Date: December 29, 2017

EIC Detector R&D Progress Report

Project ID: eRD17
Project Name: BeAGLE: A Tool to Refine Detector Requirements for eA Collisions
Period Reported: from July 2017 to December 2017
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Abstract

As part of the EIC R&D program, the BeAGLE model code for simulating e+A collisions has evolved into a key element in the current efforts to refine the detector and interaction region design for both eRHIC and JLEIC. With regard to deep inelastic scattering, the code is in good shape and the remaining improvements are mostly incremental, although important. With regard to diffractive physics, more substantive changes are needed.

The main technical changes since the last EIC R&D meeting fall into three categories: 1) Minor improvements to the basic code completed; 2) Implementation of improved handling of Fermi momentum of the struck nucleon is underway; 3) Improved handling of the A-dependence of diffraction has also started. The plan for the next period is to complete the projects which are underway and to install RAPGAP into BeAGLE as an optional alternative to Pythia. By June 2018, we expect to have RAPGAP installed and partially tested, but not yet finalized.

Even without these refinements, we have already used BeAGLE to overturn two key pieces of received lore regarding incoherent eA vector meson diffractive events. First, at the last meeting we reported that, contrary to popular wisdom, the Zero Degree Calorimeters planned at both eRHIC & JLEIC will be insufficient to veto-tag incoherent eA diffractive events without additional detectors. This is important because incoherent diffraction, where the nucleus is excited and/or breaks up, is a major background for coherent diffraction. Coherent diffraction, with a cross-section proportional to the gluon density squared, plays a key role in EIC e+A physics and the study of parton saturation. Second, since the last meeting we have demonstrated that even J/ψ diffractive events, which have the smallest rescattering probability, still

interact strongly enough with the nucleus to allow significant geometry tagging. The lore here was that the excited nuclear remnant would “forget” the details of the original collision and it would not be possible to tag the geometry using evaporation neutrons. Consequently, knockout protons were expected to be the only measure of impact parameter. We showed that both knockout (or “ballistic”) protons and evaporation neutrons are valuable for geometry tagging. This is important because incoherent diffraction allows us to measure the shape of the nucleon and to see fluctuations in the gluon configuration.

Past

What was planned for this period?

We had planned to correct the final state particles produced in the eN Pythia subevent for the missing Fermi momentum of the original nucleon with respect to the nuclear target rest frame (item 13 below). We had also planned to implement a finite coherence length for the rescattering “dipole” (item 9 below). Finally, we planned to begin the process of improving the A-dependence of the incoherent diffraction cross-section relative to DIS (item 11 below).

What was achieved?

The most important achievement since the last meeting was our demonstration that the ZDC alone already provides effective geometry tagging for incoherent diffractive events. In particular we demonstrated that even J/ψ diffractive events, which have the smallest rescattering probability, interact strongly enough with the nucleus to allow significant geometry tagging based on the ZDC. The lore here was that the excited nuclear remnant would “forget” the details of the original collision and it would not be possible to tag the geometry using evaporation neutrons. Consequently, knockout protons were expected to be the only effective measure of impact parameter. BeAGLE, however, contains a much more detailed description of the nuclear response, based on DPMJet and Fluka, than was available before. We showed that the origin of the geometry tagging effect in both diffractive and DIS events is the excitation energy of the nuclear remnant which is highly correlated with impact parameter. Energy conservation provides the “memory” of the impact parameter from the original collision even in the case of evaporation. Both knockout (or “ballistic”) protons and evaporation neutrons are therefore valuable for geometry tagging. This is important because incoherent diffraction allows us to measure the shape of the nucleon and to see fluctuations in the gluon configuration. It will be quite interesting to see if nucleons in the middle of the nucleus have a different shape or set of gluon fluctuations due to enhanced saturation compared to nucleons on the periphery.

At first glance, our two points might seem contradictory. We are saying that the evaporation neutrons are inadequate for tagging incoherent vs. coherent diffraction while they do a better than expected job at tagging the geometry in the incoherent collisions. In fact, these two points have a common origin. BeAGLE takes into account the event-by-event fluctuations in the excitation energy (E*) of the nuclear remnant left behind after the collision. The main reason that incoherent diffractive events can “sneak by” our veto tag is that the more peripheral collisions have a significant chance of a very weak nuclear excitation. Remnants with an excitation energy of less than 8 MeV are very unlikely to evaporate any nucleons at all, but rather de-excite through gamma radiation. In contrast, central collisions (small impact parameter) are likely to affect multiple nucleons either directly or indirectly, and lead to a much larger excitation energy. This can be seen in Figure 1 where we see the average excitation energy as a function of impact parameter. Note: there are two sources of fluctuation here: impact parameter variation and variation of the E_{exc} for a given b (not shown). Figure 2 shows the average number of evaporation neutrons for a given E_{exc}. Figure 3 shows the average number of evaporation neutrons for a given b while Figure 4 shows the converse.

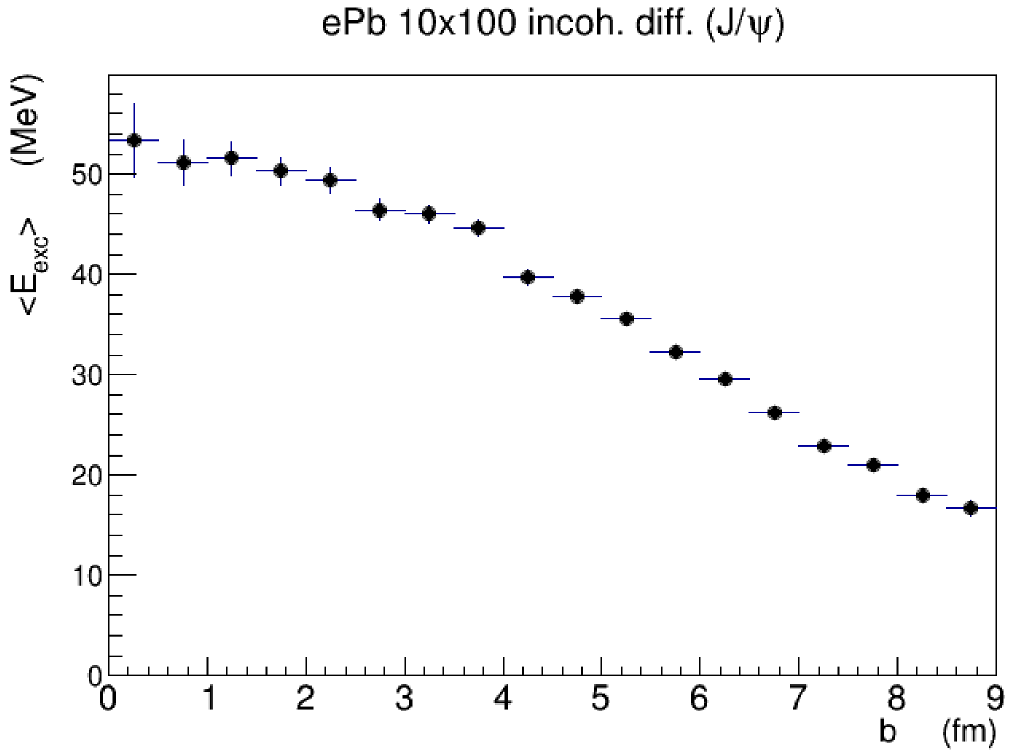

Figure 1. Average excitation energy of the nuclear remnant as a function of impact parameter for incoherent exclusive diffractive production of J/ψ particles in 10x100 GeV ePb collisions: e+Pb→e'+A'+J/ψ+X.

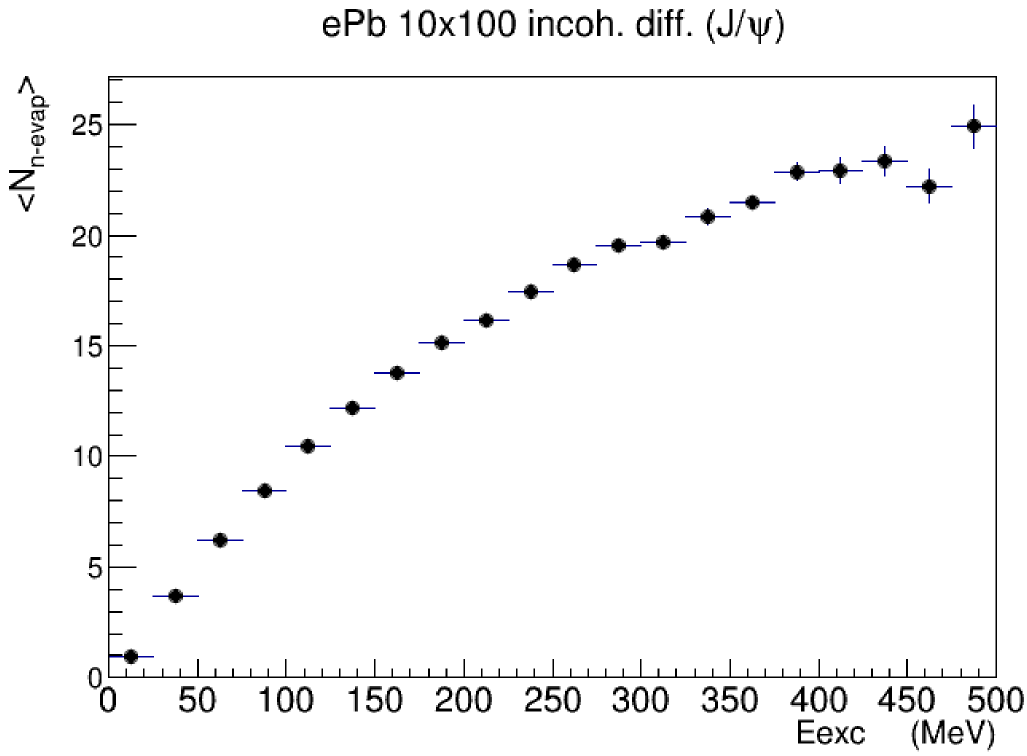

Figure 2. Average number of evaporation neutrons as a function of excitation energy for incoherent exclusive diffractive production of J/ψ particles in 10x100 GeV ePb collisions.

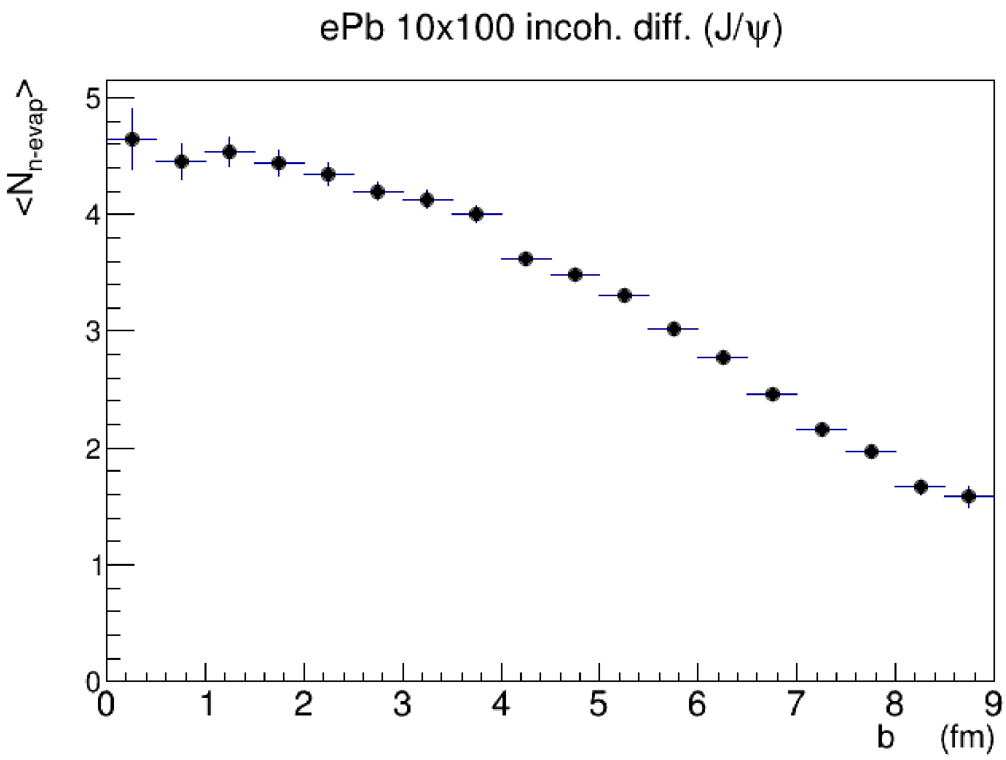

Figure 3. Average number of evaporation neutrons as a function of impact parameter for incoherent exclusive diffractive production of J/ψ particles in 10x100 GeV ePb collisions.

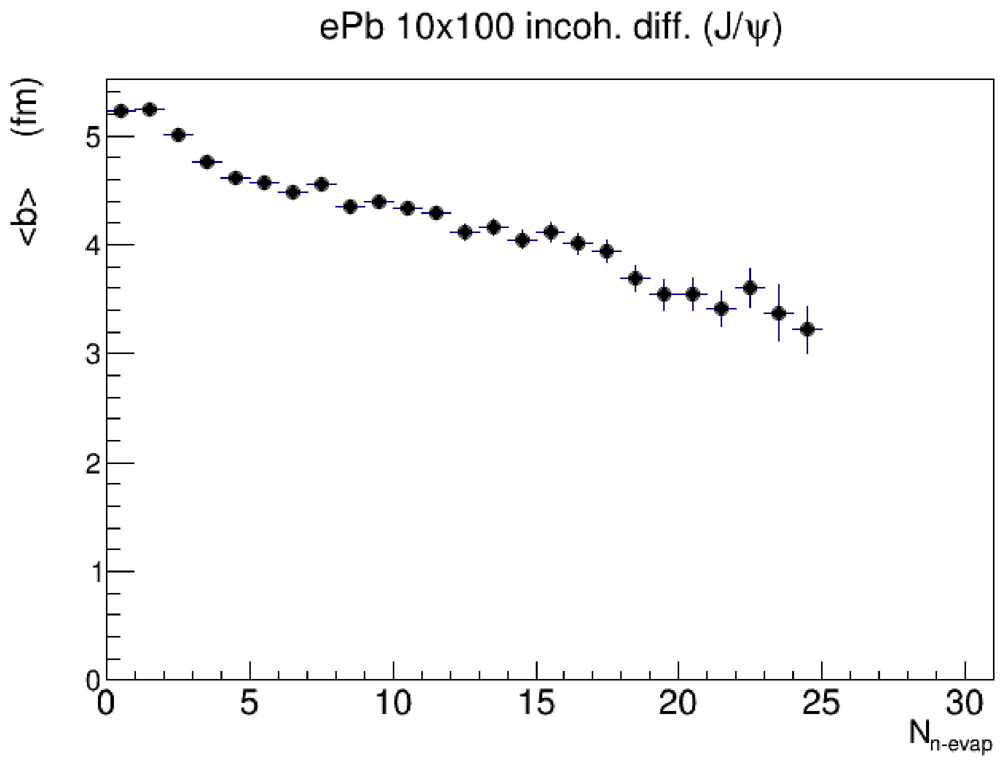

Figure 4. Average impact parameter for a given number of evaporation neutrons for incoherent exclusive diffractive production of J/ψ particles in 10x100 GeV ePb collisions.

The second most important achievement has been communicating these surprising findings regarding incoherent diffraction to the EIC community: veto-tagging is difficult, geometry tagging is reasonable. Baker gave a seminar at Jefferson Lab on July 14, 2017, where the first point was discussed. It should be noted that the JLAB LDRD "Geometry Tagging for Heavy Ions at JLEIC" (Vasiliy Morozov – PI) was renewed for FY2018 and that Jefferson Lab management stressed the importance of clarifying the detector/IR requirements for veto-tagging incoherent diffractive events at JLEIC. Baker also gave a "Center for Frontiers in Nuclear Science" Seminar at Brookhaven National Lab on December 7, 2017, emphasizing both physics points (veto-tagging and geometry tagging). This was very productive as much of the recent theoretical work concerning diffraction originated at BNL, including both pieces of lore that we have overturned.

Feature added or error corrected	BeAGLE 07/2017	BeAGLE 12/2017	BeAGLE (planned)
1-8. Early BeAGLE features (see text).	YES	YES	YES
9. Shadowing coherence length	NO	NO	YES
10. Partial shadowing effect	YES	YES	YES
11a. Effective σ_{dipole} for J/ψ averaged over x & Q^2	YES	YES	YES
11b. Effective σ_{dipole} for ϕ averaged over x & Q^2	NO	YES	YES
11c. Eff. $\sigma_{dipole}(x,Q^2)$ for V=ψ,ϕ,ρ,ω from Sartre (ePb)	NO	NO	YES
11d. Use correct $R_{diff}^{(A=208)}(x,Q^2)$ for V from Sartre	NO	NO	YES
11e. Improved σ_{dipole} for V, if necessary	NO	NO	YES
12. Tune to E665 μA Streamer Chamber data	NO	NO	YES
13. FS p_F for hard process correct	NO	(Testing)	YES
14. Kinematic matching between DPMJet&Pythia	NO	YES	YES
15. Protect against very high E_{exc} values.	NO	YES	YES
16. Enable nPDF with any value of A,Z (EPS09)	NO	YES	YES
17. Extend R→ σ_{dipole} map to more values of A	NO	NO	YES
18. Tune the t distribution for multiple scattering.	NO	NO	YES
19a-c. Install, test, & release BeAGLE/RAPGAP	NO	NO	YES
20. Implement UltraPeripheral Photon Flux	NO	NO	YES
21. Tune BeAGLE to UPC data (RHIC &/or LHC)	NO	NO	YES

Table 1. Technical accomplishments and plans through FY2019.

Table 1 contains an extended version of our list of accomplishments – achieved and planned. To save space, items 1-8 in the table were collapsed into a single line. These tasks were achieved some time ago. These include: 1) Correct hard process a la Pythia; 2) Tuned Pythia parameters to ZEUS forward proton data; 3) Intranuclear Cascade a la DPMJet; 4) Nuclear evaporation & breakup a la DPMJet/Fluka; 5)

Multinucleon shadowing; 6) Correct nucleon remnant (neutron or proton); 7) Correct eA target rest frame; 8) Tuned to E665 evaporation neutron data.

The implementation of the finite shadowing coherence length (item 9) was postponed as is discussed in the next section. Item 10 refers to the improvement that allows us to choose an option intermediate to the two extremes originally available in BeAGLE: 1) no multi-nucleon effect vs. 2) all shadowing is due to multi-nucleon scattering. A partial shadowing parameter of 0 is equivalent to turning multinucleon shadowing off, a value of 1 is normal multinucleon shadowing, intermediate values imply an intermediate rescattering cross-section. It is even possible to use values larger than one to increase the rescattering compared to the naive value. This was already implemented in July.

The key item (11) - "Process-specific A-dependence" has been broken up into several subcategories. Item 11a refers to the case already implemented in July where we use a shadowing factor (item 10) value of 1.32 to match the average Sartre shadowing effect for J/ψ incoherent diffraction. Item 11b refers to a new case implemented for ϕ incoherent diffraction using a shadowing factor of 18.5. Items 11c-e are discussed in the future section along with item 12.

Item 13 (Fermi momentum) refers to the fact that the Pythia eN subevent in BeAGLE occurs with the assumption that the nucleon is at rest in the nuclear target rest frame. The actual momentum and kinetic energy of the struck nucleon in the nuclear rest frame (from DPMJet) needs to be added back into the Pythia event skeleton before hadronization. There are two effects to consider. First the effective invariant mass of the γ^*+N system (W) can be different from the naïve value. The momenta must be rescaled in the naïve hadronic center-of-mass frame in order correct for this. Second, there is a net momentum of the reaction products in this frame which also has to be added by boosting the event appropriately. The math for all of this has been finished and the code implemented, but it has not been fully tested.

Item 14 refers to a subtle bug which was discovered as part of the implementation of the Fermi momentum correction (item 13) and which took some effort to chase down. Pythia and DPMJet independently calculate the naïve boost between the target rest frame and the hadronic center-of-mass frame (assuming the nucleon and nuclear TRF are the same). The Pythia calculation is correct, but the DPMJet calculation had a slight approximation where $y(1+M_N x/2E_{eTRF})$ was approximated as y. This effect is relatively small, especially at EIC energies, but it can cause problems when different parts of the code are even slightly inconsistent. Also, it is desirable for BeAGLE to run over a wide range of energies, including lower energies such as those used at HERMES or JLAB12. In any case, this bug has been fixed and the code is now consistent.

Item 15 refers to a problem in FLUKA, used in BeAGLE to handle the behavior of the excited nuclear remnant: possible fission, evaporation, and gamma-deexciation. If the excitation energy E_{exc} is too large, FLUKA can hang, taking a very long time for a single event – similar problems were noted with the Gemini++ code in Sartre. A protection was implemented in BeAGLE to disallow very high E_{exc} values, setting values $E_{exc}>E_{max}$ to $E_{exc}=E_{max}$. E_{max} is settable with a default of 9 GeV. For comparison, a typical value for E_{exc} in an eA collision is 0.04 GeV. The similar cutoff in Sartre/Gemini is 0.5 GeV. This limit should be hit only rarely and should not have any effect on the physics.

Item 16 refers to the fact that the most up-to-date Leading Order nuclear parton distribution function set, EPS09, is available only for a limited set of A values, including fortunately Pb and Au. In order to compare to existing data at E665 and HERMES however, more options are needed, in particular Xe. H. Paukkonen ("P" in EPS) pointed out that the scaled nuclear parton distributions ($R^{(A)}(x,Q^2)$) are a weak function of A and it should work fine to just use nearest available A-value. Tests confirmed this: the differences are small and well within the errors of the EPS09 fits. BeAGLE will now run with any value of A,Z, issuing a warning if an approximate A-value is used for $R^{(A)}(x,Q^2)$.

What was not achieved, why not, and what will be done to correct?

Item 9 is the planned implementation of a finite coherence length λ for the shadowing effect. Currently BeAGLE assumes that all events with $x_{Bj}>0.1$ have a correlation length λ of 0, meaning that one and only one nucleon is involved in the collision. In contrast all events with $x_{Bj}<0.1$ have an infinite correlation length, meaning that all nucleons in a given longitudinal tube have a chance to be involved in multiple scattering of the initial DIS or diffractive "dipole". A better approach would be to allow $\lambda \sim 1/2M_N x$ so that for modest x only longitudinally "nearby" nucleons can be involved in multiple scattering. This item was postponed because it is low priority compared to the other items being worked on. Most studies being done so far are either at relatively low x, where infinite λ is reasonable, or are at higher x and have multinucleon shadowing turned off, where λ is irrelevant. This should be implemented when possible for completeness, hopefully during this fiscal year, but it is not essential at this time.

Item 13 (Fermi momentum) is nearly finished. It was delayed due to work on item 14 and the diffractive geometry tagging studies.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Items 11c-d are further improvements to the diffractive dipole (rescattering) cross-section and the overall eA/eN diffractive cross-section ratio. These should be completed in FY2018 as they are important for the eventual comparison of E665 data with RAPGAP-enabled BeAGLE in FY2019. Item 11c refers to a plan to use the Sartre results to infer the correct dipole cross-section for multiple scattering for each vector meson as a function of Q^2 and x rather than just matching the value averaged over Q^2 and x. Item 11d refers to making sure that the overall diffractive cross-section ratio between ePb and eN matches that of Sartre. Finally, item 11e recognizes that a better formalism may be needed to relate Sartre $\sigma(eA)/\sigma(eN)$ behavior to the rescattering probability in BeAGLE, especially for the ϕ,ρ,ω mesons where the suppression due to gluon saturation is strong and therefore the inferred rescattering cross-section is large.

Line 12 refers to comparing BeAGLE+Sartre to the E665 Streamer Chamber data once BeAGLE handling of diffraction has been improved. This is really one of the main thrusts of the entire project and is currently planned for FY2019.

Line 17 and 18 refer to small improvements to the BeAGLE model. Currently the Glauber-model map between the nuclear parton distribution function R and the effective dipole rescattering cross-section has been created only for Au and Ca nuclei.

Other values of A use the map for one of these two nuclei. More values of A should be included (line 17). In the case of multiple scattering, one nucleon undergoes a hard scatter and the other nucleon undergo a soft scatter. Currently, the scale of the soft scatter is given by the intrinsic k_T of the parton in the nucleon. For the diffraction case, this scale should be given by the t distribution of the elastic component of incoherent diffraction (line 18).

Line 19 is self-explanatory: the installation of RAPGAP into BeAGLE, along with testing and release of the final code. This represents the major thrust of this project during FY2018.

Lines 20-21 refer to the plan in FY2019 to apply BeAGLE to UltraPeripheral Collisions in pA and/or AA. This has the potential to benefit both communities. First the heavy ion community has been assuming that a ZDC does a good job at tagging coherence/incoherence of the collision and this seems unlikely given our results for EIC. Second, we may be able to use existing data at RHIC and the LHC to test our nuclear breakup models. How accurate is our distribution of the number of evaporation neutrons? Can we tune BeAGLE parameters?

What are critical issues?

No major concerns.

Additional information:

Liang Zheng is now an assistant professor at the China University of Geosciences (Wuhan) and is still active in physics. Following the implied suggestion of the committee, we are likely to propose travel funds for him for the summer of 2019 during the next proposal cycle.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

Baker is the only funded person on the project and he works one-quarter time (0.25 FTE). So far this fiscal year, he has spent about 0.75 FTE months, or one quarter of the planned budget.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Laboratory Physics Department funding supported the salary of Aschenauer and Lee who have primarily been working in an advisory role. Until recently, Central China Normal University has supported the salary of Zheng who spends about 10% of his time on this project. In the future, Zheng's new institution:

China University of Geosciences (Wuhan) will support his salary.

As mentioned previously, Baker and Zheng joined with a group of JLAB staff and users in a successful proposal to acquire JLAB LDRD funds for a project called "Geometry Tagging for Heavy Ions at JLEIC" which spans FY2017-FY2018. During FY2017, we implemented two EIC R&D simulation programs (eRD17-BeAGLE and also RD-2012-5-Sartre) at JLAB and these are already being used to help validate and improve the forward detector/IR design for eA collisions in the JLEIC design configuration. The funding for this project was renewed for FY2018. Vasiliy Morozov (JLAB) is the P.I. and collaborators include: A. Accardi, M.D. Baker, W. Brooks, R. Dupre, M. Erhardt, K. Hafidi, C. Hyde, P. Nadel-Turonski, K. Park, A. Sy, T. Toll, G. Wei, L. Zheng. Care has been taken so that the work done on the JLAB LDRD project and the eRD17 project don't overlap.

Publications

Please provide a list of publications coming out of the R&D effort.

None so far.