# DPMJetHybrid Upgrade: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing / Saturation Regime EIC R& D Project eRD17: Progress Report (January-June 2016) and Proposal

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## 1 Introduction

Our project involves upgrading 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 JLEIC. 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: geometry tagging using forward particles and intrinisic $k_T$ studies using both forward particles and particles from the hard scattering.

Due to funding constraints, the project was split into two phases spanning FY2016 and FY2017. Phase I (2016) involves finalizing the Pythia code and tune used in DPM-JetHybrid, adding a simplified model for multi-nucleon scattering in the nuclear shadowing regime, and a first, quick look at the physics. Phase II (proposed for FY2017) will focus on a more complete model of the multi-nucleon effects due to nuclear shadowing and a more complete study of the physics implications.

The organization of the document is as follows. Section 2 reviews the motivation for the project: enhancing the suite of eA generators to include the effects of multinucleon collisions which must be present in the nuclear shadowing regime (low $x$). This capability is essential for optimizing the forward detectors (in the ion direction) for both eRHIC and JLEIC incarnations of the EIC. Section 3 summarizes the progress of the project from January-June 2016. Section 4 outlines the plan for the remaining part of Phase I from now through the end of Fiscal Year 2016. Section 5 contains the proposal for the completion of eRD17, which would lead to a version of DPMJetHybrid which would contain multinucleon interactions in the nuclear shadowing (low $x$ regime), possible non-trivial color connections between interactions, and would also handle the transition region (modest $x$) where there is some nuclear shadowing, but the coherence length is comparable to the nuclear radius. Finally, Section 6 contains a summary of the progress report and proposal.

# 2 EIC Physics Motivation for the Project

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 for both eRHIC and JLEIC has already started, it is important to have a complete suite of accurate eA event generators as soon as possible.

One example of an important physics topic where multi-nucleon interactions should play a key role is geometry tagging in eA collisions. In particular, we would like to be able to select events with unusually long path length, $d$, in the nucleus after the first collision and/or events with small impact parameter $b$. Preliminary geometry tagging studies without nuclear shadowing effects are already quite encouraging (see Ref. [6] and also Section 3 below). For low $x_{Bj}$, in the nuclear shadowing regime, we would especially like to be able to pick out events with small impact parameter where any parton saturation effects should be enhanced. The multinucleon effects in these events should *enhance* our ability to select "central" events with small impact parameter.

Another 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. [7] 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 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. In general, the DPMJetHybrid upgrade 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 Phase I (FY2016) Achievements through June 2016

The first phase of the project involved several accomplishments so far. First, we implemented some improvements to the program. Second, we tuned Pythia using ZEUS data [8, 9]. Third, we reexamined the ability of DPMJetHybrid to describe the E665 neutron data [10] compared to the original DPMJet code [11]. Fourth we investigated the definition of the variable, $d$, which describes the amount of so-called "cold" nuclear matter seen after the first collision. Fifth, we reexamined the geometry tagging effectiveness using forward neutrons in the standard DPMJetHybrid (which ignores nuclear shadowing). Next, using the standalone Glauber model code TGlauberMC [12], we made the "cross-section map" between the amount of nuclear shadowing in a class of events (for instance a bin in $x, Q^2$) and the effective "dipole" cross-section needed in the eA simulation for that class of events. This is the first step in the code upgrade for DPMJetHybrid to allow multinucleon events. Finally, again using TGlauberMC, we estimated the size of the expected correlation between $\langle N_{coll} \rangle$ and the event variables $b$ and $d$, for a reasonable choice of shadowing ($R = 0.711$). The remaining tasks to be completed in Phase I will be detailed below in Section 4.

## 3.1 Progress on DPMJetHybrid without multi-nucleon effects from nuclear shadowing

The DPMJetHybrid program was upgraded to include the possibility of a double gaussian distribution for intrinsic $k_T$ which should be useful in simultaneously describing ZEUS and EMC forward data.

ZEUS forward proton [8] and neutron data [9] were examined in order to optimize the Pythia parameters for the eventual intrinsic $k_T$ studies. Since the original DPMJet studies [6] had an unusual primary forward neutron distribution, it was also expected that the new tune might be important for the geometry tagging as well. Three different sets of parameters were looked at in DPMJetHybrid: the "default" value (based on HERMES experience and NOT the Pythia default with PARP(91)=2 GeV) and two parameterizations

| Parameter | Meaning | Default EIC tune | Exclusive Tune | Full Range Tune |
|---|---|---|---|---|
| MSTP(94) | Beam-remnant energy partitioning (D=3) | 3 | 2 | 2 |
| PARP(91) | Intrinsic $k_T^{rms}$ (D=2 GeV/c) | 0.4 | 0.24 | 0.11 |
| PARP(97) | power law parameter k for MSTP(94)=2 | — | 6.0 | 6.0 |

Table 1: Pythia 6.4 parameter sets. MSTP(94) controls the energy partitioning in beam remnant cluster decay. The default value of 3 uses the regular fragmentation function, while MSTP(94)=2 uses the function $P(\chi) = (k+1)(1-\chi)^k$ where $\chi$ is the light cone energy fraction taken by the hadron or diquark.

based on two different choices of fit ranges for the ZEUS data. These parameterizations are detailed in Table 1. It should be noted that in all 3 cases, we also use PARP(99)=0.4 (resolved photon $k_T$ D=1.0), MSTJ(12)=1 (no popcorn) and some HERMES-inspired changes: MSTP(19)=1, MSTP(20)=0, PARP(161)=3.0, PARP(162)=24.6, PARP(163)=18.8, PARP(165)= 0.47679, PARP(2)=2.0, CKIN(1)=1.0. All three parameter sets give reasonable primary distributions for the forward neutrons and the geometry tagging results are not significantly different between them, so further discussion of Pythia tunes will be postponed until Phase II when we expect to study intrinsic $k_T$ recoil in detail. Similarly we have postponed the use of the double gaussian fit until Phase II as well.

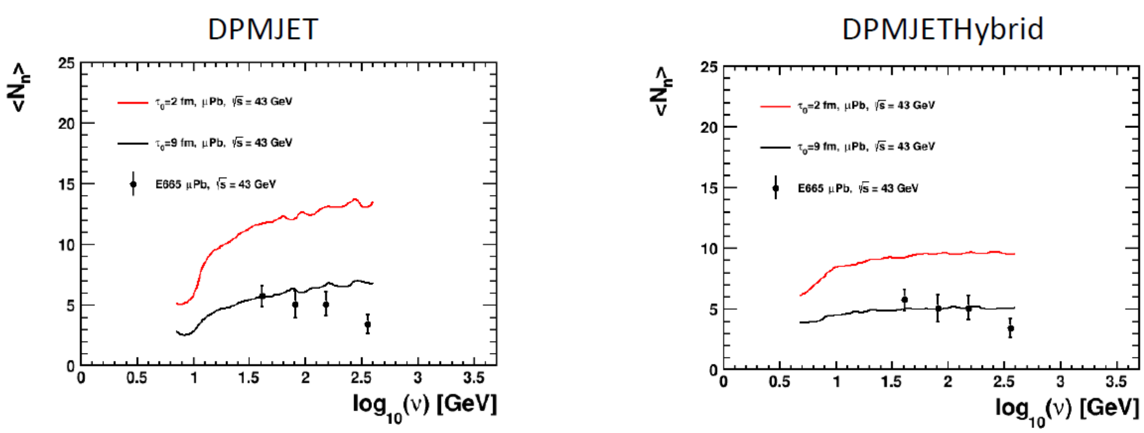
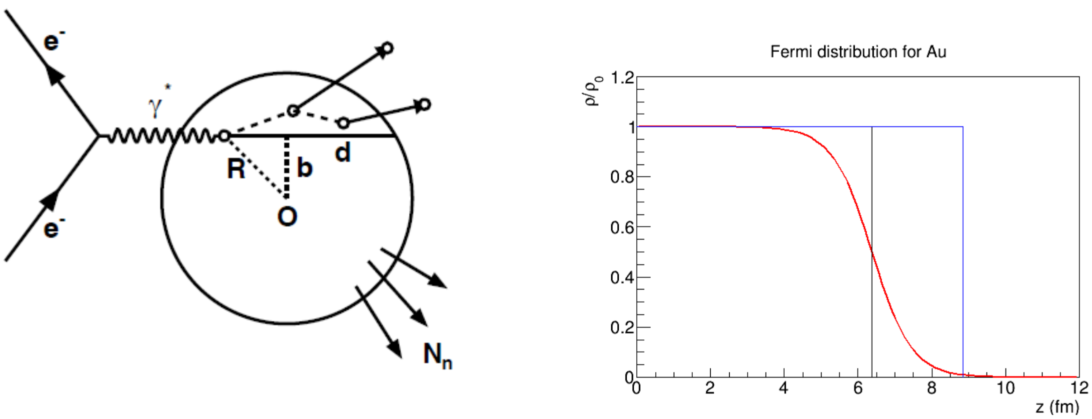



Figure 1: Comparison of E665 (fixed target) soft neutron data adapted from Ref. [10] and two different values of the DPMJET parameter $\tau_0$ for a) DPMJET (adapted from Ref. [6].) and b) DPMJETHybrid.

In order to describe the E665 soft neutron data [10], DPMJetHybrid and DPMJet both need the same intra-nuclear cascade parameter value, $\tau_0 = 9$ fm/c which describes the average formation time of hadrons in their own rest frame during the intranuclear cascade. Figure 1 shows the two cases. DPMJetHybrid does a better job at describing the $\nu$ dependence of the data. This is likely due to the fact that DPMJet is based on

PHOJET [13], which is optimized for real photons, and uses incorrect matrix elements for $Q^2 >\sim 1$ GeV$^2$. This was, in fact, the main motivation for the original development of DPMJetHybrid. Since the higher $\nu$ data also correspond to higher average $Q^2$, DPMJet is not expected to work as well there. So to conclude, DPMJetHybrid has an easier time than DPMJet in describing both ZEUS and E665 data.




(a) Schematic definition of $d$ (b) Fermi density distribution for Au

Figure 2: a) Schematic definition of $d$ taken from Ref. [6] b) Fermi density distribution for Au (red curve), along with two hard sphere approximations: $R_{max} = R = 6.38$fm (black) and $R_{max} = R_{edge} \equiv R + a \ln 100 = 8.844$fm (blue).

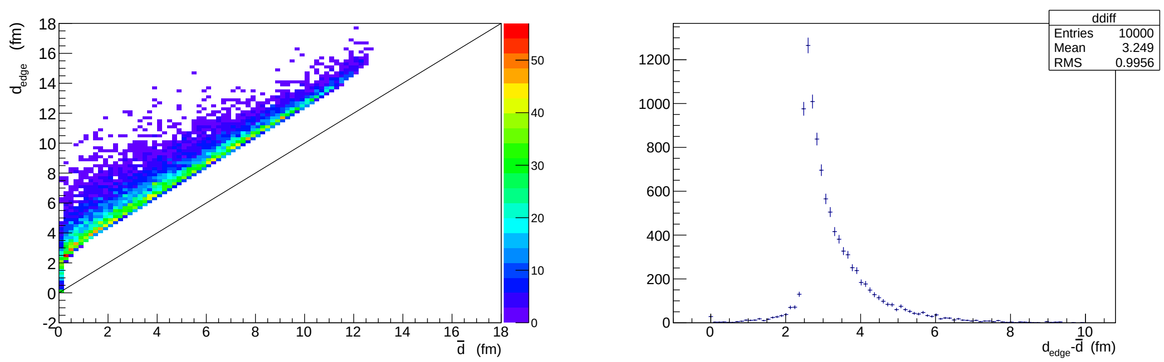
In order to study geometry tagging using DPMJetHybrid, we need to define our terms. Figure 2 illustrates the challenges we face in defining the variable $d$, which is the distance that the forward reaction products travel in the nuclear medium after the (first) collision. Panel a) shows the definition schematically. The difficulty is in defining the outer boundary of the nucleus. Panel b) shows the standard parameterization known alternately as a Woods-Saxon or Fermi density distribution:

$$\rho(r) = \rho_0 \frac{1 + wr^2/R^2}{1 + e^{(r-R)/a}} \tag{1}$$

with parameters for Au of $R = 6.35$ fm, $a = 0.535$ fm, and $w = 0$ [14]. Also shown are two approximations to the distribution, treating the outer edge of the nucleus as a hard sphere which could be used to define the outer boundary. One natural choice is to use $R_{max} = R$, where $R$ is the radius at half-max, but it has the flaw that $\sim 20\%$ of the nuclear material is at $r > R$, so that $\sim 20\%$ of the time, the collision is defined as being *outside* the nucleus. In many cases, this leaves $d_{hs} \equiv \sqrt{R^2 - b^2} - Z_{first}$ complex or negative, forcing it to arbitrarily be set to zero. In Ref. [6] this problem was solved by using $R_{max} = R_{edge} \equiv R + a \ln 100$ which is the radius at $\frac{1}{101}$-max instead of half-max and is actually the edge of the DPMJET "universe". So they define: $d_{edge} \equiv \sqrt{R_{edge}^2 - b^2} - Z_{first}$. In this case only $\sim 0.5\%$ of the collisions occur outside the nucleus, but now we are including a significant amount of relatively empty space as part of $d$. In particular, the average density (over 3 dimensions) for $r < R$ is $0.857\rho_0$ while for $R < r < R_{max}$ it is $0.124\rho_0$. On average, using the $d_{edge}$ definition adds about 3 fm to $d$.

Another way to define $d$ is to count the full-density equivalent distance, which we will notate as $\bar{d}$, so that the amount of material passed through (interaction depth) is $\rho_0\bar{d}$. This means that $d$ is defined as

$$\bar{d} \equiv \int_{Z_{first}}^{\infty} dz \rho(z,b)/\rho_0 = \int_{Z_{first}}^{\infty} dz \frac{1 + w(z^2+b^2)/R^2}{1 + e^{(\sqrt{z^2+b^2}-R)/a}} \tag{2}$$




(a) Comparison of $d_{edge}$ and $\bar{d}$ (b) Difference between $d_{edge}$ and $\bar{d}$

Figure 3: A comparison between the $d_{edge}$ variable, called "$d$" in Ref. [6] and $\bar{d}$ defined in Equation 2.

Figure 3 shows the difference between $d_{edge}$ and $\bar{d}$ first as a 2-dimensional comparison and then as a difference plot. In most cases, the first collision is well inside the high-density part of the nucleus and $d_{edge}$ contains about 2.5–3 fm of nearly empty space at the back of the nucleus, so $d_{edge} - \bar{d}$ peaks in that range. When the first collision happens very early, at the front of the nucleus, you can get instances of even more empty space being counted as part of $d_{edge}$, leading to a tail. This effect is enhanced when the impact parameter, $b$, is relatively high. More than 2% of the events have $d_{edge} - \bar{d} > 6$ fm. From now on, we will focus on $\bar{d}$.

Figure 4 shows the correlation, using DPMJetHybrid, between the geometry variable of interest, $\bar{d}$ and the number of evaporation neutrons. The plot uses the convention that the bin with edges 0–1 on the $x$-axis refers to $N_n^{Evap} = 0$, the bin with edges 1–2 refers to $N_n^{Evap} = 1$, and so on. Two cuts are shown which correspond to the 35% of events with the least activity ("peripheral") and the 2.6% of events with the largest number of evaporation neutrons ("central"). This plot corresponds to the "truth" or an ideal detector. It was already shown that an eRHIC ZDC can measure $N_n^{evap}$ reasonably well [6].

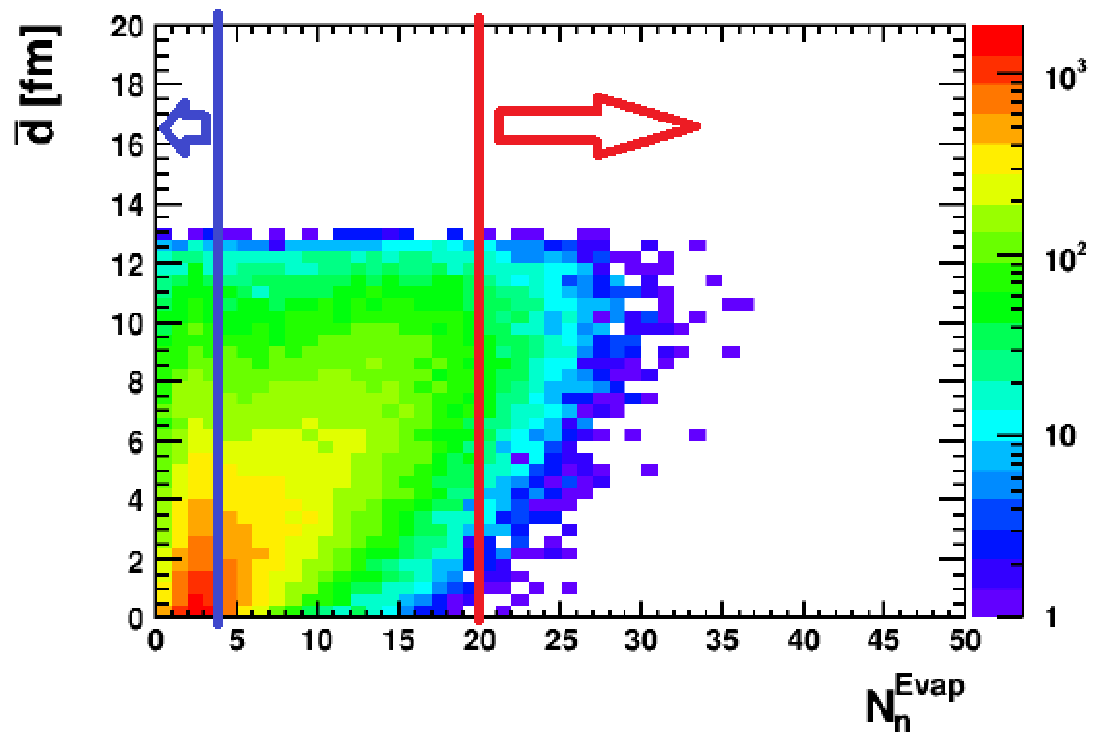
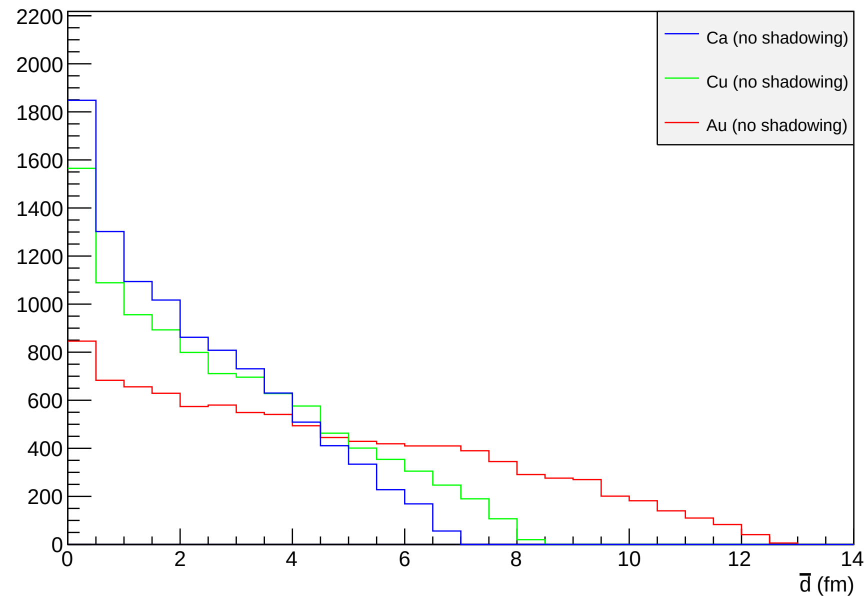
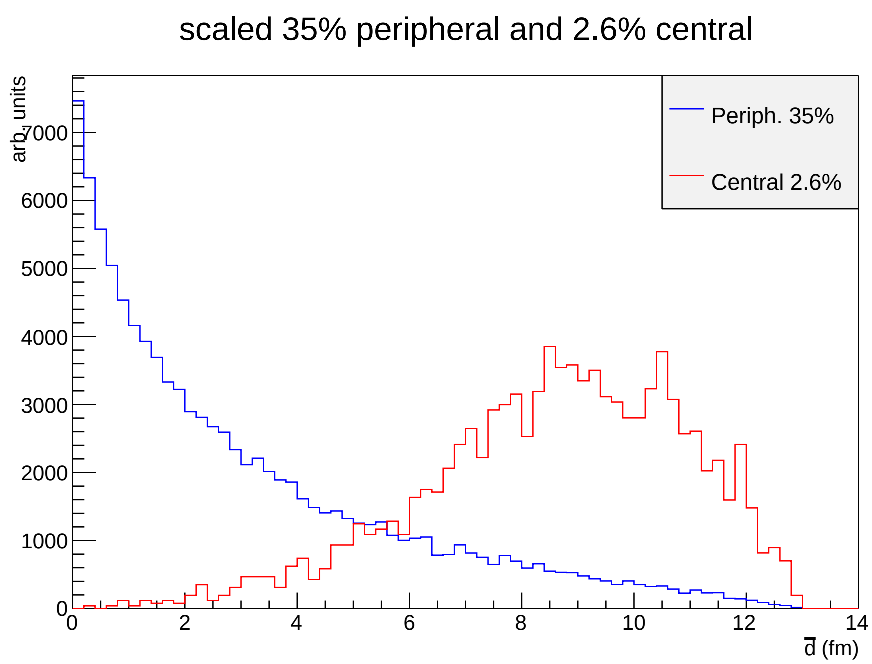



Figure 4: Correlation between the distance parameter $\bar{d}$ and the number of evaporation neutrons $N_n^{Evap}$ using DPMJetHybrid and the parameter set labeled “Exclusive” in Table 1. The events to the left of the blue line ($N_n^{Evap} < 4$) are the 35% most peripheral events while those to the right of the red line ($N_n^{Evap} > 19$) are the 2.6% most central events.




(a) Distribution of $\bar{d}$ for eCa, eCu and eAu




(b) Distribution of $\bar{d}$ for geometry tagged eAu samples

Figure 5: a) The distribution of $\bar{d}$ for three different nuclei using TGlauberMC. b) The distribution of $\bar{d}$ for the 35% most peripheral ($N_n^{Evap} < 4$) and 2.6% most central ($N_n^{Evap} > 19$) geometry tagged data sets based on (ideal) cuts on the number of evaporated neutrons, $N_n^{Evap}$, using DPMJetHybrid. The distributions are scaled to have the same area.

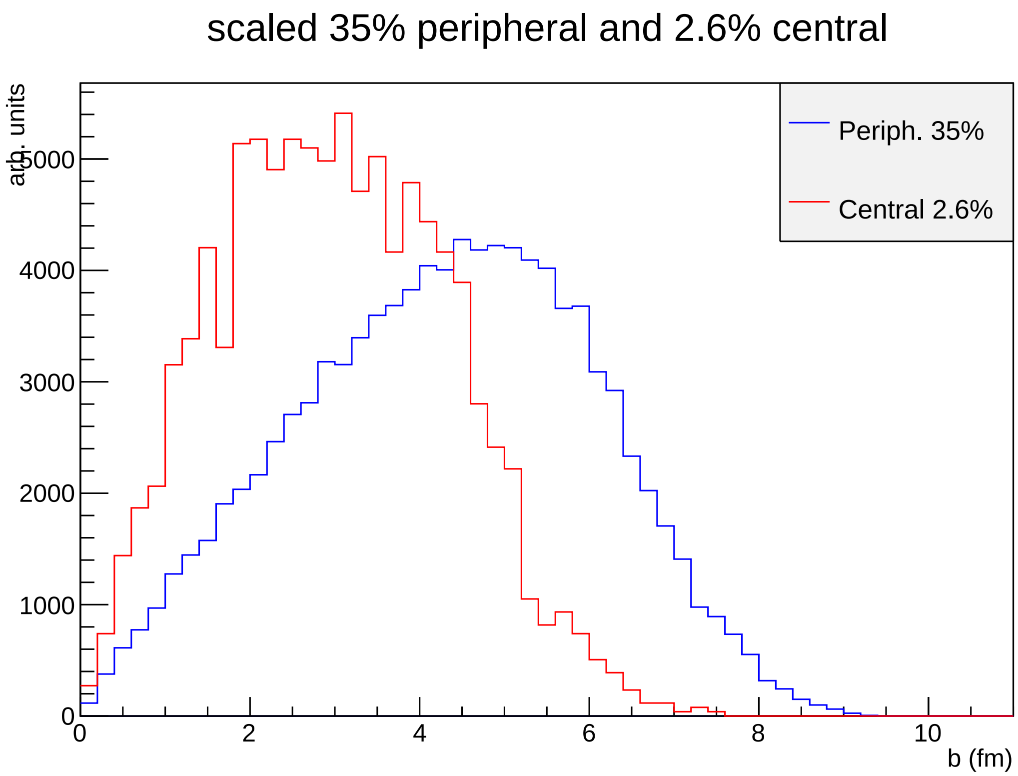



Figure 6: Distribution of $b$ for the 35% most peripheral ($N_n^{Evap} < 4$) and 2.6% most central ($N_n^{Evap} > 19$) geometry tagged data sets based on (ideal) cuts on the number of evaporated neutrons, $N_n^{Evap}$, using DPMJetHybrid. The distributions are scaled to have the same area.

Figure 5 shows the quality of the geometry tagging using evaporation neutrons only and without taking into account nuclear shadowing in the simulation. The minimum bias eCa and eAu data have a significant overlap while the peripheral and central eAu data are much more distinct. It should be noted that the distibution in the number of evaporation neutrons is highly peaked with the peak at $N_n^{Evap} = 2$ and a mean of around 4. Figure 6 shows the impact parameter ($b$) distribution for the peripheral and central eAu sample. The peripheral data sample is about 14× bigger than the central data sample so the distributions in Figure 5b and Figure 6 are scaled to have the same area for easier shape comparison. Clearly geometry tagging is already quite effective, even without multinucleon effects. It will be interesting to see how much the impact parameter resolution can be improved in the case of nuclear shadowing.

### 3.2 Progress on upgrading DPMJetHybrid to include multi-nucleon effects from nuclear shadowing

The plan for Phase I is to implement nuclear shadowing for the case when the virtual photon is fully hadronic with coherence length $\lambda \gg R$. In this case, in the target rest frame, we picture the virtual photon fluctuating into a hadronic state before it interacts with the nucleus. This hadronic state, or generalized dipole, has a cross-section which may vary with $x$ and $Q^2$ and there are many competing theories on the details. We plan to bypass that by making a map between the effective "dipole" or hadronic $\sigma_{\gamma * N}$ and the amount of nuclear shadowing $R^{Au} \equiv \sigma_{\gamma * A}/(A\sigma_{\gamma * N})$. In order to make this map, we used a standalone Glauber model program, TGlauberMC [12], which Baker was one of the original authors of, and which is now used extensively at the LHC and among the theory community [15]. This program has many options including Glauber-Gribov (event-by-event cross-section fluctuations) [16] and nonspherical nuclear shapes. We used the spherical version of Au with a non-fluctuating cross-section for now in order to match the behavior of DPMJetHybrid. The map can then be used in the DPMJETHybrid code to choose the effective "dipole" cross-section for a given $x, Q^2$ bin based on the input eAu cross-section, e.g. from EPS09 [17]. If the hadronic "dipole" state interacts with more than one nucleon in the nucleus, we will treat this as a multinucleon collision.

Figure 7 shows the correlation between the effective hadronic cross-section for the virtual photon on a nucleon and the total cross-section for the virtual photon on a Au nucleus. In particular, the figure shows the shadowing parameter vs. the effective $\sigma_{\gamma * N}$. This figure was created using TGlauberMC under the assumption that the $\gamma *$ interacts strongly — technically, we treat it as a (reduced-cross-section) proton in the code. Figure 8 is just the inverse of Figure 7, zoomed in to the region of interest. In particular, the $x$-axis now refers to the shadowing parameter $R^{Au}$ and the $y$-axis refers to the effective hadronic cross-section for the virtual photon. This is the "shadowing map" which we will use in DPMJETHybrid, allowing us to input a value of $R^{Au}(x, Q^2)$ and output $\sigma_{\gamma * N}(x, Q^2)$. As an example, a typical value for $R^{Au}$ can be inferred from EPS09LO based on the $F_2$ ratio between eAu and eN which is 0.711 for $Q^2 = 1.69$ GeV$^2$ in the limit of very small $x$. The red arrows show the example of reading off the value $\sigma_{\gamma * N} = 5.16$ mb given a shadowing parameter $R^{Au} = 0.711$. It should be noted that in the code, we'll use the actual cross-section ratio $R^{Au}(x, Q^2)$ and not just the $F_2$ ratio, which we use here for illustration purposes.

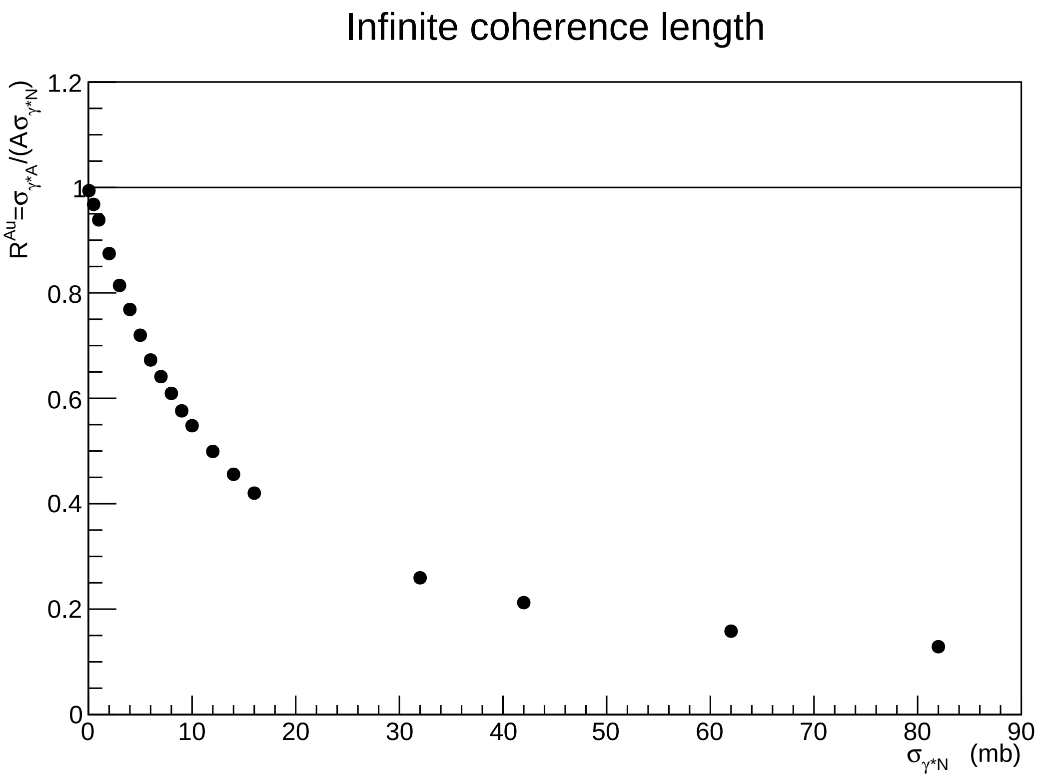



Figure 7: The shadowing parameter $R^{Au} \equiv \sigma_{\gamma*A}/(A\sigma_{\gamma*N})$ as a function $\sigma_{\gamma*N}$ for eAu using TGlauberMC assuming a fully hadronic $\gamma*$ (infinite correlation length). The straight line at 1 represents the case of no nuclear shadowing: $\sigma_{\gamma*A} = A\sigma_{\gamma*N}$.

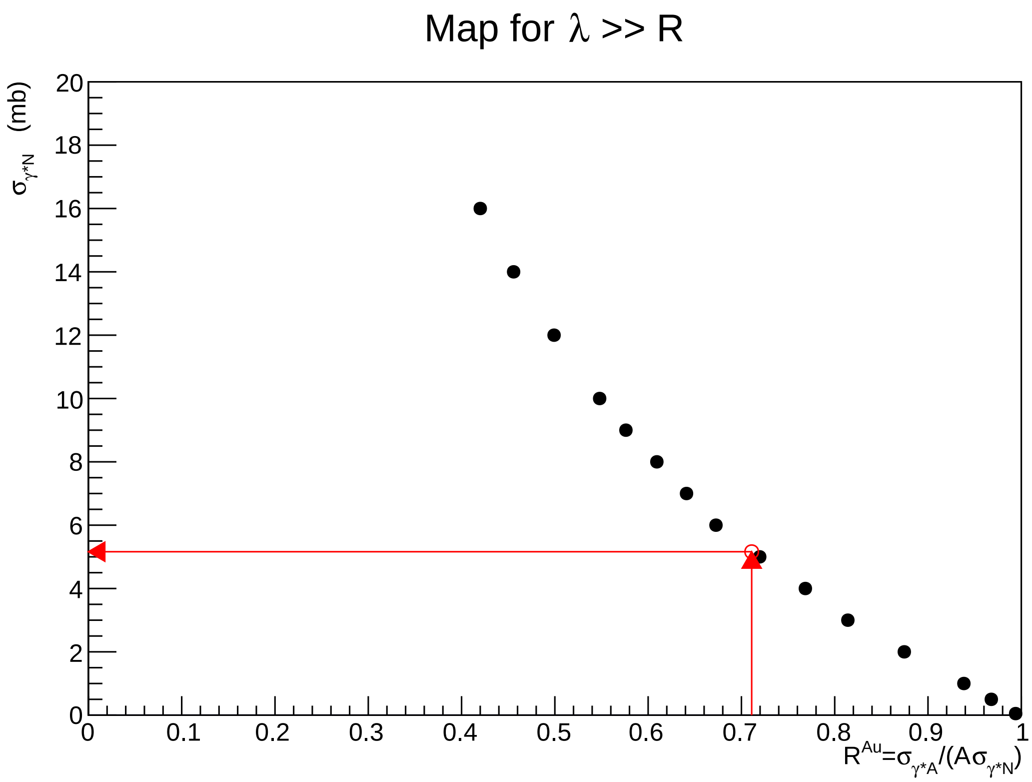
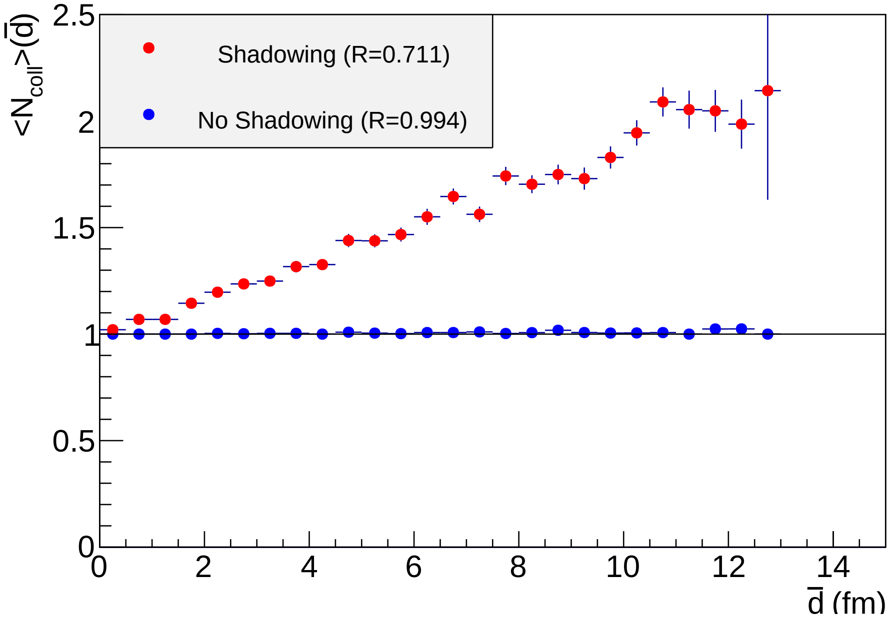
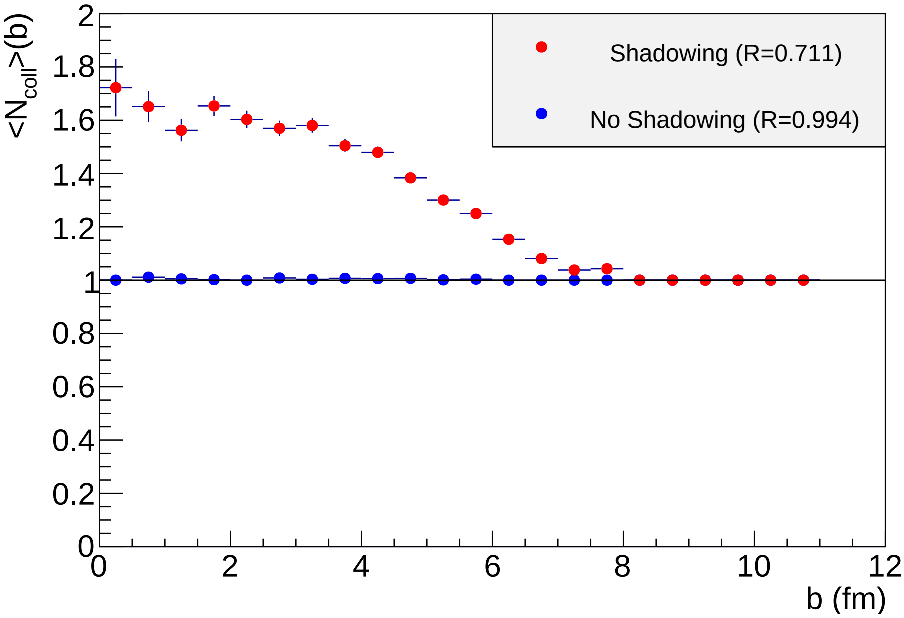



Figure 8: The shadowing map which can be used as a lookup table for the hadronic cross-section for the $\gamma * N$ given the amount of shadowing in an $x, Q^2$ bin. The red arrows show the example of reading off the value $\sigma_{\gamma * N} = 5.16$ mb given a shadowing parameter $R^{Au} = 0.711$.




(a) $\langle N_{coll} \rangle$ vs. $\bar{d}$ for the shadowing and non-shadowing cases




(b) $\langle N_{coll} \rangle$ vs. $b$ for the shadowing and non-shadowing cases

Figure 9: a) The average number of collisions $\langle N_{coll} \rangle$ vs. distance $\bar{d}$ for the shadowing and non-shadowing cases. b) Impact parameter ($b$) dependence of $\langle N_{coll} \rangle$ for shadowing and non-shadowing cases.

We can also use TGlauberMC to estimate the rough impact we can expect of nuclear shadowing in DPMJetHybrid. Figure 9 shows the distance and impact parameter dependence of the number of collisions, based on the $\sigma = 5.16$ mb that we looked up from our shadowing map. In the case of no shadowing ($\sigma = 0.05$ mb), by definition, the number of collisions is always 1, since multiple collisions would imply shadowing. For the shadowing case, we see that the highest $\bar{d}$ interactions involve about 2 nucleons on average, while the central $b = 0$ events involve almost 2 nucleons as well. We expect this to have a significant impact on the physics as each collision will contribute a hole in the nucleus and will also contribute to the intra-nuclear cascading (INC). Both of these effects will enhance the number of evaporation neutrons as well as the number of charged forward tracks in the INC region. And of course, some interactions will have more than 2 struck nucleons further enhancing our ability to pick out truly "central" events.

### 3.3 Manpower

*Include a list of the existing manpower and what approximate fraction each has spent on the project.*

The only funded manpower consists of Baker, who has officially spent 0.10 FTE-year already during the last 6 months, with 0.14 FTE-year total planned for FY2016.

Aschenauer and Lee have participated in meetings and contributed a significant amount of advice. Their main contribution is expected to come in FY2017, though, when physics results are available and we are preparing for publication. Aschenauer will also contribute to the Pythia changes planned for later this fiscal year.

Zheng is a new addition to the project and has contributed a significant amount of effort, about 0.1 FTE-year already in upgrading DPMJetHybrid, running simulations, and making plots.

### 3.4 External Funding

No external funding was obtained for this project in FY2016. Aschenauer, Lee, and Zheng's salaries were provided by their home institutions.

## 4 Planned Activities for the remainder of Phase I (FY2016)

The main activity planned for the remainder of FY2016 is to improve the shadowing map (more points with better precision) and to implement it in DPMJETHybrid. For now, DPMJETHybrid will have two options - shadowing fully on (effectively infinite correlation length) or fully off (pointlike interaction) [1]. For Phase I, another simplification is that we

[1]It should be noted that in the current incarnation of DPMJETHybrid, it is possible for the small point-like $\sigma_{\gamma * N}$ to occasionally result in an interaction with two nucleons when they happen to lie in almost the

will allow only one of the interactions to be a DIS interaction to avoid the complications of non-trivial color connections in Pythia.

Two more improvements are planned for the code. First we plan to use the specific Woods-Saxon distribution parameters for the Au nucleus [12, 14], namely $R_{Au} = 6.38$ fm and $a_{Au} = 0.535$ fm, rather than the generic approximate formula which is currently used. Second, we plan to link to the latest EIC@RHIC Pythia version [18], which is Pythia version 6.4.28 [19] along with some tweaks inspired by HERMES and an improved handling of beam remnant cluster breakup.

Once the code is complete, we plan to examine the impact of the shadowing on geometry tagging and on $k_T$-recoil plots, such as the "seagull" plot $\langle p_T^2 \rangle$ vs. $x_F$.

# 5 Phase II (FY2017) Proposal

The proposed main goal for FY2017 is to complete the DPMJetHybrid upgrade outlined in the original proposal. In particular, we would implement the general case of coherence length $\lambda \sim 1/(2Mx)$ for transition values of $x$ such that $\lambda$ may be comparable to $R$. This will require a map $\sigma_{\gamma*N}(x, R^{Au})$ rather than just $\sigma_{\gamma*N}(R^{Au})$. In addition, we will also need to allow multiple DIS interactions in the final incarnation of the code. We may also include the possibility of event-by-event fluctuations in $\sigma_{\gamma*N}$, known as Glauber-Gribov [16]. Finally, once the code is complete, we propose to study the impact on geometry tagging and on intrinsic $k_T$ recoil studies.

## 5.1 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. 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 [20].

same transverse location within the nucleus, but this is rare.

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 $\sigma_{\gamma*A}/(A\sigma_{\gamma*N})$. We can then take the known (or at least input) values for the parton distribution functions 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 will add the concept of fluctuation length as a function of $x$, so that the dipole lasts for a length $\lambda = 1/(2Mx)$ [20].

It should be noted that the eikonal approximation is known to be flawed in DIS (see e.g. Ref. [21]) 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. [7]) 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 [6], as discussed above, have not included multi-hadron correlations.

## 5.2 Personnel, Timetable and Budget

The timetable of this project covers 12 months from Oct. 1, 2016–Sept. 29, 2017, but the effort, particularly of Baker, will be concentrated in the first half of the fiscal year in finalizing the code. All participants, including Baker, will continue to pursue the physics results and paper writing during the rest of the year. Key milestones are listed below.

**Jan. 27, 2017** DPMJetHybrid upgrade code beta release.

**Mar. 31, 2017** Code release. DPMJETHybrid upgrade complete.

**Sept. 29, 2017** Physics results. 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[22] | 0.14 | $33,000 | |
| J.H. Lee | BNL | 0.05 | $0 | cost covered by BNL |
| L. Zheng | CCNU | 0.10 | $0 | cost covered by CCNU & BNL |
| TOTAL: | | 0.34 | $33,000 | |

Table 2: Personnel Budget Breakdown

### 5.3 Liang Zheng Travel

Liang Zheng, a leading expert on the DPMJetHybrid code, played a key role on this project so far, despite visa restrictions and a sometimes challenging internet connectivity between China and the U.S.. Early in FY2017, the BNL Physics Department (Elke Aschenauer & J.H. Lee) will be hosting Liang Zheng as a visitor for three months in order to collaborate on a variety of issues. The eRD17 project will benefit significantly from this development, at no cost to the project.

It should also be noted that Liang is starting the third year of his postdoc and the level of his future involvement (FY2018–) may depend on the details of his career path and other projects he gets involved in. In summary, FY2017 is the ideal time to finish this project and further delays could be costly. This is identified in Section 6 as a **critical issue**.

## 6 Summary

**What was planned for this reporting period? What was achieved?** As detailed in Section 3, we made significant progress, and expect to complete the main goals of Phase I by the end of the fiscal year.

**What was not achieved, why not, and what will be done to correct?** No major setbacks occured.

**What is planned for the coming months and beyond?** This is detailed in Section 4 and Section 5. We expect to be able to fully complete the project as originally proposed by the end of Fiscal Year 2017.

**How, if at all, is this planning different from the original plan?** The effect of tuning the Pythia parameters to better describe forward primaries was found to be less important than expected to the geometry tagging physics. Further fine-tuning using a double gaussian intrinsic $k_T$ has been postponed from Phase I to Phase II (FY2017), where it may be relevant for detailed studies of $k_T$ recoil.

**What are critical issues?** Liang Zheng, a leading expert on the DPMJetHybrid code, played a key role on this project so far, despite visa restrictions and a sometimes challenging internet connectivity between China and the U.S.. During FY2017, he plans to spend three months at Brookhaven National Laboratory which should allow rapid progress. It should be noted that if the project were further postponed, his involvement in out years (e.g. FY2018) cannot be guaranteed. We should aim to complete this project in FY2016.

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 JLEIC with forward detectors, including geometry 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.

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