Electron Ion Collider:

The Next QCD Frontier

Executive Summary

Understanding the glue that binds us all

This document is a result of a community wide effort that will be duly acknowledged in the full version of the White Paper

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Contents

Chapter 1

Executive Summary: Exploring the Glue that Binds Us All

1.1 Introduction

Nuclear science is concerned with the origin and structure of the core of the atom, the nucleus and the nucleons (protons and neutrons) within it, which account for essentially all of the mass of the visible universe. A half-century of investigations have revealed that nucleons are themselves composed of more basic constituents called quarks, bound together by the exchange of gluons, and have led to the development of the fundamental theory of strong interactions known as Quantum Chromo-Dynamics (QCD). Understanding these constituent interactions and the emergence of nucleons and nuclei from the properties and dynamics of quarks and gluons in QCD is a fundamental and compelling goal of nuclear science.

QCD attributes the forces among quarks and gluons to their color charge. In contrast to the quantum electromagnetism, where the force carrying photons are electrically neutral, gluons carry color charge. This causes the gluons to interact with each other, generating nearly all the mass of the nucleon and leading to a little-explored regime of matter, where abundant gluons dominate its behavior. Hints of this regime become manifest when nucleons or nuclei collide at nearly the speed of light, as they do in colliders such as HERA, RHIC and LHC. The quantitative study of matter in this new regime requires a new experimental facility: an Electron Ion Collider (EIC).

In the last decade, nuclear physicists have developed new phenomenological tools to enable remarkable tomographic images of the quarks and gluons inside protons and neutrons. These tools will be further developed and utilized to study the valence quark dominated region of the nucleon at the upgraded 12 GeV CEBAF at JLab and COMPASS at CERN. Applying these new tools to study the matter dominated by gluons and sea quarks originating from gluons will require the higher energy of an EIC.

As one increases the energy of the electron-nucleon collision, the process probes regions of progressively higher gluon density. However, the density of gluons inside a nucleon must eventually saturate to avoid untamed growth in the strength of the nucleon-nucleon interaction, which would violate the fundamental principle of unitarity. To date this saturated gluon density regime has not been clearly observed, but an EIC could enable detailed study of this remarkable aspect of matter. This pursuit will be facilitated by electron collisions with heavy nuclei, where coherent contributions from many nucleons effectively amplify the gluon density probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" [1]. It would extend the QCD science programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this *frontier* environment are:

- **How are the sea quarks and gluons, and their spins distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as its spin direction? What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- A collider is needed to provide kinematic reach well into the gluon-dominated regime;

- Electron beams are needed to bring to bear the unmatched precision of the electromagnetic interaction as a probe;

- Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;

- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; d) wide energy variability to enhance the sensitivity to gluon distributions. Realizing these challenging technical improvements will extend U.S. leadership in accelerator science and in nuclear science.

The scientific goals and the machine parameters of the EIC were delineated in deliberations at a community-wide program held at the Institute for Nuclear Theory (INT) [2]. The physics goals were set by identifying critical questions in QCD that remain unanswered despite the significant experimental and theoretical progress made over the past decade. This White Paper is prepared for the broader nuclear science community, and presents a summary of those scientific goals with a brief description of the golden measurements and accelerator and detector technology advances required to achieve them.

1.2 Science Highlights of the Electron Ion Collider

1.2.1 Nucleon Spin and its 3D Structure and Tomography

Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams off nucleons have taught us about how quarks and gluons (collectively called partons) share the momentum of a fast-moving nucleon. They have not, however, resolved the question of how partons share the nucleon's spin, and build up other nucleon intrinsic properties, such as its mass and magnetic moment. The earlier studies were limited to providing the longitudinal momentum distribution of quarks and gluons, a one-dimensional view of nucleon structure. The EIC is designed to yield a much greater insight into the nucleon structure (Fig. 1.1, from left to right), by facilitating multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavor.

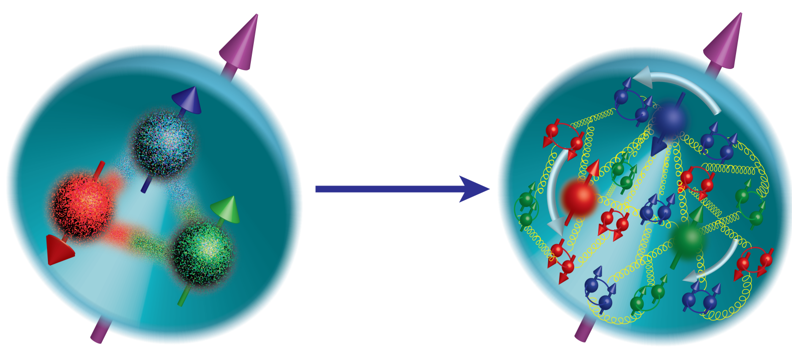

Figure 1.1: Evolution of our understanding of the nucleon spin structure. **Left:** in the 1980s, it was naively explained by the alignment of the spins of its constituent quarks. **Right:** current picture where valence quarks, sea quarks and gluons, and their possible orbital motion are expected to contribute.

The 12 GeV upgrade of CEBAF at JLab will start on such studies in the kinematic region of the valence quarks, and a similar program will be carried out by COMPASS at CERN. However, these programs will be dramatically extended at the EIC to explore the role of the gluons and sea quarks in determining the hadron structure and properties. This will resolve crucial questions, such as whether a substantial "missing" portion of nucleon spin resides in the gluons. By providing high-energy probes of partons transverse momenta, the EIC should also illuminate the role of their orbital motion contributing to nucleon spin.

The Spin and Flavor Structure of the Nucleon:
An intensive and worldwide experimental program over the past two decades has shown that the spin of quarks and antiquarks is only responsible for $\sim 30\%$ of the proton spin, while recent RHIC results indicate that the gluons' spin contribution in the currently explored kinematic region is non-zero, but not yet sufficient to account for the missing 70%. The partons total helicity contribution to the proton spin is very sensitive to their minimum momentum fraction x accessible by the experiments. 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, the EIC would offer the most powerful tool to precisely quantify how the spin of gluons and that of quarks of various flavors contribute to the protons spin. The EIC would realize this by colliding longitudinally polarized electrons and nucleons, with both inclusive and semi-inclusive DIS measurements. In the former, only the scattered electron is detected, while in the latter, an additional hadron created in the collisions is to be detected and identified.

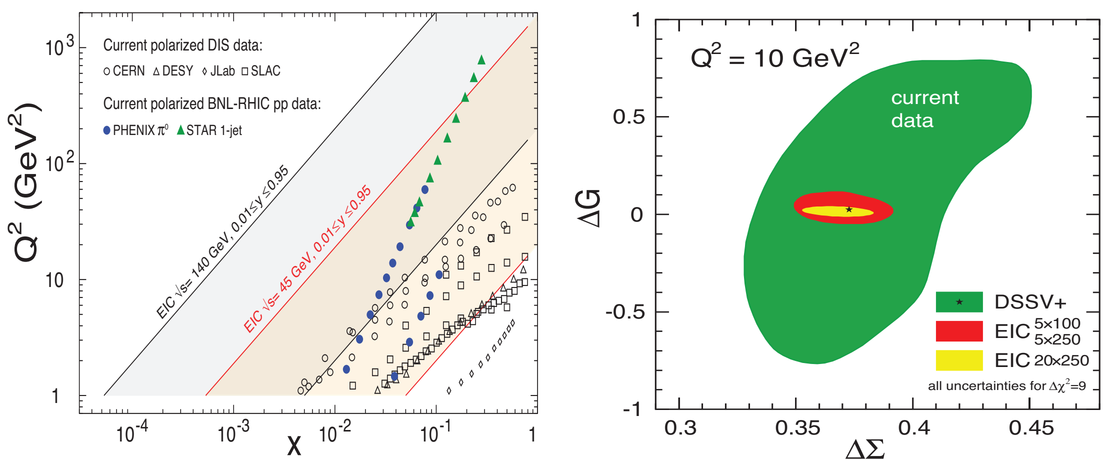

Figure 1.2: **Left:** The range in parton momentum fraction x vs. the square of the transferred momentum by the electron to the proton Q^2 accessible with the EIC in e-p collisions at two different center-of-mass energies, compared to existing data. **Right:** The projected reduction in the uncertainties of the gluon's helicity contribution ΔG vs. the quark helicity contribution $\Delta\Sigma$ to the proton spin from the region of parton momentum fractions $x > 0.001$, that would be achieved by the EIC for different center-of-mass energies.

Figure 1.2 (Right) shows the reduction in uncertainties of the contributions to the nucleon spin from the spin of the gluons, quarks and antiquarks, evaluated in the x range from 0.001 to 1.0. This would be achieved by the EIC in its early stage of operation. At the later stage, the kinematic range could be further extended down to $x \sim 0.0001$ reducing significantly the uncertainty on the contributions from the unmeasured small-x region. While the central values of the helicity contributions in Fig. 1.2 are derived from existing data, they could change as new data become available in the low x region. The uncertainties calculated here are based on the state-of-the art theoretical treatment of all available world data related to the nucleon spin puzzle. Clearly, the EIC will make a huge impact on our knowledge of these quantities, unmatched by any other existing or anticipated facility. The reduced uncertainties would definitively resolve the question of whether parton spin preferences alone can account for the overall proton spin, or whether additional contributions are needed from the orbital angular momentum of partons in the nucleon.

The Confined Motion of Partons inside the Nucleon:
The semi-inclusive DIS (SIDIS) measurements have two natural momentum scales: the large momentum transfer from the electron beam needed to achieve the desired spatial resolution, and the momentum of the produced hadrons perpendicular to the direction of the momentum transfer, which prefers a small value sensitive to the motion of confined partons. Remarkable theoretical advances over the past decade have led to a rigorous framework where information on the confined motion of the partons inside a fast-moving nucleon is matched to transverse momentum dependent parton distributions (TMDs). In particular, TMDs are sensitive to correlations between the motion of partons and their spin, as well as the spin of the parent nucleon. These correlations can arise from spin-orbit coupling among the partons, about which very little is known to date. TMDs thus allow us to investigate the full three-dimensional dynamics of the proton, going well beyond the information about longitudinal momentum contained in conventional parton distributions. With both electron and nucleon beams polarized at collider energies, the EIC will dramatically advance our knowledge of the motion of confined gluons and sea quarks in ways not achievable at any existing or proposed facility.

Figure 1.3 (Left) shows the transverse-momentum distribution of up quarks inside a proton moving in the z direction (out of the page) with its spin polarized in the y direction. The color code indicates the probability of finding the up quarks. The anisotropy in transverse momentum is described by the Sivers distribution function, which is induced by the correlation between the proton's spin direction and the motion of its quarks and gluons. While the figure is based on a preliminary extraction of this distribution from current experimental data, nothing is known about the spin and momentum correlations of the gluons and sea quarks. The achievable statistical precision of the quark Sivers function from the EIC kinematics is also shown in Fig. 1.3 (Right). Currently no data exist for extracting such a picture in the gluon-dominated region in the proton. The EIC would be crucial to initiate and realize such a program.

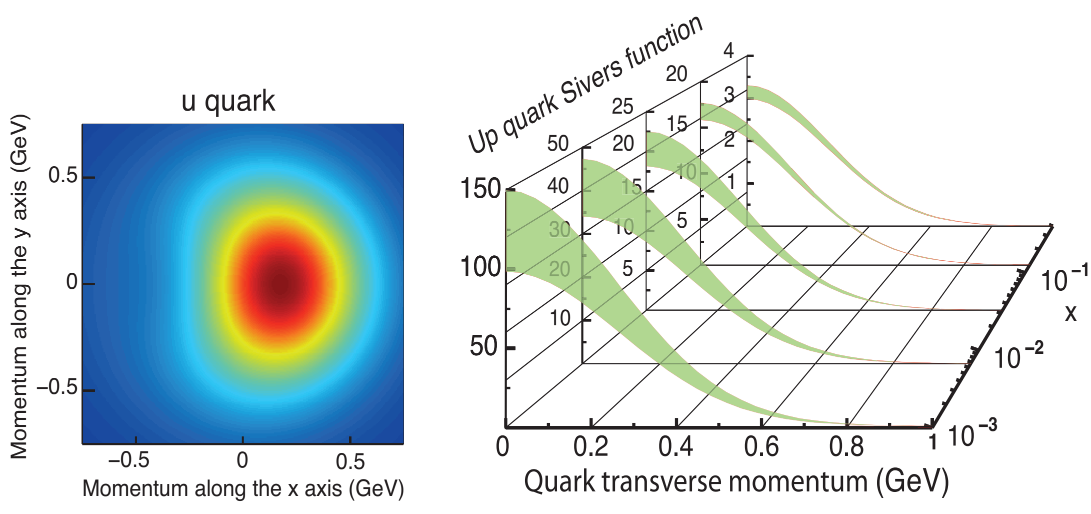

Figure 1.3: **Left:** Transverse-momentum distribution of up quark with longitudinal momentum fraction $x = 0.1$ in a transversely polarized proton moving in the z-direction, while polarized in the y-direction. The color code indicates the probability of finding the up quarks. **Right:** The transverse-momentum profile of the up quark Sivers function at five x values accessible to the EIC, and corresponding statistical uncertainties.

The Tomography of the Nucleon - Spatial Imaging of Gluons and Sea Quarks: By choosing particular final states in electron-proton scattering, the EIC would probe the transverse spatial distribution of sea quarks and gluons in the fast-moving proton as a function of the parton's longitudinal momentum fraction x. This spatial distribution yields a picture of the proton that is complementary to the one obtained from the transverse-momentum distribution of quarks and gluons, revealing aspects of proton structure that are intimately connected with the dynamics of QCD at large distances. With its broad range of collision energies, its high luminosity and nearly hermetic detectors, the EIC could image the proton with unprecedented detail and precision from small to large transverse distances. The accessible parton momentum fractions x extend from a region dominated by sea quarks and gluons to one where valence quarks become important, allowing a connection to the precise images expected from the 12 GeV upgrade at JLab and COMPASS at CERN. This is exemplified in Fig. 1.4, which shows the precision expected for the spatial distribution of gluons as measured in the exclusive process: electron + proton $\to$ electron + J/Ψ + proton.

The tomographic images obtained from cross sections and polarization asymmetries for exclusive processes are encoded in generalized parton distributions (GPDs) that unify the concepts of parton densities and of elastic form factors. They contain detailed information about spin-orbit correlations and the angular momentum carried by partons, including their spin and their orbital motion. The combined kinematic coverage of EIC and of the upgraded CEBAF as well as COMPASS is essential for extracting quark and gluon angular momentum contributions to the proton spin.

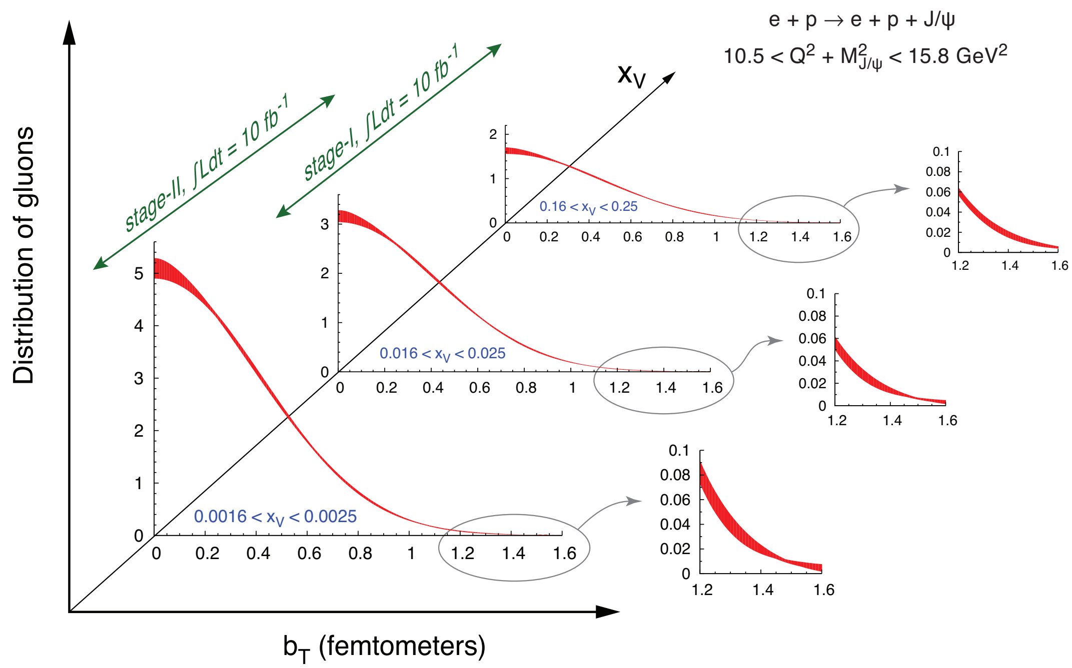

Figure 1.4: Projected precision of the transverse spatial distribution of gluons as obtained from the cross section of exclusive J/Ψ production. It includes statistical uncertainty and systematic uncertainties including that due to extrapolation into the unmeasured region of momentum transfer to the scattered proton. The distance of the gluon from the center of the proton is b_T in femtometers, and the kinematic quantity $x_V = x_B\,(1 + M^2_{J/\Psi}/Q^2)$ determines the gluon's momentum fraction. The collision energies assumed for Stage-I and Stage-II are $E_e = 5, 20$ GeV and $E_p = 100, 250$ GeV, respectively.

1.2.2 The Nucleus, a QCD Laboratory

The nucleus is a QCD "molecule", with a complex structure corresponding to bound states of nucleons. Understanding the emergence of nuclei from QCD is an ultimate long-term goal of nuclear physics. With its wide kinematic reach, as shown in Fig. 1.5 (Left), the capability to probe a variety of nuclei in both inclusive and semi-inclusive DIS measurements, the EIC would be the first experimental facility capable of exploring the internal 3-dimensional sea quark and gluon structure of a fast-moving nucleus. Furthermore, the nucleus itself would be an unprecedented QCD laboratory for discovering the collective behavior of gluonic matter at an unprecedented occupation number of gluons, and for studying the propagation of fast-moving color charge in a nuclear medium.

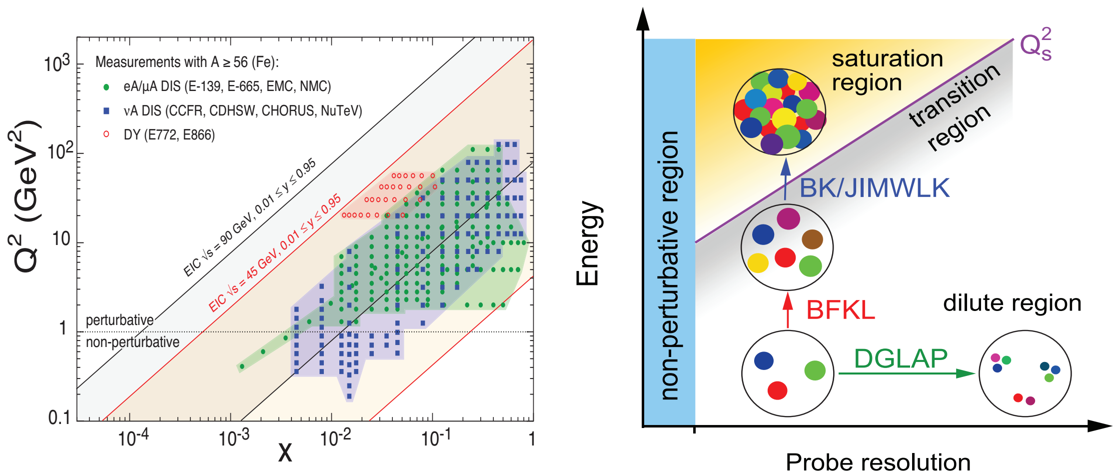

Figure 1.5: **Left:** The range in parton momentum fraction x vs. the square of the transferred momentum Q^2 by the electron to the nucleus accessible to the EIC in e-A collisions at two different center-of-mass energies, compared with the existing data. **Right:** The probe resolution vs. energy landscape, indicating regions of non-perturbative and perturbative QCD, including in the latter, low to high parton density, and the transition region between them.

QCD at Extreme Parton Densities:
In QCD, the large soft-gluon density enables the non-linear process of gluon-gluon recombination to limit the density growth. Such a QCD self-regulation mechanism necessarily generates a dynamic scale from the interaction of high density massless gluons, known as the saturation scale, Q_s, at which gluon splitting and recombination reach a balance. At this scale the density of gluons is expected to saturate, producing new and universal properties of hadronic matter. The saturation scale Q_s separates the condensed and saturated soft gluonic matter from the dilute but confined quarks and gluons in a hadron, as shown in Fig. 1.5 (Right).

The existence of such a saturated soft gluon matter, often referred to as Color Glass Condensate (CGC), is a direct consequence of gluon self-interactions in QCD. It has been conjectured that the CGC of QCD has universal properties common to nucleons and all nuclei, which could be systematically computed if the dynamic saturation scale Q_s is sufficiently large. However, such a semi-hard Q_s is difficult to reach unambiguously in electron-proton scattering without a multi-TeV proton beam. Heavy ion beams at the EIC could provide precocious access to the saturation regime and the properties of the CGC because the virtual photon in forward lepton scattering probes matter coherently over a characteristic length proportional to $1/x$, which can exceed the diameter of a Lorentz-contracted nucleus. Then, all gluons at the same impact parameter of the nucleus, enhanced by the nuclear diameter proportional to $A^{1/3}$ with the atomic weight A, contribute to the probed density, reaching saturation at far lower energies than would be needed in electron-proton collisions. While HERA, RHIC and the LHC have only found hints of saturated gluonic matter, the EIC would be in a position to seal the case, completing the process started at those facilities.

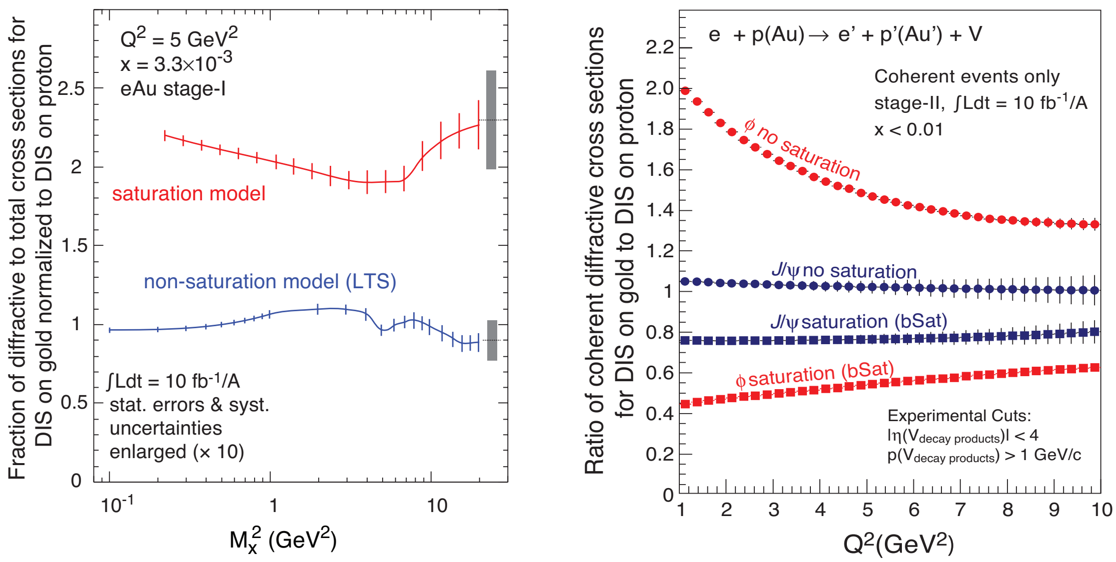

Figure 1.6: **Left:** The ratio of diffractive over total cross section for DIS on gold normalized to DIS on proton plotted for different values, M_X^2, the mass square of hadrons produced in the collisions for models assuming saturation and non-saturation. The grey bars are estimated systematic uncertainties. **Right:** The ratio of coherent diffractive cross section in e-Au to e-p collisions normalized by $A^{4/3}$ plotted as a function of Q^2, plotted for saturation and non-saturation models. The $1/Q$ is effectively the initial size of the quark-antiquark systems (ϕ and J/Ψ) produced in the medium.

Figure 1.6 illustrates some of the dramatic predicted effects of gluon density saturation in electron-nucleus vs. electron-proton collisions at an EIC. The left frame considers coherent diffractive processes, defined to include all events in which the beam nucleus remains intact and there is a rapidity gap containing no produced particles. As shown in the figure, gluon saturation greatly enhances the fraction of the total cross section accounted for by such diffractive events. An early measurement of coherent diffraction in e+A collisions at the EIC would provide the first unambiguous evidence for gluon saturation.

Figure 1.6 (Right) shows that gluon saturation is predicted to suppress vector meson production in e+A relative to e+p collisions at the EIC. The vector mesons result from quark-antiquark pair fluctuations of the virtual photon, which hadronize upon exchange of gluons with the beam proton or nucleus. The magnitude of the suppression depends on the size (or color dipole moment) of the quark-antiquark pair, being significantly larger for produced ϕ (red points) than for J/Ψ (blue) mesons. An EIC measurement of the processes in Fig. 1.6 (Right) would provide a powerful probe to explore the properties of the saturated gluon matter.

Both the coherent diffractive and total DIS cross sections on nuclei are suppressed comparing to those on the proton in all saturation models. But, the suppression on the diffractive cross section is weaker than that on the total cross section leading to a dramatic enhancement in the double ratio as shown in Fig. 1.6 (Left).

The Tomography of the Nucleus:
With its capability to measure the diffractive and exclusive processes with a variety of ion beams, the EIC would also provide the first 3-dimensional images of sea quarks and gluons in a fast-moving nucleus with sub-femtometer resolution. For example, the EIC could obtain the spatial distribution of gluons in a nucleus by measuring the coherent diffractive production of J/Ψ in electron-nucleus scattering, similar to the case of electron-proton scattering shown in figure 1.4.

Propagation of a Color Charge in QCD Matter:
One of the key pieces of evidence for the discovery of quark-gluon plasma (QGP) at RHIC is jet quenching, manifested as a strong suppression of fast-moving hadrons produced in the very hot matter created in relativistic heavy ion collisions. The suppression is believed to be due to the energy loss of partons traversing the QGP. It has been puzzling that the production is nearly as much suppressed for heavy as for light mesons, even though a heavy quark is much less likely to lose its energy via medium-induced radiation of gluons. Some of the remaining mysteries surrounding heavy vs. light quark interactions in hot matter can be illuminated by EIC studies of related phenomena in cold nuclear matter. For example, the variety of ion beams available for electron-nucleus collisions at the EIC would provide a femtometer filter to test and to help determine the correct mechanism by which quarks and gluons lose energy and hadronize in nuclear matter (see schematic in Fig. 1.7 (Left)).

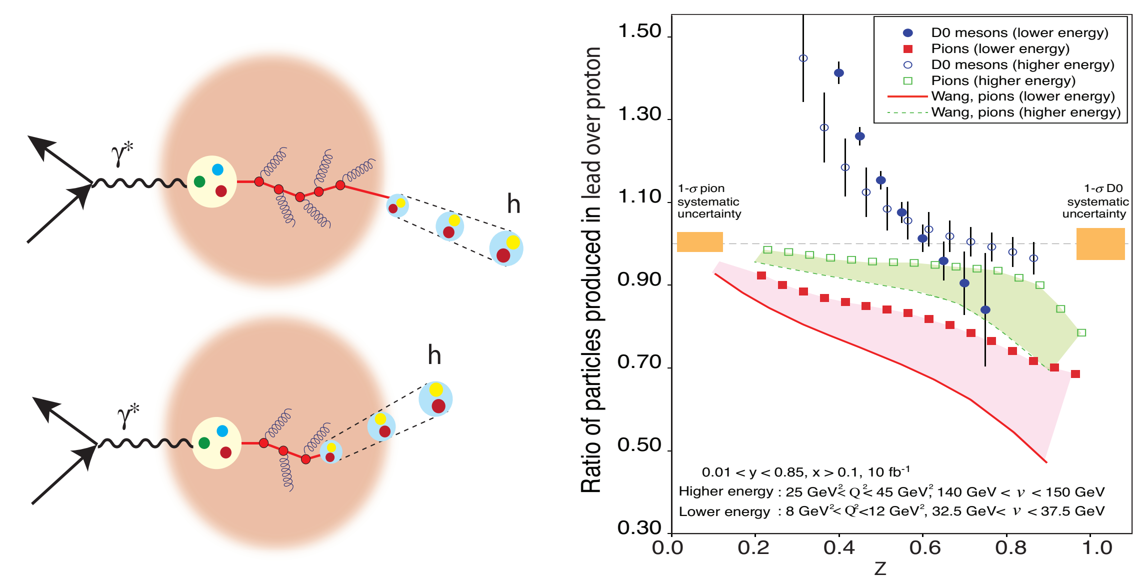

Figure 1.7: **Left:** Schematic illustrating the interaction of a parton moving through cold nuclear matter: the hadron is formed outside (top) or inside (bottom) the nucleus. **Right:** Ratio of semi-inclusive cross section for producing a pion (red) composed of light quarks, and a D^0 meson (blue) composed of heavy quarks in e-Lead collisions to e-deuteron collisions, plotted as function of z, the ratio of the momentum carried by the produced hadron to that of the virtual photon (γ^*), as shown in the plots on the Left.

Figure 1.7 (Right) shows the ratio of number of produced mesons in electron-nucleus and electron-deuteron collisions for pion (light mesons) and D^0-mesons (heavy mesons) at both low and high virtual photon energy ν, as a function of z - the momentum fraction of the virtual photon taken by the observed meson. The calculation of the lines and blue circle symbols assumes the mesons are formed outside of the nucleus, as shown in the top sketch of Fig. 1.7 (Left), while the square symbols are simulated according to a model where a color neutral pre-hadron was formed inside the nucleus, like in the bottom sketch of Fig. 1.7 (Left). The location of measurements within the shaded area would provide the first direct information on when the mesons are formed. Unlike the suppression expected for pion production at all z, the ratio of heavy meson production could be larger than unity due to very different hadronization properties of heavy mesons. The discovery of such a dramatic difference in multiplicity ratios between light and heavy mesons at the EIC would shed light on the hadronization process and on what governs the transition from quarks to hadrons.

The Distribution of Quarks and Gluons in the Nucleus:
The EMC experiment at CERN and experiments in the following two decades clearly revealed that the distribution of quarks in a fast-moving nucleus is not a simple superposition of their distributions within nucleons. Instead, the ratio of nuclear over nucleon structure functions follows a non-trivial function of Bjorken x, deviating significantly from unity, with a suppression (often referred to as nuclear shadowing) as x decreases. Amazingly, there is as of yet no knowledge whether the same holds true for gluons. With its much wider kinematic reach in both x and Q, the EIC could measure the suppression of the structure functions to a much lower value of x, approaching the region of gluon saturation. In addition, the EIC could for the first time reliably quantify the nuclear gluon distribution over a wide range of momentum fraction x.

1.2.3 Physics Possibilities at the Intensity Frontier

The subfield of Fundamental Symmetries in nuclear physics has an established history of key discoveries, enabled by either the introduction of new technologies or the increase in energy and luminosity of accelerator facilities. While the EIC is primarily being proposed for exploring new frontiers in QCD, it offers a unique new combination of experimental probes potentially interesting to the investigations in Fundamental Symmetries. For example, the availability of polarized beams at high energy and high luminosity, combined with a state-of-the-art hermetic detector, could extend Standard Model tests of the running of the weak-coupling constant far beyond the reach of the JLab12 parity violation program, namely toward the Z-pole scale previously probed at LEP and SLC.

1.3 The Electron Ion Collider and its Realization

Two independent designs for a future EIC have evolved in the US. Both use the existing infrastructure and facilities available to the US nuclear science community. At Brookhaven National Laboratory (BNL) the eRHIC design (Figure 1.8, top) utilizes a new electron beam facility based on an Energy Recovery LINAC (ERL) to be built inside the RHIC tunnel to collide with RHICs existing high-energy polarized proton and nuclear beams. At Jefferson Laboratory (JLab) the ELectron Ion Collider (ELIC) design (Figure 1.8, bottom) employs a new electron and ion collider ring complex together with the 12 GeV upgraded CEBAF, now under construction, to achieve similar collision parameters.

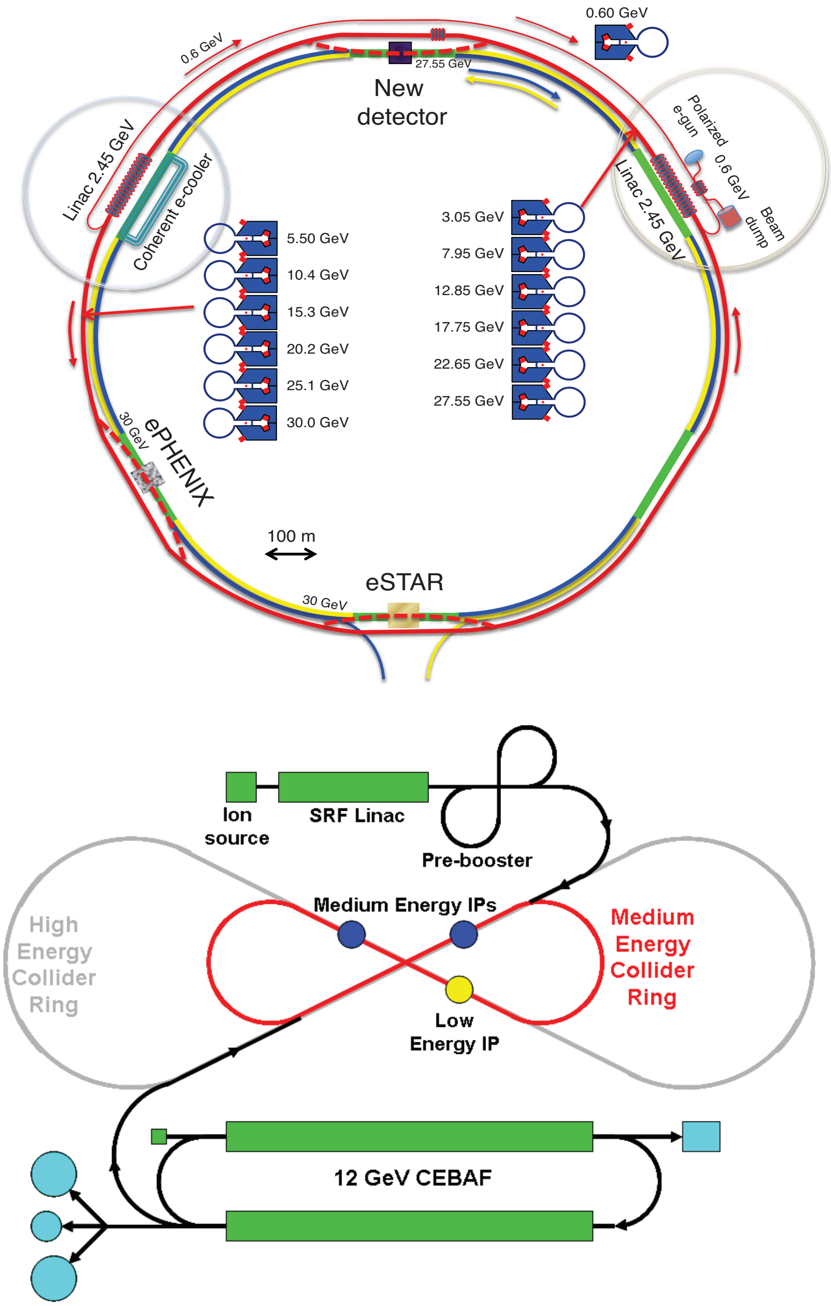

Figure 1.8: **Top:** The schematic of eRHIC at BNL: require construction of an electron beam facility (red) to collide with the RHIC blue beam at up to three interaction points. **Botton:** The schematic of ELIC at JLab: require construction of the ELIC complex (red, black/grey) and its injector (green on the top) around the 12 GeV CEBAF.

The EIC machine designs are aimed at achieving

- Highly polarized ($\sim 70\%$) electron and nucleon 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 ~ 150 GeV
- Collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region

The EIC requirements will push the accelerator designs to the limits of current technology, and will therefore need significant R&D. Cooling of the hadron beam is essential to attain the luminosities demanded by the science. Development of coherent electron cooling is now underway at BNL, while the JLab design is based on conventional electron cooling techniques, but proposes to use bunched electron beams for the first time.

An energy recovery linac at the highest possible energy and intensity are key to the realization of eRHIC at BNL, and this technology is also important for electron cooling in ELIC at JLab. The eRHIC design at BNL also requires a high intensity polarized electron source, that would be an order of magnitude higher in intensity than the current state of the art, while the ELIC design at JLab, will utilize a novel figure-8 storage ring design for both electrons and ions.

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. Lessons learned from past experience at HERA have been considered while designing the EIC interaction region. Driven by the demand for high precision on particle detection and identification of final state particles in both e-p and e-A programs, modern particle detector systems will be at the heart of the EIC. In order to keep the detector costs manageable, R&D efforts are under way on various novel ideas for: compact (fiber sampling & crystal) calorimetry, tracking (NaI coated GEMs, GEM size & geometries), particle identification (compact DIRC, dual radiator RICH & novel TPC) and high radiation tolerance for electronics. Meeting these R&D challenges will keep the U.S. nuclear science community at the cutting edge in both accelerator and detector technology.

1.4 Physics Deliverables of the Stage I of EIC

A staged realization of the EIC is being planned for both the eRHIC and ELIC designs. The first stage is anticipated to have up to $\sim 60 - 100$ GeV in center-of-mass-energy, with polarized nucleon and electron beams, a wide range of heavy ion beams for nuclear DIS, and a luminosity for electron-proton collisions approaching 10^{34} cm^{-2}s^{-1}. With such a facility, the EIC physics program would have an excellent start toward addressing the following fundamental questions with key measurements:

- **The proton spin:** Within just a few months of operation, the EIC would be able to deliver decisive measurements, no other facility in the world could achieve, on how much the intrinsic spin of quarks and gluons contribute to the proton spin as shown in Fig. 1.2 (Right).

- **The motion of quarks and gluons in the proton:** Semi-inclusive measurements with polarized beams would enable us to selectively probe with precision the correlation between the spin of a fast moving proton and the confined transverse motion of both quarks and gluons within. Images in momentum space as shown in Fig. 1.3 are simply unattainable without the polarized electron and proton beams of the proposed EIC.

- **The tomographic images of the proton:** By measuring exclusive processes, the EIC with its unprecedented luminosity and detector coverage would create detailed images of the proton gluonic matter distribution as shown in Fig. 1.4, as well as the images of sea quarks. Such measurements would reveal aspects of proton structure that are intimately connected with QCD dynamics at large distances.

- **QCD matter at an extreme gluon density:** By measuring the diffractive cross sections together with the total DIS cross sections in electron-proton and electron-nucleus collisions as shown in Fig. 1.6, the EIC would provide the first unambiguous evidence for the novel QCD matter of saturated gluons. The EIC is poised to explore with precision the new field of the collective dynamics of saturated gluons at high energies.

- **Quark hadronization:** By measuring pion and D^0 meson production in both electron-proton and electron-nucleus collisions, the EIC would provide the first measurement of the quark mass dependence of the hadronization along with the response of nuclear matter to a fast moving quark.

The Relativistic Heavy Ion Collider (RHIC) at BNL has revolutionized our understanding of hot and dense QCD matter through its discovery of the strongly coupled quark-gluon plasma that existed a few microseconds after the birth of the universe. Unprecedented studies of the nucleon and nuclear structure including the nucleon spin, and the nucleon's tomographic images in the valence quark region have been, and will be, possible with the high luminosity fixed target experiments at Jefferson Laboratory using the 6 and 12 GeV CEBAF, respectively. The EIC promises to propel both programs to the next QCD frontier, by unraveling the three dimensional sea quark and gluon structure of the visible matter. Further, the EIC will probe the existence of the universal saturated gluon matter and has the capability to explore it in detail. The EIC will thus enable the US to continue its leadership role in nuclear science research through the quest for understanding the unique gluon-dominated nature of visible matter in the universe.

References

[1] NSAC Long Range Plan (2007), http://science.energy.gov/np/nsac/.

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