Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROPOSAL

TITLE: GEOMETRY TAGGING FOR HEAVY IONS AT JLEIC

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Abstract

Two of the main goals of the program at an electron-ion collider (EIC), such as the JLab EIC (JLEIC), are the search for evidence of parton saturation at low x and studying the propagation of produced partons in nuclear matter. Geometry tagging – using information from the nuclear breakup to categorize the geometry of the collision – can significantly enhance these essential measurements. For example, we find that geometry tagging can increase the accessible parton saturation scale (Q_s^2) as effectively as an increase in beam energy by more than a factor of 3.

The first year of the project was approved for FY17 and is currently underway. We are applying existing modeling tools (BeAGLE and Sartre) to investigate and develop the geometry tagging capabilities of the JLEIC full-acceptance detector. Due to improvements in the capabilities of BeAGLE which have occurred in parallel to the LDRD effort, we can now extend our studies to cover the full range of x_{Bj} (down to $x \approx 0.0008$ for Q^2>1 GeV^2 at 10GeVx40 GeV/nucleon).

We are proposing to extend the project in year two to address three key questions essential for JLEIC physics and the optimization of the IR and detector design: How much can e+U further improve the JLEIC reach in saturation scale? How well can we select coherent diffraction events to precisely measure the spatial distribution of gluons in the nucleus? How big of a reach can we achieve in the distance traveled in the nucleus by propagating partons, again including e+U? We also plan to validate and benchmark the developed simulations tools using the e+A program at JLab 12 GeV.

1.0 Summary of Proposal

1.1 Description of Project

Electron-nucleus collisions form an essential part of the program for the Electron-Ion Collider (EIC) [1] including studies of gluon anti-shadowing, studies of parton propagation, attenuation and hadronization in the nucleus, and ultimately the search for parton saturation.. It can greatly benefit from *geometry tagging* [2], which is an experimental analysis technique for selecting event samples where we can, on a statistical basis, control the geometry of the collision. Using geometry tagging, we can create an event sample in ePb collisions with a saturation scale or an average path length equivalent to a minimum bias nucleus of size *A*=600-900. In the case of the saturation scale, this is also equivalent to a minimum bias ePb collision at more than 3 times the baseline energy.

We propose a dedicated R&D Project to apply and improve existing modeling codes and detector descriptions to study this physics. We will use BeAGLE [3] (which includes PyQM[4-6]) to investigate the geometry tagging capabilities of the JLEIC full-acceptance detector for studying the in-medium propagation of color charges and the space-time evolution of the hadronization process [7] in semi-inclusive deep inelastic scattering (SIDIS) at modest Bjorken x (x>0.02), where the complications of nuclear shadowing can be avoided.

We will then use BeAGLE combined with Sar*t*re [8] to estimate the geometry tagging capabilities of the JLEIC full-acceptance detector for SIDIS as well as inclusive incoherent diffraction, both at *low x* (x<0.002). Low x SIDIS is valuable since the saturation scale is enhanced there, and "central" diffractive events have been shown to be sensitive to rare parton configurations with a large saturation scale Q_s [9]. In order to study gluon saturation more directly, we will use Sar*t*re [8] to compare coherent diffraction of J/ψ & ϕ which is a sensitive measure of gluon saturation [8,10]. Preliminary simulations using BeAGLE indicate that more than 10% of incoherent diffractive events yield *no* evaporation neutrons, so a ZDC-only detection strategy is unlikely to be successful in rejecting this background at the required level of 100-1000. This may, in fact, turn out to be the "killer app" for the JLEIC full acceptance detector.

The project meets three of the criteria for eligibility for JLab LDRD support: 1) Advanced study of new hypotheses, new concepts and innovative approaches to scientific or technical problems; 2) Conception and preliminary technical analysis of experimental facilities or devices; 3) Computer modeling, conceptual design and feasibility studies.

The project addresses a key DOE Office of Science mission: "fundamental understanding of matter and energy", by advancing our understanding of QCD and strong interaction as discussed in the 2015 Long Range Plan for Nuclear Science [11].

1.2 Expected Results

Specific expected results include:

- The implementation of the model codes at JLAB, interfacing them to detector simulations and making any needed improvements.
- A detailed study of the resolution of the nuclear geometry parameters d (distance traveled in the nucleus after first collision) and b (impact parameter) using the JLEIC Full Acceptance Detector.
- A detailed study of the efficiency and purity of the tag for deeply virtual coherent exclusive vector meson production on heavy nuclei.
- Measuring the physics impact of various forward detector capabilities, such as very large neutral Zero Degree Calorimeter acceptance, complete coverage for protons (and other Z=+1 particles), coverage for nuclear fragments (light ions and evaporation residues), coverage/id of forward photons, coverage for forward negatively-charged particles.

- Simulated physics results showing the ability of JLEIC to use geometry tagging to address key goals of the EIC Program: study the sensitivity of JLEIC to gluon saturation and a detailed study of light and heavy flavor propagation in the target nucleus n.
- Development of a simulation and a plan for how to validate geometry tagging using beam time already approved for JLab experiment E12-06-117.

2.0 Proposal Narrative

2.1 Purpose/Goals

Electron-ion collisions are essential for realizing key goals of the EIC program for studying QCD. Specifically, heavy ion beams are needed in order to access the regime of saturated gluon densities at EIC energies, and to study the propagation of color charges in nuclear matter.

The purpose of this proposal is to make these measurements even more incisive using forward going particles in the ion direction to tag the geometry of the collisions on an event-by-event basis. For a given energy and nuclear beam species, this will allow even better access to saturated gluon densities and it can significantly improve the precision and reach of the nuclear path length "dial" for the study of color-charge propagation. The JLEIC Full-acceptance detector, ideally suited to such measurements, constitutes a unique strength of the JLEIC design approach. In order to fully exploit this advantage, the JLEIC technical advantages need to be tied quantitatively to physics impact and physics tradeoffs need to be explored between detector capability and the accelerator in terms of the IR design.

2.2 Approach/Methods

Due to the different strength of the primary fundamental interaction, geometry tagging in eA collisions is different than in AA or pA collisions and presents several unique challenges and opportunities. The relatively weaker interaction of the virtual photon with the nucleus reduces the multiplicity of the primary particle production in the eA collision compared to pA. As an advantage, this means that the effects of evaporation from the excited nucleus and intranuclear cascading are much easier to detect. In fact, the main experimental handles we have are neutrons produced by evaporation from the excited nuclear remnant after the collision [12-14], and "knock-out" protons and other charged particles produced during the primary interaction or during the "intranuclear cascade" as remnants of the primary collision re-interact with the rest of the nucleus [15-16]. These experimental handles are correlated with the nuclear path length seen by the reaction products [14]. Previous models of geometry tagging in eA have focused on either evaporation neutrons [13-14] or charged particles [16], but not both together.

On the technical front, the JLEIC Full Acceptance Detector, capable of detecting nuclear fragments of all rigidities over a wide range in transverse momentum, p_T, will represent a significant advance in capability over previous (fixed target) studies which comprised low-acceptance soft neutron measurements [12] and high-efficiency, but very low statistics, measurements of highly ionizing (low energy) charged particles using emulsions or streamer chambers [15-16]. The combination of large acceptance and high luminosity will allow us to measure the number of neutrons, protons and even charged nuclear fragments on an event-by-event basis with large statistics, which will allow fine binning in new degrees of freedom. This capability will provide an unprecedented handle on nuclear effects and geometry tagging.

Figure 1, reproduced from [14], shows the schematic definition of "*d*", the path length traveled in the medium following the first collision. Since the back of the nucleus is not a hard edge, the actual definition of *d* is given by an integral:

$$d=\int_z^{\infty} \rho\left(z',b\right)/\rho_0\, dz' \qquad (1)$$

where $\rho(z',b)$ is the nuclear density and ρ_0 = 0.16 nucleons/fm^3 is the central nuclear density for the Pb nucleus, to provide a consistent normalization. The variable *d*, then, represents the equivalent full density nuclear matter thickness traveled in units of distance (fm). The quantity $\rho_0 d$ is the material thickness traversed in units of nucleons/fm^2.

In many A-dependence studies, such as in semi-inclusive hadron production, eA→e'hX, we have to average over all possible values of *d*, potentially washing out our desired physics effect. Figure 2 shows the distribution of *d* for minimum bias e+A DIS collisions on three different nuclei. The average value of *d* increases with *A*, $\langle d\rangle = -0.71 + 0.90A^{1/3}$, but, for each nucleus *A*, the distribution is quite wide and there is substantial overlap between the distributions for different choices of *A*. Figure 3 shows the result of a centrality selection for a single species, e+Pb, based on the multiplicity of evaporation neutrons (the larger the number of detected evaporation neutrons, the longer the in-medium interaction). There are two features that are advantageous: first of all the two samples, central and peripheral, are more distinct and second, the $\langle d\rangle$ (7.85±0.08 fm) for the central ePb sample is quite a bit larger than for the minimum bias (Figure 2). To get a $\langle d\rangle$ value that large with a minimum bias eA would require an unphysical value of *A*, approximately 860, more than quadruple the size of the Pb nucleus.

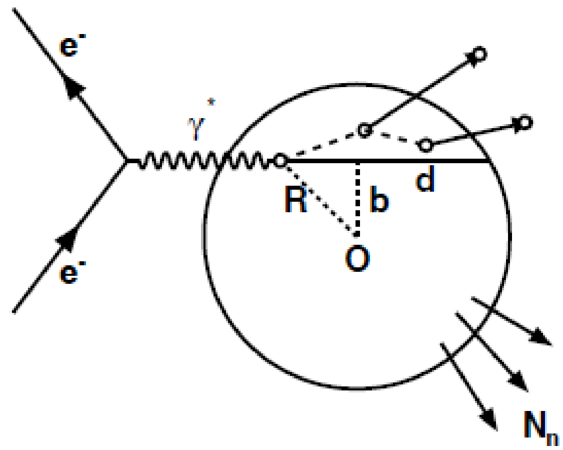

Figure 1: Geometric parameters *b*, representing the impact parameter, and *d*, the distance traveled in the nuclear medium after the first collision. Reproduced from Ref. [14].

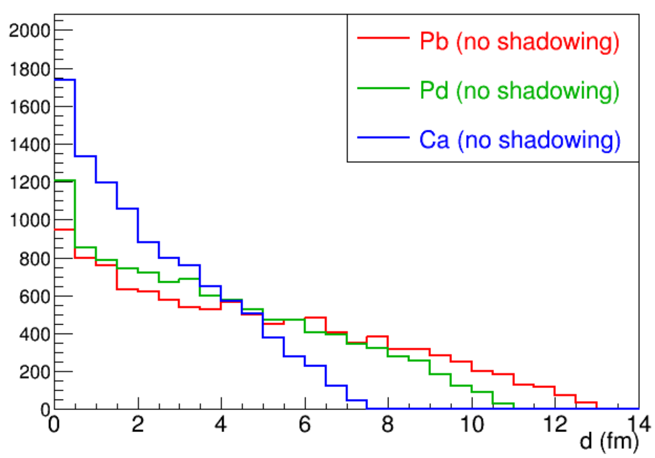

Figure 2: Distance traveled in the nucleus after first collision for a variety of minimum bias collisions with Q^2>1 GeV^2, x>0.02 and 0.01<y<0.95 at 10x40 GeV: e+^{40}Ca, e+^{108}Pd, e+^{208}Pb using BeAGLE with multinucleon shadowing turned off (genShd=1).

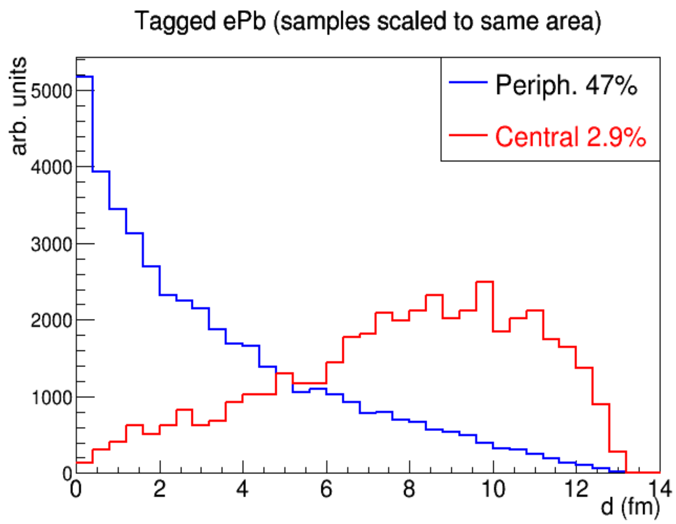

Figure 3: Distance traveled in the nucleus after first collision for geometry tagged e+Pb collisions at 10x40 GeV: Peripheral 47% means a selection of the 47% events with the lowest evaporation neutron multiplicity, while 2.9% central, means a selection of the 2.9% events with the highest evaporation neutron multiplicity. The kinematic cuts and model are the same as in Figure 2.

We also expect to achieve an improved resolution by using more information than just the forward neutrons, as we expect high efficiency for the detection of forward fragments over a very wide kinematic range. In particular:

- Neutrons can be detected in a high resolution (~30%/$\sqrt{E}$, 0.3 mr for energy and angular resolution) ZDC in a cone of half-opening angle 10 mr (θ<10mr).
- Protons, deuterons, and other light charged fragments will be detected with high resolution and PID in a cone of half-angle 8mr.
- Wide angle charged fragments (up to a 75 mr half-angle cone, offset 25 mr from the ion beam direction) will be analyzed in the 2Tesla-m forward dipole with a momentum resolution $\Delta p/p$~(0.2%)p/GeV. This includes negative fragments, e.g. pions.

Using BeAGLE and the JLAB Full-Acceptance Detector simulation, we will be able to study the propagation of strongly interacting matter in the nucleus. The EIC White Paper [1] again describes this well: "The suppression [of fast moving hadrons produced in relativistic heavy ion collisions] is believed to be due to the energy loss of colored partons traversing the QGP. It has been puzzling that the production is nearly as much suppressed for heavy as for light mesons, even though a heavy quark is much less likely to lose its energy via medium-induced radiation of gluons. Some of the remaining mysteries surrounding heavy vs. light quark interactions in hot matter can be illuminated by EIC studies of related phenomena in a better known cold nuclear matter.

The variety of ion beams available for electron-nucleus collisions at the EIC would provide a femtometer filter to test and to help determine the correct mechanism by which quarks and gluons lose energy and hadronize in nuclear matter." Geometry tagging should allow us to significantly extend the reach of this "femtometer filter" in <*d*> as well as potentially providing narrower distributions in d for each sample (see Figures 2 and 3). It should be noted that for studies involving d, going to low values of Bjorken x is not necessarily beneficial. At low x, nuclear shadowing means that more than one nucleon may be involved in the original hard collision, making it harder to disentangle effects of the nucleus on the reaction products from a single nucleon. For this reason, we are expecting to focus on modest values of x (x>0.02) where the effects of multinucleon shadowing are minimized.

In the second year of the proposal we will extend the geometry tagging studies to lighter nuclei such as Ca, and heavier nuclei such as U. In the case of light nuclei, we can determine if we have any resolution for <*d*> bins in such collisions. In order to study eU collisions, we will need to upgrade the code to handle deformed nuclei, which will allow us to potentially extend our <*d*> reach even further as some collisions will occur when the nucleus is oriented with the long-axis along the direction of the γ^* momentum. Figure 4 compares a Uranium nucleus with a Lead nucleus.

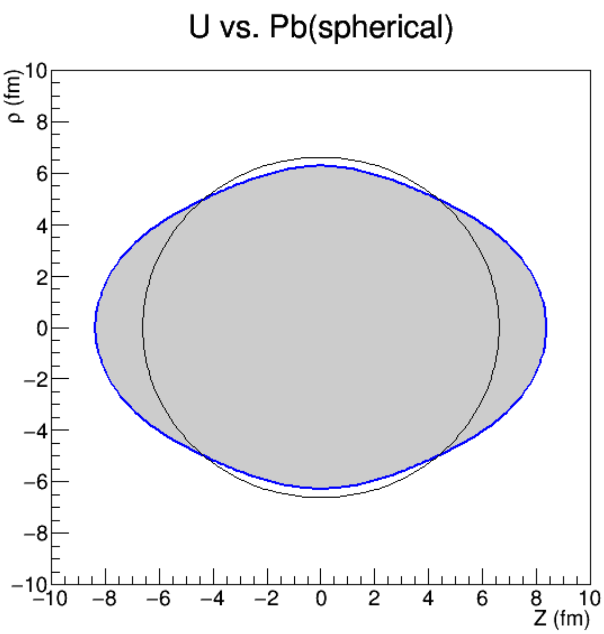

Figure 4: A comparison of Lead (Pb) and Uranium (U) nuclei. The black circle represents the contour where the density of matter inside the Lead nucleus falls to half its peak value. The blue ellipse represents a similar contour for Uranium.

In addition, during year 2, we will investigate the use of BeAGLE at fixed target JLab energies. While not as easy to detect as in the collider mode, slow recoil nucleons can be informative even in fixed target experiments [12]. In particular, the experiment E12-06-117 approved for CLAS12 plans to study parton propagation with a wide scan of nuclear species (up to Au or Pb) and should be able to use the developed tools with minimal adaptation. The event generator described above will need only minor adaptation of its parameters to describe lower energy DIS and can therefore be used to prepare for the JLab 12 measurement. This study will allow us to explore the possibility to perform geometry tagging in this experiment, enhancing significantly its scientific reach and at the same time allowing to directly check against data, when they will be available, some of the main assumptions made for the development of the event generator. The tools developed in this proposal will facilitate the analysis and enhance the physics output of many proposed JLab12 experiments, making these timely and relevant for the design of the EIC project.

Geometry tagging at JLEIC is also valuable for understanding the transition from a diluted to a saturated gluon state because the higher density for small impact parameter b (see again Figure 1) increases the saturation scale Q_s^2 [17], leading to a corresponding increase in saturation effects. In general, the exact value of the saturation scale is still unknown and there are a variety of thoeretical results. Further complicating the picture, the gluon saturation scale is expected to be higher than that for the quarks by the color factor ratio $2N_c^2/(N_c^2-1) = 9/4$ [18]. Figure 5, however, adapted from the EIC White Paper [1], is representative of the general structure of $Q_s^2(x,A)$ and can help us qualitatively visualize the value of geometry tagging. The curves represent the saturation scale:

$$Q^2_s \sim A^{1/3} x^{-\lambda} \tag{2}$$

with $\lambda \simeq 0.3$ for a given value of Bjorken x for four cases: minimum bias ep, minimum bias, eCa, minimum bias eAu and central eAu.

The ep and eAu minbias curves at fixed x differ by a factor of $A^{1/3}$ (~6 for Au), which is often called the nuclear “oomph” factor. At fixed Q^2, the ep and eAu curves differ in x by a factor of about 300. Since the minimum achievable x value at fixed Q^2 is given by $x_{min} \cong Q^2/s_{eN}$, where s_{eN} is the square of the e-nucleon cms collision energy, an eAu collision has a saturation reach similar to an ep collision with a factor 300 larger beam energy ($s \cong 4E_eE_N$). This immediately illustrates the power of using eA collisions to search for saturation effects. Our original proposal for this LDRD (FY2017) contains a similar exercise using Figure 5, comparing central and minimum bias eAu collision, in an attempt to quantify the maximum possible additional geometric “oomph” factor of about 1.45, potentially achievable using geometry tagging. This is equivalent to either using an effective A of ~600 or an additional effective shift in E_{beam} of 3.3, for a bin where the geometry tagging is used to enhance the Q_s^2 of the sample. Thus, the impact of the combination of geometry tagging and high luminosity on the reach in Q_s^2 is almost exactly equivalent to an increase of the accelerator energy for eAu from 12 on 40 GeV/A to 20 on 80 GeV/A. A future energy upgrade would further add to this effective Q_s^2 reach. As is detailed in Section 2.5 this estimate turned out to be overly conservative, and the results were more encouraging than expected.

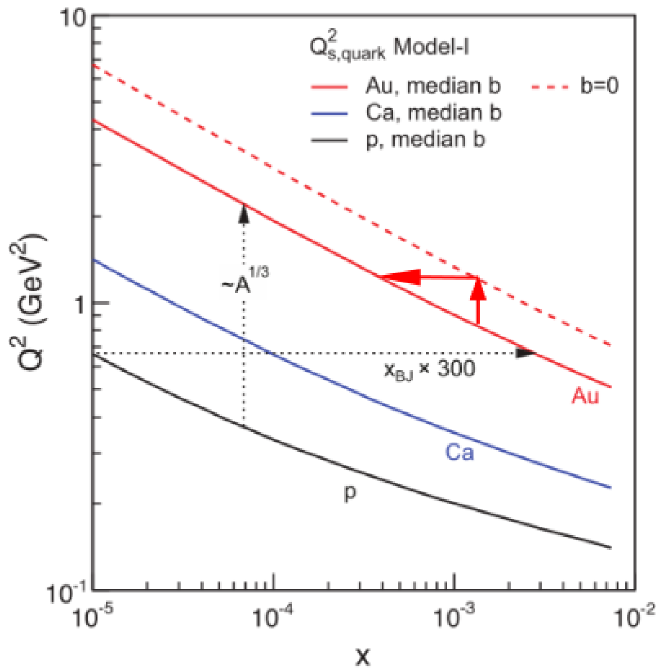

Figure 5: Theoretical expectations for the quark saturation scale for p, minbias Ca and Au and central Au. Adapted from Fig 3.9 of Ref.[1].

In order to have a first look at this physics, we will use a combination of the BeAGLE and Sar*t*re codes to investigate the geometry tagging capabilities of the JLEIC Full Acceptance detector for low x (x<0.002) central (small "b") deep inelastic and incoherent exclusive diffractive events. In general, measuring b is more difficult than measuring d (see e.g. [14]), so the complete coverage for neutrals and charged particles may be a significant advantage for JLEIC. E665 showed that even a single slow charged particle in the nucleus rest frame ("grey track") is an excellent tag for the existence of an Intra-Nuclear Cascade (INC) [16], which in turn should be correlated with large d and small b. It is possible that forward negative charged hadrons, again unique to JLEIC, will also be a sensitive measure of INC since forward π^-'s are otherwise rare. In year two, we will again look at the impact of geometry tagging in e+U collisions at JLEIC to see if we can further extend the reach in Q_s^2 beyond that available in central e+Pb.

Finally, another powerful probe of gluon saturation is coherent exclusive diffraction: comparing J/ψ and ϕ production in cases where the nucleus remains intact, leading to a quantum mechanical diffraction pattern. By measuring this to large values of the target four-momentum transfer, $|t|$, we can obtain a Fourier transform of the gluon distribution in the nucleus. In order to measure this diffraction pattern accurately, we must ensure that the nucleus really remains intact and unexcited. Again, this is a potential strength of JLEIC. Figure 6, taken from Ref. [8], shows the t distribution for 20x100 GeV eAu collisions for two different models, one with and one without saturation. Note that at the highest values of t plotted, the coherent diffraction pattern is up to a factor of 1000 smaller than incoherent diffraction, posing an experimental challenge. In this project, we will investigate the efficiency and purity of our ability to tag coherent events by vetoing on incoherent diffraction where nuclear breakup products are detected. For heavy elements, such as Pb, we will look for neutrons, protons or light nuclear fragments. In addition, the Beam-Stay-Clear (BSC) at the focus of the Far Forward Spectrometer (FFS), will allow us to detect daughter nuclei that differ in magnetic rigidity by as little as 0.6% from the incident beam (combined effect of 10x the beam momentum spread and a crabbing effect). Thus for ^{208}Pb, we can directly observe and veto the daughter nuclei if $\Delta Z \leq -2$ or $\Delta A \leq -3$. We will also study our ability to veto events where the nucleus was excited to bound states below neutron threshold. For ^{208}Pb, specifically, we will use the fact that all gamma-decays either pass through the $3^- \to$g.s. 2.614 MeV transition, or through a higher energy γ-decay[19]. For a 40 GeV/A Pb beam, the relativistic boost is ~40. Thus ≥50% of these photons will be detectable with energy > 100 MeV either in the ZDC, or a pre-Ecal, or in the high resolution $PbWO_4$ forward calorimeter in front of the first ion FFQ. In fact, most of these decay sequences have multiple photons above 1 MeV in the Pb rest frame, which will further enhance the veto-tagging efficiency.

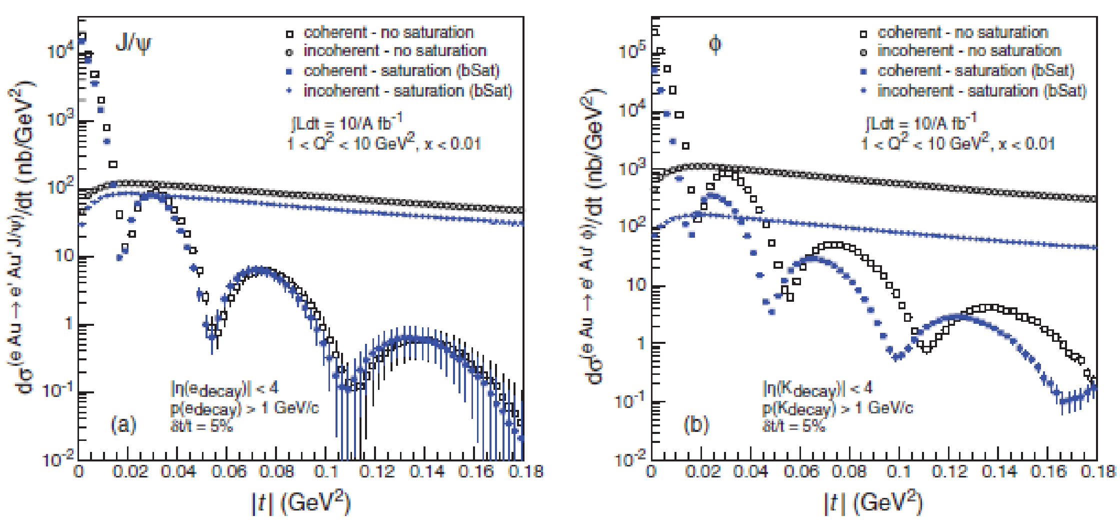

Figure 6: Differential distributions with respect to t for coherent and incoherent (a) exclusive J/ψ and (b) ϕ production from Ref. [8].

In year two, we will extend our study of coherent diffraction to include a lighter nucleus, Ca. Comparing the diffraction pattern for J/ψ and ϕ for both a light and a heavy nucleus should provide a stronger constraint on the physics. In this case, we may be able to detect *all* of the products of a nuclear breakup, including a large nuclear remnant, such as ^{39}Ca (after a neutron emission) or ^{39}K (after a proton emission).

In summary, this proposed project, "Geometry Tagging for Heavy Ions at JLEIC", when completed, will highlight the fact that key strengths of the JLEIC design allow us to fully realize two of the key goals of the EIC program for studying QCD with eA collisions: studying parton/hadron propagation in "cold" nuclear matter as well as the approach to saturation in QCD at large gluon densities. Simulation and analysis tools will be in place to take advantage of the unique JLEIC capabilities and to refine the design of its full-acceptance detector. We expect three key questions to be addressed in year 2: How much can e+U further improve the JLEIC reach in saturation scale? How well can we reject incoherent diffraction background using unique JLEIC detector/IR capabilities in order to use coherent diffraction to precisely measure the spatial distribution of gluons in the nucleus? How big of a reach can we achieve in the distance traveled in the nucleus by propagating partons, again including e+U?

2.3 Specific Location of Work

The development and adaptation of the event generators will be subcontracted to Mark Baker (MDBPADS). Having played a significant role in developing AA geometry (centrality) tagging in PHOBOS, being a co-author of E665, and having worked on the BeAGLE code, Mark is an expert in the field whose input is essential for the success of the project. Mark will carry out most of the work remotely, but be in close contact with the JLab staff.

The work on detector simulations and development will be undertaken at JLab by a postdoc, Guohui Wei, who will be supervised by Vasiliy Morozov (PI). The standard JLEIC GEMC Geant4 framework will be used. V. Morozov will carry out the corresponding design and optimizations for the JLEIC interaction region.

Optimizations of the detector layout will be carried out by Charles Hyde and a summer student, Caleb Fogler, at ODU, in close collaboration with JLab staff.

2.4 Anticipated Outcomes/Results

By April 2018 (mid-year proposal year 2)

- Implement a 3D version of Glauber in BeAGLE, allowing deformed nuclei such as U to be studied.
- Using parameterizations of the data on elastic and inelastic electron scattering on ^{208}Pb, together with a simple, but qualitatively accurate model, we will

estimate the relative probability of coherent diffraction to bound excited states vs. coherent diffraction to the ground state in e+Pb scattering. This will be implemented in Sartre as an option.

- The Forward PbWO calorimeter is expected to have a yield of 20 photo-electrons per MeV (integrated over 100 ns) [20]. This gives a ~10% energy resolution for boosted photons from excited state decays in ^{208}Pb. We will estimate the random background in the calorimeter from two sources: Quasi Real photo excitation, summing over all bound excited states in Pb^{208}; and side-splash from hadrons in the striking the iron yoke of the Dipole just upstream of the calorimeter. This will be done using the existing GEMC model of the detector.
- Implement a combination of BeAGLE and Sartre to allow investigation of combined intranuclear cascade (ballistic protons) and nuclear evaporation for incoherent exclusive diffraction (J/ψ and φ), extending down to the lowest values of *x* available at JLEIC.
- A more comprehensive look at geometry tagging and color propagation physics for SIDIS at JLEIC, including a light nucleus (such as Ca) and the heavy deformed nucleus U, investigating the maximum range of "*d*" that can be reached.
- Investigate whether forward negatively charged hadrons (mostly π-) improve geometry tagging resolution because of their strong correlation with INC.

By October 2018 (end of proposal year 2)

- Using the upgraded Sartre, we will investigate the value of forward photon tagging in further purifying the sample for coherent J/ψ and φ diffraction in e+Pb collisions.
- We will study tagging of the nuclear remnant in the case of coherent diffractive eCa collisions and see if it further increases the purity.
- Using a combination of Sartre and BeAGLE, we will
  - refine our estimate of our ability to tag coherent diffraction events by rejecting incoherent diffraction.
  - perform a first estimate of the resolution of the nuclear geometry parameters *d* and *b* for exclusive incoherent J/ψ and φ diffraction for eA using the JLEIC Full Acceptance Detector.
- If simulations show that it is warranted, we will attempt to benchmark and calibrate the event generators and validate the geometry tagging concept for JLEIC physics by developing and submitting a run group proposal for CLAS12 E12-06-117 experiment (due in June 2018).

2.5 Prior Year Accomplishments

Our basic goal for mid-year (April 2017), as reflected in the detailed milestones below, was to install the eA models at JLAB and interface them with GEMC. We have succeeded in that endeavor and also started on the future milestones by taking a quick look at the impact of evaporation neutrons on geometry tagging for inelastic events in general and background rejection for coherent diffraction. Preliminary simulations already show that geometry tagging allows for significant improvement in measuring d, the distance traveled by produced particles in the nucleus compared to a beam species (A) scan. They also show that the effective reach in saturation scale due to tagging is equivalent to an energy increase of a factor of 3 or more. In addition, for both d and thickness T(b), the tagged samples have a narrower distribution than minimum bias, as well as a higher mean. Finally, we note that evaporation neutrons alone are unlikely to provide enough background rejection to allow a clean measurement of coherent diffraction. All of these results are extremely encouraging and warrant further systematic study.

It should be noted that the simulation code referred to as “DPMJetHybrid” in the original proposal has been renamed BeAGLE (**B**enchmark **eA** **G**enerator for **LE**ptoproduction) by its authors. We will refer to the code using the new name. More importantly, the BeAGLE code has been upgraded to model multi-nucleon shadowing in the low x region [21], which has allowed us to meaningfully extend our studies of inelastic (DIS and diffraction) geometry tagging to low x. As wisely noted by the referee in response to our 2nd year LOI, this is the critical region for finding “precocious onset of saturation effects”, and extending our work to low x should enhance the “strategic advantage” provided by geometry tagging.

The detailed milestones from the proposal were:

By April 2017 (mid-year of proposal year 1)

- Implementation of the BeAGLE and Sar*t*re codes at JLab, and interfacing them to JLEIC Large-Acceptance Detector simulations (GEMC).
- Confirmation that the BeAGLE code is tuned to describe key existing data, as well as possible for the non-shadowing region, fine-tuning it if needed.
- Investigating the interpolation properties of existing Sar*t*re cross-section tables for Au, Pb and Ca. If needed for accurate interpolation at JLEIC energies, we will improve the interpolation mechanism and/or add finer grid tables in certain kinematic regions for Au.

The BeAGLE and Sar*t*re codes have been successfully implemented at JLAB and interfaced to GEMC. We would like to thank Maurizio Ungaro (JLAB), Robert Michaels (JLAB), and Thomas Ullrich (BNL) for their essential help as well as Markus Diefenthaler (JLAB), Elke Aschenauer (BNL) and Raju Venugopalan (BNL) for their advice.

A new input format called "beagle" has been added to GEMC by Maurizio Ungaro. It allows one to directly read BeAGLE and Sar*t*re output files in GEMC. All physics parameters from the BeAGLE and Sar*t*re files such as collision parameters are copied to GEMC output. While these parameters are not used in tracking, since we are only simulating the dynamics of the final state particles, this streamlines analysis of the simulation results. We are currently working on recasting the data into a ROOT Tree format to further optimize the data analysis process.

We used the latest model of the JLEIC full-acceptance detector implemented in GEMC to start quantifying the detector's performance with events generated in BeAGLE and Sar*t*re. Figure 7 is a snapshot of the GEMC event display. It shows the detector region with tracks of the final state particles from a few typical BeAGLE and Sar*t*re events. The different color tracks indicate different particle types and illustrate the detector's acceptance in the far forward direction.

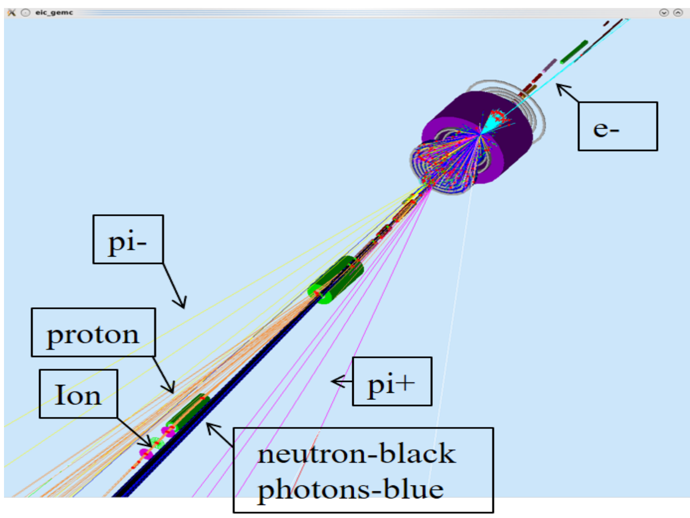

Figure 7: Snapshot of the GEMC event display showing the detector region with tracks from a few BeAGLE and Sar*t*re events.

Figures 8-10 show an example of initial analysis of the simulation results for e+Pb collisions at 10x40 GeV with $Q^2 > 1$ GeV^2, 0.01<y<0.95, and multinucleon shadowing turned on (genShd=3). Figure 8 shows a density plot correlating the parameter d with the neutron multiplicity of an event. As expected, average d is higher for larger-multiplicity events. Figure 9 quantifies this by plotting the average d vs. the fraction of neutrons left after a multiplicity cut. When making a cut, only events with neutron multiplicity above a certain number are included in the analysis. The fraction of neutrons coming from these events is calculated and used as the horizontal variable. For example, the point at 2.6% gives the average d obtained by analyzing the top 2.6% of events with highest forward neutron multiplicity (after the 2nd dipole). The point at 100% means that all events are included, i.e. it is the minimum bias result.

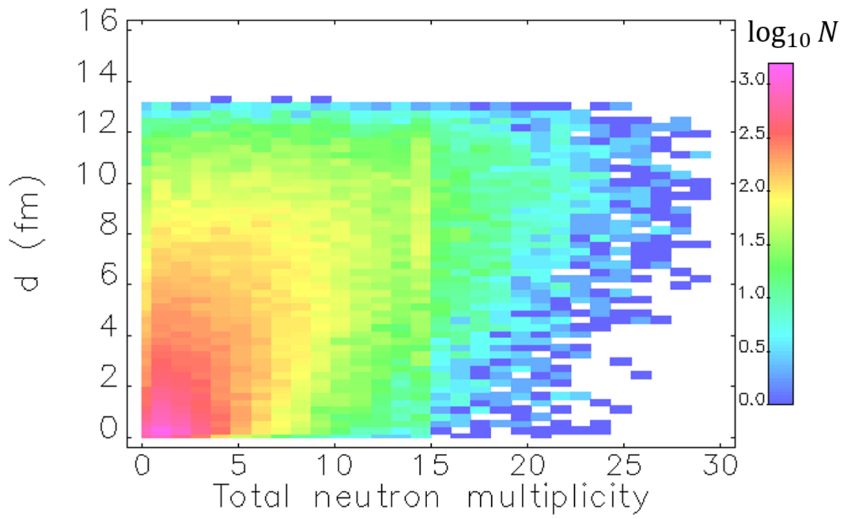

Figure 8: Density plot showing the number of BeAGLE events after the 2nd spectrometer dipole as a function of *d* and the number of detected neutrons.

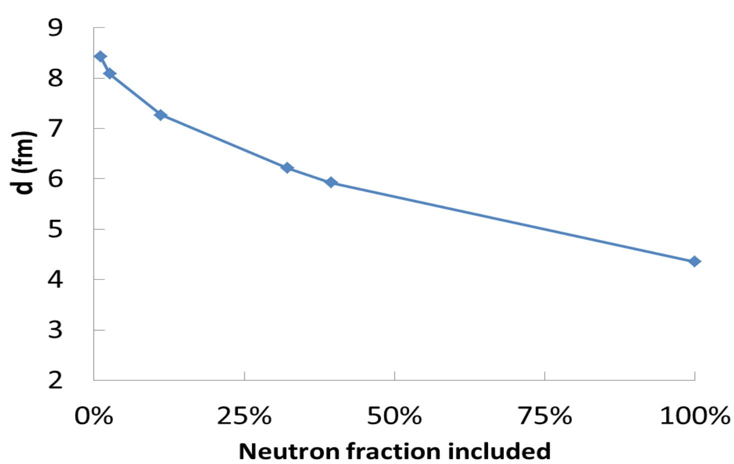

Figure 9: Average *d* vs. the fraction of neutrons corresponding to the top-multiplicity events after the 2nd spectrometer dipole.

Figure 10 demonstrates the efficiency of a multiplicity cut. It compares the histograms of d for 2.6% of the highest-multiplicity (most central) events and for 26.6% of the lowest multiplicity (most peripheral) events. Clearly, the enhancement of the average *d* by a centrality cut is quite dramatic. Note that Figures 8-10 are produced by analyzing neutrons that pass the 2nd dipole, i.e. neutrons detectable in the ZDC. These studies so far only involved forward neutrons. We plan to study how combining detection of forward neutrons with detection of other reaction products can tighten these cuts while maintaining or even improving the statistics.

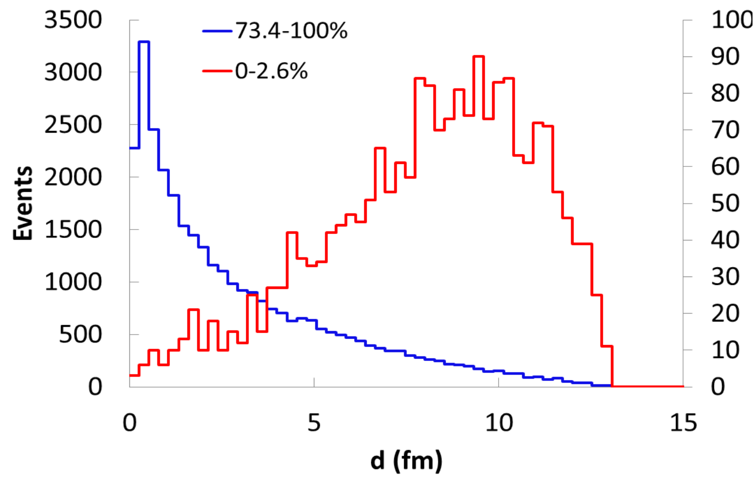

Figure 10: Histograms of *d* for 2.6% of the highest-multiplicity (most central) events and for 26.6% of the lowest multiplicity (most peripheral) events after the 2nd spectrometer dipole.

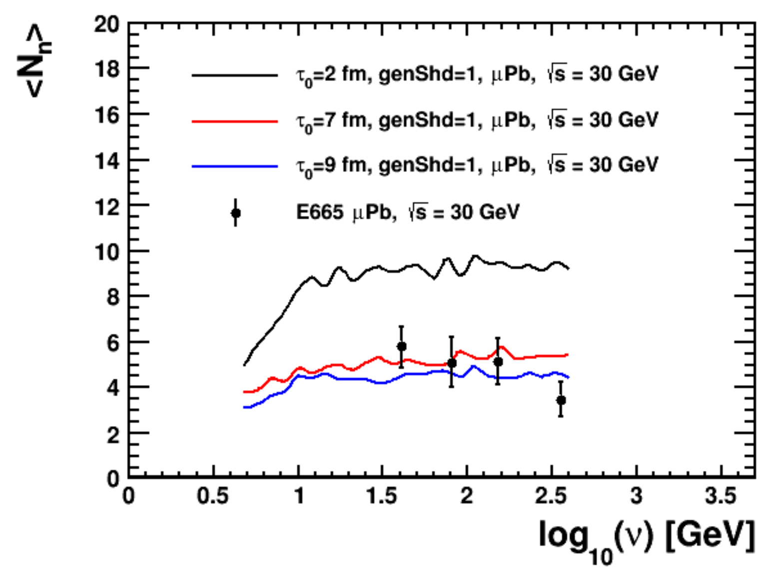

Fig. 11: The original tune for BeAGLE's IntraNuclear Cascade formation time parameter, τ_0, for genShd=1 (multinucleon shadowing off), using E665 fixed target e+Pb neutron data [12].

The BeAGLE code has been tuned as well as possible to E665 e+Pb forward neutron data as well as the ZEUS ep forward proton and neutron data. Figure 11 shows the use of the E665 fixed target data [12] to tune the τ_0 parameter in BeAGLE which refers to the formation time in the produced-particle rest frame in the IntraNuclear Cascade. Going beyond the requirements of the bullet, we have confirmed that the tune also works with shadowing turned on in BeAGLE as well as with shadowing turned off, as seen in Figure 12. Both genShd (generator shadowing mode) =2 and 3 refer to the use of multinucleon shadowing according to a Glauber model [21] and the EPS09 nuclear PDF (Parton Distribution Function) [22]. The difference is in which of the participating nucleons undergo the hard collision, for genShd=2, it's random while for genShd=3 it is the first nucleon seen by the virtual photon.

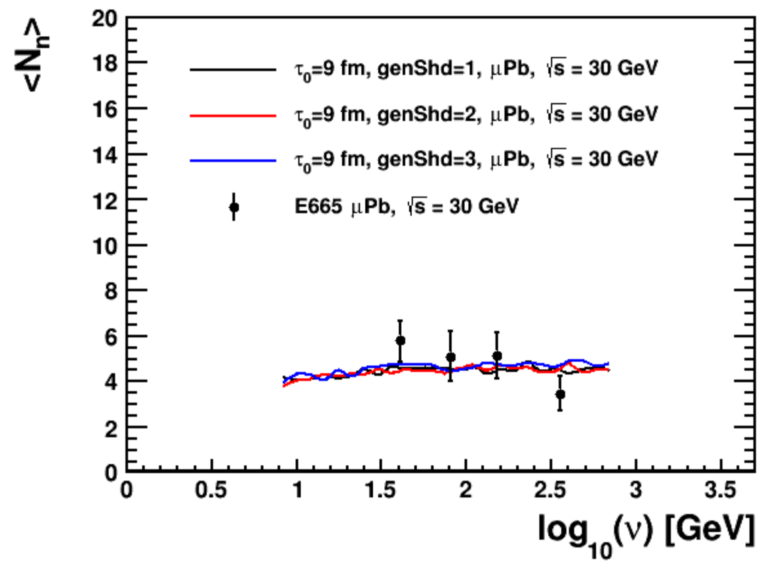

Figure 12: The (lack of) impact of the BEAGLE shadowing model choice on the tuning of the IntraNuclear Cascade formation time parameter, τ_0, using E665 fixed target e+Pb neutron data [12].

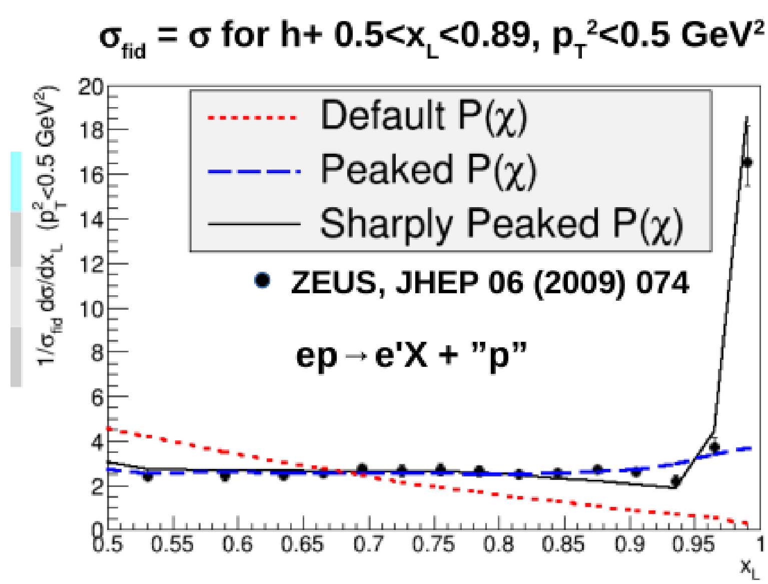

Figure 13: A comparison of ZEUS forward proton data [23] to Pythia 6.4 with three different choices for the parametrization of the nucleon target remnant breakup distribution P(χ). Figure taken from Ref. [24].

The BeAGLE program includes Pythia 6.4, which must also be tuned to describe forward ep data. Figure 13 shows one example of a collection of fits to forward protons from ZEUS ep data which were used by the BeAGLE authors [24] to tune the Pythia part of BeAGLE. P(χ) refers to the probability distribution of χ, which is the light-cone momentum fraction taken by the diquark or baryon when a complicated nucleon target remnant cluster is broken up. The quantity x_L is the fraction of the lab longitudinal momentum of the original struck proton taken by the produced proton. Data for x_L>0.95 may be of a different character and was not considered necessary to fit. Therefore both the blue (peaked) and black (sharply peaked) distributions would be considered good fits.

Forward neutrons were also used as part of the Pythia tune, and ruled out the “sharply peaked” fit above, but are not shown here. The final result was:

Parameter	Default Value	Tuned Value	Note
MSTP(94)	3	2	
PARP(97)	1.0 (not used)	6.0	Used for MSTP(94)=2 only
PARP(91)	2.0	0.32	HERMES value: 0.4
PARJ(21)	0.36	0.32	
MSTJ(12)	2	1	From HERMES

The combination MSTP(94)=2, PARP(97)=6.0, leads to $P(\chi)=7(1-\chi)^6$. PARP(91) refers to the RMS intrinsic transverse momentum k_T of the partons in the nucleon while PARJ(21) is the RMS transverse momentum p_T acquired during string fragmentation or when the target remnant cluster breaks up. The forward ZEUS data cannot fully distinguish between intrinsic k_T and fragmentation $p_{T.}$ To break this ambiguity, an arbitrary constraint was added that they be equal. This yielded PARP(91)=PARJ(21)=0.32 GeV. Finally, we adopted the BNL-EIC Pythia value for MSTJ(12), which is based on the experience of the HERMES collaboration. This parameter controls the baryon production model in the string fragmentation. The default allows diquark-antidiquark pair production during fragmentation and also includes a “popcorn” scheme where mesons can interpose between them. MSTJ(12)=1 allows diquark-antidiquark pair production, but no “popcorn”.

We investigated Sar*t*re interpolation. It will work at JLEIC energies for Ca and Au. In order to use Pb, we will need to make a copy of the Au tables, perhaps with small modifications for the difference between Pb and Au. The authors have said that the uncertainties in Sar*t*re are larger than that difference in any case. As planned, this work will occur as part of the relevant October 2017 bullet. As part of our investigation, we suggested some improvements in the interpolation which have been implemented by the authors. It should also be noted that in the long run, the Sar*t*re authors are planning to make an improved set of tables for Pb using the latest theoretical fits to the dipole cross-section and an improved high Q^2 cutoff. We can use the new tables when they are available, but such precision will not be necessary for our purposes.

The results for tagging samples using the geometry variable d for studies of parton propagation were discussed in Section 2.2 and shown in Figures 2-3, as well as Figures 8-10. The results for tagging samples in the geometry variable b (impact parameter) have been recast in terms of the Thickness variable $T(b)$ which represents the effective thickness of the nucleus as seen at a given impact parameter:

$$T(b)=\int_{-\infty}^{\infty} \rho(z',b)/\rho_0\, dz' \qquad (3)$$

Note: We have chosen to normalize the thickness to the Pb ρ_0 as in Equation 1 so that is in units of fm. Multiplying by $\rho_0 = 0.16$ nucleons/fm^3 will recover the standard thickness in terms of nucleons/fm^2. For the impact parameter saturation scale $Q_s^2(b)$ the $A^{1/3}$ from Equation 2 is naturally replaced by $T(b)$ so that:

$$Q_s^2(b) \sim \langle T(b)\rangle_{sample}\, x^{-\lambda} \qquad (4)$$

This means that the effective energy enhancement factor for the most central tagged bin is given by:

$$\mathrm{F_E} \equiv (\langle T(b)\rangle_{cent.}/\langle T(b)\rangle_{minbias})^{1/\lambda} = (\langle T(b)\rangle_{cent.}/\langle T(b)\rangle_{minbias})^{10/3} \qquad (5)$$

Again, as emphasized by the referee, this factor is most interesting at low x. Figure 14 shows the x distribution for inelastic events (DIS + diffractive) for 10x40 GeV e+Pb collisions for Q^2>1 GeV^2, y<0.95, and x<0.002. The distribution is relatively flat from 0.0008 to 0.002 with a mean of 0.0014 and represents a reasonable "low x" bin at JLEIC energies. Figure 15 shows a comparison of the 1.1% most central bin with the 41.1% most peripheral bin using only the evaporation neutrons (in an ideal detector) from BeAGLE with multinucleon shadowing turned on (genShd=3 mode). The average thickness for the central bin is 10.62 fm while for the minimum bias distribution (not shown) it is 7.50 fm. This results in a Thickness enhancement of 1.42 and an effective energy enhancement factor F_E of **3.2!** It should be possible to improve this result through even tighter cuts and/or the use of extra information as detailed in section 2.2. It should also be noted that according to the white paper [1], estimates of λ range from 0.2–0.3, which means that the power in equation 5 could be as high as 1/0.2=5 which would imply F_E=5.7! In calculating F_E=3.2 we used the most conservative value of 1/λ=1/0.3=10/3.

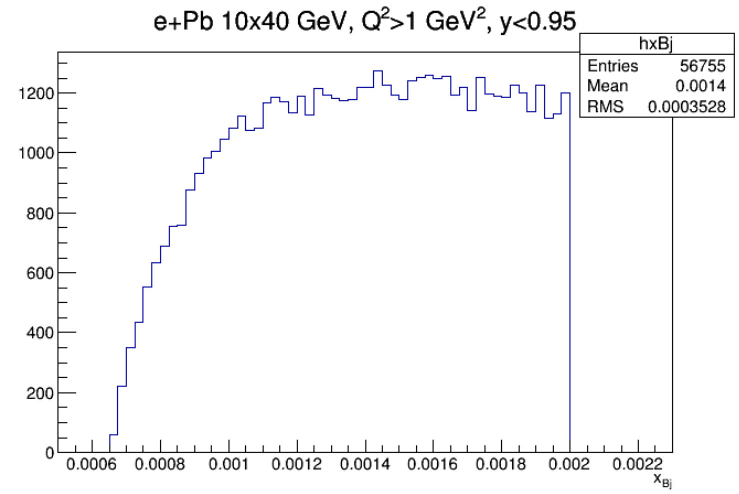

Figure 14: Bjorken x distribution for Q^2>1 GeV^2, y<0.95 and x<0.002 for 10x40GeV e+Pb collisions.

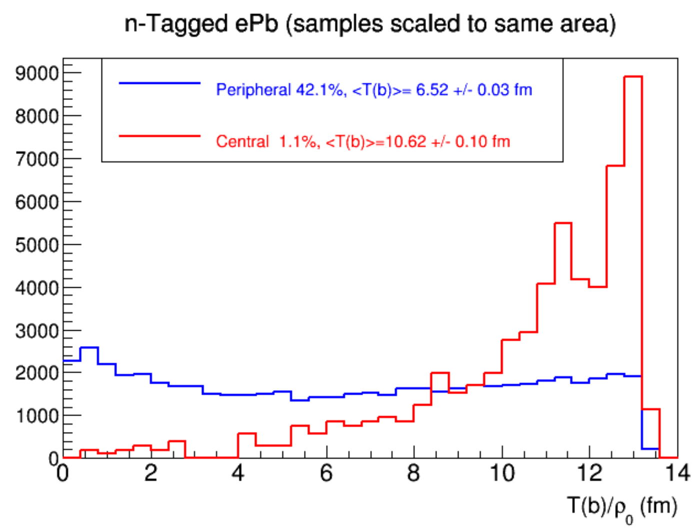

Figure 15: Average thickness for peripheral (42.1%) and central (1.1%) samples tagged using evaporation neutrons in 10x40 GeV e+Pb collisions for Q^2>1 GeV^2, y<0.95 and x<0.002.

We did not expect to achieve an energy enhancement factor as high as 3.2 so easily, given that Figure 5 predicts an enhancement of only 3.3 for perfect selection of b=0, which is not realistic. The key, however, is that Figure 5 is pessimistic in two ways. First for the minimum bias estimate it uses the median rather than mean value of T(b) which is a 10% overestimate of the denominator. Second, the ratio $T(b{=}0)/T(b_{\mathrm{median}})$ is sensitive to the details of shadowing. Our estimate using BeAGLE and the EPS09 nuclear parton distribution function for shadowing for exactly the JLEIC kinematics, increases the ideal result by another 13%. And of course the power $1/\lambda$ magnifies these small changes. Our estimate for the ideal $T(b=0)/<T(b)>_{\mathrm{minbias}}$ is 1.76 which would yield an ideal F_E of 6.6 even for the conservative choice of λ=0.3. One of the key issues for study during the remainder of this LDRD project is to see how far we can advance the F_E further from 3.2 towards 6.6 using tighter cuts and more information, such as forward charged particle multiplicity.

Although it wasn't in the original milestones for mid-year, we have also made progress on our ability to tag incoherent diffractive events using photons.

Using the quasi-real photon spectrum in eA collisions, we have estimated the background rate for excitation of individual bound nuclear excited states. We have also estimated the total rate for excitation of the Giant Dipole Resonance (GDR). For ^{208}Pb with a luminosity per nucleus of 10^{34}/cm^2/sec/A, the total GDR rate is approximately 1 MHz. This gives an estimate for the random neutron flux in the ZDC. In addition, if we assume that 10% of GDR events have an associated gamma-ray, then with a 100 ns integration time for a $PbWO_4$ calorimeter, the random pile-up of low energy (<100 MeV) photons in the Forward Electromagnetic Calorimeter is ≤ 1%. This estimate will be refined in year 2.

We expect to achieve the following milestones by the end of the fiscal year as stated in the original proposal.

By October 2017 (end of proposal year 1)

- A detailed study of the resolution of the nuclear geometry parameters *d* (distance traveled in the nucleus after first collision) and *b* (impact parameter), for SIDIS eAu collisions using the JLEIC Large Acceptance Detector, using BeAGLE.
- Using the geometry tagging, a detailed study of the ability to constrain key physics model parameters: τ_0, the average formation time of the produced particles in their own rest frame before they are allowed to participate in intranuclear cascades and *q*-hat, the parameter controlling the strength of particle absorption in nuclear matter.
- Using the geometry tagging, a detailed study of light and heavy flavor propagation in the target nucleus to better confront and constrain theoretical models of in-medium parton propagation and hadronization.
- A first look, using Sar*t*re, at our ability to tag coherent diffraction events by rejecting incoherent diffraction based on nuclear evaporation.
- If needed for accurate interpolation at JLEIC energies, we will add finer grid tables (for Sar*t*re) in certain kinematic regions for Pb and Ca.
- Tuning BeAGLE to JLab12 energies.

The first milestone, studying SIDIS resolution for *d* and *b* is underway. As discussed above, we now expect to be able to extend this study to cover the full range of accessible x down to x~0.0008. This is most meaningful for the *b* or *T(b)* studies, where we can quantify the enhancement of the saturation scale Q_s^2. The next two milestones, concerning parton propagation should be able to proceed as planned.

A very preliminary first look at our ability to tag incoherent exclusive vector diffraction events for the purpose of background rejection, using both Sar*t*re and BeAGLE has already occurred and led to a surprising discovery. These codes have very different nuclear responses to incoherent diffraction. Sar*t*re appears to assume that the struck nucleon always breaks up and that the full kinetic energy of the diffractive nucleon breakup (typically more than 500 MeV) goes into heating the nucleus leading to a lot of evaporation nucleons and an easy tagging task. BeAGLE, based on Pythia, on the other hand, includes a substantial amount of cases where the struck nucleon is merely knocked out of the nucleus (elastic collision subprocess=91) as well as those cases where the nucleon breaks up on its way out (single diffraction subprocess = 93). In either case, the energy of the semi-hard diffractive collision mostly escapes the nucleus and the main source of nuclear excitation energy is the "hole" left in the nucleus by the collision as well as any intranuclear cascading that occurs subsequently. The mean excitation energy is just 40 MeV and a substantial fraction, 20% overall, of these events lead to *no* evaporation neutron. Even in the case where the nucleon breaks up, 9% of the events lead to no evaporation neutron. The BeAGLE approach seems more reliable at the moment and suggests that the JLEIC strategy of near-complete forward detection may well be invaluable for this essential physics. We are working to better understand and resolve this discrepancy, but it is possible that the "first look" we expect to make this summer will be inconclusive. In any case, we had always planned to use a combination of BeAGLE and Sar*t*re to better understand this physics during the *second* year of the proposal (see Section 2.4). This effort in year 2 now becomes even more essential. Tagging coherent diffraction is crucial to EIC physics and it seems likely that the JLEIC detector concept will be very valuable for this physics.

As discussed above, we investigated Sar*t*re interpolation. It will work at JLEIC energies for Ca and Au. In order to use Pb, we will need to make a copy of the Au tables, perhaps with small modifications for the difference between Pb and Au. This work is straightforward and will occur as part of the relevant October 2017 bullet.

Tuning BeAGLE to JLAB12 energies is not expected to be difficult and we should emphasize that JLEIC is the main focus of the LDRD effort both in year 1 and in the proposed year 2.

In summary, we have achieved our main project goals so far: implement e+A model codes at JLAB and have a very preliminary first look at the results. Due to improvements in the model code BeAGLE (external to the project), we were able to extend our results to the very lowest values of x accessible, as suggested by the referee. Our results so far clearly indicate that geometry tagging using the large acceptance forward detector capabilities will have an essential impact on JLEIC physics. In particular, we have *already* achieved an effective energy-enhancement factor for saturation of more than 3, and an effective A-enhancement factor for propagation length studies of more than 4. Furthermore, we have found indications that precision measurement of gluon saturation using coherent diffraction is faced with challenging backgrounds which will likely require the very best forward detector suite to remove.

For the remainder of project year 1, we look forward to using the newly installed model codes to study these issues systematically and to understand any possible tradeoffs or optimizations in the detector/IR design.

In year 2, we plan to push these studies further. For geometry tagging (distance d and thickness $T(b)$), we will implement and study the capability for further improvements using e+U collisions, taking advantage of the nonspherical nature of the Uranium nucleus. For coherent diffraction studies (gluon saturation), we will study the impact of forward photon detection to eliminate the most pernicious background where the nucleus is only very delicately excited and de-excites with photons only. We also plan to validate and benchmark the developed simulations tools using the e+A program at JLab 12 GeV.

Overall, we believe that this LDRD project is well underway and will be very valuable to the laboratory in understanding and making the case for the JLEIC program, as well as in optimizing the detector and IR design.

3.0 VITA (Lead Scientist)

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Academic Degrees

Ph.D., Physics, University of Michigan, Ann Arbor, MI, April 2007
(Ph.D. dissertation: "Using spin resonances to manipulate polarization of spin-1/2 and spin-1 particle beams")
M.S., Physics, Moscow State University, Moscow, Russia, January 2001

Professional Appointments

Staff Accelerator Physicist, Jefferson Lab, 2010 - present
Postdoctoral Research Associate, Old Dominion University, Norfolk, VA, 2009-2010
Postdoctoral Research Fellow, University of Michigan, Ann Arbor, MI, 2007-2009

Main Areas of Research

JLEIC design (optics design, non-linear beam dynamics, detector integration, polarization dynamics)
Advanced muon beam cooling techniques
Experimental studies of polarization dynamics in storage rings

Publications

A list of approximately 174 papers is available from Google Scholar Profile:
https://scholar.google.com/citations?hl=en&user=xy72p94AAAAJ

4.0 Budget Explanation

1. **Effort of JLab Staff:** As PI, Vasiliy Morozov (0.075 FTE) will coordinate project activities, supervise the postdoc, and take responsibility for integration with the JLEIC detector and accelerator. The postdoc, Guohui Wei, (0.4 FTE) will carry out the detector simulations.

2. **Subcontract:** M. Baker ($48k in FY18) is a highly experienced physicist (PHOBOS, E665) and an expert in simulations of geometry tagging of the final state in collisions with heavy nuclei. As a subcontractor, he will be responsible for the development of the event generators and evaluation of the physics results. An ODU student, Caleb Fogler ($3k/year), will work under the supervision of C. Hyde on optimizations of the tagging detectors. C. Hyde is a long-time collaborator in the development of the JLab EIC, with particular interest in forward detection.

3. **Travel for visiting scientists:** A key to the success of this project also lies in the expertise the unfunded users who are involved in JLab experiments (Brooks, Dupre, Hafidi, Nadel-Turonski), development of simulation tools (Toll, Zheng) and theory (Accardi) for electron scattering on heavy ions. In-person meetings for detailed discussions are thus essential. We request $22k/year to cover such travel. We plan to use this funding to cover two international trips for international collaborators, two domestic trips for US collaborators, and an attendance of a conference to present the project's results.

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