Exploring Gluonic Matter with Electron-Ion Collisions

J.H. Lee

Brookhaven National Laboratory, Upton, NY11973, USA

Abstract

Light and heavy nuclei probed in deep inelastic scattering and diffractive processes in the high-energy regime open a new precision window into fundamental questions in QCD. The proposed Electron-Ion Collider (EIC) is a new high-energy and high-luminosity electron-ion machine. The design offers unprecedented access to explore the nature of QCD matter and strong color fields. In particular, the new collider will allow us to reach and explore the regime where the gluon density saturates, one of the fundamental outstanding questions in QCD, and test the validity of the Color Glass Condensate approach. Selected key measurements in electron-ion collisions with an emphasis on probing and characterizing the gluonic matter are discussed.

1. Introduction

Quantum Chromodynamics has established itself as a successful theory of strong interactions, yet the details of the underlying mechanism of the theory have not been fully understood. Despite gluons being the mediator of the strong force and mostly responsible for the visible mass of the universe, their dynamics are far from being completely understood. The difficulty of the theoretical understanding lies mainly in the nature of the self-coupling of gluons, which is conjectured to lead to the phenomenon of parton saturation at small parton momentum fraction (x) theorized as the Color Glass Condensate (CGC) [1]. The non-linear saturated regime, where the increase of the number of gluons through gluon radiation and parton splitting is balanced by multi-gluon fusion between self-interacting gluons, is the state with the maximum occupancy allowed in QCD. There have been strong hints of gluon saturation in high-energy ep, dA, and pp collisions [2, 3, 4, 5]. The dynamic scale Q_s^2 characterizes the onset of saturation for a high density of gluons in the target, and increases as x gets smaller, as shown in Fig. 1. The proposed electron-ion collider (EIC) [6, 7] is designed to explore the nature of QCD matter and strong color fields with a unprecedentedly wide kinematic reach accessing deep into the saturation regime by utilizing the nuclear enhanced saturation scale $(Q_s^A)^2 \approx A^{\frac{1}{3}}(Q_s^p)^2$. The kinematic coverages of the EIC for the planned maximum electron and nucleon energy ranges from 5(e)+100(N) GeV (stage-I) to 30+100 GeV (stage-II) with predicted saturation scales are shown for ep and eA collisions in Fig. 1. Selected key measurements in eA collisions with the EIC, probing and characterizing the gluonic matter, will be discussed. A more detailed description of the physics capabilities and proposed machine designs of the EIC can be found in [8, 9, 10].

2. Key Measurements with the EIC

2.1. Nuclear Structure Functions

The nuclear structure functions $F_2^A(x,Q^2)$ and $F_L^A(x,Q^2)$, which characterize the partonic structure of nuclei, are the most basic observables in *eA*, and they will be one of the first observables at the EIC. F_2 describes the quark and anti-quark momentum distribution, and is sensitive to gluons via scaling violations. The longitudinal structure function F_L is directly proportional to the gluon momentum distribution. The extraction of nuclear F_L requires running at multiple beam energies, which can be accommodated by the flexibility of the EIC. Higher-twist effects [11] in non-linear evolution in x can be realized as variations of the nuclear modification factors of the structure functions defined as $R_{2,L}(x,Q^2) = F_{2,L}^A(x,Q^2)/(AF_{2,L}^p(x,Q^2))$. Various models with different treatments of conventional QCD effects and the expected phenomenology of saturation, have a wide range of predictions for $R_{2,L}(x,Q^2)$. Within the expected precision of the measurements at the EIC, differentiation between the different models is clearly possible in the region $10^{-4} \lesssim x \lesssim 1$. In addition to inclusive DIS measurements for structure functions, nuclear diffractive structure functions $F_{2,L}^D$, which have never been measured in $e+A$, can be also accessed at the EIC. At the EIC energy regime, diffractive processes are expected to share a large (> 30%) fraction of the total cross-section, and nuclear $F_{2,L}^D$ will be a sensitive measurement of saturation [12].

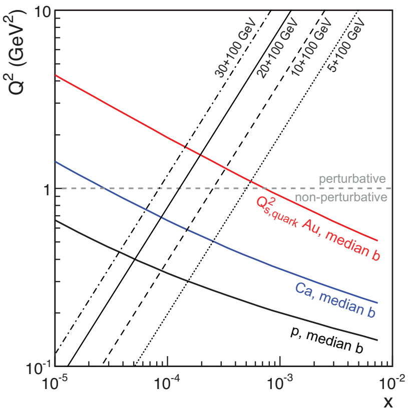

Figure 1: Kinematic coverage in x and Q^2 of the EIC for different beam energies, compared with predictions of the saturation scale, Q_s^2, in p, Ca, and Au.

2.2. *Di-hadron Correlations*

The nonlinear QCD evolution of multi-gluon distributions are expected to be different from that of the single-gluon distribution, and it can be measured through modification of di-hadron correlations [13] in the semi-inclusive DIS process $e+A \rightarrow e' + h_1 + h_2 + X$ dominantly through a photon-gluon fusion process. Saturation physics models allow us to compute the functional form of the multi-gluon distribution as functions of gluon transverse momentum $k_\perp$ and saturation momentum $Q_s^2(x)$. Figure 2 shows the difference in azimuthal angle between a trigger- ($p_T^{trig} > 2$ GeV/c) and associate- ($p_T^{trig} > p_T > 1$ GeV/c) hadrons for theoretical predictions and expected experimental measurements at the EIC. Precise measurements of these di-hadron correlations at the EIC would allow one to extract the spatial multi-gluon correlations in the transverse plane and study their non-linear evolution. Saturation effects in this channel correspond to a progressive disappearance of the back-to-back correlations of hadrons with increasing atomic number A.

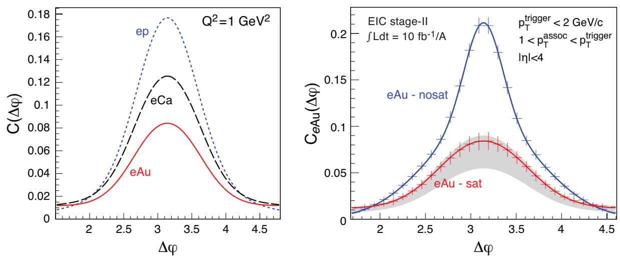

Figure 2: Saturation model [14] prediction of azimuthal angle difference ($\Delta\varphi$) between two hadrons in *ep*, *eCa*, and *eAu* (left), and comparisons with calculations from conventional non-saturated model for *eAu* (right).

2.3. *Exclusive Diffractive Vector Meson Production*

For precise transverse imaging of gluon distributions and how the small-x evolution modifies the transverse distributions, exclusive vector meson production, $e + A \rightarrow e' + V + A'$ where $V = \rho, \phi, J/\psi$ in coherent and incoherent diffractive processes will be studied. The vector mesons are formed from the interaction of a $q\bar{q}$ color dipole fluctuation of the virtual photon with the nucleus. Coherent diffraction, where the nucleus stays intact, probes the space-time distribution of the partons in the nucleus. Incoherent diffractive processes with the excited nucleus breaking up is sensitive to fluctuations of high parton densities at small impact parameter with large momentum transfer in the collision. The impact parameter dependence of the gluon distribution is obtained from the dependence of the squared momentum transfer (t) on the cross-section by Fourier transformation. The EIC allows one to study how this changes with the non-linear QCD evolution towards small x in exclusive diffractive processes. Experimentally coherent processes can be tagged by vetoing on the neutrons emitted by the nuclear breakup of the nucleus in the incoherent diffractive eA collision. Figure 3 shows the $d\sigma/dt$ distribution for J/ψ on the left and ϕ mesons on the right, and they are compared with predictions of saturation and non-saturation models. The curves were generated with the Sartre [9] event generator.

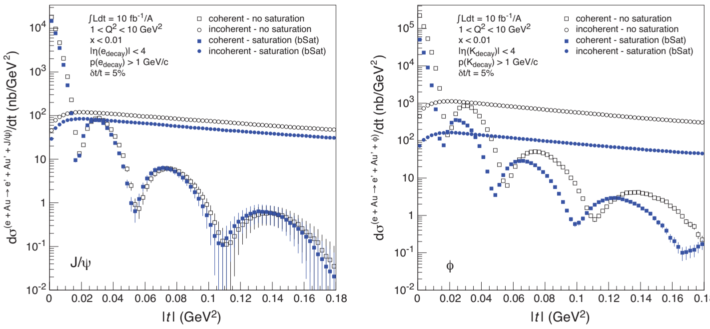

Figure 3: $d\sigma/dt$ distributions for exclusive J/ψ (left) and ϕ (right) production in coherent and incoherent events in diffractive eAu collisions. Predictions from saturation and non-saturation models are shown.

2.4. *Energy loss, Fragmentation at Large x*

The EIC can reveal the nuclear structure throughout the (x, Q^2) plane, from gluon saturation at low-x to the gluon EMC effect and its Q^2 evolution at high-x, which allows the estimation of the nuclear quark and gluon distributions and their uncertainties. The EIC will provide a wide ν $(= \frac{Q^2}{2Mx})$ range, which greatly extend the existing fixed-target measurements [15]. At small ν, studying in-medium hadronization can provide information on the dynamics of confinement: the stages of hadronization and their time scales. At large ν, parton propagation through the medium will allow us to study the energy loss and p_T-broadening of leading partons as well as jet-shape modifications. For the first time, the in-medium hadronization and propagation of heavy quarks can be also studied, and the pQCD description of cold nuclear matter can be tested. The EIC can provide the insight into how colorless hadrons emerge from the quarks and gluons and the dynamics governs color neutralization and hadron formation.

Table 1 shows a summary of the key measurements at the EIC.

to study	measurements	access to	stage-I	stage-II
nuclear wave function; saturation, Q_s	$F_{2,L}$	integrated gluon momentum distribution	gluons at $10^{-3} \lesssim x \lesssim 1$	exploration of saturation regime saturation
nonlinear QCD evolution/universality	di-hadron correlations	k_T-dependent gluons; gluon correlations	onset of saturation; Q_s	nonlinear small-x evolution
nonlinear small-x evolution; saturation dynamics	diffractive process; σ_{diff}, exclusive vector mesons	spatial gluon distributions	moderate x with nuclei Q_s	saturation regime; evolution
parton energy loss, shower mechanism and evolution	large-x SIDIS; jets	transport coefficients in cold matter	light flavors and charm; jets	rare probes and bottom; large-x gluons

Table 1: Key measurements in *eA* collisions at the EIC (stage-I and stage-II) addressing the physics of high gluon densities and dynamics of quarks and gluons in a nucleus.

3. Conclusion

The proposed EIC will be the world's first electron ion collider with high luminosity at high-energy. The versatility of the machine will allow systematic exploration of strong gluon fields in nucleons and nuclei with unprecedented precision and kinematic range and reach/establish a new QCD phase - gluon saturation in *eA* collisions. The physics program of the EIC is geared towards a unified understanding of strongly interacting matter.

References

[1] F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan. Ann. Rev. Nucl. Part. Sci., **60** (2010) 463.
[2] J.L. Albacete *et al.* arXiv:1203.1043.
[3] A. Stasto, B. Xiao, and F. Yuen, arXiv:1109.1817.
[4] P. Tribedy and R. Venugopalan, arXiv:1112.2445.
[5] K. Dusling and R. Venugopalan, arXiv:1201.2658.
[6] A. Deshpande, these proceedings.
[7] C. Marquet, these proceedings.
[8] C. Aidala *et al.* "A Hign Luminosity, High Energy Electron Ion Collider", A white paper prepared for the NSAC LRP 2007.
[9] D. Boer *et al.*, "Gluons and the quark sea at high energies: distributions, polarization, tomography", A report on the joint BNL/INT/Jlab program on the science case for an Electron-Ion Collider, Sept. 13 to Nov. 19 2010, Institute for Nuclear Theory, Seattle, arXiv:1108.1713, 2011.
[10] V.N. Litvinenko *et al.*, "High-energy high-luminosity electron-ion collider eRHIC", arXiv:1109.2819, 2011.
[11] J. Bartels, K. Golec-Biernat, and L. Motyka. Phys. Rev., **D81** (2010) 054017.
[12] M.S. Kugeratski *et al.*, Eur. Phy. J., **C46** (2006) 413.
[13] D. Kharzeev, E. Levin, and L. McLerran. Nucl. Phys., **A748** (2005) 627.
[14] C. Marquet, B. Xiao, and F. Yuan. Phys. Lett., **B682** (2009) 207.
[15] A. Accardi *et al.*, Rivista del Nuovo Cimento, **32** (2009) 439.