Statement on Nature and Significance of Scholarship

My nuclear experimental program aims at answering the following questions: "How does subatomic matter organize itself and what phenomena emerge?" and "Are the fundamental interactions that are basic to the structure of matter fully understood?" Both questions have been framed as overarching questions central to nuclear physics in the 2013 report of the National Research Council on the Assessment of and Outlook for Nuclear Physics titled *Nuclear Physics: Exploring the Heart of Matter*[1]. My research has two distinct foci that are carried out with a common tool: the electron beam at JLab in Virginia. JLab is a U.S. Department of Energy nuclear physics research facility, providing world-class, unique research capabilities to an international scientific user community. The $338M energy upgrade of the electron beam was completed in the Fall of 2017. Nearly 200 experiments have been completed at JLab since it started operating in 1997. One third of all nuclear science Ph.D.s awarded in the U.S. is based on Jefferson Lab research. In the experiments performed at JLab, an electron scatters off static protons and neutrons in an atom target. Information about this collision are gathered by detectors which measure the direction and energy of the products of the collision (typically the scattered electron and at least one recoiling particle). The incident electron beam acts like a polarizing microscope in which the focus can be modified (by changing the energy of the beam) or in which filters can be swapped out (by changing the direction of the *spin*[2] of the electron).

First focus: Internal structure of protons and neutrons. Protons and neutrons that make up the nuclei at the center of atoms are composite particles. They are made up of elementary constituents called quarks held together by particles called gluons, the messengers of the Strong force. Gluons are exchanged back and forth between quarks and they are the source of the proton's mass. Over ninety-nine percent of the mass of the visible matter in the universe is created by the Strong Nuclear Force. Of the four known *fundamental forces* existing in our universe, the Strong nuclear force is perhaps the least understood. While the strength of the electric force decreases when two electric charges are pulled apart ; the strength of the strong force increases dramatically as the distance between the two quarks on which it acts increases. It would take an infinite amount energy to separate two quarks; this property is called Confinement. As a result of confinement, free quarks have never been observed; quarks are said to be confined inside the hadrons Because of the dramatic increase of the strength of the interaction at distance scales comparable to the size of the hadrons, it is not possible to describe the structure of these hadrons using the mathematical techniques used for the other forces. These usual techniques describe particle interactions as a sum of small perturbations, these perturbation techniques are not applicable in the confinement region where the Strong force is so strong. In that sense, the internal structure of the proton is an ideal laboratory to study the Strong Force.
The goal of my current research is to produce a 3-D tomographic picture of the internal

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[1] https://www.nap.edu/catalog/13438/nuclear-physics-exploring-the-heart-of-matter

[2] Potentially unfamiliar words are defined in Section **??**.

structure of the proton against which models of the Strong force can be tested. We simultaneously map out the momentum and spatial distribution of the quarks inside the proton. The ideas that make these studies possible are new (less than 20 years), and my collaborators and I are leaders in the exploration of the limit of validity of these ideas. To do so, our experiments measure of the absolute probability of the Deeply Virtual Compton Scattering (aka DVCS) process. In this process, an electron strikes a proton, which in turn emits a photon before recoiling undisturbed ($ep \to ep\gamma$). I am the co-spokesperson of 3 such experiments at JLab: E07-007 (took data in 2010, final publication stages), E12-06-114 (took data from 2014 to 2016, being analyzed) and E12-13-010 (not taking data before 2020). For these experiments, our collaboration is "small", typically a dozen of core collaborators (see Section **??**). Because of the size of the collaboration and because I am a spokesperson, I am involved at the leadership level in all aspects of the experiment: proposing, advocating, preparing the hardware, taking data , analyzing and publishing.

Second focus: Search for Physics beyond the Standard Model. One of the biggest achievement of the twentieth-century science is the establishment of the Standard Model of Particle Physics. The model describes the universe as made up of twelve elementary particles bound together by three fundamental forces: strong, weak and electromagnetic. Everything that happens in our world (except for the effects of gravity) results from particles interacting as described by the rules and equations of this model. Though still called a model, the Standard Model is a fundamental and well-tested physics theory. Indeed, since it was developed in the early 70?s, physicists use it to explain and calculate a vast variety of particle interactions and quantum phenomena. All particles predicted by the model have been found, and the consistency of the model has been tested and found to be correct for about 20 years. Despite its incredible robustness tested world-wide since the 1980's, and the majestic 2012 discovery of *Higgs* particle, the Standard Model is known to be incomplete. For example, the Standard Model does not include the effect of gravity, no explanations are given for the small differences seen in the properties of matter and *anti-matter* or the nature of *dark matter* and *dark energy*. In that sense, the quest for "Physics beyond the Standard Model" presses deeper into our imperfect understanding of the fundamental forces that make up our universe. This question is to be answered by current and future experiments and is the larger context of my work.

Many strategies are developed to search for new inputs to the Standard Model. One of them is to perform precision measurements of interactions which can be reliably predicted by the Standard Model. Deviations from predictions of the Standard Model provide a signature of new physics. I am currently engaged in two different projects which explore different possible extensions of the Standard Model. The QWEAK experiment is a finishing project: we took data up to 2012 and released the main final results in the Summer of 2017. We found that our measurement was compatible will the prediction of the Standard Model. My group is still working on an ancillary measurement that we hope to publish next year. The MOLLER experiment is the next experiment we will be working on. While this experiment has been approved by the Jefferson Lab PAC, it is currently waiting for funding approval by the US

Department of Energy via the Major Item of Equipment funding mechanism, a wait extended by current budget uncertainties. This type of experiments is large, typically about 50 core collaborators. In such a case, while all collaborators are encouraged to participate to all aspects of the experiment, in practice one group will be take charge of one specific aspect of the experiment. For the QWEAK experiment, my group was involved in data acquisition and software development. We are committed to play the same role for the MOLLER experiment.

NSF has funded the activities of my group continuously since 2007 (four competitive proposal cycles). My regular NSF grant supports the stipends of two graduate students and two summer undergraduate interns a year. It also supports summer salary for senior personnel: my close OU collaborator Dr King and myself. NSF is also funding my group through a Major Research Instrument grant for the construction of the detector for E12-13-110.

According to the popular High Energy Physics data base inSPIRE[3] where I make sure my papers are correctly accounted for, I have published a total of 77 papers in peer reviewed journals, 15 post tenure. Ten of these papers were co-authored with Ohio University students working under my supervision. My h-index is 38, my articles have gathered 3872 citations - excluding self-citations (October 2017 numbers provided by the inSPIRE database). Our research is most often published in Physical Review Letters. Other publications we use are Physical Review C, Nuclear Instruments and Methods in Physics Research, Nature Communications. Of my 21 core publications, 14 were published in Physical Review Letters (impact factor 8.462 in 2016) and 1 was published in Nature Communication. One paper was published on the front page of Physical Review Letter. The work of my DVCS collaboration resulted so far in 8 publications and gathered over 400 citations since 2006. The work of my QWEAK collaboration resulted so far in two published articles gathering over 110 citations since 2013.

I have many ideas for forthcoming scholarship as described in the previous paragraphs. For the internal structure of the nucleon part of the program, the future is completing the analysis of E12-06-114, performing and analyzing E12-13-010. I expect both activities to take about 10 years. A longer term project is to work on the TDIS experiment of which my close collaborator Dr P. King is a spokesperson. This experiment aims at measuring the internal structure of the pion. The pion is a composite particle made of a quark and anti-quark, aka a meson. While simpler than the proton (made of three quarks, aka a baryon) it is not a stable particle and therefore its structure is not well known as static target of pion cannot be prepared. Nevertheless successful models of confinement need to be able to describe the internal structure of mesons and baryons.
For the "Search for Physics beyond the Standard Model" part of the program, the MOLLER experiment is the next project. I also expect this large experiment to take about 10 years to complete. While the experiment has not received funding yet, it was recommended for completion by the 2015 "Long Range Plan" published by the National Science Advisory

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[3] http://inspirehep.net/info/general/project/index

Committee (NSAC)[4] so it is very likely to happen. NSAC is an advisory committee that provides official advice to the Department of Energy (DOE) and the National Science Foundation (NSF).

0.1 Glossary associated to my Statement on Nature and Significance of Scholarship.

The following possibly unfamiliar words are used in Section **??**. Some of the definitions given hereafter are directly copied from sources.

- **Spin**: The spin of a particle is an intrisic quantum property of this particle. It can be associated to the rotation of an object around its own center of mass. For example Earth spin is associated to its daily rotation around the polar axis.
- **Fundamental forces:** The fundamental forces (or interactions) dictate how individual particles interact with each other. To this date, four forces are necessary to explain all observed interaction: gravity, electromagnetic, weak and strong. Gravity draws two masses toward each other. Electromagnetism is the interaction of particles with an electrical charge. The weak interaction is responsible for radioactive decays of nuclei. The strong force keeps nucleons (protons and neutrons) bound together in a nucleus.
- **Hadrons**: Hadrons are composite particles made up of quarks, anti-quarks and gluons. Proton and neutrons are hadrons.
- **Higgs particle**: The Higgs particle may be the key to understanding why elementary particles have mass. In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do intrinsically massive particles arise? Peter Higgs proposed that the vacuum contains an omnipresent field that can slow down some (otherwise massless) elementary particles like a vat of molasses slowing down a high-speed bullet. Such particles would behave like massive particles traveling at less than light speed. Other particles such as the photons of light are immune to the field: they do not slow down and remain massless. Although the Higgs field is not directly measurable, accelerators can excite this field and "shake loose" detectable particles called Higgs bosons. The Higgs particle was discovered in 2012 at the Large Hadron Collider.
  Source: http://www.symmetrymagazine.org/cms/?pid=1000368
- **Anti-matter**: Antimatter is made up of particles with equal but opposite characteristics of everyday particles of matter. For particles, properties like electrical charge are opposite to their antiparticles one positive, one negative. Antimatter will annihilate

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[4] https://science.energy.gov/np/nsac/

its matter counterpart in a burst of energy. The universe seems to contain no significant amounts of antimatter, despite expectations that both should have been created equally during the big bang. So where did all the antimatter go? One possible explanation could be a subtle and unexpected difference in the properties of matter and antimatter, leading to a slight excess of matter which survived the initial cataclysm of matter-antimatter annihilation.
Source: http://www.symmetrymagazine.org/cms/?pid=1000009

- **Dark matter**: Dark matter is an elusive form of matter. Although it has mass, it does not interact with everyday objects . Yet, we know it exists. Because dark matter has mass, it exerts a gravitational pull. It causes galaxies and clusters of galaxies to develop and hold together. If it weren't for dark matter, our galaxy would not exist as we know it. Whatever dark matter is, it is not made of any of the particles ever detected in experiments. Dark matter could have at the subatomic level very weak interactions with normal matter, but physicists have not yet been able to observe those interactions.
  Source: http://www.symmetrymagazine.org/cms/?pid=1000451

- **Dark energy:** Dark energy is causing the expansion of the universe to speed up. However, we don't know much about dark energy. Dark energy is like a continuous, extraordinarily elastic medium. Its elasticity leads to its defining and most spectacular feature: its gravity repels rather than attracts. For the first nine billion years after the big bang, the attractive gravity of matter caused the expansion of the universe to slow down. Five billion years ago, dark energy's repulsive gravity overcame matter?s attractive gravity, leading to the accelerating universe. Dark energy is a profound mystery of science and therefore figuring it out is high on the to-do lists of both astronomers and physicists.
  Source: http://www.symmetrymagazine.org/cms/?pid=1000518