Measurement of deeply virtual Compton scattering off Helium-4 with CLAS at Jefferson Lab

R. Dupré,1,21,* M. Hattawy,1,21,33 N.A. Baltzell,1,40 S. Bültmann,33 R. De Vita,17 A. El Alaoui,1,41 L. El Fassi,1,27 H. Egiyan,40 F.X. Girod,40 M. Guidal,21 K. Hafidi,1 D. Jenkins,47 S. Liuti,46 Y. Perrin,25 S. Stepanyan,40 B. Torayev,33 E. Voutier,21,25 M.J. Amaryan,33 W.R. Armstrong,1 H. Atac,39 C. Ayerbe Gayoso,48 F.X. Girod,40 M. Guidal,21 K. Hafidi,1 D. Jenkins,47 S. Liuti,46 Y. Perrin,25 S. Stepanyan,40 B. Torayev,33 E. Voutier,21,25 M.J. Amaryan,33 W.R. Armstrong,1 H. Atac,39 C. Ayerbe Gayoso,48 L. Barion,15 M. Battaglieri,40,17 I. Bedlinskiy,28 F. Benmokhtar,8 A. Bianconi,43,20 A.S. Biselli,9 M. Bondi,17 F. Bossù,4 S. Boiarinov,40 W.J. Briscoe,13 D. Bulumulla,33 V. Burkert,40 D.S. Carman,40 J.C. Carvajal,11 M. Caudron,21 A. Celentano,17 P. Chatagnon,21 V. Chesnokov,37 T. Chetry,27,32 G. Ciullo,15,10 B.A. Clary,6 P.L. Cole,24 M. Contalbrigo,15 G. Costantini,43,20 V. Crede,12 A. D’Angelo,18,36 N. Dashyan,49 M. Defurne,4 A. Deur,40 S. Diehl,34,6 C. Djalali,32 M. Ehrhart,1,21 L. Elouadrhiri,40 P. Eugenio,12 S. Fegan,45 A. Filippi,19 T.A. Forest,14 Y. Ghandilyan,49 G.P. Gilfoyle,35 R.W. Gothe,38 K.A. Griffioen,48 H. Hakobyan,41,49 T.B. Hayward,48 K. Hicks,32 A. Hobart,21 M. Holtrop,29 Y. Ilieva,38 D.G. Ireland,44 E.L. Isupov,37 H.S. Jo,23 K. Joo,6 S. Joosten,1 D. Keller,46 G. Khachatryan,49 A. Khanal,11 M. Khandaker,31 A. Kim,6 W. Kim,23 A. Kripko,34 V. Kubarovsky,40 S.E. Kuhn,33 L. Lanza,18 K. Livingston,44 M.L. Kabir,27 M. Leali,43,20 P. Lenisa,15,10 I.J.D. MacGregor,44 D. Marchand,21 N. Markov,40,6 V. Mascagna,42,20 M. Mayer,33 B. McKinnon,44 M. Mirazita,16 V.I. Mokeev,40 K. Neupane,38 S. Niccolai,21 T. R. O’Connell,6 M. Osipenko,17 M. Paolone,30,39 L.L. Pappalardo,15,10 R. Paremuzyan,40,29 E. Pasyuk,40 D. Payette,33 W. Phelpe,5 N. Pivnyuk,28 O. Pogorelko,28 J. Poudel,33 Y. Prok,33 M. Ripani,17 J. Ritman,22 A. Rizzo,18,36 G. Rosner,44 P. Rossi,40 J. Rowley,32 F. Sabatie,4 C. Salgado,31 A. Schmidt,13,26 R. Schumacher,3 V. Sergeyeva,21 Y. Sharabian,40 U. Shrestha,32 D. Sokhan,44 O. Soto,16,41 N. Sparveris,39 I.I. Strakovsky,13 S. Strauch,38 N. Tyler,38 M. Ungaro,40,6 L. Venturelli,43,20 H. Voskanyan,49 A. Vossen,7,40 D. Watts,45 K. Wei,6 X. Wei,40 L.B. Weinstein,33 R. Wishart,44 M.H. Wood,2 B. Yale,48 N. Zachariou,45 and J. Zhang46

(The CLAS Collaboration)

1Argonne National Laboratory, Argonne, Illinois 60439

1
2Canisius College, Buffalo, NY
3Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
4IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
5Christopher Newport University, Newport News, Virginia 23606
6University of Connecticut, Storrs, Connecticut 06269
7Duke University, Durham, North Carolina 27708-0305
8Duquesne University, 600 Forbes Avenue, Pittsburgh, PA 15282
9Fairfield University, Fairfield CT 06824
10Universita’ di Ferrara, 44121 Ferrara, Italy
11Florida International University, Miami, Florida 33199
12Florida State University, Tallahassee, Florida 32306
13The George Washington University, Washington, DC 20052
14Idaho State University, Pocatello, Idaho 83209
15INFN, Sezione di Ferrara, 44100 Ferrara, Italy
16INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy
17INFN, Sezione di Genova, 16146 Genova, Italy
18INFN, Sezione di Roma Tor Vergata, 00133 Rome, Italy
19INFN, Sezione di Torino, 10125 Torino, Italy
20INFN, Sezione di Pavia, 27100 Pavia, Italy
21Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
22Institute für Kernphysik (Juelich), Juelich, Germany
23Kyungpook National University, Daegu 41566, Republic of Korea
24Lamar University, 4400 MLK Blvd, PO Box 10046, Beaumont, Texas 77710
25LPSC, Université Grenoble-Alpes, CNRS/IN2P3, 38026 Grenoble, France
26Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307
27Mississippi State University, Mississippi State, MS 39762-5167
28National Research Centre Kurchatov Institute - ITEP, Moscow, 117259, Russia
29University of New Hampshire, Durham, New Hampshire 03824-3568
30New Mexico State University, PO Box 30001, Las Cruces, NM 88003, USA
31Norfolk State University, Norfolk, Virginia 23504
32Ohio University, Athens, Ohio 45701
33Old Dominion University, Norfolk, Virginia 23529
II Physikalisches Institut der Universitaet Giessen, 35392 Giessen, Germany

University of Richmond, Richmond, Virginia 23173

Università’ di Roma Tor Vergata, 00133 Rome Italy

Skobeltsyn Institute of Nuclear Physics, Lomonosov
Moscow State University, 119234 Moscow, Russia

University of South Carolina, Columbia, South Carolina 29208

Temple University, Philadelphia, PA 19122

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile

Università degli Studi dell’Insubria, 22100 Como, Italy

Università degli Studi di Brescia, 25123 Brescia, Italy

University of Glasgow, Glasgow G12 8QQ, United Kingdom

University of York, York YO10 5DD, United Kingdom

University of Virginia, Charlottesville, Virginia 22901

Virginia Tech, Blacksburg, Virginia 24061-0435

College of William and Mary, Williamsburg, Virginia 23187-8795

Yerevan Physics Institute, 375036 Yerevan, Armenia

(Dated: February 11, 2021)
Abstract

We report on the measurement of the beam spin asymmetry in the deeply virtual Compton scattering off $^4$He using the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab using a 6 GeV longitudinally polarized electron beam incident on a pressurized $^4$He gaseous target. We detail the method used to ensure the exclusivity of the measured reactions, in particular the upgrade of CLAS with a radial time projection chamber to detect the low-energy recoiling $^4$He nuclei and an inner calorimeter to extend the photon detection acceptance at forward angles. Our results confirm the theoretically predicted enhancement of the coherent ($e^4\text{He} \rightarrow e'^4\text{He}'\gamma'$) beam spin asymmetries compared to those observed on the free proton, while the incoherent ($e^4\text{He} \rightarrow e'p'\gamma'X'$) asymmetries exhibit a 30% suppression. From the coherent data, we were able to extract, in a model-independent way, the real and imaginary parts of the only $^4$He Compton form factor, $H_A$, leading the way toward 3D imaging of the partonic structure of nuclei.

*corresponding author: raphael.dupre@ijclab.in2p3.fr
I. INTRODUCTION

In the past few decades, the study of the proton structure has made significant progress thanks to the theoretical and experimental developments of three dimensional structure functions [1]. These studies, which have focused on generalized parton distributions (GPDs) and transverse momentum dependent parton distribution functions (TMDs) can be generalized to the nucleus and offer a unique opportunity to revisit the quark structure of the nucleus with an original perspective [2]. This new approach is particularly needed as the quark structure of the nucleus remains today the subject of numerous controversies. Indeed, while much progress has been made in measuring the nuclear parton distribution functions, their shape can be explained with very different model assumptions [3–5].

In nuclei, the GPDs can be probed conveniently through the measurement of the spin asymmetries generated by the deeply virtual Compton scattering (DVCS) process [6–9]. The measurement of the exclusive production of a photon limits the possibilities of final state interactions (FSIs) in the nuclear medium and offers a unique opportunity to make a measurement free of them. Moreover, with a spin-0 nuclear target, the extraction of the GPD from the DVCS data is significantly simplified since a single GPD is involved in the process at leading order. However, the measurement of the nuclear DVCS is challenging experimentally and the first attempts by the HERMES Collaboration [10] led to controversial conclusions. We present here in detail the more recent measurements by the CLAS Collaboration, which has been already partially presented in two short letters [11, 12]. We extend in this article the description of the CLAS nuclear DVCS experiment, detail the methods used for the data analysis and produce the complete experimental results for each channel measured.

II. THEORETICAL FRAMEWORK

A. The GPD Formalism

The theory of GPDs has been already reviewed in detail in various publications [6–9], and we summarize here only the necessary elements to discuss the present experimental results. The GPDs are real structure functions $F_{q}^{g}(x,\xi,t)$, where $x + \xi$ and $x - \xi$ are the incoming and outgoing quark momenta respectively and $t = \Delta^2$ is the squared transferred
four momentum to the target, as illustrated in Fig. 1.

The different possible spin states lead to several independent GPDs for any given hadron. The proper accounting of the number of GPDs must be done with regard to the symmetries of the system. At leading order and leading twist, we find that there are $2(2J + 1)^2$ GPDs for a particle of spin $J$. Therefore for a spin-0 hadron like the helium-4 nucleus, we will have two GPDs, and for a spin-1/2 hadron like the proton, eight GPDs. Half of these involve a parton helicity flip, they are called transversity GPDs and do not contribute to the DVCS process.

DVCS is the main experimental probe of the GPDs. However, this process does not allow for an extraction of the GPDs in the full phase space of the parameters. Instead, DVCS gives access to the GPDs integrated over $x$. To account for this and simplify the notation, we define the complex Compton form factors (CFF, noted with curved $\mathcal{F}$ for a given GPD $F$) for each GPD as follows:

$$
\Re e(\mathcal{F}(\xi, t)) = \sum_q e_q^2 \mathcal{P} \int_{-1}^{1} dx \mathcal{F}^q(x, \xi, t) \left[ \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right],
$$

$$
\Im m(\mathcal{F}(\xi, t)) = -\pi \sum_q e_q^2 \left[ \mathcal{F}^q(\xi, \xi, t) \mp \mathcal{F}^q(-\xi, \xi, t) \right].
$$

These are the quantities directly present in the DVCS cross sections. We note that they are summed over the different quark flavors present in the hadron, as the electromagnetic probe does not differentiate quark flavors.

Experimentally, another process is indistinguishable from DVCS, the Bethe-Heitler (BH) process in which the final state photon is emitted by the scattering lepton rather than the hadron. In this case, the photon-hadron interaction is the same as in elastic scattering and
depends on the target form factors rather than its GPDs. The DVCS and BH processes are experimentally indistinguishable as they have identical final states, such that they interfere in the squared amplitude of the exclusive photo-production process:

\[ |T|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + T_{DVCS}^* T_{BH} + T_{DVCS} T_{BH}^*. \]  

(3)

The interference terms significantly increase the cross section in specific parts of the phase space and lead to significant beam spin asymmetries (BSAs), which are the focus of the measurements presented here.

Finally, we need to define the kinematics. We use the conventions from Fig. 2 for angles and the experimental kinematic variables used here are defined as: \(-t = -(p_p - p'_p)^2 = \Delta^2\) and \(x_B = \frac{Q^2}{2M_N\nu} \sim \frac{\nu}{1+\xi}\), with \(M_N\) the nucleon mass and \(\nu\) the energy transfer to the target, \(\nu = E - E'\).

### B. Coherent Nuclear DVCS

The first reaction measured in the experiment is the coherent electro-production of a photon on helium \(e + ^4He \rightarrow e' + \gamma + ^4He'\) at large 4-momentum transfer squared \((Q^2)\). The leading order diagram of the nuclear coherent DVCS is represented in Fig. 3. In the present experiment, we focused on the measurement of the BSA noted \(A_{LU}\) with \(L\) for the
longitudinally polarized electron beam and $U$ the unpolarized target, which is defined as:

$$A_{LU} = \frac{d^5\sigma^+ - d^5\sigma^-}{d^5\sigma^+ + d^5\sigma^-}, \quad (4)$$

where $d^5\sigma^+(d^5\sigma^-)$ is the differential cross section for a positive (negative) beam helicity. At leading order and leading twist, the BSA can be expressed as [13]:

$$A_{LU} = \frac{x_A(1 + \epsilon^2)^2}{y} \frac{s_{1\,\text{INT}}}{s_1} \sin(\phi) \left[ \sum_{n=1}^{n=2} c_{n}^{BH} \cos(n\phi) + \frac{x_A^2(1 + \epsilon^2)^2}{Q^2} P_1(\phi) P_2(\phi) c_{0}^{\text{DVCS}} + \frac{x_A(1 + \epsilon^2)^2}{y} \sum_{n=0}^{n=1} c_{n}^{\text{INT}} \cos(n\phi) \right], \quad (5)$$

where $P_1(\phi)$ and $P_2(\phi)$ are the BH propagators, and $x_A = \frac{M_{e} x}{M_{He}}$. The factors: $c_{0,1,2}^{BH}$, $c_{0,1}^{\text{DVCS}}$, $c_{0,1}^{\text{INT}}$ and $s_{1}^{\text{INT}}$ are the Fourier coefficients of the BH, the DVCS and the interference amplitudes for a spin-zero target, respectively. The explicit expressions of these coefficients, which have been derived based on the work of Kirchner and Müller [13], can be found in Appendix A.

This formula can be expressed in a simplified manner for a spin-0 target as [14]:

$$A_{LU}(\phi) = \frac{\alpha_0(\phi) \Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi) \Re e(\mathcal{H}_A) + \alpha_3(\phi) \left( \Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2 \right)}, \quad (6)$$

where $\Im m(\mathcal{H}_A)$ and $\Re e(\mathcal{H}_A)$ are the imaginary and real parts, respectively, of the CFF $\mathcal{H}_A$ associated with the GPD $H_A$ of the spin-0 nucleus. The $\alpha_i$ factors are $\phi$-dependent.
kinematical terms that depend on the nuclear form factor $F_A$ and the independent variables $Q^2$, $x$ and $t$. These factors have the following simplified expressions:

$$
\begin{align*}
\alpha_0(\phi) &= \frac{x_A(1 + \epsilon^2)^2}{y} S_{++}(1) \sin(\phi) \\
\alpha_1(\phi) &= c_0^{BH} + c_1^{BH} \cos(\phi) + c_2^{BH} \cos(2\phi) \\
\alpha_2(\phi) &= \frac{x_A(1 + \epsilon^2)^2}{y} (C_{++}(0) + C_{++}(1) \cos(\phi)) \\
\alpha_3(\phi) &= \frac{x_A^2 t(1 + \epsilon^2)^2}{y} \mathcal{P}_1(\phi) \mathcal{P}_2(\phi) \cdot \frac{2 y^2 - 2y + y^2 + \epsilon^2 y^2}{1 + \epsilon^2},
\end{align*}
$$

where $S_{++}(1)$, $C_{++}(0)$, and $C_{++}(1)$ are the Fourier harmonics found in the leptonic tensor [14]. Their explicit expression are provided in Appendix A.

Eq. 6 is particularly convenient to perform an extraction of $\Im m(H_A)$ and $\Re e(H_A)$ through a fit of the BSA as a function of $\phi$. As can be seen in Fig. 4, the form of each $\alpha$ coefficient has a characteristic $\phi$ dependence, such that a fit can easily separate their respective contributions. The only caveat is the large difference of magnitude between the $\alpha$ factors, which can lead to rather different error propagation for the two parts of the CFF.

An important issue with the use of this theoretical framework is the large mass of the helium nucleus. Recent work indicates that the effect of this correction is moderate [15], however the applicability to such a large mass remains to be fully explored from the theoretical point of view.
FIG. 5: Diagram representing the incoherent nuclear DVCS.

C. Incoherent Nuclear DVCS

The incoherent nuclear DVCS process, is the DVCS off a bound nucleon in a nucleus as represented in Fig. 5 for an helium-4 target. The remnants of the nucleus ($X$) contain only the missing three nucleons. The theory for incoherent DVCS on the nucleon is largely based on the free proton theory already reviewed widely in the literature [6, 7, 9]. Two important differences need to be accounted for however: the different initial state and the addition of FSIs. In the initial state, the intrinsic Fermi motion of the nucleons in the nucleus leads to an uncertainty on the exact kinematics of the reaction. Moreover, in general, the nucleon is in an off-shell state that is not exactly identical to its final state. In the final state, interactions between the outgoing nucleon from the DVCS reaction and the remnants of the nuclear target are possible. The latter leads to contamination from other channels; in particular, charge exchange processes can lead to a large contribution from such background reactions.

Since DVCS is a process selected using tight exclusivity constraints, some of the initial and final-state effects are automatically mitigated. Selection criterion on missing energy and momentum are performed, constraining the range of initial Fermi motion and FSIs possible. However, no theoretical calculation is available to correct for the reminder of these effects yet. Modern calculations exist for such effects in deep inelastic scattering [16] and quasi-elastic scattering [17], and we can expect them to be extended to the DVCS process as more data
become available. Another avenue of progress on this topic will be the use of experimental techniques like tagging. This process can help to control both initial and final state effects by detecting the nuclear remnant. In the tagged process the target breaks in two, thus measuring the nuclear remnant provides information about the initial state of the struck nucleon, while a backward fragment also limits significantly the probability of FSIs.

III. PAST NUCLEAR DVCS MEASUREMENTS

The first measurement of nuclear DVCS was performed by the HERMES Collaboration [10]. This experiment covered an array of nuclear targets and looked at the $A$ dependence of the BSA signal. Their main results, reproduced in Figs. 6 and 7, suffer from large uncertainties, which makes them consistent with the free proton data and prevents us to reach strong conclusions about possible nuclear effects. Yet, in the coherent DVCS case a rather strong effect was expected, leading to a conflict between the HERMES results and theoretical expectations.

An issue with the HERMES measurement and how it is obtained from data has been raised in Ref. [18] to explain the discrepancy with theoretical expectations. The main concern is that the DVCS process is not fully detected and the scattered target is instead reconstructed through a missing mass measurement of the other reaction products. The issue with this method is that the detector resolution is not good enough to separate the coherent and incoherent channels properly. Instead, the results are labeled 'coherent enriched' and 'incoherent enriched' at low and high $-t$, respectively. This label is based on the assumption that the very different behavior of the cross sections of the two channels in $t$ will lead to a clear differentiation. However, the results in Fig. 7 show similar behaviors in both sectors of $t$, which challenges this assumption and could explain the tension between theory and experiment.

Altogether, large error bars and the failure to properly separate the coherent and incoherent channels have strongly impaired the interpretation of the measurement and the conclusions that can be obtained from it. The CLAS experiment presented here has profited largely from this result and was designed specifically to solve these two issues of low statistics and exclusivity.
FIG. 6: The $\sin(\phi)$ moment of the BSA as a function of $-t$ measured by HERMES for a series of nuclei [10]. The gray bands represent the systematic uncertainties.

FIG. 7: The $\sin(\phi)$ moment of the BSA at low and high $-t$ as a function of $A$ measured by HERMES [10]. The inner error bars represent the statistical uncertainty, while the outer represent the quadratic sum of the statistical and systematic uncertainties.
IV. THE CLAS NUCLEAR DVCS EXPERIMENTAL SETUP

The CLAS nuclear DVCS experiment had as its main objectives to explore coherent DVCS on helium-4, to assess if the predicted BSA increase could be observed, and to extract the helium-4 GPD. In order to perform this measurement however, several instrumentation challenges needed to be resolved. First, to measure the scattered electron and the small angle photon from DVCS, we used CLAS in its DVCS setup, i.e. with the addition of a forward angle calorimeter and a 5-T solenoid magnet. Second, a radial time projection chamber (RTPC) was installed to measure the helium recoils and thus ensure the exclusivity of the process in the coherent channel. In this section, we will review the important elements of this detection setup.

A. The CEBAF Large Acceptance Spectrometer (CLAS)

The CLAS [19] spectrometer was installed in Hall B of Jefferson Lab (JLab) continuous electron beam accelerator facility (CEBAF). This detector was specifically designed to study the multi-particles final states that cannot be observed conveniently with multi-arm spectrometers. It was naturally well-suited for measuring DVCS, and several DVCS experiments were successfully conducted before this experiment using multiple different configurations. CLAS was composed of six identical sectors separated by the coils of a toroidal magnet, with each sector made of four detectors as shown in Fig. 8. Three regions of drift chambers [20] were placed between the torus magnet to reconstruct the charged particles’ tracks and calculate their momentum. An array of scintillators was placed behind the drift chambers to measure the precise time-of-flight for each track [21]. These detectors covered the polar angle from 8 to 142 degrees. In the forward region, from 8 to 45 degrees, these detectors were complemented with Cerenkov counters [22] and electromagnetic calorimeters [23], important for electron identification and photon detection.

Altogether, CLAS provided a large acceptance for momenta starting at 200 MeV. The nuclear DVCS experiment took place from October to December 2009 at an electron beam energy of 6.064 GeV, with the beam intensity varying between 120 and 150 nA. This beam, on the helium-4 target pressurized between 5 and 6 atm, corresponds to luminosities in the range of $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$. During the experiment, the data acquisition operated at a
rate of about 3 kHz with about 70% live-time using an inclusive electron trigger.

B. Adaptations for DVCS

The CLAS Collaboration has established a specific setup to measure the typically small angle photons of the DVCS process. This setup is composed of an inner calorimeter and a solenoid and has been employed for numerous DVCS measurements on proton targets [24–26].

The inner calorimeter, illustrated in Fig. 9, is a homogeneous calorimeter composed of 424 lead tungstate (PbWO) crystals read out by $5 \times 5 \text{mm}^2$ avalanche photo-diodes (APDs). It covers angles from 4 to 15 degrees. However, placing a detector at such small angles makes it particularly sensitive to the low energy Moller electrons scattered from the target. To protect the calorimeter from this background, a 5 T solenoid was placed around the target to form a magnetic shield. Thanks to this field, low energy charged particles (particularly electrons) curled around the beamline and never made it to the calorimeter or other CLAS detectors as illustrated by the simulation results presented in Fig. 10. This allows to run much higher luminosity experiments, a necessity for low rate processes like DVCS.
FIG. 9: Representation of the inner calorimeter (IC) of CLAS. The crystals that compose the sensitive part of the detector are represented in purple.

FIG. 10: Representation of the center of CLAS with the beam background in red with and without the solenoid field activated, right and left, respectively.

C. The Radial Time Projection Chamber

The recoil helium nuclei from coherent DVCS are mostly emitted between 150 and 200 MeV at the beam energy of 6 GeV. Therefore, a specific detector was needed to detect them. To design the present setup, inspiration was drawn from the BONUS setup that also used a GEM-based RTPC [27] in CLAS to detect slow protons coming out of a deuterium target [28]. In such an RTPC the ionization electrons drift toward large radii rather than toward the endcaps, as is more traditional in time projection chambers. This design allows to reduce significantly the drift time and reduce the amount of pile-up from accidental events. The
RTPC design, its operation, calibration and the track reconstruction have been described in more details elsewhere [29]. Here a summary of key elements is provided.

In order to detect the recoil helium nuclei from a DVCS reaction, we first need to ensure that it will come out of the target. For this, we used a light straw target made of a thin kapton wall of 27 $\mu$m filled with helium at 6 atm pressure. The entrance and exit windows are thin aluminum foils and an helium bag was placed downstream of the target to avoid interaction with air in the gap between the target and the beamline vacuum. The cylindrical chamber surrounds the target as illustrated in Fig. 11. Here we list the elements composing it based on their radii:

- Up to a radius of 3 mm the pressurized helium target.
- From 3 to 20 mm a keep-out zone filled with 1 atm of helium to minimize the production of secondaries.
- At 20 mm a grounded foil made of 4 $\mu$m aluminized Mylar to isolate the chamber from the beamline region and collect charges. It also serves to separate the gas regions.
- From 20 to 30 mm a dead zone filled with the drift gas to separate the ground from the cathode.
- At 30 mm the cathode foil made of 4 $\mu$m aluminized Mylar.
- From 30 to 60 mm the drift region filled with the drift gas, a mix of neon and dimethyl ether (DME) in an 80/20 proportion.
- From 60 to 69 mm the amplification regions, filled with drift gas, with GEM foils placed at 60, 63 and 66 mm.
- At 69 mm the collection pads connected to the preamplifiers placed directly outside the chamber.

The time-to-position calibration of the detector has been performed with a dependence on $z$, the position along the beamline axis, due to variations in the magnetic fields. To perform this calibration we took dedicated data at 1.2 GeV beam energy. In this data set, we were able to select elastic events, for which the kinematics of the helium recoil can be calculated from the electron kinematics and directly compared to the measurement in the RTPC. This
comparison helped to map the correspondence between time and position in the chamber and determine the drift path of electrons. A more detailed description of the calibration process is available in Ref. [29].

V. DVCS EVENT SELECTION

A. Particle Identification

The scattered electrons were detected with the baseline CLAS detectors. The drift chamber measured the kinematics of the electron and the signal measured in both the Cerenkov counter and electromagnetic calorimeter provided the identification. A signal of good quality was also required in the time-of-flight system, which served as a time reference for all detectors. Protons were detected with the baseline CLAS detectors as well, the drift chamber measured the kinematics of the proton and the time-of-flight system ensured its identification. Several fiducial cuts are applied to ensure that particles did not go through part of the inner calorimeter or the solenoid, as well as to reject the edges of the detectors, where their efficiency is rapidly decreasing. Kinematic corrections are also applied to the electrons and protons to correct for energy loss and biases in calibration, which are at the subpercent level except for protons below 500 MeV for which they go up to 10% at the
detection limit of 200 MeV.

The photons from DVCS are mainly detected with the inner calorimeter. No specific identification cuts were used in this detector as large energy deposit was dominantly from electrons and photons, which could not be separated reliably. However, the detection of an electron at large angle in CLAS highly suppressed the number of electrons in the calorimeter; moreover, the exclusivity cuts used later in the analysis further this suppression. Left-over accidentals were accounted for in the background subtraction described below. The inner calorimeter was calibrated through a series of steps, involving the reconstruction of $\pi^0$ from their decay into two photons. Calibration was obtained with an iterative process to adjust each crystal gain to obtain the most accurate $\pi^0$ mass. A global calibration of the calorimeter was also performed to account for incident angle, energy and time dependent effects.

The helium-4 nuclei were detected with the RTPC using a series of constraints on the quality of the track reconstruction. As the chamber was operated at low gain and had very low efficiency for protons, we did not apply further identification cuts for the helium-4 nuclei detection [29].

Finally, we selected events that contain a single electron, a high energy photon ($E > 2$ GeV) and either a helium or a proton. We applied a selection cut on the two charged particles to ensure they originated from the same vertex inside the target, thus rejecting accidentals and events from the target windows. Moreover, since we are aiming to study deep processes occurring at the partonic level, we selected $Q^2 > 1$ GeV$^2$. Also, the transferred momentum squared to the recoil $^4$He was bound by a minimum value based on basic energy-momentum conservation:

$$t_{\text{min}} = -Q^2 \frac{2(1 - x_A)(1 - \sqrt{1 + \epsilon^2}) + \epsilon^2}{4x_A(1 - x_A) + \epsilon^2},$$

(11)

where $\epsilon^2 = \frac{4M_{^4He}^2x_A^2}{Q^2}$. For incoherent DVCS, we used a similar cut where $x_A$ is replaced by $x$ and $M_{^4He}$ by $M_p$.

**B. Exclusive Photo-Production Selection**

In principle, a selection based only on the missing energy of the system would be enough to guarantee the exclusivity of the process. However, in our experiment, where particles were detected at very different energies and with very different detector resolutions, this
method was not sufficient. For instance the momentum of the helium nuclei is negligible in
the missing energy observable, thus this valuable information has no impact on a selection
using this observable only. To address this issue, we constrained the selection of our exclusive
events by using seven variables selected to optimize the use of all the detector information
available. The seven variables are defined as follows for coherent DVCS case (replace helium
by proton for the incoherent case):

• Co-planarity ($\Delta\phi$) of the virtual photon, the real photon and the recoil helium;

• Missing energy of the complete final state;

• Missing mass of the complete final state;

• Missing transverse momentum of the complete final state;

• Missing mass of the electron-helium system;

• Missing mass of the electron-photon system;

• Co-linearity ($\theta$) of the measured photon with the missing momentum of the electron-
helium system.

In the analysis, we applied selection cuts based on a fit of the exclusive peak at $3\sigma$ around
the mean value for each variable. This systematic method helps to avoid any bias in the
selection of the events. The selection of coherent DVCS with these variables is illustrated in
Fig. 12. We note on these distributions only a few minor anomalies, where the distributions
have some asymmetries. These are linked with the detector resolution, which impact some
of the kinematic variables non-linearly. The selection of incoherent DVCS is presented in
Fig. 13, with two main differences: wider distributions and larger offset from the nominal
expectations. The wider distributions are mainly attributed to the effect of Fermi motion,
but simulations have shown that this effect is not strong enough to fully reproduce the
distribution widths and FSIs must play a role as well. The offsets of some distributions
are caused by slight detector misalignment between CLAS sectors and are within the levels
obtained with free proton targets [26] to which they can be directly compared.
FIG. 12: Distributions of the coherent photon production events before (blue) and after (black line filled in gray) the exclusivity cuts used to select coherent DVCS represented by the red dashed lines. The histograms are shown as a function of the seven variables used for the exclusivity selection described in the text, plus the missing $P_x$ and $P_y$ components, in order left to right and top to bottom.

C. Background Subtraction

The main signal contamination comes from the exclusive production of a $\pi^0$, the final state of which is very similar to DVCS with only an extra photon. In such an event, if one of the photons is produced at low energy, it is easy to confuse this process with single photon production. In order to estimate the contribution from this channel in the data, we measured the exclusive $\pi^0$ production in the same way as DVCS, with a series of exclusivity cuts, completed by a selection cut on the invariant mass of the two photons to match the $\pi^0$ mass. The events obtained for the coherent and incoherent channels are shown in Figs. 14
FIG. 13: Distributions of the incoherent photon production events before (blue) and after (black line filled in gray) the exclusivity cuts used to select coherent DVCS represented by the red dashed lines. The histograms are shown as a function of the seven variables used for the exclusivity selection described in the text, plus the missing $P_x$ and $P_y$ components, in order left to right and top to bottom.

and 15, respectively. Using this sample, we developed an event generator and adjusted it to the data. The result of which is shown with the red histograms of Figs. 14 and 15. To correct the experimental data, we then estimated the number of single photon events coming from the exclusive $\pi^0$ production as:

$$N_{1\gamma,\pi^0}^{Exp} = \frac{N_{1\gamma,\pi^0}^{Sim}}{N_{2\gamma,\pi^0}^{Sim}} \times N_{2\gamma,\pi^0}^{Exp},$$  \hspace{1cm} (12)$$

where $N_{1\gamma,\pi^0}^{Sim}$ is the number of simulated exclusive $\pi^0$ mistaken for DVCS events, $N_{2\gamma,\pi^0}^{Sim}$ the number of simulated exclusive $\pi^0$ fully reconstructed and $N_{2\gamma,\pi^0}^{Exp}$ the number of experimentally
measured exclusive $\pi^0$. This number was then subtracted from the experimentally measured number of DVCS events ($N^{Exp}_{DVCS}$) to get the corrected result:

$$N^{Corr}_{DVCS} = N^{Exp}_{DVCS} - N^{Exp}_{1\gamma,\pi^0}. \quad (13)$$

We show in Fig. 16 the $\pi^0$ contamination for the $-t$ bins, where it varies the most from one bin to another. The study shows 2 to 4% contamination in the coherent channel and 3 to 17% in the incoherent channel. After subtracting this contamination from the denominator of the asymmetry, we make no further correction to the DVCS BSA, \textit{i.e.}, we assume the exclusive $\pi^0$ production has no such asymmetry in either the coherent or incoherent channels. Our own exclusive $\pi^0$ data rules out any BSA above approximately 10%, a level which would have an insignificant effect on our results given the small amount of contamination.

The second important source of background comes from accidentals. Despite the many exclusivity cuts, it is possible to have particles from different events being combined and pass all the cuts to get into the data sample. To evaluate the number of such events, we inverted the vertex selection of the two charged particles of the process, electron and helium (or proton in the incoherent case), and requested that they are separate. We found that 4.1% of the coherent and 6.5% of the incoherent samples were accidentals, they are also subtracted from the denominator of the asymmetry.

D. Systematic Uncertainties

To further evaluate the systematic uncertainty of the measurements, we performed several specialized studies. We evaluated the impact of changing the exclusivity selection cuts by varying them from 1 to $5 \sigma$. We also evaluated the impact of changing the binning in $\phi$ on the extraction of the BSA at $90^\circ$. The beam polarization was measured using Møller scattering runs, the uncertainty was estimated based on the known precision of the dedicated apparatus and the spread of the measurements during the complete run period. We studied how different methods of simulating the exclusive $\pi^0$ production affected the single-photon background and further estimated how much bias could arise from an undetected BSA in the process. As radiative corrections are expected to be small for this process, we did not apply them, but associated an uncertainty equal to their expected value. These uncertainties are
FIG. 14: The measured (filled blue) and simulated (red) distributions of coherent exclusive $\pi^0$ production as a function of $x$, $Q^2$, $-t$ and $\phi$.

FIG. 15: The measured (filled blue) and simulated (red) distributions of incoherent exclusive $\pi^0$ production as a function of $x$, $Q^2$, $-t$ and $\phi$. 
FIG. 16: The estimated coherent (left) and incoherent (right) $\pi^0$ contamination fraction in the DVCS events as a function of the transferred momentum squared $-t$ and integrated over the kinematic variables $Q^2$, $x_B$, and $\phi$.

| Systematic source               | Coherent channel | Incoherent channel | Type of systematic error |
|--------------------------------|------------------|--------------------|--------------------------|
| Beam polarization              | 3.5%             | 3.5%               | Normalization            |
| DVCS cuts                      | 8%               | 6%                 | Bin to bin               |
| Data binning                   | 5.1%             | 7.1%               | Bin to bin               |
| $\pi^0$ subtraction            | 0.6%             | 2.0%               | Bin to bin               |
| Radiative corrections          | 0.1%             | 0.1%               | Bin to bin               |
| **Total bin to bin**           | **10.1%**        | **10.1%**          | **Bin to bin**           |

TABLE I: The systematic uncertainties on the measured coherent and incoherent BSAs at $\phi = 90^\circ$.

summarized in Tab. I, with their respective evaluated values. They are added quadratically to obtain the total systematic uncertainty presented in the results.

An extra problem that was studied is the best way to define $t$ in the incoherent channel, which is not completely straightforward. As can be seen in Fig. 5, we can either use $t$ or $t'$ ($= (p - p')^2$). In principle, the two are identical, but experimentally we face some issues. The measurement of $t$ is less precise than $t'$ because it involves the photon rather than charged particles. However, the exact measurement of $t'$ is impossible and one needs to assume a proton at rest in the initial state to calculate $t'$. As it is not obvious which solution is best, we studied the difference between the two results by analyzing the data independently using the two definitions. We found no significant difference between them, as is illustrated in Fig. 17. We use in the final results $t$ as it is based on the rigorous definition. Since the effect of resolution appears small and is partly accounted for in the systematic uncertainty associated to the DVCS cuts, we decided not to associate an extra systematic uncertainty based on this
VI. RESULTS

A. Coherent DVCS

In Fig. 18, we present the results for the BSA in the coherent DVCS channel. We observe the dominant sinusoidal component typical of the DVCS BSA, with an amplitude almost double that measured for the free proton [25]. This predicted feature of nuclear DVCS [18] is observed here for the first time, due to the fact that this measurement cleanly isolates the coherent DVCS process. The absence of this feature in the previous measurement by HERMES [10] and its clear observation here indicates that the recoil detection is necessary to isolate the effects of the coherent DVCS process from the incoherent background.

We show the extraction of the BSA at 90° in Fig. 19 together with the past HERMES Collaboration results [10]. Two models are compared to the data, they are both based on the hypothesis that the main nuclear effects are included by accounting for the nucleon off-shellness and the kinematics of nucleons in nuclei. The one by Liuti et al. [30, 31] appears to undershoot the results systematically. However, the more recent and independent calculation by Fucini et al. [32], using similar principles but with a non-diagonal nuclear spectral function [33] based on the AV18 nucleon-nucleon potential [34] and the UIV three-body forces [35], has been able to reproduce the data very well. A factor in the difference is that the recent calculation by Fucini et al. [32] benefited from using the precise kinematics of each of the
points presented in Appendix B. Including this information appears to have a significant impact on some points, for instance the $-t$ distribution appears to have a peculiar structure that is well reproduced when using this information.

One of the motivations for the choice of helium-4 for the coherent DVCS measurement was a simplified extraction of the CFF $\mathcal{H}_A$ from the data. To perform this step, we used the form from Eq. 6 to fit the data in Fig. 18. We present in Fig. 20 the extracted real and imaginary parts of the single CFF of the helium-4 nucleus. The results are rather encouraging. The two parts of the CFF are constrained by data without the need for any model assumption. This capacity to obtain a model independent result with such a limited data set offers a striking contrast with the situation of the free proton fits [36, 37].

The CFF extraction allows us to compare the results to other theoretical calculations. These are performed within the impulse approximation [18, 38] and give the nuclear GPD directly from the proton and neutron GPDs. In Fig. 20, we show two versions of this

![Image of graphs showing data and fits](image-url)

**FIG. 18:** The BSA in the coherent exclusive photo-production off helium-4 as a function of $\phi$ and $Q^2$ (top panels), $x$ (middle panels) and $-t$ (lower panels). The error bars are statistical and the gray bands represent the systematic uncertainties. The full red lines show the fit of the data with the form of Eq. 6.
FIG. 19: The BSA at 90° as a function of $Q^2$ (top panel), $x$ (middle panel) and $-t$ (lower panel). Our results are shown with black squares, HERMES results with green circles [10]. The theoretical prediction by Liuti et al. [30, 31] is shown by the full blue line, while the calculation by Fucini et al. [32] is shown with the magenta dashed line.

FIG. 20: The imaginary (top panels) and real (bottom panels) parts of the helium-4 CFF $H_A$ as a function of $Q^2$ (left panels), $x$ (middle panels) and $-t$ (right panels). The red full line is the theoretical calculation by Guzey et al. [18, 38], the black dashed line is the same calculation using the VGG model as input [39, 40], and the blue long dashed line shows the predictions by Liuti et al. [30, 31].

calculation, where two different nucleon GPD models are used as input, compared with the calculation previously shown by Liuti et al. [30] with an updated nucleon model [31]. We can see that the effect of changing the input nucleon GPD model is of similar size or larger than the difference between the nuclear models. However, at the level of precision of the present data, it is not possible to resolve which variant is best. This feature highlights the
importance of the choice of nucleon model to study nuclear effects with this data.

In summary, this measurement of the BSA in the deeply virtual coherent exclusive photo-production on a nucleus is the first to clearly isolate the effect of coherent nuclear DVCS and of nuclear GPDs. While the statistical precision and the kinematic coverage are still behind the experimental results of the proton, the results appear to match very well the predictions using the GPD framework. Moreover, the extraction of the CFF appears to be very convenient based on the BSA measurement only. Together, these findings validate the relevance of coherent nuclear DVCS to study the nucleus globally in terms of quarks and gluons.

![Graphical representation](image)

**FIG. 21:** The BSA in the incoherent exclusive photo-production off a proton bound in helium-4 as a function of $\phi$ and $Q^2$ (top panels), $x$ (middle panels) and $-t$ (lower panels). The error bars are statistical and the gray bands represent the systematic uncertainties. The data is fitted with the form $\frac{\alpha \sin(\phi)}{1 + \beta \cos(\phi)}$; the results of the fits are drawn with black full lines.
The results for the measurement of the BSA in the incoherent DVCS channel are presented in Fig. 21. They display patterns rather similar to those observed with the free proton, with a clear domination of their sinusoidal component. To compare the data to models, we extract the BSA at 90° with a fit of the form \( \frac{\alpha \sin(\phi)}{1 + \beta \cos(\phi)} \).

The asymmetries at 90° are presented in Fig. 22 together with the theoretical calculation by the same groups as presented in Fig. 19. We observe a significant improvement on the precision compared to the HERMES data, which offers more constraint on the models presented. As in the coherent case, the calculation appears to have issues reproducing the shape of the data, with Fucini et al. [41] doing better than the others. However, this time the calculations overshoot the data, sometimes by a significant amount.

An interesting way to look into this data is to show the result on incoherent nuclear DVCS compared with the free proton one. We can for instance make a ratio, in a fashion similar to the EMC effect, which allows to cancel out the effects from the nucleon structure and highlight nuclear effects. Such a ratio is presented in Fig. 23. Notably, the calculation by Fucini et al. [41] appears closer than the others with this observable. This feature indicates that the different raw asymmetry results might be linked to the different input model used for the free nucleon GPD rather than to differences in the treatment of the nuclear effects. Also, Fucini et al. appear to roughly reproduce the shape of the \( x_B \) distribution, which might indicate that it is linked to correlations between kinematic variables. In conclusion, the BSA in the incoherent DVCS channel is suppressed by 20 to 30% compared to the free proton, which was not expected by most models.

The explanation for this surprising behavior can come from different sources both in the initial state and in the final state. Further work is needed to fully comprehend this newly discovered nuclear effect. On the experimental side, the use of tagging methods, where the nuclear fragments are measured appear to offer the best option forward. Indeed, tagging offers the best chance to understand better this result by offering better control over both the initial and the final state effects [2].
FIG. 22: The BSA at 90° as a function of $Q^2$ (top left), $x$ (top right) and $-t$ (bottom). Our measurement is represented with black squares and the HERMES measurement [10] with green circles. The theoretical prediction by Liuti et al. [30, 31] is shown by the full blue line, while the calculation by Fucini et al. [41] is shown with the magenta dashed line.

VII. SUMMARY

We report the measurement of the coherent and incoherent DVCS processes off helium-4 with CLAS at JLab. To properly isolate the coherent channel, the experiment used a specially designed RTPC to detect the scattered helium-4. This coherent DVCS measurement reveals the large BSA ($\sim 35\%$) expected by theoretical calculations made in the impulse approximation. Moreover, we showed that the CFF extraction can be immediately performed using these data without any model assumptions. The incoherent DVCS measurement however reveals relatively small asymmetries in comparison to previous free proton measurements. The source of this suppression of the BSA remains unclear as both initial and final state effect contributions could lead to such outcome. We presented various models for both channels. While old and recent work agree nicely with the data from the coherent channel, it appears more difficult to reproduce the incoherent DVCS data. A future experimental program using
FIG. 23: DVCS BSA ratio of the bound proton to the free proton as a function of $Q^2$ (top left), $x$ (top right) and $-t$ (bottom). The present measurement is represented with black squares and the HERMES measurement [10] with green circles. The theoretical prediction by Liuti et al. [30, 31] is shown by the full blue line, the calculation by Fucini et al. [41] is shown with the magenta dashed line, and the black dot-dashed line is the calculation by Guzey et al. [38].

VIII. ACKNOWLEDGMENTS

The authors acknowledge the staff of the Accelerator and Physics Divisions at the Thomas Jefferson National Accelerator Facility who made this experiment possible. This work was supported in part by the Chilean Comisión Nacional de Investigación Científica y Tecnológica (CONICYT), by CONICYT PIA grant ACT1413, the Italian Instituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique, the French Commissariat à l’Energie Atomique, the U.S. Department of Energy under Contract No. DE-AC02-06CH11357, the United Kingdom Science and Technology Facilities Council (STFC), the Scottish Universities Physics Alliance (SUPA), the National Research Foundation of Korea,
and the Office of Research and Economic Development at Mississippi State University. M. Hattawy also acknowledges the support of the Consulat Général de France à Jérusalem. This work has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (Grant agreement No. 804480). The Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under Contract No. DE-AC05-06OR23177.

[1] M. Anselmino, M. Guidal, P. Rossi, et al. Topical issue on the 3-D structure of the nucleon. *Eur. Phys. J.*, A52:164, 2016.

[2] R. Dupré and S. Scopetta. 3D Structure and Nuclear Targets. *Eur. Phys. J.*, A52(6):159, 2016.

[3] P. R. Norton. The EMC effect. *Rept. Prog. Phys.*, 66:1253, 2003.

[4] S. Malace, D. Gaskell, D. W. Higinbotham, and I. Cloet. The Challenge of the EMC Effect: existing data and future directions. *Int. J. Mod. Phys.*, E23(08):1430013, 2014.

[5] O. Hen, G. A. Miller, E. Piasetzky, and L. B. Weinstein. Nucleon-Nucleon Correlations, Short-lived Excitations, and the Quarks Within. *Rev. Mod. Phys.*, 89(4):045002, 2017.

[6] M. Diehl. Generalized parton distributions. *Phys. Rept.*, 388:41, 2003.

[7] A. V. Belitsky and A. V. Radyushkin. Unraveling hadron structure with generalized parton distributions. *Phys. Rept.*, 418:1, 2005.

[8] S. Boffi and B. Pasquini. Generalized parton distributions and the structure of the nucleon. *Riv. Nuovo Cim.*, 30:387, 2007.

[9] M. Guidal, H. Moutarde, and M. Vanderhaeghen. Generalized Parton Distributions in the valence region from Deeply Virtual Compton Scattering. *Rept. Prog. Phys.*, 76:066202, 2013.

[10] A. Airapetian et al. Nuclear-mass dependence of azimuthal beam-helicity and beam-charge asymmetries in deeply virtual Compton scattering. *Phys. Rev.*, C81:035202, 2010.

[11] M. Hattawy et al. First Exclusive Measurement of Deeply Virtual Compton Scattering off $^4$He: Toward the 3D Tomography of Nuclei. *Phys. Rev. Lett.*, 119(20):202004, 2017.

[12] M. Hattawy et al. Deeply Virtual Compton Scattering measurement off bound protons. *Phys. Rev. Lett.*, 123(3):032502, 2019.

[13] A. Kirchner and D. Müller. Deeply virtual Compton scattering off nuclei. *Eur. Phys. J.*, 32
[14] A. V. Belitsky and D. Müller. Refined analysis of photon leptoproduction off spinless target. 
Phys. Rev., D79:014017, 2009.

[15] V. M. Braun, A. N. Manashov, and B. Pirnay. Finite-t and target mass corrections to DVCS 
on a scalar target. Phys. Rev., D86:014003, 2012.

[16] W. Cosyn and M. Sargsian. Nuclear final-state interactions in deep inelastic scattering off the 
lightest nuclei. Int. J. Mod. Phys., E26(09):1730004, 2017.

[17] J.J. Ethier, N. Doshi, S. Malace, and W. Melnitchouk. Quasielastic electron-deuteron scattering 
in the weak binding approximation. Phys. Rev. C, 89:065203, 2014.

[18] V. Guzey and M. Strikman. DVCS on spinless nuclear targets in impulse approximation. Phys. 
Rev., C68:015204, 2003.

[19] B.A. Mecking et al. The CEBAF Large Acceptance Spectrometer (CLAS). Nucl. Instrum. 
Meth., A503:513, 2003.

[20] M.D. Mestayer et al. The CLAS drift chamber system. Nucl. Instrum. Meth., A449:81, 2000.

[21] E.S. Smith et al. The time-of-flight system for CLAS. Nucl. Instrum. Meth., A432:265, 1999.

[22] G. Adams et al. The CLAS Cherenkov detector. Nucl. Instrum. Meth., A465:414, 2001.

[23] M. Amarian et al. The CLAS forward electromagnetic calorimeter. Nucl. Instrum. Meth., 
A460:239–265, 2001.

[24] E. Seder et al. Longitudinal target-spin asymmetries for deeply virtual Compton scattering. 
Phys. Rev. Lett., 114(3):032001, 2015. [Addendum: Phys. Rev. Lett.114,no.8,089901(2015)].

[25] 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.

[26] N. Hirlinger Saylor et al. Measurement of Unpolarized and Polarized Cross Sections for Deeply 
Virtual Compton Scattering on the Proton at Jefferson Laboratory with CLAS. Phys. Rev., 
C98(4):045203, 2018.

[27] H. C. Fenker et al. BoNuS: Development and Use of a Radial TPC using Cylindrical GEMs. 
Nucl. Instrum. Meth., A592:273, 2008.

[28] N. Baillie et al. Measurement of the neutron F2 structure function via spectator tagging with 
CLAS. Phys. Rev. Lett., 108:142001, 2012. [Erratum: Phys. Rev. Lett.108,199902(2012)].

[29] R. Dupré et al. A radial time projection chamber for α detection in CLAS at JLab. Nucl. 
Instrum. Meth., A898:90, 2018.
[30] S. Liuti and S. K. Taneja. Microscopic description of deeply virtual Compton scattering off spin-0 nuclei. *Phys. Rev.*, C72:032201, 2005.

[31] J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein, and K. Kathuria. Interpretation of the Flavor Dependence of Nucleon Form Factors in a Generalized Parton Distribution Model. *Phys. Rev.*, C88(6):065206, 2013.

[32] S. Fucini, S. Scopetta, and M. Viviani. Coherent deeply virtual Compton scattering off $^4$He. *Phys. Rev.*, C98(1):015203, 2018.

[33] M. Viviani, A. Kievsky, and A. Rinat. GRS computation of deep inelastic electron scattering on He-4. *Phys. Rev. C*, 67:034003, 2003.

[34] R. B. Wiringa, V.G.J. Stoks, and R. Schiavilla. An Accurate nucleon-nucleon potential with charge independence breaking. *Phys. Rev. C*, 51:38–51, 1995.

[35] B.S. Pudliner, V.R. Pandharipande, J. Carlson, and R. B. Wiringa. Quantum Monte Carlo calculations of $A \leq 6$ nuclei. *Phys. Rev. Lett.*, 74:4396–4399, 1995.

[36] R. Dupré, M. Guidal, and M. Vanderhaeghen. Tomographic image of the proton. *Phys. Rev.*, D95(1):011501, 2017.

[37] R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen. Analysis of Deeply Virtual Compton Scattering Data at Jefferson Lab and Proton Tomography. *Eur. Phys. J.*, A53(8):171, 2017.

[38] V. Guzey. Neutron contribution to nuclear DVCS asymmetries. *Phys. Rev.*, C78:025211, 2008.

[39] M. Vanderhaeghen, P. A. M. Guichon, and M. Guidal. Deeply virtual electroproduction of photons and mesons on the nucleon: Leading order amplitudes and power corrections. *Phys. Rev.*, D60:094017, 1999.

[40] M. Guidal, M. V. Polyakov, A. V. Radyushkin, and M. Vanderhaeghen. Nucleon form-factors from generalized parton distributions. *Phys. Rev.*, D72:054013, 2005.

[41] S. Fucini, S. Scopetta, and M. Viviani. Catching a glimpse of the parton structure of the bound proton. *Phys. Rev. D*, 101(7):071501, 2020.

[42] W. R. Armstrong et al. Spectator-Tagged Deeply Virtual Compton Scattering on Light Nuclei. *A proposal to PAC 45*, 2017.
Appendix A: Expressions for the BSA of the Coherent DVCS

We present in this appendix the detailed expressions used for Eq. 5 and Eqs. 7 to 10. These are adapted from the work of Kirchner and Müller [13] to match the notations and conventions used in this work.

First, $P_1(\phi)$ and $P_2(\phi)$ are BH propagators and defined as:

$$P_1(\phi) = \frac{(k - q')^2}{Q^2} = -\frac{1}{y(1 + \epsilon^2)} \left[ J + 2K \cos(\phi) \right]$$  \hspace{1cm} (A1)

$$P_2(\phi) = \frac{(k - \Delta)^2}{Q^2} = 1 + \frac{t}{Q^2} + \frac{1}{y(1 + \epsilon^2)} \left[ J + 2K \cos(\phi) \right]$$  \hspace{1cm} (A2)

with,

$$J = \left( 1 - y - \frac{y^2}{2} \right) \left( 1 + \frac{t}{Q^2} \right) - (1 - x_A)(2 - y) \frac{t}{Q^2}$$  \hspace{1cm} (A3)

$$K^2 = -\delta t \left( 1 - x_A \right) \left( 1 - y - \frac{y^2 \epsilon^2}{4} \right) \left\{ \sqrt{1 + \epsilon^2} + \frac{4x_A(1 - x_A) + \epsilon^2}{4(1 - x_A)} \delta t \right\}$$  \hspace{1cm} (A4)

$$\delta t = \frac{t - t_{min}}{Q^2} = \frac{2(1 - x_A) \left( 1 - \sqrt{1 + \epsilon^2} \right) + \epsilon^2}{4x_A(1 - x_A) + \epsilon^2}.$$  \hspace{1cm} (A5)

The Fourier coefficients for BH contributions are defined as:

$$c^B_0 = \left[ \left\{ (2 - y)^2 + y^2(1 + \epsilon^2)^2 \right\} \left\{ \frac{\epsilon^2 Q^2}{t} + 4(1 - x_A) + (4x_A + \epsilon^2) \frac{t}{Q^2} \right\} \right.$$

$$+ 2\epsilon^2 \left\{ 4(1 - y)(3 + 2\epsilon^2) + y^2(2 - \epsilon^4) \right\} - 4x_A^2(2 - y)^2(2 + \epsilon^2) \frac{t}{Q^2}$$

$$+ 8K^2 \epsilon^2 \frac{Q^2}{t} F_A^2(t) \right] F_A^2(t)$$  \hspace{1cm} (A6)

$$c^B_1 = -8(2 - y)K \left\{ 2x_A + \epsilon^2 - \frac{\epsilon^2 Q^2}{t} \right\} F_A^2(t)$$  \hspace{1cm} (A7)

$$c^B_2 = 8K^2 \epsilon^2 \frac{Q^2}{t} F_A^2(t),$$  \hspace{1cm} (A8)

where $F_A(t)$ is the electromagnetic form factor of $^4$He. The coefficient for the DVCS contribution is given by:

$$c^D_{DVCS} = \frac{2 - 2y + y^2 + \frac{\epsilon^2 y^2}{2}}{1 + \epsilon^2} \mathcal{H}_A \mathcal{H}^*_A.$$  \hspace{1cm} (A9)
Finally, the interference amplitude coefficients are written as:

\[ s_1^{\text{INT}} = F_A(t) Im(\mathcal{H}_A) S_{++}(1), \quad (A10) \]

with

\[ S_{++}(1) = \frac{-8K(2-y)y}{1+\epsilon^2} \left( 1 + \frac{1 - x_A + \frac{\sqrt{1+\epsilon^2} - 1}{2} \frac{t - t_{min}}{Q^2}}{1 + \epsilon^2} \right) \quad (A11) \]

\[ c_0^{\text{INT}} = F_A(t) \Re(\mathcal{H}_A) C_{++}(0), \quad (A12) \]

with

\[ C_{++}(0) = \frac{-4(2-y)(1 + \sqrt{1+\epsilon^2})}{(1+\epsilon^2)^2} \left\{ \frac{\bar{K}^2 (2-y)^2}{Q^2 \sqrt{1+\epsilon^2}} \right\} \]
\[ + \frac{t}{Q^2} \left( 1 - y - \frac{\epsilon^2}{4} y^2 \right) (2 - x_A) \left( 1 + \frac{2x_A(2 - x_A + \frac{\sqrt{1+\epsilon^2} - 1}{2} + \frac{\epsilon^2}{2x_A} \frac{t}{Q^2} + \epsilon^2)}{(2 - x_A)(1 + \sqrt{1+\epsilon^2})} \right) \quad (A13) \]

\[ c_1^{\text{INT}} = F_A(t) \Re(\mathcal{H}_A) C_{++}(1), \quad (A14) \]

with

\[ C_{++}(1) = \frac{-16K(1 - y + \frac{\epsilon^2}{4} y^2)}{(1+\epsilon^2)^{5/2}} \left\{ \left( 1 + (1 - x_A) \frac{\sqrt{1+\epsilon^2} - 1}{2x_A} + \frac{\epsilon^2}{4x_A} \right) \frac{x_A t}{Q^2} - \frac{3\epsilon^2}{4.0} \right\} \]
\[ - 4K \left( 2 - 2y + \frac{\epsilon^2}{2} y^2 \right) \frac{1 + \sqrt{1+\epsilon^2} - \epsilon^2}{(1+\epsilon^2)^{5/2}} \left\{ 1 - (1 - 3x_A) \frac{t}{Q^2} + \frac{1 - \sqrt{1+\epsilon^2} + 3\epsilon^2 x_A t}{1 + \sqrt{1+\epsilon^2} - \epsilon^2 \frac{Q^2}{Q^2}} \right\} \quad (A15) \]

Appendix B: Tables of Results with Kinematics Information
| $(Q^2)$ (GeV$^2$) | $(x_B)$ | $(-t)$ (GeV$^2$) | $\langle \phi \rangle$ (degree) | $A_{LU}$ ± stat. ± syst. |
|---|---|---|---|---|
| 1.14 | 0.136 | 0.096 | 24 | 0.133 ± 0.109 ± 0.026 |
| | | | 61 | 0.321 ± 0.093 ± 0.019 |
| | | | 99 | 0.371 ± 0.103 ± 0.040 |
| | | | 141 | 0.245 ± 0.152 ± 0.027 |
| | | | 178 | 0.023 ± 0.163 ± 0.028 |
| | | | 219 | -0.053 ± 0.148 ± 0.025 |
| | | | 263 | -0.264 ± 0.120 ± 0.039 |
| | | | 302 | -0.176 ± 0.097 ± 0.026 |
| | | | 338 | -0.279 ± 0.105 ± 0.034 |
| 1.42 | 0.172 | 0.099 | 21 | 0.192 ± 0.089 ± 0.027 |
| | | | 57 | 0.282 ± 0.087 ± 0.025 |
| | | | 97 | 0.486 ± 0.129 ± 0.043 |
| | | | 140 | 0.100 ± 0.168 ± 0.025 |
| | | | 180 | 0.146 ± 0.191 ± 0.030 |
| | | | 219 | -0.111 ± 0.185 ± 0.034 |
| | | | 263 | -0.352 ± 0.137 ± 0.037 |
| | | | 302 | -0.414 ± 0.084 ± 0.038 |
| | | | 338 | -0.279 ± 0.084 ± 0.026 |
| 1.90 | 0.224 | 0.107 | 21.4 | 0.180 ± 0.081 ± 0.023 |
| | | | 57.2 | 0.350 ± 0.082 ± 0.019 |
| | | | 96.2 | 0.270 ± 0.123 ± 0.017 |
| | | | 139.5 | 0.305 ± 0.239 ± 0.017 |
| | | | 178.2 | 0.103 ± 0.267 ± 0.013 |
| | | | 221.4 | -0.212 ± 0.215 ± 0.015 |
| | | | 263.3 | -0.306 ± 0.131 ± 0.026 |
| | | | 303.3 | -0.138 ± 0.094 ± 0.021 |
| | | | 338.5 | -0.163 ± 0.079 ± 0.016 |

**TABLE II:** Values of the coherent $A_{LU}$ in $Q^2$ bins from Fig. 18.
| \(Q^2\) (GeV\(^2\)) | \(x_B\) | \(-t\) (GeV\(^2\)) | \(\phi\) (degree) | \(A_{LU}\) ± stat. ± syst. |
|---|---|---|---|---|
| 1.16 | 0.132 | 0.095 | 26 | \(0.017 \pm 0.144 \pm 0.022\) |
| | | | 62 | \(0.348 \pm 0.087 \pm 0.020\) |
| | | | 99 | \(0.381 \pm 0.095 \pm 0.041\) |
| | | | 142 | \(0.294 \pm 0.138 \pm 0.033\) |
| | | | 178 | \(0.043 \pm 0.152 \pm 0.029\) |
| | | | 219 | \(-0.035 \pm 0.132 \pm 0.024\) |
| | | | 263 | \(-0.277 \pm 0.105 \pm 0.037\) |
| | | | 301 | \(-0.214 \pm 0.084 \pm 0.026\) |
| | | | 335 | \(-0.234 \pm 0.122 \pm 0.032\) |
| | | | 23 | \(0.158 \pm 0.085 \pm 0.023\) |
| | | | 57 | \(0.173 \pm 0.088 \pm 0.020\) |
| | | | 96 | \(0.226 \pm 0.133 \pm 0.030\) |
| | | | 139 | \(0.245 \pm 0.176 \pm 0.019\) |
| | | | 180 | \(-0.102 \pm 0.192 \pm 0.020\) |
| | | | 219 | \(-0.288 \pm 0.191 \pm 0.027\) |
| | | | 264 | \(-0.294 \pm 0.136 \pm 0.029\) |
| | | | 303 | \(-0.398 \pm 0.092 \pm 0.033\) |
| | | | 338 | \(-0.269 \pm 0.083 \pm 0.025\) |
| 1.44 | 0.170 | 0.099 | 23 | \(0.158 \pm 0.085 \pm 0.023\) |
| | | | 57 | \(0.173 \pm 0.088 \pm 0.020\) |
| | | | 96 | \(0.226 \pm 0.133 \pm 0.030\) |
| | | | 139 | \(0.245 \pm 0.176 \pm 0.019\) |
| | | | 180 | \(-0.102 \pm 0.192 \pm 0.020\) |
| | | | 219 | \(-0.288 \pm 0.191 \pm 0.027\) |
| | | | 264 | \(-0.294 \pm 0.136 \pm 0.029\) |
| | | | 303 | \(-0.398 \pm 0.092 \pm 0.033\) |
| | | | 338 | \(-0.269 \pm 0.083 \pm 0.025\) |
| 1.84 | 0.225 | 0.107 | 20 | \(0.263 \pm 0.076 \pm 0.025\) |
| | | | 56 | \(0.428 \pm 0.089 \pm 0.022\) |
| | | | 96 | \(0.493 \pm 0.139 \pm 0.027\) |
| | | | 138 | \(-0.274 \pm 0.280 \pm 0.017\) |
| | | | 180 | \(0.847 \pm 0.250 \pm 0.020\) |
| | | | 225 | \(-0.051 \pm 0.281 \pm 0.027\) |
| | | | 263 | \(-0.342 \pm 0.169 \pm 0.035\) |
| | | | 305 | \(-0.136 \pm 0.103 \pm 0.026\) |
| | | | 340 | \(-0.166 \pm 0.077 \pm 0.018\) |

**TABLE III:** Values of the coherent \(A_{LU}\) in \(x_B\) bins from Fig. 18.
\[
\begin{array}{c|c|c|c|c}
(Q^2) & (x_B) & (-t) & (\phi) & A_{LU} \pm \text{stat.} \pm \text{syst.} \\
(\text{GeV}^2) & & (\text{GeV}^2) & (\text{degree}) & \\
\hline
1.36 & 0.160 & 0.080 & 23 & 0.238 \pm 0.093 \pm 0.026 \\
& & & 58 & 0.301 \pm 0.087 \pm 0.024 \\
& & & 98 & 0.490 \pm 0.112 \pm 0.039 \\
& & & 139 & 0.197 \pm 0.160 \pm 0.025 \\
& & & 179 & 0.058 \pm 0.192 \pm 0.037 \\
& & & 223 & -0.165 \pm 0.164 \pm 0.037 \\
& & & 266 & -0.347 \pm 0.134 \pm 0.040 \\
& & & 300 & -0.289 \pm 0.093 \pm 0.029 \\
& & & 339 & -0.185 \pm 0.086 \pm 0.028 \\
& 1.51 & 0.179 & 0.094 & 21 & 0.248 \pm 0.093 \pm 0.027 \\
& & & 56 & 0.339 \pm 0.083 \pm 0.028 \\
& & & 98 & 0.347 \pm 0.116 \pm 0.031 \\
& & & 142 & 0.146 \pm 0.189 \pm 0.022 \\
& & & 180 & -0.281 \pm 0.186 \pm 0.036 \\
& & & 219 & 0.210 \pm 0.200 \pm 0.015 \\
& & & 263 & -0.240 \pm 0.128 \pm 0.028 \\
& & & 304 & -0.199 \pm 0.096 \pm 0.029 \\
& & & 339 & -0.210 \pm 0.088 \pm 0.020 \\
& 1.61 & 0.193 & 0.127 & 22 & 0.028 \pm 0.091 \pm 0.021 \\
& & & 61 & 0.358 \pm 0.093 \pm 0.020 \\
& & & 97 & 0.256 \pm 0.127 \pm 0.031 \\
& & & 140 & 0.221 \pm 0.193 \pm 0.020 \\
& & & 179 & 0.514 \pm 0.183 \pm 0.035 \\
& & & 218 & -0.247 \pm 0.166 \pm 0.019 \\
& & & 261 & -0.292 \pm 0.130 \pm 0.033 \\
& & & 303 & -0.249 \pm 0.089 \pm 0.028 \\
& & & 337 & -0.283 \pm 0.090 \pm 0.026 \\
\end{array}
\]

TABLE IV: Values of the coherent $A_{LU}$ in $-t$ bins from Fig. 18.
| $(Q^2)$ (GeV$^2$) | $\langle x_B \rangle$ | $\langle -t \rangle$ (GeV$^2$) | $\langle \phi \rangle$ (degree) | $A_{LU} \pm$ stat. $\pm$ syst. |
|---|---|---|---|---|
| 1.40 | 0.166 | 0.376 | 21 | 0.054 ± 0.044 ± 0.012 |
| | | | 63 | 0.077 ± 0.046 ± 0.016 |
| | | | 95 | 0.191 ± 0.047 ± 0.026 |
| | | | 140 | 0.108 ± 0.056 ± 0.016 |
| | | | 182 | 0.045 ± 0.069 ± 0.023 |
| | | | 220 | -0.029 ± 0.068 ± 0.015 |
| | | | 258 | -0.126 ± 0.046 ± 0.023 |
| | | | 303 | -0.124 ± 0.040 ± 0.020 |
| | | | 337 | -0.012 ± 0.054 ± 0.014 |
| 1.89 | 0.232 | 0.415 | 20 | 0.014 ± 0.036 ± 0.012 |
| | | | 61 | 0.067 ± 0.046 ± 0.017 |
| | | | 96 | 0.130 ± 0.052 ± 0.020 |
| | | | 141 | 0.165 ± 0.077 ± 0.029 |
| | | | 180 | 0.159 ± 0.089 ± 0.015 |
| | | | 222 | -0.259 ± 0.081 ± 0.043 |
| | | | 260 | -0.128 ± 0.056 ± 0.018 |
| | | | 304 | -0.176 ± 0.039 ± 0.020 |
| | | | 338 | -0.030 ± 0.045 ± 0.011 |
| 2.34 | 0.288 | 0.497 | 21 | 0.074 ± 0.033 ± 0.014 |
| | | | 58 | 0.136 ± 0.046 ± 0.010 |
| | | | 95 | 0.184 ± 0.057 ± 0.018 |
| | | | 141 | -0.018 ± 0.101 ± 0.016 |
| | | | 182 | 0.092 ± 0.133 ± 0.024 |
| | | | 225 | -0.075 ± 0.107 ± 0.021 |
| | | | 261 | -0.244 ± 0.060 ± 0.024 |
| | | | 303 | -0.198 ± 0.038 ± 0.015 |
| | | | 339 | -0.089 ± 0.040 ± 0.015 |
| 3.10 | 0.379 | 0.641 | 20 | 0.096 ± 0.030 ± 0.015 |
| | | | 57 | 0.082 ± 0.048 ± 0.015 |
| | | | 94 | 0.163 ± 0.069 ± 0.028 |
| | | | 138 | 0.093 ± 0.141 ± 0.013 |
| | | | 180 | -0.227 ± 0.192 ± 0.027 |
| | | | 226 | -0.033 ± 0.160 ± 0.027 |
| | | | 264 | -0.163 ± 0.080 ± 0.021 |
| | | | 303 | -0.164 ± 0.041 ± 0.022 |
| | | | 341 | -0.091 ± 0.037 ± 0.014 |

TABLE V: Values of the incoherent $A_{LU}$ in $Q^2$ bins from Fig. 21.
| $(Q^2)$ (GeV$^2$) | $(x_B)$ | $(-t)$ (GeV$^2$) | $(\phi)$ (degree) | $A_{LU} \pm $ stat. $\pm $ syst. |
|-----------------|--------|-----------------|-------------------|-----------------------------|
| 1.45            | 0.163  | 0.374           | 21                | $0.094 \pm 0.046 \pm 0.014$ |
|                 |        |                 | 63                | $0.069 \pm 0.044 \pm 0.017$ |
|                 |        |                 | 96                | $0.147 \pm 0.044 \pm 0.022$ |
|                 |        |                 | 140               | $0.102 \pm 0.052 \pm 0.015$ |
|                 |        |                 | 181               | $0.071 \pm 0.062 \pm 0.024$ |
|                 |        |                 | 220               | $-0.045 \pm 0.062 \pm 0.020$|
|                 |        |                 | 259               | $-0.115 \pm 0.043 \pm 0.018$|
|                 |        |                 | 303               | $-0.098 \pm 0.039 \pm 0.015$|
|                 |        |                 | 337               | $0.033 \pm 0.057 \pm 0.011$ |
| 1.93            | 0.225  | 0.381           | 22                | $0.002 \pm 0.038 \pm 0.013$ |
|                 |        |                 | 60                | $0.056 \pm 0.044 \pm 0.016$ |
|                 |        |                 | 96                | $0.168 \pm 0.050 \pm 0.018$ |
|                 |        |                 | 141               | $0.142 \pm 0.079 \pm 0.025$ |
|                 |        |                 | 182               | $0.167 \pm 0.096 \pm 0.017$ |
|                 |        |                 | 223               | $-0.262 \pm 0.083 \pm 0.034$|
|                 |        |                 | 260               | $-0.185 \pm 0.052 \pm 0.023$|
|                 |        |                 | 303               | $-0.196 \pm 0.037 \pm 0.021$|
|                 |        |                 | 337               | $-0.041 \pm 0.046 \pm 0.010$|
| 2.33            | 0.283  | 0.468           | 21                | $0.069 \pm 0.033 \pm 0.020$ |
|                 |        |                 | 59                | $0.124 \pm 0.046 \pm 0.020$ |
|                 |        |                 | 94                | $0.165 \pm 0.058 \pm 0.019$ |
|                 |        |                 | 139               | $0.111 \pm 0.110 \pm 0.024$ |
|                 |        |                 | 181               | $-0.194 \pm 0.155 \pm 0.015$|
|                 |        |                 | 225               | $0.008 \pm 0.111 \pm 0.014$ |
|                 |        |                 | 261               | $-0.242 \pm 0.066 \pm 0.027$|
|                 |        |                 | 303               | $-0.171 \pm 0.038 \pm 0.018$|
|                 |        |                 | 338               | $-0.065 \pm 0.041 \pm 0.010$|
| 2.98            | 0.389  | 0.688           | 20                | $0.081 \pm 0.029 \pm 0.014$ |
|                 |        |                 | 55                | $0.121 \pm 0.054 \pm 0.015$ |
|                 |        |                 | 93                | $0.253 \pm 0.090 \pm 0.031$ |
|                 |        |                 | 135               | $-0.230 \pm 0.225 \pm 0.039$|
|                 |        |                 | 180               | $-0.052 \pm 0.425 \pm 0.036$|
|                 |        |                 | 231               | $-0.377 \pm 0.334 \pm 0.047$|
|                 |        |                 | 266               | $-0.093 \pm 0.103 \pm 0.020$|
|                 |        |                 | 303               | $-0.198 \pm 0.045 \pm 0.023$|
|                 |        |                 | 341               | $-0.108 \pm 0.035 \pm 0.016$|

**TABLE VI:** Values of the incoherent $A_{LU}$ in $x_B$ bins from Fig. 21.
| \( (Q^2) \) (GeV\(^2\)) | \( (x_B) \) | \( (-t) \) (GeV\(^2\)) | \( \langle \phi \rangle \) (degree) | \( A_{LU} \) ± stat. ± syst. |
|-----------------|--------|-----------------|-----------------|------------------|
| 1.84            | 0.215  | 0.135           | 22              | 0.120 ± 0.037 ± 0.014 |
|                 |        |                 | 61              | 0.027 ± 0.042 ± 0.019 |
|                 |        |                 | 96              | 0.219 ± 0.041 ± 0.018 |
|                 |        |                 | 142             | 0.150 ± 0.054 ± 0.026 |
|                 |        |                 | 180             | 0.008 ± 0.067 ± 0.015 |
|                 |        |                 | 221             | -0.119 ± 0.065 ± 0.018 |
|                 |        |                 | 260             | -0.204 ± 0.043 ± 0.020 |
|                 |        |                 | 303             | -0.160 ± 0.037 ± 0.014 |
|                 |        |                 | 338             | -0.049 ± 0.047 ± 0.010 |
| 2.15            | 0.257  | 0.281           | 21              | 0.036 ± 0.040 ± 0.013 |
|                 |        |                 | 61              | 0.093 ± 0.045 ± 0.013 |
|                 |        |                 | 96              | 0.149 ± 0.051 ± 0.034 |
|                 |        |                 | 139             | 0.111 ± 0.073 ± 0.018 |
|                 |        |                 | 183             | 0.105 ± 0.093 ± 0.030 |
|                 |        |                 | 223             | -0.074 ± 0.076 ± 0.018 |
|                 |        |                 | 259             | -0.091 ± 0.055 ± 0.025 |
|                 |        |                 | 302             | -0.200 ± 0.039 ± 0.025 |
|                 |        |                 | 338             | -0.104 ± 0.047 ± 0.017 |
| 2.37            | 0.291  | 0.492           | 21              | 0.111 ± 0.037 ± 0.015 |
|                 |        |                 | 60              | 0.154 ± 0.045 ± 0.018 |
|                 |        |                 | 94              | 0.096 ± 0.060 ± 0.015 |
|                 |        |                 | 138             | -0.107 ± 0.105 ± 0.017 |
|                 |        |                 | 183             | 0.248 ± 0.119 ± 0.039 |
|                 |        |                 | 224             | -0.069 ± 0.110 ± 0.013 |
|                 |        |                 | 261             | -0.190 ± 0.062 ± 0.023 |
|                 |        |                 | 303             | -0.174 ± 0.036 ± 0.016 |
|                 |        |                 | 338             | -0.067 ± 0.047 ± 0.018 |
| 2.45            | 0.312  | 1.089           | 20              | 0.032 ± 0.030 ± 0.018 |
|                 |        |                 | 57              | 0.091 ± 0.058 ± 0.011 |
|                 |        |                 | 91              | 0.163 ± 0.112 ± 0.011 |
|                 |        |                 | 131             | 0.042 ± 0.307 ± 0.018 |
|                 |        |                 | 175             | -0.936 ± 0.397 ± 0.018 |
|                 |        |                 | 231             | -1.189 ± 0.517 ± 0.015 |
|                 |        |                 | 264             | -0.072 ± 0.109 ± 0.017 |
|                 |        |                 | 305             | -0.119 ± 0.048 ± 0.013 |
|                 |        |                 | 341             | -0.044 ± 0.036 ± 0.016 |

TABLE VII: Values of the incoherent \( A_{LU} \) in \(-t\) bins from Fig. 21.
| $\langle Q^2 \rangle$ (GeV$^2$) | $\langle x_B \rangle$ | $\langle -t \rangle$ (GeV$^2$) | $A_{LU}(90^\circ)$ ± stat. ± syst. |
|-------------------------------|-------------------|-----------------------|----------------------------------|
| 1.14                          | 0.136             | 0.096                 | 0.304 ± 0.051 ± 0.032            |
| 1.42                          | 0.172             | 0.099                 | 0.364 ± 0.059 ± 0.037            |
| 1.90                          | 0.224             | 0.107                 | 0.295 ± 0.061 ± 0.028            |
| 1.16                          | 0.132             | 0.095                 | 0.320 ± 0.045 ± 0.038            |
| 1.44                          | 0.17              | 0.099                 | 0.278 ± 0.079 ± 0.027            |
| 1.84                          | 0.225             | 0.107                 | 0.320 ± 0.161 ± 0.037            |
| 1.36                          | 0.160             | 0.080                 | 0.376 ± 0.042 ± 0.033            |
| 1.51                          | 0.179             | 0.094                 | 0.245 ± 0.072 ± 0.031            |
| 1.61                          | 0.193             | 0.127                 | 0.318 ± 0.095 ± 0.035            |

TABLE VIII: Values of the coherent $A_{LU}(90^\circ)$ in $Q^2$ (top block), $x_B$ (middle block), and $-t$ (bottom block) bins.

| $\langle Q^2 \rangle$ (GeV$^2$) | $\langle x_B \rangle$ | $\langle -t \rangle$ (GeV$^2$) | $A_{LU}(90^\circ)$ ± stat. ± syst. |
|-------------------------------|-------------------|-----------------------|----------------------------------|
| 1.40                          | 0.166             | 0.376                 | 0.137 ± 0.022 ± 0.014            |
| 1.89                          | 0.232             | 0.415                 | 0.153 ± 0.027 ± 0.017            |
| 2.34                          | 0.288             | 0.497                 | 0.190 ± 0.030 ± 0.017            |
| 3.10                          | 0.379             | 0.641                 | 0.130 ± 0.041 ± 0.016            |
| 1.45                          | 0.163             | 0.374                 | 0.117 ± 0.021 ± 0.012            |
| 1.93                          | 0.225             | 0.381                 | 0.177 ± 0.024 ± 0.018            |
| 2.33                          | 0.283             | 0.468                 | 0.178 ± 0.031 ± 0.015            |
| 2.98                          | 0.389             | 0.688                 | 0.160 ± 0.048 ± 0.014            |
| 1.84                          | 0.215             | 0.135                 | 0.183 ± 0.021 ± 0.014            |
| 2.15                          | 0.257             | 0.281                 | 0.141 ± 0.027 ± 0.020            |
| 2.37                          | 0.291             | 0.492                 | 0.137 ± 0.029 ± 0.024            |
| 2.45                          | 0.312             | 1.089                 | 0.139 ± 0.062 ± 0.024            |

TABLE IX: Values of the incoherent $A_{LU}(90^\circ)$ in $Q^2$ (top block), $x_B$ (middle block), and $-t$ (bottom block) bins.