Annual Progress Report:
FROM QUARKS TO NUCLEI

submitted to the
U.S. Department of Energy, Office of Science

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December 15, 2024

Period covered: Sep. 15, 2023 — Dec. 14, 2024

Recipient: Old Dominion University Research Foundation
P.O. Box 6369
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(ODURF project 100388-160)

DOE Grant: DE-FG02-96ER40960

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I. PROJECT NARRATIVE: PROGRESS IN THE PAST YEAR

A. Overview

Over the past 12 months our group has played a leading role in preparing and taking data for 12 GeV experiments at Jefferson Lab and worked towards the realization of an Electron-Ion Collider. Here are some highlights:

- We led the data taking of one Jefferson Lab 12 GeV experiments, the Hall-C NPS experiment group, including deep virtual Compton scattering and deep virtual π^0 scattering (9/2023 to 5/2024).
- We completed all preparations of the Hall C LAD experiment, scheduled to begin data taking next month (January 2025).
- We gained PAC jeopardy approval for two experiments, Run Group C and G in Hall B, measuring spin structure of the nucleons and for the first time the EMC effect in spin structure functions.
- We are co-spokespersons of 14 approved 12-GeV experiments and coordinate three CLAS12 Run Groups;
- We published 4 peer-reviewed papers as primary authors, out of a total of 16 papers.
- We graduated three Ph.D. students.
- We gave 24 colloquia, seminars, and conference talks or posters.
- We submitted 2 jeopardy proposals to the Jefferson Lab PAC.
- C. Hyde received the 2024 Virginia Scientist of the Year Award for the Physical Sciences by the Virginia Academy of Sciences;

B. Nucleon Structure

1. *BONuS*

Our group is presently leading the analysis of the data collected during the successful run of Run Group F in Jefferson Lab's Hall B during spring and summer 2020. This group of experiments used a custom-built radial time projection chamber (RTPC) surrounding a 40 cm long straw target filled with 5.5 atm deuterium gas to detect spectator protons in deep electron scattering processes on a quasi-free neutron in the deuteron ("Barely Off-shell Nucleon Structure with CEBAF at 12 GeV" = BONuS12). We are studying several channels, including Deeply Virtual Compton Scattering (DVCS) on the neutron, and in particular the ratio of the neutron structure function $F_2(x, Q^2)$ to that of the proton at moderate to large Bjorken-x. Our goal is to extract the asymptotic behavior of the ratio of d over u valence quark distributions as $x \to 1$.

At the beginning of the present grant cycle, we had completed all calibrations and the event reconstruction. We published details of the RTPC design, construction and operation as a technical publication in Nucl. Instrum. Meth. A [1]. We also had completed all cuts, corrections, and background subtraction procedures.

During the past 12 months, we have been working to finalize the high-level analysis of the data, including simulations. Our method of extracting the ratio of structure functions of the neutron to those of the deuteron (and, further, to the proton) relies on the simultaneous measurement of inclusive Deep Inelastic Scattering (DIS) on the deuteron and the tagged DIS on a bound neutron in the deuteron, with the spectator proton detected in the RTPC in coincidence. By forming the ratio of tagged over inclusive yields, we can minimize the systematic uncertainties coming from CLAS12 efficiency and acceptance as well as overall normalization factors like beam charge and target density. Furthermore, we compare this ratio to the same ratio for a full simulation of the entire experiment, including the RTPC and CLAS12, to correct for any remaining variation between the tagged and inclusive acceptance. We then form the "super-ratio" of experimental over simulated ratios, and multiply with the the input structure function ratios in the generator, to extract the corrected ratio F_{2n}/F_{2d} at each kinematic point. We account for the overall normalization factor by setting this ratio equal to the rather well-known result from various fits to the world data in the region $0.26 < x < 0.34$, where nuclear effects are minimal and all existing parametrizations agree well with each other.

From this description, it is obvious that the simulation must reproduce all aspects of the data faithfully, to avoid any bias. We spent most of the past year on refining some of our cuts and corrections, especially for the simulation, to ensure this is the case. For instance, we found that momentum corrections for the slow backward spectator protons in the RTPC could be improved to get identical results for the minimum momentum threshold in the data and the simulation. Similarly, we found that the experimental efficiency of the RTPC fell of more quickly with proton momentum than that from the

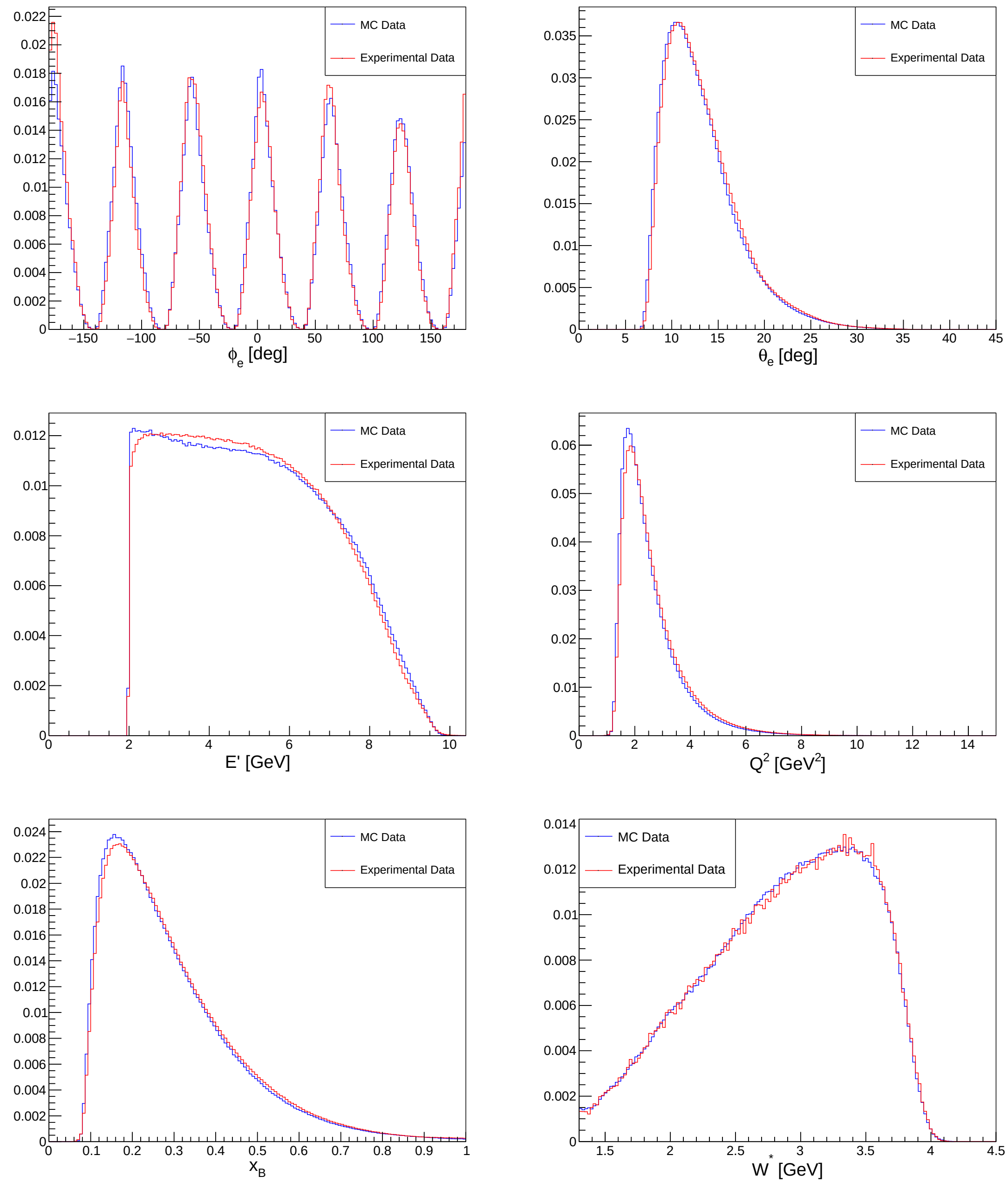

FIG. 1. Comparison between experimental (red line distributions) and MC (blue line distributions) datasets for proton-tagged nDIS $D(e, e'p_s)X$ channel. The plots from left to right and from top to bottom are: electron's azimuthal-angle (ϕ), polar-angle (θ), energy, Q^2, x^*, and struck-nucleon invariant-mass (W^*) distributions.

simulation, so we introduced a weighing factor for the latter that improved the agreement in the measured momentum spectra. Finally, we found some regions in the CLAS12 forward detector (in particular the Electromagnetic Calorimeter) that had to be cut to avoid inefficient regions of the phase space. Following these cuts, we re-derived the electron identification cuts based on the EC signal, and made sure they had the same efficiency for data and simulation. We also removed some data points that had very low (and uncertain) acceptance according to our simulation. As a consequence of this work, all relevant kinematic variables are now in remarkable agreement between the experimental data and the simulation, see Fig. 1.

We have now in hand all pieces necessary to extract the structure function ratio and estimate the implications for the d over u valence quark ratios. We are submitting the analysis note to the Deep Processes Physics Working Group of the CLAS collaboration. The first publication of physics results will focus on the structure function ratios and likely be submitted for publication by the end of this second year of the grant cycle. The publication of the neutron DVCS analysis will follow during the third year. The work will be carried out by our Ph.D. students, Yu-Chun Hung and Madhusudan Pokhrel (expected graduation in May 2025), who will complete their Ph.D. theses based on this work. In addition, Drs. Bültmann, Hattawy and Kuhn will support this effort as one of their two main research activities. The publication of the final archival paper is planned for the end of the third year of the grant cycle.

2. Nucleon Spin Structure

Over the past year, our longstanding program to elucidate the spin structure of the nucleon has focused on analyzing the large dataset collected during the 9-month run of Run Group C with CLAS12 in 2022-23. We have also completed an archival paper on the EG4 experiment with CLAS and published a higher-level analysis based on these results. We continue preparing for a run of Run Group G, which will be the first ever experiment to measure the EMC effect in polarized structure functions. Finally, we have embarked on a new effort to model spin structure functions over the entire kinematic range using ML/AI methods. In the following, we present some details of these efforts.

EG4

The EG4 experiment measured the spin structure functions g_{1p} and g_{1d} at very low Q^2 (down to $Q^2 \approx 0.012$ GeV^2) to test predictions for various sum rules based on chiral perturbation theory (χPT) and other theoretical models. Over the past year, we have completed an archival paper that summarizes all experimental details and results, and for the first time also presents results on the neutron extracted from proton and deuteron data. The paper has been posted on the arXive [2] and is under review at Phys. Rev. C.

We have also published a paper that uses the results from EG4, together with the "g2p" experiment in Jefferson Lab's Hall A, to improve the two-photon corrections to the hyperfine splitting (HFS) of the hydrogen and muonic hydrogen atom. These corrections dominate the uncertainty on measurements of the proton Zemach radius from ordinary hydrogen and the prediction for the correct frequency to search for the HF transition in muonic hydrogen, an important ingredient in the ongoing program to understand the "proton radius puzzle". This paper has been published by Phys. Lett. B. [3].

Run Group C

Run Group C (RG-C) is the first CLAS12 run group to take data with longitudinally polarized proton and deuteron targets and ran for a total of 9 months spanning from Summer 2022 through March 2023. Dr. Kuhn is the overall coordinator of this run group. The experiment ran successfully but lost significant time (about 1/3 of the scheduled run time) due to a failure of the CLAS12 central solenoid power supply and other CEBAF machine down-time periods. Therefore, 40 PAC days (80 calendar days) remain "on the books".

Our group has played a central role in the preparation and execution of the experiment. Our students Pushpa Pandey and Victoria Lagerquist were involved in all aspects of the design, construction and operation of the new polarized target "APolLo". Victoria has been awarded a Ph.D. in May, 2023, and is now working as a postdoc with the high-energy group at the University of Bonn. Pushpa completed her thesis based on RG-C in May 2024, including her fit to world data using a parametrization of resonance contributions to the spin structure functions and a thorough offline analysis of the NMR polarization data taken during and after the experiment. She has joined the MIT polarized ^{3}He group as a postdoc. Our new Ph.D. student, Darren Upton, has begun analyzing the inclusive spin structure functions measured with RG-C.

During the run of RG-C, we already started the effort to calibrate all detector systems, the raster system, and the polarization measurements for the polarized target. We have also led the dilution factor analysis which is required to extract physics asymmetries in the presence of non-polarized target material. Two of the 3 parts of the experiments (Summer and Fall 2022) have been fully calibrated, received "Pass-1" authorization and completed low-level analysis ("cooking"). The remaining part (Winter/Spring 2023) is nearly completely calibrated and we expect Pass-1 cooking to begin early in 2025.

We have begun extracting preliminary asymmetries from the Summer 2022 data, and taken a first look at the Fall 2022 data. The results were presented during the PAC52 meeting in July 2024 at Jefferson Lab, where the remaining run time for RG-C (40 PAC days, equivalent to 80 calendar days) were under "jeopardy review". We passed the review (presented by S. Kuhn) with an endorsement for the full remainder of the run time. At present, this second run of RG-C is tentatively planned for the 2026-2027 CEBAF schedule, in conjunction with Run Group G (see below).

For the coming year, we plan to develop all higher-level analysis tools to extract spin structure functions of the proton and the deuteron, out to the highest momentum fraction $x \approx 0.8$, based on the entire existing RG-C data set. First preliminary results are expected towards the end of the current 3-year grant.

Run Group G

Run Group G with CLAS12 (Drs. W. Brooks and S. Kuhn, co-spokespersons) will use a polarized ^{7}Li target (^{7}LiD) to measure, for the first time ever, the spin structure function of a proton bound in a nucleus. This experiment will test a wide range of theoretical predictions that differ dramatically in the predicted binding effect - from nearly no reduction in the spin structure function g_1 inside the nucleus (models based on the assumption that the EMC effect is entirely due to short-range correlated nucleon pairs) to significant reductions, beyond the unpolarized EMC effect. This experiment underwent a second "jeopardy review" during PAC52 (July 2024), where it was reaffirmed for 55 PAC days of running at A- priority.

Over the past year, significant progress towards realizing RG-G has been made. Jefferson Lab has hired one technician and one engineer who will help the polarized target group setting up a new irradiation facility and a test cryostat, which will make producing and characterizing the polarized target material possible in-house. These hires are part of the spin-polarized fusion project which will use the same material (^{7}Li) to assess the possibility of using polarization in Tokamak reactors to increase the fusion cross section. This project is synergistic with RG-G and has already succeeded in acquiring the ^{7}LiD material.

On the experimental side, we have been able to simplify the experimental setup such that we can use the existing "APolLo" polarized target from RG-C with only very minor modifications. This in turn will allow us to schedule the remainder of RG-C and all of RG-G in sequence, minimizing the overhead in setting up and operating the polarized target, while also minimizing the systematic uncertainties in the required comparison between spin structure functions measured on a free proton (NH_3 as part of RG-C) and a proton bound in ^{7}Li. At present, RG-G is planned to run in conjunction with RG-C (part 2) in the 2026-7 CEBAF schedule.

ML fit to world data on g_{1p}

Our new Ph.D. student, Darren Upton, has begun a project to use various machine-learning tools for a comprehensive fit of spin structure functions covering all kinematic domains, from the resonance region to the deep inelastic regime and from near-real photons to high Q^2. His preliminary results are already promising; he is presently refining his approach with the goal to have a model with quantifiable uncertainties that can be interpolated and extrapolated into unmeasured kinematics. This model will then become the basis for a new event generator for simulations of experiments like RG-C, which is required to achieve the highest possible accuracy in extracting physics observables from the measured asymmetries.

3. Deep Virtual Exclusive Scattering

Deeply virtual Compton scattering (DVCS) on the nucleon, $eN \to e'N\gamma$, and related deep virtual meson production (DVMP) are centerpieces of the Jefferson Lab 12 GeV program, in which we have played a leading role since its inception. DVCS and DVMP are also central to the physics program of a future Electron Ion Collider.

a. Hall C: DVCS and Deep Virtual π^0 Production on the proton and deuterium (C.Hyde and doctoral students Mitchell Kerver and Christine Ploen). C. Hyde is co-Spokesperson of Hall C experiments E12-13-010 (Hydrogen) and E12-22-006 (Deuterium). The goal of this program is to measure absolute cross sections (unpolarized and electron helicity-dependent) as functions of the incident beam energy at fixed values of Q^2 and x_B. The Q^2-dependence of these cross sections at fixed x_B and invariant momentum transfer t is *the* essential test of factorization, and quantifies the contribution to the scattering amplitude of higher-twist quark-gluon correlations. The larger goal of the global Deep Virtual Exclusive Scattering (DVES) effort is to provide sufficient constraints on the Generalized Parton Distributions (GPDs) to form spatial images of the quarks and gluons inside the proton (and other atomic nuclei) and to identify the individual quark-flavor and gluon contributions to the proton spin. Our previous Hall A work at 6 and 12 GeV established the power of measurements of the beam-energy dependence of the cross section to extract both the Real and Imaginary parts of the Compton amplitude [4, 5].

From Sept 2023 through May 2024, we ran these experiments concurrently, for a total of $\sim$ 100 PAC days of beam. The analysis of this massive dataset is advancing well. Christine Ploen leads the analysis of the optics calibration data for the Hall C High Momentum Spectrometer (HMS). Although this spectrometer has been in use for nearly 30 years, our measurements required high momentum settings that had never previously been used or tested. Furthermore, at these settings there is significant saturation in iron yokes of the QQQD magnets. Her optics calibration results are illustrated in Fig. 2. For the optics calibration, the acceptance defining octagonal aperture at the entrance to the first quadrupole is replaced by a sieve slit matrix of 78 0.2 in diameter and two 0.1 in diameter holes in a grid with 1 in vertical spacing and 0.6 in horizontal spacing. Inclusive electron scattering data were accumulated on thin carbon foils at target center, at $\pm$3 cm and $\pm$8 cm. Additional optics calibrations at 5.878 and 6.117 GeV/c are nearly complete. During the experiment we took dedicated Beam Current Monitor (BCM) calibration data roughly every 3 weeks. Christine Ploen coordinated these dedicated runs and has completed the BCM calibration analysis, indicating a precision on the beam charge of 1% in range of 5 to 30 μ A. She has also completed the Beam Position Monitor calibration analysis. Mitch Kerver has completed the HMS electron id calibrations. He has also investigated the absolute inclusive DIS cross section measured in the experiment and the GEANT simulation of the $PbWO_4$ calorimeter response. The full kinematic coverage of the NPS data, together with our previous Hall A 12 GeV DVCS data is illustrated in Fig. 3.

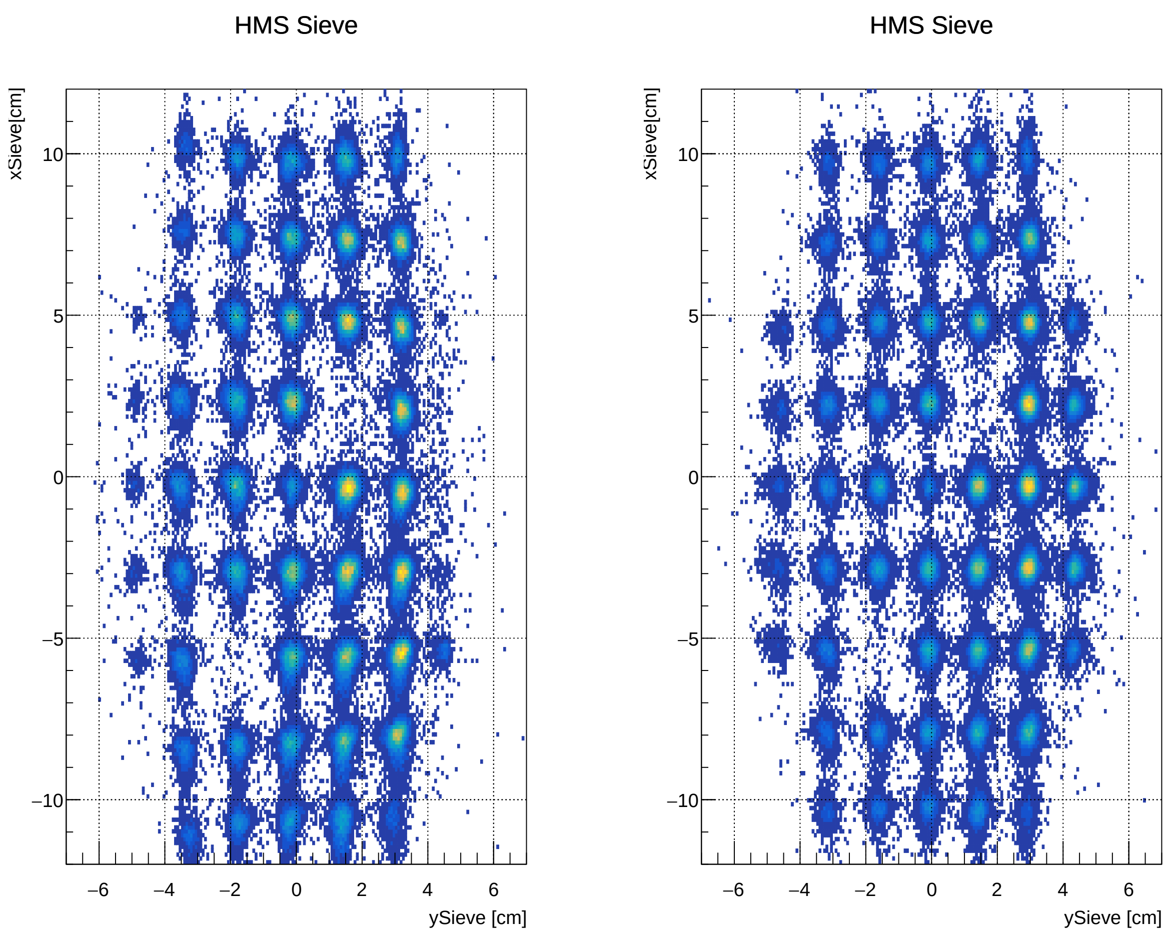

FIG. 2. HMS optics calibration results for 6.667 GeV/c electrons. Each plot shows the reconstruction of tracks at the location of the sieve. Note the transport coordinate system in which $-x$ is up and $+y$ is horizontal, pointing towards the beam line. **Left:** Raw results, with standard optics matrix calibrated for momenta $\leq$ 5.4 GeV/c. **Right:** Results with re-optimized optics matrix. Note strong improvement in reconstruction of the columns of sieve holes at $y = \pm 4.6cm$.

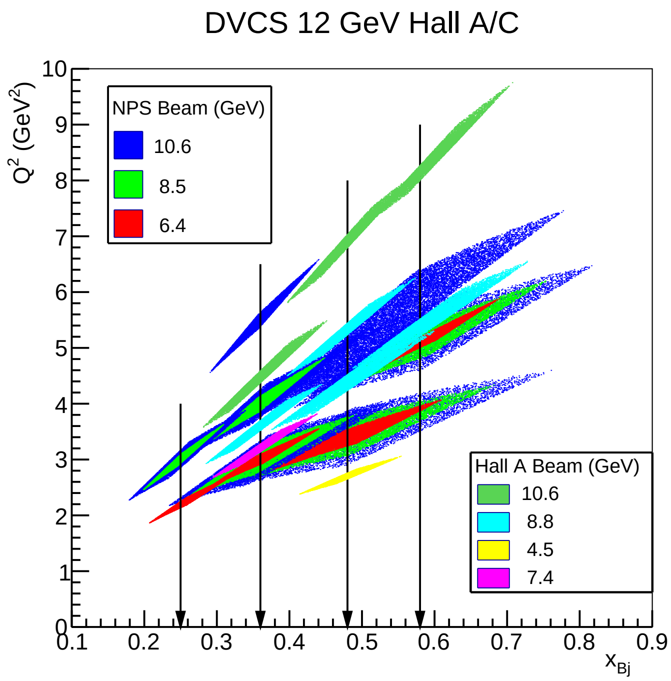

FIG. 3. DVCS kinematic coverage in Q^2 *vs.* x_B for Hall C NPS 2023-2024 data and previous Hall A E12-06-114 12 GeV era data [5]

4. Timelike Compton Scattering and J/Psi Production

We continue the analysis of dilepton production, e^+e^- and $\mu^+\mu^-$, on hydrogen to study Time-like Compton scattering and J/ψ photoproduction. The experiments E12-12-001 and E12-12-001A are part of the Hall-B CLAS12 Run Group A (RG-A). The run group recently completed second pass data processing with a new, improved tracking software. With improved tracking, the new data has better resolution and about twice more statistics than what was available in the first round of the analysis. ODU graduate student Mariana Tenorio Pita works together with a team of students and post docs on the calibration and quality assessment of the data. Mariana's analysis will include untagged and tagged production of J/ψ meson. In the former, final state e^+e^-p will be used, while the latter will detect the scattered electron in the reaction $e^-p \rightarrow e^+e^-pe'$ in the CLAS12 forward tagger system at very forward angles. Mariana is also heavily involved in the validation of CLAS12 MC, in particular in the correct simulation of the drift chamber response. As part of her analysis, Mariana is building a Machine Learning (ML) algorithm for electron/positron identification.

Below is the summary of the ongoing work.

Time-like Compton Scattering with CLAS12

The Time-like Compton Scattering provides two important checks for the formalism of Generalized Parton Distributions (GPD), the universality of GPDs and the direct access to the real part of Compton amplitude. The asymmetry measured with circularly polarized photons (BSA) gives access to the imaginary part of the Compton form-factors (CFFs) and hence is similar to the beam spin asymmetry in Deeply Virtual Compton Scattering (DVCS) and addresses the question of the universality of the GPDs. At the same time, the cosine moment of the TCS cross-section [6] projects out the real part of the CFF, which is important for the determination of the D-term in the GPD parametrization. The D-term contains the form-factor $d_1(t)$, which characterizes the spatial distribution of shear forces experienced by quarks inside the nucleon [7]. Measuring observables containing GPDs in a time-like regime will also help in understanding the "deconvolution problem", i.e., extraction of GPDs from the experimental measurements. The first measurement of asymmetries in TCS, the reaction $e^-p \rightarrow e^+e^-p(X)$, has been published in Physical Review Letters [8] with Prof. S. Stepanyan (ODU) as one of the lead authors.

The ODU group is part of the lepton pair electro- and photo-production analysis sub-group. The TCS analysis resumed after a new processing resulted in much larger statistics than what was available in the first publication. The larger statistics will allow finer binning of observables on kinematic variables and studying the kinematical dependencies.

J/ψ Photoproduction with CLAS12

The near-threshold J/ψ production is studied in the reaction $e^-p \rightarrow e'e^+e^-p'$ where e' is the scattered electron, p' the recoil proton, and the e^+e^- are the J/ψ decay products. The analysis will employ two strategies with semi-exclusive final states. The first is the untagged production with the final state e^+e^-p' when the scattered electron goes undetected. The second is when the scattered electron is detected in the CLAS12 forward tagger (FT) system, tagged production. The latter one is statistically limited but has the advantage that multiple topologies can be studied, $e'e^+e^-$, $e'e^+p'$, and $e'e^-p'$, and there is no uncertainty in the photon flux calculation for the total cross-section measurement. It is important to note that in the tagged final states, the charmed pentaquark states discovered in the (J/ψp) decay channel by the LHCb collaboration at CERN [9] will appear as a resonance in the missing mass of the reaction $e^-p \rightarrow e'X$. An important aspect of these analyses is the clean identification of e^+ and e^- from the J/ψ decay in the CLAS12 forward detector. The charged pion background is large, and special care is needed to suppress it. ODU graduate student, Mariana Tenorio Pita, was tasked by the Lepton pair analysis sub-group to address the issue using machine learning methods. Using the available TMVA tools in ROOT (Tools for Multivariate Analysis), she studied multiple methods. She found the Multilayer Perceptron (MLP) and the Boosted Decision Tree (BDT) most suitable for this work. Mariana trained and tested both methods using MC. The final validation was done using data. The lepton identification efficiency ratio between data and MC performed better for the BDT model with six variables. Mariana published her work as a CLAS12 internal note [10]. The developed tool has been implemented as part of the collaboration-wide analysis framework Iguana.

C. Hadron Spectroscopy

At low energies the coupling constant of Quantum Chromodynamics (QCD) becomes large and renders perturbation theory useless. The phenomenology of the strong interactions in this domain remains one of the major challenges of modern particle physics. Experimental study of the photo-production of different mesons above the resonance region is a unique way to study the non-perturbative domain of strong interactions and provides important information for a firmer foundation of hadronic physics rooted in the standard model. Although there are experimental data on the photoproduction of pseudoscalar and vector mesons, no data are available until now on the photoproduction of axial-vector mesons at high energies.

Doctoral student Tyler Viducic (supervisor Dr. Amaryan) defended his PhD thesis *Measurement of the photoproduction cross-section of $f_1(1285)$ in the exclusive reactions $\gamma p \to K_s K^{\pm}\pi^{\mp} p$ at 7.5 $< E_\gamma <$ 11.5 GeV with GlueX at Jefferson Lab* in May 2024. The aim of this analysis was to measure for the first time the t-Mandelstam dependence of the cross section of the photoproduction of axial-vector $f_1(1285)$ meson at high energies far above the baryon resonance production region with photon energies in the range of $E_\gamma = (7-10)$ GeV. As quantum numbers of this meson $J^{PC} = 1^{++}$ are different from the quantum numbers of the photon, the simple mechanism of splitting the photon into $q\bar{q}$ pair with the pomeron exchange, as in the case of vector mesons ρ, ω, ϕ, can not happen. Therefore it provides additional information for phenomenological studies and theoretical models to explain photoproduction of axial-vector mesons.

Another major effort of our group is devoted to setting up a new facility with a secondary beam of neutral kaons, the so called K-long Facility (KLF) for strange hadron spectroscopy (see below).

The proposal to install KLF in Hall D at JLab, led by Dr. Moskov Amaryan (spokesperson and contact person) was approved in 2020 for 200 days of running time on liquid hydrogen and deuterium targets. Currently, about 200 members from 70 universities of 20 countries joined and a new KLF Collaboration was created to run the experiment. This collaboration has the largest number of institutions ever in the history of JLab.

More details on the current status and future plans of our group related to hadron spectroscopy are presented below.

1. *Photoproduction of $f_1(1285)$ axial-vector meson at GlueX in Hall D*

The reaction of study was photoproduction of $f_1(1285)$ in the reaction $\gamma p \to K_s K^{\pm}\pi^{\mp} p$. In particular, the invariant mass of $K_s K^- \pi^+$ is presented in Fig. 4, on left panel and the t-Mandelstam dependence on the $f_1(1285)$ meson on the right panel. As one can see the peak of $f_1(1285)$ is clearly identified and it is much closer to its expected value and a possible contribution of the elusive $\eta(1295)$ is either absent or negligible in comparison to $f_1(1285)$. On the second panel one can see the t-dependence of f_1 photoproduction with solid curves derived from the model. As one can see, there is a significant, about an order of magnitude difference between the model prediction and experimental data, which will require further studies. This data represent the first ever measurement of photoproduction of $f_1(1285)$ way above the resonance region at the incoming photon energies of E_γ = 8-9 GeV. Currently the analysis note is in preparation and will be submitted to the collaboration for a publication.

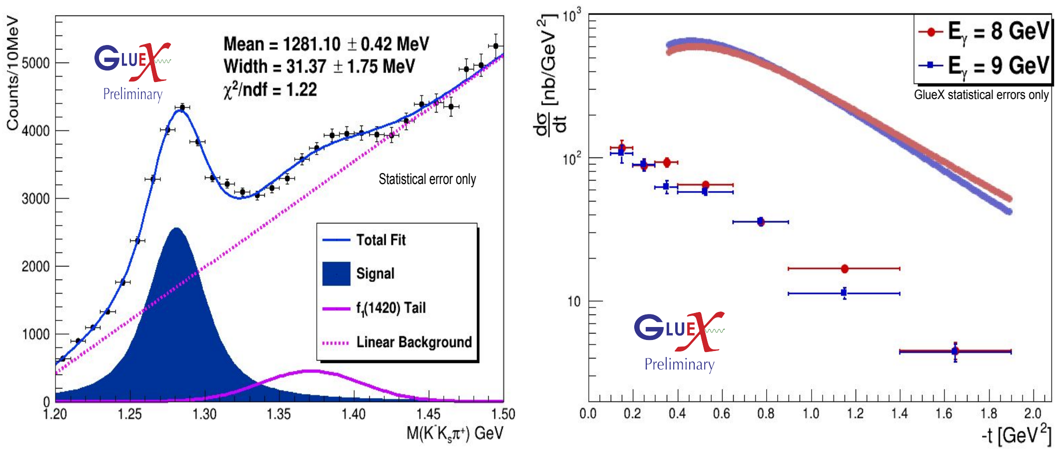

FIG. 4. Invariant mass $M(K_s K^- \pi^+)$ (left panel) and first ever measured t-Mandelstam distribution in photoproduction reaction $\gamma p \to p f1(1285)(K_s K^- \pi^+)$ (right panel) at high energies.

2. The K_L Facility in Hall D

The JLab PAC in 2020 approved the KLF proposal "Strange Hadron Spectroscopy with Secondary K_L beam in Hall-D" (spokesperson and contact person M. Amaryan) for 200 days of the beam time. The unprecedented 10^3 times increase of the intensity of the secondary K_L beam flux on a physics target, compared with what was previously obtained at SLAC, provides a unique opportunity to study strange hadron spectroscopy with KLF at JLab. The main goal of KLF is to observe and measure quantum numbers of almost all yet unobserved excited states of $\Lambda^\star, \Sigma^\star, \Xi^\star$ and $\Omega^\star$ hyperons up to $M = 2.5$ GeV. This will provide an experimental test of recent LQCD calculation [11] predicting not only a large amount of missing hyperon states, but also hybrid states.

A meson sector measurement of $K-\pi$ scattering at very low $|t|$-Mandelstam will allow to unravel the still not well established scalar κ meson, thus solving the long standing problem of existence or non-existence of scalar meson nonet. Experimental data obtained with the KLF facility will also enable us to clarify existence of heavier $K^{*'}s$ possibly belonging to the higher excited strange meson multiplets.

In addition, results obtained with the KLF will have a strong impact on our understanding of the evolution of the Early Universe at freeze-out 1 μs after the Big Bang at temperatures $\simeq$160 MeV. The comparison of the chemical potential of the Early Universe as a function of temperature obtained with LQCD calculations and constituent quark model prediction including only currently observed hyperon states is not satisfactory being off by 1.5-2 times (see [12]), while assuming existence of all missing hyperon states makes excellent agreement within errors with LQCD calculations. The search of missing baryon resonances was a decades long program in Hall-B. The difference between a search of ordinary baryons and hyperons is that the latter have much narrower widths therefore will be easier to observe experimentally with greater precision. Physics topics with KLF have been developed in three international workshops chaired by M. Amaryan [13], [12] and [14]. The KLF proposal C12-19-001 was approved by PAC48 in 2020 for 200 days of beam time. The approved version of the proposal is posted on arXiv [15].

In summary, in the KLF project we have three physics topics related to: a) observing the predicted by both, the Constituent Quark Model and LQCD, but yet unobserved hyperon states, b) observing the strange meson states including elusive κ meson to complete the nonet of the scalar mesons and c) providing necessary information to the calculation of thermodynamic properties of the Early Universe at freeze-out 1μs after the Big Bang.

In particular the following tasks have been accomplished over the past year within our group efforts:

a) A full design is completed for the Compact Photon Source (CPS), including calculations of radiation shielding, melting temperature of different components, stress forces using FLUKA simulation code

b) Similar calculations have been performed by our group for the Be target, the source of the secondary beam of K_L, as well as the flux of remnant photons and neutrons impinging on the liquid hydrogen target of the GlueX setup.

c) The level of radiation in the Hall D beamline was estimated based on the FLUKA simulation code and is at an acceptable limit established by the Radiation Control group at JLab.

In August 2024, an Intermediate Experimental Readiness Review (IERR) meeting was held at JLab with all parties involved, JLab management, Hall D staff, members of the accelerator group, as well as members of the KLF Collaboration. The final report of the IERR contains recommendations for optimizing the beam line of KLF and demonstrate progress in simulations of different physics channels outlined in the proposal. Our group is focused on simulations of the reactions $K_Lp \to K^+n$ and $K_Lp \to K_Sp$, in particular to search for a light pentaquark (Θ^+). The first of these reactions was discussed in [16], where it was shown that this is the most direct formation reaction to observe the exotic Θ^+ pentaquark with thousands of events in the peak with experimental resolution of 1-2 MeV, based on a measurement of not the invariant mass of K^+n system, but rather the square root of the invariant energy of this reaction.

In the coming year we plan to be heavily involved in the construction of all hardware components. In addition to this, we are involved in detailed calculations of efficiencies and acceptances, taking active part in the software development for analysis and Monte Carlo simulations of different final states produced by the K_L beam.

According to the current plan outlined by JLab management in the recent CLAS Collaboration Meeting in November 2024, the new beam line is scheduled to be built in 2025-2026 with start of the installation in 2026. The experimental data taking is scheduled to start in 2027-2028.

A part of our group will take responsibility to test hardware components of the Flux Monitor that will be delivered from Juelich, Germany to JLab then transferred to the ODU High Bay area.

D. Physics of the Nucleus

Our group continues to lead studies of short range correlated (SRC) nucleon-nucleon (NN) pairs in nuclei and their implications for bound nucleon structure, neutron stars, and neutrino interactions. The work described in this section has been done by L.B. Weinstein in collaboration primarily with E. Piasetzky (Tel Aviv) and Or Hen (MIT).

We continue to analyze Run Group M, which includes two experiments E12-17-006 "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues" and E12-17-006A: "Exclusive Studies of Short Range Correlations in Nuclei using CLAS12", L.B. Weinstein co-spokesperson and Analysis Coordinator. The first phase of the analysis note has been expanded to include energy and momentum corrections and is under CLAS review. The first paper is expected in 2025.

Run preparations for E12-11-007, "In Medium Nucleon Structure Functions, SRC, and the EMC effect" the Hall C LAD experiment (L.B. Weinstein co-spokesperson) are complete and the experiment will run in January 2025, one year later than expected. C. Ayerbe-Gayoso worked on the testing and refurbishment of the LAD scintillator bars, on the GEANT4 simulation, and on the data acquisition system. Alexander Garrett, our technician, assembled, tested, and debugged the laser and laser control system for calibrating the LAD scintillator bars.

LAD will measure the virtuality-dependence of tagged neutron structure functions in the $d(e, e'p_s)$ measurement. It will complement the BAND experiment which measured tagged proton structure functions in the $d(e, e'n_s)$ measurement.

L.B. Weinstein is helping to coordinate the on-going BAND analysis, which is under CLAS Analysis Review and nearing completion. In the last year we responded to many questions from the analysis review committee, including showing that neutrons emitted at smaller angles which rescattered into BAND did not significantly affect our results.

"The CaFe Experiment: Short-Range Pairing Mechanisms in Heavy Nuclei" (L.B. Weinstein co-spokesperson and Analysis Coordinator) used $A(e, e'p)$ to measure the ratio of high-initial-momentum (i.e., SRC) protons to low-initial-momentum (i.e., mean field) protons in ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{40}Ca, ^{48}Ca, ^{54}Fe, and ^{197}Au to understand the effects of adding *neutrons* on the *proton* momentum distribution as a test of np dominance in SRC

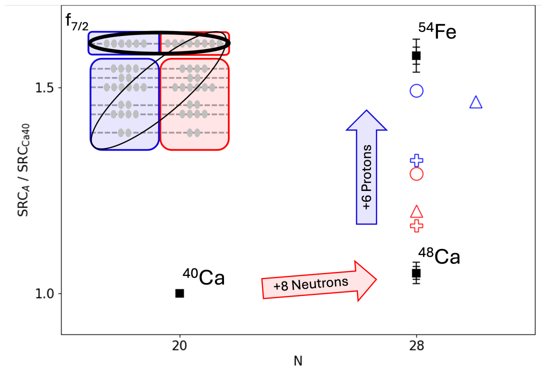

FIG. 5. Cafe preliminary results. The per-nucleus ratio of high missing-momentum protons in ^{48}Ca and ^{54}Fe to ^{40}Ca. The black points show the data, the crosses show the Similarity Renormalization Group calculation of Furnstahl, et al, the triangles show the $n = 0, s = 0$ pairing calculation of Colle, et al, and the circles show a spatial overlap model. The red and blue points refer to ^{48}Ca and ^{54}Fe, respectively.

pairs and to disentagle the relative contributions of increasing A and changing nuclear asymmetry (neutron to proton N/Z ratio).

In the past year we have finalized the radiative and transparency corrections and the systematic uncertainties. Results are almost final (see Fig. 6). The number of correlated (high-initial momentum) protons in ^{48}Ca is much less than expected and the number of correlated protons in ^{54}Fe is much greater than expected, indicating that inter-shell neutron-proton pairing is much weaker than intra-shell np pairing. This experiment was co-led by Carlos Yero (now at Catholic University), then an NSF ASCEND Fellow working under the supervision of L.B. Weinstein, and is being analyzed by Noah Swan, an ODU graduate student. A paper is in preparation.

Caleb Fogler has finished his analysis of the $d(e, e'\pi^{\pm})$ channel from the 4-GeV Run Group B data set. He compared his measured cross sections to two different cross section models, including GENIE, the standard eA and νA event generator developed for neutrino experiments, and onepigen, a MAID-based single-pion-knockout cross section model including the effects of Fermi momentum. He is preparing an Analysis Note for CLAS Collaboration approval.

The electrons for neutrinos effort continues at a very low level. E12-17-006 "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues" analysis continues, primarily by the Tel Aviv University group led by Prof. Adi Ashkenazi. L.B. Weinstein is Analysis Coordinator. A paper on general radiative corrections for any electron-nucleus event generator has been accepted for publication by Computer Physics Communications. A proton transparency paper using CLAS6 data is under CLAS paper review.

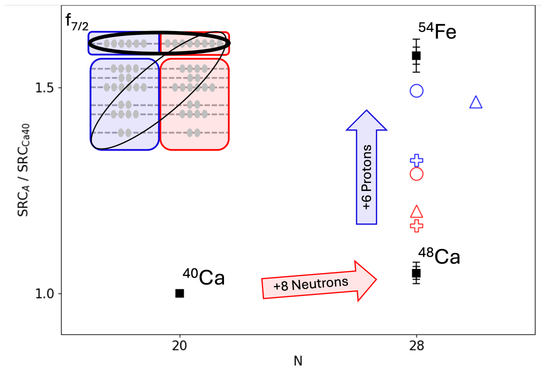

FIG. 6. Cafe preliminary results. The per-nucleus ratio of high missing-momentum protons in ^{48}Ca and ^{54}Fe to ^{40}Ca. The black points show the data, the crosses show the Similarity Renormalization Group calculation of Furnstahl, et al, the triangles show the $n = 0, s = 0$ pairing calculation of Colle, et al, and the circles show a spatial overlap model. The red and blue points refer to ^{48}Ca and ^{54}Fe, respectively.

1. *Nucleon Knockout and Correlations Studies*

"The CaFe Experiment: Short-Range Pairing Mechanisms in Heavy Nuclei" (L.B. Weinstein co-spokesperson and Analysis Coordinator) used $A(e, e'p)$ to measure the ratio of high-initial-momentum (i.e., SRC) protons to low-initial-momentum (i.e., mean field) protons in ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{40}Ca, ^{48}Ca, ^{54}Fe, and ^{197}Au to understand the effects of adding *neutrons* on the *proton* momentum distribution as a test of *np* dominance in SRC pairs and to disentagle the relative contributions of increasing A and changing nuclear asymmetry (neutron to proton N/Z ratio).

In the past year we have finalized the radiative and transparency corrections and the systematic uncertainties. Results are almost final (see Fig. 6). The number of correlated (high-initial momentum) protons in ^{48}Ca is much less than expected and the number of correlated protons in ^{54}Fe is much greater than expected, indicating that inter-shell neutron-proton pairing is much weaker than intra-shell *np* pairing. This experiment was co-led by Carlos Yero (now at Catholic University), an NSF ASCEND Fellow working under the supervision of L.B. Weinstein, and is being analyzed by Noah Swan, an ODU graduate student. A paper is in preparation.

Caleb Fogler has finished his analysis of the $d(e, e'\pi^{\pm})$ channel from the 4-GeV Run Group B data set. He compared his measured cross sections to two different cross section models, including GENIE, the standard eA and νA event generator developed for neutrino experiments, and onepigen, a MAID-based single-pion-knockout cross section model including the effects of Fermi momentum. He is preparing an Analysis Note for CLAS Collaboration approval.

The electrons for neutrinos effort continues at a very low level. E12-17-006 "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues" analysis continues, primarily by the Tel Aviv University group led by Prof. Adi Ashkenazi. L.B. Weinstein is Analysis Coordinator. A proton transparency paper using CLAS6 data is under CLAS paper review.

E. Physics Beyond the Standard Model

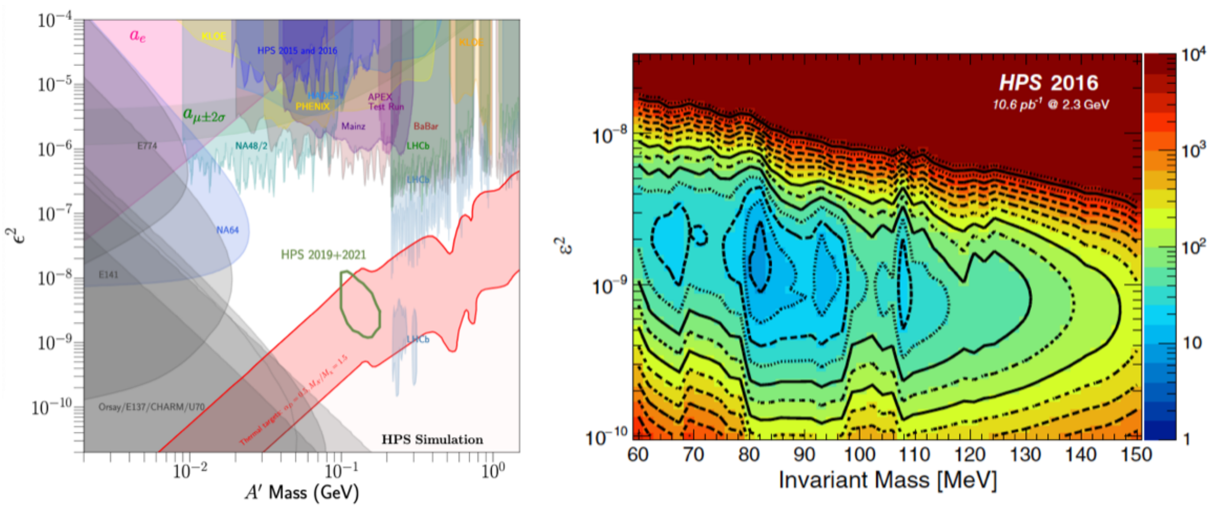

FIG. 7. Left: The exclusion region of the dark photon parameter space by the analysis of 2016 data and statistical recasting of the 2015 result.
Right: The expected detected A' yield for the combination of both L1L1 and L1L2 categories versus mass and epsilon.

The Heavy Photon Search (HPS) experiment in Hall-B at Jefferson Lab [17, 18], which utilizes the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab, exploits resonance and displaced vertex signatures to search for heavy photons over a wide range of couplings, $\epsilon^2 > 10^{-10}$, and masses, 20 MeV/$c^2 < m_{A'} <$ 220 MeV/c^2, using a compact, large-acceptance forward spectrometer consisting of a silicon micro-strip vertex tracker (SVT), a scintillation hodoscope (SH), and a $PbWO_4$ electromagnetic calorimeter (ECal). Over the years, the HPS collaboration made significant progress in the analysis of engineering run data and in the calibration of data from the physics runs in 2019 and 2021.

The analysis of the engineering run data was completed last year, and the results have been reviewed and approved by the collaboration for publication. The article has been published in Physical Review D[19]. These new results have extended the coverage of the heavy photon mass to 180 MeV/c^2 in the resonance search, and excluded the canonical A' production in the mass range from 40 to 180 MeV/c^2 down to the level of $\epsilon^2 \simeq few \times 10^{-5}$, as shown on the left in Fig.7. This result confirms the findings of previous searches but does not extend their sensitivity. The reported displaced vertex search explores A' masses in the range from 60 to 150 MeV/c^2 for ϵ^2 in the region 10^{-8} to 10^{-10}. This is parameter space previously unexplored by other experiments, which is the preferred territory for models assuming thermal production of hidden-sector dark matter in the early Universe. The optimum interval method (OIM) [20] is used to set a limit on the cross-section of the canonical A' model. The result for the OIM is shown on the right in Fig.7. Combining the two categories of tracks gives the best limit at $m_{A'} = 82.0$ MeV and $\epsilon^2 = 1.7 \times 10^9$ with a factor of 7.9 times the canonical A' cross-section. The interpretation of this value is for an A'-like model with 7.9 times the cross-section excluded at this mass and ϵ^2 with 90% confidence. With the engineering run's luminosity, it is impossible to set upper limits on canonical A' production in the parameter plane.

The required sensitivity for the displaced vertex search will be achieved with 2019 and 2021 physics run data sets with integrated luminosities of about 122 pb^{-1} and 160 pb^{-1}, respectively. Both physics runs should offer a window into the highly motivated parameter space and together will cover a significant part of it, as shown on the left in Fig.7.

The ODU professors Stepan Stepanyan and Stephen Bueltmann played an important role in the success of the HPS. In particular, Prof. Stepanyan, as co-spokesperson of the HPS experiment, directed the efforts in the preparation and the running of the experiment and in the data calibration and analysis.

F. An Electron Ion Collider

Dr. Charles Hyde leads our EIC research program. In 2024, Dr. Hyde served as 'Physics Convener' on the Second Detector Working Group organized by the EIC Users Group. Our research focus is on simulations of exclusive processes on light nuclei and performance studies for Detection of Internally Reflected Cherenkov light (DIRC) detectors.

In collaboration with Dr. Grzegorz Kalicy (Catholic University of America), we maintain a laser test facility at ODU to measure the optical properties of prototype DIRC lenses. Dr. Hyde, our Post-doc Dr. Carlos Ayerbe Gayoso and our technician Alex Garrett constructed a CO_2 Cherenkov detector. This is now integrated into a precision Cosmic Ray Telescope at Stony Brook University to test DIRC prototypes (both for ePIC and future development). The purpose of the gas Cherenkov is to velocity select high momentum muons in order to minimize the intrinsic Cherenkov angle dispersion in the fused silica DIRC radiators under test.

The preliminary design of the EIC Interaction Region 8 (IR8) beam optics include a high dispersion focus in the ion beam line ~ 45 m downstream of the Interaction Point (IP). This would enable the detection of any beam fragments with magnetic rigidity that differs by more than $\pm 1\%$ from the beam rigidity. The momentum of these fragments would be measured by high precision trackers (*e.g.* AC LGAD) in Roman Pot detectors near the high dispersion focus. We propose to enhance the physics program of a second

EIC detector by identifying the atomic number Z of each ion fragment, on an event-by-event basis. This would be accomplished by measuring the absolute Cherenkov light emitted by a thin silica radiator located with the Roman Pot detection system at the downstream focus. Drs. Hyde and Ayerbe Gayoso have imported the GEANT-based GSI/PANDA DIRC simulation framework to ODU/JLab. Initial studies, illustrated in Fig. 8 verify that the photo-statistics of collected Cherenkov emission provides resolution $\delta Z < 1$ for all ion species from protons to Uranium. We are now studying additional details regarding photo-sensor uniformity and saturation. This work is also supported by EIC Generic R&D project 2023_09 (C.Hyde, P.I.).

Although a significant fraction of our EIC effort has historically been funded by other sources, the support from this grant is crucial to the continuity of our effort.

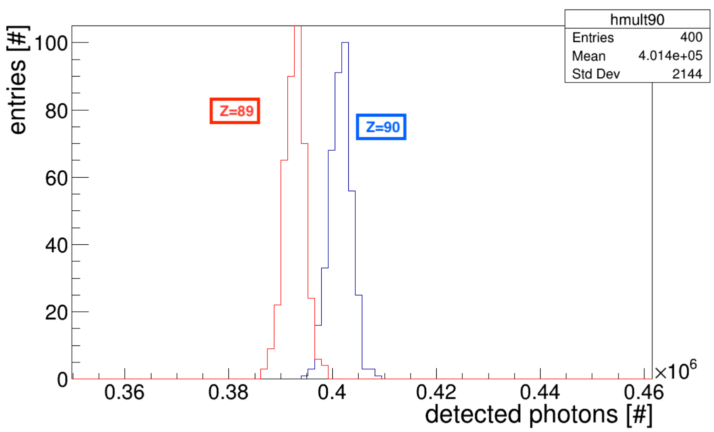

FIG. 8. Cherenkov light statistics from $Z = 89$ and $Z = 90$ ions of momentum 100 GeV/u striking a 0.6 cm thick silica Cherenkov radiator. The radiation is 1.0 cm tall and 15 cm long (perpendicular to beam direction). The light is further propagated to a SiPM photosensor array via a $(2.5\ \text{cm})^3$ expansion volume. Statistics include light collection and SiPM quantum efficiency.

G. Milestones for 2024

- Investigate the quark-gluon structure of protons and neutrons in deep inelastic scattering and through precision measurements of deeply virtual Compton scattering
  - Complete full analysis of the entire RG-F (BONuS12) data set, including nDVCS (Kuhn, Bueltmann) (analysis note ready and release of first results requested from collaboration)
  - Low-level analysis ("cooking") of the entire RG-C data set (Kuhn, Bueltmann) (completed for the Summer and Fall 2022 data sets, underway for Winter/Spring 2023 data set)
  - Complete NPS data taking in Hall C and calibrate data (Hyde) (achieved)
  - Publish full data set of Time-like Compton Scattering analysis (Stepanyan) (in progress for 2025)
- Hadron Spectroscopy: GlueX and KLF (Amaryan)
  - Complete prototyping and construction of hardware components (partially started)
- Study the role of two-nucleon correlations in nuclei and the origin of the EMC effect (Weinstein)
  - Complete data taking for the Hall C LAD experiment (experiment ready, data taking scheduled for Spring 2025)
  - Publish final Cafe experiment paper on mean field and SRC $(e, e'p)$ cross sections (first paper to be published in 2025)
  - Publish more RG-M SRC papers (first paper to be published in 2025)
  - Publish $d(e, e'\pi)$ 4 GeV cross sections from RG-B (analysis complete, requesting analysis approval)
  - Achieve full PAC approval for $A = 3$ SIDIS experiment in CLAS12 (not resubmitted in 2024)
- Explore physics beyond the Standard Model with the Heavy Photon Search experiment (Stepanyan, Bueltmann)
  - Publish results of displaced vertex analysis (in progress for 2025)
- Prepare for the Electron Ion Collider (Hyde)
  - Complete GEANT4-based simulations of a candidate second EIC detector (working group has not yet produced a detector design)
  - Complete full EIC DVCS simulations on light $N = Z$ nuclei, including electron-helicity observables (in progress, results in 2025)

II. BIBLIOGRAPHY

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III. PUBLICATIONS, TALKS, AND THESES

Summary of Publications: Dec.2023–Dec.2024

Name	**Letter Publications**	**Other Refereed Journals**	**Invited Talks**
Faculty/Staff			
M. Amaryan	2 (1)	5 (0)	2
S.L. Bültmann	3 (0)	1 (1)	0
M. Hattawy	3 (0)	4 (1)	2
C.E. Hyde	1 (0)	2 (0)	5
S.E. Kuhn	3 (1)	2 (1)	6
S. Stepanyan	2 (0)	2 (0)	1
L.B. Weinstein	1 (0)	7 (1)	2
Post-docs			
V. Baturin	0 (0)	0 (0)	0
C. Ayerbe-Gayoso	1 (0)	7 (1)	3
Total	5 (2)	7 (2)	21

Numbers in parentheses refer to primary-author publications.

A. Refereed Publications

In the past year, our group published a total of 16 refereed journal articles, including 4 papers with ODU principal authors.

ODU Principal authors

1. M. J. Amaryan *et al.* [KLF], "Search for Θ+ in KLp → K+n reaction in KLF at JLab," Mod. Phys. Lett. A **39**, no.14, 2450063 (2024) doi:10.1142/S0217732324500639 [arXiv:2401.05887 [hep-ex]].

2. I. Albayrak, S. Aune, C. Ayerbe Gayoso, P. Baron, S. Bültmann, G. Charles, M. E. Christy, G. Dodge, N. Dzbenski and R. Dupré, *et al.* "Design, construction, and performance of the GEM based radial time projection chamber for the BONuS12 experiment with CLAS12," Nucl. Instrum. Meth. A **1062**, 169190 (2024) doi:10.1016/j.nima.2024.169190 [arXiv:2402.01904 [physics.ins-det]].

3. D. Ruth *et al.* , "New spin structure constraints on hyperfine splitting and proton Zemach radius", Phys. Lett. B **859**, 139116 (2024).

4. Julia Tena Vidal, Adi Ashkenazi, Larry B. Weinstein, Peter Blunden, Steven Dytman, and Noah Steinberg, "A universal implementation of radiative effects in neutrino event generators", Computer Physics Communications, in press; https://arxiv.org/abs/2409.05736.

General Refereed Publications

5. F. Hauenstein, C. Ayerbe Gayoso, S. Ratliff, H. Szumila-Vance, A. Schmidt, L. Ehinger, O. Hen, D. Higinbotham, I. Korover and T. Kutz, *et al.* "Tagged deep inelastic scattering measurement on deuterium with the LAD experiment," Eur. Phys. J. A **60**, no.10, 201 (2024) doi:10.1140/epja/s10050-024-01356-w

6. A. Kim *et al.* [CLAS], "Beam spin asymmetry measurements of deeply virtual $\pi 0$ production with CLAS12," Phys. Lett. B **849**, 138459 (2024) doi:10.1016/j.physletb.2024.138459 [arXiv:2307.07874 [nucl-ex]].

7. A. Schmidt, A. W. Denniston, E. M. Seroka, N. Barnea, D. W. Higinbotham, I. Korover, G. A. Miller, E. Piasetzky, M. Strikman and L. B. Weinstein, *et al.* "A=3(e,e')xB≥1 cross-section ratios and the isospin structure of short-range correlations," Phys. Rev. C **109**, no.5, 054001 (2024) doi:10.1103/PhysRevC.109.054001 [arXiv:2402.08199 [nucl-th]].

8. K. Okuyama . . . F. Hauenstein, . . . C. Hyde *et al.* [JLab Hypernuclear], "Electroproduction of the Λ/Σ^0 hyperons at $Q^2 \simeq 0.5$ (GeV/c)^2 at forward angles," Phys. Rev. C **110** (2024) no.2, 025203 doi:10.1103/PhysRevC.110.025203 [arXiv:2403.01173 [nucl-ex]].

9. I. A. Skorodumina *et al.* [CLAS], "Double-pion electroproduction off protons in deuterium: Quasifree cross sections and final-state interactions," Phys. Rev. C **109**, no.6, 065205 (2024) doi:10.1103/PhysRevC.109.065205 [arXiv:2308.13962 [nucl-ex]].

10. A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C. S. Akondi, N. Akopov, M. Albaladejo, H. Albataineh, M. Albrecht and B. Almeida-Zamora, *et al.* "Strong interaction physics at the luminosity frontier with 22 GeV electrons at Jefferson Lab," Eur. Phys. J. A **60**, no.9, 173 (2024) doi:10.1140/epja/s10050-024-01282-x [arXiv:2306.09360 [nucl-ex]].

11. S. N. Santiesteban *et al.* [Jefferson Lab Hall A], "Novel Measurement of the Neutron Magnetic Form Factor from A=3 Mirror Nuclei," Phys. Rev. Lett. **132**, no.16, 162501 (2024) doi:10.1103/PhysRevLett.132.162501 [arXiv:2304.13770 [nucl-ex]].

12. P. Achenbach, D. Adhikari, A. Afanasev, F. Afzal, C. A. Aidala, A. Al-bataineh, D. K. Almaalol, M. Amaryan, D. Androić and W. R. Armstrong, *et al.* "The present and future of QCD," Nucl. Phys. A **1047**, 122874 (2024) doi:10.1016/j.nuclphysa.2024.122874 [arXiv:2303.02579 [hep-ph]].

13. R. Li, N. Sparveris, H. Atac, M. K. Jones, M. Paolone, Z. Akbar, M. Ali, C. Ayerbe Gayoso, V. Berdnikov and D. Biswas, *et al.* "Pion electroproduction measurements in the nucleon resonance region," Eur. Phys. J. A **60**, no.8, 168 (2024) doi:10.1140/epja/s10050-024-01391-7 [arXiv:2409.03750 [nucl-ex]].

14. J. R. Pybus, T. Kolar, B. Devkota, P. Sharp, B. Yu, O. Hen, E. Piasetzky, S. N. Santiesteban, A. Schmidt and A. Somov, *et al.* "Search for axion-like particles through nuclear Primakoff production using the GlueX detector," Phys. Lett. B **855**, 138790 (2024) doi:10.1016/j.physletb.2024.138790 [arXiv:2308.06339 [hep-ex]].

15. A. Hobart *et al.* [CLAS], "First Measurement of Deeply Virtual Compton Scattering on the Neutron with Detection of the Active Neutron," Phys. Rev. Lett. **133**, 211903 (2024) doi.org/10.1103/PhysRevLett.133.211903 [arXiv:2406.15539 [hep-ex]].

16. D. Abrams, . . . F. Hauenstein, . . . C. Hyde, . . . M.Khachatryan, . . . M.N.H. Rashad *et al.* "The EMC Effect of Tritium and Helium-3 from the JLab MARATHON Experiment," [arXiv:2410.12099 [nucl-ex]], submitted to Physical Review Letters Oct 2024.

B. Talks, Colloquia and Seminars

1. Moskov Amaryan, "K-long Facility at JLab for the Strange Hadron Spectroscopy", talk at APS April Meeting in Sacramento, CA, April 2 - 6, 2024.

2. Moskov Amaryan, "K-long Facility at JLab for the Strange Hadron Spectroscopy", invited talk at NSTAR2024 in York, United Kingdom, June 17 - 21, 2024.

3. Carlos Ayerbe-Gayoso: The Large Area/Acceptance Detector (LAD) experiment (E12-11-107) Status, invited talk at the Hall C Winter Meeting, Jefferson Lab, Jan 19th 2024.

4. Carlos Ayerbe-Gayoso: DIRC Tagger simulation, invited talk at the EIC-DIRC meeting, May 21st 2024.

5. Carlos Ayerbe Gayoso: The Large Area/Acceptance Detector (LAD) experiment, invited talk at the 2024 Joint Photonuclear Reactions and Frontiers and Careers Workshop, MIT, Cambridge, MA, 710 Aug 2024.

6. Mohammad Hattawy: "BONuS12 experiment update", Working Group Talk at the CLAS Collaboration Meeting, CNU Newport News (VA), June 25-28, 2024.

7. Mohammad Hattawy: "Update on BONuS12 Analysis", Working Group Talk at the CLAS Collaboration Meeting, Newport News (VA), November 12-15, 2024.

8. Charles Hyde: “Z-Tagging Mini-DIRC at the Downstream Ion Focus of an Electron Ion Collider 2nd Detector”, contributed talk to APS DNP Meeting Oct 6-10, 2024, Boston MA, Mini Symposium: “EIC Beyond ePIC”.

9. Charles Hyde: “DVCS on Nuclei” invited talk to CFNS Workshop on Precision QCD predictions for *ep* physics at the EIC (III): Opportunities with a second IR, 23–27 Sept 2024.

10. Charles Hyde: “Experimental Aspects of Deep Virtual Exclusive Scattering”, two lectures (3 hours total) at the First International School of Hadron Femtography, 16–25 Sept 2024, Newport News, VA.

11. Charles Hyde: “Deep Threshold Phi-Production”, invited talk to Super Big Bite Collaboration meeting 13 Sept 2024, Newport News VA.

12. Charles Hyde: co-organizer of the First International School of Hadron Femtography 16–25 Sept 2024, Jefferson Lab, Newport News, VA.

13. Mitchell Kerver “NPS Setup & Performance”, Hall C Winter Meeting, 18-19 Jan 2024, Newport News VA.

14. Mitchell Kerver: “The Neutral Particle Spectrometer in Hall C”, invited talk, Joint Hall A/C Collaboration Meeting, 15-16 July 2024, Newport News, VA.

15. Sebastian Kuhn: “Measurement of the Nucleon Spin Structure Functions for $0.01 < Q^2 < 1$ GeV^2 Using CLAS”, Plenary Talk at the CLAS Collaboration Meeting, Newport News (VA), March 12-15, 2024.

16. Sebastian Kuhn: “Duality in Spin Structure Functions”, Presentation to the Theory-Experiment Dialog (TED) Meeting, Newport News (VA), June 21, 2024.

17. Sebastian Kuhn: “RG-C Jeopardy”, Working Group Talk at the CLAS Collaboration Meeting, CNU Newport News (VA), June 25-28, 2024.

18. Sebastian Kuhn: “CLAS12 RG-C Jeopardy Review”, Presentation to PAC52, Newport News (VA), July 10, 2024.

19. Sebastian Kuhn: “Update on RG-G Preparation”, Working Group Talk at the CLAS Collaboration Meeting, Newport News (VA), November 12-15, 2024.

20. Christine Ploen: “Beamline Calibrations Status - BPMs and BCMs”, NPS Collaboration Meeting, 17-18 July 2024, Newport News, VA.

21. Noah Swan: “The CaFe Experiment”, Jefferson Lab Hall A/C Collaboration meeting, Newport News, VA, 15 July, 2024.

22. Darren Upton, Sebastian Kuhn: “Machine Learning Parameterization of the Proton’s Spin Structure Function”, 91st Annual Meeting of the Southeastern Section of the APS, UNC Charlotte (NC), October 24-26, 2024.

23. L.B. Weinstein: "Data Visualization", invited talk presented at the 2024 Joint Photonuclear Reactions and Frontiers and Careers Workshop, Cambridge, MA, August 7-10, 2024.

24. L.B. Weinstein: "Novel Experimental Results in Nucleon-Nucleon Short Range Correlations", invited talk presented at the APS April meeting, Sacramento, CA, April 3-6, 2024.

C. Theses

1. Pushpa Pandey, "Longitudinal Solid Polarized Target for CLAS12 and Study of Spin Structure of Nucleons", Ph.D Thesis, Old Dominion University, May 2024, Dr. S Kuhn, supervisor.

2. Tyler Viducic, "Measurement of the Photoproduction Cross-Section of f_1 (2085) in the exclusive reactions $\gamma p \to p' K^{\mp} K_s \pi^{\pm}$ at $7.5 < E_\gamma < 11.5$ GeV with GlueX at Jefferson Lab", Ph.D. Thesis, Old Dominion University, August 2024, Dr. M. Amaryan, supervisor.

3. Caleb Fogler, "Measuring CLAS12 D(e,e'pi) Cross Sections for e4nu", Ph.D. Thesis, Old Dominion University, December 2024, Dr. L. Weinstein, supervisor.

D. Proposals with ODU co-Spokespersons

1. H. Avakian, T. Hayward, C. Dilks, K. Gates, C. Keith, S. Kuhn,* S. Niccolai, N. Pilleux, and S. Polcher Rafael, "Run Group C Jeopardy Update Document", submitted to PAC52 in May 2024. Approved for the requested 40 PAC days extension.
   * Spokesperson and Contact Person

2. W. Brooks,*,** ..., S. Kuhn,* ..., M. Arriata,* *et al.*, "CLAS12 Run Group G Jeopardy Update Document", submitted to PAC52 in May 2024. Re-approved for the requested 55 PAC days.
   * Spokesperson
   ** Contact Person

IV. PERSONNEL

A. Faculty

- Moskov Amaryan is a member of the GlueX collaboration and is also leading the K-Long Facility (KLF) collaboration. The KLF collaboration formed to work on realization of the approved KLF proposal to conduct experiments with a secondary beam of neutral K-long in Hall D. The collaboration has attracted members from 68 universities world wide and is among the largest collaborations at JLab. The proposal was approved by PAC 48 in 2020.

- Stephen Bültmann is working on the analysis of the Bonus12 experiment, which took data in the spring and summer 2020. He is also involved in the HPS experiment. He is supervising graduate students Madhusudhan Pokhrel and Yu-Chun Hung who are working on the Bonus12 experiment, focusing on all aspects of the data analysis.

- Charles Hyde is focused on Deep Virtual Exclusive Reactions, and and simulations and R&D for the electron-ion collider. Dr. Hyde is co-spokesperson on 12 GeV DVCS experiments E12-13-010 and E12-22-006, both part of the Neutral Particle Spectrometer (NPS) suite of experiments in Hall C. His doctoral student Dilini Bulumulla graduated in August 2023 with a thesis on deep virtual σ- and ρ-meson production with CLAS-12 Run Group A data. His doctoral students Mitchel Kerver and Christine Ploen are working on the NPS DVCS and Deep π^0 experiment(s) currently running in Hall C. Mitchel Kerver received partial support in 2023 from a Center for Nuclear Femtography graduate fellowship. Christine Ploen received partial support in 2022 from a JSA graduate fellowship. Dr. Hyde collaborates with CUA, Stony Brook University, and GSI on DIRC development for the EIC. He is also a 'Physics Convener' of the EICUG working group on a "2nd EIC Detector'. He continues simulation work on exclusive processes on nuclei at the EIC.

- Sebastian Kuhn continues to lead the CLAS12 run group C. RG-C has completed a 9-month experimental run in 202223 which used longitudinally polarized ammonia and deuterated ammonia targets to measure inclusive, semi-inclusive and exclusive spin observables with protons and deuterons. He supervised Dr. Pushpa Pandey, who received her Ph.D. in May 2024, on the design, prototyping, construction and testing of the polarized target, and Darren Upton, who is analyzing RG-C data. In addition, he is working on fits of world data for spin structure functions and two publications based on the EG4 experiment. Dr. Kuhn is also leading the BONuS collaboration (run group F), which took data in 2020 and is now preparing the first publication of results on the neutron to proton structure function ratio.

- Stepan Stepanyan is a senior staff scientist in Hall B at Jefferson Lab and Jefferson Lab professor at ODU. He is a co-spokesperson of the Time-like Compton scattering and J/ψ experiments on CLAS12 and a co-spokesperson of the HPS experiment. He is supervising graduate student Mariana Tenorio on her J/Ψ analysis of the CLAS12 run group A data.

- Lawrence Weinstein studies short range correlations in nuclei, with attention to the relationships between correlations and nucleon modification in nuclei (the EMC effect). He is supervising postdoc Carlos Ayerbe Gayoso on preparations for the LAD experiment in Hall C, and graduate students Caleb Fogler (analysis of pion production from Run Group B, graduated December 2024) and Noah Swan (analysis of the CaFe experiment). He is analysis coordinator for Run Group M (short range correlations and $e4\nu$) and for the Hall C CaFe experiment. He is co-spokesperson of seven active Jefferson Lab experiments.

- Dr. Mohammad Hattawy is a Research Assistant Professor in the ODU Physics Department. He is working on simulation and is leading the data analysis for the BONuS experiment (Run Group F). He is co-supervising our Ph.D. students Madhusudhan Pokhrel and Yu-Chun Hung on this analysis. He is also responsible for our computational cluster. He is supported 50% by this grant and 50% by matching funds from ODU.

B. Postdoctoral Research Associates

- Dr. Carlos Ayerbe-Gayoso joined our group in September 2023. His work is focused on our Hall C experiments in Deep Exclusive Compton Scattering (Hyde), and the structure of bound nucleons (Weinstein), as well as R&D for the future electron-ion collider

- Dr. Vitaly Baturin joined our group in July 2019. He is working with Dr. Amaryan on the K-Long Facility realization in Hall D.

C. Graduate Students

We supported eleven full time graduate students at least partially from the grant during the past year. Information about the starting and estimated completion dates for each student is available in Table 9.

1. Caleb Fogler (supervisor L. Weinstein) analyzed 4-GeV RGB $d(e, e'\pi^{\pm})$ data from CLAS12 He graduated in December 2024.

2. Mitchell Kerver (supervisor C. Hyde) is currently working on the DVCS experiment in Hall C. He is in part supported by the Center for Nuclear Femtography.

Student	Passed Written Qualifier	Funding Source	Degree Actual (Expected)	Advisor	Project Status
Tyler Viducic	Aug 2017	DoE	Aug 2024	Amaryan	Photoproduction of axial-vector meson f1(1285) GlueX
Madhusudhan Pokhrel	Aug 2018	DoE	(May 2025)	Bueltmann	Neutron structure function (Hall B Bonus12)
Caleb Fogler	Jan 2019	DoE	Dec 2024	Weinstein	E4nu analysis (Hall B RG-B / BAND)
Mitchell Kerver	Aug 2018	DoE	(May 2025)	Hyde	p,n DVCS/pi0 Hall C
Christine Ploen	Aug 2021	DoE	(Dec 2025)	Hyde	p,n DVCS/pi0 Hall C
Pushpa Pandey	Aug 2018	0.5 DoE + 0.5 SURA fellow	May 2024	Kuhn	Nucleon spin structure (Hall B RG-C)
Yu-Chun Hung	Jan 2020	DoE	(Aug 2025)	Bueltmann	Hall B Bonus12 analysis
Mariana Tenorio	Jan 2022	DoE (CNF)	(Aug 2025)	Stepanyan	Tagged J/psi production (Hall B RG-A)
Noah Swan	Aug 2021	DoE	(Aug 2025)	Weinstein	Short range correlations (Hall C CaFe)
Daniel Barton	(Jan 2025)	DoE	(2027)	Amaryan	Axial-vector meson f1(1420) with GlueX
Darren Upton	May 2024	DoE	(2028)	Kuhn	CLAS12 nucleon spin structure
Sashi Nepal	May 2024	ODU	(2028)	Amaryan	K_L Facility

FIG. 9. ODU graduate students.

3. Pushpa Pandey (supervisor S. Kuhn) analyzed 2022 RG-C data and graduated in May 2024.

4. Christine Ploen (supervisor C. Hyde) is working on the DVCS experiment in Hall C.

5. Tyler Viducic (advisor Dr. Amaryan) joined the GlueX collaboration in the fall 2020 and analyzed an axial vector meson channel. He graduated in August 2024.

6. Madhusudhan Pokhrel (supervisor S. Bueltmann) is working on Bonus12 data analysis.

7. Yu-Chun Hung (supervisor S. Bueltmann) is working on Bonus12 data analysis.

8. Mariana Tenorio (supervisor S. Stepanyan) is working on the J/psi analysis of RG-A data.

9. Noah Swan (supervisor L. Weinstein) analyzing the CaFe experiment data taken in Hall C.

10. Daniel Barton (supervisor M. Amaryan) is working on the analysis of an axial vector meson with data taken by the GlueX collaboration.

11. Darren Upton (supervisor S. Kuhn) is working on the analysis of the RG-C experiment in Hall B.

D. Technician

Alexander Garrett is our full time technician. He was hired in the spring of 2024. Having a dedicated technician is critical for our ability to efficiently mount large hardware projects. 50% of this salary is paid by ODU as part of the Institutional Support for this grant. He has worked on the LAD laser system and on detector development for the EIC.

E. Computer Support

ODU provides funds for computer support as a cost share contribution to this grant. These funds are used in 50% FTE support of Dr. Mohammad Hattawy.