Quantifying the glue - understanding the initial conditions at RHIC and the LHC

Matthew A. C. Lamont for the BNL EIC Science Task Force

Brookhaven National Lab, Upton, NY 11777, USA

E-mail: `macl@bnl.gov`

Abstract. Recent results on the suppression of hadrons at forward rapidities from the STAR collaboration indicate that high gluon densities play an important role in the initial conditions of heavy-ion collisions. The study of these initial conditions is therefore crucial in the next stage of understanding and quantifying the data from RHIC and the LHC. The best way to perform these measurements is through Deep Inelastic Scattering measurements on nuclei. Currently, there are no accelerator facilities which are able to perform this measurement. In this paper, I will outline the latest developments of the eRHIC proposal at BNL as well as preliminary designs of a new detector as well as an assessment of the current detectors (PHENIX and STAR) abilities to run in an eRHIC era.

1. Introduction
One of the principal results emanating from the heavy-ion programme at RHIC was of the energy loss of high momentum particles at mid-rapidity ($|y| < 1$), referred to as *jet quenching*. This energy loss, manifested as the absence of a back-to-back peak in azimuthal correlations of high momentum particles separated by $180°$ in azimuth, was only present in the most central (head-on) heavy-ion collisions. In peripheral (large impact parameter) Au+Au collisions and in d+Au collisions, this correlation looked like that observed in p+p collisions. Therefore, the interpretation of this effect was that it was a final-state effect, with the suppression occurring due to final-state interactions of the fast-moving partons in the de-confined medium (Quark-Gluon Plasma) produced in central heavy-ion collisions.

However, recent results from the STAR experiment have taken this one step further. Instead of performing the measurement at mid-rapidity as in the past, the same azimuthal correlation analysis was performed with both particles being at forward rapidity, with the measurement taking place in the forward meson spectrometer (FMS) [1]. The acceptance of the FMS detector is $2.3 < \eta < 4.0$, which means that for this measurement, the particles have $< \eta > \sim 3.1$. This time, the correlations showed a suppression in central d+Au collisions, whereas previously no suppression had been observed in d+Au collisions at mid-rapidity. As a cross-check, this analysis at forward rapidities was also performed in p+p collisions and no suppression was observed. The difference between these two measurements is then simply the value of x (the fractional value of the hadron momentum carried by the interacting parton), given by the relation:

$$x = \frac{2p_T}{\sqrt{s}} e^{-\eta}$$

Therefore, at mid-rapidity, the collision is happening at a much higher value of x than those at forward rapidities.

2. Gluons at small-x

In order to fully understand the momentum distributions of partons inside hadrons as a function of x, it is necessary to perform Deep-Inelastic Scattering (DIS) measurements of electrons on hadrons. These offer a clean probe of the hadron. Whilst hadron-hadron interactions provide a complementary probe, additional colour interactions between the partons make interpreting the phenomena difficult whilst at the same time, they offer no access to the collision kinematics.

DIS measurements on protons were performed at the HERA collider by the H1 and ZEUS collaborations. The invariant cross-section in DIS can be written as:

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[\left(1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$

where y is the fraction of the energy lost by the lepton in the rest frame of the nuclei. F_2 represents the quark and anti-quark structure function and F_L represents that of the gluons. At HERA, the gluon distribution in nucleons was measured indirectly via the scaling violation of the F_2 structure function. By fitting these distributions with a pQCD fit based on the linear DGLAP model, it was found to be dominated by gluons for $x < 10^{-1}$ and increases rapidly with decreasing x [2]. This is believed to occur due to gluon Bremsstrahlung, where large-x gluons radiate smaller-x gluons and was observed to grow more rapidly with increasing Q^2. However, the Froissart Unitarity Bound relation places a limit on the size of the overall cross-section and if this is to be adhered to, then the Bremsstrahlung cannot continue unabated to smaller and smaller x. Therefore, a competing mechanism must tame the growth of the gluon cross-section. One such explanation is that of recombination of gluons, whereby small x gluons can recombine to form higher x gluons depending on the density. As such, at small enough x, the competing processes cancel each other out and there will be a saturation of the gluon densities. These processes are described by the Colour Glass Condensate (CGC) effective field theory and the relevant non-linear JIMWLK equations [3]. A CGC-inspired model is so far the only one able to reproduce the quenching of high p_T azimuthal correlations at forward rapidities in d+Au collisions, giving hints that the onset of saturation in nuclei may be observed at RHIC [4].

3. Gluon distributions in nuclei and the nuclear enhancement factor

As outlined in other presentations at this conference [5], whilst the distribution of sea and valence quarks in nuclei, relative to those in nucleons, are well constrained, very little is known about the gluon distribution for large ranges of x. Therefore, it is desirable to perform DIS experiments on nuclei. Secondly, it is also desirable to perform these experiments in order to search for saturation.

In DIS collisions on nucleons at HERA, the x range was not large enough to explore the saturation regime, which has a characteristic scale associated with it referred to as Q_S. However, simple geometric considerations give Q_S^A as the following:

$$(Q_S^A)^2 \approx c \, Q_0^2 (\frac{A}{x})^{1/3}$$

meaning that Q_S scales with the nuclear size ($A^{1/3}$). This is confirmed by rigorous calculations which increase the dependence on A further for large nuclei. This has a significant impact, meaning that for large nuclei, the effective value of x which is being probed is an order of magnitude and more smaller than in $e+p$ collisions at the same energies.

4. The eRHIC proposal at Brookhaven National Lab

Although DIS experiments on nuclei are desirable for many reasons, there is currently no facility in the World which provides for these collisions. However, there is an ever growing section of the community interested in this and one such proposal is to build an electron-ion collider (EIC), namely eRHIC at Brookhaven National Lab in New York, USA. This proposal will build upon the current complex which houses an ion-ion collider and will build an electron ring to provide both polarised $e+p$ and unpolarised $e+A$ collisions.
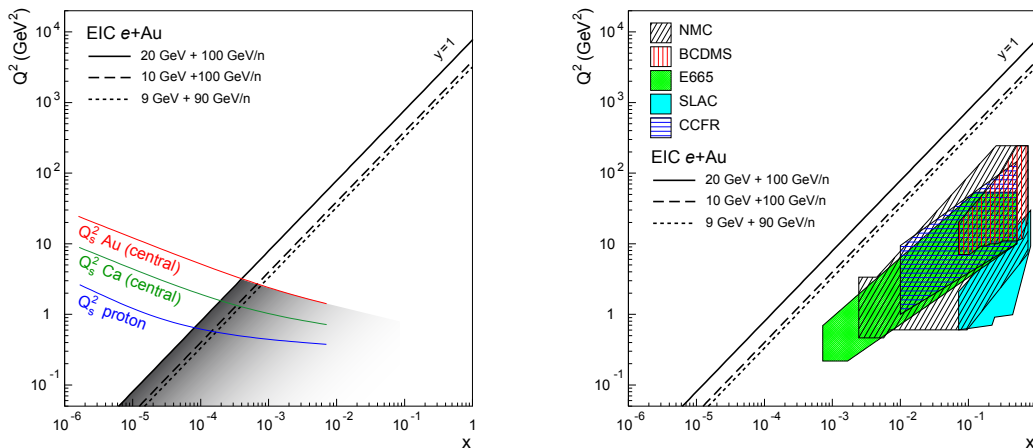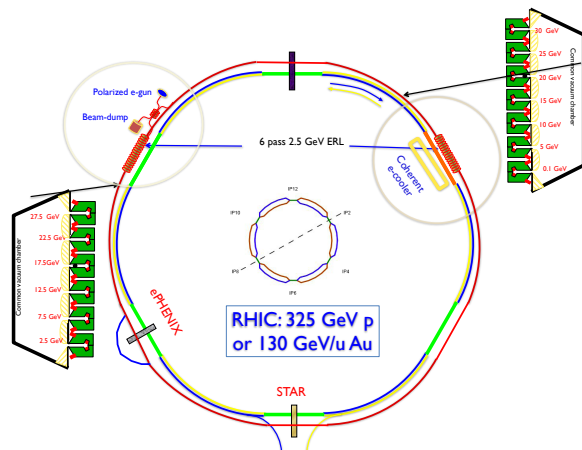

Figure 1. Left: the coverage of the EIC and the projected values of Q_s for different nuclei. Right: the coverage of previous $l+A$ experiments together with that projected for various combinations of EIC energies.

The electron ring will provide energies in the range 5 - 30 GeV and will collide with p (50-325 GeV) and A (5-130 GeV) in the same interaction points as are currently available at RHIC. The x and Q^2 phase-space for various energies are shown in Figure 1, together with the ranges for existing $l+A$ experiments.

A schematic of the eRHIC design is given in Figure 4, which shows that the electron acceleration will occur in two energy recovery linacs and collisions will be possible in either PHENIX, STAR or a new collision point. Whilst eRHIC will be able to run $p+p$ and $e+h$ collisions, it will not be able to do so simultaneously and hence it is a worthwhile exercise to determine whether or not STAR and PHENIX, which were designed specifically for heavy-ion collisions, will be able to run in an eRHIC mode.

The PHENIX experiment has been specifically designed to be a high-rate and low-

Figure 2. The eRHIC complex, comprising two energy recovery linacs for accelerating the electrons and capabilities of providing $e+p/A$ collisions at PHENIX, STAR or a new IP.

acceptance experiment. However, a high-acceptance experiment is optimal in DIS and hence the PHENIX experiment, as it currently stands, would not be optimal for this. The STAR

experiment, on the other hand, is a lower-rate but high-acceptance spectrometer. Additionally, not only is the mid-rapidity region well instrumented, but one of the forward regions has large coverage with electro-magnetic calorimetry. Figure 3 shows the capability of STAR to measure both the outgoing electron and jet produced in the collision respectively, depending on whether or not the hadron beam will be in the anti-clockwise or clockwise direction.
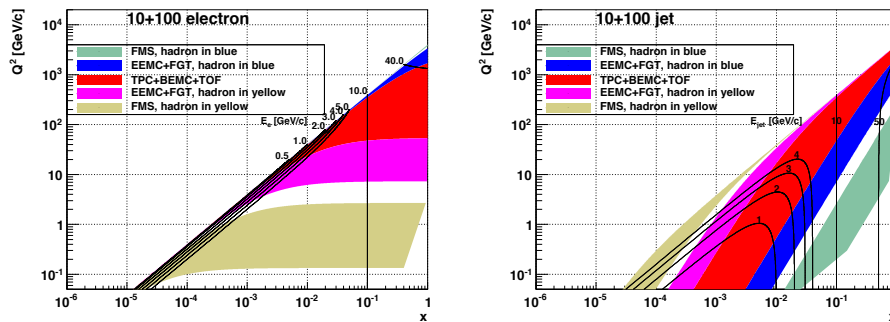

Figure 3. The coverage in x and Q^2 of the different detectors in STAR for 10+100 GeV $e + h$ collisions for measuring the scattered e^- (left) and jet (right) respectively. In each case, the two different options for the hadron beam being in the blue beam pipe (clockwise) or yellow beam pipe (anti-clockwise) are given.

5. A dedicated detector for eRHIC

Despite the large acceptance coverage of STAR, it is desirable to be able to design and build a detector for eRHIC from scratch. For example, the measurement of exclusive vector meson production (which is very sensitive to the gluon distribution) is significantly easier if the struck nucleon/nucleus is measured.

In order to perform this measurement, it is therefore desirable to have as hermetic as possible, detector coverage in the forward region (both tracking and calorimetry) coupled with Roman-Pot type detectors to measure nuclear break-up. A sketch of a proposed detector is shown in Fig 4 which outlines both the detector technology and the magnet design currently under investigation. This is ongoing work and there are many open questions to be resolved (such as is a DIRC necessary or is a barrel time-of-flight detector desirable?).
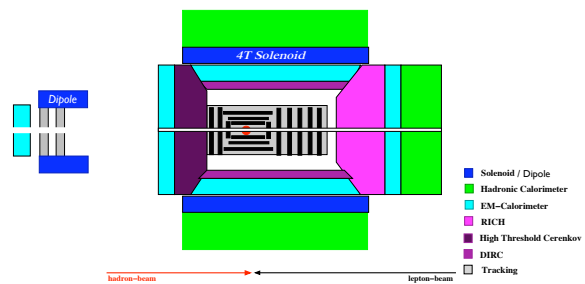
Figure 4. A sketch of a proposed detector for eRHIC.

References
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