1 The Emerging Science Frontier: The Electron Ion Collider

Much of the focus in contemporary nuclear physics research is on mapping and understanding the emergent phenomena from QCD that determine the unique properties of strongly interacting matter: the breaking of chiral symmetry that gives light-quark hadrons most of their mass; the spin, flavor, space and momentum structure of hadrons; the nearly perfect liquid behavior of the hot matter created in RHIC collisions; possible color superconductivity in the dense interior of compact stars. A key to understanding the rich panoply of QCD phenomena is identifying conditions under which the theory is amenable to controlled solution. Numerical solutions on a space-time lattice have made impressive advances in the treatment of strongly interacting matter in equilibrium at both low and high temperatures. A perturbative expansion in powers of the running QCD coupling constant α_s is successful in describing hadron dynamics in high-energy processes involving large momentum transfer. Interactions of pions and nucleons at low momentum have been successfully analyzed via chiral effective field theories.

Recent theoretical advances have introduced a new QCD regime that may be amenable to a quite different effective field theory approach. This new interpretability frontier occurs in matter probed at moderate momentum transfers, where the QCD coupling is still relatively weak, but at gluon densities high enough to produce extremely strong color fields that can be treated by classical field theory. This regime is dominated by direct manifestations of the defining feature of QCD: the self-interaction of gluons. Gluon splitting and gluon recombination are predicted to reach a competitive balance, leading to a saturation of gluon density that should be universal to all strongly interacting matter probed under suitable conditions. Hints of this saturation have been extracted from measurements of electron-proton collisions at HERA and of deuteron-nucleus and nucleus-nucleus collisions at RHIC. Saturated gluon densities would have a profound influence on heavy-ion collisions at the LHC, and may well be the source of certain general features of high-energy hadron cross sections. In order to tie these phenomena together and map the universal properties of gluon-dominated matter, one needs to probe partonic structure at very low values of Bjorken x, where individual partons carry $<\sim 0.1\%$ of a nucleon's overall momentum, but within a "sweet spot" in momentum transfer (Q^2) where the color interaction is neither too weak nor too strong.

The ideal accelerator to test this classical field theory approach well into the gluon saturation regime with an *a priori* understood probe is an Electron-Ion Collider, EIC. Coherent contributions from many nucleons within a heavy-ion beam particle at such a collider amplify gluon densities, thereby broadening the Q^2 "sweet spot" and extending the effective reach to small x-values by about two orders of magnitude, in comparison with e-p collisions at the same energy per nucleon. In addition to providing precocious entry into the anticipated universal saturation regime, how does the nuclear environment affect the *path* to saturation? Do the momentum and space distributions of gluons in nuclei differ in non-trivial ways from those in nucleons, as has been found for quarks? Are there small clumps of gluons, or are they more uniformly distributed? These questions will be addressed by a combination of deep inelastic inclusive scattering and vector meson production from nucleons and nuclei.

The addition of *polarized* proton and light-ion beams to collide with polarized electrons and positrons at EIC would dramatically expand our understanding of the nucleon's internal wave function. It would greatly extend the kinematic reach and precision of deep inelastic scattering measurements of nucleon spin structure. The contribution of gluons and of sea quarks and antiquarks of different flavor to the nucleon's spin would be mapped well into the gluon-dominated region. The study of Generalized Parton Distributions (GPD's) in deep exclusive reactions will be pushed far beyond presently accessible energies at JLab, HERA and CERN, extending three-dimensional spatial maps of the nucleon's internal landscape from the valence quark region down into the region dominated by sea quarks, antiquarks and gluons. This extension may be critical for completing the picture of how the nucleon gets its spin, by providing sensitivity via GPD's to the orbital motion of sea partons.

High-energy scattering from nucleons in a collider environment lends itself specifically to study how the creation of matter from energy is realized in QCD when an essentially massless (and colored) quark or gluon evolves into massive (and color-neutral) hadrons. Numerical solutions of QCD on a space-time lattice cannot provide guidance for the dynamical process by which the scattered parton picks up other colored partners from either the QCD vacuum or the debris of the high-energy collision. Rather, we rely on experiment to map the result of these parton fragmentation dynamics. The availability of a high-energy, high-luminosity polarized electron-ion collider, using high-efficiency detectors with good particle identification, will facilitate experiments to measure new features of the fragmentation process, such as its dependence on quark spin, flavor and motion, and on passage through nuclear matter.

In short, EIC is a machine that would expand the intellectual horizons of nuclear physics research into the non-linear heart of QCD, where gluon self-interactions dominate. It would address the following fundamental science questions:

- Does the self-limiting growth of color field strengths in QCD lead to universal behavior of all nuclear and hadronic matter in the vicinity of these limits?
- How does the nuclear environment affect the distribution of gluons in momentum and space?
- What is the internal landscape of a nucleon in the region dominated by sea quarks and gluons?
- How do hadronic final states form from light quarks and massless gluons in QCD?

It would build on the scientific and technical expertise developed over decades at the nation's two premier QCD laboratories at Jefferson Lab and RHIC, but would add new state-of-the-art accelerator technology to reach its design goals.

In this section, we highlight several of the science programs that EIC would foster and outline two design options under consideration, referring the reader to the more detailed White Papers [**?**,**?**] that have been written on EIC alone. We also describe briefly below the R&D necessary to demonstrate feasibility of various aspects of accelerator and detector design for such a facility.

With its wide range in energy, nuclear beams, high luminosity and clean collider environment, the EIC will offer an unprecedented opportunity for discovery and for the precision study of a novel universal regime of strong gluon fields in QCD. The EIC will allow measurements, in a wide kinematic regime, of the momentum and spatial distribution of gluons and sea-quarks in nuclei, of the scattering of fast, compact probes in extended nuclear media, and of the role of color neutral (Pomeron) excitations in scattering from nuclei. These measurements at the EIC will deepen and corroborate our understanding of the formation and properties of the strongly interacting Quark Gluon Plasma (QGP) in high energy heavy ion collisions at RHIC and the LHC.

Strong color fields in nuclei. One of the major discoveries of the last decade was just how dominant a role gluons play in the wave function of a proton viewed by a high-energy probe with high spatial resolution (*i.e.*, with large 4-momentum transfer squared Q^2). HERA deep inelastic scattering data revealed that the density of partons, especially gluons, in the plane transverse to the probe momentum grows rapidly with decreasing parton momentum fraction x. This growth is attributable in QCD to the successive emission of soft partons by higher-momentum partons. The resulting gluon field can be treated linearly within QCD when x and Q^2 are not too small. But for given x, the dynamics of the gluon fields becomes highly non-linear below a certain saturation momentum scale Q_s^2, where the recombination of soft gluons into harder ones sets in to tame further growth of the parton densities. If the saturation momentum is large on a typical QCD scale, $Q_s \gg \Lambda_{\mathrm{QCD}}$, then the coupling strength $\alpha_s(Q_s^2) \ll 1$ and the gluon dynamics can be described with weak-coupling techniques. The occupation number of gluon field modes with transverse momenta below Q_s saturates at values $\sim 1/\alpha_s(Q_s^2) \gg 1$, so that the probe sees a very strong, essentially classical, color field frozen by time dilation, a system often referred to as the "color glass condensate" (CGC). A goal of theoretical treatments of this high-density QCD matter is to establish a rigorous effective field theory approach for controlled inclusion of higher-order effects beyond the CGC limit.

Since the saturation momentum grows slowly with decreasing x (see Fig. 1), so does the window ($\Lambda_{\mathrm{QCD}} \ll Q \ll Q_s$) into the CGC regime. However, a much more effective opening of this window can be arranged by exploiting the Lorentz contraction of a fast-moving nucleus, which amplifies the parton density in proportion to the nuclear diameter, so that $Q_s^2 \propto A^{1/3}$. Thus, as illustrated in Fig. 1, one can enter the predicted saturation regime in e-Au collisions at x-values a couple of orders of magnitude larger than what would be required in e-p collisions at the same Q^2. An electron-ion collider thus represents the most robust and cost-effective approach to study the physics of these strong color fields. Can a clear saturation scale be identified experimentally? Are the properties of partonic matter in the saturation regime indeed *universal* to all hadrons and nuclei? Are these properties consistent with inferences from particle multiplicities and momentum spectra observed at RHIC and with dynamics soon to be explored in heavy-ion collisions at the LHC? Can the properties of saturated gluon fields in heavy nuclei provide a natural explanation for the very rapid thermalization inferred from analysis of relativistic heavy-ion collisions? These

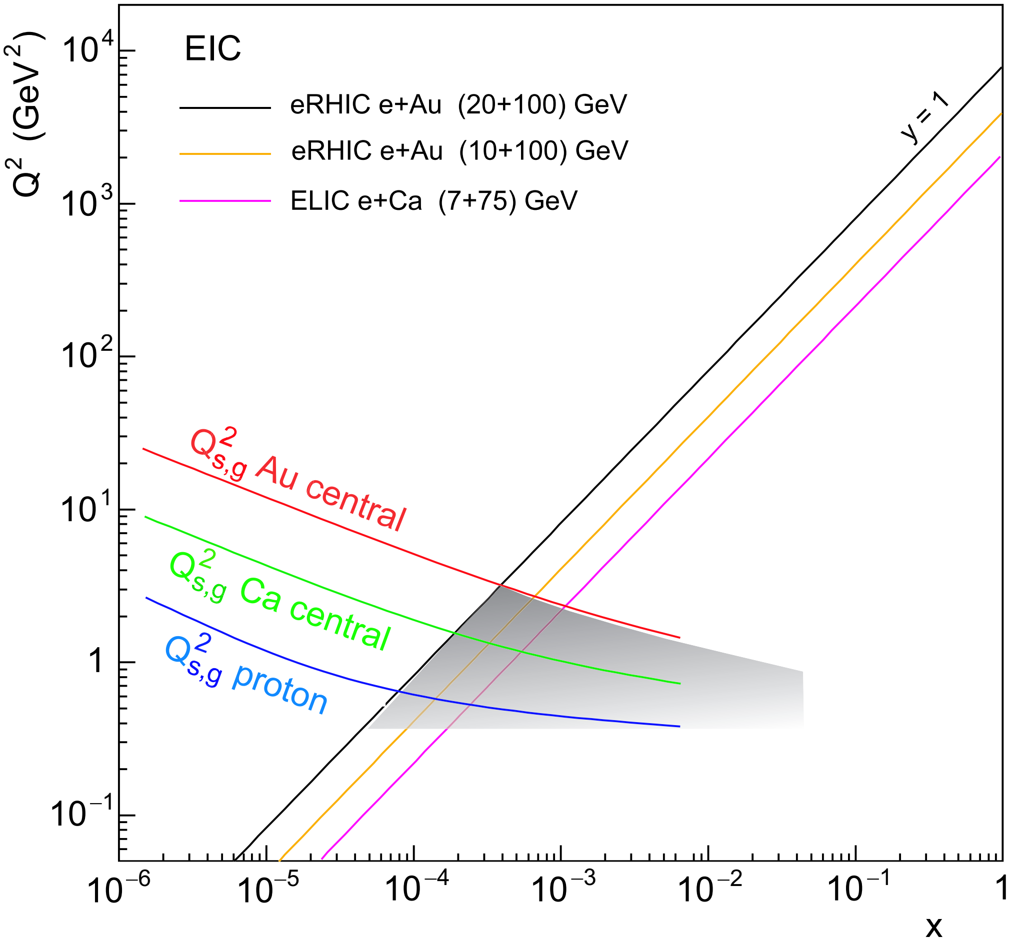

Fig. 1. Kinematic acceptance and exposure of the predicted gluon saturation regime in the (x, Q^2) plane for the EIC. The accessible regions fall to the right of the three diagonal straight lines, representing different choices for beam energies (per nucleon in the case of ion beams) and maximum mass of the ion beams. Curves showing the gluon saturation scale Q_s^2 for protons and for central collisions with Ca and Au nuclei are superposed on the kinematic acceptance. The shaded area indicates the kinematically accessible region of saturated gluon density that should be reached in the maximum-energy e+Au collisions considered.

questions will be addressed via deep inelastic scattering (DIS) and other cleanly interpretable electromagnetic processes at EIC, as explained in more detail below.

Measurements of momentum distributions of gluons and sea quarks in nuclei. Gluon momentum distributions overwhelm their quark counterparts in the proton for $x <\sim 0.01$. DIS experiments have established that quark and gluon distributions in nuclei exhibit “shadowing”: they are modified significantly relative to their distributions in the *nucleon* wavefunction. However, the detailed nature of gluon shadowing at $x <\sim 0.01$ is *terra incognita* in QCD. This physics, bearing directly on the universality of gluon saturation, can be fully studied in electron–nucleus scattering at the EIC, over the broad kinematic coverage shown in Fig. 1.

The inclusive DIS structure functions $F_2^A(x, Q^2)$ and $F_L^A(x, Q^2)$ offer the most precise determination of quark and gluon momentum distributions in nuclei. Independent extraction of F_2^A and F_L^A is only possible via measurements over a range of center of mass energies, an essential requirement of the EIC. The F_2^A structure function is directly sensitive to the sum of quark and anti-quark momentum distributions in the nucleus; at small x, these are predominantly sea quarks. Information on the gluon distribution in the nucleus, $G^A(x, Q^2)$, can be indirectly garnered from the well-known logarithmic scaling violations of F_2^A with Q^2, $\partial F_2^A/\partial \ln(Q^2)$. In Fig. 2 we show projections for the normalized ratio of $F_2^A(x, Q^2)$ in gold relative to deuterium from a saturation (CGC) model in comparison to the usual linear evolution of perturbative QCD for three models incorporating differing amounts of shadowing. Saturation of gluon densities in the CGC model is manifested by the weak x- and Q^2-dependence of the slope $\partial F_2^{Au}/\partial \ln(Q^2)$ at low x and moderate Q^2. The projected statistical precisions attainable for inclusive DIS measurements with 10 GeV electrons on 100 GeV/nucleon Au nuclei and an integrated luminosity of 4/A fb^{-1}, also shown in Fig. 2, suggest that EIC data can readily distinguish among differing model predictions.

The structure function $F_L^A \equiv F_2^A - 2xF_1^A$ for absorption of longitudinal photons by the proton vanishes in the naive parton model, but in QCD it is proportional at small x to the gluon momentum distribution. Hence, its measurement will allow a new and independent direct determination of $G^A(x, Q^2)$ in the low-x region where little is presently known. The high precision attainable for both F_2 and F_L at EIC will facilitate definitive tests of the universality of saturated gluonic matter. Measurements for different nuclei, x and Q^2 values can be combined in a single plot of the structure functions vs. Q^2x^γ/A^δ to search for values of the adjustable powers γ and δ that yield a universal curve, and hence define the x- and A-dependence of the saturation scale $Q_s^2(x, A)$.

Additional strong sensitivity to gluon densities in nuclei will be provided by semi-inclusive and exclusive final states. An example of the former is di-jet production in e-A collisions, which is dominated at EIC energies by the photon-gluon fusion process. An exclusive example is elastic vector meson production $e+\text{A} \longrightarrow (\rho, \phi, J/\psi)+\text{A}$, where forward cross sections for longitudinal virtual photons depend on the square of the gluon density.

The gluon spatial distribution. The spatial distribution of gluons in a nucleus provides a complementary handle on the physics of strong color fields and has important ramifications for a wide range of final states in hadronic and nuclear collisions. Information on the spatial distribution can be inferred from forward vector meson production in e-A, which can be viewed at small x as the result of coherent interactions of quark-antiquark fluctuations of the virtual photon with the nucleus. The differential cross section for the vector mesons, as a function of momentum transfer t along the proton line, can be analyzed to extract a survival probability of these small color dipole fluctuations as a function of impact parameter b at which the dipole traverses the nucleus. The survival probability is, in turn, sensitive to the strength of the gluon field seen. Systematic studies of vector meson production over a wide range of kinematic conditions and for several ion species can thereby illuminate the b-dependence as well as the A-dependence of the saturation scale.

Color neutral (Pomeron) excitations in scattering off nuclei. Another predicted

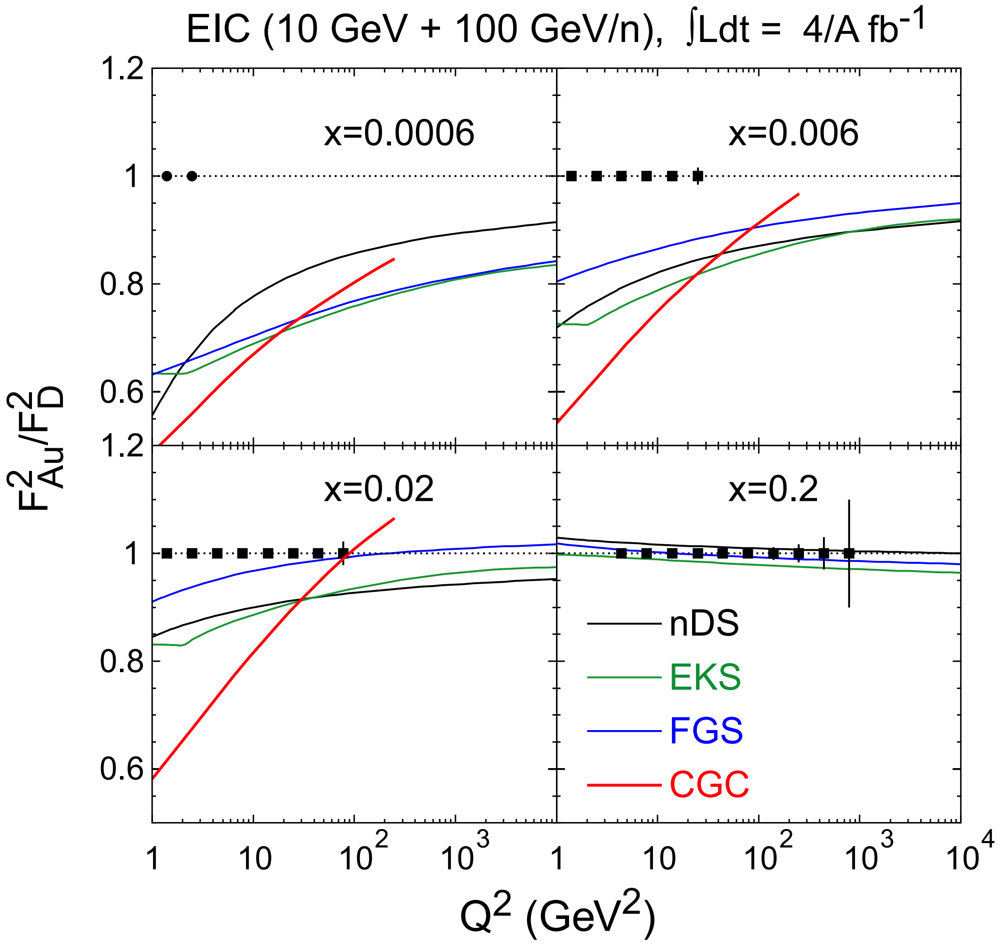

Fig. 2. The ratio of the structure function $F_2^{\rm Au}$ in Au nuclei relative to the structure function $F_2^{\rm D}$ in deuterium nuclei as a function of Q^2 for several bins in x. The filled circles and error bars correspond respectively to the estimated kinematic reach in F_2 and the statistical uncertainties for a luminosity of $4/\mathrm{A}\,\mathrm{fb}^{-1}$ with the EIC. The curves labeled nDS, EKS and FGS correspond to different parameterizations of parton distributions at the initial scale for pQCD evolution, while the one labeled CGC corresponds to a Color Glass Condensate model prediction applicable at small x.

manifestation of strong gluon fields in QCD is an enhanced probability for a high-energy probe to interact with a color-neutral multi-gluon excitation of the vacuum – an excitation that may be associated with the so-called Pomeron – leaving the target nucleus intact. These interactions lead to diffractive final states that may dominate forward scattering. At HERA, an unexpected discovery was that diffraction accounted for 15% of the total e+p cross-section. This is a striking result implying that a proton at rest remains intact one seventh of the time when struck by a 25 TeV electron. The effect may be even more dramatic in nuclei. Several models of strong gluon fields in nuclei suggest that large nuclei will remain intact nearly 40% of the time in EIC collisions, in comparison to the quantum mechanical black disk limit of 50%. Measurements of coherent diffractive scattering on nuclei are easier in the collider environment of EIC than in fixed-target experiments, but nonetheless place strong demands on the forward acceptance of detectors. With suitable detectors, EIC measurements should be able to distinguish the onset of non-linear dynamics for the gluon field, leading to a weak x-dependence but strong Q^2-dependence of the ratio of diffractive structure functions for heavy *vs.* light nuclei. These dependences are distinct from those expected in non–perturbative ("soft" Pomeron) models of diffractive scattering.

Fast probes of an extended gluonic medium. How are the propagation of fast partons and their space-time evolution into hadrons affected by traversal of nuclear matter characterized by strong gluonic fields? Semi-inclusive DIS (SIDIS) experiments at EIC, with high-momentum hadrons detected in coincidence with scattered electrons for a wide range of kinematic conditions and ion species, will use nuclei as femtometer-scale detectors to study these issues in cold nuclear matter. These experiments will provide an essential complement to studies of jet quenching in the hot matter produced in RHIC heavy-ion collisions. The RHIC jet quenching studies have produced a series of striking and surprising results: a strong suppression of high-momentum hadrons usually attributed to rapid energy loss of partons traversing matter of high color charge density, but little apparent dependence of the suppression factor on quark flavor, in sharp contrast to expectations from perturbative QCD models of the parton energy degradation. SIDIS on *fixed* nuclear targets has so far revealed an analogous but weaker suppression of light hadron production in cold nuclear matter. EIC will enormously expand the virtual photon energy range in such studies, from 2–25 GeV in the HERMES experiment at HERA to $10\,\mathrm{GeV} < \nu < 1600\,\mathrm{GeV}$, thereby providing access to the kinematic region relevant for LHC heavy-ion collisions and to such important new issues as the suppression of heavy-flavor mesons travelling through cold nuclear matter.

One of the basic physics questions to be answered here concerns the time scale on which the color of the struck quark is neutralized, acquiring a large inelastic cross-section for interaction with the medium. The parton energy loss models used to interpret RHIC results assume long color neutralization times, with "pre-hadron" formation outside the medium and quark/gluon energy loss as the primary mechanism for hadron suppression. Alternative models assume short color neutralization times with in-medium "pre-hadron" formation and absorption as the primary mechanism. There do exist hints of short formation times from HERMES data and JLab preliminary data, but these must be pursued over the wider kinematic range and much broader array of final-state channels that can be explored at EIC.

1.2 A New Era of Hadronic Physics

The EIC will provide definitive answers to compelling physics questions essential for understanding the fundamental structure of hadronic matter. It will allow precise and detailed studies of the nucleon in the regime where its structure is overwhelmingly due to gluons and to sea quarks and anti-quarks. Some of the scientific highlights at the EIC in this area would be: (1) definitive answers to the question of how the proton's spin is carried by its constituents, (2) determination of the three-dimensional spatial quark and gluon structure of the proton, (3) precision study of the proton's gluon distribution over a wide range of momentum fractions, and (4) maps of new spin-dependent features of the quark fragmentation process. In the following we briefly address three of these highlights of future research in hadronic physics.

The spin structure of the proton. Few discoveries in nucleon structure have had a bigger impact than the surprising finding that quarks and anti-quarks together carry only about a quarter of the nucleon's spin. Determining the partonic source of the "missing" spin in this complex composite system has developed into a world-wide quest central to nuclear physics. The sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

states that the proton spin projection along its momentum is the sum of the quark and gluon intrinsic spin ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) contributions. EIC with its unique high luminosity, highly polarized electron and nucleon capabilities, and its extensive range in center-of-mass energy, will allow DIS access to quark and gluon spin contributions at substantially lower momentum fractions x than important current and forthcoming experiments at RHIC, DESY, CERN and JLab. A key measurement at the EIC would be of the spin-dependent proton structure function $g_1(x, Q^2)$ of the proton over a wide range in Q^2, and down to $x \sim 10^{-4}$. Studies of the scaling violations of $g_1(x, Q^2)$ prove to be a most powerful and clean tool to determine the spin contribution by gluons. This is demonstrated by Fig. 3, which shows projections for EIC measurements of $g_1(x, Q^2)$ in comparison with four model predictions that make different assumptions regarding the sign and magnitude of the gluon spin contribution to the proton spin. Each of these models is compatible with the currently available polarized fixed-target DIS data. While data from polarized proton collisions at RHIC are already beginning to establish preferences among these particular four models at $x >\sim 0.01$, the RHIC data will not be able to constrain the shape of the gluon helicity distribution at lower x, where the density of gluons rapidly increases. The great power of the EIC in providing precise information on $\Delta G(x <\sim 0.01)$ is evident.

With polarized ^{3}He beams at an EIC, measurements of g_1 would also be possible off polarized neutrons, allowing a precision test of the fundamental Bjorken sum rule, which relates the proton and neutron spin structure via the axial weak coupling strength measured in neutron beta-decay. Furthermore, semi-inclusive DIS measurements, for which a specific hadron is detected from the struck quark jet, would provide information with unprecedented detail on the individual contributions by quark and anti-quark spins to the proton spin, testing models of nucleon structure and lattice QCD calculations.

There are various avenues for investigating the role of orbital angular momenta in nucleon structure. One of them is the study of correlations of the transverse momentum of a parton in the nucleon with the nucleon spin transverse to its momentum. Such correlations produce characteristic patterns of azimuthal-angular dependences for final-state hadrons in SIDIS experiments. Initial experimental results from fixed-target SIDIS indicate the presence of such correlations. Measurements at an EIC would allow precision studies of such orbital effects. An alternative approach will utilize deep exclusive reactions to extract generalized parton distributions (GPDs), to which we turn next. The GPDs provide unique access to the total – spin plus orbital – angular momentum contributions of quarks and gluons, as well as to many other important aspects of nucleon structure. While initial maps of GPDs in the valence-quark region will be carried out with the 12 GeV upgrade at JLab, access to orbital contributions associated with virtual mesons in the nucleon wave function will require the EIC kinematic reach well into the region of the quark-antiquark sea.

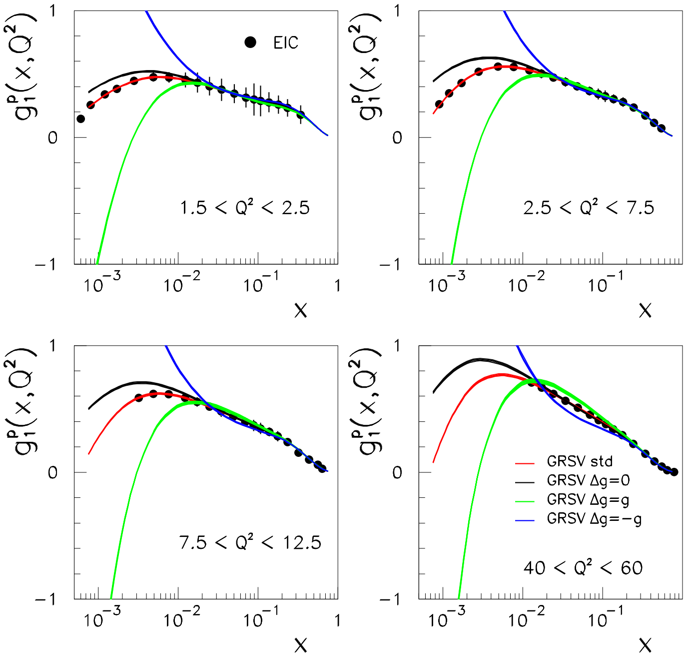

Fig. 3. Projected EIC data for the proton structure function $g_1(x, Q^2)$ as a function of x in four Q^2 bins, for 7 GeV electrons colliding with 150 GeV protons at an integrated luminosity of $5\,\text{fb}^{-1}$. The curves show theoretical predictions based on different sets of spin-dependent parton distribution functions that mostly differ in the gluon helicity distribution.

Measurements of Generalized Parton Distributions. GPDs may be viewed as the Wigner quantum phase space distributions of the nucleon's constituents – functions describing the simultaneous distribution of particles with respect to position and momentum in a quantum-mechanical system, representing the closest analog to a classical phase space density allowed by the uncertainty principle. In addition to information about spatial density (form factors) and momentum density (parton distribution), these functions describe correlations of the two, i.e., how the spatial shape of the nucleon changes when one probes quarks and gluons of different wavelengths. The concept of GPDs has revolutionized the way scientists visualize nucleon structure, in the form of either two-dimensional tomographic images (analogous to CT scans in medical imaging) or genuinely six-dimensional phase space images. In addition, GPDs allow us to quantify how the angular momenta of partons in the nucleon contribute to the nucleon spin.

Measurements of GPDs are possible in hard exclusive processes such as deeply virtual Compton Scattering (DVCS), $\gamma^* p \to \gamma p$. The experimental study of these processes is typically much more challenging than of traditional inclusive DIS. In addition to requiring substantially higher luminosities (because of small cross sections) and the need for differential measurements, the detectors and the interaction region have to be designed to permit full reconstruction of the final state. A properly designed collider is much better suited for this purpose than a fixed-target experiment. A collider also achieves momentum transfers of the order $Q^2 \sim 10\ \text{GeV}^2$, where higher-twist QCD corrections in the GPD analysis are under control. The EIC would allow unique access to the gluon and sea-quark and anti-quark GPDs, entirely complementary to what will be achieved by the 12-GeV upgrade program

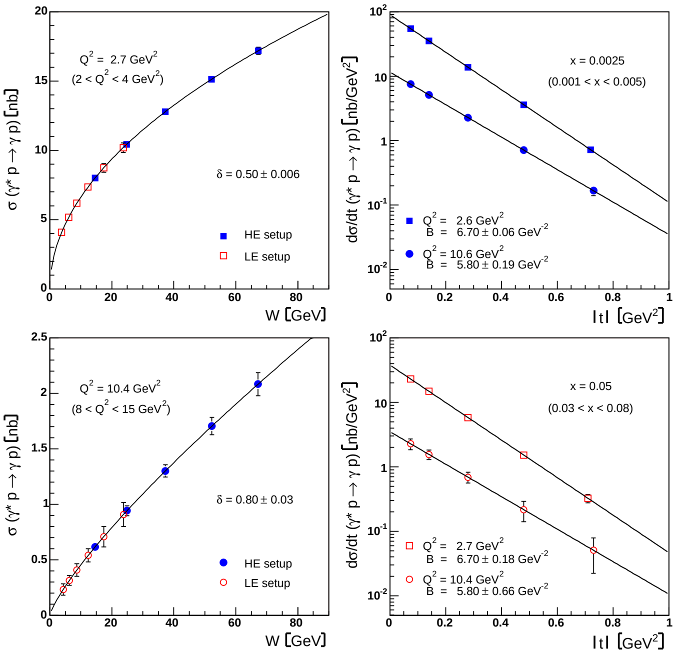

Fig. 4. Left: projected results for total DVCS cross section measurements with an EIC, as a function of invariant $\gamma^* p$ mass W, for two values of Q^2. Right: t differential DVCS cross section for two representative values of x and Q^2. The projections assume a high-energy setup (10 GeV on 250 GeV), with an integrated luminosity of $530\,\mathrm{pb}^{-1}$ for the smaller x-value, and a low-energy setup (5 GeV on 50 GeV) with $180\,\mathrm{pb}^{-1}$ for the larger x-value. The estimates of the event rates here assume 100% detector acceptance.

at JLab. This would be possible through study of a variety of exclusive final states, ranging from photons to pions, kaons and J/ψ. As an example of the potential of an EIC in this area, we show in Fig. 4 the expected uncertainties of measurements of the DVCS cross section. In particular, we show the cross section differential in t, the momentum transfer on the nucleon line. By a Fourier transform, the t-dependence encodes the information about the transverse spatial distribution of partons in the proton. One can see that excellent statistics can be obtained in fully differential measurements in x, Q^2 and t, and over a wide kinematic range. This will allow for precise extraction of information about the nucleon GPDs and for numerous detailed studies, for example, of their Q^2-evolution.

Spin-dependent Quark Fragmentation. Semi-inclusive DIS experiments at a high-luminosity polarized EIC will map the spin-dependence of the process by which quarks transform to jets of hadrons. Recoiling quarks from a polarized proton will initiate the fragmentation process with a spin orientation preference. How does this preference affect the yields, momenta and spin preferences of various types of hadronic fragments, and what do such effects teach us about the fragmentation dynamics? It is already apparent from measurements in electron-positron collisions and in fixed-target SIDIS that there are correlations between the momentum components of hadron fragments transverse to the jet axis and any quark spin preference transverse to its momentum. In addition to systematic exploration of these initial hints at EIC, it may be possible for selected final-state hadrons – e.g., ρ-mesons – reconstructed from their decay daughters to correlate their density matrices with the spin orientation of the fragmenting quark. In combination with the study of in-medium fragmentation in e-A collisions at EIC, such measurements are likely to launch a new stage in modeling how quarks accrete colored partners from the vacuum or their environment to form colorless hadrons.

1.3 Accelerator Designs

A high luminosity (at or above 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) Electron-Ion Collider, covering the full range of nuclear masses A with variable center-of-mass energy in the range of 20 to 100 GeV/nucleon, and the additional capability of colliding polarized protons and light-ions with polarized electrons and positrons, appears to be the ideal accelerator to explore these fundamental questions of QCD and expand nuclear physics research into the gluon-dominated regime. Presently there are two distinct design approaches to an EIC: eRHIC, based on the RHIC ion complex, and ELIC, using CEBAF as a full energy injector into an electron storage ring. Research and development needed for a detailed design of each approach is outlined in this section.

eRHIC Two accelerator design options for eRHIC were developed in parallel and presented in detail in the 2004 Zeroth-Order Design Report[**?**]. Presently the most promising option is based on the addition of a superconducting Energy Recovery Linac (ERL) to provide the polarized electron beam. This ERL-based design option can achieve peak luminosity of 2.6×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for e-p collisions, with the potential for improvement. The peak luminosity per nucleon for electron-Au collisions is 2.9×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for 100 GeV/N gold ions colliding with 20 GeV electrons. R&D for a high-current polarized electron source and high-energy and high-current ERL are needed to achieve these design goals. A second option is based on the addition of an electron storage ring to provide polarized electron or positron beams. This option is technologically more mature and promises peak e-p luminosity of 0.47×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The general layout of the ERL-based design option of the eRHIC collider is shown in Fig. 5. A polarized electron beam is generated in a photo-injector and accelerated to the energy of the experiment in the ERL. After colliding with the hadron beam in as many as four detector locations, the electron beam is decelerated to an energy of a few MeV and dumped. Positron beam is possible with the addition of a conversion system and a compact storage ring, at one quarter of the RHIC circumference, for positron accumulation, storage and self-polarization. In the present design, the ERL provides electrons in the energy range from 3 to 20 GeV, leading to a center-of-mass energy range from 25 to 140 GeV in combination with RHIC proton beams.

The main highlights of the ERL-based eRHIC design are:

- luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and higher in electron-hadron collisions
- high electron beam polarization (∼80%)
- full polarization transparency at all energies for the electron beam
- multiple electron-hadron interaction points (IPs) and detectors
- ±3m "element-free" straight section(s) for detector(s)
- ability to take full advantage of electron cooling of the hadron beams

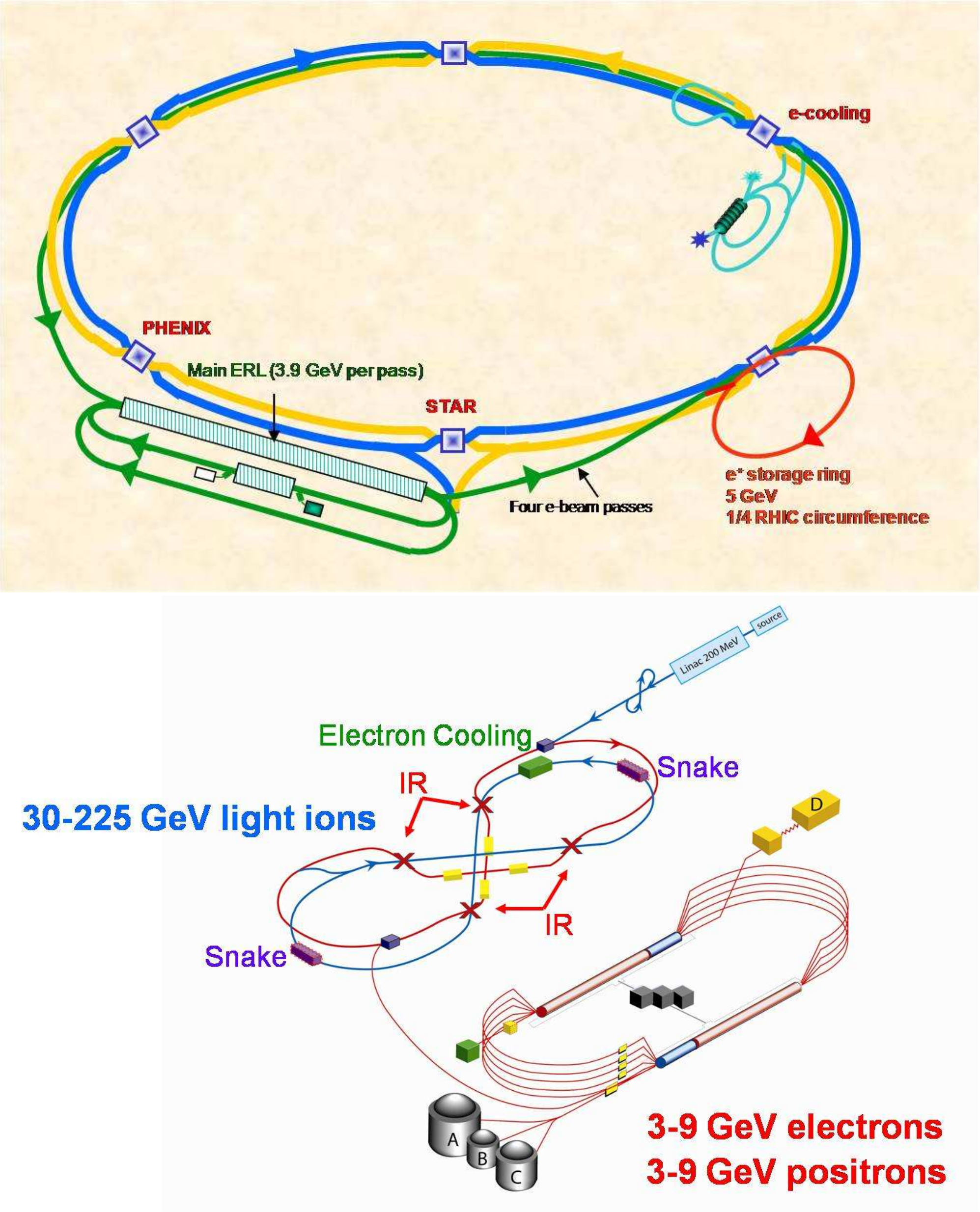

Fig. 5. Design layouts of the ERL-based eRHIC, and the CEBAF-based ELIC colliders.

- easy variation of the electron bunch frequency to match it with the ion bunch frequency at different ion energies

ELIC ELIC is an electron-ion collider with center of mass energy of 20 to 90 GeV and luminosity up to 8 × 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (at a collision frequency of 1500 MHz). It is described in detail in the 2007 Zeroth Order Design Report [**?**] and shown schematically in Fig. 5. This high-luminosity collider is envisioned as a future upgrade of CEBAF, beyond the 12 GeV Upgrade, and compatible with simultaneous operation of the 12 GeV CEBAF (or a potential extension to 24 GeV) for fixed-target experiments. The CEBAF accelerator with polarized injector is used as a full-energy injector into a 3-9 GeV electron storage ring. A positron source is envisioned as an addition to the CEBAF injector for generating positrons that can be accelerated in CEBAF, accumulated and polarized in the electron storage ring, and collide with ions with luminosity similar to the electron-ion collisions. The ELIC facility is designed for a variety of polarized light ion species: p, d, ^{3}He and Li, and unpolarized light to heavy (up to A $\sim$ 200) ion species. To attain the required ion beams, an ion facility must be constructed, a major component of which is a 30-225 GeV collider ring located in the same tunnel and below the electron storage ring. A critical component of the ion complex is an ERL-based continuous electron cooling facility, anticipated to provide low emittance and simultaneously very short ion bunches. ELIC is designed to accommodate up to four intersection points (IP's), consistent with realistic detector designs. Longitudinal polarization is guaranteed for protons, electrons, and positrons in all four IP's simultaneously and for deuterons in up to two IP's simultaneously.

An alternate design approach for ELIC is based on the linac-ring concept, in which CEBAF operates as a single-pass ERL providing full energy electrons for collisions with the ions. Although this approach promises potentially higher luminosity than the ring-ring option, it requires significant technological advances and associated R&D. The main highlights of the ELIC design are:

- "Figure-8" ion and lepton storage rings ensure spin preservation and ease of spin manipulation
- spin transparency to energy for all species
- unprecedented luminosity at the 10^{35} cm^{-2}s^{-1} level
- four interaction regions with ±2m element-free region
- the present JLab DC polarized electron gun routinely delivers ~85% polarization and meets the beam current requirements for filling the storage ring
- the 12 GeV CEBAF accelerator can serve as an injector to the ring
- collider operation remains compatible with 12 GeV CEBAF operation for a fixed-target program

R&D Required

I. Common R&D Topics In order for either eRHIC or ELIC to reach luminosity at or above 10^{33} cm^{-2}s^{-1} level, R&D on high energy electron cooling and on the production of polarized ^{3}He beams is required. Electron cooling is required to achieve the design transverse emittances, to counteract the effects of intrabeam scattering, and in the case of ELIC to reach short ion bunches. An electron cooling system based on ERL technology is presently under development for RHIC-II, intended to lead to an order of magnitude higher ion-ion luminosities in RHIC. The same system will be used for eRHIC. ^{3}He ions have not yet been used for experiments. EBIS, the new ion source under construction at BNL, will provide the ability to produce polarized ^{3}He beams, given a ^{3}He source. In addition, R&D will be required on a variety of detector and polarimetry items, such as the development of cost-effective and compact high-rate tracking and associated readout systems, small angle detector instrumentations, multi-level trigger systems and precision ion polarimetry.

II. R&D Required for eRHIC R&D applicable to both ERL and ring-ring options for eRHIC is required in order to increase the number of bunches in RHIC from 111 to 166, and for better understanding of the machine tolerances required for ^{3}He polarization preservation in RHIC and its injectors. In addition, the ERL eRHIC design requires R&D on high-current polarized electron sources and on high-energy and high-current energy recovery. To achieve the design eRHIC luminosities, 260 mA average current is required from a polarized electron source. The best existing source, at JLab's CEBAF accelerator, operates at approximately 0.3 mA of average current (1 mA is expected to be reached shortly) with current densities of about 50 mA/cm^2. The development of large cathode guns should provide a path to electron currents of tens to hundreds of milliamps. The eRHIC ERL is envisioned to employ state-of-the-art 703.75 MHz 5-cell SRF cavities. The cavity design was developed at BNL in the course of the electron cooling project and allows the minimization and efficient damping of the higher-order modes, opening a way for higher electron currents. Simulations of multi-bunch and multi-pass breakup instabilities showed that the design eRHIC currents can be achieved in an ERL based on this cavity.

III. R&D Required for ELIC With the exception of electron cooling, no additional R&D is necessary for ELIC at the luminosity level of 10^{33} cm^{-2}s^{-1}. To achieve the ELIC design luminosity of 10^{35} cm^{-2}s^{-1}, R&D is critical in the areas of crab crossing, stability of intense ion beams accumulated at stacking, and electron cooling using a circulator ring. For the former, R&D is required for the design of a 1500 MHz multi-cell crab cavity, for understanding the beam dynamics with crab cavities in both rings, and for achieving phase and amplitude stability requirements. Understanding beam stability of intense ion beams in boosters and the collider ring also requires R&D. One approach is to overcome space charge at injection by increasing the beam size while preserving the 4D emittance, using a circular painting technique for stacking similar to the technique proposed at SNS. An alternate approach is to admit a large beam emittance in the pre-booster and cool it after injection in the collider ring using stochastic cooling for coasting beam. ELIC's electron cooling concept is unique, in that it relies on the use of a circulator ring to ease requirements on the average current from the electron source and on the ERL. Simulation studies are required to establish beam stability conditions and to optimize the beam and cooling ring operating parameters. Lastly, the ELIC design requires a dedicated R&D effort to develop the high-speed data acquisition and trigger systems that would be needed to accommodate the high collision frequencies.