

# The physics of the EIC

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**Abstract.** In this presentation I will give brief overview of the main physics topics which will be explored at the new Deep Inelastic Scattering facility, the Electron Ion Collider (EIC), planned for the construction at Brookhaven National Laboratory in the United States.

## 1 Introduction

Deep Inelastic Scattering allows for a very precise exploration of the complex structure of the protons and nuclei using lepton beams. Seminal DIS experiments by the SLAC-MIT group [1] in the late 60's, lead to the discovery of the partons, which are constituents of nucleons. Since then many DIS experiments have been performed, including ones with nuclear targets, or with beam polarization. While many experiments have used fixed target, so far the only collider DIS experiment, HERA in Hamburg, Germany, accelerated both electrons(or positrons) and protons. Thanks to this design, HERA collider was able to achieve high center-of-mass energies, and thus probe a very interesting domain of small Bjorken  $x$ , previously unexplored by fixed target experiments. A major discovery of ZEUS and H1 experiments at HERA collider was the first observation of the strong rise of the proton structure function towards small  $x$  [2, 3]. This important effect is now understood as being due to the strong rise of the underlying gluon density in the proton, which is driven by the non-abelian gluon splitting. In addition to the structure function measurement and possibility of the extraction of the parton distribution functions, HERA provided many unique results, like observation of diffraction in DIS, strong coupling measurement, physics with jets and heavy flavors, exclusive processes, to name the few. Its results, particularly on the structure function and constraints on the PDFs, provide an important input for the description of the plethora of processes at the Large Hadron Collider (LHC). Therefore the electron-proton collisions provide complementary information to proton-proton and electron-electron collisions, and it is of vital importance to perform these various experiments in order to gain complete understanding of the strong and electro-weak interactions. New facilities need to be built with more capabilities, such as polarized beams and with possibilities to accelerate various nuclei, to explore in more details the fundamental aspects of Nature: the structure of nucleons and nuclei.

The Electron Ion Collider (EIC) is a future DIS facility that will be built at Brookhaven National Laboratory [4, 5]. This unique facility will be based on the existing RHIC complex, which will be upgraded and additional electron ring will be added. It is a partnership project between BNL and Jefferson Laboratory. EIC will have unique capabilities that will allow to

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extend and complement HERA and previous fixed target experiments. The projected luminosity will be between  $10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . The machine will have variable center of mass energies, between 20 GeV and 140 GeV, and perform collisions of electrons with protons and wide range of nuclei, from deuteron to uranium. It will have highly polarized electron ( $\sim 70\%$ ) and proton ( $\sim 70\%$ ) beams, with a possibility of polarization for light ions as well. The beams will be collided in up to two interaction regions.

In the comprehensive Yellow Report [5], which describes the physics case and the detector requirements for the EIC, the following key science questions were listed:

- *How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?*
- *How are partons inside the nucleon distributed in both momentum and position space?*
- *How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?*
- *How does a dense nuclear environment affect the dynamics of quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to gluonic matter or a gluonic phase with universal properties in all nuclei and even in nucleons?*

In the following I will give brief summary of different physics topics and main processes that can be studied at the EIC, which will allow to explore the above-mentioned science questions.

## 2 Global structure of nuclei

One of the main measurements that can be performed in DIS with very high precision is that of the structure functions of nuclei. While the proton structure function has been relatively well explored, thanks to fixed target experiments and HERA, much less is known about the nuclear structure. EIC will be able to perform very precise measurements of the reduced cross section for a wide range of nuclei and in a wide kinematic range of  $x$  and  $Q^2$ . The unique advantage of the EIC is that structure functions of proton, deuteron and other nuclei, up to the uranium, will be measured at one facility, thus allowing for a substantial reduction of uncertainties. Thanks to the large luminosity the statistical uncertainties will be mostly negligible, except for very high  $x$  and  $Q^2$ . The projected systematic uncertainties will be at most few %. The structure function measurement will allow for the extraction of the nuclear parton distribution functions, and for study of their modification with respect to the proton parton distribution functions. Usually this is studied using the nuclear ratio, that is taking the nuclear parton distribution function and dividing it by the proton parton distribution functions, normalized by the mass number of the respective nucleus. The deviation of this ratio from unity is an indication of the nuclear effects. EIC will allow for better constraints on the nuclear parton distribution ratio in a wide range of  $Q^2$  and  $x$ . The information from the measurement of the inclusive cross section can be complemented by the precise measurement of the charm structure function in nuclei. Since charm is produced in DIS mainly through the photon-gluon fusion process, this measurement will allow for additional tighter constraints on the nuclear gluon distribution function. The unpolarized cross section in DIS depends on two structure functions  $F_2$  and  $F_L$ . The  $F_2$  structure function dominates the reduced cross section, particularly at small values of inelasticity  $y$ . The longitudinal structure function  $F_L$  can provide additional information on the gluon density. Its measurement is challenging, since it requires running at various energies. EIC is in a unique position to measure  $F_L$  in

nuclei with precision, due to its variable beam energies and high luminosity across the wide range of center of mass energies.

## 2.1 Parton saturation

As mentioned above, at low  $x$ , the dominant role is played by gluons, which are responsible for the increase of the cross sections with energy and for the multi-particle production at high energies. QCD predicts that this rise, driven by the splitting of the gluons, must be tamed due to the competing mechanism of the gluon recombination, once sufficiently dense system is created. This region of the dense gluon fields is the gluon saturation. The boundary between the region of the dense and dilute gluon density is given by the saturation scale which is dynamically generated energy dependent scale. Parton saturation can be also obtained in the scattering off nuclei, as the projectile can interact coherently at large energies with many nucleons, hence probing effectively very dense system of gluons. The saturation scale roughly depends on the  $x$  as well as the mass number as  $Q_s^2(x) \sim x^{-\lambda} A^{1/3}$ , with the power  $\lambda \simeq 0.3$ . The effective theory of QCD at high energy and density is the Color Glass condensate (CGC).

EIC will offer unique opportunity to test the onset of parton saturation in nuclei. Sensitive measurements include the inclusive structure function  $F_L$ , where the deviation from the linear evolution can lead to the differences of the order of 20% (for heavy nuclei). Another sensitive process is the production of di-hadrons and measurement of the angular decorrelations between them. Calculations based from the CGC predict suppression of the correlation peak in  $eA$  with respect to the  $ep$  case. The width of the azimuthal correlation peak is direct measure of the saturation scale. Similar measurements can be performed using dijets in  $eA$  and  $ep$ . Further observables include correlations of dihadrons and dijets in diffraction or other probes like photon+jet.

## 3 Tomography of protons and nuclei

Inclusive structure function measurements and subsequent extraction of the parton distribution functions, provides information about the distribution of partons in longitudinal momentum fractions at a given value of the hard scale, usually provided by the virtuality of the exchanged photon in DIS. These distributions do not however provide information about the transverse momenta or the spatial structure of the constituent partons in the proton or nucleus. The most general object that contains in principle such information is the so-called Wigner function, which depends on the transverse momentum, impact parameter and longitudinal momentum fraction of the proton carried by the parton. It can be regarded as the quantum-mechanical analogs of the classical phase-space distributions. When integrated over the impact parameter, it reduces to the transverse momentum dependent distributions (TMDs), on the other hand when integrated over the transverse momentum, it corresponds to the generalized parton distribution function (GPDs). A large part of the scientific program at the EIC is devoted to the extraction of the TMDs and GPDs and subsequent mapping of the 3-dimensional structure of hadrons—the tomography of protons and nuclei.

The main process through which transverse momentum dependent distributions (TMDs) can be measured in electron-proton scattering is the semi-inclusive deep inelastic scattering, where at least one hadron is detected in addition to the scattered lepton. Other processes that can be used in DIS to extract TMDs can include di-hadron production, and jets. For the GPD measurements, which contain information about the spatial distribution of partons in the proton or nucleus, exclusive processes can be used. The Deeply Virtual Compton scattering (DVCS) serves as a unique process which is sensitive to the quark distribution, and

the exclusive vector meson production can provide complementary information on the gluon distribution. By measuring momentum transfer dependence of these processes one can extract the spatial profile of the quark and gluon densities, through the Fourier transform from the momentum to impact parameter space. EIC thanks to the dedicated forward instrumentation, which includes B0 spectrometers, off-momentum detectors, Roman Pots and ZDC will be able to measure precisely the differential cross sections for these processes as a function of the momentum transfer in a wide range of this variable.

Exclusive diffractive vector meson production in the scattering with nuclei provides excellent opportunity for mapping spatial distribution in the nucleus. For this case, it is essential to separate the coherent process, where the nucleus stays intact and the incoherent process, when the nucleus breaks up. These two processes have very different dependence on the momentum transfer  $t$ . The coherent production exhibits characteristic dips, whose position is sensitive to the modeling of the dynamics of the gluon distribution, and can offer probe to the saturation effects. The incoherent production, dominant at large  $|t|$ , provides information about the lumpiness of the source, or the fluctuations in the density profile. Thus both processes are very interesting, and need to be experimentally well separated. There are further prospects for this process at the EIC, with deuterons and light ions. In such processes one can study nuclear shadowing in a more controlled environment, possibly have sensitivity to double and triple scattering. In addition the spectator tagging on a deuteron allows to study the short range correlations in the nucleus and the role of gluons.

## 4 Spin of the nucleon

Spin is fundamental property of elementary particles, and it is known that all particles carry integer or half-integer spin. Understanding the origin of the nucleon spin in terms of the contributions from quark and gluons is a major goal of particle and nuclear physics. The seminal result from the EMC experiment at CERN [6] in the late 80's, which performed polarized muon-proton collisions, was that only a small fraction of the proton spin is carried by the spin of the quarks. Thus proton spin cannot be naively explained within the static picture and it is an emergent property stemming from the intrinsic properties of quarks and gluons and interactions between them. One can perform in QCD the decomposition of the proton spin into three distinct contributions stemming from the quark spin, gluon spin as well as the quark and gluon orbital angular momenta. EIC will extend the kinematic range in  $(x, Q^2)$  by 1-2 orders of magnitude for polarized measurements. It will offer precision measurements of the  $g_1$  structure function, provide information about the gluon contribution to the proton spin, quark contribution. Also accessible will be the constraints on the strange contributions, and with polarized deuterons there is possibility for the measurement of the  $g_1$  in a neutron.

For example the measurements of the structure function  $g_1$ , could be performed down to values of  $x \sim 10^{-4}$ , greatly reducing uncertainties in this region. Such precise measurements down to small  $x$  will allow for the extraction of the quark contribution. Precise measurements of  $g_1$  scaling violations can provide a handle on the gluon contribution. Once these contributions are known, they can be used to constrain the orbital angular momentum contribution to the proton spin. Even the measurements at the lowest center-of-mass energy for EIC,  $\sqrt{s} = 45$  GeV, will help to dramatically reduce the uncertainties on these different contributions to the proton spin, while adding the measurements at higher energy will constrain them even further more.

## 5 Diffraction

At HERA  $ep$  collider it was observed that about  $\sim 10\%$  of events were diffractive, see for example [7, 8]. That means, that in these events one observed the presence of the wide rapidity gap–region in the detector where there were no particles–, which separated the elastically scattered proton (or its low mass excitation) and the rest of the event. The theoretical description of such process is a challenge, since in order for the rapidity gap to be present, there needs to be some sort of color neutralization in the event. One approach is to describe this process in terms of the colorless exchange, usually referred to as the Pomeron for a leading contribution. Therefore there is a fundamental question as to what is the nature of this colorless exchange. Diffraction is connected to many other interesting problems in QCD, like confinement and parton saturation. It is also related to the effect of the nuclear shadowing. For sufficiently high values of the photon virtuality  $Q^2$  diffraction can be described using the collinear factorization theorem, which allows for the separation of the perturbatively calculable partonic cross sections and the non-perturbative or a long distance part. The non-perturbative part of this process can be parametrized using the diffractive parton distribution functions (DPDFs). At HERA, DPDFs were measured for the first time in the proton. Through the measurements of the diffraction with nuclear beams at EIC, it will be possible for the very first time to extract the nuclear diffractive parton distribution functions. Various ratios, for example of diffractive in  $eA$  to diffractive in  $ep$  structure functions are particularly sensitive to the modeling, and differ in the models which include the parton saturation. Thus they can offer sensitive probe to the physics of parton saturation.

EIC offers also excellent prospects for the measurement of the diffractive longitudinal structure function  $F_L^D$ . This observable was measured only once at HERA, and unfortunately it was limited by the statistics. Similarly to the inclusive case the diffractive longitudinal structure function measurement requires the runs with variable energy beams, something that EIC will be able to provide. Coupled with the high luminosity, EIC will be able to extract this quantity with good precision. This observable is particularly interesting as it is very sensitive to the diffractive gluon density and possible nonlinear gluon dynamics. Given excellent forward instrumentation of the EIC, it will be possible to extract the four-dimensional diffractive structure function as a function of the momentum transfer  $t$  in a wide range. This offers prospects for the first extraction of the diffractive parton distribution and Pomeron and Reggeon fluxes as a function of the momentum transfer  $t$ . In addition, thanks to the possibility of running at lower energies, EIC can constrain the secondary exchange in the diffractive processes.

## 6 Passage of color charges through cold nuclear matter

In addition to rich physics associated with the probe of the internal structure of nuclei and nucleons through the measurements of the PDFs, TMDs and GPDs, EIC will offer opportunity to study the details of the final state effects. When the virtual photon interacts with the quark in the nucleon or nucleus it transmits large energy to it. The struck quark will hadronize, and how this process occurs is of considerable interest. Depending on the mass number of the nucleus and the energy of the process the hadronization can happen inside or outside the nucleus. The measurements of the various hadrons in  $eA$  and  $ep$  will allow for the test of the modern theories of QCD parton evolution in medium. For example by studying the ratios of the modification of the  $eA$  vs  $ep$  of light and heavy mesons as a function of the fragmentation fraction will allow for the constraints of the space-time picture of the hadronization. One will be able to potentially differentiate between the energy-loss and hadron absorption models.

In addition to hadrons, one can use jets to study the properties of the cold nuclear matter. For example using jets one can elucidate the properties of in-medium parton showers. By studying the nuclear ratios as a function of the transverse momentum, and using different jet cone sizes, one can separate the initial and final state effects.

Apart from the inclusive production of light hadrons and jets, one can use heavy flavors to study the role of the heavy quark mass role and its effects on the transport through the nuclear matter.

## 7 Conclusions

The Electron Ion Collider project is a high energy, high luminosity, polarized electron-proton and electron-nucleus collider, which will be built at Brookhaven National Laboratory in a partnership between BNL and Jefferson Lab. Given the unique requirements on the variable beam energies, high luminosity, polarization and possibility of various nuclear beams, it will be one of the most challenging and versatile accelerator complexes ever built. EIC will be a precision tool which will be able to address the most profound questions in QCD and provide a unique opportunity for younger generations to advance their carriers in science and technology.

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