Gluon Saturation at the Electron Ion Collider

Renaud Boussarie,[1, *] Tuomas Lappi,[2, 3, †] Björn Schenke,[1, ‡] and Sören Schlichting[4, §]
[1]*Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[2]*Department of Physics, University of Jyväskylä,*
P.O. Box 35, 40014 University of Jyväskylä, Finland
[3]*Helsinki Institute of Physics, P.O. Box 64, 00014 University of Helsinki, Finland*
[4]*Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*

Hadrons and nuclei probed in high-energy scattering experiments feature an increasingly large number of small Bjorken-x gluons that populate its transverse extend, leading to a dense saturated wave function. This phenomenon of gluon saturation is a consequence of unitarity and can be quantitatively described by an effective theory of Quantum Chromo Dynamics (QCD), the Color Glass Condensate [1–3].

Saturation effects are important for all high energy collisions of hadrons and nuclei. They need to be taken into account for understanding particle production and multiparticle correlations in proton-proton and proton-nucleus collisions at the LHC and at RHIC, especially at forward rapidities. For the heavy ion collision program, gluon saturation is the key ingredient of our current theoretical understanding of the production and equilibration process of deconfined quark-gluon plasma in the initial stage of the collision [4, 5].

While experimental data from a large variety of hadronic collision experiments is consistent with the presence of saturation effects, the theoretical interpretation of the experimental signals is always affected by complexities inherent to QCD: hadronization and final state interactions, in particular the whole spacetime evolution of the quark gluon plasma in the case of heavy ion collisions. This situation can only be addressed with a program of high energy deep inelastic scattering on proton and nuclear targets, which give a more direct and precise access to the partonic constituents of protons and nuclei. Such measurements will be performed at the Electron Ion Collider (EIC), to be built at Brookhaven National Laboratory and planned to start operation around 2030 [6]. The EIC will collide polarized electrons with energies up to 18 GeV with polarized protons of up to 275 GeV and heavy ions of up to 100 GeV per nucleon. There is currently an intensive ongoing effort to quantify the detector requirements set by the EIC physics program, setting the goals for a detailed design of the machine and detector. This effort will culminate in an EIC Yellow Report, to be published towards the end 2020 [7].

Gluon saturation will affect many of the different cross sections measured at the EIC. The CGC effective theory framework provides a way to perform a coherent global analysis of different kinds of scattering processes at small x that provide complementary information on the small-x gluons. Specific measurements at the EIC that will shed more light on the physics of gluon saturation include [8–10]:

- Inclusive cross sections for electron-nucleus and electron-proton scattering, parametrized in terms of longitudinal and transverse structure functions, will probe the gluon density in nuclei and protons.
- Total diffractive cross sections and diffractive dijet production have cross sections proportional to the square of the gluon density and are thus particularly sensitive to gluon saturation.
- Exclusive (and diffractive) production of vector mesons, deeply virtual Compton scattering and timelike Compton scattering at small x provide access to the distribution of gluon fields in the transverse coordinate plane of the proton or nucleus, and to the fluctuations in this spatial distribution [11].
- Azimuthal correlations provide access to the combined momentum-, coordinate- and polarization structure of the gluon distributions in the target (linear gluon polarization, transverse momentum distributions, Wigner distributions), which is strongly influenced by gluon saturation [12].

Related measurements have already been performed in earlier DIS experiments at HERA, and are being done in photon-mediated ultraperipheral collisions at the LHC. Compared to HERA, which operated at a roughly comparable center-of-mass energy, the EIC has two crucial advantages in terms of saturation physics. Firstly, it can collide heavy nuclei, which are expected to exhibit saturation phenomena at significantly lower collision energies than protons [13].

---

[*] Electronic address: rboussarie@bnl.gov
[†] Electronic address: tuomas.v.v.lappi@jyu.fi
[‡] Electronic address: bschenke@bnl.gov
[§] Electronic address: sschlichting@physik.uni-bielefeld.de

Secondly, it will have significantly better capabilities for exclusive and diffractive processes, where saturation effects are generically larger than in inclusive reactions. This is due to both the luminosity that is three orders of magnitude greater than at HERA, and to forward instrumentation designed with a higher emphasis on diffractive and exclusive physics. Ultraperipheral collisions at the LHC give access to higher photon-target collisions energies than the EIC. Unlike DIS experiments they are, however, restricted to only quasi-real-photons, which significantly restricts the access to hard processes that would probe the perturbative partonic structure. Also the necessity of triggering on photon-mediated events that are relatively rare compared to hadronic ones limits the kind of processes that can be accessed (making e.g. inclusive photon-nucleus scattering difficult). The active program of ultraperipheral collisions at the LHC is therefore complementary to the EIC.

This Snowmass contribution will discuss the processes in e+p and e+A collisions most sensitive to gluon saturation effects and multigluon correlations, and perspectives for measuring them at the EIC. Besides advancing our fundamental understanding of QCD many-body structure of hadronic bound states, the improved understanding of gluon saturation via experiments at the EIC can be expected to have a significant impact on future computations of a variety of processes in high-energy hadron collisions (p+p, p+A and A+A) at present and future colliders, as well as in the development of cosmic ray showers.

---

[1] E. Iancu and R. Venugopalan, *The Color glass condensate and high-energy scattering in QCD*, pp. 249–3363. 3, 2003. `arXiv:hep-ph/0303204`.

[2] H. Weigert, *Evolution at small x(bj): The Color glass condensate*, *Prog. Part. Nucl. Phys.* **55** (2005) 461 [`arXiv:hep-ph/0501087`].

[3] F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, *The Color Glass Condensate*, *Ann. Rev. Nucl. Part. Sci.* **60** (2010) 463 [`arXiv:1002.0333 [hep-ph]`].

[4] F. Gelis and B. Schenke, *Initial State Quantum Fluctuations in the Little Bang*, *Ann. Rev. Nucl. Part. Sci.* **66** (2016) 73 [`arXiv:1604.00335 [hep-ph]`].

[5] J. Berges, M. P. Heller, A. Mazeliauskas and R. Venugopalan, *Thermalization in QCD: theoretical approaches, phenomenological applications, and interdisciplinary connections*, `arXiv:2005.12299 [hep-th]`.

[6] Press release Jan 9th, 2020: U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility. `https://www.bnl.gov/newsroom/news.php?a=116996`.

[7] EIC Yellow Report homepage. `http://www.eicug.org/web/content/yellow-report-initiative`.

[8] D. Boer *et. al.*, *Gluons and the quark sea at high energies: Distributions, polarization, tomography*, `arXiv:1108.1713 [nucl-th]`.

[9] A. Accardi *et. al.*, *Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all*, *Eur. Phys. J. A* **52** (2016) 268 [`arXiv:1212.1701 [nucl-ex]`].

[10] E. Aschenauer, S. Fazio, J. Lee, H. Mäntysaari, B. Page, B. Schenke, T. Ullrich, R. Venugopalan and P. Zurita, *The electron–ion collider: assessing the energy dependence of key measurements*, *Rept. Prog. Phys.* **82** (2019) 024301 [`arXiv:1708.01527 [nucl-ex]`].

[11] S. R. Klein and H. Mäntysaari, *Imaging the nucleus with high-energy photons*, *Nature Rev. Phys.* **1** (2019) 662 [`arXiv:1910.10858 [hep-ex]`].

[12] E. Petreska, *TMD gluon distributions at small x in the CGC theory*, *Int. J. Mod. Phys. E* **27** (2018) 1830003 [`arXiv:1804.04981 [hep-ph]`].

[13] H. Kowalski, T. Lappi and R. Venugopalan, *Nuclear enhancement of universal dynamics of high parton densities*, *Phys. Rev. Lett.* **100** (2008) 022303 [`arXiv:0705.3047 [hep-ph]`].