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FROM QUARKS TO NUCLEI

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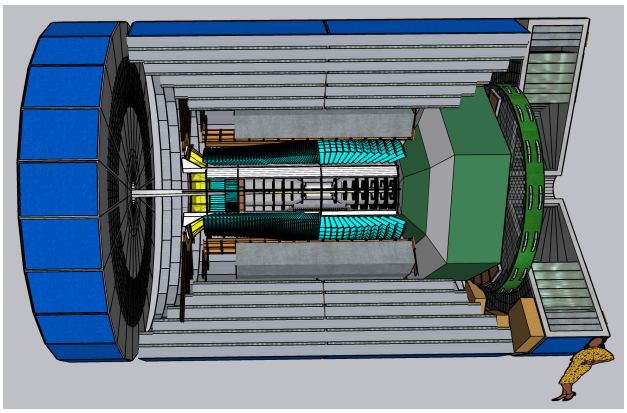

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I. INTRODUCTION

A. Project Introduction

The Experimental Nuclear Physics Group at Old Dominion University proposes to lead a program of six major research initiatives:

- Investigate the quark-gluon structure of protons and neutrons in Deep Inelastic Scattering and through precision measurements of deeply virtual Compton scattering.
- Study the role of two-nucleon correlations in nuclei and the origin of the EMC effect.
- Conduct a comprehensive study of light mesons and baryons and their decay modes.
- Explore physics beyond the Standard Model with the Heavy Photon Search experiment.
- Prepare for the Electron Ion Collider.
- Prepare a K_L Facility for Strange Hadron Spectroscopy.

B. Summary of Accomplishments in the Last Three Years

Over the past three years 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 several Jefferson Lab 12 GeV experiments including
  - the CLAS12 Run Group F Bound Nucleon Structure (Bonus12) experiment (2020);
  - the Heavy Photon Search (HPS) experiment in Hall B (Summer 2021);
  - the CLAS12 Run Group M experiments using nuclear targets (2021 – 2022);
  - the CLAS12 Run Group C experiments using the new solid polarized target (6/2022 to 3/2023).
- We gained PAC approval for three experiments.
- We are co-spokespersons of 14 approved 12-GeV experiments and coordinate three CLAS12 Run Groups;
- We helped build crucial apparatus for many Jefferson Lab experiments (in addition to the CLAS12 Region II Drift Chambers from a prior grant period) including
  - the new BONuS12 proton recoil detector and high pressure deuterium gas target,
  - the (separately funded) CLAS12 longitudinally polarized target (NH_3, ND_3, LiD and LiH);
- We published 24 peer-reviewed papers as primary authors, including five PRL, two Nature (one with ODU co-lead author) and three Nature Physics papers, out of a total of 57 papers.
- We graduated eight Ph.D. students.
- We supervised six Bachelor's Theses on topics linked to our research program.
- We gave 77 colloquia, seminars, and conference talks or posters.
- We co-organized one International Workshop.

C. Project Summary

The research program outlined below is carried out predominantly at Jefferson Lab, involving electron or photon beams scattering off nuclear targets. It is focused on investigating the quark-gluon structure of nucleons, the spectroscopy of hadrons, nuclear effects due to the correlation of nucleons inside the nucleus, and physics beyond the Standard Model.

We are currently taking data with the new solid polarized proton and deuteron target and the CLAS12 detector for Run Group C, measuring the spin structure of the nucleon and Deeply Virtual Compton Scattering (DVCS) to investigate the three-dimensional quark-gluon structure of the nucleon. We will complete data taking in 2023, followed by calibration and data analysis.

We are leading the analysis of the recently collected data for the BONuS12 experiment to measure the structure function of the quasi-free neutron. The experiment used a new Radial Time Projection Chamber fo tag recoiling protons in the electron scattering process off a high-pressure deuterium gas target. Over the next three years we plan to complete the analysis and publish results for the neutron to proton structure function ratio.

Our group is involved with and preparing for DVCS and time-like Compton scattering experiments in Halls A, B and C.

Our hadron spectroscopy program will focus on decay modes of light mesons and the search for hybrid mesons with CLAS and in Hall D with photoproduction experiments (GlueX collaboration). We will also lead the development and construction of the K_L facility in Hall D with data taking envisioned for 2025.

The nature of nucleon-nucleon Short Range Correlations and their connection to bound-nucleon and nuclear structure are the focus of our Physics of the Nucleus program. In the fall 2022 we will measure the change in the proton momentum distribution when one adds eight neutrons to the ^{40}Ca nucleus in the Hall C CaFe experiment. We are leading the analysis of Run Group M, which took data on SRCs using many targets and beam energies in Hall B. We will also continue to test neutrino-scattering energy-reconstruction techniques and event generators using electron scattering data with known incident energies.

We will continue our leadership role in the effort to find physics beyond the Standard Model in the Heavy Photon Search experiment in Hall B.

Finally, we are leading contributors to the detector development for the new Electron Ion Collider.

D. List of Personnel

Faculty: Drs. M. Amaryan, S. Bueltmann, G. Dodge (senior personnel), C. Hyde, S. Kuhn, S. Stepanyan, L.B. Weinstein.
PostDocs: Drs. V. Baturin, A. Karki and M. Hattawy (Research Assistant Prof.).
Graduate Students: D. Bulumulla, C. Fogler, Yu-C. Hung, M. Kerver, V. Lagerquist, P. Pandey, C. Ploen, M. Pokhrel, N. Swan, M. Tenorio-Pita, T. Viducic.
Technician: T. Hartlove.
Six graduate students, two postdocs and half of the technician salary are presently funded through this grant.

II. PROJECT DESCRIPTION

A. Nucleon Structure

1. Tagged Structure Functions

As part of a complete three-dimensional mapping of the parton (quark and gluon) distribution inside the nucleon, the longitudinal momentum and spin carried by valence quarks at very high Bjorken-x is still of high theoretical [1] and experimental [2] interest, both as a limiting case and as a constraint for perturbative QCD (pQCD)-based analyses of Generalized (GPD) and Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs). At the same time, quark distributions at large x are also needed as input for cross section calculations at colliders such as the LHC or the Tevatron [2], to extract spin structure functions from measured asymmetries [3, 4], for tests of quark-hadron duality in the nucleon [5, 6] and as ingredients for precision measurements of the EMC effect [7]. For a very recent prominent example, see the Supplementary Materials for the paper on new results on the mass of the W-boson [2]. Of particular interest is the asymptotic behavior of the ratio of d over u quark distributions as $x \to 1$. Several experiments in Jefferson Lab's Halls A and B have been approved, with high rating, to access this observable, and have been featured in the 2015 NSAC Long Range Plan.

The first such experiment, "Marathon", has been successfully completed [8]. However, due to the model-dependent assumptions needed to extract the free nucleon ratio $F_{2n}(x)/F_{2p}(x)$ from a measured ratio of tritium over helium-3 nuclei [9, 10], it is highly desirable to measure this ratio with a different method, with largely independent systematic and model uncertainties, through the BONuS12 experiment. In BONuS, a slow, backward-going spectator proton is detected in coincidence with the scattered electron in $\mathrm{D}(e, e' p_s)X$ to ascertain that the scattering took place on a relatively low-momentum neutron inside the deuteron, which is not far off-shell and doesn't have significant final state interactions with the spectator proton. In addition, the measured proton momentum can be used to kinematically correct the scattering kinematic variables for the initial motion of the neutron. The first pioneering measurement of this kind [11–14] used the CLAS detector in Jefferson Lab's Hall B to detect the scattered electrons from electron beams of 2.1, 4.2 and 5.3 GeV impinging on a deuteron target, together with a novel low-momentum proton recoil detector (a Radial Time Projection Chamber, or RTPC [15]).

The follow-up experiment BONuS12 is part of the "CLAS12 Run Group F" (RG-F, led by Dr. Kuhn) which also includes a second experiment to measure neutron DVCS using the same spectator method. BONuS12 uses the energy-upgraded CEBAF beam and CLAS12 to significantly extend the precision and kinematic coverage, extending the measured range in x up to $x = 0.8$. Members of the ODU group, including three regular faculty (Drs. Bültmann, Dodge and Kuhn), one Research Assistant Professor (Dr. M. Hattawy), five graduate students (N. Dzbenski, Ph.D. May 2020; D. Payette, Ph.D. May 2021; J. Poudel, Ph.D. May 2022; Madhusudan Pokhrel and Yu-Chun Hung - advisor: S. Bültmann) as well as four undergraduate senior thesis students (D. Cruickshank, F. Estacion, S. Minier and

FIG. 1. The BONuS12 Radial Time Projection Chamber on the floor in Jefferson Lab's Hall B. The detector is to the left, surrounded with flex-board adaptor electronics. All 17280 readout channels are connected with mini-coax cables to the DREAM front-end electronics (far right). The entire detector was inserted in the center of the CLAS12 detector (background), replacing the standard Central Vertex Tracker.

C. Stubenrauch) and our technician, T. Hartlove, have been central to the preparation and execution of the experiment and the analysis of the collected data. We were responsible for the final testing of the RTPC detector with cosmic radiation and its installation in the beamline, for the target design and other ancillary gas systems, for the operation and trouble-shooting of the data acquisition electronics and readout, and for developing the online monitoring and analysis software as well as the Monte Carlo simulation.

RG-F was scheduled for 80 calendar days (corresponding to 40 "PAC days" or the full approved run time) in Spring of 2020. Due to the pandemic, the run was interrupted for 4 months while Jefferson Lab was in lockdown, but then resumed and completed the entire allotted time during the time span August-September 2020. During that time, the ODU group assumed 70% of all run coordinator duties and covered about one quarter of all experiment shifts (due to travel restrictions for out-of-state CLAS collaboration members). We also provided on-call target and detector experts, and supported the run with near-online data analysis and detector calibration.

Since the conclusion of the experiment in September 2020, we have provided much of the effort to calibrate CLAS12 and the RTPC, and to analyze the data, including analysis software development and "cooking" (low-level decoding and analysis of the data). Our Research Assistant Professor, Dr. Hattawy, has served as "chef" and as analysis and cal-

ibration coordinator for Run Group F. We have also continued to study the performance of the RTPC used during the experiment, setting up a test stand with cosmic ray triggers in our lab at ODU and involving 3 undergraduate and one graduate student in a series of measurements of the drift properties of the RTPC for different gases and high voltage settings.

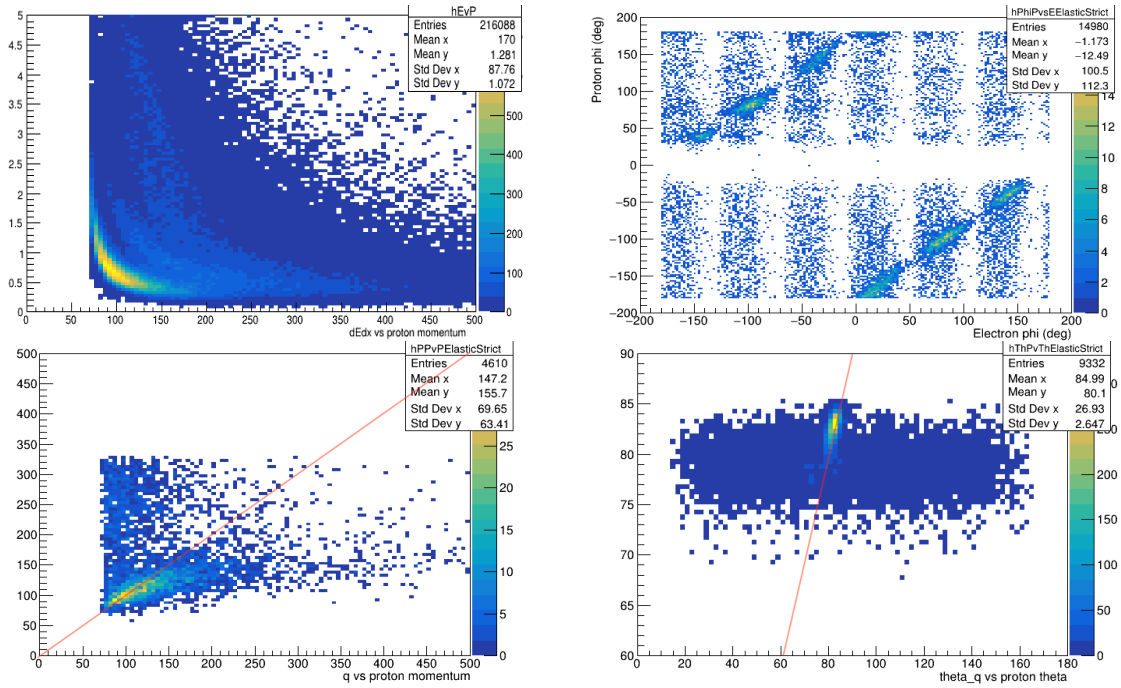

FIG. 2. First analysis results from the BONuS12 experiment. The top left panel shows the energy loss of particles in the RTPC vs. their momentum, clearly exhibiting the band for protons (bottom left). The top right panel shows the correlation between the azimuthal angle of elastically scattered electrons and coincident protons in the RTPC, which are expected to be 180° apart. The bottom two panels show the expected (y-axis) vs. measured (x-axis) proton momentum (left) and polar angle (right) for events from radiative elastic scattering. The red lines indicate the theoretical expectation.

Status: At this point, we have completed all required improvements to the tracking and reconstruction software, including a new Kálmán filter to improve the momentum resolution of the RTPC (contributed by our collaborators at IJCLab, France). We have developed particle ID methods to separate protons, deuterons, and heavier target fragments from electron interactions in the target. We have established a set of golden runs with acceptable running conditions, and studied timelines of all detector responses. All CLAS12 detectors and the RTPC have been thoroughly calibrated and characterized. Based on this work, we have passed the required Pass1v1 cooking review on June 17, 2022, and have since processed the entire data set from summer 2020 (which contains most of the statistics for our Physics analysis) for higher-level analysis. Some of the results of our calibration procedures can be seen in Fig. 2.

Planned work for the next 3 years: With the major part of the data from RG-F decoded and ready for higher-level physics analysis, we are aiming for preliminary Physics results

to be available during the first year of the renewed grant. Until then, we will refine all quality, particle ID and event selection cuts for each set of running conditions, and develop the necessary background subtraction and acceptance corrections. We will first follow the model of the original BONuS experiment (Baillie et al. [11]), where the ratio of tagged to inclusive yield is used to extract the ratio of neutron to deuteron structure function, normalized to the well-understood region around $x = 0.3$. During the remainder of the first year, we will present these results and prepare a first publication in a letter journal. We will also publish a technical paper describing the construction, operation and performance of the RTPC - this paper is already partially written.

During the second year, we will refine our analysis, adding data from the Spring 2020 run that had to be stopped due to the pandemic, and using a full-blown Monte Carlo simulation of all aspects of the experiment to extract tagged neutron structure functions as a function of spectator proton momentum and angle. This will allow us to compare our results with existing and future calculations of nuclear corrections and Final State Interactions [16], and apply corrections based on these models. During that time, we will also extract data on neutron DVCS with spectator tagging.

We expect to complete the final, archival paper including all results in year three of the grant cycle.

To support this effort, we will need continued funding for at least two graduate students working on RG-F as well as a postdoc working on BONuS12 analysis for about 50% of their time.

2. Spin Structure Functions

Understanding the composition of not only the nucleon mass, but also its total angular momentum, in terms of the elementary partons (quarks and gluons) and their strong interactions (QCD), has been a fundamental goal of hadronic physics and the focus of a long-standing world-wide experimental effort. Our group has provided strong leadership in this effort, beginning with SLAC experiments E142, E143, E154 and E155-E155x. Since 1992, we have assumed a central role in the large program to map out the spin structure of the proton and the deuteron in Jefferson Lab's Hall B. This program encompasses measurements of inclusive, semi-inclusive and exclusive target and double-spin observables in electron-nucleon (proton and deuteron) scattering over a wide range in momentum transfer Q^2 (from near the photon point to the scaling region) and final state mass W (from elastic and quasi-elastic to deep inelastic scattering). Once again, we focus in particular on the valence quark region and the transition from hadronic to partonic degrees of freedom.

We have completed our analysis of the data sets taken in the 6-GeV era in Jefferson Lab's Hall B with polarized targets and beams in CLAS (EG1a, EG1b, EG4 and EG1-DVCS). Our main effort for the last 3 years and the coming 3 years is the CLAS12 Run Group C with a new longitudinally polarized proton and deuteron target, and 11 GeV polarized electron beam in Hall B. This run group, which is coordinated by S. Kuhn, comprises eight different experiments which have been scheduled for a total of 120 "PAC days", corresponding to nearly 9 calendar months, starting in June 2022.

Questions that will be addressed by the expected data from RG-C include:

- What is the the polarization of the valence u and d quarks in the limit $x \to 1$, where a single quark carries nearly all of the nucleon momentum? There are significantly different predictions for this quantity from various quark models, pQCD expectations and parametrizations of existing data. This question is not yet resolved [17–19] and will require input from measurements with polarized ^{3}He, proton and deuteron targets at the highest Bjorken-x accessible at Jefferson Lab.

- How much does orbital angular momentum of quarks contribute to the nucleon spin? This will be addressed by measuring Deeply Virtual Compton Scattering on polarized protons and neutrons, and extracting Generalized Parton Distributions within a global fit.

- How does the transverse momentum and spin of quarks correlate with the helicity of the nucleon? Measurements of semi-inclusive single- and double hadron production in the DIS region (SIDIS) will allow us to extract information on the relevant transverse momentum dependent (TMD) parton distribution functions.

The first of these physics goals is the subject of Experiment E12-06-109 which will measure spin structure functions over the range $0.06 < x < 0.8$. (S. Kuhn is the contact person for E12-06-109, and he and S. Bültmann are co-spokespersons). In addition, the data from this experiment will improve the precision of polarized PDFs from DGLAP-based parametrizations and the Q^2-dependence of moments of spin structure functions, which are sensitive to higher twist contributions.

In the following, we give more details on the work done over the past three years, as well as our plans for the next three-year grant period.

EG4

The EG4 experiment measured spin structure functions g_{1p} and g_{1d} at very low Q^2 (down to $Q^2 \approx 0.02$ GeV^2) to test predictions for various sum rules based on chiral perturbation theory (χPT). Over the past 3 years, we have completed the analysis of the proton data which were published in "Nature Physics" [20]. Based on data from both proton and deuteron, we extracted the Q^2-dependence of the Bjorken integral down to very low Q^2 [21]. We are now finalizing an archival paper that summarizes all results from EG4, including a first ever extraction of neutron spin structure functions in the resonance region.

Run Group C

Over the past three years, our group has led the preparation for a successful execution of the RG-C suite of experiments. We helped design, prototype, construct and test the new longitudinally polarized target "APolLo" (Ammonia Polarized Longitudinally) as well as the dedicated Moller shield "ELMo" (Extra Large Moller shield) and the beam raster system required for high polarization. This effort involved Drs. Kuhn and Bültmann as well as

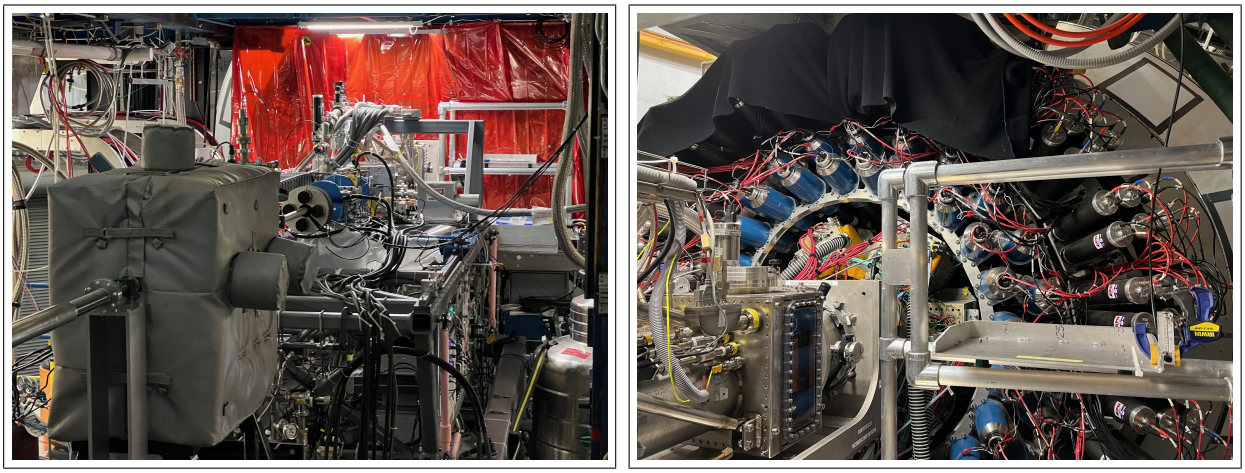

FIG. 3. Left: CLAS12 longitudinally polarized target "APolLo" after installation in CLAS12. The beamline enters from left into a beam position monitor, followed by two raster magnets and then the target assembly, which sits on top of an electronics and pumping rack. Right: Detailed view of the target loading port next to the entrance to the central vertex tracker of CLAS12.

Ph.D. students Pushpa Pandey and Victoria Lagerquist (the right-hand photo on the title page of this proposal shows our students exchanging a target cell during the experiment). Since the beginning of RG-C, Dr. Hattawy has also joined the experiment, serving as near-online data decoder ("chef") and handling monitoring timelines.

We have organized the successful ERR and beam scheduling request for RG-C. The entire 120 approved PAC-days have been scheduled to run from June 2022 through March 2023 (excluding a short holiday break from December 2022 to January 2023). The polarized target was successfully installed in CLAS in May/June 2022 (see Fig. 3) and data taking began in mid-June (see Fig. 4 for first results). Since then, we have already collected two months (30 PAC days) of data with the so-called FT-On configuration, which uses the CLAS12 forward tagger to access the most forward photons in DVCS. We will continue running for the next 4-6 months without the forward tagger and the new, larger "ELMo" Moller shield optimized for rastering the beam, to achieve the highest possible luminosity ($1 \times 10^{35}/\text{cm}^2/\text{s}$) consistent with manageable backgrounds. Some additional running in the FT-On configuration may be added in Winter 2023. Both configurations consist of equal number of days on polarized deuterons and protons, to optimize the information on the neutron that can be extracted.

Status: Over the last three years, we have

- finalized all components of the polarized target, including the cells holding the target material,
- simulated magnetic fields for NMR coils, correction coils and raster magnets and installed the magnetic field correction coils and their leads in the target,
- extensively tested the raster system, including the new driver and power supplies,

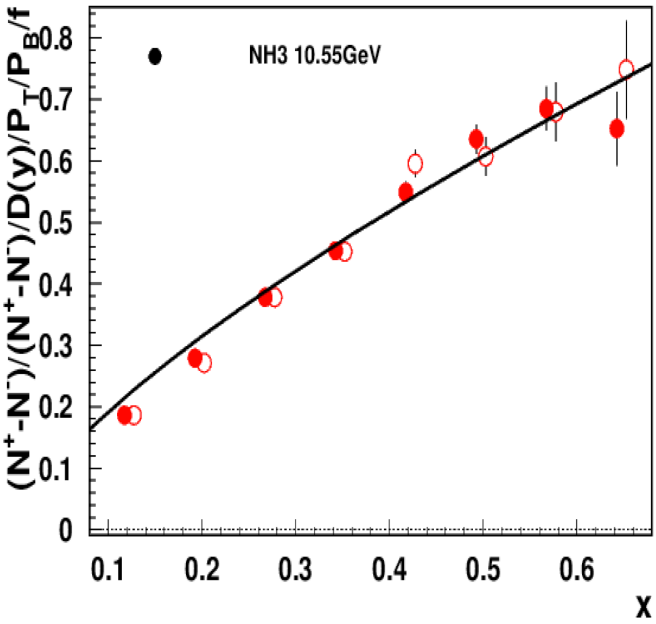

FIG. 4. First near-online analysis results for the double-spin asymmetry A_{1p} in DIS of the proton from RG-C. The points are data from two runs (corrected for beam and target polarization and dilution factor), taken with opposite target polarization, and the line is a simple parametrization of world data

- conducted several cryogenic tests of the entire target at Jefferson Lab and demonstrated that all design parameters were achieved,

- organized biweekly meetings to orchestrate the preparation of RGC among the group of spokespersons of all 8 experiments, and served as liaison with the Hall B RG-C task force,

- prepared a detailed run plan with proper accounting of all physics and background target runs, and set up all run documents, websites, and run coordinator and target expert schedules.

Roughly 1/2 of all 1-week run coordinator assignments so far were covered by our group, as well as a good fraction of the target expert on-call shifts.

Planned work for the next 3 years: Data taking for RG-C will continue through the beginning of our next grant period. For the following year, we will contribute to the massive effort necessary to calibrate all CLAS12 detectors for this extended time period, as well as developing analysis cuts and corrections. After a review by the CLAS collaboration, we will decode the entire data set ("cooking") and begin higher level analysis (expected for year 2 of the renewed grant). In year 3, we should have first results on inclusive and semi-inclusive double spin asymmetries, which we will present and publish. For the entire duration of the grant, we will need continued funding for 1-2 graduate students and 50% effort from a postdoc to complete this analysis.

3. Deeply Virtual Compton Scattering and Generalized Parton Distributions

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. Our leadership role in the EIC program is detailed in section II E

a. Hall C: DVCS and Deep Virtual π^0 Production on the proton and deuterium in Halls A & C C. Hyde is co-Spokesperson of Hall A DVCS experiments E00-110, E07-007, E08-025, E12-06-114, and Hall C experiments E12-13-010 and E12-22-006. The goal of this program is to measure absolute cross sections (unpolarized and electron helicity-dependent) as functions of Q^2 at fixed values of x_B. The Q^2-dependence of these cross sections 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. In the last three years, we published final results on neutron DVCS from our 6 GeV era DVCS experiment E08-025 [22](Nature Physics), and published the first 12 GeV deep π^0[23] (PRL) and DVCS[24](PRL) cross sections (Hall A experiment E12-06-114). We also continue preparing the Hall C Neutral Particle Spectrometer (NPS) for DVCS & deep π^0 experiments E12-13-010, the extension of E12-06-114 and a new neutron DVCS experiment ($eD \to e\gamma X$) E12-22-006 [25] approved in 2022 with an *A* rating by JLab PAC 50 [26].

We published new 6 GeV era neutron DVCS data (E08-025) in Nature Physics in 2020 [22]. In this paper, we performed a combined analysis of our $ep \to ep\gamma$ and $en \to en\gamma$ cross sections obtained at two incident beam energies for each Q^2 value, obtaining flavor separated Compton Form Factors (CFFs).

In the past three years, we completed our analysis of 12 GeV Hall A DVCS (and deep π^0 production) experiment E12-06-114. The data span three Q^2 values at $x_B = 0.36$, four Q^2 values at $x_B = 0.48$ and two Q^2 valus at $x_B = 0.60$, for a total of 2064 $(E, Q^2, x_B, t, \phi_{\gamma\gamma})$ points. The $\mathrm{H}(e, e'\pi^0)p$ data confirm the dominance of the scattering amplitude via a coupling of chiral-odd (transversity) GPDs to a higher twist distribution amplitude (DA) of the pion [23]. The dominant contribution of transversity GPDs in the model predictions is a striking consequence of chiral symmetry breaking [27–29]. We published the 12 GeV $\mathrm{H}(e, e'\gamma)p$ cross sections in [24]. We analyzed the full data set in the context of the formalism of Braun *et al.,* [30]. The primary contributions to the cross sections come from the photon helicity-conserving Compton Form Factors (CFFs): $\{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\}_{++}$. However, there are additional contributions in powers of $1/\sqrt{Q^2}$ from CFFs involving one unit of photon helicity flip: $\{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\}_{0+}$ and two units of photon helicity flip: $\{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\}_{-+}$. The variety of beam energies and Q^2 values in our data at each (x_B, t) setting, provide differential sensitivity to all 12 complex CFFs, under the assumption that we neglect QCD evolution within the range of our data [24]. Ph.D. student Hashir Rashad (C. Hyde, supervisor)

completed his dissertation on analysis of these Hall A 12 GeV DVCS data of E12-06-114 and graduated in December 2020.

b. Hall B: Deep virtual exclusive production on the proton and deuteron :

Our doctoral student Dilini Bulumulla (supervisor C. Hyde) is analyzing exclusive $H(e,e'p\pi^+\pi^-)$ data of CLAS12 Run Group A (electroproduction on liquid hydrogen). Near threshold in the $\pi\pi$ system, this process is sensitive to the pure glue component of the σ-meson wave function (the $f(500)$) [31, 32]. By analyzing the angular distribution (in the $\pi\pi$ rest frame), we aim to separate the σ- and ρ-meson channels. This is enabled by the fact that the mass spectrum in each partial wave is exactly given by the $\pi\pi$ phase shifts, in the diffractive limit. The analysis can also test s-channel helicity conservation in the ρ channel. We have completed initial efficiency studies of the four-fold coincidence spectra. The preliminary $H(e,e'p\pi^+\pi^-)$ cross section as a function of the two-pion mass is plotted in Fig. 5. The fit curve up to 0.8 GeV in the figure is a superposition of the $(J,I)=(0,0)$ and $(1,1)$ Omnès functions derived from $\pi\pi$ phase-shifts [33]. We are working on acceptance corrections to the full $\pi\pi$ angular distribution in bins of (Q^2,x_B,t). We expect Ms. Bulumulla to graduate in December 2022.

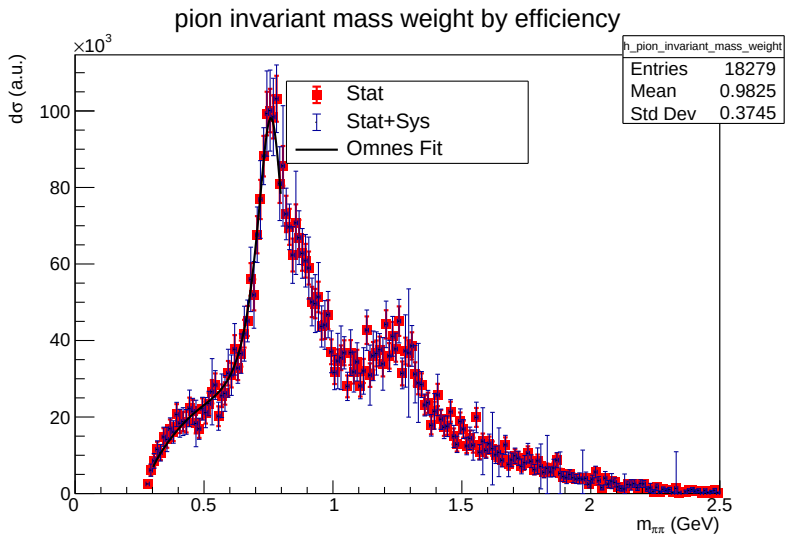

FIG. 5. Preliminary $H(e,e'p\pi^+\pi^-)$ cross section. The Omnès fit is described in the text.

Planned Deep Virtual Exclusive Workin Hall C for the Next 3 Years

In 2022, JLab PAC50 approved our new proposal, E12-22-006 with an A rating, for 44 days of beam to extract the nDVCS cross sections from the $D(e,e'\gamma)pn$ reaction with the NPS equipment in Hall C. The Neutral Particle Spectrometer (Fig. 6) features a new sweep magnet (replacing the Horizontal Bender magnet on the SHMS carriage), which allows the new $PbWO_4$ calorimeter to operate at central angles as small as 6°. Combined with the scattered electron detected in the HMS, we can reach a much broader range of DVCS kinematics (Fig. 7). In particular, we achieve up to three different incident beam energies for a fixed (Q^2,x_B) setting, greatly reducing the systematic uncertainties of our "generalized Rosenbluth" separations of the $\Re e[DVCS^\dagger BH]$ and $|DVCS|^2$ cross section terms. Projected

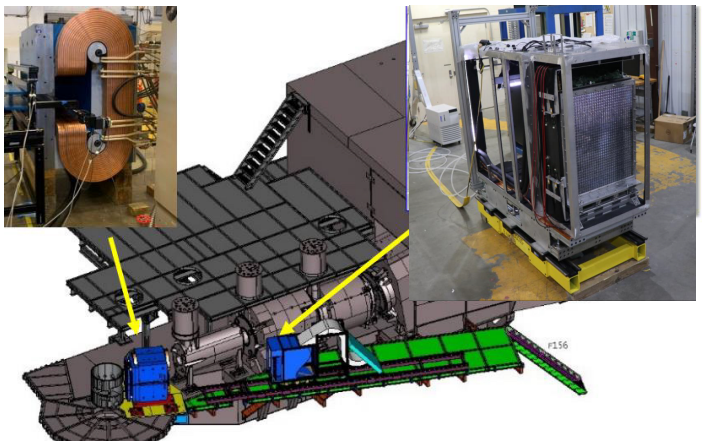

FIG. 6. CAD Drawing of NPS DVCS configuration for Hall C. Scattered electrons will be detected in the HMS (beam right. not shown). Gamma-rays will be detected in the $PbWO_4$ calorimeter (inset photo) mounted on the beam-side of the SHMS carriage (beam left). The Horizontal Bender magnet of the SHMS is removed, and replaced with the Sweep Magnet (inset photo).

proton and neutron DVCS cross sections are illustrated in Fig. 8. We anticipate pDVCS E12-13-011 and nDVCS E12-22-006 experiments will run concurrently July 2023 to March 2024. We request funding for 50% FTE Post Doc and two GRA (Christine Ploen and one new doctoral student) for this projectg.

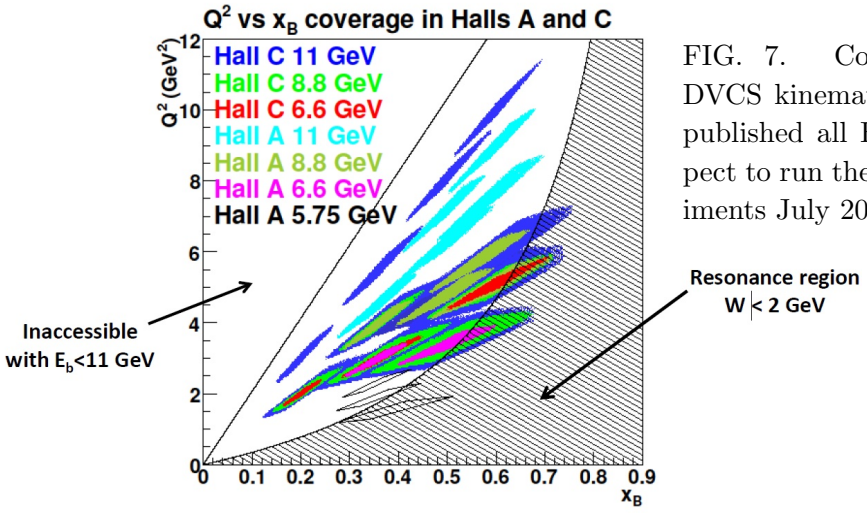

FIG. 7. Comprehensive Hall A/C DVCS kinematics. We completed and published all Hall A settings. We expect to run the Hall C p,nDVCS experiments July 2023 – March 2024.

4. Lepton-Pair Production with CLAS12

Experiments E12-12-001 and E12-12-001A aim to study the nucleon structure using the production of lepton pairs, e^+e^-, and $\mu^+\mu^-$, in the reaction $e^-p \rightarrow l^+l^-p(X)$. The experiments are part of the Hall-B CLAS12 Run Group A (RG-A), which collected about 48% of the expected statistics during the 2018 and 2019 run periods.

The analysis of Time-like Compton scattering and J/ψ photoproduction is ongoing. We have a new ODU graduate student, Mariana Tenorio Pita, who works together with students from AANL (Armenia), and Glasgow U. (UK) on the calibration and quality assessment of the data. While the previous J/ψ analysis by Dr. Joseph Newton was focused on

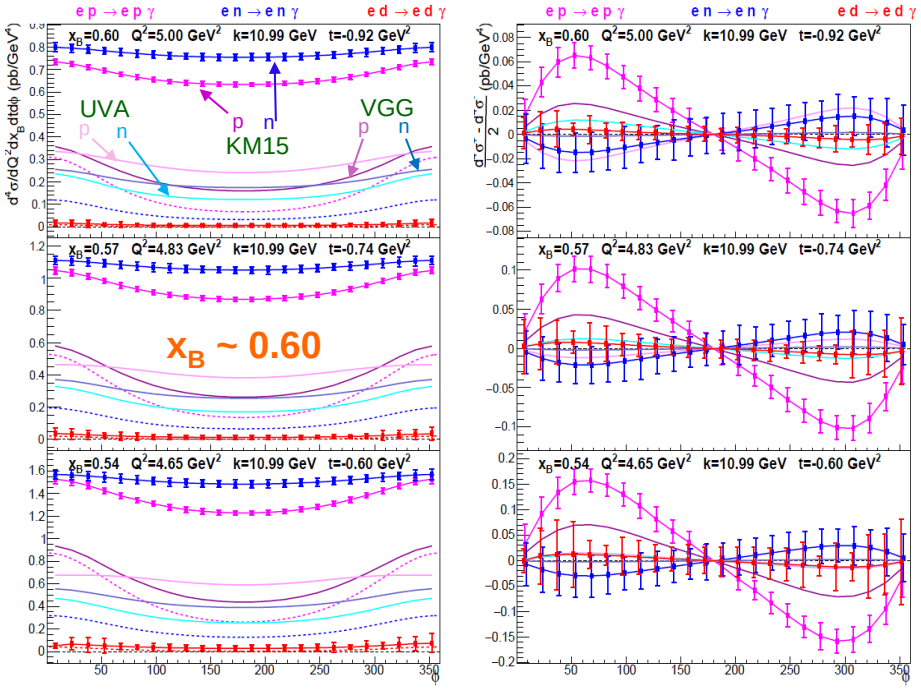

FIG. 8. Example projected cross section results for Hall C NPS DVCS experiments E12-13-010 (proton) and E12-22-006 (neutron), for $x_B \sim 0.60$. The data projections for p, n use the KM15 model [34]. Additional projections of the $|DVCS|^2$ only terms are shown for the UVA [35] and VGG [36] models. The coherent deuteron projections are from [37, 38].

untagged photoproduction, Mariana is working on the analysis of tagged production, where the scattered electron in the reaction $e^-p \rightarrow e^+e^-pe'$ is detected in the CLAS12 forward tagger system at very forward angles. This reaction has low statistics compared to the untagged case, but has the advantage of allowing the study of the reaction in a few different topologies. As a start, Mariana analyzed the reaction channel $e^-p \rightarrow e^+e^-e'(X)$ where the e^+ and e^- are from the J/ψ decay, and the missing system X is the recoil proton.

Below are some preliminary results from the physics analysis of electron pair final state.

a. Time-like Compton Scattering with CLAS12 :

The two main reasons to measure Time-like Compton Scattering are to check the universality of the Generalized Parton Distributions (GPD) formalism 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). The BSA in this reaction is similar to the beam spin asymmetry in Deeply Virtual Compton Scattering (DVCS) and, hence, addresses the question of universality of the GPDs. At the same time, the cosine moment of the TCS cross-section [39] 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 [40]. The first measurement of asymmetries in TCS, the reaction $e^-p \rightarrow e^+e^-p(X)$, has been published in Physical Review Letters [41] with Prof. S. Stepanyan (ODU) as one of the lead authors. In Fig.9, the obtained forward-backward and the beam spin asymmetries are shown as a function of the transferred momentum squared $(-t)$.

The ODU group is part of the CLAS collaboration analysis sub-group for lepton pair

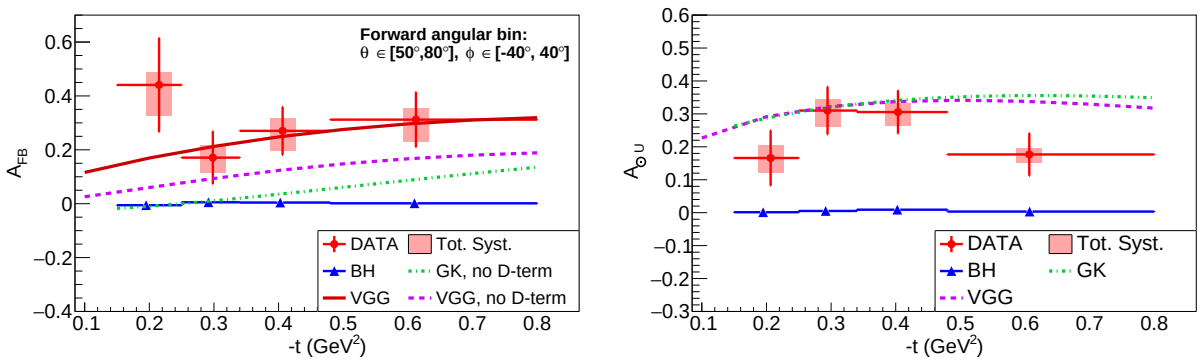

FIG. 9. The first ever measured asymmetries in the time-like Compton scattering. Left: The transferred momentum $(-t)$ dependence of the forward-backward asymmetry (A_{FB}) for the average kinematics $E_\gamma = 7.23 \pm 1.61$ GeV and $M_{e^+e^-} = 1.81 \pm 0.26$ GeV. Right: The beam spin asymmetry BSA as a function of $-t$. The average kinematics of these points is $E_\gamma = 7.29 \pm 1.55$ GeV and $M_{e^+e^-} = 1.8 \pm 0.26$ GeV. The data points are represented in red with statistical vertical error bars. The horizontal bars represent the bin widths. The shaded error bars show the total systematic uncertainty. The blue triangles show the asymmetry computed for simulated BH events. The dashed and dashed-dotted lines are the predictions of, respectively, the VGG [36, 42–44] and the GK [45–47] models, evaluated at the average kinematics.

electro- and photoproduction. Currently, the group is working on extracting detector efficiencies and photon flux normalizations using the well-known Bethe-Heitler process. A future TCS analysis will have access to a much larger data sample, which will allow finer binning of observables and studying their kinematic dependencies.

b. J/ψ Photoproduction with CLAS12 :

The continuation of the near-threshold J/ψ production measurement using electron tagging in the CLAS12 forward tagger (FT) system has two main advantages. First, it will eliminate uncertainty in the photon flux calculation for the total cross-section measurement. Second, in this final state, $e^-p \rightarrow e'e^+e^-p$, the charmed pentaquark states discovered in the (J/ψp) decay channel by the LHCb collaboration at CERN [48] will appear as a resonance in the missing mass of the reaction $e^-p \rightarrow e'X$. The analysis of CLAS12 data for the tagged J/ψ production from the CLAS12 RG-A fall 2018 data set started. Results of a subset of data collected by RG-A are shown in Fig.10.

Currently, graduate student Mariana Tenorio Pita is working on finalizing the analysis code, defining efficient cuts, and particle identification using the available data from the early processed RG-A data. The final analysis will use larger data samples.

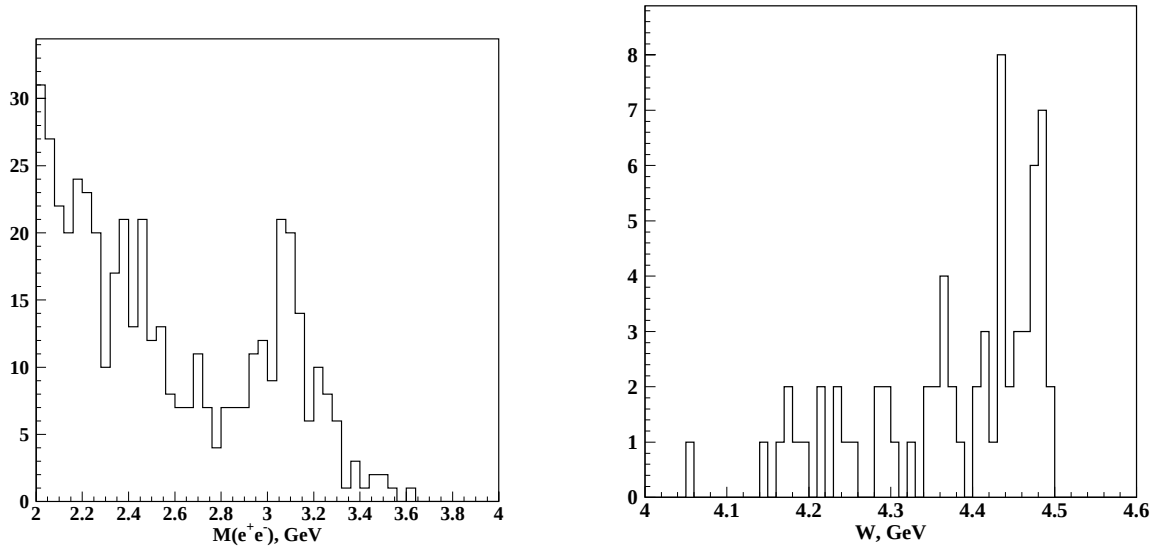

FIG. 10. Left: The invariant mass distribution of the e^+e^- pair in the reaction $e^-p \rightarrow e'e^+e^-(X = p)$. The J/$\psi$ peak is clearly visible. Right: The missing mass distribution of events under the J/ψ peak from the left is shown. The missing mass is calculated from the kinematics of the reaction $e^-p \rightarrow e'X$. Here is where one would expect to see LHCb pentaquarks.

B. Hadron Spectroscopy

1. Introduction

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 decays of light mesons in general and π^0, η and η' pseudoscalars in particular is a unique way to explore low energy QCD. By comparing data with predictions of effective field theory at low energy, Chiral Perturbation Theory (ChPT), one gains an insight into the non-perturbative regime of strong interactions and provides important information for a firmer foundation of hadronic physics rooted in the standard model. Until recently the quest for high statistics accurate experimental data was not fulfilled.

The analysis of the photoproduction and radiative decay of $\eta \rightarrow \pi^+\pi^-\gamma$ from the CLAS g11 running period was performed by graduate student Torri Roark (Ph.D. 2020, supervisor Dr. Moskov Amaryan). Obtained results were summarized in the CLAS Note and currently are under review by the collaboration.

Nilanga Wickramaarachchi, (Ph.D. 2020, supervisor Dr. Amaryan), analysed experimental data from the GlueX experiment by measuring the beam asymmetry in the photoproduction reaction $\gamma p \rightarrow K^+\Sigma^0(\Lambda\gamma)$ using polarized photon beam in Hall D. Results of this analysis are published as the fourth paper [49] from overall publications by the GlueX

collaboration.

Doctoral student Tyler Viducic (supervisor Dr. Amaryan) is analysing the photoproduction data in the reaction $\gamma p \to K_s K^{\pm}\pi^{\mp} p$ obtained with the GlueX setup in Hall D. The aim of this analysis is to measure for the first time Mandelstam t-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 $E_\gamma = (8-9)$ GeV. The same final state with $K_s K^- \pi^+ p$ can be used to study photoproduction of the a_2^- tenesor meson in the reaction $\gamma p \to a_2^-(K_s K^-)\Delta^{++}(p\pi^+)$. Preliminary analysis of this reaction was performed by undergraduate student Dakota Christian (Undergraduate Thesis supervisor M. Amaryan). It was further analysed by postdoc Shankar Adhikari by performing Partial Wave Analysis (PWA) of this reaction, however results of this analysis were not finalized yet. The main interest to this channel is due to the main GlueX topic of the search for an exotic π_1 meson, which decays to the $\eta\pi$ final state, which at the same time has another decay channel via the a_2 meson. We will continue the PWA analysis of $K_s K^-$ decay mode, which will be a valuable test in the search of the exotic π_1 meson. This may become one of the analysis tasks of the new postdoc, Abishek Karki, who will join our group October 1st, 2022.

Another major effort of our group is devoted to the development of a new secondary beam of neutral kaons, K_L for strange hadron spectroscopy, so called (KLF). The proposal was led by Dr. Moskov Amaryan, who acted as a spokesperson for this proposal and newly created KLF Collaboration with 160 members from 70 universities of 20 countries, the largest number of institutions in one collaboration ever in the history of JLab.

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

2. Photon Beam Spin Asymmetry Measurement in $\gamma p \to K^+\Sigma^0$ with GlueX

Based on general principle of the crossing symmetry, Stichel showed [50] that at small four-momentum transfer t- and large s- Mandelstam variables pion photoproduction can receive contributions from only natural parity exchange mechanism. Later, this theorem was extended to any allowed pseudoscalar meson photoproduction independent of the flavor content of mesons [51], [52]. However experimental proof in the exclusive reaction $\gamma p \to K^+\Sigma^0$ reaction has until now not been done. The SLAC measurement [53] of the beam spin asymmetry in this reaction was obtained from the sum of $K^+\Lambda$ and $K^+\Sigma^0$ reactions. Experimental study of photoproduction reaction $\gamma p \to K^+\Sigma^0$ from GlueX data was carried out with graduate student Nilanga Wickramaarachchi. In Fig. 11 (left panel) Σ^0 is reconstructed in the invariant mass of $\Lambda\gamma$. As one can see very clean peak is observed with 2% background under the peak. The beam spin asymmetry as a function of $-t$-Mandelstam is presented in Fig. 11 (right panel). The GlueX data are presented as black solid circles, while red square points with error bars are from previous SLAC measurement extracted from the sum of $K^+\Lambda$ and $K^+\Sigma^0$. The dotted line is a prediction of RPR theoretical model [54] based on Regge theory. The paper based on this analysis is published in PRC [49]

and constitute Ph.D. Thesis of Nilanga Wickramaarachchi, graduated in the Spring 2020 (supervisor Dr. Moskov Amaryan).

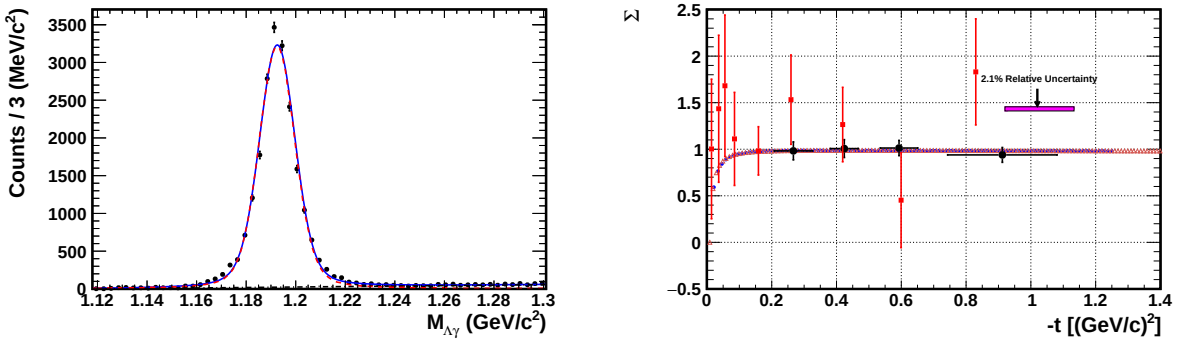

FIG. 11. (a) Invariant mass $\Lambda\gamma$ in the reaction $\gamma p \to K^+\Sigma^0(\Lambda\gamma)$. (b) Beam Asymmetry Σ vs $-t$-Mandelstam, red squares with large error bars are from previous SLAC measurement [53], solid black circles are results of GlueX measurement. The dotted curve is a result of RPR [54] model calculation.

3. Measurement of Reaction $\gamma p \to a_2^-(K^-K_s)\Delta^{++}$ with GlueX

We started to analyze reaction $\gamma p \to a_2^-(K^-K_s)\Delta^{++}$ from GlueX 2017 and 2018 data. Before doing it we reconstructed K_s in the invariant mass of $\pi^+\pi^-$ presented in Fig. 12 (left panel) using decay distance to be greater than 2 cm and collinearity angle cut, defined as the angle between the line connecting primary vertex and decay vertex and the direction of the momenta of two pions to be $\cos\Theta$ >0.98. As one can see by applying these cuts the K-short is reconstructed with a small $\sim 5\%$ background, estimated from the fit with a Gaussian plus a constant function. This allows to cleanly observe a_2^- meson and another peak around 1660 MeV, which may be superposition of π_2 and exotic π_1 meson. We are planning to perform Partial Wave Analysis to see if there is a sign for hybrid meson π_1 in this data. Currently statistics is not high enough to perform such an analysis, however we expect to get five times more in the next year. This is the first observation of a_2^- meson in photoproduction via K^-K_s decay mode and belongs to the mainstream GlueX physics program for the search of exotic mesons. One should mention that along with installation of DIRC detector in GlueX for identification of charged kaons, here it is demonstrated that reconstruction of clean K_S particle may become very important for the second phase of GlueX running for a search of hidden strangeness exotic meson states. These preliminary results were summarized in the undergraduate thesis of Dakota Christian in Spring 2020.

4. The K_L Facility at GlueX

The JLab PAC in 2020 approved KLF proposal "Strange Hadron Spectroscopy with Secondary K_L beam in Hall-D" (spokesperson M. Amaryan) for 200 days of the beam time.

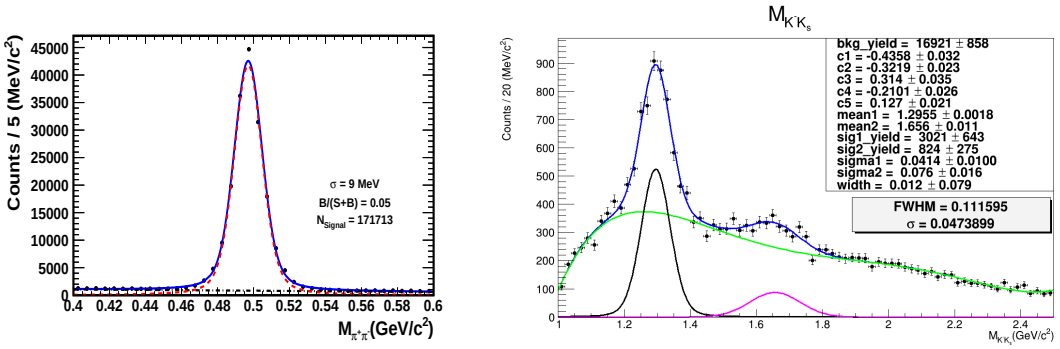

FIG. 12. Invariant mass $M(\pi^+\pi^-)$ (left panel) and invariant mass $M(K^-K_s)$ distribution in the reaction $\gamma p \to a_2^-(K^-K_s)\Delta^{++}$ (right panel).

The unprecedented 10^3 times increase of the intensity of secondary K_L beam flux on physics target, compared with previously obtained at SLAC [55] 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 missing excited states of $\Lambda^\star, \Sigma^\star, \Xi^\star$ and $\Omega^\star$ hyperons states up to M=2.5 GeV. This will provide experimental test of recent LQCD calculation [56] predicting not only 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 still not well established scalar κ meson, thus solving 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 $K^{*'}s$ with different angular momentum states.

In addition results obtained with the KLF will have a strong impact on our understanding of evolution of Early Universe at freeze-out after the Big Bang at temperatures $\simeq$160 MeV. The comparison of chemical potential of the Early Universe as a function of tepmerature 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 [57]), 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 much easier to be measured with a greater precision. Physics topics with KLF have been developed in three international workshops chaired by M. Amaryan [58–60]. The KLF proposal C12-19-001 was approved by PAC48 in 2020 for 200 days of beam time. We submitted the approved version of the proposal to the arXiv [61].

In summary in the KLF project we have three physics topics related to: a) measure missing hyperon states, b) missing strange meson states including elusive κ meson to complete the nonet of the scalar mesons and c) impact on the calculation of thermodynamic properties of the Early Universe at freeze-out 1μs after the Big Bang. The major efforts of our group in the following three years together with other KLF collaborators will be related

to build the hardware components of the KLF beamline. This includes Compact Photon Source, the Be target, as well as well as the Flux Monitor. Our postdoc Vitaly Baturin made a significant contribution to develop conceptual design for both Compact Photon Source and Be target assembly together with RadCon group of JLab and Hall D staff and engineers. The 50% of the salary of another postdoc, Abishek Karki will be paid by the Hall D at JLab to continue our efforts in the GlueX experiment as well as KLF project.

C. 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 with E. Piasetzky (Tel Aviv), Or Hen (MIT) and Axel Schmidt (GWU).

In the past three years we have taken data on three experiments at Jefferson Lab (the BAND experiment in 2019–2020 and two Run Group M experiments in 2021–2022), gained PAC approval for two new experiments [62, 63], learned a lot more about SRC, tested lepton-nucleus energy reconstruction, and made a number of connections between SRC and other phenomena, resulting in ten papers in Nature [64, 65], Nature Physics [66], Physical Review Research [67], Physical Review Letters [68], Physics Letters B [69, 70], and Physical Review C and D [71–73].

We performed the first analysis of the ratio of two-proton knock out $(e, e'pp)$ to one-proton knock out $(e, e'p)$ up to missing momenta of 1000 MeV/c from nuclei from carbon to lead [64]. We found that the pp/p ratio increased from a minimum at 400 MeV/c to a plateau at 700–1000 MeV/c. This was the first strong evidence for the transition from tensor to central correlations in nuclei. We reinforced this evidence with analysis of $(e, e'pn)$ data [70], where the pn/p ratio was flat and consistent with unity over the entire missing momentum range.

We published the second and final paper on proton knock-out cross sections from ^{3}He and ^{3}H [68]. We found that the isoscalar sum of ^{3}He plus ^{3}H, which is largely insensitive to single charge exchange rescattering, is described by calculations to within the accuracy of the data over the entire pmiss range. This validates current models of the ground state of the three-nucleon system up to very high initial nucleon momenta of 500 MeV/c.

We showed that the relative abundance of short-range pairs in the nucleus is a long-range (i.e., mean-field) quantity that is insensitive to the short-distance nature of the nuclear force [66]. This validated the scale-separated description of SRCs in nuclei.

We also continued exploring the connection between nuclear and nucleon structure [67, 74]. We found that the nucleon modification is driven by nucleons in SRC pairs.

SRC remain a fascinating topic, not just as an aspect of nuclear structure, but also because of their connections to the structure of the bound nucleon, to atomic physics, to neutrino interactions, and to neutron stars.

1. *Bound Nucleon Modification in Deuterium*

In order to provide the first direct evidence for the origin of the EMC Effect, we are measuring deep inelastic electron scattering from deuterium, detecting a high-momentum ($250 < p_s < 550$ MeV/c) spectator recoil nucleon, to determine the dependence of the neutron or proton structure function F_2 on p_s. These experiments were motivated both by the earlier $d(e, e'p_s)X$ results [75] and also by the correlation between the strength of the EMC effect in a given nucleus and the probability that the nucleons in that nucleus belong to a Short Range Correlation [13, 76–78]. These experiments complement the BoNuS program described in Section II A 1.

Jefferson Lab Experiment E12-11-107, "In Medium Nucleon Structure Functions, SRC, and the EMC effect", approved by PAC38 for 40 days of beam time in Hall C (L.B. Weinstein, co-spokesperson) will detect the scattered electron in either the HMS or the SHMS and the recoil spectator proton in a GEM and the Large Acceptance Detector (LAD). The expected results are shown in Fig. 13. In the previous grant period we completed the design of the scattering chamber and detector supports and passed the Jefferson Lab Experimental Readiness Review. This work was done by F. Hauenstein and L.B. Weinstein, working with the Hall C engineering staff. In the coming grant period we will help plan and setup the experiment, take data (anticipated in 2024), and begin analyzing the data. This work will be done by L.B. Weinstein, in conjunction with a future postdoc.

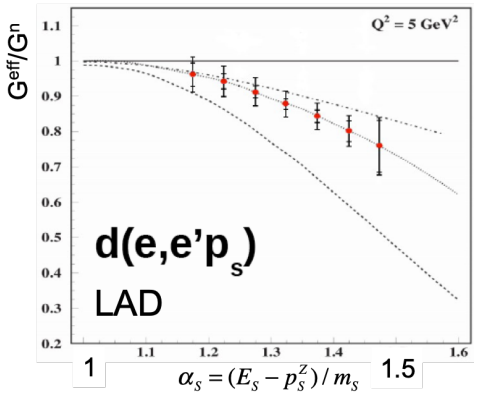

FIG. 13. Expected experimental results and model predictions for the ratio F_2^{bound}/F_2 for the neutron measured in the $d(e, e'p_s)$ reaction using LAD in Hall C. The calculations are for $x = 0.6$, $Q^2 = 5$ GeV^2 and $\theta_{pq} = 180°$ [79]. $\alpha_s = (E + p_z)/m$ is the light cone momentum where p_z is the spectator nucleon momentum antiparallel to $\vec{q}$.

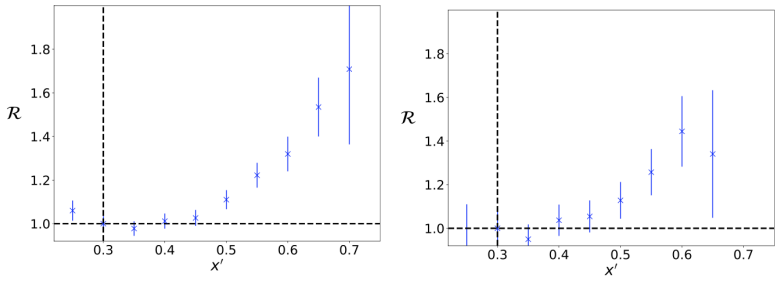

FIG. 14. PRELIMINARY: The double ratio of measured DIS $(e, e'n)$ events as a function x' to those at $x' = 0.3$ divided by the same ratio for simulation. (left) $1.3 \leq \alpha_s < 1.4$ and (right) $1.4 \leq \alpha_s < 1.5$.

Experiment E12-11-003A, "In Medium Proton Structure Functions, SRC, and the EMC Effect" (L.B. Weinstein, co-spokesperson) took data with other CLAS12 deuterium measurements as part of RGB in 2019–2020. This experiment complements E12-11-107 by measuring deep inelastic electron scattering from deuterium, detecting the spectator recoil *neutron*, in order to determine the dependence of F_2^p on p_s.

In the previous grant period we implemented the BAND detector and the material between BAND and the target into GEMC, the Hall B simulation package. While the analysis was primarily performed at MIT, we helped calibrate BAND and measure its neutron detection efficiency, analyze the data, and write the analysis note. The analysis note is under CLAS collaboration review. We looked at the double ratio for events with $Q^2 > 2$ GeV^2, $W^2 > 4$ GeV^2, $W' > 1.8$ GeV, $-1 \leq \cos\theta_{nq} \leq -0.8$, and $p_T < 0.2$ GeV/c:

$$\begin{aligned} &\frac{d\sigma_{\rm dat}(x', \alpha_S, p_T, Q^2)}{d\sigma_{\rm dat}(x'_{\rm ref}, \alpha_S, p_T, Q^2_{\rm ref})} \Bigg/ \frac{d\sigma_{\rm sim}(x', \alpha_S, p_T, Q^2)}{d\sigma_{\rm sim}(x'_{\rm ref}, \alpha_S, p_T, Q^2_{\rm ref})} = \\ &\frac{N_{\rm dat}(x', \alpha_S, p_T, Q^2)}{N_{\rm dat}(x'_{\rm ref}, \alpha_S, p_T, Q^2_{\rm ref})} \Bigg/ \frac{N_{\rm sim}(x', \alpha_S, p_T, Q^2)}{N_{\rm sim}(x'_{\rm ref}, \alpha_S, p_T, Q^2_{\rm ref})} \equiv \mathcal{R}, \end{aligned} \tag{1}$$

The preliminary results are shown in Fig. 14.

The ODU BAND work was done by graduate student Caleb Fogler, postdoc Florian Hauenstein, technician Thomas Hartlove, and co-PI L.B. Weinstein.

In the coming grant period we will continue to help analyze the data in order to get CLAS analysis approval and publication. Caleb Fogler will analyze $(e, e'\pi)$ data from the 4-GeV BAND running to compare to semi-inclusive models of pion production.

We are looking to further explore nucleon modification in nuclei with our conditionally approved proposal, C12-21-004, "Semi-Inclusive Deep Inelastic Scattering Measurement of A=3 Nuclei with CLAS12 in Hall B", L.B. Weinstein, Contact Person. This will measure ^{3}He and ^{3}H $(e, e'\pi)$ and $(e, e'K)$ SIDIS cross sections and ratios to understand the flavor-dependent EMC effect, to provide inputs to extract the d/u ratio at large x, and to measure nuclear effects in unpolarized TMDs (transverse momentum distributions) and fragmentation functions. This experiment will take advantage of the approved Hall B tritium target. During this grant period, we will work to achieve full PAC approval.

2. Nucleon knockout and Correlation Studies

Based on the ^{3}He$(e, e'p)$ and ^{3}H$(e, e'p)$ results [68], a new experiment E12-20-005: "Precision measurements of A=3 nuclei in Hall B", L.B. Weinstein, co-spokesperson, was approved by the PAC. This measurement represents a major investment by the lab to develop a new tritium target in Hall B. It will cover a much broader kinematic range and detect $(e, e'n)$, $(e, e'pn)$ and $(e, e'pp)$ events in addition to $(e, e'p)$. Work on this experiment during this grant period will primarily be by the JLab target group.

We took data for Run Group M from 11/2021 to 3/2022, including 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. L.B. Weinstein was Run Group Coordinator. We took data on d, ^{4}He, C, ^{40}Ar, ^{40}Ca, ^{48}Ca, and ^{120}Sn at 2, 4, and 6 GeV. The data is largely calibrated and we anticipate replaying the data in Fall 2022. Noah Swan implemented the solid targets in GEMC for Run Group M.

The SRC data analysis will use the high statistics and large kinematical coverage to look for 3N correlations, to separate the effects of increasing mass number and the neutron to proton ratio, to better measure the transition from mean field to short range correlated behavior and the transition from tensor to scaler dominance in SRC knockout, and to study the Q^2 dependence of *pn* dominance and other SRC characteristics. L.B. Weinstein is Analysis Coordinator for both experiments. He anticipates being on Research Leave in Spring 2023 in order to focus on the data analysis.

We will also take data in September 2022 for E12-17-005: "The CaFe Experiment: Short-Range Pairing Mechanisms in Heavy Nuclei". We will 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, and ^{54}Fe to understand the effects of adding *neutrons* on the *proton* momentum distribution as a test of *np* dominance in SRC pairs. This experiment is co-led by Carlos Yero, an NSF ASCEND Fellow working under the supervision of L.B. Weinstein, and will be analyzed by Noah Swan, an ODU graduate student.

Electrons for Neutrinos:

Accelerator-based oscillation experiments detect neutrinos by measuring charged particles produced by the interaction of neutrinos with nuclei. The extraction of neutrino oscillation parameters relies on reconstructing the incident energy of the interacting neutrino from these measured charged particles. This requires detailed understanding of the neutrino-nucleus interaction cross-section for various interaction channels, different nuclei, and a wide range of neutrino energies. However, none of these energy reconstruction techniques have been tested experimentally using beams of known energy. We exploited the similarity of electron-nucleus and neutrino-nucleus interactions to test these techniques using electron scattering.

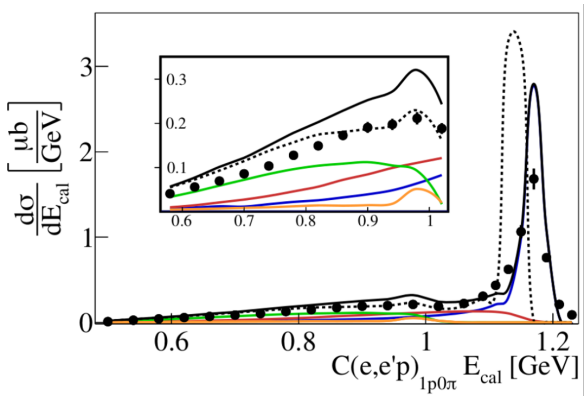

FIG. 15. The 1.159 GeV $C(e,e'p)_{1p0\pi}$ cross section plotted as a function of the reconstructed calorimetric energy $E_{cal} = E'_e + T_p + \epsilon$ for data (black points), SuSAv2 (black solid curve) and G2018 (black dotted curve) [65]. The inset shows the cross section with the same horizontal scale and an expanded vertical scale. The colored lines show the contributions of different processes to the GENIE SuSAv2 cross section: QE (blue), MEC (red), RES (green) and DIS (orange).

We analyzed 1.1, 2.2 and 4.4 GeV CLAS6 data on nuclear targets in order to deter-

mine the validity of incident-energy reconstruction techniques for charged-current neutrino-nucleus scattering. We analyzed the simplest event topology, with exactly one proton and zero charged pions. We developed a sophisticated data-based method to determine the contribution of events with undetected pions and extra protons. We found that, contrary to expectation, only a small fraction of events are reconstructed to the correct incident energy, see Fig. 15 [65]. Our results indicate significant shortcomings in the neutrino event generators used to reconstruct oscillation parameters from experiments. ODU student Mariana Khachatryan (Ph.D. 2019, supervisor L.B. Weinstein) was co-lead author on the Nature paper presenting these results.

Based on these results, the PAC approved E12-17-006 "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues", which took data in winter 2021/22 (see above). In the next grant period L.B. Weinstein will coordinate the analysis, but there are currently no funds to support ODU personnel to analyze this data.

L.B. Weinstein is also supervising an ODU undergraduate, Alicia Mand, a JSA Minority/Female Undergraduate Research Assistant (MFURA), in analyzing $(e, e'p\pi)$ events from CLAS6 to better understand resonance production in nuclei and how these events reconstruct (or not) to the correct beam energy.

D. Physics Beyond the Standard Model

The Heavy Photon Search (HPS) experiment in Hall-B at Jefferson Lab [80, 81] exploits resonance and displaced vertex signatures to search for heavy photons over a wide range of couplings, $\epsilon^2 > 10^{-10}$, and masses, $20\ \mathrm{MeV}/c^2 < m_{A'} < 220\ \mathrm{MeV}/c^2$, 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 is complete. The results of both the resonance and displaced vertex searches with 2016 data have been reviewed and approved by the collaboration review committee. It will now go to a collaboration wide review before submission for publication. The 2016 data 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 $\epsilon^2 = 10^{-5}$, as shown on the left in Fig.16. This result confirms the results of previous searches but does not extend their sensitivity. The reported 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}. Being statistics limited, the present search does not reach the sensitivity needed to see canonical A' production in this region, but provided a necessary base to validate the experiment concept and analysis software.

During the first physics run of HPS in the summer of 2019, the experiment was able to collect about 122 pb^{-1} integrated luminosity and an accumulated sample of 40 billion events. While little or no new sensitivity is expected in the resonance search, it forms the basis for the displaced vertex search, which should follow within a year. The integrated luminosity for the second run is about 160 pb^{-1}. Both physics runs should offer a window

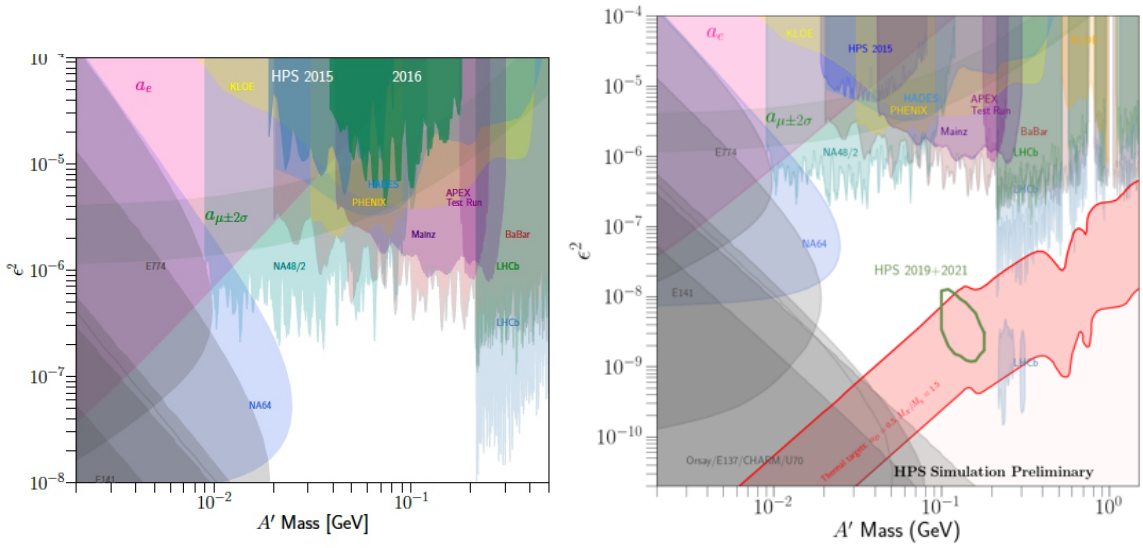

FIG. 16. Left: The exclusion region of the dark photon parameter space by the analysis and statistical recasting of the 2015 and 2016 results.
Right: Expected reach of 2019 and 2021 data combined in terms of mass and coupling of heavy photons. The region accessible for HPS includes parameter space motivated by thermal dark matter in this mass range, where a dark photon is the preferred mediator of DM-SM interactions responsible for setting the observed dark matter abundance through freeze-out: the so-called "thermal targets."

into the highly motivated parameter space and together will cover a significant part of it as shown on the right in Fig.16.

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

E. An Electron Ion Collider

In the past three years, Dr. Hyde has given seventeen invited talks and published seven conference proceedings on the EIC. Although a significant fraction of our EIC effort is funded by other sources, the support from this grant is crucial to the continuity of our effort. Postdoc Vitaly Baturin was funded substantially from BNL Generic Detector R&D funding for eRD21: *Detector Backgrounds for the EIC* [82], and from the Center for Frontiers in Nuclear Science at Stony Brook University, and by this grant. The eRD21 project provided partial funding for graduate student Christine Ploen, who also received a Jefferson Lab EIC Center Fellowship, with the balance of her support coming Department of Physics resources (GTA). Mitchell Kerver received a graduate fellowship from the Center for Nuclear Femtography (SURA), which has been extended this fall for a second year. Travel funds are provided by the present grant. We have recently submitted two funding proposals to

the new Generic Detector R&D Program.

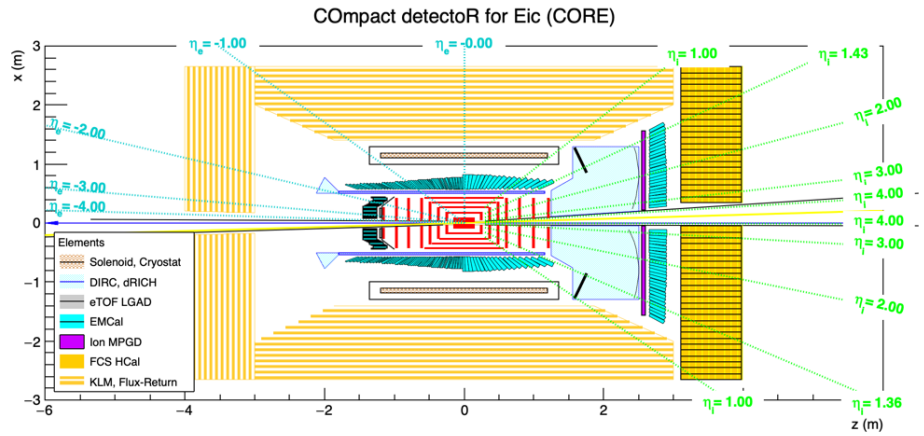

FIG. 17. 2D detail of CORE detector concept [83]. A 3D CAD image is shown on the title page of this proposal.

1. *CORE*

Dr. Hyde co-led (with Dr. Pawel Nadel-Turonski, Stony Brook U.) the development of the **COmpact detectoR for Eic** (CORE) proposal [83], in response to the *Call for Collaboration Proposals for Detectors at the Electron-Ion Collider* [84]. Key features include:
• A compact detector, both radially and along the beam line (Fig. 17).
• An all-Si tracker that meets or exceed the Yellow Report requirements.
• Precision electromagnetic calorimetry enabling an extensive DVCS program on nuclei.
• Full muon detection over the pseudo-rapidity range $[-3.5, 3.5]$
The unique and broad capabilities of CORE, especially coupled to a potential second Interaction Region with a downstream (ion) high-dispersion focus was recognized in the Detector Proposal Advisory Panel (DPAP) report ([85] p.5):

> *The CORE studies for DVCS and exclusive meson production find that the reaction kinematics can be reconstructed from the central detector alone. This allows the extension of the parton imaging program from the proton to nuclei, and it may increase the precision of measuring t in ep collisions. The panel regards this as a good example of specialization/optimization to enhance the complementarity between two detectors, discussed below.*
> *The CORE proposal makes a convincing case for the significant gain in physics reach achievable with a secondary focus:*
>
> - *increased acceptance in the invariant momentum transfer t of the scattered proton in ep collisions, which directly translates into an increased resolution power for imaging partons in the transverse plane,*
> - *significantly improved abilities to detect nuclear breakup in exclusive and diffractive scattering on light and heavy nuclei. The distinction between coherent and incoherent scattering is essential for the physics interpretation of these processes,*

- *prospects for a program of low-background gamma spectroscopy with rare isotopes in the beam fragments.*

We continue to develop and promote CORE as a comprehensive design for a second detector at the EIC. We collaborate with the EIC design team on the interaction region (IR) design for IR8, including the downstream ion focus. CORE is shorter than ePIC by 1 meter in the ion downstream directions. The central solenoid of any EIC detector concept twists both incoming beam bunches in the transverse plane. This must be compensated by either skew quads or solenoids of opposing fields along the beam lines near the IP. Opposing solenoids are the preferred solution, but there is no space for them in the IR6 (ePIC) design. We work on an IR8 design incorporating opposing solenoids, which could be enabled by the shorter length of CORE while also maximizing the ion downstream acceptance. In the next three years, we will also participate in the Far-Forward and Far-Backward working groups of the ePIC collaboration.

2. DIRC

We continue our collaboration with the EIC PID consortium, particularly on R&D for high performance "'Detection of Internally Reflected Cherenkov light" (DIRC) in the central (barrel) regions of both ePIC and a possible second detector. We are constructing a CO_2 Cherenkov detector to select high momentum muons for a high precision cosmic ray test stand for DIRC prototyping at Stony Brook University. We also host a laser optics facility to map the precise optics of the three-layer lenses that are key to pushing the DIRC π/K three-sigma PID separation up to 6 GeV. A photograph of the setup in our lab is presented in Fig. 18. This optics work is led by our former post doc, Greg Kalicy (now Ass't Prof. at CUA). Aside from supplies, we anticipate any purchases over $\$1,000$ for this project will be provided by the eRD103 EIC Project Detector R&D funding at SBU & CUA. The baseline plan for the ePIC DIRC is to reuse BABAR fused silica bars. This requires that the bar boxes be disassembled at SLAC, the glue joints decoupled and the bars shipped to Jefferson Lab. If funding permits, we anticipate playing a major role in the required measurements at Jefferson Lab to re-test the optical integrity of the bars.

FIG. 18. DIRC optics test bench in ODU Lab.

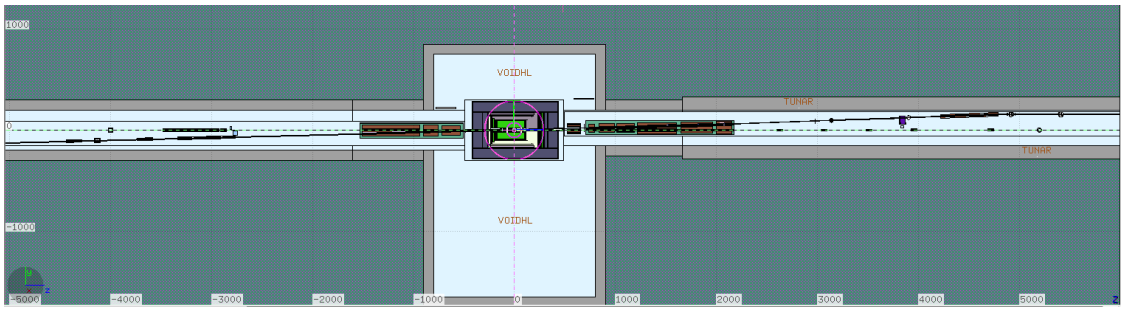

FIG. 19. Top view of FLUKA model of EIC interaction region (IR) and detector. Horizontal scale: $z = -s$ in cm; vertical coordinate (x) in floor plane is given in cm. All magnets and beam vacuum pipes are included between -50 m and $+50$ m. The ion beam enters from lower left and exits at upper right. The electron beam enters from the right traveling in $-z$ direction on the axis of the detector solenoid.

3. EIC Background Studies

From Dec 2017 to March 2021, we received funding for *EIC Background Studies and the Impact on the IR and Detector Design* (eRD21) from the program of Generic Detector R&D for an Electron Ion Collider [82]. The main conclusion from these studies is that the primary sensor technology choices for the central detector (Si MAPS tracker, SiPMT for RICH and calorimetry) do not face longevity issues from the backgrounds that will be generated either by beam-gas interactions or the primary *ep* interactions. The one exception is the ion-side EMCal, where SiP sensors within 20 cm of the detector axis may need to be replaced with a more robust choice *e.g.* MCP PMTs.

We use FLUKA to simulate the full hadronic cascade of secondaries from both interactions of the proton beam with the residual gas in the vacuum, and from the primary inelastic *ep* collisions at the Interaction Point (IP). The FLUKA model includes the full beam tunnel, detector hall, all magnets within $\pm$50m of the IP, and a simplified model of an EIC detector (Fig. 19). The background results in the central detector are shown in Fig. 20 for beam-gas interactions (left) and for primary *ep* collisions at the IP (right). More detailed studies (not shown) of the background levels in region of the Si MAPS tracker ($|z| < 200$ cm) indicate that the sensors closest to the beam line will receive an annual fluence of $6 \cdot 10^{10}$ equivalent 1 MeV n/cm^2. This is orders of magnitude below the demonstrated life time of Si MAPS technology in excess of $10^{14} n/\mathrm{cm}^2$. On the other hand, the electromagnetic and hadronic calorimeters ($|z| \geq 300$ cm) will likely be readout by SiPMs, which have a lifetime of only $10^{11} n/\mathrm{cm}^2$. Fig. 20 demonstrates that these calorimeters are strong conversion sources of neutrons. In particular, at the back of the forward EM calorimeter ($z \sim 300$ cm), at radial distances ≤ 20 cm the neutron fluence is high. The combined annual neutron fluence at maximal luminosity is $2 \cdot 10^{11} n/\mathrm{cm}^2$, dominated by primary *ep* interactions at the IP, necessitating an alternate sensor technology to SiPMs. We will continue background studies in the far forward (ZDC, B0, Off-Momentum, and Roman Pots) detectors.

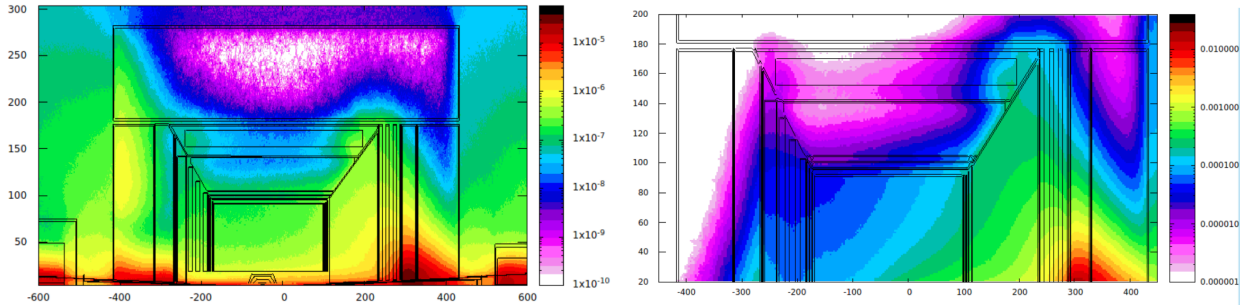

FIG. 20. FLUKA simulations of EIC Backgrounds. **Left:** beam-gas interactions. **Right:** 10 GeV $e^- \otimes$ 275 GeV proton interactions. Horizontal axes aree the z-coordinate (cm), antiparallel to the electron beam direction. Vertical axes are the radial coordinate (cm) from the electron beam axis. **Left plot color scale:** 1 MeV equivalent n/cm^2 per primary 275 GeV proton at an artificial residual gas pressure $P_F = 100$ mbar. To convert to $n/\text{cm}^2/\text{sec}$ at the anticipated residual gas pressure $P = 10^{-9}$ mbar, the color scale must be multiplied by the scale factor $(I_p/e)(P/P_F) = 6.25 \cdot 10^7/\text{sec}$. **Right plot color scale:** 1 MeV neutron equivalent fluence per cm^2 per primary inelastic $10 \otimes 275$ GeV^2 ep collision. With a total ep cross section of 50μb (photoproduction) and an annual maximal integrated luminosity of 100/fb, the fluence at the back of the ion side EM calorimeter ($z \sim 430$ cm) closest to the beamline is $> 10^{11} n/\text{cm}^2$.

F. Goals and Milestones

- Investigate the quark-gluon structure of protons and neutrons in deep inelastic scattering and through precision measurements of deeply virtual Compton scattering

  2023 Complete first results on tagged neutron structure functions with BONuS12 and publish first paper plus NIM article on the RTPC (Kuhn, Bueltmann, Dodge), complete data taking and calibration for all CLAS12 subsystems for Run Group C (nucleon spin structure) and advance past Pass1 review for data cooking (Kuhn, Bueltmann, Dodge), start data taking for deeply virtual Compton scattering experiments in Hall C with NPS (Hyde).

  2024 Complete full analysis of the entire RG-F (BONuS12) data set, including nDVCS, and low-level analysis ("cooking") of the entire RG-C data set (Kuhn, Bueltmann, Dodge), complete NPS data taking in Hall C and calibrate data (Hyde), publish full data set of Time-like Compton Scattering analysis (Stepanyan)

  2025 Publish archival paper on RG-F with all results and first results on inclusive and semi-inclusive spin structure functions from RG-C (Kuhn, Bueltmann, Dodge), prepare for Hall C Wide Angle Compton Scattering experiment (Hyde), publish J/*psi* photoproduction analysis of RG-A data set (Stepanyan)

- Hadron Spectroscopy: GlueX and KLF (Amaryan)

  2023 Publish results of photoproduction cross section of $f1(1285)$ from the GlueX data

  2023 Complete design of components (Compact Photon Source, Be target, and Flux Monitor)

  2024 Complete prototyping and construction of hardware components

  2025 Complete hardware testing and begin anticipated data taking in Hall D

- Study the role of two-nucleon correlations in nuclei and the origin of the EMC effect (Weinstein)

  2023 Complete preparation for the Hall C LAD experiment E12-11-107, publish first Cafe experiment paper on mean field and SRC $(e, e'p)$ ratios in symmetric and asymmetric nuclei, complete Pass1 data replay for CLAS Run Group M, publish first RG-M paper and publish first BAND paper on F2p modification in deuterium

  2024 Complete data taking for the LAD experiment, publish final Cafe experiment paper on mean field and SRC $(e, e'p)$ cross sections, publish more RG-M SRC papers, and publish $d(e, e'\pi)$ 4 GeV cross sections from RG-B, achieve full PAC approval for $A = 3$ SIDIS experiment in CLAS12

  2025 Analyze the LAD experiment and determine preliminary results, prepare for CLAS12 tritium experiments, continue analyzing and publishing RG-M data

- Explore physics beyond the Standard Model with the Heavy Photon Search experiment (Stepanyan, Bueltmann)

  2023 Complete calibration of 2019 and 2021 data set

  2024 Publish results of displaced vertex analysis

- Prepare for the Electron Ion Collider (Hyde)

  2023 Complete FLUKA simulations of backgrounds in the far-forward (ion) region of IR6
  Complete CO_2 Cherenkov for DIRC prototyping at SBU Cosmic Ray Test Stand

  2024 Complete GEANT4-based simulations of a candidate second EIC detector and complete full EIC DVCS simulations on light $N = Z$ nuclei, including electron-helicity observables

  2025 Finalize plans for ODU contribution to ePIC

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IV. DATA MANAGEMENT PLAN

The storage, safeguarding and public availability of the collected data under this proposal will follow the Digital Data Principles enunciated in the Office of Science Statement on Digital Data Management [86].

The research outlined in this proposal is carried out pre-dominantly at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). All data collected will be stored and handled by the Jefferson Lab Scientific Computing Center following the Jefferson Lab Data Management Plan [87]. Individual experiments additionally follow the data management plans developed for the relevant experimental hall. Those data management plans are available for CLAS12 [88], Hall A [89], Hall C [90], and Hall D [91].

The analyzed data will also be managed by Old Dominion University as outlined in ODU's data management plan [92].

V. PUBLICATIONS

Summary of Publications: Oct.2019–Sept.2022

	Letter	Other Refereed	Invited
Name	**Publications**	**Journals**	**Talks**
Faculty/Staff			
M. Amaryan	9 (0)	18 (3)	7
S.L. Bültmann	1 (0)	3 (2)	0
G.E. Dodge	1 (0)	2 (1)	
M. Hattawy	13 (0)	14 (2)	3
C.E. Hyde	11 (3)	5 (2)	16
S.E. Kuhn	7 (1)	6 (2)	10
S. Stepanyan	9 (1)	14 (1)	4
L.W. Weinstein	3 (2)	14 (9)	9
Post-docs			
S. Adhikari	0 (0)	5 (1)	
V. Baturin	0 (0)	0 (0)	
F. Hauenstein	7 (2)	12 (6)	11
Total	19 (5)	37 (15)	

Numbers in parentheses refer to primary-author publications.

A. Refereed Journal Articles

In the past three years, our group published a total of 57 refereed journal articles, including 24 papers with ODU principal authors.

ODU Principal authors

1. A. Deur, J.P. Chen, S.E. Kuhn *et al.*, "Experimental Study of the Behavior of the Bjorken Sum at Very Low Q^2", Phys. Lett. B **825**, 136878 (2022)

2. M. Amaryan, "History and geography of light pentaquark searches: challenges and pitfalls," Eur. Phys. J. Plus **137**, no.6, 684 (2022) doi:10.1140/epjp/s13360-022-02888-0 [arXiv:2201.04885 [hep-ex]].

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4. F. Hauenstein, A. Jentsch, J. R. Pybus, A. Kiral, M. D. Baker, Y. Furletova, O. Hen, D. W. Higinbotham, C. Hyde, V. Morozov, D. Romanov, and L.B. Weinstein, "Measuring recoiling nucleons from the nucleus with the future Electron Ion Collider," Phys. Rev. C **105**, no.3, 034001 (2022) doi:10.1103/PhysRevC.105.034001 [arXiv:2109.09509 [physics.ins-det]].

5. M. Khachatryan *et al.* [CLAS and e4v], "Electron-beam energy reconstruction for neutrino oscillation measurements," Nature **599**, no.7886, 565-570 (2021) doi:10.1038/s41586-021-04046-5

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9. I. Korover, *et al.* (the CLAS Collaboration), "^{12}C$(e, e'pN)$ measurements of short range correlations in the tensor-to-scalar interaction transition region", Phys. Lett. B **820** (2021) 136523.

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12. R. Weiss, A.W. Denniston, J.R. Pybus, O. Hen, E. Piasetzky, A. Schmidt, L.B. Weinstein, and N. Barnea, "Extracting the number of short-range correlated nucleon pairs from inclusive electron scattering data", Phys. Rev. C **103** (2021) L031301, arXiv:2005.01621.

13. Cruz-Torres, R., Lonardoni, D., Weiss, R. et al., "Many-body factorization and position-momentum equivalence of nuclear short-range correlations", Nature Physics **17**, 306 (2021) https://doi.org/10.1038/s41567-020-01053-7

14. M. Dlamini *et al.* [Jefferson Lab Hall A], "Deep Exclusive Electroproduction of $\pi 0$ at High Q2 in the Quark Valence Regime," Phys. Rev. Lett. **127**, no.15, 152301 (2021) doi:10.1103/PhysRevLett.127.152301 [arXiv:2011.11125 [hep-ex]].

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18. E. P. Segarra, *et al.*, "The CLAS12 Backward Angle Neutron Detector (BAND)," Nucl. Instrum. Meth. A **978**, 164356 (2020) doi:10.1016/j.nima.2020.164356 [arXiv:2004.10339 [physics.ins-det]].

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General Refereed Publications

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26. S. Adhikari *et al.* [GlueX], "Measurement of spin density matrix elements in $\Lambda(1520)$ photoproduction at 8.2–8.8 GeV," Phys. Rev. C **105**, no.3, 035201 (2022) doi:10.1103/PhysRevC.105.035201 [arXiv:2107.12314 [nucl-ex]].

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34. V. Sulkosky *et al.* [Jefferson Lab E97-110], "Measurement of the ^{3}He spin-structure functions and of neutron (^{3}He) spin-independent sum rules at $0.035 \leq Q^2 \leq 0.24$ GeV^2," Phys. Lett. B **805**, 135428 (2020) doi:10.1016/j.physletb.2020.135428 [arXiv:1908.05709 [nucl-ex]].

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41. N. Zachariou *et al.* [CLAS], "Double polarisation observable $\mathbb{G}$ for single pion photoproduction from the proton," Phys. Lett. B **817**, 136304 (2021) doi:10.1016/j.physletb.2021.136304

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55. V. D. Burkert, *et al.*, "The CLAS12 Spectrometer at Jefferson Laboratory," Nucl. Instrum. Meth. A **959**, 163419 (2020) doi:10.1016/j.nima.2020.163419

56. J. Adam *et al.* [STAR],
"Results on total and elastic cross sections in proton-proton collisions at $\sqrt{s} = 200$ GeV", Phys. Lett. B **808**, 135663 (2020).

57. S. Li *et al.* [Hall A Collaboration], "Revealing the short-range structure of the mirror nuclei ^{3}H and ^{3}He," Nature **609**, 41 - 45 (2022)
doi:10.1038/s41586-022-05007-2

B. Presentations

1. C. Fogler, "Investigating the EMC effect on highly-virtual nucleons at Jefferson Lab's Hall B", DNP Fall 2019 Meeting; Crystal City, VA; Oct 16, 2019; contributed talk

2. C. Fogler, "Investigating the EMC effect on highly-virtual nucleons at Jefferson Lab's Hall B", ODU Nuclear Seminar; Norfolk, VA. May 7, 2020

3. C. Fogler, "Tagged DIS with BAND: Experimental overview", DNP Fall 2020 Meeting; 10/30/2019; New Orleans, La. (held virtually), contributed talk

4. C. Fogler, " Measuring the Deuterium Inclusive and Semi-Inclusive Pion Production Cross Sections in CLAS12", e-HUGS 2021; Newport News, VA; June 16, 2021; poster

5. C. Fogler, "Measuring the Deuterium Inclusive and Semi-Inclusive Pion Production Cross Sections in CLAS12", 2021 JLUO Annual Meeting; Newport News, VA; June 23, 2021; poster

6. C. Fogler, "Measuring CLAS12 deuterium pion electro-production cross sections for e4nu", 2022 Frontiers and Careers in Nuclear and Hadronic Physics; Cambridge, MA; Aug 6th, 2022; contributed talk

7. C. Fogler, "Measuring CLAS12 deuterium pion electro-production cross sections for e4nu", 2022 Gordon Research Conference on Photonuclear Reactions; Holderness, NH; Aug 8th, 2022; poster

8. M. Hattawy, "Design and Construction of BONuS12 Radial Time Projection Chamber" (in French), invited talk at the "Mécanique des Détecteurs et Systèmes Similaires (MDS2)" conference, Paris/France October 7-8, 2019.

9. M. Hattawy, "Exploring the 3D Partonic Structure of Nucleons and Light Nuclei", seminar at Los Alamos National Lab, Nov 6th, 2019.

10. M. Hattawy, "Catching a Glimpse of the 3D Partonic Structure of Nucleons and Nuclei", Contributed talk at the 2019 DNP Fall Meeting of the Division of Nuclear Physics of the American Physical Society, October 14-17 2019, Arlington (VA).

11. M. Hattawy, "Exploring the 3D Partonic Structure of Nucleons and Nuclei", Invited seminar at Jussieu (Paris), France, March 9, 2020.

12. M. Hattawy, "CLAS12 Run Group F Summary", Invited talk at the CLAS Collaboration meeting, Nov 10-13, 2020, Jefferson Lab.

13. M. Hattawy, "The BONuS Experiment with CLAS12", Contributed talk at the APS April Meeting 2021, April 17-18, 2021.

14. M. Hattawy, "Exploring the 3D Partonic Structure of Nucleons and Nuclei", Colloquium at Birzeit University, West Bank, June 24, 2021.

15. F. Hauenstein, "Pairing and Bonding of Nucleons in Nuclei", MIT Nuclear Physics Seminar, 11/20/2020, Massachusetts Institute of Technology, Cambridge M A, USA.

16. F. Hauenstein, "Tagged Measurements of SRCs at the EIC", Division of Nuclear Physics (DNP) Fall Meeting 2020 (contributed), 10/30/20, online meeting.

17. F. Hauenstein, "Short-Range Correlations and Backward Nucleon Tagging", Jefferson Lab Worksh op on Backward Angle Physics (invited talk), 09/22/20, online meeting.

18. F. Hauenstein, "Update on SRC Measurements at the EIC", EIC 2nd Yellow Report Meeting (contr ibuted talk), 05/21/2020, online meeting.

19. F. Hauenstein, "From Quarks to Nuclei from JLab to the EIC", American Physical Society April 2020 Meeting (invited talk), 04/19/2020, online meeting.

20. F. Hauenstein, "Tagged EMC measurements at the EIC", EIC 1st Yellow Report Meeting (contribu ted talk), 03/19/2020, online meeting.

21. F. Hauenstein, "Pairing and Bonding in Nuclei", Physics Colloquium, 01/31/2020, College of William and Mary, Williamsburg VA, USA.

22. F. Hauenstein, "Tagged EMC measurements at the EIC", Workshop - Exploring QCD with light nuc lei at the EIC (invited talk), 01/23/2020, Stony Brook University, Stony Brook NY, USA.

23. F. Hauenstein, "Short-Range Correlations - Past, Present and Future", Hall A/C seminar, 12/0 6/2019, Jefferson Lab, Newport News VA, USA.

24. F. Hauenstein, "Tagged Short-Range Correlations for Medium to Heavy Ions", Division of Nucle ar Physics (DNP) Meeting 2019 (contributed), 10/15/2019, Crystal City VA, USA.

25. F. Hauenstein, "SRC and EMC Experimental Overview and Simulation Studies", EIC workshop (con tributed), 09/24/2019, Stony Brook University, Stony Brook NY, USA.

26. C.E. Hyde, Andrey Kim (UConn), Carlos Muñoz Camacho (IJCLab), "Coherent Deep Virtual Compton Scattering on ^{4}He with CORE@EIC" , Contributed talk to XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2022), Santiago de Compostela, Galicia, Spain, 2–6 May 2022.

27. C.E. Hyde, Malek Mazouz (Monastir U, Tunisia), Carlos Muñoz Camacho (IJCLab, France), Julie Roche (Ohio U), "Deeply virtual Compton scattering cross sections at high Bjorken x", Contributed talk to XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2022), Santiago de Compostela, Galicia, Spain, 2–6 May 2022.

28. C.E. Hyde, "Deep Virtual Exclusive Scattering on Nuclei at the EIC: Prospects and Challenges", invited seminar (online) Center for Frontiers in Nuclear Science, Stony Brook University, NY, 18 Nov 2021, `https://www.stonybrook.edu/cfns/activities/seminars`

29. C.E. Hyde, "CORE: a COmpact detectoR for the EIC", invited talk at the "Workshop on Physics Opportunities with Heavy Quarkonia at the EIC",Center for Nuclear Femtography, 25-27 October 2021 `https://indico.bnl.gov/event/12899/`

30. C.E. Hyde, "CORE: a COmpact detectoR for the EIC", invited talk at the Electron Ion Collider Users Group (EICUG) Quarterly Meeting, 28 Oct 2021

31. C.E. Hyde, "CORE Far-Forward Detectors", contributed talk at EICUG Annual Meeting, 1–5 August 2021 `https://indico.bnl.gov/event/11463`

32. C.E. Hyde, "CORE: A Detector for Precision QCD", Invited talk at the "Second Workshop on Precision Studies of QCD at the EIC", online, hosted jointly by the Asia Pacific Center for Theoretical Physics (Korea), and the Center for Frontiers in Nuclear Science (US), 19–23 July 2021, `https://indico.bnl.gov/event/11669`

33. C.E. Hyde, "CORE: COmpact detectoR for Eic", invited seminar (online) Center for Nuclear Femtography, 26 May 2021, `https://www.femtocenter.org/seminars-news`

34. C.E. Hyde, "Far Forward Calorimetry Overview: ZDC", invited talk (online) "EIC Calorimetry Workshop: From Yellow Report towards Implementation", 15–6 March 2021, Oak Ridge National Laboratory TN.

35. C.E. Hyde, "Deep Virtual Exclusive Scattering in Hall A", invited talk, Center for Nuclear Femtography mini-workshop on Intersections of Theory and Experiment, 10 Feb 2021, `https://indico.jlab.org/event/429/timetable/#20210210`

36. C.E. Hyde, "A Compact Detector for Electron-Ion Collider Science", invited seminar at Irène Joliot-Curie Laboratory of the Two Infinities (IJCLab-Orsay, France), 5 October 2020, Virtual.

37. C.E. Hyde, "A novel compact detector concept for the Electron-Ion Collider", invited seminar (jointly with P. Nadel-Turonski) at Oak Ridge National Laboratory, 17 September 2020, Virtual.

38. C.E. Hyde, "Compton Form Factors in Nuclear Femtography", invited talk to Virginia Center for Nuclear Femtography workshop *Data Science Roadmap to Compton Form Factors of Quarks and Gluons*, 18–19 September, 2020, Old Dominion University, Virtual.

39. C.E. Hyde, "Beam-Related Background Studies for the EIC Interaction Region", invited talk to *Pixel Si-based Particle Vertex and Tracking Detectors Towards the US Electron Ion Collider Workshop*, 2–4 September 2020, Virtual.

40. C.E. Hyde, "Initial State Radiation : A tool for varying $\sqrt{s}$ on an event-by-event basis for exclusive processes", contributed talk (with Christian Weiss) to the Pavia EIC Yellow Report workshop, 20–22 May 2020, Virtual.

41. C.E. Hyde, "Challenges and Opportunities in Nucleon and Nuclear Femtography", Invited talk to the Mini-Symposium on Nuclear Femtography at the APS April Meeting, 18–21 April 2020, Virtual.

42. C.E. Hyde, "eRD21 Update: EIC Background Studies and the Impact on the IR and Detector", presentation to the Generic Detector R&D for an Electron Ion Collider Committee Meeting 30–31 January 2020, BNL NY.

43. C.E. Hyde, "Beam optics and momentum resolution in forward ion detection with EIC", invited talk at the CFNS Workshop *Exploring QCD with light nuclei at EIC*, 21-24 January 2020, Stony Brook NY.

44. C.E. Hyde, "Physics Requirements for Zero-Degree Electromagnetic and Hadronic Calorimetry: Spectator Tagging in light systems and Impact Parameter Tagging in heavy systems", Invited talk at the Joint CFNS & RBRC Workshop *Physics and Detector Requirements at Zero-Degree of Colliders* 24-26 September 2019, Stony Brook NY.

45. M. Kerver, "Smart Tessellated Look-up Tables for Nuclear Femtography", contributed talk to 2021 Fall Meeting of the APS Division of Nuclear Physics October 11-14, 2021; Virtual paper MG.00007

46. S. Kuhn, "Nucleon (Spin) Structure at High X", Invited Talk at the workshop "J-FUTURE", Messina/Italy, March 28-30, 2022 (virtual).

47. S. Kuhn, "RG-C Status Report", Plenary Talk at the CLAS collaboration meeting, Jefferson Lab, November 9-12, 2021 (virtual).

48. S. Kuhn, "A Brief History of Spectator Tagging at Jefferson Lab", Invited lead-off talk for the 2nd week of the workshop "Exploring QCD with Tagged Processes", October 11-22 2021, Institut Pascal of the University Paris-Saclay (France) (hybrid)

49. S. Kuhn, "Radial Time Projection Chambers for the BONuS measurements of the free neutron structure function", invited Seminar for the "Gaseous Detector Experts Network" at Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France, May 12, 2021 (virtual).

50. S. Kuhn, "Collinear PDF: Status and Outlook", invited Talk at the 9th Workshop of the APS Topical Group on Hadronic Physics, April 13-16, 2021 (virtual).

51. S. Kuhn, "The BONuS measurements of the free neutron structure function", invited Talk at the 3rd Workshop on Quantitative Challenges in EMC and SRC Research (MIT), March 22-26, 2021 (virtual).

52. S. Kuhn, "RG-F Report", Plenary Talk at the CLAS collaboration meeting, Jefferson Lab, July 21-24, 2020 (virtual).

53. S. Kuhn, "RG-F Report", Plenary Talk at the CLAS collaboration meeting, Jefferson Lab, April 28-29, 2020 (virtual).

54. S.E. Kuhn, "Spin structure from short to large distances", invited talk at the workshop "Strong QCD from Hadron Structure Experiments", Nov 6-9, 2019, Newport News, Virginia.

55. S.E. Kuhn, Panelist on the "Round Table" at the workshop "Strong QCD from Hadron Structure Experiments", Nov 6-9, 2019, Newport News, Virginia.

56. V. Lagerquist, "Design of a Longitudinally Polarized Target for CLAS12", contributed talk at the 2021 (virtual) Fall APS DNP Meeting, 10/13/21.

57. V. Lagerquist, "Magnetic Field Requirements for the CLAS12 Polarized Target". Talk at the 2019 Workshop on Polarized Sources, Targets, and Polarimetry, September 22-27, 2019, Knoxville (TN).

58. A. Mand, "Electrons for Neutrinos: Lepton Energy Reconstruction in the Resonance Excitation Region", contributed talk at the 2021 Virtual Conference for Undergraduate Women in Physics, 1/24/21.

59. A. Mand, "Electrons for Neutrinos: Analysis of the 1p1pi Channel", contributed talk at the 2021 (virtual) Fall APS DNP Meeting, 10/13/21.

60. P. Pandey, "Longitudinally Polarized Solid Target for CLAS12", contributed talk at the annual ANPA conference, July 16-17 2022, Old Dominion University.

61. P. Pandey, "First Tests of the New Longitudinally Polarized Target for CLAS12", contributed talk at the 2021 (virtual) Fall APS DNP Meeting, 10/13/21.

62. D. Payette, "Tracking Low Momentum Protons in a Radial Time Projection Chamber", 2019 Fall Meeting of the APS Division of Nuclear Physics, October 14-17, 2019, Crystal City (VA).

63. L. Tracy, "Electrons for Neutrinos: Lepton Energy Reconstruction", 2019 Society of Physics Students Congress, Nov 15, 2019, Providence, RI.

64. L. Tracy, "Electrons for Neutrinos: Lepton Energy Reconstruction in the Resonance Excitation Region", contributed talk at the (virtual) 2020 Fall DNP meeting, Oct 31, 2020.

65. L.B. Weinstein, "Data Visualization", invited talk presented at the 2022 Workshop on Frontiers and Careers in Nuclear and Hadronic Physics, 5-6 Aug, 2022

66. L.B. Weinstein, "Guesstimation: Solving the world's problems on the back of a cocktail napkin", invited talk (remote), EIC User Group Early Career Workshop 24-25 July, 2022.

67. L.B. Weinstein, "The Future of $e4\nu$", invited talk (remote) at NuSTEC Workshop on Electron Scattering, Tel Aviv, Israel, 28–31 March, 2022.

68. L.B. Weinstein, "Guesstimation: Solving the world's problems on the back of a cocktail napkin", Physics Colloquium (remote), University of Tennessee Knoxville, 24 Jan, 2022.

69. L.B. Weinstein, "The Nucleons Go Two By Two: Correlations in Nuclei", Physics Colloquium, Virginia Tech, Blacksburg, VA, 8 Oct, 2021.

70. L.B. Weinstein, "Everything a neutrino experimentalist wants to ask the electron scattering community", invited talk presented at NuFact 2021: The 22nd International Workshop on Neutrinos from Accelerators, Cagliari, Sardinia, Sep 6-11, 2021.

71. L.B. Weinstein, "Data Visualization", invited talk presented at the EIC User Group Meeting Early Career Workshop, July 31, 2021.

72. L.B. Weinstein, "Electron-scattering constraints for neutrino-nucleus interactions", invited talk presented at New Physics on the Low-Energy Precision Frontier, CERN, Switzerland, Jan 27-31, 2020.

73. L.B. Weinstein, "Electron-scattering constraints for neutrino-nucleus interactions", invited talk presented at NUSTEC Workshop on Neutrino Nucleus Pion Production in the Resonance Region, Pittsburgh, PA, Oct. 2-5, 2019.

74. S. Stepanyan, "JLAB physics program: overview", invited talk presented at International Workshop on Hadron Structure and Spectroscopy - 2022 (IWHSS-2022), CERN in Geneva, Switzerland, August 29 - 31, 2022.

75. S. Stepanyan, "Overview of hard exclusive measurements in Hall-B at JLab, from 6 to 12 GeV", invited talk presented at Towards improved hadron femtography with hard exclusive reactions, Virginia Tech, Blacksburg, VA, USA, July 18 - 22, 2022.

76. S. Stepanyan, "CLAS12 luminosity upgrade and future physics opportunities", invited talk presented at DIS2022, Santiago de Compostela, Spain May 2 - 6, 2022.

77. S. Stepanyan, "Dark matter searches at Jefferson Lab", invited talk presented at APS April meeting, NYC, April 9-12, 2022.

C. Conference Proceedings

1. B. Gamage, E. C. Aschenauer, J. S. Berg, V. Burkert, R. Ent, Y. Furletova, D. Higinbotham, A. Hutton, C. Hyde and A. Jentsch, *et al.* "Design Concept for the Second Interaction Region for Electron-Ion Collider," JACoW **IPAC2021**, TUPAB040 (2021) doi:10.18429/JACoW-IPAC2021-TUPAB040 [arXiv:2105.13564 [physics.acc-ph]].

D. Technical Reports

1. R. Alarcon, C.E. Hyde, P. Nadel-Turonski *et al.*, "CORE – a COmpact detectoR for the EIC", [arXiv:2209.00496 [physics.ins-det]].

2. F. Bock, N. Schmidt, P. K. Wang, N. Santiesteban, T. Horn, J. Huang, J. Lajoie, C. Munoz Camacho, J. K. Adkins and Y. Akiba, *et al.* "Design and Simulated Performance of Calorimetry Systems for the ECCE Detector at the Electron Ion Collider," [arXiv:2207.09437 [physics.ins-det]].

3. R. Abdul Khalek, A. Accardi, J. Adam, D. Adamiak, W. Akers, M. Albaladejo, A. Al-bataineh, M. G. Alexeev, F. Ameli and P. Antonioli, *et al.* "Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report," [arXiv:2103.05419 [physics.ins-det]].

4. M. Amaryan *et al.* [KLF], "Strange Hadron Spectroscopy with Secondary KL Beam in Hall D," [arXiv:2008.08215 [nucl-ex]].

5. Y. Hatta, Y. V. Kovchegov, C. Marquet, A. Prokudin, E. Aschenauer, H. Avakian, A. Bacchetta, D. Boer, G. A. Chirilli and A. Dumitru, *et al.* "Proceedings, Probing Nucleons and Nuclei in High Energy Collisions: Dedicated to the Physics of the Electron Ion Collider: Seattle (WA), United States, October 1 - November 16, 2018," doi:10.1142/11684 [arXiv:2002.12333 [hep-ph]].

E. Theses

1. Sudeep Ghosh, "Study of the Decay Matrix for $\eta' \to \eta\pi^+\pi^-$ using CLAS Detector at JLab", Ph.D. Thesis, Indore Institute of Technology, India, September 2019, Dr. M. Amaryan, co-supervisor.

2. Mariana Khachatryan, "Validation of Neutrino Energy Estimation using Electron Scattering Data", Ph.D. Thesis, Old Dominion University, December 2019, Dr. L.B. Weinstein, supervisor.

3. Nilanga Wickramaarachchi, "Measurement of the Photon Beam Asymmetry in $\vec{\gamma}p \to K^+\Sigma^\circ$ at E_γ=8.5 GeV with GlueX", Ph.D. Thesis, Old Dominion University, May 2020, Dr. M. Amaryan, supervisor.

4. Nathan Dzbenski, "Simulation and Development of the Radial Time Projection Chamber for the BONuS12 Experiment in CLAS12", Ph.D. Thesis, Old Dominion University, August 2020, Dr. G. Dodge, supervisor.

5. Torri Jeske, "Measurement of pion-pion final state interactions in $\eta \to \pi^+\pi^-\gamma$ in CLAS at Jefferson Lab", Ph.D. Thesis, Old Dominion University, December 2020, Dr. M. Amaryan, supervisor.

6. Mohamed Nuhman Hashir Rashad, "Deeply Virtual Compton Scattering", Ph.D. Thesis, Old Dominion University, December 2020, Dr. C. Hyde, supervisor.

7. David Payette, "Spectator Proton Detection and Reconstruction in Deep Inelastic D(e,ep$_s$) Scattering", Ph.D. Thesis, Old Dominion University, May 2021, Dr. S. Kuhn, supervisor.

8. Joseph Newton, "J/ψ Photoproduction Near Threshold With CLAS12", Ph.D. Thesis, Old Dominion University, August 2021, Dr. S. Stepanyan, supervisor.

9. Jiwan Poudel, "Study of Bonus12 Radial GEM Detector and TCS Beam Spin Asymmetry in CLAS12", Ph.D. Thesis, Old Dominion University, May 2022, Dr. S. Bueltmann, supervisor.

10. Duncan Cruickshank, "Testing and Data Taking with Gaseous Particle Detectors", Senior Thesis (B.S.), Old Dominion University, May 2020, Dr. S. Kuhn, supervisor.

11. Dakota Christian, "Analysis of Reaction $\gamma p \to a_2\Delta^{++}$", Senior Thesis (B.S.), Old Dominion University, May 2020, Dr. M. Amaryan, supervisor.

12. Lucas Tracy, "Incident Energy Reconstruction For Neutrino Experiments", Senior Thesis (B.S.), Old Dominion University, May 2020, Dr. L.B. Weinstein, supervisor.

13. Francis Estacion, "Cosmic Ray Muon Ionization in a Radial Time Projection Chamber", Senior Thesis (B.S.), Old Dominion University, December 2021, Dr. S. Bueltmann, supervisor.

14. Samuel Minier, "Characterization of a Radial Time Projection Chamber", Senior Thesis (B.S.), Old Dominion University, April 2022, Dr. S. Kuhn, supervisor.

15. Chad Stubenrauch, "Cosmic Rays for Calibration Of A Time Projection Chamber", Senior Thesis (B.S.), Old Dominion University, May 2022, Dr. S. Bueltmann,

F. New Proposals with ODU co-Spokespersons

1. E12-22-006: "Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C", Co-spokespersons, C. Hyde (ODU), M. Mazouz (Monastir, Tunisia), C. Muñoz Camacho (IJCLab, France), J. Roche (Ohio U.). Approved by PAC50 (2022) with A rating, for 44 days of beam.

2. C12-21-004: "Semi-Inclusive Deep Inelastic Scattering Measurement of A=3 Nuclei with CLAS12 in Hall B", Contact person L.B. Weinstein, conditionally approved by PAC50.

3. "COmpact detectoR for Eic (CORE)", C. Hyde (ODU), P. Nadel-Turonski (SBU) co-leaders. A proposal to the EIC "Call for Collaboration Proposals for Detectors at the Electron-Ion Collider", `https://www.bnl.gov/eic/cfc.php`. Submitted Dec 1, 2021.

4. "Generic R&D Proposal: Z-Tagging Mini DIRC", C.Hyde, *et al.* Submitted 25 July 2022 to the Generic EIC-Related Detector R&D program: `https://www.jlab.org/research/eic_rd_prgm`

5. "Machine Learning for Detection of Low-Energy Photons in the EIC ZDC", Lynn Wood (PNNL) P.I.. C. Hyde co-PI for ODU. Submitted 25 July 2022 to the Generic EIC-Related Detector R&D program: `https://www.jlab.org/research/eic_rd_prgm`

6. C12-19-001:
M. Amaryan *et al.* [KLF], "Strange Hadron Spectroscopy with Secondary KL Beam in Hall D", [arXiv:2008.08215 [nucl-ex]]. Contact person M. Amaryan. Approved by PAC48 (2020) for 200 days of beam.

G. Conferences and Workshops Organized

1. C.E. Hyde, Chair: SURA/Center for Nuclear Femtography Workshop *Data Science Roadmap to Compton Form Factors of Quarks and Gluons.* 24–25 Sept 2020. `https://crtc.cs.odu.edu/DATA_SCIENCE_ROADMAP_TO_COMPTON_FORM_FACTORS_OF_QUARKS_AND_GLUONS`

VI. PRINCIPAL COLLABORATORS

A. Principal Collaborators, in the past four years

James Ritman, Juelich, IKP, Germany ; Mikhail Bashkanov, University of York, York, UK; Eugene Chudakov, Jefferson Lab, Newport News; Marco Battaglieri, INFN Genova, Italy; Angela Biselli, Fairfield University, Fairfield, CT; Werner Boeglin, Florida International Univ., Miami, FL; Will Brooks, UTFSM, Valparaiso, Chile; Volker Burkert, Jefferson Lab, Newport News, VA; Alexandre Camsonne, Jefferson Lab, Newport News, VA; Jian-Ping Chen, Jefferson Lab, Newport News, VA; Eric Christy, Hampton University, Hampton, VA; Don Crabb, University of Virginia, Charlottesville, VA; Alexandre Deur, Jefferson Lab, Newport News, VA; Raphael Dupre, IPN Orsay, France; Rolf Ent, Jefferson Lab, Newport News, VA; Howard Fenker, Jefferson Lab, Newport News, VA; Yulia Furletova, Jefferson lab, Newport News, VA; Shalev Gilad, MIT, Cambridge, MA; Keith Griffioen, William and Mary, Williamsburg, VA; Kawtar Hafidi, Argonne National Lab, Argonne, IL; Hayk Hakobyan, UTFSM, Valparaiso, Chile; Or Hen, MIT, Cambridge, MA; Doug Higinbotham, Jefferson Lab, Newport News, VA; Tanya Horn, Catholic University of America, Washington, DC; Yordanka Ilieva, University of South Carolina, Columbia, SC; Narbe Kalantarians, Virginia Union University, Richmond, VA; Greg Kalicy, Catholic University of Americay, Washington, DC; Christopher Keith, Jefferson lab, Newport News, VA; Dustin Keller, University of Virginia, Charlottesville, VA; Cynthia Keppel, Jefferson Lab, Newport News, VA; Andi Klein, Los Alamos National Lab, Los Alamos, NM ; Malek Mazouz, Faculté des Sciences, Monastir, Tunisia; Wally Melnitchouk, Jefferson Lab, Newport News, VA; Mac Mestayer, Jefferson Lab., Newport News, VA; Gerald Miller, U Washington, Seattle, WA; Carlos Munoz Camacho, Institut de Physique Nucléaire-Orsay, Orsay, France; Pawel Nadel-Turonski, Stony Brook University, Stony Brook NY; Eli Piasetzky, Tel Aviv University, Tel Aviv, Israel; Brian Raue, Florida International Univ., Miami, FL; Marco Ripani, INFN Genoa, Italy; James Ritman, Forschungszentrum Juelich, Jülich, Germany; Julie Roche, Ohio University, Athens, OH; Ankhi Roy, Indian Institute of Technology, Indore, Madhya Pradesh, India; Jan Ryckebusch, U Ghent, Ghent, Belgium; Franck Sabatié, CEA Saclay, France; Misak Sargsian, Florida International Univ., Miami, FL; Susan Schadmand, Forschungszentrum Juelich, Jülich, Germany; Igor Strakovsky, George Washington Univ., Washington, DC; Mark Strikman, Pennsylvania State Univ., University Park, PA; Christian Weiss, Jefferson Lab, Newport News, VA; Rikotura Yoshida, Jefferson Lab (now Argonne National Lab); Bogdan Wojtsekhowski, Jefferson Lab, Newport News, VA; Xiaochao Zheng, Univ. of Virginia, Charlottesville, VA.

B. Current Affiliations of Former Postdoctoral Advisees

Shankar Adhikari, Industry; Florian Hauenstein, Jefferson Laboratory, Newport News, VA; Gabriel Charles, IPN Orsay, Orsay, France; Marouen Baalouch, industry, France; Ilya Larin, Univ. of Massachusetts, Amherst, MA; Kijun Park, Hampton University Proton Therapy Institute, Hampton VA; Greg Kalicy, Catholic University, Washington, DC, Assistant Professor; Lamiaa ElFassi, Mississippi State University, Starkville, MS, Associate Professor; Chandra Nepali, Christopher Newport University, Newport News VA; Robert Bennett, Princeton Consultants, Inc.; Franck Sabatié, CEA/DSM/DAPNIA Saclay, Gif-sur-Yvette, France ; Gagik Gavalian, Jefferson Laboratory, Newport News, VA; Tony Forest, Idaho State Univ., Pocatello, ID, Professor; Mher Agasyan, INFN Frascati, Italy; Brian Raue, Florida International University, FL, Professor; Wendy Hinton, Norfolk State University, Hampton, VA, Associate Professor; Liming Qin, unknown; Henry Juengst, Technisch-Mathematische Studien (TDS) GmbH, Bonn, Germany; Rikki Roche, Homemaker; Jeffrey Lachniet, Arete Associates; Stepan Stepanyan, Jefferson Laboratory, Newport News, VA.

C. Current Affiliations of Former Graduate Students

Jiwan Poudel (Ph.D. May 2022) Jefferson Laboratory, Newport News, VA; Joseph Newton (Ph.D. August 2021) Jefferson Laboratory, Newport News, VA; David Payette (Ph.D. May 2021) Industry; Torri Jeske (Ph.D. December 2020) Jefferson Laboratory, Newport News, VA; Hashir Rashad (Ph.D. December 2020) Post-Doc, UVA Medical School; Nathan Dzbenski (Ph.D. August 2020) University of North Carolina, Greensboro, NC; Nilanga Wickramaarchchi (Ph.D. May 2020) Post-Doc CUA; Mariana Khachatryan (Ph.D. December 2019) Florida International University, Miami, FL; S. Lee Allison (Ph.D. August 2017) Institute for Defense Analysis, Alexandria, VA; Mathieu Ehrhart (M.S. August 2017) IPN Orsay, Orsay, France; Georgie MBianda (Ph.D. May 2017) industry; Holly Szumila-Vance (Ph.D. May 2017), Jefferson Laboratory, Newport News, VA; Bayram Torayev (Ph.D. December 2016) Hampton University Proton Therapy Institute, Hampton, VA; Michael Kunkel (Ph.D. December 2014) industry; Suman Koirala (Ph.D. August 2014), Postdoc, Taiwan; Dasuni Adikaram (Ph.D. May 2014), Postdoc, Hampton University Proton Therapy Inst., Hampton, VA; Ivan Koralt (Ph.D. Dec 2013) Intel Corp., Portland, OR; Donika Plyku (Ph.D. May 2013), Research Scientist, US Food and Drug Administration, Silver Spring, MD; Michael Mayer (Ph.D. May 2013), Staff Scientist, Pacific Northwest National Laboratory; Sharon Careccia (Ph.D. May 2012), Instructor, Georgia College and State University, Milledgeville, GA; Heghine Seraydaryan (Ph.D. Dec 2011), U.S. Patent Office, Alexandria VA; Mustafa Canan (Ph.D. Dec 2010), Naval Postgraduate School, Monterey CA, Assistant Professor; Serkan Golge (Ph.D. Aug 2010), NASA Senior Research Scientist, Johnson Space Center, Houston TX; Jixie Zhang (Ph.D. May 2010), Postdoc, Univ. of Virginia, Charlottesville, VA; Megh Niroula, (Ph.D. 2010) unknown; Svjatoslav Tkachenko (Ph.D. Dec 2009), Univ. of Virginia, Charlottesville, VA; Nevzat Guler (Ph.D. Dec 2009), Spectral Sciences, Burlington, MA; Hovhannes Baghdasaryan, (Ph.D. May 2007), U.S. Patent Office, Alexandria VA; Alexander Klimenko (Ph.D. 2004), Los Alamos National Lab, Los Alamos, NM; Vipuli Dharmawardane (Ph.D. 2004), industry; Mehmet Bektasoglu (Ph.D. 2002), Sakarya University, Turkey; Rustam Niyazov (Ph.D. 2003), Passport Systems, Bil-

lerica, MA; Junho Yun, (Ph.D. 2001), unknown; Christophe Jutier, (Ph.D. Dec 2001), CEA/DIF/DASE, Bruyères-le-Chatêl, France; Luminita Todor, (Ph.D. Dec 2000), Patent Attorney at Potomac Patent Group PLLC, Fredericksburg, VA; Frank Wesselmann, (Ph.D. 2000); Kathy McCormick (Ph.D.), U.S. Government.

D. Graduate Advisors

M. Amaryan: Kim Egiyan, Yerevan Physics Institute, Armenia (deceased); S.L. Bültmann: Günter Baum, Univ. of Bielefeld, Germany (retired); G.E. Dodge: Stanley Hanna, Stanford Univ. (deceased); C.E. Hyde: William Bertozzi, Dep't of Physics MIT, and PASSPORT Systems (retired); S.E. Kuhn: Frank Hinterberger, Univ. of Bonn, Germany (retired); S. Stepanyan: Kim Egiyan (Yerevan Physics Institute, Armenia, deceased); L.B. Weinstein: William Bertozzi, Dep't of Physics, MIT, and PASSPORT Systems (retired).

E. Postdoctoral Advisors

M. Amaryan: Kim Egiyan (Yerevan Physics Institute, Armenia, deceased); S.L. Bültmann: James S. McCarthy (Univ. of Virginia, retired), Volker Burkert (Jefferson Lab), Gerry Bunce (Brookhaven National Lab, retired); G.E. Dodge: Henk Blok (Vrije Universiteit, Amsterdam, retired); C.E. Hyde: William Bertozzi (Department of Physics, MIT, and PASSPORT Systems, retired), Bernard Frois (CNRS, Paris, France); S.E. Kuhn: Henry Weller (Duke University, Durham, NC, retired); S. Stepanyan: Kim Egiyan (Yerevan Physics Institute, Armenia, deceased); L.B. Weinstein: William Bertozzi (Department of Physics, MIT, and PASSPORT Systems, retired).

VII. BIOGRAPHICAL SKETCHES

Dr. Stephen L. Bültmann, Professor of Physics, ODU

Academic Degrees

University of Bielefeld, Germany	Diploma in Solid State Physics	M.S. 1991
University of Bielefeld, Germany	Dr. rer. nat. in Nuclear Physics	Ph.D. 1996

Appointments

2020 –	Professor of Physics	Old Dominion University
2012 – 2020	Associate Professor of Physics	Old Dominion University
2007 – 2012	Assistant Professor of Physics	Old Dominion University
2003 – 2007	Research Assistant Professor of Physics	Old Dominion University
2000 – 2003	Research Associate	Brookhaven National Lab
2000	Research Associate	Jefferson Lab
1996 – 2000	Research Associate	University of Virginia

Professional Service

Supervised undergraduate students at ODU during summer research (drift chamber R&D and solid polarized target for JLab, exoplanet search). Advisor to the Society of Physics Students at ODU. Participation in science fairs, Jefferson Lab Open House, and other public outreach events.

Recent Doctoral Students

Donika Plyku, Ph.D. May 2013 (now at US Food and Drug Administration)
Ivan Koralt, Ph.D. December 2013 (now at Intel Corp.)
Bayram Torayev, Ph.D. December 2016 (now at Hampton University Proton Therapy Institute)
Jiwan Poudel, Ph.D. May 2022 (now at Jefferson Lab)

Selected Publications (Total of over 150 publications in refereed journals with over 6,700 citations, including three renowned with over 500 citations, 16 publications in the last three years.)

- R. Fersch *et al.* [CLAS Collaboration],
  Determination of the proton spin structure functions for $0.05 < Q^2 < 5\mathrm{GeV}^2$ *using CLAS*,
  Phys. Rev. C **96**, no. 6, 065208 (2017).
- M. Hattawy *et al.* [CLAS Collaboration],
  First Exclusive Measurement of Deeply Virtual Compton Scattering off ^{4}*He: Toward the 3D Tomography of Nuclei*,
  Phys. Rev. Lett. **119**, 202004 (2017).
- S. Jawalkar *et al.* [CLAS Collaboration],
  Semi-Inclusive π^0 *Target and Beam-Target Asymmetries from 6 GeV Electron Scattering with CLAS*,
  Phys. Lett. B **782**, 662 – 667 (2018).
- K. P. Adhikari *et al.* [CLAS Collaboration],
  Measurement of the Q^2 *Dependence of the Deuteron Spin Structure Function* g_1 *and its Moments at Low* Q^2 *with CLAS*,
  Phys. Rev. Lett. **120**, no. 6, 062501 (2018).

- R. Dupre *et al.*,
  A Radial Time Projection Chamber for α Detection in CLAS at JLab,
  Nucl. Instrum. Meth. A **898**, 90 – 97 (2018).
- P. H. Adrian *et al.* [HPS Collaboration],
  Search for a dark photon in electroproduced e^+e^- pairs with the Heavy Photon Search experiment at JLab,
  Phys. Rev. D **98**, 091101 (2018).
- M. Hattawy *et al.* [CLAS Collaboration],
  Exploring the Structure of the Bound Proton with Deeply Virtual Compton Scattering,
  Phys. Rev. Lett. **123**, 032502 (2019).
- M. Mestayer *et al.*, [CLAS Collaboration]
  The CLAS12 Drift Chamber System,
  Nucl. Instrum. Meth. A **959**, 163518 (2020).
- J. Adam *et al.* [STAR],
  Results on total and elastic cross sections in proton–proton collisions at $\sqrt{s}$ = 200 GeV,
  Phys. Lett. B **808, 135663 (2020).**
- **R. Dupre** *et al.***, [CLAS Collaboration]**
  *Measurement of deeply virtual Compton scattering off ^{4}He with the CEBAF Large Acceptance Spectrometer at Jefferson Lab***,**
  Phys. Rev. C 104, 025203 (2021).

Invited Seminars or Conference Presentations

- S. Bültmann (invited presentation),
  The Future of 3D Imaging at Jefferson Lab,
  26^{th} International Workshop on Deep Inelastic Scattering and Related Subjects (DIS 2018), Kobe, Japan, April 16 – April 20, 2018.

Dr. Moskov Amaryan, Professor of Physics, ODU

Academic Degrees

Armenian Pedagogical Institute	Master of Science in Physics	M.S. 1972
Yerevan Physics Institute	Doctor of Philosophy in Physics	Ph.D. 1993

Professional Positions

2010–	Professor of Physics	Old Dominion University
2004 – 2010	Associate Professor of Physics	Old Dominion University
1997 – 2000	Visiting Senior Scientist	INFN, Roma-I, Rome
2000 – 2001	Visiting Senior Scientist	NIKHEF, Amsterdam
2001 – 2004	Visiting Senior Scientist	DESY, Hamburg
1972 – 1997	Research Scientist	Yerevan Physics Institute

Honors and Awards

2018	Fellow, American Physical Society
2002–2004	HERMES Collaboration, Physics Analysis Coordinator
1994–1997	Yerevan HERMES Group Leader
1982	The YerPhI best young scientist

Doctoral Students: Heghine Seraydaryan (Ph.D. 2012), Michael Kunkel (Ph.D. 2014), Georgie Mbianda (Ph.D. 2017), Sudeep Ghosh (Ph.D. 2019), Nilanga Wickramaarachchi (Ph.D. 2020), Torri Roark (Ph.D. 2020).

Selected Publications: (Total of over 210 publications in refereed journals with over 14,5000 citations, h-index = 67.)

- S. Adhikari *et al.* [GlueX], "Measurement of the photon beam asymmetry in $\vec{\gamma}p \to K^+\Sigma^0$ at $E_\gamma = 8.5$ GeV," Phys. Rev. C **101**, no.6, 065206 (2020) doi:10.1103/PhysRevC.101.065206 [arXiv:2003.08038 [nucl-ex]].
- A. Ali *et al.* [GlueX], "First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton," Phys. Rev. Lett. **123**, no.7, 072001 (2019) doi:10.1103/PhysRevLett.123.072001 [arXiv:1905.10811 [nucl-ex]].
- M. C. Kunkel *et al.* [CLAS], "Exclusive photoproduction of π^0 up to large values of Mandelstam variables s, t and u with CLAS," Phys. Rev. C **98**, no.1, 015207 (2018) doi:10.1103/PhysRevC.98.015207. [arXiv:1712.10314 [hep-ex]].
- H. Seraydaryan *et al.* [CLAS], "ϕ-meson photoproduction on Hydrogen in the neutral decay mode," Phys. Rev. C **89**, no.5, 055206 (2014) doi:10.1103/PhysRevC.89.055206 [arXiv:1308.1363 [hep-ex]].
- A. Airapetian *et al.* [HERMES], "Measurement of azimuthal asymmetries associated with deeply virtual Compton scattering on an unpolarized deuterium target," Nucl. Phys. B **829**, 1-27 (2010) doi:10.1016/j.nuclphysb.2009.12.004 [arXiv:0911.0095 [hep-ex]].
- A. Airapetian *et al.* [HERMES], "Measurement of the spin asymmetry in the photoproduction of pairs of high p(T) hadrons at HERMES," Phys. Rev. Lett. **84**, 2584-2588 (2000) doi:10.1103/PhysRevLett.84.2584 [arXiv:hep-ex/9907020 [hep-ex]].

Invited Talks:

- Over last five years:

- M. Amaryan, "The K_L Facility at JLab", APS Meeting, Washington DC, January 28-31, 2017.
- M. Amaryan, editor of Mini-Proceedings of Workshop on Excited Hyperons in QCD Thermodynamics at Freeze-Out (YSTAR2016), Newport News, VA, USA, November 16-17, 2016, arXiv:1701.0734 [hep-ph].
- M. Amaryan, "The K_L Facility at JLab and $\pi - K$ Interactions", $\pi - K$ Interactions Workshop (PIK2018), Newport News, VA, USA, February 14-15, 2018.
- APS Meeting, April 2019, Denver, Colorado, USA. Hadron Spectroscopy with secondary K_L beam at GlueX. Invited talk.
- GlueX-Panda Workshop, May 2019, Washington DC, USA. Hadron Spectroscopy with secondary K_L beam at GlueX. Invited talk.
- MIAPP Workshop, October 2019, Munich, Germany. Physics opportunities with KL beam at JLab. Invited talk.
- "Hadron Spectorskopy with Secondary K_L Beam in Hall D", Jefferson Lab User Group Meeting, June 23, 2021

Dr. Gail Dodge, Professor of Physics, ODU

Academic Degrees

Princeton University	B.A. in Physics	June 1986
Stanford University	M.S. in Physics	September 1988
Stanford University	Ph.D. in Physics	January 1993

Professional Positions

2017 –	Dean, College of Sciences	Old Dominion University
2012 – 2014	Visiting Scientist	National Science Foundation
2006 –	Professor of Physics	Old Dominion University
2005 – 2011	Chair, Department of Physics	Old Dominion University
2001 – 2006	Associate Professor of Physics	Old Dominion University
1995 – 2001	Assistant Professor of Physics	Old Dominion University
1992 – 1994	Postdoctoral Fellow	Vrije Universiteit, Amsterdam

Honors and Awards

2016	APS Woman Physicist of the Month for February 2016
2015	Outstanding Faculty Award, State Council of Higher Education in Virginia
2013	Francis Slack Award, Southeastern Section of the American Physical Society
2012	Gene W. Hirschfeld Faculty Excellence Award, College of Sciences , ODU
2003	Annual "Faculty Excellence" Award of the College of Sciences, ODU
1991	Luise Meyer-Schutzmeister Memorial Award

Doctoral Students: Mehmet Bektasoglu (Ph.D. 2002), Vipuli Dharmawardane (Ph.D. 2004), Jixie Zhang (Ph.D. 2010), Mary Hing-Hickman (Ph.D. 2011; physics education), Sharon Careccia (Ph.D. 2012), Nathan Dzbenski (2020)

Selected Professional Service

2021 – pres	Chair, Nuclear Science Advisory Committee
2021 – pres	Member, IUPaP Working Group 9: International Cooperation in Nuclear Physics
2021 – pres	Observer, Nuclear Physics European Collaboration (NuPECC)
2019	Member, DOE Committee of Visitors, Office of Nuclear Science
2016 – 2018	Elected Member, DNP Executive Committee
2016	Organizer, Conference for Undergraduate Women in Physics, ODU and JLab
2016	Chair, DOE Committee of Visitors, Office of Nuclear Science
2010 – 2012	Member of the Nuclear Science Advisory Committee
2010	DOE Committee of Visitors, Office of Nuclear Science
2009	NSF Committee of Visitors, Physics Division
2005 – 2010	Hall B Steering Committee for the CLAS12 upgrade, chair 2005–2008
2005 – 2007	Jefferson Lab Users Group Board of Directors

Selected Publications: (Total of over 140 publications in refereed journals with over 9,000 citations, 4 publications in the last 3 years.)

1. *"Measurements of the Bjorken Sum at very low Q^2"*, A. Deur, *et al.* , *Phys. Lett. B* **825**, 136878 (2022).
2. *"Probing high-momentum protons and neutrons in neutron-rich nuclei"*, M. Duer, *et al.* [CLAS Collaboration] , *Nature* **560**, 617 - 621 (2018).
3. *"Measurement of the Q^2 Dependence of the Deuteron Spin Structure Function g_1 and its Moments at Low Q^2 with CLAS"*, S. Adhikari, *et al.* [CLAS Collaboration], *Phys. Rev. Lett.* **120**, 065501 (2018).

4. *"Determination of the proton spin structure functions for* $0.05 < Q^2 < 5\ GeV^2$*"*, R. Fersch, *et al.* [CLAS Collaboration], *Phys. Rev. C* **96**, 055208 (2017).
5. *"Precise determination of the deuteron spin structure at low to moderate* Q^2 *with CLAS and extraction of the neutron contribution"*, G. Dodge *et al.* [CLAS Collaboration], proceedings of the XVII International Workshop on Neutrino Factories and Future Neutrino Facilities, August 10 - 15, 2015, Rio de Janeiro, Brazil.
6. *"Measurement of the nearly free neutron structure function using spectator tagging in inelastic* $^2H(e,e'p_s)X$ *scattering with CLAS"*, S. Tkachenko, *et al.* [CLAS Collaboration], *Phys. Rev. C* **89**, 045206 (2014).
7. *"Measurement of the neutron* F_2 *structure function via spectator tagging with CLAS"*, N. Baillie, S. Tkachenko, J. Zhang, P. Bosted, S. Bultmann, M.E. Christy, H. Fenker, K.A. Griffioen, C.E. Keppel, S.E. Kuhn, W. Melnitchouk, V. Tvaskis *et al.* [CLAS Collaboration], *Phys. Rev. Lett.* **108**, 199902 (2012).
8. *"Moments of the spin structure functions* g_{1p} *and* g_{1d} *for* $0.05 < Q^2 < 3.0\ GeV^2$*"*, Y. Prok, P. Bosted, V.D. Burkert, A. Deur, K.V. Dharmawardane, G.E. Dodge, K.A. Griffioen, S.E. Kuhn *et al.* [CLAS Collaboration], *Phys. Lett. B* **672**, 12-16 (2009).
9. *"Experimental Study of Isovector Spin Sum Rules"*, A. Deur, P. Bosted, V. Burkert, D. Crabb, V. Dharmawardane, G. E. Dodge, T. A. Forest, K. A. Griffoen, S. E. Kuhn, R. Minehart, and Y. Prok, *Phys. Rev. D* **78**, 032001 (2008).
10. *"BoNus: Development and use of a radial TPC using cylindrical GEMs"*, H. Fenker, N. Baillie, P. Bradshaw, S. Bueltmann, V. Burkert, M. Christy, G. Dodge, D. Dutta, R. Ent, J. Evans, R. Fersch, K. Giovanetti, K. Griffioen, M. Ispiryan, C. Jay-alath, N. Kalantarians, C. Keppel, S. Kuhn, G. Niculescu, I. Niculescu, S. Tkachenko, V. Tvaskis and J. Zhang, *Nucl. Inst. and Meth. Phys. Res., Sect. A* **592**, 273-286 (2008).
11. *"Quark-hadron duality in spin structure functions* g_{1p} *and* g_{1d}*"*, P.E. Bosted, K.V. Dharmawardane, G.E. Dodge, T.A. Forest, S.E. Kuhn, Y. Prok *et al.* [CLAS Collaboration], *Phys. Rev. C* **75**, 035203 (2007).
12. *"Measurement of the x- and* Q^2*-dependence of the asymmetry* A_1 *on the nucleon"*, K.V. Dharmawardane, S.E. Kuhn, P. Bosted, Y. Prok *et al.* [CLAS Collaboration], *Phys. Lett. B* **641**, 11 (2006).
13. *"Measurement of inclusive spin structure functions of the deuteron with CLAS"*, J. Yun, S.E. Kuhn, G.E. Dodge, T.A. Forest, M. Taiuti, *et al.* [CLAS Collaboration], *Phys. Rev. C* **68**, 055204 (2003).

Selected Invited Talks: (Over 25 invited talks.)

- *"USA NSAC Long Range Plan Report,"* invited talk at IUPaP working Group 9 Meeting, June 15, 2022, Washington, DC
- *"Probing the Neutron with the BONuS Experiment at Jefferson Lab,"* invited colloquium at Virginia Commonwealth University, March 25, 2016, Richmond, VA
- *"The BONuS Experiment: New Results and Future Plans,"* invited talk at XVII International Workshop on Neutrino Factories and Future Neutrino Facilities, August 10 - 15, 2015, Rio de Janeiro, Brazil
- *"Investigating the Neutron in the Resonance Region,"* invited seminar, James Madison University, October 2, 2014, Harrisonburg VA
- *"Accelerator Science: Opportunities for Growth,"* invited talk at the Southeastern Section of the American Physical Society, Nov. 22, 2013, Bowling Green, KY

Dr. Charles Earl Hyde, University Professor of Physics and Eminent Scholar

Academic Degrees

University of California, San Diego	Bachelor of Arts in Mathematics	1978
Massachusetts Institute of Technology	Doctor of Philosophy in Physics	1984

Professional Positions

2017–2020 Chair, Department of Physics, Old Dominion University
2015– University Professor, Old Dominion University
2014– Eminent Scholar, Old Dominion University
2007–2010 Professeur de Physique, Université Blaise Pascal,
2002– Professor of Physics, Old Dominion University
1993–2002 Associate Professor of Physics, Old Dominion University
1987–1993 Assistant Professor of Physics, University of Washington
1986–1987 NSF-NATO Postdoctoral Fellowship, CEA Saclay
1984–1986 Sponsored Research Staff, MIT Laboratory for Nuclear Science,

Leadership Positions

2017–2019 EIC Users Group Steering Committee, Vice-Chair
2016–2017 EIC Users Group Steering Committee, At-Large member
2016 Electron Ion Collider Users Group Charter drafting committee
2016–2017 Director, Jefferson Lab Users Group Board of Directors
International Advisory Committee Member:
2019: EICUG Annual Meeting, Paris France
2018: INT program *Probing Nucleons and Nuclei in High Energy Collisions*, Convenor on eA collision
2018: EICUG Annual Meeting, Catholic University of America
2017: International Workshop on Physics with Positrons at Jefferson Lab:

Honors and Awards

2016 State Council for Higher Education in Virginia Outstanding Faculty Award
2012 ODU Provost's Award for Leadership in International Education
2007–2010 Chaire d'Excellence, French "Agence Nationale pour la Recherche"
2006 ODU College of Sciences, Hirschfeld Faculty Excellence Award
2005 Fellow, American Physical Society
1987–1992 NSF Presidential Young Investigator
1986 Peter Demos Dissertation Award, Bates Linac Users Group
1978 UCSD: *summa cum laude* and Phi Beta Kappa

Professional Service

Reviewer:
Physical Review C, European Journal of Physics A
Journal of the Korean Physics Society
DOE Nuclear Physics, NSF Nuclear Physics, NSERC Canada

Doctoral Students

Hashir Rashar, Ph.D. December 2020 (ODU)
S. Lee Allison, Ph.D. August 2017 (ODU)
Mustapha Canan, Ph.D. May 2011 (ODU)
Serkan Golge, Ph.D. Aug. 2010 (ODU)
Eric Fuchey, Ph.D. Sep. 2010 (Université Blaise Pascal, Clermont-Ferrand, France)
Christophe Jutier, Ph.D. Dec 2001 (joint thesis, ODU and U. Blaise Pascal)
Luminita Todor, Ph.D. Dec 2000 (ODU)

Selected Publications: Total of over 200 refereed publications and conference proceedings (18 in last 3 years), over 13,000 citations (`http://inspirehep.net/`, including C. Hyde-Wright 1984–2007). $h_{\rm HEP}$ index 82.

- F. Georges *et al.* [Jefferson Lab Hall A], "Deeply Virtual Compton Scattering Cross Section at High Bjorken xB," Phys. Rev. Lett. **128**, no.25, 252002 (2022) doi:10.1103/PhysRevLett.128.252002 [arXiv:2201.03714 [hep-ph]].
- F. Hauenstein, A. Jentsch, J. R. Pybus, A. Kiral, M. D. Baker, Y. Furletova, O. Hen, D. W. Higinbotham, C. Hyde and V. Morozov, *et al.* "Measuring recoiling nucleons from the nucleus with the future Electron Ion Collider," Phys. Rev. C **105**, no.3, 034001 (2022) doi:10.1103/PhysRevC.105.034001 [arXiv:2109.09509 [physics.ins-det]].
- M. Dlamini *et al.* [Jefferson Lab Hall A], "Deep Exclusive Electroproduction of $\pi 0$ at High Q2 in the Quark Valence Regime," Phys. Rev. Lett. **127**, no.15, 152301 (2021) doi:10.1103/PhysRevLett.127.152301 [arXiv:2011.11125 [hep-ex]].
- M. Benali, C. Desnault, M. Mazouz, Z. Ahmed, H. Albataineh, K. Allada, K. A. Aniol, V. Bellini, W. Boeglin and P. Bertin, *et al.* "Deeply virtual Compton scattering off the neutron," Nature Phys. **16**, no.2, 191-198 (2020) doi:10.1038/s41567-019-0774-3 [arXiv:2109.02076 [hep-ph]].
- E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams, M. Alfred, F. Barbosa, L. Barion, V. Berdnikov, W. Brooks and T. Cao, *et al.* "AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case," JINST **15**, no.05, P05009 (2020) doi:10.1088/1748-0221/15/05/P05009 [arXiv:1911.05797 [physics.ins-det]].

Seminars and Conference Presentations: (19 total, Sept 2019–Sept 2022):

- **"Coherent Deep Virtual Compton Scattering on ^{4}He with CORE@EIC"**, C.E. Hyde, Andrey Kim (UConn), Carlos Muñoz Camacho (IJCLab). Contributed talk to XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2022), Santiago de Compostela, Galicia, Spain, 2–6 May 2022.
- **" Deeply virtual Compton scattering cross sections at high Bjorken x"**, C.E. Hyde, Malek Mazouz (Monastir U, Tunisia), Carlos Muñoz Camacho (IJCLab, France), Julie Roche (Ohio U). Contributed talk to XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2022), Santiago de Compostela, Galicia, Spain, 2–6 May 2022.
- **"Deep Virtual Exclusive Scattering on Nuclei at the EIC: Prospects and Challenges"**, invited seminar (online) Center for Frontiers in Nuclear Science, Stony Brook University, NY, 18 Nov 2021, `https://www.stonybrook.edu/cfns/activities/seminars`
- **"CORE: a COmpact detectoR for the EIC"**, invited talk at the "Workshop on Physics Opportunities with Heavy Quarkonia at the EIC",Center for Nuclear Femtography, 25-27 October 2021 `https://indico.bnl.gov/event/12899/`
- **"Far Forward Calorimetry Overview: ZDC"**, invited talk (online) "EIC Calorimetry Workshop: From Yellow Report towards Implementation", 15–6 March 2021, Oak Ridge National Laboratory TN.

Dr. Sebastian Kuhn, Professor of Physics and Eminent Scholar

Department of Physics, College of Sciences, Old Dominion University, Norfolk VA 23529
Phone: (757) 683-5804 Email: skuhn@odu.edu Web: http://www.odu.edu/~skuhn

Academic Degrees

March 1982	Diploma in Physics (comparable to M.S.)	University of Bonn
January 1986	Dr. rer. nat. (Ph.D.) in Physics	University of Bonn

Professional Positions

2008 –	Eminent Scholar	Old Dominion University
2003 –	Professor of Physics	Old Dominion University
1997 – 2003	Associate Professor of Physics	Old Dominion University
1992 – 1997	Assistant Professor of Physics	Old Dominion University
1988 – 1992	Acting Assistant Professor	Stanford University
1986 – 1988	Visiting Postdoctoral Fellow	Lawrence Berkeley Laboratory

Leadership Positions

2017 – 2018	Member of the APS DNP Mentoring Award and Nominating Committees
2014 – 2015	Member of the NSAC Long Range Plan Writing Panel
2012 – 2015	Steering Group member, Programs Committee of Jefferson Science Associates
2011 – 2012	Member, Jefferson Lab Program Advisory committee (also in 2002)
2010 – 2014	Chair elect, Chair and Past Chair of the Jefferson Lab Users Group Board of Directors
2009 – 2010	Elected to Executive Committee, APS Topical Group on Hadronic Physics
2005 – 2008	Chair, Deep Processes Physics Working Group of the CLAS Collaboration
2001 – 2003	Director, Jefferson Lab Users Group Board of Directors

Honors and Awards

April 2022	Doctoral Mentoring Award and College of Science Research Award, ODU
March 2017	SCHEV Virginia Outstanding Faculty Award Nominee, Old Dominion University
May 2014	Gene W. Hirschfeld Faculty Excellence Award, College of Sciences (ODU)
April 2008	Recipient of the Annual Research Prize at Old Dominion University
Nov. 2007	Elected as Fellow of the American Physical Society
July 1986	Recipient of a NATO postdoctoral fellowship
June 1983	Recipient of a fellowship of the "Studienstiftung des Deutschen Volkes"

Doctoral Students: Graduated: Frank Wesselmann (Ph.D. 2000), Junho Yun (Ph.D. 2001), Alexei Klimenko (Ph.D. 2004), Nevzat Guler (Ph.D. 2009), Svjatoslav Tkachenko (Ph.D. 2009), Michael Mayer (Ph.D., 2013), Krishna Adhikari (Ph.D., 2014), Suman Koirala (Ph.D., 2014), David Payette (Ph.D., 2021). Presently: Victoria Lagerquist, Pushpa Pandey.

Selected Publications: (Over 170 publications in refereed journals with over 17,000 citations, h_{HEP} index 74.)

- *"Experimental study of the behavior of the Bjorken sum at very low Q^2"*, A. Deur, J.P. Chen, S.E. Kuhn, C. Peng, M. Ripani, *et al.*, *Phys. Lett. B* **825**, 136878 (2022).
- *"Measurement of the proton spin structure at long distances"*, X. Zheng *et al.* [CLAS Collaboration], *Nature Phys.* **17**, 736 (2021).
- *"The CLAS12 drift chamber system"*, M. Mestayer *et al.*, *Nucl. Inst. and Meth. Phys. Res., Sect. A* **959**, 163518 (2020).
- *"Semi-inclusive π^0 target and beam-target asymmetries from 6 GeV electron scattering with CLAS"*, S.Jawalkar, S.Koirala, H.Avakian, P.Bosted, K.A.Griffioen, C.Keith, S.E.Kuhn, *et al.* [CLAS Collaboration], *Phys. Lett. B* **782**, 662 (2018).
- *"Measurement of the Q^2-dependence of the deuteron spin structure function g_1 and its moments at low Q^2 with CLAS"*, K.P. Adhikari, A. Deur, L. El Fassi, H. Kang, S.E. Kuhn, *et al.* [CLAS Collaboration], *Phys. Rev. Lett.* **120**, 062501 (2018).
- *"Iterative Monte Carlo analysis of spin-dependent parton distributions"*, Nobuo Sato, W. Melnitchouk, S.E. Kuhn, J.J. Ethier, and A. Accardi, *Phys. Rev. D* **93**, 074005 (2016).
- *"Precise determination of the deuteron spin structure at low to moderate Q^2 with CLAS and extraction of the neutron contribution"*, N. Guler, R.G. Fersch, S.E. Kuhn, *et al.* [CLAS Collaboration], *Phys. Rev. C* **92**, 055201 (2015).
- *"Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic $^2H(e,e'p_s)X$ scattering with CLAS"*, S. Tkachenko, N. Baillie, S. E. Kuhn, J. Zhang, J. Arrington, *et al.* [CLAS Collaboration], *Phys. Rev. C* **89**, 045206 (2014).
- *"Spin structure of the nucleon – status and recent results"*, S.E. Kuhn, J.-P. Chen and E. Leader, *Prog. Part. Nucl. Phys.* **63**, 1-50 (2009).

Selected Invited Talks: (80 invited talks; 9 in the last 3 years.)

- *"Nucleon (Spin) Structure at High X"*, Workshop "J-FUTURE", Mar 28-30, 2022, Messina (Italy).
- *"Collinear PDF: Status and Outlook"*, 9th Workshop of the APS Topical Group on Hadronic Physics, April 13-16, 2021 (virtual).
- *"Spin structure from short to large distances"*, Workshop "Strong QCD from Hadron Structure Experiments", Nov 6-9, 2019, Newport News, VA.
- *"The JLab Hall B Experimental Program of Nucleon Spin Structure Functions"*, 5th International Workshop on the Structure of the Nucleon at Large Bjorken x (HiX2019), Aug 16-21, 2018, Kolymbari (Greece).
- *"Tagged Structure Functions"*, Workshop on "Correlations in Partonic and Hadronic Interactions", Sep 24-28, 2018, Yerevan (Armenia).
- *"Overview of new measurements of electromagnetic form factors, polarizabilities and spin structure function functions"*, keynote address at the ECT* Workshop "Nucleon Spin Structure at low Q: A Hyperfine View", July 2-6, 2018, Trento (Italy).
- *"The BONuS measurements of the free neutron structure function"*, International Workshop on (e,e'p) Processes (EEP17), July 2-5 2017, Bled (Slovenia).
- *"Modifications of Nucleons in Nuclei"*, Twelfth Conference on the Intersections of Particle and Nuclear Physics (CIPANP2015), May 19-24, 2015, in Vail (CO).

Dr. Stepan Stepanyan Jefferson Lab Professor of Physics at ODU and Senior Scientist at Jefferson Lab

Academic Degrees

Yerevan State University, Yerevan, Armenia, B.A./M.A. in Physics, 1979
Yerevan Physics Institute, Yerevan, Armenia ,Ph.D. in Physics, 1996

Professional Positions

2022–present: Senior Scientist, acting Hall-B leader, Thomas Jefferson National Accelerator Facility
2009–present: Jefferson Lab Professor of Physics, Old Dominion University
2003–present: Senior Scientist, deputy Hall-B leader, Thomas Jefferson National Accelerator Facility
2001–2003: Research Professor, Old Dominion University
2000-2001 : Research Associate, Christopher Newport University
1997–2000: Visiting Scientist, The Thomas Jefferson National Accelerator Facility
1979–1997: Staff Scientists, Yerevan Physics Institute, Yerevan, Armenia

Honors and Awards

2014 Fellow, American Physical Society

Professional Service

Reviewer:
Physical Letter B, European Journal of Physics A
NSF Nuclear Physics, NSERC Canada
Jefferson Labs Experimental Readiness Reviews, Technical Advisory Committee for Jefferson Lab PAC

Conference Co-Organizer
"International Conference on Correlations in Partonic and Hadronic Interactions", Yerevan, Armenia, September 24 - 28, 2018
"Light Dark Matter 2019", Venice, Itamy, 20-22 November, 2019
"International workshop on Detection Systems and Technologies in Nuclear and Particle Physics", Massina, Italy, September 11-13, 2019.

Doctoral Students

Yeranuhi Ghandilian, PhD. October 2016 (Yerevan Physics Institute, Armenia)
Rafayel Paremuzyan, PhD October 2012 (Yerevan Physics Institute, Armenia)
Joseph Newton, PhD August 2021 (Old Dominion University)

Selected Publications: Total of over 200 refereed publications (27 in last 3 years), with over 10,100 total citations (`http://inspirehep.net/`).

- "Exploring the Structure of the Bound Proton with Deeply Virtual Compton Scattering", M. Hattawy *et al.*, Phys. Rev. Lett. **123** (2019), 032502
- "Search for a dark photon in electroproduced e^+e^- pairs with the Heavy Photon Search experiment at JLab", P.H. Adrian *et al.,*, Phys. Rev. D **98** (2018), 091101.

- "First Exclusive Measurement of Deeply Virtual Compton Scattering off ^{4}He: Toward the 3D Tomography of Nuclei " M. Hattawy *et al.*, Phys. Rev. Lett. **119** (2017), 202004

- "Upper limits for the photoproduction cross section for the $\Phi^{--}(1860)$ pentaquark state off the deuteron" H. Egiyan *et al.* [CLAS Collaboration]. Phys. Rev. **C85** (2012), 015205

- "Measurement of Deeply virtual Compton scattering beam-spin asymmetries", F. X. Girod *et al.* [CLAS Collaboration]. Phys. Rev. Lett. **100**, 162002 (2008).

- "Search for the Theta+ pentaquark in the reaction gamma d —¿ p K- K+ n," B. McKinnon *et al.* [CLAS Collaboration], Phys. Rev. Lett. **96**, 212001 (2006)

- "Observation of exclusive deeply virtual Compton scattering in polarized electron beam asymmetry measurements," S. Stepanyan *et al.* [CLAS Collaboration], Phys. Rev. Lett. **87**, 182002 (2001)

- "The P(33)(1232) resonance contribution into the amplitudes M**3/2(1+), E**3/2(1+), S**3/2(1+) from an analysis of the p(e,e-prime p) pi0 data at Q**2 = 2.8, 3.2, and 4-(GeV/C)**2 within dispersion relation approach," I. G. Aznaurian and S. G. Stepanian, Phys. Rev. D **59**, 054009 (1999);

Selected Invited Talks: (24 invited talks; 4 in the last 3 years.)

- *JLAB physics program: overview*, International Workshop on Hadron Structure and Spectroscopy - 2022 (IWHSS-2022), CERN in Geneva, Switzerland, August 29 - 31, 2022.
- *CLAS12 luminosity upgrade and future physics opportunities*, DIS2022, Santiago de Compostela, Spain May 2 - 6, 2022.
- *"Deep exclusive scattering off 4He"*, International workshop Partons and Nucleus, IPN Orsay, France, June 2017
- *"Coherent DVCS on 4He"*, workshop on Nucleon and resonance structure with hard exclusive processes, PN Orsay, France, May 2017
- *"J/psi production with CLA12"*, the Proton Mass Workshop 2017 at the ECT* in Trento, Italy, April 2017.
- *"Search for Heavy Photons"*, Baryon2013, Glasgow University, Glasgow (UK), June 2013
- *"Time-like Compton Scattering*, Photo-nuclear Reactions at Gordon Conferences, Holderness NH (USA), August 2012
- e^+e^- *pair production in Hall B, including* J/Ψ, International workshop on Non-Perturbative Color Force in QCD, Temple University, Philadelphia, PA (USA), March 2012
- *CLAS12 Particle Identification*, International workshop on Probing Strangeness in Hard Process PSHP2010, INFN Frascati (Italy), October 2010
- *"Hadron Physics with CLAS12"*, HADRON09 Conference, Tallahassee, Florida (USA), November 2009

Dr. Lawrence Weinstein, Professor of Physics and Eminent Scholar, ODU

Academic Degrees

Yale University	Bachelor of Science in Physics	B.S. 1981
Massachusetts Institute of Technology	Doctor of Philosophy in Physics	Ph.D. 1988

Professional Positions

2007 –	University Professor	Old Dominion University
2003 –	Professor of Physics	Old Dominion University
1998 – 2003	Associate Professor of Physics	Old Dominion University
1992 – 1998	Assistant Professor of Physics	Old Dominion University
1991 – 1992	Research Scientist	Massachusetts Institute of Technology
1988 – 1991	Sponsored Research Staff	Massachusetts Institute of Technology

Honors and Awards

2019	Research Scholarship and Creative Achievement Award, Old Dominion University
2016	Chair, Jefferson Lab Users Group
2015	George B. Pegram Award, Southeast Section of the American Physical Society
2014	A. Rufus Tonelson Distinguished Faculty Award, Old Dominion University
2012	Eminent Scholar, Old Dominion University
2009	Virginia Outstanding Faculty Award
2008	Finalist, Society of Physics Students, Outstanding Chapter Advisor
2007	University Professor, Old Dominion University
2007	Teaching With Technology Award, Old Dominion University
2004	Fellow, American Physical Society
2003–2005	Chair of the Jefferson Lab CLAS Collaboration

Books

L. Weinstein and J. Adam, *Guesstimation: Solving the World's Problems on the back of a cocktail napkin*, Princeton University Press, Princeton, NJ, 2008.

L. Weinstein, *Guesstimation 2.0 : Solving today's problems on the back of an envelope*, Princeton University Press, Princeton, NJ, 2012.

Doctoral Students: Rustam Niyazov (Ph.D. 2003), Hovhannes Baghdasaryan (Ph.D. 2007), Megh Niroula (Ph.D. 2010), Dasuni Adikaram (Ph.D. 2014), Holly Szumila-Vance (Ph.D. 2017) and Mariana Khachatryan (Ph.D. 2019).

Selected Publications: (Total of over 220 publications in refereed journals with over 13,000 citations, 24 in the last three years. h-index = 64.)

- **"Electron-beam energy reconstruction for neutrino oscillation measurements"**, M. Khachatryan, *et al.* (the CLAS and $e4\nu$ Collaborations), Nature **599**, 565 (2021).
- **"^{12}C$(e,e'pN)$ measurements of short range correlations in the tensor-to-scalar interaction transition region"**, I. Korover, *et al.* (the CLAS Collaboration), Phys. Lett. B **820** (2021) 136523.
- **"Short-range correlations and the nuclear EMC effect in deuterium and helium-3"**, E. P. Segarra, J. R. Pybus, F. Hauenstein, D. W. Higinbotham, G. A. Miller, E. Piasetzky, A. Schmidt, M. Strikman, L. B. Weinstein, and O. Hen Phys. Rev. Research 3, 023240 (2021).
- **"Inclusive electron scattering and the genie neutrino event generator"**, A. Papadopoulou, A. Ashkenazi, S. Gardiner, M. Betancourt, S. Dytman, L.B. Weinstein, E. Piasetzky, F. Hauenstein, M. Khachatryan, S. Dolan, G.D. Megias, and O. Hen ($e4\nu$ Collaboration), Phys. Rev. D **103** 113003 (2021).

- **"Many-body factorization and position-momentum equivalence of nuclear short-range correlations",** Cruz-Torres, R., Lonardoni, D., Weiss, R. et al., Nature Physics **17**, 306 (2021)
- **"Probing the core of the strong nuclear interaction,"** A. Schmidt *et al.* [CLAS Collaboration], Nature **578**, 540-544 (2020)
- **"Modified structure of protons and neutrons in correlated pairs,"** B. Schmookler *et al.* [CLAS Collaboration], Nature **566**, no. 7744, 354 (2019).
- **"Can Long-Range Nuclear Properties Be Influenced By Short Range Interactions? A chiral dynamics estimate"**, G.A. Miller, A. Beck, S. May-Tal Beck, L.B. Weinstein, E. Piasetzky, and O. Hen, Phys.Lett. **B793**, 360 (2019).
- **"Probing High Momentum Protons and Neutrons in Asymmetric Nuclei"**, M. Duer, et al. (The CLAS Collaboration), Nature **560**, 617 (2018).
- **"Nucleon-nucleon correlations, short-lived excitations, and the quarks within"**, Or Hen, Gerald A. Miller, Eli Piasetzky, and Lawrence B. Weinstein, Rev. Mod. Phys. **89** (2017) 045002.
- **"Momentum sharing in imbalanced Fermi systems"**, O. Hen, M. Sargsian, L.B. Weinstein, *et al.*, Science **346**, 614 (2014).

Selected Invited Talks: (138 invited talks, seminars and colloquia; nine in the last three years. Most recent ones listed.)

- **"Data Visualization"**, invited talk presented at the 2022 Workshop on Frontiers and Careers in Nuclear and Hadronic Physics, 5-6 Aug, 2022
- **"Guesstimation: Solving the world's problems on the back of a cocktail napkin"**, invited talk (remote), EIC User Group Early Career Workshop 24-25 July, 2022.
- **"The Future of** $e4\nu$**"**, invited talk (remote) at NuSTEC Workshop on Electron Scattering, Tel Aviv, Israel, 28–31 March, 2022.

  135) **"Guesstimation: Solving the world's problems on the back of a cocktail napkin"**, Physics Colloquium (remote), University of Tennessee Knoxville, 24 Jan, 2022.
- **"The Nucleons Go Two By Two: Correlations in Nuclei"**, Physics Colloquium, Virginia Tech, Blacksburg, VA, 8 Oct, 2021.
- **"Everything a neutrino experimentalist wants to ask the electron scattering community"**, invited talk presented at NuFact 2021: The 22nd International Workshop on Neutrinos from Accelerators, Cagliari, Sardinia, Sep 6-11, 2021.
- **"Data Visualization"**, invited talk presented at the EIC User Group Meeting Early Career Workshop, July 31, 2021.
- **"Electron-scattering constraints for neutrino-nucleus interactions"**, invited talk presented at New Physics on the Low-Energy Precision Frontier, CERN, Switzerland, Jan 27-31, 2020.
- **"Electron-scattering constraints for neutrino-nucleus interactions"**, invited talk presented at NUSTEC Workshop on Neutrino Nucleus Pion Production in the Resonance Region, Pittsburgh, PA, Oct. 2-5, 2019.

VIII. STUDENT TRACKING INFORMATION

Experimental Nuclear Physics Graduate Students

Student	Admitted to ODU	Passed Written Qualifier	Paid as RA in Nuclear Physics	Degree Program	Date Degree Awarded (Expected)	Advisor
Hashir Rashad	8/10	1/11	8/10 - 9/19	Ph.D.	Dec 2020	C. Hyde
Mariana Khachatryan	1/14	8/14	8/14 (part JSA)	Ph.D.	Dec 2019	L. Weinstein
Torri Jeske (Roark)	8/14	8/15	1/16	Ph.D.	Dec 2020	M. Amaryan
Nathan Dzbenski	8/14	1/16	6/16	Ph.D.	Aug 2020	G. Dodge
David Payette	8/14	8/15	1/16	Ph.D.	May 2021	S. Kuhn
Dilini Bulumulla	8/14	8/16	(RA)*	Ph.D.	(Dec 2022)	C. Hyde
Victoria Lagerquist	8/15	8/16	8/17*	Ph.D.	(Dec 2022)	S. Kuhn
Jiwan Poudel	8/15	8/16	0.5 (RA) 8/17*	Ph.D.	May 2022	S. Bueltmann
Nilanga Wickramaarchchi	8/15	8/16	5/17	Ph.D.	May 2020	M. Amaryan
Joseph Newton	8/15	10/16	(JLAB) 1/18	Ph.D.	Aug 2021	S. Stepanyan
Tyler Viducic	8/16	8/17	5/18	Ph.D.	(May 2023)	M. Amaryan
Madhusudhan Pokhrel	8/17	8/18	5/19	Ph.D.	(May 2024)	S. Bueltmann
Caleb Fogler	8/17	1/19	5/19**	Ph.D.	(Dec 2023)	L. Weinstein
Mitchell Kerver	8/17	8/18	8/19	Ph.D.	(May 2024)	C. Hyde
Pushpa Pandey	8/17	8/18	5/19**	Ph.D.	(May 2024)	S. Kuhn
Christine Ploen	8/18	8/21	8/20***	Ph.D.	(Dec 2024)	C. Hyde
Yu-Chun Hung	8/18	1/20	5/22	Ph.D.	(May 2024)	S. Bueltmann
Noah Swan	8/19	8/21	5/22	Ph.D.	(2025)	L. Weinstein
Mariana Tenorio-Pita	8/20	1/22	8/22	Ph.D.	(2025)	S. Stepanyan

TABLE I. Current graduate students in the experimental nuclear physics group. The date each student joined our group does not refer to the first summer in which they worked with us but rather the date at which he/she stopped working as a TA and became a full-time RA.
(JLAB) Jefferson Lab supported RA (until Jan. 1, 2018)
(TA) or (RA) Student supported by department as TA or RA
* We provided support to these students in the summers of 2015, 2016 and 2017.
** We provided support to these students in the summers of 2018 and 2019.
*** Mostly external funding.

IX. CURRENT AND PENDING SUPPORT

A. Current Support

1 Source of Support: Department of Energy
Project Title: From Quarks to Nuclei
Investigators: M. Amaryan, S. Bültmann (PI), G.E. Dodge, C.E. Hyde, S.E. Kuhn, and L.B. Weinstein
Amount Awarded: $3,051,000; Anticipated carryover $0, or $< 2\%$ of year 3 budget.
Period Covered: March 15, 2020 – March 14, 2023
Effort: 100% of research time
Location: Old Dominion University

Source of Support: SURA (Center for Nuclear Femtography)
Project Title: Next Generation Imaging Filters and Mesh-Based Data Representation
Investigators: N. Chrisochoides (Computer Science, P.I.), C. Hyde
Amount Awarded: $31,000
Period Covered: June 1, 2022 – December 31, 2022
Effort: 10% of research time (synergistic with present proposal)
Location: Old Dominion University

B. Pending Support

3) Source of Support:	Department of Energy
Project Title:	From Quarks to Nuclei (This Proposal)
Investigators:	M. Amaryan, S. L. Bültmann (PI), C.E. Hyde, S.E. Kuhn, S. Stepanyan, and L.B. Weinstein
Amount Requested:	$4,051,564
Period Covered:	March 15, 2023 – March 14, 2026
Effort:	100% of research time
Location:	Old Dominion University

4) Source of Support:	Jefferson Laboratory (Generic EIC-Related Detector R&D Program)
Project Title:	Z-Tagging Mini DIRC
Investigators:	C.E. Hyde
Amount Requested:	$114,000
Period Covered:	October 1, 2022 – September 30, 2023
Effort:	20% of research time, synergistic with this proposal
Location:	Old Dominion University and Jefferson Lab

5) Source of Support:	Jefferson Laboratory (Generic EIC-Related Detector R&D Program)
Project Title:	Machine Learning for Detection of Low-Energy Photons in the EIC ZDC
Investigators:	C.E. Hyde
Amount Requested:	$29,000 (ODU)
Period Covered:	October 1, 2022 – September 30, 2023
Effort:	5% of research time, synergistic with this proposal
Location:	Old Dominion University and Jefferson Lab

X. FACILITIES AND RESOURCES

1. Old Dominion University

Old Dominion University is a state supported university located in Norfolk, Virginia. It is classified as "Research 1" university with very high research activity and offers a Ph.D. degree in physics with an average enrollment of 50 physics graduate students. The physics department at ODU has strong research programs in nuclear and particle physics, atomic, molecular and optical physics, accelerator physics, nano-science, and in computational physics (see sci.odu.edu/physics/). A new center for accelerator science was established in 2008 in partnership with Jefferson Lab.

Old Dominion University serves a large number of minority students ($> 25\%$ African American).

The nuclear and particle physics group consists of six professors (Profs. M. Amaryan, S.L. Bueltmann, G.E. Dodge, C.E. Hyde [PYI 1987 and APS Fellow], S.E. Kuhn [APS Fellow], and L.B. Weinstein [APS Fellow]) and six professors in theoretical nuclear physics (Profs. I. Balitsky, R. Briceno, A. Radyushkin [APS Fellow], F. Ringer, T. Rogers, and R. Schiavilla [APS Fellow]) whose research interests overlap significantly with those of the experimental group. In addition, Drs. S. Covrig, D. Mack and S. Stepanyan are JLab Professors of Nuclear Physics (Jefferson Lab staff who enjoy faculty privileges at ODU).

During the previous grant period, the University supported our group with

- 50% FTE support for our technician, Thomas Hartlove.
- 50% FTE support for a Post Doctoral Research Associate to provide network and computational support.

ODU has agreed to continue this funding support at the same level for the next three years.

2. Facilities

The proposed research will take place at the ODU Department of Physics. Most of the experimental effort will be conducted at Jefferson Lab in Newport News, VA, approximately a 45 minute drive from ODU.

The University continues to provide the nuclear physics group with substantial support in material and infrastructure. This includes the position of a machinist for the College of Sciences, who can help with building parts for our group.

Laboratory:

Our group has 5,000 square feet of laboratory space, including a two-story high-bay area in the Physical Sciences Annex to the Oceanography and Physical Sciences Building. We have the space and equipment necessary to undertake large hardware projects, as shown by the construction of the CLAS12 Region 2 Drift Chambers and large anode wire planes for a COMPASS drift chamber at CERN. The laboratory space also includes a small permanent clean room, four multi-purpose laboratory rooms, a computer server room, preparation

room, and a technician office. The laboratories contain machine room equipment and tools, standard VME, NIM and CAMAC electronics, and other research equipment.

Computer:

The experimental nuclear physics group has a LINUX farm of 13 nodes and 12 TeraBytes of disc storage. The farm includes three 64-bit nodes, each with 8 processors.

Office:

Student, post-doc, and faculty office spaces are adjacent to the lab space in the Physical Sciences Building.