Physics Opportunity with an Electron-Ion Collider

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Abstract. Understanding the emergence of nucleons and nuclei and their interactions from the properties and dynamics of quarks and gluons in Quantum Chromodynamics (QCD) is a fundamental and compelling goal of nuclear science. A high-energy, high-luminosity polarized electron-ion collider (EIC) will be needed to explore and advance many aspects of QCD studies in the gluon dominated regions in nucleon and nuclei. The federal Nuclear Science Advisory Committee unanimously approved a high-energy electro-ion collider to explore a new frontier in physics research. In fact, the committee calls the collider the country's next "highest priority" in new facility construction, and is one of four main recommendations contained in its 2015 Long Range Plan for Nuclear Science. Two proposals for the EIC are being considered in the U.S.: one each at Jefferson Laboratory (JLab) and at Brookhaven National Laboratory (BNL). An overview of the physics opportunities an EIC presents to the nuclear science community in future decades is presented.

1. Introduction

Recently the last missing piece in the current Standard Model was discovered: the Higgs boson. It plays a unique role by explaining why the other elementary particles, except the photon and gluon, are massive. However, this is not the end of the story. The interaction of quarks and gluons in high-energy experiments is well described by the QCD, but an exact understanding of how QCD works under normal conditions found in the every day world is quite limited. Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. However, despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. For instance, it is not yet understood why parton distribution functions, the most prominent quantities that describe the relation between the basic degrees of freedom of QCD and the observable physical states, reveale a large abundance of soft gluons inside the proton at very small x (the fraction of the proton momentum carried by the struck partons).

Past and present experiments have provided critical information to understand how the properties and structure of nuclear matter emerge from the dynamics encoded in QCD, but many open questions still remains:

- How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?
- How do gluon and sea quarks contribute to the nucleon-nucleon force, as manifested in the internal landscape of light nuclei?

- Can one find evidence for saturation of the gluon density?
- How do quarks and gluons propagate in nuclear matter and join together to form hadrons?

These questions can be answered with a powerful new electron ion collider which will provide unprecedented precision and versatility, and whose realization is enabled by recent advances in accelerator technology. The federal Nuclear Science Advisory Committee unanimously approved it as one of the four main recommendations contained in its 2015 Long Range Plan for Nuclear Science [1]. Two options are under study: at Jefferson Lab and at Brookhaven National Lab. The basic scientific requirements for such a facility are:

- Highly polarized ($\sim 70\%$) electron, proton, and light ions (d,^3He) beams
- Ion beams from deuteron to the heaviest nuclei (Uranium or Lead)
- Variable center of mass energies from $\sim$20 - $\sim$100 GeV, upgradable to $\sim$150 GeV
- High collision luminosity $\sim 10^{33-34} cm^{-2} s^{-1}$

The EIC will be unique in colliding polarised electrons off polarised protons and light nuclei, providing the spin degrees of freedom essential to pursue its physics program driven by spin structure, multi-dimensional tomographic images of protons and nuclei, and discovery of the role of collective effects of gluons in nuclei [2]. Such a facility would capitalize on the powerful new experimental techniques for exploring nucleon structure that are being developed nowdays for the 12 GeV JLab program and the RHIC program, and apply them to the low x region where the dynamics is dominated by the gluons. Addressing this kinematic regime with high luminosity and fully polarized beams is necessary to complete our understanding of the basic partonic structure of the nucleon.

2. The Nucleon Structure

Although the nucleon is the only stable hadron in the Standard Model, its structure is not fully understood. Understanding it from first principles is considered a milestone of hadronic physics and numerous experiments are, and will continue to be, devoted to its study.

2.1. The Nucleon Spin

The decomposition of the proton's overall intrinsic spin into quark and gluon contributions remains a fascinating open question. We know that the spin of quarks and antiquarks is only responsible for $\sim$ 30% of the proton spin. We know also, that the latest more precise RHIC results [3] indicate that the gluons' spin contribution in the currently explored kinematic region is non-zero[4]. However, as the partons' total helicity contribution to the proton spin is very sensitive to the minimum momentum fraction x accessible by the experiments, we can not yet assess wether parton spin alone can account for the overall proton spin, or wether additional contributions are needed from the orbital angular momentum of partons. With the unique capability to reach two orders of magnitude lower in x and to span a wider range of momentum transfer Q than previously achieved, with just few month of operation the EIC would be able to precisely quantify how much the intrinsic spin of quarks of various flavors and gluons contribute to the proton spin. This is shown in the two plots of Fig. 1 for the parton helicity distributions (left) and for the gluon helicity contribution versus the quark helicity contribution (right).

2.2. The Three Dimentional Imaging of Quarks and Gluons

In understanding the microscopic structure of the nucleon, we had so far relied mainly on two types of physical quantities: its spatial distribution of charge and current probed through elastic lepton scattering and described by the elastic form factors, and its longitudinal momentum distributions probed through Deep Inelastic Scattering (DIS) experiments and described by the parton distribution functions. Although form factors and parton distribution functions have

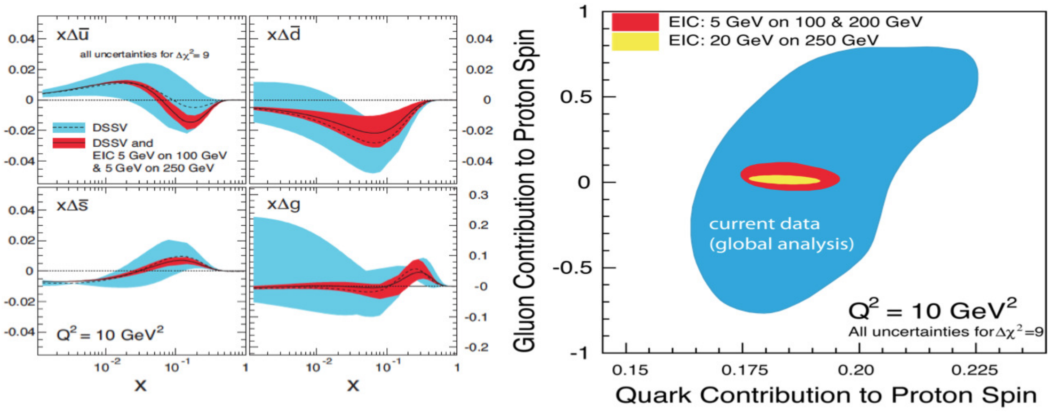

Figure 1. Left: Uncertainty bands on helicity parton distributions, in the first DSSV analysis [5, 6] (light blue bands) and with EIC data (red bands), using projected inclusive and semi-inclusive EIC data sets. Right: Accuracies for the correlated truncated integrals of $\Delta\Sigma$ and Δg over $0.001 \leq x \leq 1$, on the basis of "DSSV+" analysis (outer area) and projected for an EIC (inner area)[7].

provided much to shape our physical picture of the nucleon, they have similar deficiencies. The form factors contain no dynamical information on the constituents, such as their speed and angular momentum, and the momentum distributions provide no knowledge of their spatial locations. To have a unified picture of the nucleon in momentum and space, we have to invoke a new framework provided by the the Wigner distributions [8], a quantum mechanical concept. They have inspired a three-dimensional description of the nucleon through the construction of quantities known as generalized parton distributions (GPDs) and transverse momentum-dependent parton distributions (TMDs). The GPDs encode the correlation between the quark/gluon transverse position in the nucleon and its longitudinal momentum, i.e., hold information how the transverse spatial shape of the nucleon changes when probing quarks with different longitudinal momentum. In other words GPDs can be viewed as form factors distributions at different values of the longitudinal momentum of the quark. They can be measured in exclusive electron-nucleon scattering processes at large Q^2 where a virtual photon interacts with a single quark in the nucleon. The most prominent processes to access GPDs are Deeply Virtual Compton Scattering (DVCS), which has been recognized being the cleanest process. The TMDs arise by integrating the Wigner distributions over the spatial position of the parton and are functions of both the longitudinal momentum fraction x and transverse motion k_T of partons. They offer a momentum tomography of the nucleon complementary to the spatial tomography of GPD. When adding the spin degree of freedom, TMDs may link the parton spin to the parent proton spin and to the transverse motion, and also the parton transverse momentum to the nucleon spin, and are hence related to the orbital motion of partons inside the proton. At leading order there are eight independent TMDs, each one related to different couplings between spin and transverse motion. One of these is the Sivers function which describes the correlation between the momentum direction of the struck parton and the spin of its parent nucleon. As a result, in a transversely polarized nucleon the quark distribution is azimuthally asymmetric in the transverse momentum space. Fig. 2 demonstrates such deformation for the up quark distribution.

Although there has been tremendous progress in understanding TMDs and GPDs, an EIC with its wide kinematical coverage, high polarization and high luminosity will give an unprecedent insight into the three-dimensional description in both momentum and space of quarks, antiquark and gluons. As an exemple of what we can reach with an EIC, in the upper part of Fig. 3 the spacial distribution of sea quarks in an unpolarized proton (left) and in a polarized one (right) obtained from a GPD fit to simulate data for the DVCS cross section and spin asymmetry measurements, is shown. In the bottom part of the same figure, the corresponding density partons in the transverse plane is reported.

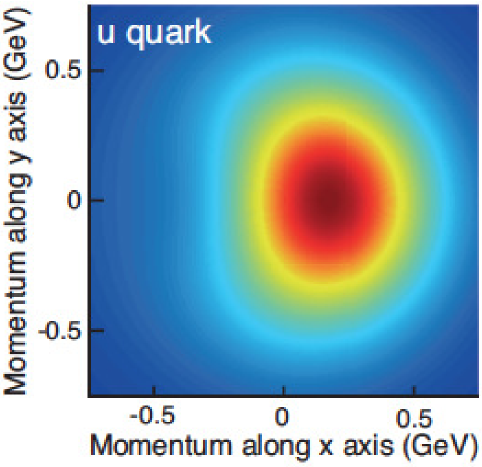

Figure 2. The density in the transverse-momentum plane for unpolarized quarks with $x = 0.1$ in a nucleon polarized along the $\hat{y}$ direction. The anisotropy, due to the proton polarization, is described by the Sivers function.

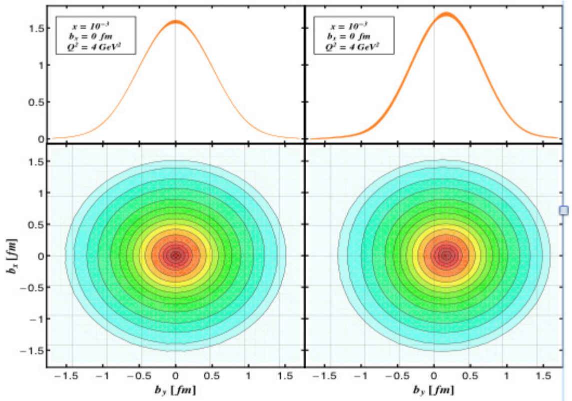

Figure 3. Upper: the spatial distribution of sea quarks in an unpolarized proton (left) and in a proton polarized along the positive x axis (right) obtained from a GPD fit data for the DVCS cross section and spin asymmetry measurements with the EIC. Bottom: The corresponding density of partons in the transverse plane.

3. The nucleus: a laboratory for QCD

3.1. Hadronization and energy loss in cold QCD matter

The experimental program of the EIC is targeted to answer also fundamental questions concerning the dynamics of quarks and gluons in a nuclear environment, such as:

- How do hadrons emerge from quarks and gluons?
- What is nature telling us about confinement?

Semi-inclusive DIS in e+A collisions provides *i)* known and stable nuclear medium; *ii)* well-controlled kinematics of hard scattering; *iii)* final state particles with well-known properties. Thus cold QCD matter could be an excellent femtometer-scale detector of the hadronization process from its controllable interaction with the produced quark (or gluon). With an EIC we will reach unprecedent precision and control on parton kinematics by selecting ν (the virtual photon energy range), and on the length-in-medium by selecting appropriate nuclei. The data will provide essential information for understanding the response of the nuclear medium to a colored fast moving quark. For instance, by measuring pion and D^0 meson production in both $e + p$ and $e + A$ collisions, the EIC will provide the first measurement of the quark mass dependence of the response of nuclear matter to a fast moving quark. The dramatic difference between them, shown in Fig. 4, would be easily discernable at the EIC.

3.2. Gluon saturation

The nucleon structure in the small-x region is dominated by gluons which show a rapid rise with decreasing x. At low x, the large soft-gluon density growth is quenched by the non-linear process of gluon-gluon recombination. This mechanism necessarily generates a dynamic scale known as the saturation scale, Q_s, at which gluon splitting and recombination reach a balance. The existence of such a state of saturated, soft gluon matter, often referred to as the Color Glass Condensate (CGC), is a direct consequence of gluon self-interactions in QCD. It has been conjectured that the CGC has universal properties common to nucleons and all nuclei. HERA, RHIC and LHC have found hints of saturated gluonic matter. The construction of an EIC will allow an exploration of this region in great detail (with luminosities 100x that of HERA). In particular, colliding electrons with a wide variety of nuclei, the saturation region will be more accessible due to the amplification of the saturation scale with nuclear size [9]. By measuring the ratio of diffractive cross-sections over the total DIS cross-sections in both $e + A$ and $e + p$ collisions, as shown in Fig. 5, the EIC would provide the first unambiguous evidence for the novel QCD matter of saturated gluons.

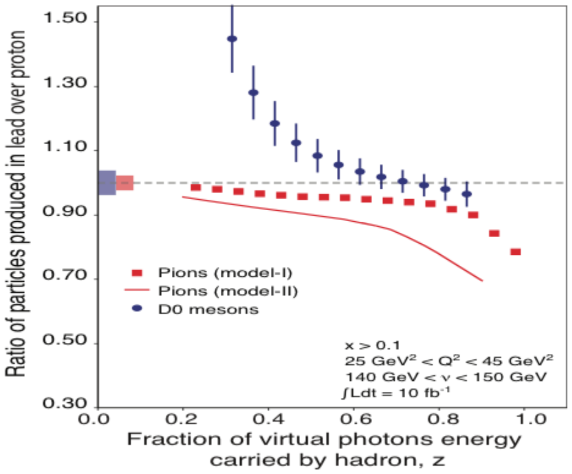

Figure 4. The ratio of π production in $e + Pb$ collisions over that in $e + d$ collisions (red square symbols) is always below unity, while the ratio of heavy meson (D^0) production (blue full circle symbols) can be less than as well as larger than unity due to the difference in hadronization.

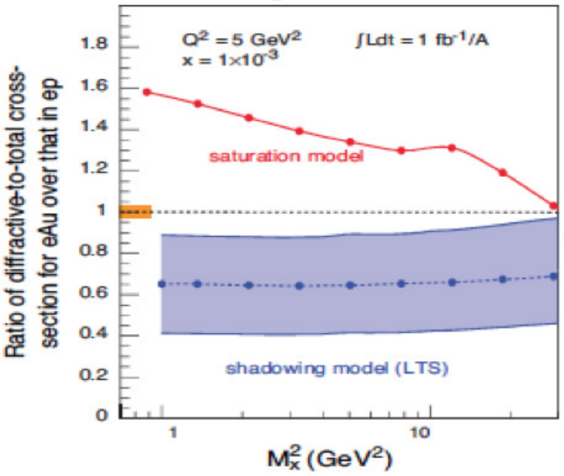

Figure 5. The ratio of diffractive over total cross section for DIS on gold normalized to DIS on proton for different values of mass squared of hadrons produced in the collisions with and without saturation.

4. The EIC Designs and Detectors

Two proposals for the EIC are being considered in the U.S.: one each at JLab (JLEIC) and at BNL (eRHIC) [2]. Both designs use DOEs significant investments in infrastructure. eRHIC is based on the existing Relativistic Heavy Ion Collider (RHIC) hadron facility with its two intersecting superconducting rings, each 3.8 km in circumference (Fig. 6 Left). JLEIC will utilize the 12 GeV CEBAF as an injector to a collider facility. The storage rings would be in a "figure 8" layout to mitigate the effects of depolarizing resonances and facilitate high beam polarization (Fig. 6 Right).

The physics-driven requirements on the EIC accelerator parameters and extreme demands on the kinematic coverage for measurements makes integration of the detector into the accelerator a particularly challenging feature of the design. Driven by the demand for high precision on

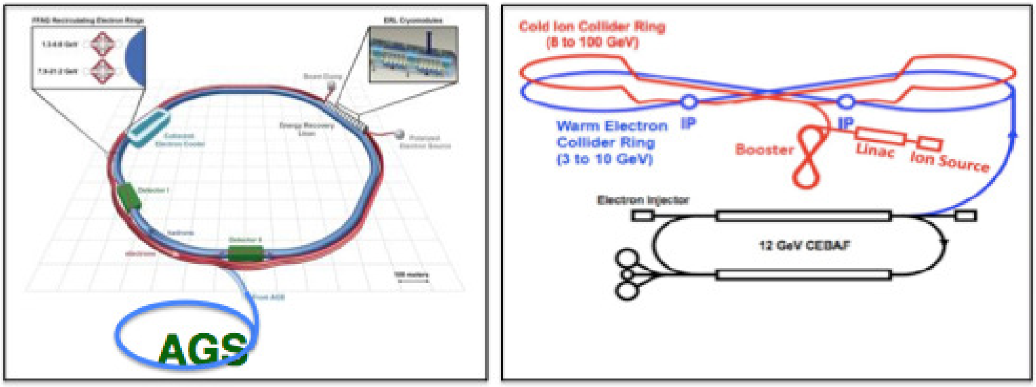

Figure 6. Left: The schematic of eRHIC at BNL, which would require construction of an electron beam facility to collide with the RHIC beam at up to three interaction points. Right: The schematic of JLEIC at JLab, which would require construction of an ion linac, and an electron-ion collider ring with at least two interaction points, around the 12 GeV CEBAF.

particle detection and identification of final state particles in both $e + p$ and $e + A$ programs, R&D efforts are under way on various novel ideas for modern particle detector systems.

5. Conclusions

The EIC is conceived to profoundly impact our understanding of the structure of nucleons and nuclei in terms of quarks, sea quarks and gluons. It will enable the three-dimensional quark-gluon structure of nucleons in yet unexplored regions of phase spaces in QCD with its high luminosity, energy, and beam polarization. Il it will allow also, to study the color neutralization, and to probe the existence of the saturated gluonic matter and to explore it in detail. The EIC promises to unite and extend the scientific programs at CEBAF and RHIC in dramatic and fundamentally important ways, and to propel them to the next QCD frontier. Two designs have been proposed by scientists at RHIC and JLab both capable of delivering a frontier accelerator facility. With the endorsement of the US Nuclear Science Advisory Committee, the US EIC is on track to become a reality in the near future. Its realization will ensure US leadership in nuclear science research.

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References

[1] Aprahamian A *et al* 2015 $http://science.energy.gov/\sim/media/np/nsac/pdf/2015LRP/2015\_LRPNS\_091815.pdf$
[2] Accardi A *et al* 2016 *Eur. Phys. J. A* **52** 268
[3] Adamczyk L *et al* 2015 *Phys. Rev. Lett.* **115** 092002
[4] de Florian D, Sassot R, Stratmann M and Vogelsang W 2014 *Phys. Rev. Lett.* **113** 012001
[5] de Florian D, Sassot R, Stratmann M and Vogelsang W 2008 *Phys. Rev. Lett.* **101** 072001
[6] de Florian D, Sassot R, Stratmann M and Vogelsang W 2009 *Phys. Rev. D* **80** 034030
[7] Aschenauer E C, Sassot R and Stratmann M 2012 *Phys. Rev. D* **86** 054020
[8] Hillery M, O'Connell R, Scully M and Wigner E P, 1984 *Phys. Rept.* **106** 121
[9] Kowalski H and Teaney D 2003 *Phys. Rev. D* **68** 114005