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The low-x programme at an electron-ion collider

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One of the important results to come out of the HERA physics programme was the observation of the dominance of gluons at small momenta in the nucleon. In fact, these gluons show an explosion as you go to smaller-x. Due to limits on the cross-section, this explosion must be tamed and a saturation of the gluon occupancy must occur at small-x. This is particularly interesting in the case of heavy-ion physics where many of the interesting processes (jet-quenching, entropy/viscosity ratio) are strongly dependent on the initial conditions and the gluon distributions in regions of x which are relevant to collisions at RHIC and the LHC are unknown theoretically.

In this paper, I will outline the proposed measurements to be made at an Electron-Ion Collider, with particular emphasis of e+A collisions, where the nuclear enhancement factor allows us to explore dense matter at equivalent values of x which are orders of magnitude smaller than is achievable in e+p collisions in the same collider system.

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1. Low-x physics in nucleons at HERA

Through the measurement of the cross-section in Deep-Inelastic Scattering (DIS) $e+p$ collisions at HERA, it was possible to extract the gluon momentum distribution in the nucleon. The invariant cross-section in DIS can be written as:

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

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. As the measurement of F_L directly requires running at different energies, the gluon distribution in nucleons was measured indirectly at HERA, as a function of x, 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 $x < 10^{-1}$, increasing rapidly with decreasing x [1]. This is envisioned as occurring due to gluon Bremsstrahlung, whereby large-x gluons radiate smaller-x gluons and was observed to grow more rapidly with increasing Q^2.

However, the Froissart Unitarity Bound conjecture limits the size of the total cross-section to be proportional to $(ln\ s)^2$. In order to satisfy this condition of unitarity, there must be a mechanism which limits the growth of the gluon distribution at small-x. As gluons are self-interacting, not only are they able to radiate gluons through Bremsstrahlung, they can also recombine. At small enough x, the density of gluons is large enough that the recombination processes are equal in magnitude to the radiation processes and hence a saturation in the gluon density will occur. This scale at which this occurs is known as the saturation scale, Q_s and is inversely proportional to x. This process of recombination is described by the Colour Glass Condensate (CGC) effective field theory [2] and can be described by non-linear pQCD equations, namely the JIMWLK [3] equation. Unfortunately, the experiments at HERA did not go to small-enough values of x to be able to observe the effects of saturation in $e+p$ collisions.

2. Saturation in Nuclei

In order to extend the reach in x in $e+p$ collisions, then one must go to higher energies. The only possibility for this are proposed plans to build an electron accelerator at the LHC at CERN to form an LHeC. However, it is possible to go to smaller effective values of x by studying DIS in nuclei. Due to simple geometric considerations, as well as being inversely proportional to x, the saturation scale, Q_s, is proportional to $A^{1/3}$ [4]. This means that in heavy nuclei such as Pb or Au, it is possible to measure the gluon distributions at a much smaller effective value of x and opens up the possibility of observing saturation effects in nuclear colliders such as RHIC and the LHC.

2.1 Saturation at RHIC

One of the most important results to emanate from RHIC is that of the observation of a suppression of high-p_T particles in azimuthal correlations at mid-rapidity, often referred to as jet quenching. In this analysis, one high-p_T particle is tagged and all particles above a certain p_T threshold are correlated with it azimuthally. In p+p collisions, peaks were found at relative angles ($\Delta\phi$) of 0 and π, indicative of back-to-back jets. These peaks were also observed in peripheral (large impact-parameter) A+A collisions but in central A+A (small impact-parameter) collisions, only the peak at $\Delta\phi = 0$ was observed. This has been interpreted as being due to triggering on a high-p_T particle formed near the edge of the collision medium and the particle at $\Delta\phi = \pi$ losing it's energy in a de-confined medium (or Quark-Gluon Plasma (QGP)). To investigate whether this was an initial-state or final-state effect, the same measurement was performed in d+Au collisions which, whilst still providing for a "nuclear laboratory", are not expected to produce a de-confined medium. Indeed, no such suppression was observed.

Recently, however, a new analysis was performed in d+Au collisions at forward rapidities ($< \eta > \approx 3.1$) utilising the forward meson spectrometer in the STAR experiment. This analysis showed that in peripheral d+Au collisions, the peaks at $\Delta\phi = 0, \pi$ closely resembled those in p+p collisions. However, in central collisions, the peak at $\Delta\phi = \pi$ was significantly broadened and suppressed. Therefore, a suppression was observed at forward rapidities ($x \approx 10^{-4}$) but not at central rapidities ($x \approx 10^{-2}$) [5]. This feature has been reproduced qualitatively in the CGC model, indicating that saturation of gluons is playing a role in this measurement [6].

3. Low-x capabilities at an Electron-Ion Collider

One proposal for an electron-ion collider is to build an electron accelerator at the RHIC complex at BNL to form eRHIC. This would add the capability to accelerate polarised electrons in energies from 5 to 30 GeV to the already demonstrated features of RHIC which allow for the acceleration of polarised protons to energies of 50-250 GeV and heavy-ions to energies of 5-100 GeV/A. Figure 1 shows plots of the range in both x and Q^2 where eRHIC can contribute, compared with previous l+A experiments and the expected values of the saturation scale.

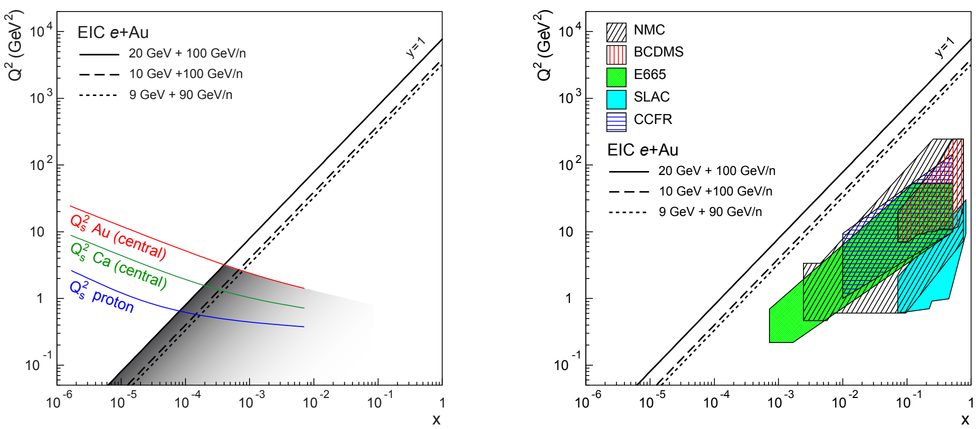

Figure 1: Left: the coverage of the EIC and the projected values of Q_s for different nuclei. RIght: the coverage of previous l+A experiments together with that projected for various combinations of EIC energies.

Therefore, by running at the highest proposed eRHIC energies, DIS measurements in heavy nuclei will, for the first time, make it possible to study gluon-saturation processes.

4. The e+A programme at eRHIC

Four fundamental questions have been identified pertaining to the physics of gluons and nuclei which can be addressed at eRHIC. These are:

- What is the momentum distribution of gluons in nuclei?
- What is the space-time distribution of gluons in nuclei?
- How do fast probes interact with an extended gluonic medium?
- What is the role of colour neutral (Pomeron) excitations in scattering off nuclei?

In the rest of this manuscript, I will elucidate further on the subject of the first bullet.

4.1 What is the momentum distribution of gluons in nuclei?

As well as being used as a tool in the understanding of saturation at low-x, where it has been postulated that, at small x, the physics of saturation is universal in nuclei and nucleons, the distribution of gluons in nuclei in general is an important topic of study. Recent studies of the nuclear parton-distribution functions have shown that although the valence and sea quark distributions are relatively well understood, very little is known about the distribution of gluons over a wide range of x in nuclei [7]. This has important implications in the field of relativistic heavy-ion physics as little is understood about the initial conditions of the colliding nuclei and gluons are the dominant source of many key observables such as heavy-flavour quarks (charm and beauty) and jets. In fact, whilst the distribution at values of x which correspond to mid-rapidity physics at RHIC appears to be in a sweet-spot, for forward-rapidities at RHIC and indeed mid-rapidity at the LHC, there is little, if any, constraint to the theory, as observed in Fig. 2.

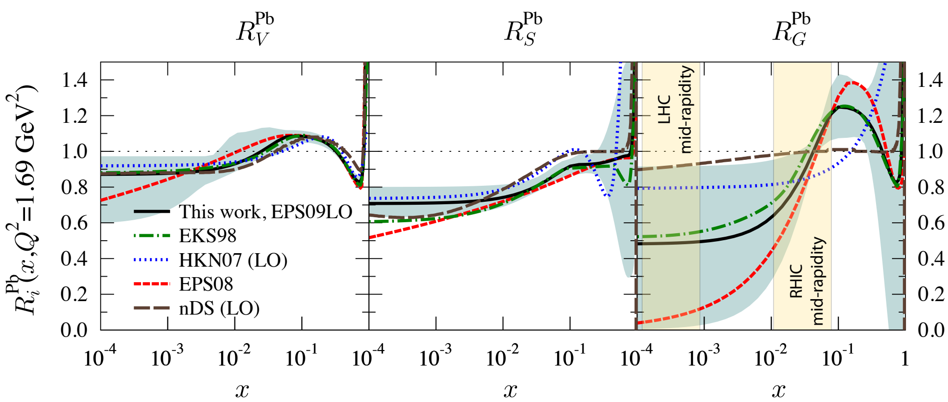

Figure 2: The nuclear PDFs taken as a ratio between Pb and d as a function of x for the valence quarks, sea quarks and gluons. The errors are associated with the EPS09LO fit. The shaded rectangles represent the values of x for mid-rapidity collisions at RHIC and the LHC respectively. Plot taken from ref. [7]

In order to measure the gluon momentum distribution, a number of approaches are valid. Firstly, an indirect calculation is possible via a measurement of the scaling violation of F_2^A. This was shown to be successful at HERA for the case of nucleons. However, one of the successes of RHIC in its present $p+p$ and A+A modes has been its versatility in running at many different energies (from 50-250 GeV for protons and 3-100 GeV/A for Au). This means that it is possible to make a direct measurement of the gluon structure function, F_L^A. However, although it will be possible to make a small-statistics measurement in just 2 years of running ($\approx$ 10 fb^{-1}), as shown in Figure 3 (compiled from estimates for running at 3 different energies). This method is dominated by significant systematic errors which are currently being investigated.

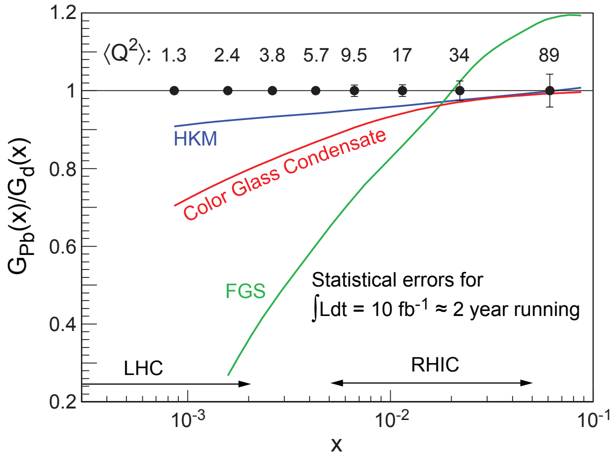

Figure 3: The capabilities for measuring F_L^A at eRHIC with $\approx$ 2 years (10 fb^{-1}) data over 3 different energies.

Together with the direct measurement of F_L^A and indirect measurement via the scaling violation of F_2^A, there remain a number of other tools to extract the gluon distribution. These include 2+1 jet cross-sections (where the +1 refers to the beam remnant jet) and the measurement of diffractive vector meson production. In the case of jets, at small x, gluon processes will dominate over quark processes. The quark contribution can be calculated from the inclusive studies leaving access to the gluon-initiated processes from the jet cross-sections. Diffractive vector meson production is also important as the cross-section is proportional to the square of the gluon distribution. However, one of the difficulties in measuring diffractive events in e+A collisions is measuring the struck nuclei. In $e+p$ collisions, this can be achieved through measuring the struck proton in Roman-Pot type Si detectors in the beam-line. However, in e+A collisions, this is not possible for heavy nuclei as the energy required to kick them out of the beam-line into the detectors will break them up. Therefore, alternative methods are being pursued in order to make this measurement, such as photo-production of J/Ψ mesons. A detailed description of the detector options under consideration at eRHIC was the subject of a separate presentation at this conference [8].

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