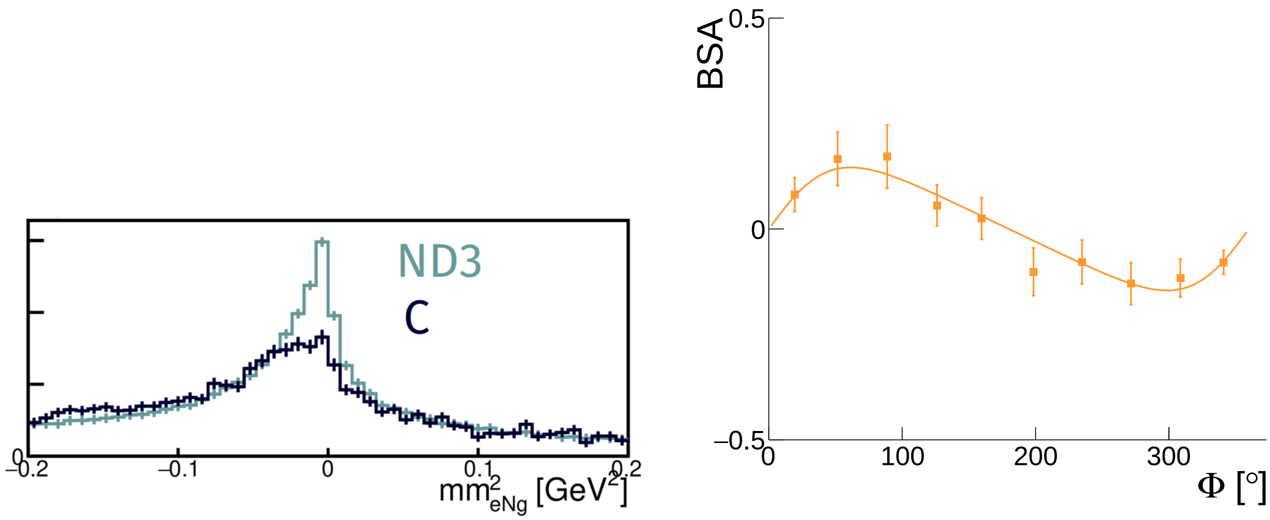

FIG. 4. Preliminary results for pDVCS in an ND3 target. Left: Missing mass for the pDVCS reaction, data on an ND3 and a C target are compared. Right: Preliminary extraction of the beam-spin asymmetry, it contains contamination from the N background and the π^0 channel in particular.

C. Timelike Compton Scattering

An important channel for exploring the universality of the GPD formalism is Timelike Compton Scattering (TCS), which with will be measured for the first time on a longitudinally polarized NH_3 target with this experiment. The TCS cross section is largely dominated by the Bethe-Heitler process and therefore the observables of interest, similarly to DVCS, are asymmetries. The two measurements planned for this channel are a beam-spin and target-spin asymmetry, the latter of which will be a first-time measurement.

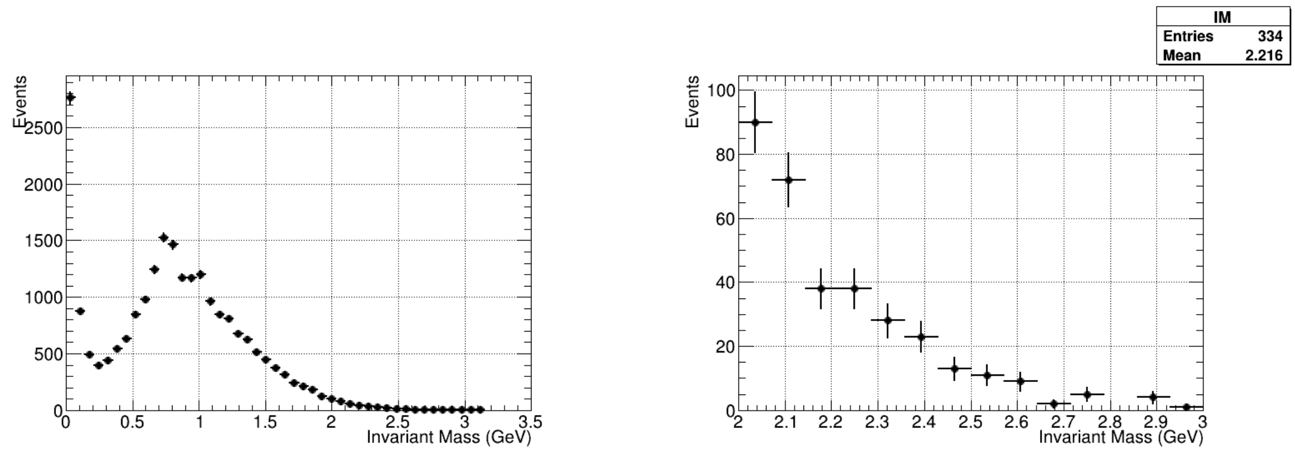

FIG. 5. Preliminary invariant mass distribution of the di-lepton pair. LEFT: Full distribution, with known meson peaks visible. RIGHT: The TCS Kinematic region of interest. Neither distribution takes nuclear background contamination into account.

To isolate the signal as best as possible with the limited statistics, the cuts chosen were;

- Event Builder PID (including a 3σ cut on electron sampling fraction for removal of pion contamination)
- Decay lepton pair in the forward detector, proton topology not yet split into FD and CD due to statistics
- $\frac{Pt}{P} < 0.05$ where P represents the momentum of the scattered electron and Pt represents its transverse momentum, in order to ensure the initial photon is quasi-real
- $1.8\,\mathrm{GeV} < Q' < 3\,\mathrm{GeV}$ in order to isolate the region of dilepton invariant mass where there are fewer meson resonaces (namely removing the ρ, ϕ, ω and J/ψ, See Fig. 5)
- $-0.4\,\mathrm{GeV}^2 < MM^2 < 0.4\,\mathrm{GeV}^2$ to limit the missing mass to around the mass of the scattered electron within detector resolution

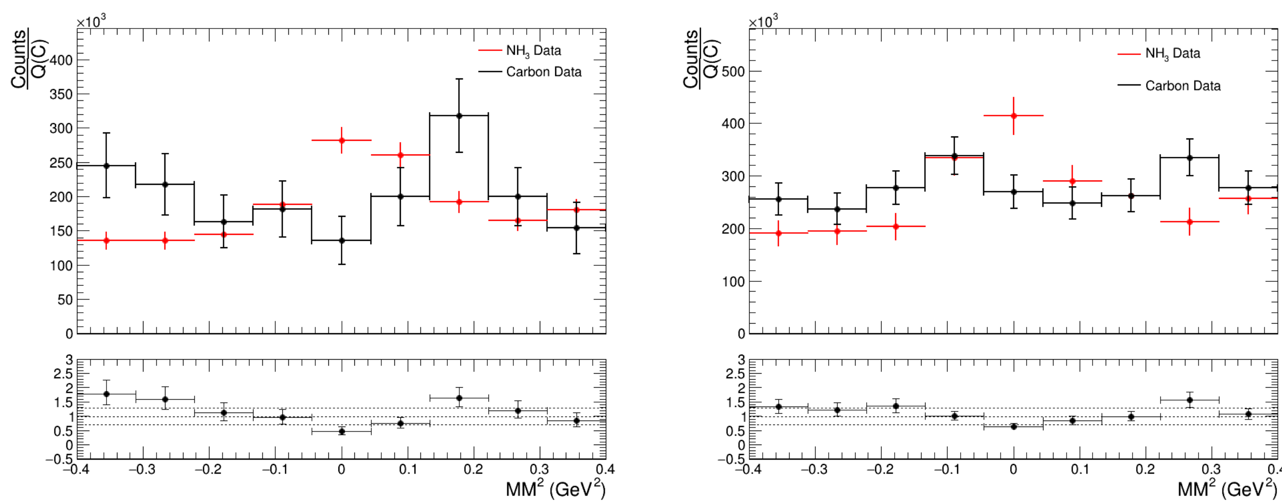

FIG. 6. Preliminary results comparing data, normalised by Faraday cup accumulated charge (Q) from the NH_3 target and the Carbon target (Top) along with the ratio of $\frac{C}{NH_3}$ (Bottom). On the left is Carbon and NH_3 data from the un-calibrated cook, and on the right has both Carbon and NH_3 datasets from the ongoing Pass-1 cooking.

The statistics are still too limited at this stage to extract a meaningful asymmetry. The signal to background ratio, taking the dilution factor as $1 - \frac{C}{NH_3}$, is shown to lie somewhere between 10% and 50%, and after the current loose

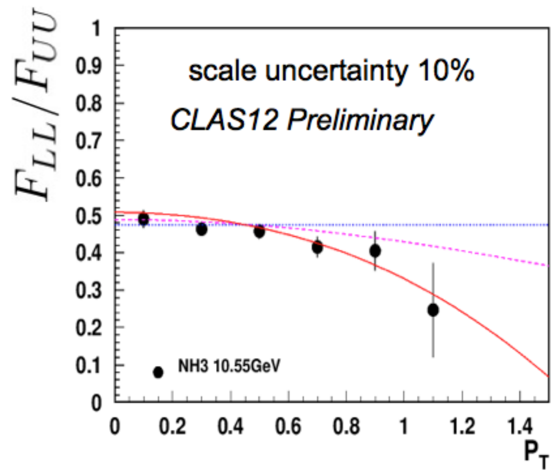

FIG. 7. The double spin asymmetry as a function of P_T in $ep \to e'\pi^+X$ in a given bin in x The curves correspond to different widths in k_T of $g_1(x, k_T)$ compared to $f_1(x, k_T)$.

cuts this gives a signal yield in the phase space of interest of between 33-167 events. Scaling these 23 available runs to the full 149 good NH_3 runs available, the total conservative yield estimate is 213-1081 events. Supplementing with the Fall dataset will serve to increase this yield but since TCS is a low statistics channel, with a cross section largely dominated by the Bethe-Heitler process, it would greatly benefit from more beamtime.

D. Semi-inclusive deep inelastic scattering

One of the most important questions about the 3D structure of the nucleon is the transverse momentum dependence of the distribution and fragmentation of quarks in the nucleon and the flavor and spin dependence of these structures. Understanding the dynamics of partons, including the non-perturbative sea quarks, is crucial for gaining insights into strong interactions. The correlations between the spin of the target and/or the momentum and spin of quarks, along with final state interactions, determine the azimuthal distributions of produced particles.

The transverse momentum of hadrons is most sensitive to spin-orbit correlations, providing a direct access to partonic transverse momenta. The transverse momentum distributions of the valence and sea quarks are predicted to have distinct shapes, particularly at high values of k_T. The effect of dynamical chiral symmetry breaking on the partonic structure of nucleons has important implications for the transverse momentum distributions of particles produced in hard scattering processes.

Collinear PDFs have flavour dependence, therefore it is not unexpected that the transverse momentum dependence may also be different for the different flavours [3]. Model calculations of the transverse momentum dependence of TMDs [4–7] and lattice QCD results [8, 9] suggest that the dependence of the widths of TMDs on the quark polarization and flavor may be significant. Measurements of the P_T-dependence in double-spin asymmetries (DSAs) in charged pion electroproduction, conducted for the first time across different x-bins, have revealed interesting insights. These measurements suggest the existence of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin [**?** **?**], consistent with findings from LQCD simulations [9]. The double spin longitudinal asymmetries, provide access to the SF F_{LL} and the underlying helicity TMD $g_1(x, k_T)$. Since the ϵ-dependent pre-factor in the valence region is rapidly decreasing with energy, measurements at higher energies of F_{LL} become very challenging, making Jefferson Lab a unique place to study helicity TMDs in the valence region. The new RG-C results, using a small fraction ($\sim 1\%$) of data with the 10.6 GeV longitudinally polarized beam scattering off longitudinally polarized NH_3 target, are shown in Fig.7. These full statistics for these new data would allow fine binning of transverse momentum dependence of pion double spin asymmetries in x, critical for reduction of the systematics due to correlations between x and P_T of hadrons.

Remarkable progress has been made in recent decades on the study of Parton Distribution Functions (PDFs) that originate from current fragmentation studies and represent our understanding of the momentum distribution of partons inside the nucleus. Significantly less effort has been oriented toward the target fragmentation region (TFR), and relatively little is known about the mechanism by which the spectator partons undergo hadronization after deep inelastic scattering.

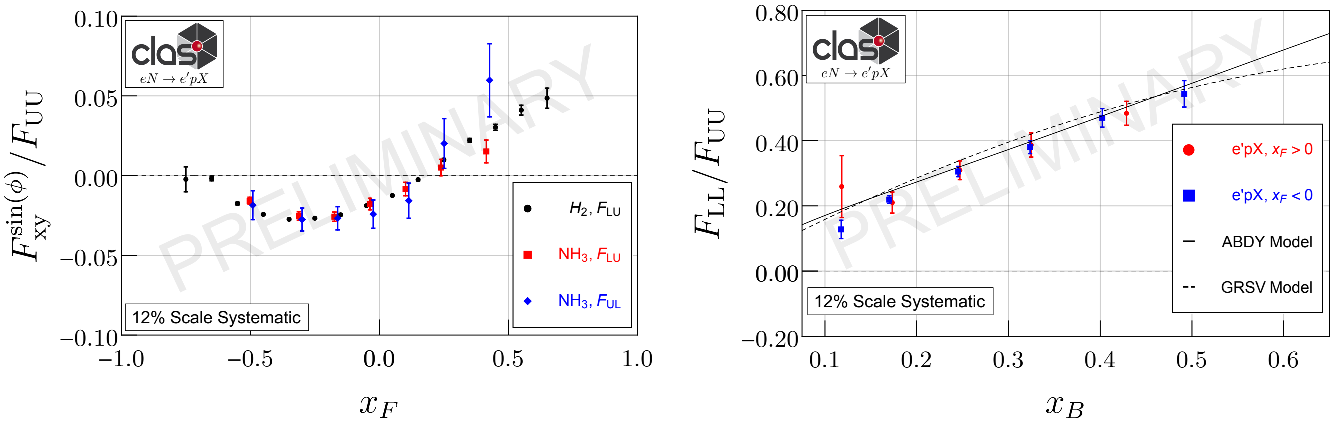

FIG. 8. Left: Preliminary single-spin structure function ratios for H_2 and NH_3 as a function of x_F. A clear sign change is observed in the positive regions corresponding to the transition from target to current fragmentation. Right: Preliminary F_{LL}/F_{UU} structure function ratio for TFR and CFR SIDIS protons compared to model predictions for the helicity-distribution dependence. Good agreement is observed, even for the preliminary data.

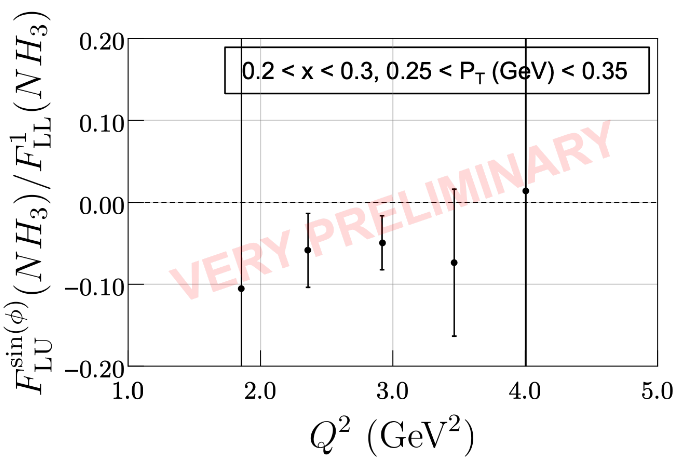

FIG. 9. Preliminary extraction of the "double-ratio" F_{LL}/F_{UU} in three-dimensional Q^2, x and P_T binning. The double ratio will allow for the study of the Q^2 dependence of subleading twist objects without the influence of the potentially unconstrained F_{UU} term with unknown longitudinal virtual photon contributions. Significant statistics and precise four-dimensional binning will be required to differentiate between either a flat or $1/Q$ dependence.

The same fixed target experiments where Deep Inelastic Scattering (DIS) plays a key role in providing high quality data can also provide access to information on hadrons produced in the TFR by enabling the study of various observables related to nucleonic structure including azimuthal distributions of final state particles that encode key information on the orbital motion of quarks and provide opportunities to study their transverse momentum dependence. In particular, the modulations arising in the TFR can be linked to objects called fracture functions, which have the probabilistic interpretation of finding a particular final state hadron formed out of the target remnant after the emission of a particular quark.

At leading twist for the longitudinally polarized target case, the cross section can be written at tree level as [10]

$$\frac{d\sigma}{dxdyd\zeta dP_T^2} = 2\pi\hat{\sigma}_U \sum_q e_q^2 \left[\tilde{u}_1(x,\zeta,P_T^2) + \lambda S_L\sqrt{1-\varepsilon^2}\tilde{l}_{1L}(x,\zeta,P_T^2)\right]. \quad (1)$$

Of particular interest is the double-spin asymmetry for inclusive hadron production in the TFR which is sensitive to the ratio of the leading-twist fracture function, $\hat{l}_{1L}$, which carries probabilistic information about the hadronization of the target remnant after the emission of a longitudinally polarized quark in a longitudinally polarized nucleon, and $\hat{u}_1$, the unpolarized fracture function. After integration over all final-state baryon kinematics and summing over all baryon types, the double-spin asymmetry is equivalent to the g_1/F_1 ratio measured in DIS. This important connection will allow for the first ever direct test of the momentum-sum rules that link TFR FrFs to their CFR TMD-PDF counterparts (the FrF accessible in the previous back-to-back measurements has no TMD-PDF analog) and is an important prediction of the TFR formalism.

E. Semi-Inclusive Dihadron Spin Asymmetries

Spin asymmetries of semi-inclusive dihadrons provide insight into various spin-dependent PDFs and dihadron fragmentation functions (DiFFs). Measurements of the longitudinal beam-spin asymmetry A_{LU} of $\pi^+\pi^-$ dihadrons from RG-A data [11] allowed for the first point-by-point extraction of the collinear twist-3 PDF $e(x)$ [12]. The longitudinally polarized target of RG-C provides the ability for CLAS12 to measure the target spin and double spin asymmetries, respectively A_{UL} and A_{LL}, in the same kinematic binning as A_{LU}, the primary goal of E12-09-007A. In particular, A_{UL} accesses the collinear twist-3 PDF $h_L(x)$, which can be extracted point-by-point analogously to the $e(x)$ extraction, as well as other PDFs and DiFFs. A_{LL} accesses the leading-twist unpolarized DiFF D_1 partial waves, providing complementary constraints on D_1 to those that would come from multiplicity measurements. Moreover, A_{LL} helps constrain twist-3 DiFFs, which although they are thought to be relatively small they are necessary for accurate extraction of $e(x)$ and $h_L(x)$; additional leverage on twist-3 DiFF constraints may also be provided by the kinematic dependence of the ratio A_{LU}/A_{UL}, which is uniquely available from CLAS12 data. These measurements, especially A_{LU}/A_{UL} would benefit from more statistics and allow for better constraints on the underlying PDFs and DiFFs.

F. Inclusive Spin Structure functions

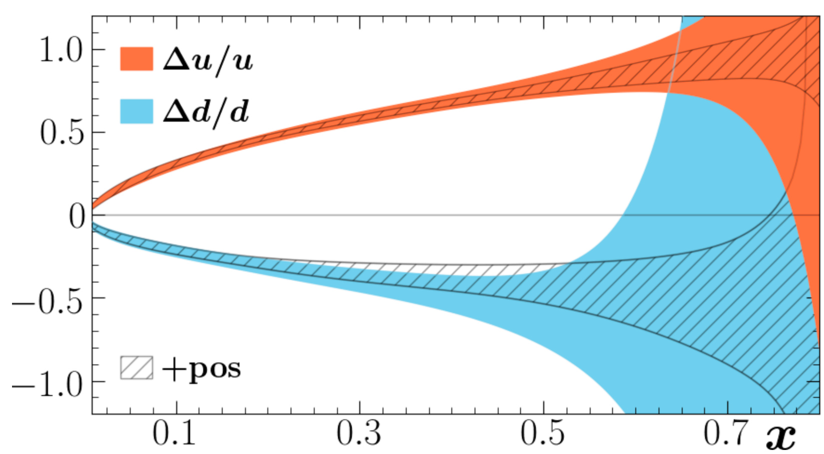

FIG. 10. Present knowledge of polarized valence quark distributions at high x from a global QCD analysis of all world data (including RHIC) [13].

The original first proposal in RG-C, E12-06-109, is a measurement of inclusive spin structure functions of the proton and the deuteron, aimed at improving the precision with which polarized parton distribution functions can be extracted from DGLAP analyses, in particular in the extreme valence region of very large x, and to anchor both TMD and GPD extractions for which 1-dimensional structure functions are a limiting case. The polarization of the d-quark at large x is still very uncertain (even in sign) at $x > 0.6$ (see Fig. 10 from a recent analysis of the global data set), and its determination is one of the main goals of E12-06-109 and E12-09-007(b) (RG-C) and the JLab 12 GeV program. Preliminary analysis of the RG-C data set already processed shows that the precision of the measured double spin asymmetry will come close to matching the proposed accuracy for the proton, while the deuteron needs significant additional statistics (about 20 more PAC days) to reach the precision necessary for an extraction of the polarization of the d-quark at large x, due to the lower polarization achievable for deuterons relative to protons.

V. CONCLUSIONS

While the preliminary data shown in the previous section constitute only a small fraction of the overall data set collected, it is already apparent that additional statistics will be needed to achieve the goals of most experiments in RG-C, in particular for the DVCS channels which are notoriously "statistics hungry", and on the deuteron. Furthermore, some crucial auxiliary measurements during the first run of RG-C (e.g., with outbending torus polarity and with reversed solenoid field) had to be abandoned or cut short because of the significant down-times that could not have been anticipated when the overall run plan was developed.

We request that the remaining 40 PAC days for RG-C be re-affirmed by the PAC and scheduled for a run in 2026-2027, in conjunction with RG-G which will share the same target.

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