DPMJetHybrid 2.0: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing / Saturation Regime
An EIC R& D Proposal

E. Aschenauer[1], **M.D. Baker[2*]**,**J.H. Lee[1*]**

[1] Brookhaven National Laboratory, Upton, NY 11973
[2] MDB Physics and Detector Simulation Consulting, Miller Place, NY 11764
[*] **co-PIs** - contact: mdbaker@mdbpads.com

June 15, 2015

Abstract

We propose to upgrade the eA DIS event generator DPMJetHybrid [1] to include some key nuclear shadowing / parton saturation effects that are currently missing in the suite of eA event generators available for physics simulations. These event generators, partly supported by previous EIC R&D funding, have been essential in establishing detector requirements for various physics measurements [2, 3]. However, the particle production model in the forward region for eA (along the ion direction) needs improvement in order to clarify those requirements for measurements at either eRHIC or MEIC. We plan to add a flexible model for intrinsic k_T and multi-nucleon k_T-recoil sharing for eA collisions. This model will automatically factor in improved information as we include updated nuclear PDFs from RHIC or the LHC. In order to test and shakedown the model, we plan to use it to study the impact of forward detectors on two important topics in eA: centrality measures and correlations between forward particles and particles from the hard scattering.

1 Introduction

The phenomena of nuclear shadowing and parton saturation are increasingly topical and important in the study and interpretation of AA, pA and potential eA data at RHIC and LHC energies. In fact they provide a lot of connections between these data sets [4]. One important feature of nuclear shadowing in eA is that it necessarily involves the interaction of multiple nucleons from the nucleus with the probe [4, 5]. Currently, we are lacking a DIS model Monte Carlo which has these key features of parton saturation and multi-nucleonic interactions. This in turn means that our models are inaccurate in how they handle the recoil from intrinsic k_T in the nucleus and in how they simulate very forward particles in DIS. Since the design of the forward hadronic detectors and their integration with the IR and the EIC machine elements has already started, it is important to have a complete suite of accurate eA event generators as soon as possible.

2 Forward Detectors at RHIC, eRHIC and MEIC

2.1 Lessons from RHIC

There are three main types of forward detectors used at RHIC for pp, pA, and AA:

ZDCs Zero Degree Calorimeters. Used in BRAHMS, PHENIX, PHOBOS, and STAR. These measure forward neutron energy.

FCAL/PCAL Forward CALorimeter (PHENIX) and Proton CALorimeter (PHOBOS). These measure forward protons (& π^+, K^+) in pA, dA, and AA collisions.

Roman Pots Roman Pots in STAR measure forward protons (& π^+, K^+) in pp collisions. In collisions involving heavy nuclei, these mostly measure nuclear fragments and some forward protons, but with less efficiency then in ep.

The ZDCs (Zero Degree Calorimeters) [6] are hadronic calorimeters, designed to measure forward neutron energy, placed at zero degrees (in both directions), covering approximately a 4 mrad polar angle cone ($0 < \theta < 0.004$). The ZDCs are placed after the "DX" bending dipole which should sweep away the forward charged particles (mostly protons and nuclear fragments) from the collision. Figure 1, taken from the RHIC ZDC technical NIM paper [6], shows the trajectory of spectator neutrons, protons and the gold beam (Au) as seen from the point of view of the beam. Gold ions are deflected about 40% as much as protons (recall $(Z/A)_{Au} = 0.401$) while nuclear fragments (not shown), such as α particles, with $Z/A = 0.5$ are deflected about 50% as much as protons. Figure 2, taken from Ref. [7] shows the PHOBOS ZDC and PCAL positions for the Au beam side for the 2003 dAu run. PHOBOS, along with PHENIX, took advantage of the fact that the protons are outside the beam pipe to optimize the forward charged particle detection for heavy ion running. Roman Pots, on the other hand, as used in STAR, are further downstream and surround the beampipe rather than being offset. Roman Pots, therefore, are optimized for pp running, and especially for diffractive pp.

The IRs for eRHIC and MEIC will be different in important ways, but they will certainly share this main feature: for eA running, the beam and the forward protons will end up on very different trajectories. It will be crucial to optimize the forward region for *both* ep and eA running.

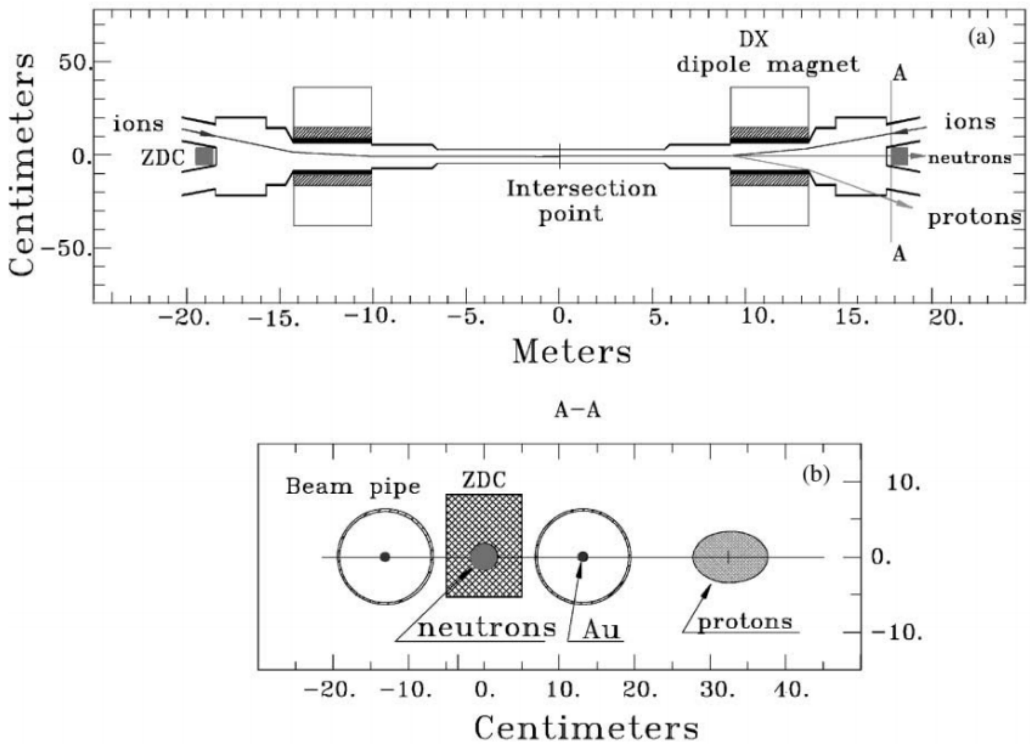

Figure 1: Plan view of the RHIC collision region and "beam's eye" view of the ZDC location indicating deflection of protons and charged fragments with $Z/A \sim 1$ downstream of the DX magnet. Figure taken from Ref. [6].

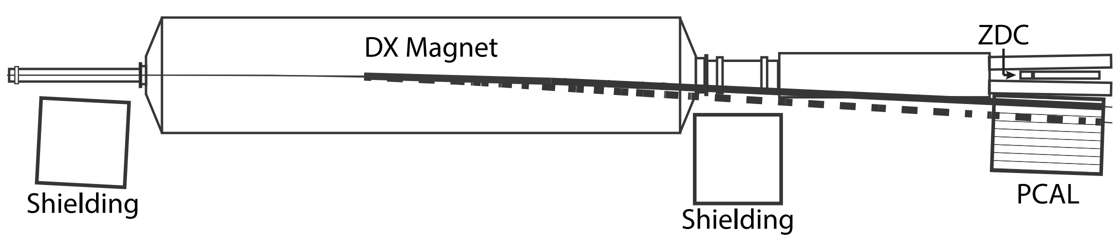

Figure 2: Schematic overview of the PHOBOS Au-side "PCAL" or proton-calorimeter from the RHIC Run 3 d+Au running, along with the ZDC. The thick solid line starting in the middle of the DX magnet shows the approximate trajectory for a 100 GeV spectator proton emitted at zero degrees from the collision point (far to the left on the drawing). The dashed line shows the approximate trajectory for a 50 GeV proton emitted at zero degrees. Note: the Au energy in this run was 100 GeV/nucleon. Figure taken from Ref. [7].

2.2 Optimizing eRHIC and MEIC

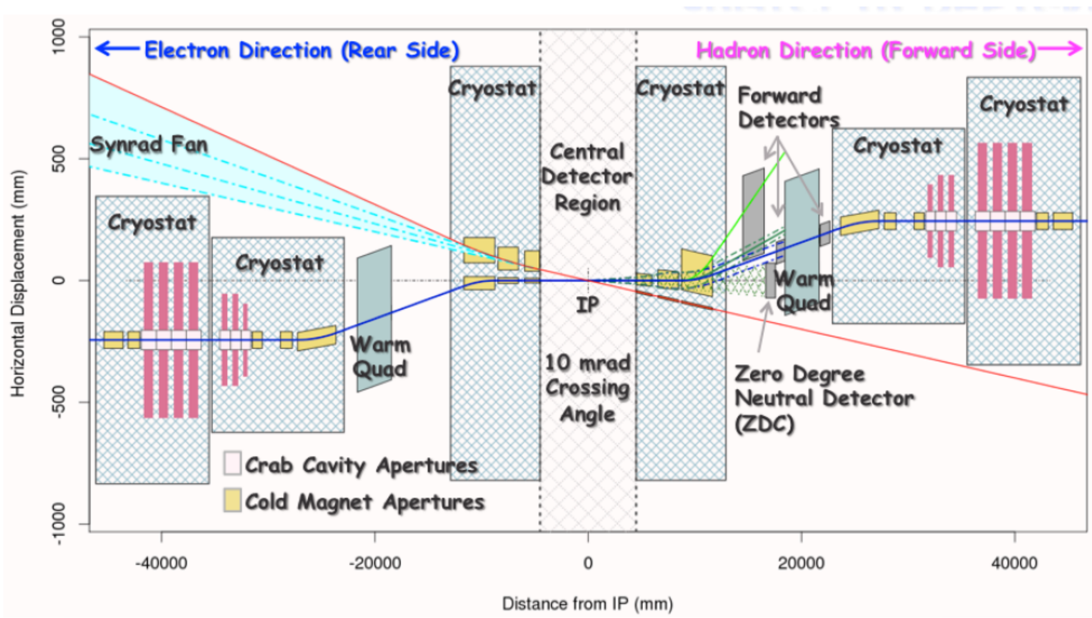

Figure 3: eRHIC IR Design. Reproduced from Figure 1 in Ref. [8].

In the case of eRHIC, to quote from the lastest ERD12 progress report [8] concerning the IR design: "experimental physicists are currently working with and providing feedback to the machine developers on the current design and we are beginning the iteration process to converge on a design that meets the requirements posed by the EIC physics on the IR design." This discussion is already quite advanced as can be seen in Figure 3 taken from the progress report. The eRHIC Design Study [3], in Section 4.2.4 lists the physics topics currently driving the designs of the zero-degree calorimeter and low angle hadron tagger as well as their integration into the IR. These include many important topics in ep. In eA, it includes exclusive processes where we must insure that the eA remains intact. It also includes the idea of tagging centrality in eA using forward neutrons [9], but this simulation can be improved significantly, as discussed in more detail in the next section.

One important topic that is missing altogether in eA is the idea of correlating the intrinsic k_T seen in the current jet with the equal and opposite k_T recoil in the target remnant. This has been examined for ep collisions (see figure 2-10 in the eRHIC Design Study [3] for one example and Ref. [10] for a more extensive discussion), but not yet for eA. The main reason that this hasn't been examined for eA is that it relies on an improved understanding of how the intrinsic k_T recoil is shared among the nucleons in the nucleus, as we propose to include in the upgrade to DPMJetHybrid.

The MEIC design ideas, also include a fully integrated detector and interaction region design which aims for full acceptance and high resolution even for far forward particles (see for example Ref. [11]), including all nuclear fragments. This is achieved, in part, by having

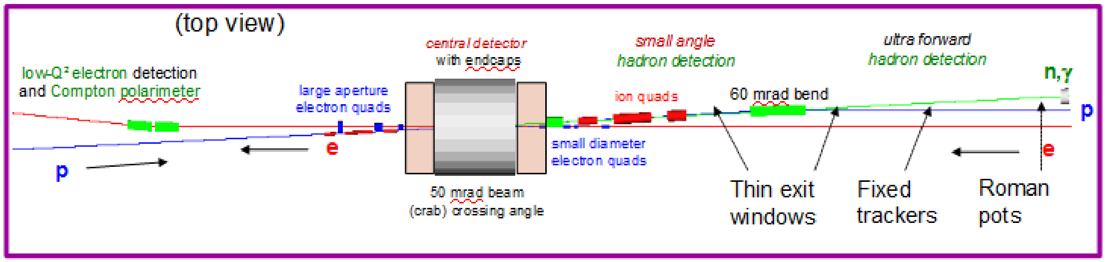

Figure 4: MEIC IR Design. Figure taken from Ref. [11].

a large crossing angle and by using low gradient, high aperture quadrupoles. The physics studies so far, have focused on the impact of spectator tagging on polarized e ^{3}He collisions, allowing effective measurement of polarized electron neutron DIS.

The upgraded version of DPMJetHybrid would allow us to study a more complete set of measurements including eA centrality measures and also intrinsic k_T in eA based on the correlation between the current jet p_T and that of the recoil nucleons. The full acceptance of the MEIC integrated detector/IR design should be optimal for this physics.

In general, the DPMJetHybrid 2.0 project will help inform the cost-benefit discussions and decisions that have already started. How much effort and expense should go into forward detectors at the EIC? What will the impact be of any compromises in detector acceptance? We need as many different physics inputs to these questions as possible. In particular, important physics effects, such as multi-nucleonic sharing of k_T recoil in low x eA collisions should not be excluded from the discussion.

3 Impact of Nuclear Shadowing on centrality measurement in eA collisions

As a more detailed example of how the nuclear shadowing effects can impact physics results, let us consider the intriguing possibility of selecting a sample of “central” eA collisions with a low impact parameter. In particular, in the saturation regime, a central sample should show stronger evidence of saturation than a peripheral sample in other variables such as dihadron correlations [3, 12]. Just such a possibility is discussed in Ref. [9]. The authors use DPMJet, which models eA collisions as single eN collisions embedded in a nucleus, accounting for such effects as intranuclear cascading and neutron and proton evaporation from the excited nuclear remnant. Figure 5b from that paper reproduced here as Figure 5 shows a modest correlation, with the average impact parameter ranging from about 5 fm for $E_n^{ZDC} = 0$ TeV to about 3 fm for$E_n^{ZDC} = 2.7$ TeV, but with a large spread. The main message of the paper was that it is possible to make event classes with very different values of “d”, the distance traveled in the nucleus. The authors also conclude, though, that it is challenging to make samples with very different impact parameters using ZDC cuts and they also note that an additional cut on forward proton energy does not add much value

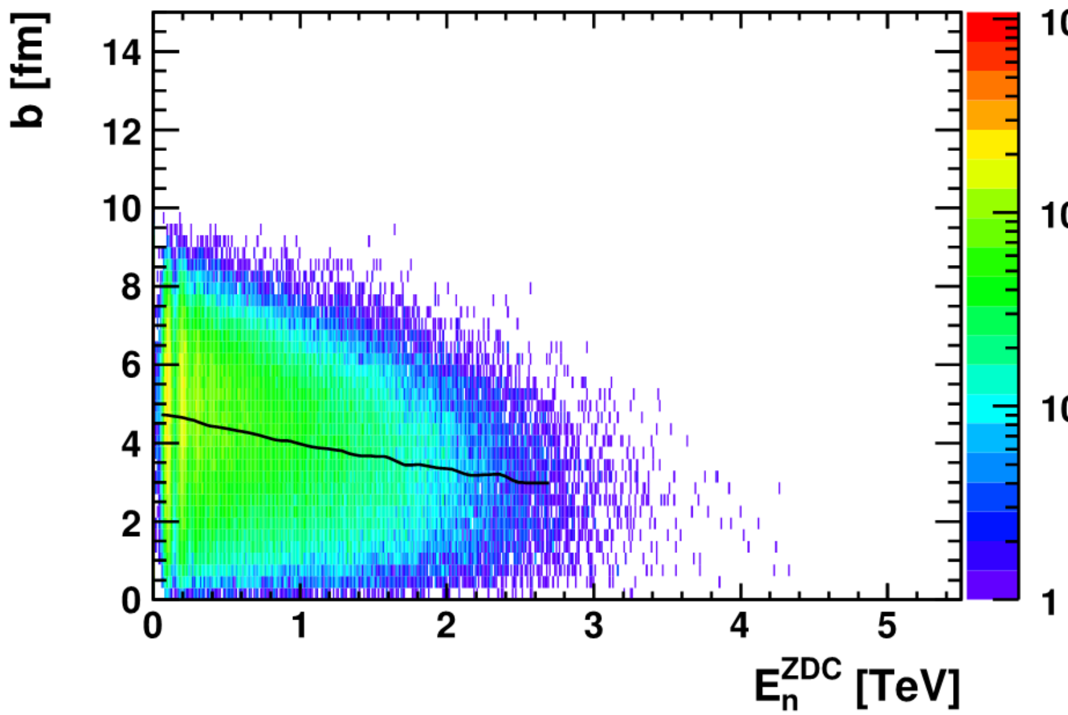

Figure 5: Correlation between impact parameter and ZDC energy from Ref. [9].

due to the fact that there are far fewer evaporation protons than neutrons.

These last two conclusions, however, may be unduly pessimistic, because the model ignores the multi-nucleon interaction implied by the existence of nuclear shadowing. These effects, occurring in exactly the region of saturation that we are most interested in, could improve the correlation between impact parameter on the one hand and forward neutron and proton energy on the other hand. Furthermore, they should enhance the forward "cascade" nucleons relative to the evaporation nucleons. Figure 8 from the paper, reproduced here as Figure 6, shows the pseudorapidity distribution for neutrons from 10 GeV x 100 GeV eAu collisions from three different sources in DPMJet. Primary refers to those from the primary eN collision, cascade refers to those from intranuclear cascading, while evaporation refers to neutron evaporation from the excited nuclear remnant after the collision. In this model, the forward neutrons are dominated by evaporation neutrons. In the case of forward protons, there are fewer overall due to the Z/N ratio and there are far fewer evaporation protons since many protons remain captured in nuclear fragments (such as α particles).

For events in the saturation region, in the enhanced DPMJet-Hybrid 2.0 model we are proposing, there would be additional neutrons and protons in the "Cascade" region of pseudorapidity for central events for two reasons. First, a typical collision would involve a k_T-recoil from more than one nucleon giving a typical p_T kick to each involved nucleon of about 0.44 GeV or 4.4 mr, equivalent to $\eta = 6.1$. Second, those nucleons would also partic-

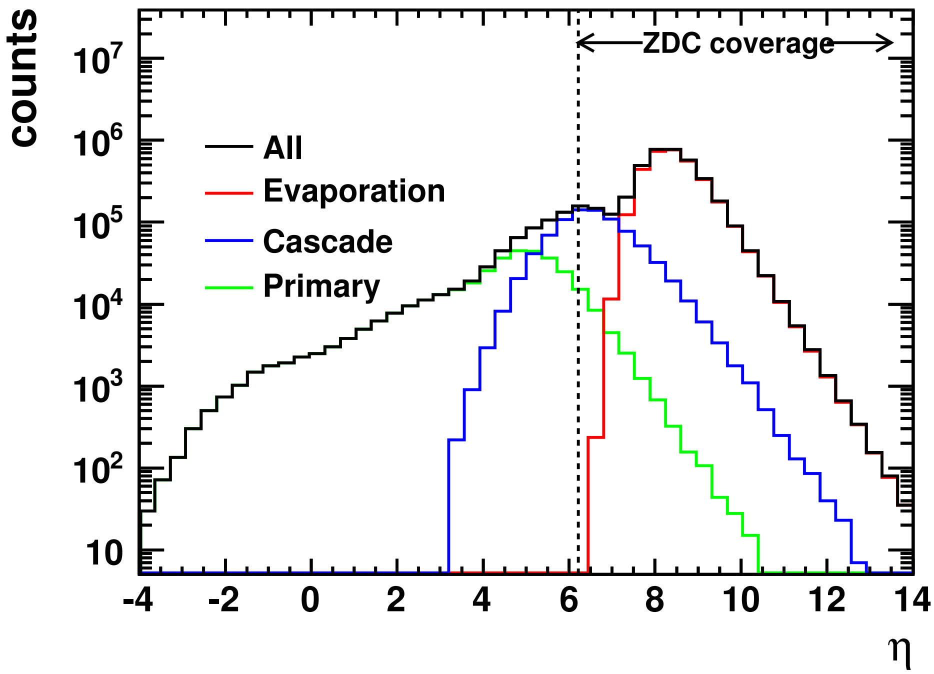

Figure 6: Pseudorapidity (η) distributions for neutrons from DPMJet (not DPMJet-Hybrid) from a variety of sources from Ref. [9].

ipate in and enhance the intranuclear cascade. This would enhance our impact parameter correlation and it would also add a new physics possibility. If we can measure enough of the recoiling higher p_T nucleons, we may be able to correlate them with the strength and direction of the monojet k_T in the hard part of the collision.

It should be noted that Fermilab E665 already demonstrated the measurement of thermal evaporation neutrons [13] as well as "grey track" protons from intranuclear cascades [14] in μXe collisions at energies similar to that of the planned EIC. In particular, E665 showed that it is possible to make meaningfully different event samples using "cascade" region protons alone even from as small a nucleus as Xenon. This is a promising subject which should be fully explored at eRHIC.

With the above handwaving arguments, it is not possible to evaluate the value of measuring forward neutrons over a larger polar angle or the value of measuring forward protons with a good efficiency in eA. In order to evaluate these issues, we need an improved model.

4 Description of Project

The existing eA event generator DPMJetHybrid combines the DPMJet description of nuclear breakup and intranuclear cascading with PYTHIA 6's rather comprehensive description of deep inelastic scattering (including the generalized vector meson dominance model, LO DIS, higher order hard QCD diagrams and soft QCD parton showers). In addition it includes a afterburner to simulate the nuclear fragmentation effect in cold nuclear matter. We plan to add a consistent treatment of intrinsic k_T (parton saturation), and multiple recoiling nucleons and/or "beam remnants" from the nucleus which are a part of the physics in the nuclear shadowing regime of eA collisions. Based on the input nuclear and nucleonic PDFs, our new model will infer a distribution of the number of nucleons involved in the collision. For each event, the k_T of the struck parton will potentially include contributions from multiple nucleons and the recoil will be shared appropriately. The program will have the option to have the excess nucleons recoil elastically or to have color connections with the struck parton. The program will also have the option to include flavor-dependent k_T, including the option of different values for gluons and quarks. This code will automatically factor in improved information as we include updated nuclear PDFs from RHIC or the LHC.

The key point of the new model is that it's data-driven, or more specifically PDF driven. DIS in the saturation regime can be viewed in the target rest frame as a virtual photon fluctuating into a $q\bar{q}$ dipole which then interacts hadronically with a nucleon [15]. A complete theoretical model of saturation requires a detailed understanding of the dipole cross-section, $\sigma_{q\bar{q}}$ as a function of x and Q^2. Instead, however, we can use a Glauber-style model, also known as an eikonal approximation to make a map from $\sigma_{q\bar{q}}$ to $F_2^A/(AF_2^N)$. We will then take the known (or at least input) values for F_2 at a given value of x, Q^2 and invert the map to get the dipole cross-section. This will allow us to determine on an event-by-event basis, based on impact parameter (b), x and Q^2, the number of nucleons participating in a given collision. As a refinement to the model, important at modest x, from say $0.01 < x < 0.07$, we can add the concept of fluctuation length as a function of x, so that the dipole lasts for a length $\lambda = 1/(2Mx)$ [15].

It should be noted that the eikonal approximation is known to be flawed in DIS (see e.g. Ref. [16]) because, among other things, it fails to predict the right Q^2 dependence. However, we will not be relying on it for the x or Q^2 dependence, which we get from the input PDFs. In order to make a map from the amount of nuclear shadowing in the cross-section to the number of nucleons hit, this model should be good enough.

Using this upgraded version of DPMJetHybrid, we will then study two key questions in the physics of eA where multi-nucleon effects may be important and determine the detector acceptance and resolution needed.

First, we plan to extend the existing studies of our ability to measure intrinsic kt in ep (See section 2.1.2 in Ref. [3] as well as Ref. [10]) to the very interesting case of eA. In the ep case, the problem is made simpler since the proton remnant should have an equal and opposite recoil k_T compared to the struck parton intrinsic k_T. In the case of eA, in the most interesting nuclear shadowing / saturation regime, we expect the recoil to be shared among the nucleons from the nucleus. The study will determine whether a complete enough forward detector will allow us to reconstruct the recoil and correlate it with particles in the current jet ($x_F > 0$).

Second, we plan to re-examine our ability to measure the centrality (impact parameter) of the eA collisions, also using forward particles. Previous studies of this question [9], as discussed above, have not included multi-hadron correlations.

5 Personnel, Timetable and Budget

Normally, one might expect a project of this complexity to be a multi-year, multi-FTE project, especially if it involved postdoctoral researchers. Instead, we have the opportunity to assemble an expert team with a very specific set of skills and experience, ideally suited to making this project happen in one year with less than 0.5 FTE of total effort. The personnel involved in the proposal are all well known to the RHIC and eRHIC community as well as the broader EIC community, so the following summary will just emphasize some specific points relevant to this proposal. Mark Baker will be covered in more detail because all of the cost in the project is associated with his involvement.

Elke Aschenauer is a PYTHIA and LHAPDF expert and was involved in assembling DPMJetHybrid and in the earlier studies of eA centrality measures.

J.H. Lee is an expert in simulating forward proton tracking through the RHIC magnets for RHIC and eRHIC with emphasis on Roman Pots, was consulted on DPMJetHybrid and was involved in the earlier studies of eA centrality measures.

Mark Baker (MIT PhD 1993) worked on DIS as a graduate student on FNAL E665, participating in the nuclear shadowing paper [17], the eA centrality paper using neutrons [13] and in studies of intrinsic k_T [18, 19]. From 1993-present he worked on PHOBOS at RHIC, with duties ranging from Software Coordinator to Project Manager to Deputy Spokesperson to Acting Spokesperson. It should be noted that the first paper from PHOBOS [21] triggered a lot of theoretical work on saturation in AA collisions at RHIC energies, while the most recent paper from PHOBOS involves forward proton and neutron tagging in dA collisions [7]. From 2009-present, Mark has been working on eRHIC simulations: creating LEPTO-PHI [22] (LEPTO DIS model code with the "Cahn effect" added), finding and fixing bugs in LEPTO and in PYTHIA, and studying the use of forward particles to measure intrinsic k_T in ep collisions at eRHIC [3, 10]. In 2011, Mark stepped down from his position at BNL (tenured physicist) but continued working on eRHIC simulations as a consultant.

The timetable of this project covers 11 months from Nov. 2, 2015–Sept. 30, 2016. Key milestones are listed below.

Feb. 26, 2016 Simplified implementation in model: no color connections with extra nucleons, no flavor-dependent k_T

Apr. 29, 2016 Model testing and physics results with simplified model. Code release.

June 29, 2016 Full model implementation

Sept. 30, 2016 Final physics results. Code release. Project complete.

Person	Institution	Effort (FTE-year)	Cost to Proposal	Remarks
E. Aschenauer	BNL	0.05	$0	cost covered by BNL
M.D. Baker	MDBPADS[20]	0.24	$64,000	
J.H. Lee	BNL	0.10	$0	cost covered by BNL
TOTAL:		0.39	$64,000	

Table 1: Personnel Budget Breakdown - fully loaded costs

While this project is self-contained and would benefit from being completed in one year, it should be noted that it would be possible to break the project up into two phases: the simplified model (Nov. 2, 2015–Apr. 29, 2016 above) and the full model implementation (Apr. 29-Sept.30,2016 above). The first phase would then cost $35,000 and the second phase $29,000 (in FY2016$).

6 Summary

The EIC will be the first electron-ion collider in the world and should lead to a comprehensive understanding of saturation effects. It is essential that we have as many models available which treat this physics. We propose to upgrade the eA event generator DPMJetHybrid to include some key nuclear shadowing / parton saturation effects that are currently missing in the suite of eA event generators available for physics simulations. This upgrade will significantly improve the particle production model in the forward region for eA (along the ion direction). This improvement is needed in order to clarify those requirements for measurements at either eRHIC or MEIC with forward detectors, including centrality tagging and correlations between forward particles and jets from the hard scattering. These detector requirements are an essential part of the IR design and the ongoing feedback process between nuclear physicists and accelerator physicists.

References

[1] `https://wiki.bnl.gov/eic/index.php/DpmjetHybrid`

[2] A. Accardi et al., "Electron Ion Collider: The Next QCD Frontier, Second Edition", arXiv:1212.1701.

[3] E.C. Aschenauer et al., "eRHIC Design Study: An Electron-Ion Collider at BNL" (2014), arXiv:1409.1633.

[4] L. Frankfurt, V. Guzey, M. Strikman, "Leading twist nuclear shadowing phenomena in hard processes with nuclei." Phys. Rep. **512** (2012) 255.

[5] N.N. Nicolaev and V.I. Zakharov, “Parton model and deep inelastic scattering on nuclei”, Phys. Lett. **B55** (1975) 397.

[6] C. Adler et al., “The RHIC zero degree calorimeters”, NIM **A470** (2001) 488.

[7] B.B. Back et al. (PHOBOS Collaboration), “Nucleon-Gold Collisions at 200 AGeV Using Tagged d+Au Interactions in PHOBOS”, arXiv:1505.06766

[8] E. Achenauer et al., “eRD12 Progress Report - Status Update on Polarimeter, Luminosity Monitor and low Q^2-Tagger for Electron Beam”, Dec. 30, 2014. `https://wiki.bnl.gov/conferences/images/2/24/ERD12_report.pdf`

[9] L. Zheng, E.C. Aschenauer, J.H. Lee, “Determination of electron-nucleus collision geometry with forward neutrons”, Eur. Phys. J. **A50** (2014) 189.

[10] M.D. Baker, “Measuring primordial k_T (the) EIC”, EIC International Users Meeting, Stony Brook, NY June 24–27, 2014, `http://skipper.physics.sunysb.edu/~abhay/2014/EICUM/Talks/06262014-PM//3_Baker.pdf`
M.D. Baker, “Can we distinguish between primordial k_T and parton showers?”, EIC Task Force meeting, BNL, Sept. 13, 2012, `https://wiki.bnl.gov/eic/index.php/File:2012-09-13-MDB-DistinguishKt.pdf`

[11] V.S. Morozov et al., “MEIC Interaction Region & Tagging”, talk at High Energy Nuclear Physics with Spectator Tagging, Old Dominion University, March 10, 2014. `https://www.jlab.org/indico/getFile.py/access?contribId=16&sessionId=7&resId=0&materialId=slides&confId=91`

[12] F. Dominguez et al., “Universality of unintegrated gluon distributions at small x”, Phys. Rev. **D83** (2011) 105005.

[13] M.R. Adams et al., “Nuclear Decay Following Deep Inelastic Scattering of 470 GeV Muons”, Phys. Rev. Lett. **74** (1995) 5198, Erratum: Phys. Rev. Lett. **80** (1998) 2020.

[14] M.R. Adams et al., “Nuclear shadowing, diffractive scattering and low momentum protons in μXe interactions at 490 GeV”, Z. Phys. **C65** (1995) 225.

[15] L. Frankfurt, M. Strikman, “Hard Nuclear Processes and Microscopic Nuclear Structure”, Phys. Rep. 160 (1988) 235,
T.H. Bauer et al., “The hadronic properties of the photon in high-energy interactions”, Rev. Mod. Phys. **50** (1978) 261, Erratum: Rev. Mod. Phys. **51** (1979) 407

[16] L. Frankfurt, V. Guzey, M. McDermott, M. Strikman, “Nuclear shadowing in deep inelastic scattering on nuclei: leading twist versus eikonal approaches”, JHEP 02 (2002) 027.

[17] M.R. Adams et al., "Shadowing in the muon-xenon inelastic scattering cross section at 490 GeV", Phys. Lett. **B287** (1992) 375, M.R. Adams et al., "Saturation of Shadowing at Very Low Bjorken x", Phys. Rev. Lett. **68** (1992) 3266.

[18] M.R. Adams et al., "Perturbative QCD effects observed in 490 GeV deep-inelastic muon scattering", Phys. Rev. **D48** (1993) 5057.

[19] M.D. Baker, "Azimuthal asymmetry and transverse momentum of hadrons in deep inelastic scattering at 490 GeV", PhD Thesis, MIT (1993), FERMILAB-THESIS-1993-57, http://lss.fnal.gov/archive/thesis/1900/fermilab-thesis-1993-57.pdf

[20] http://mdbpads.com

[21] B.B. Back et al. (PHOBOS Collaboration), "Particle multiplicity near mid-rapidity in central Au+Au collisions at $\sqrt{s_{NN}} = 56$ and 130 GeV", Phys. Rev. Lett. **85** (2000) 3100.

[22] https://wiki.bnl.gov/eic/index.php/LEPTO-PHI