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

An electron-ion collider (EIC), such as the JLab EIC (JLEIC), is designed to provide breakthrough insights into the strong interaction between quarks and gluons (partons). Two of the main goals of such a program 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. Excellent detection of the nuclear final state is a key strength of JLEIC and has been an important consideration in the development of the detector and interaction region (IR). In particular, the JLEIC large-acceptance detector, with full acceptance for forward-going neutrons, protons and nuclear fragments, and a high data-taking rate, should be ideally suited to such measurements. However, since the EIC will be the world's first eA collider, data are naturally scarce. Thus, a detailed simulation of these processes is currently the highest priority item for finalizing the JLEIC IR design, and optimization of detector capabilities in preparation for CD0. Such simulations are also essential for articulating the physics impact of the JLEIC e+A capabilities. 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, enhancing the value of the energy-staging strategy favored for JLEIC.

To address the issues of improving the simulations and studying the impact of forward detection, we developed this LDRD project as a joint effort between the physics and accelerator divisions, with a strong involvement from experts in high-energy nuclear reactions. 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 large-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 10x40 GeV).*

We are proposing to extend the project in year two by increasing the capabilities of the modeling allowing us to further study the impact of geometry tagging on JLEIC physics and on the optimization of the IR and detector design. 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 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? In addition, we plan to apply the developed simulations tools to the e+A program at JLab 12 GeV. Data on nuclear breakup following an e+A collision is scarce and more incisive low-energy measurements

in the near future, combined with high quality simulations, could lead to an even stronger case for JLEIC down the road.

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). The EIC White Paper [1] describes this concisely: “Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter”. Unfortunately, a minimum bias scan of beam species (A) is not really all that precise a dial as it only gives a limited experimental handle on the amount of nuclear matter traversed by the collision products, and it also involves substantial accelerator and detector setup time to prepare for new running conditions for each new species. The detection of the nuclear final state can significantly improve the precision and reach of the nuclear path length “dial”, through the technique of geometry tagging.

Geometry tagging is an experimental analysis technique for selecting event samples where we can, on a statistical basis, control the geometry of the collision in order to make more incisive physics measurements. This technique has been heavily exploited in heavy ion (AA) collisions at RHIC and the LHC, and played an essential role in the discovery and detailed characterization of the quark gluon plasma (see e.g. [2]), but it has seen only very limited use to date in deep-inelastic scattering. Several physics measurements at the EIC would benefit significantly from the use of this technique, including studies of gluon anti-shadowing, studies of parton propagation, attenuation and hadronization in the nucleus, and ultimately the search for parton saturation. 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. The JLEIC large-acceptance detector, with full acceptance for forward-going neutrons, protons and nuclear fragments and a high data-taking rate should be ideally suited to such geometry tagging.

We propose a dedicated R&D Project to apply and improve existing modeling codes and detector descriptions to study this physics. In order to study color propagation in the nucleus, we will use BeAGLE to investigate the geometry tagging capabilities of the JLEIC large-acceptance detector in semi-inclusive deep inelastic scattering (SIDIS) at modest Bjorken x (x>0.02) where the complications of nuclear shadowing can be avoided. BeAGLE [3] combines the nuclear modeling of DPMJet, including a Glauber model with formation-time suppressed intranuclear cascading and a nuclear evaporation model, with Pythia, and a parton quenching afterburner [4-5] based on the Salgado-Wiedemann quenching weight formalism [6] for final state interactions. This will allow us to estimate the capabilities of the JLEIC detector to study the in-medium propagation of color charges and the space-time evolution of the hadronization process [7]. We will then use BeAGLE combined with Sar*t*re [8] to estimate the geometry tagging capabilities of the JLEIC large-acceptance detector for SIDIS as well as inclusive incoherent diffraction, both at *low* x ($x<0.003$). 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]. In the case of coherent diffraction, we are not tagging the geometry per se, but rather the fact that the nucleus remains intact for coherent events. We also plan to test our ability to tag "truly coherent" events where the nucleus not only remains intact, but also unexcited. This is another measurement where excellent forward detection can make a qualitative difference. The key physics observable, a precision measurement of the gluon spatial distribution in the nucleus, relies on measuring the exact location and shape of the "dips" in the coherent distribution. Incoherent diffraction, where the nucleus does not remain unaffected, but is excited, is the main background and it needs to be rejected at the level of a factor of 100-1000. 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. This may, in fact, turn out to be the "killer app" for the JLEIC large-angle 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 of the strong interaction as discussed in the 2015 Long Range Plan for Nuclear Science [11]. Specifically, this proposal is relevant to Section 2 "Quantum Chromodynamics: The Fundamental Description at the Heart of Visible Matter" particularly Section 2.3 "Understanding the Glue that Binds Us All: The Next QCD Frontier in Nuclear Physics".

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), in SIDIS and incoherent exclusive diffractive events using the JLEIC Large Acceptance Detector.
- A detailed study of the efficiency and purity of the tag for coherent exclusive vector diffraction.
- Measuring the physics impact of various forward detector capabilities:
  - Very large neutral Zero Degree Calorimeter acceptance
  - Complete coverage for protons (and other Z=+1 particles)
  - Coverage for nuclear fragments
  - 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 by tagging exclusive coherent diffractive events and showing that the gluon distribution seen by ϕ particles is suppressed at small impact parameters, using the J/ψ as a control.
  - 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.
- Development of a simulation and a plan for how to explore geometry tagging using already approved JLab 12 experiment (E12-06-117). This will improve the scientific reach of the experiment and help validate the simulation tools developed.

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 Large-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 Large 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:

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

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 ρ_0d 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 in d is quite wide and there is substantial overlap between the d distributions for different choices of A. Figure 3 shows the result of a centrality selection based on 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 <d> (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 <d> 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.

We also expect to achieve an improved resolution in *d* 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%/√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 Δp/p~(0.2%)p/GeV. This includes negative fragments, e.g. pions.

Using BeAGLE and the JLAB Large-Angle 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.

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. Furthermore, the gluon saturation scale is expected to be higher than that for the quarks by a factor of about 9/4 [cite]. Figure 5, 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:

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

with $\lambda \simeq\cong 0.3$ 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 ($s \cong 4E_e E_N$). 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 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.

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 Large Angle detector for low x (x<0.003) 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.

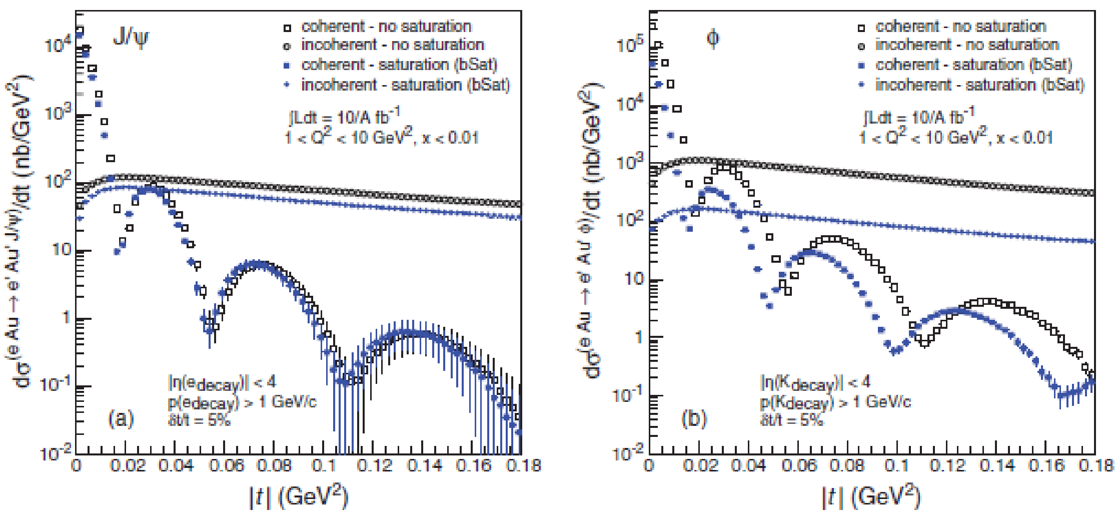

Figure 6. Differential distributions with respect to t for coherent and incoherent (a) exclusive J/ψ and (b) ϕ production from Ref. [8].

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. 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 $3^- \rightarrow$g.s. 2.614 MeV transition, or through a higher energy γ-decay[18]. For a 40 GeV/A Pb beam, the relativistic boost is ~40. Thus ≥50% of these photons will be detectable 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.

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 large-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?

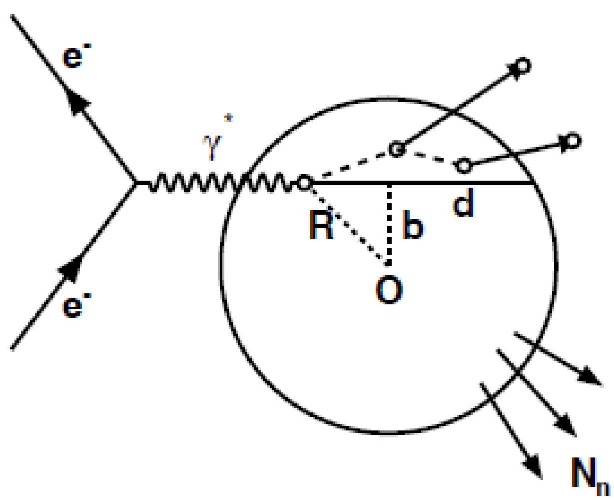

Figure 1. Geometric parameters b, representing the impact parameter, and d, the distance traveled in the nuclear medium after the first collision. Reproduced from Ref.[14].

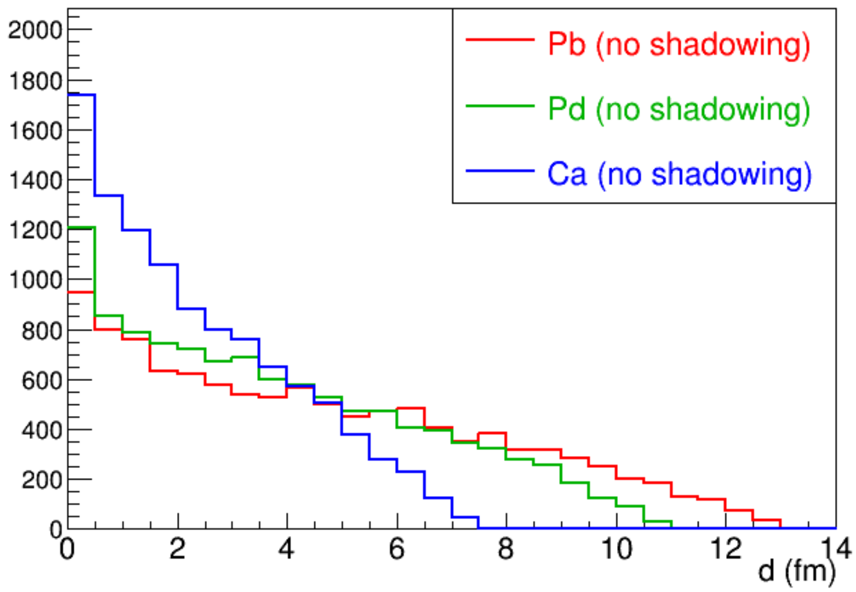

Figure 2: Distance traveled in the nucleus after first collision for a variety of minimum bias collisions with Q^2>1 GeV^2, x>0.02 and 0.01<y<0.95 at 10x40 GeV: e+^{40}Ca, e+^{108}Pd, e+^{208}Pb using BeAGLE with multinucleon shadowing turned off (genShd=1).

Fig. 3:

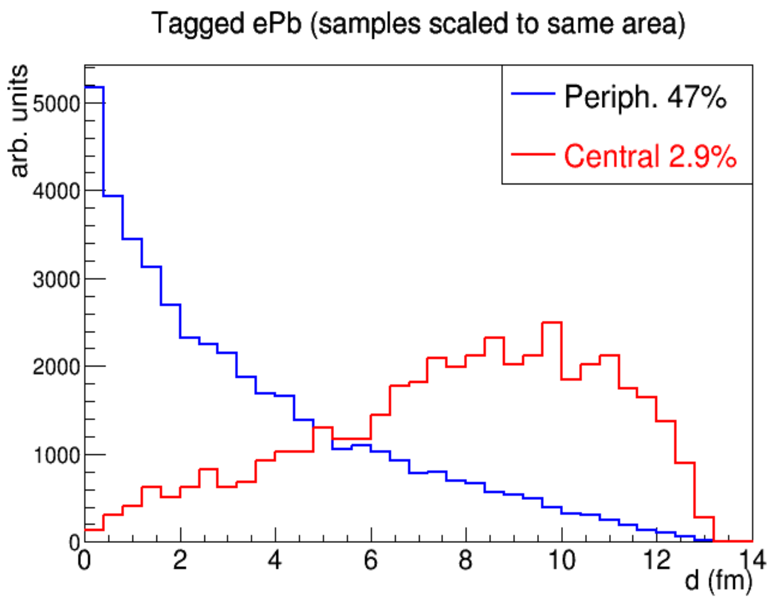

Figure 3: Distance traveled in the nucleus after first collision for geometry tagged e+Pb collisions at 10x40 GeV: 47% most peripheral and 2.9% most central. The kinematic cuts and model are the same as in Figure 2: Q^2>1 GeV^2, x>0.02 and 0.01<y<0.95 at 10x40 GeV, using BeAGLE with multinucleon shadowing turned off (genShd=1).

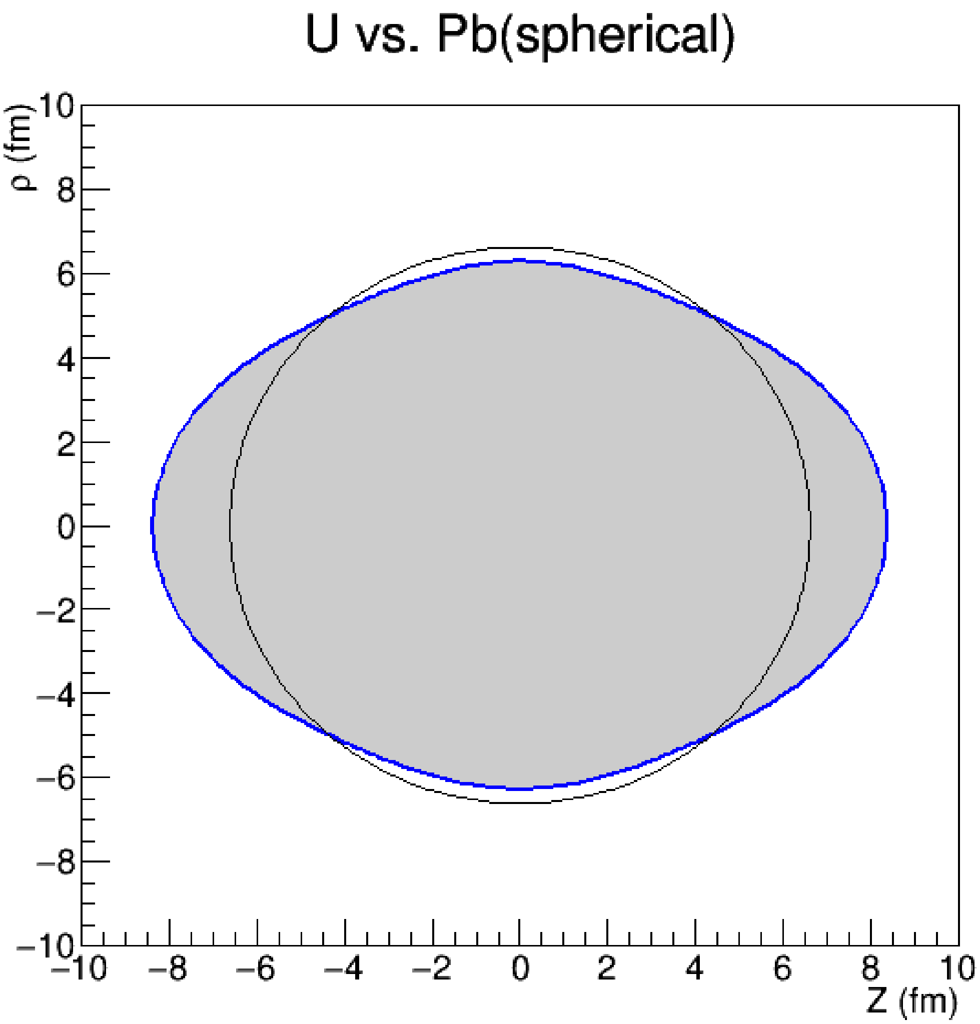

Figure 4. A comparison of Lead (Pb) and Uranium (U) nuclei. The black circle represents the contour where the density of matter inside the Lead nucleus falls to half its peak value. The blue ellipse represents a similar contour for Uranium.

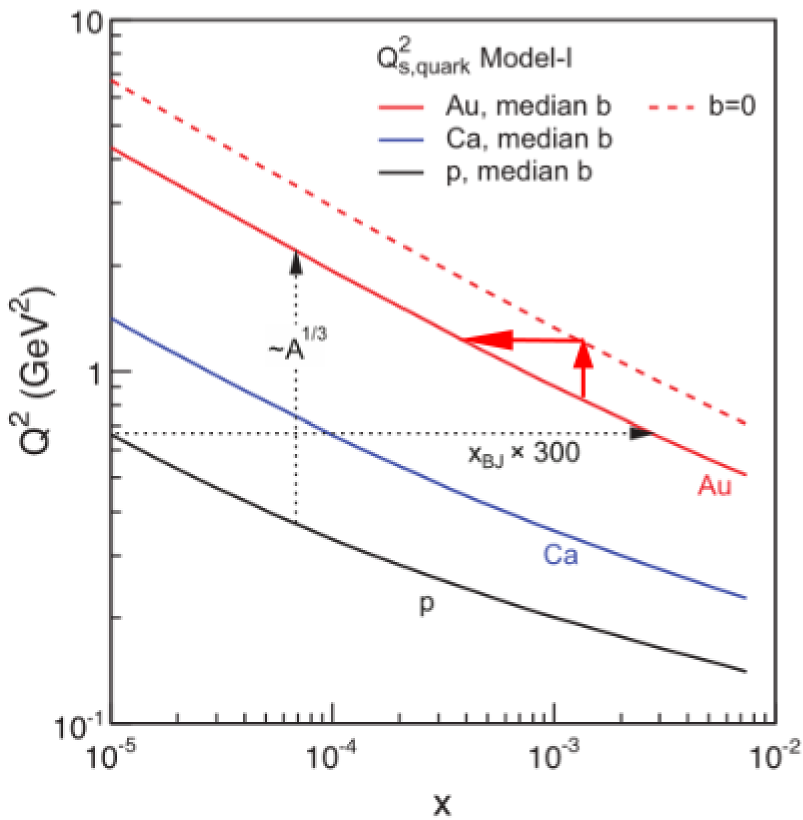

Figure 5. Theoretical expectations for the quark saturation scale for p, minbias Ca and Au and central Au. Adapted from Fig 3.9 of Ref.[1].

2.3 Specific Location of Work

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2.4 Anticipated Outcomes/Results

Where should we put the NEW bullet about low x SIDIS and increasing our saturation reach (effective energy)? Mid-year 2 or end-year 1? Note: It's easier than the ballistic proton study below because we don't need Sartre, just BeAGLE.

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.
- 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).
- 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 Large Acceptance Detector.
- If simulations show that it is warranted, 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 [eRD17-report], 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-Angle 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. Figure 7 and 8 (and more?) (TO BE ADDED – Guohui GEMC using BeAGLE and/or Sartre) shows (DESCRIBE).

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 9a 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 9b. Both genShd (generator shadowing mode) =2 and 3 refer to the use of multinucleon shadowing according to a Glauber model [cite] and the EPS09 nuclear PDF (Parton Distribution Function) [cite]. 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. The BeAGLE program includes Pythia 6.4, which must also be tuned to describe forward ep data. Figure 10 shows one example of a collection of fits to forward protons from ZEUS ep data which were used by the BeAGLE authors [cite] 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, but are not shown here. The final result was:

ADD TABLE & DESCRIPTION OF PYTHIA PARAMETERS WE USE.

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 errors 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. 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:

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

Again, as emphasized by the referee, this factor is most interesting at low *x*. Figure 11 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 12 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.

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 $T(b=0)/T(b_{median})$ 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 $T(b=0)/\langle T(b)\rangle_{minbias}$ is 1.76 which would yield an ideal F_E of 6.6 even for the conservative choice of $\lambda=0.3$. 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.

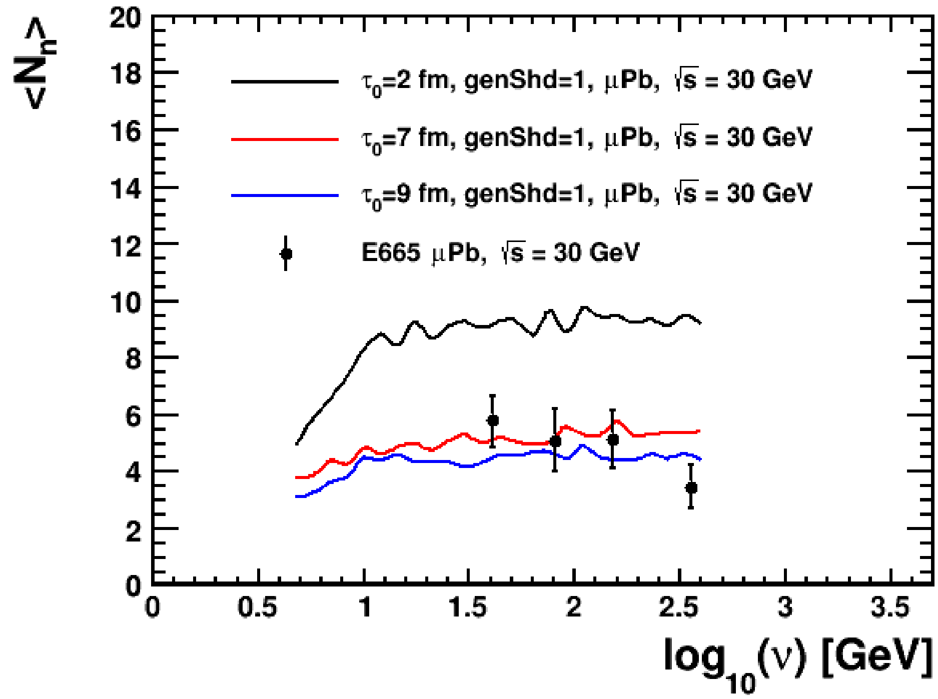


Fig. 9a. The original tune for BeAGLE's IntraNuclear Cascade formation time parameter, τ_0, for genShd=1 (multinucleon shadowing off), using E665 fixed target e+Pb neutron data [12].

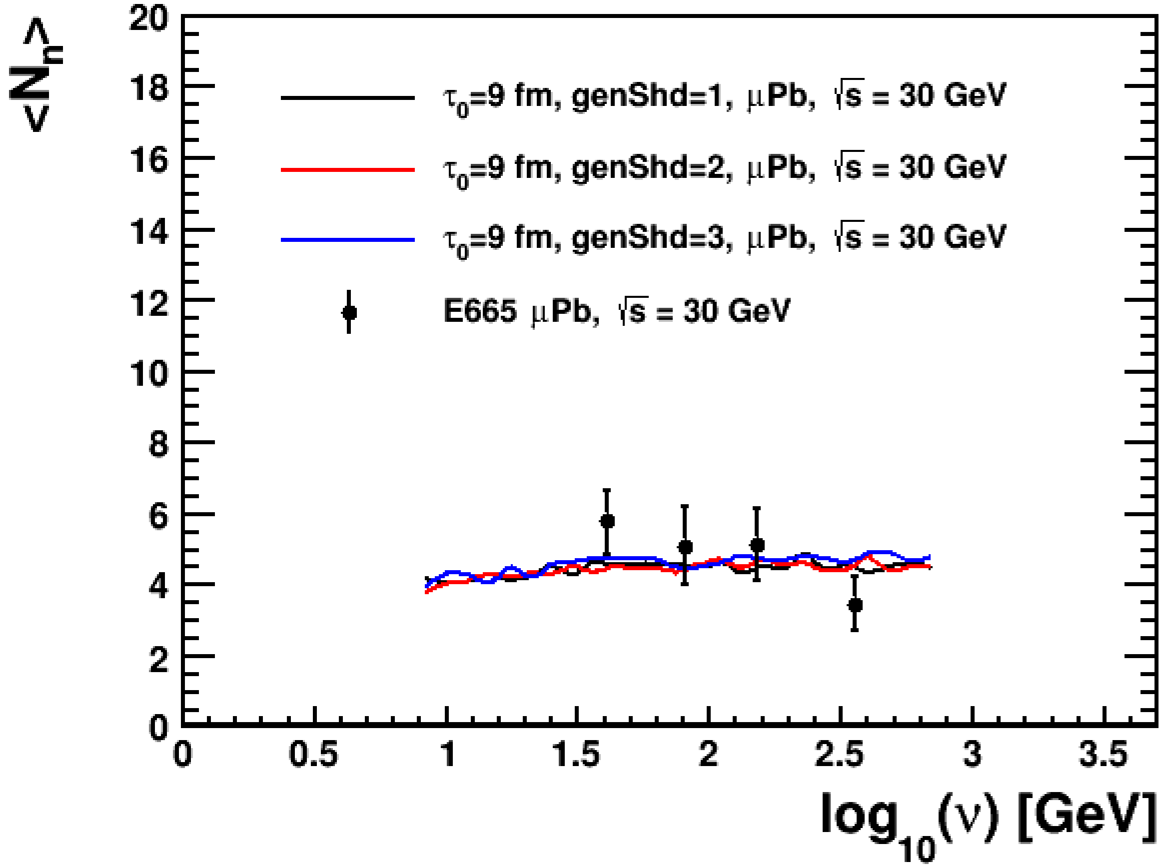


Fig. 9b. The (lack of) impact of the BEAGLE shadowing model choice on the tuning of the IntraNuclear Cascade formation time parameter, τ_0, using E665 fixed target e+Pb neutron data [12].

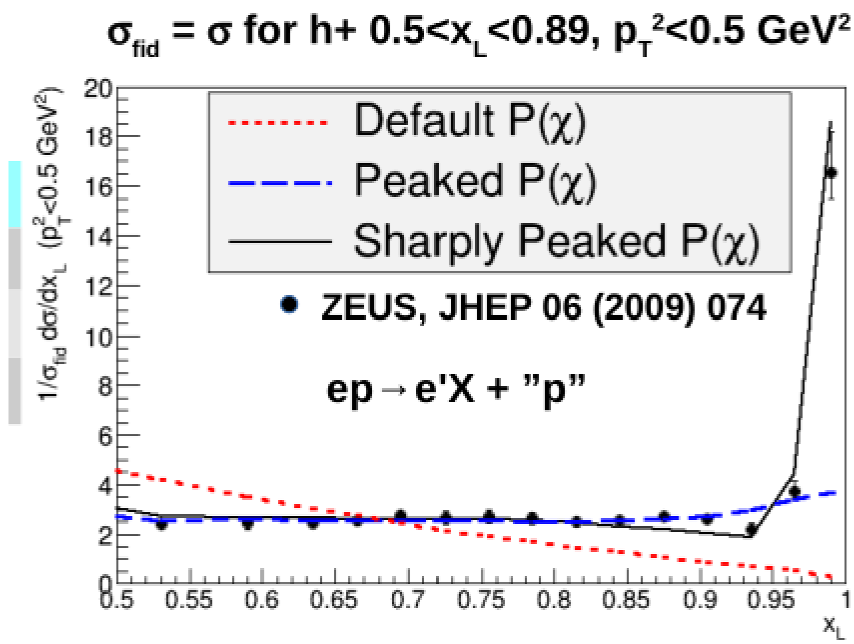


Figure 10. A comparison of ZEUS forward proton data [cite] to Pythia 6.4 with three different choices for the parametrization of the nucleon target remnant breakup distribution P(χ) [cite BeAGLE talk].

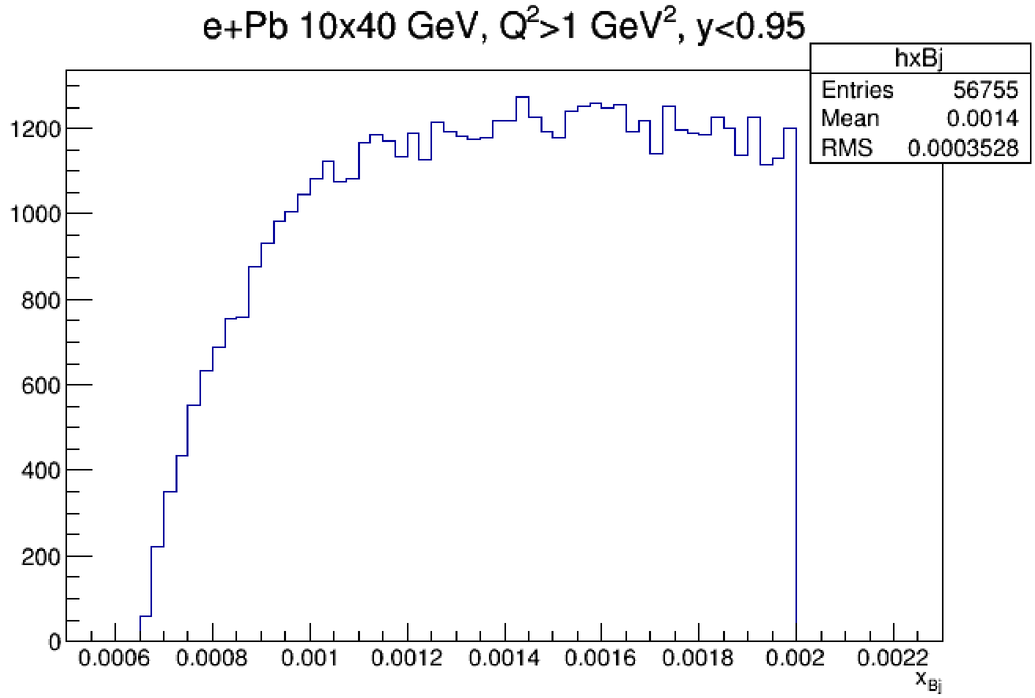
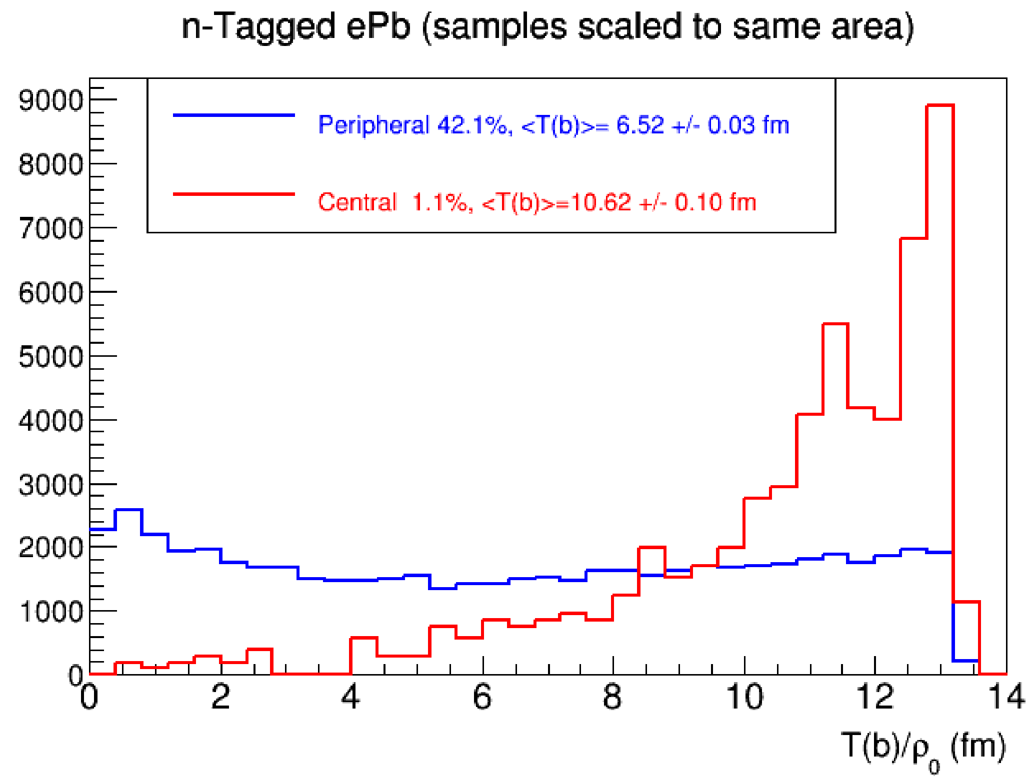


Figure 11. Bjorken x distribution for Q^2>1 GeV^2, y<0.95 and x<0.002 for 10x40GeV e+Pb collisions.

Figure 12. 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 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: $\tau_{0,}$ 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 three milestones are straightforward and are underway. As described above, the preliminary results are quite encouraging. The next three milestones deserve some explanation.

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.

SUMMARY HERE

3.0 VITA (Lead Scientist)

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4.0 Budget Explanation

Insert your budget explanation here.
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Do NOT insert the budget spreadsheet here – rather submit it as a separate document.

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Attachments

Include here (if desired), starting on a new page for each, additional information in the form of attachments.