1 The Electron Ion Collider

The EIC Collaboration (BNL/IUCF/MIT/Yale)

It has been over 25 years since the formulation of Quantum Chromodynamics (QCD), the theory which identifies colored quarks and gluons as the basic constituents of strongly interacting matter. In the intervening decades, a great amount of information has been obtained about the partonic (quarks and gluons) structure of hadronic matter. However, our knowledge is still far from complete. Crucial questions in this field remain open:

- What is the structure of hadrons in terms of their quark and gluon constituents?
- How do quarks and gluons evolve to form hadrons?
- Can nuclei be used to produce and study partonic matter under extreme conditions?

The answer to these questions is the key to our ultimate understanding of the microscopic structure of matter. A high-luminosity electron-ion collider turning on at the end of this decade will be the ideal machine to address the above questions decisively. The Electron-Ion Collider (EIC) should have a luminosity $\geq 10^{33}$ cm^{-2}sec$^{-1}A^{-1}$ and a center-of-mass energy in the range of 30 to 100 GeV. It is crucial that the collider should allows collisions of electrons not just with protons, but with light and heavy ions, in order to explore the full ramifications of QCD. With the parameter space given in Figure 1) EIC will provide a capability beyond anything presently existing in the world.

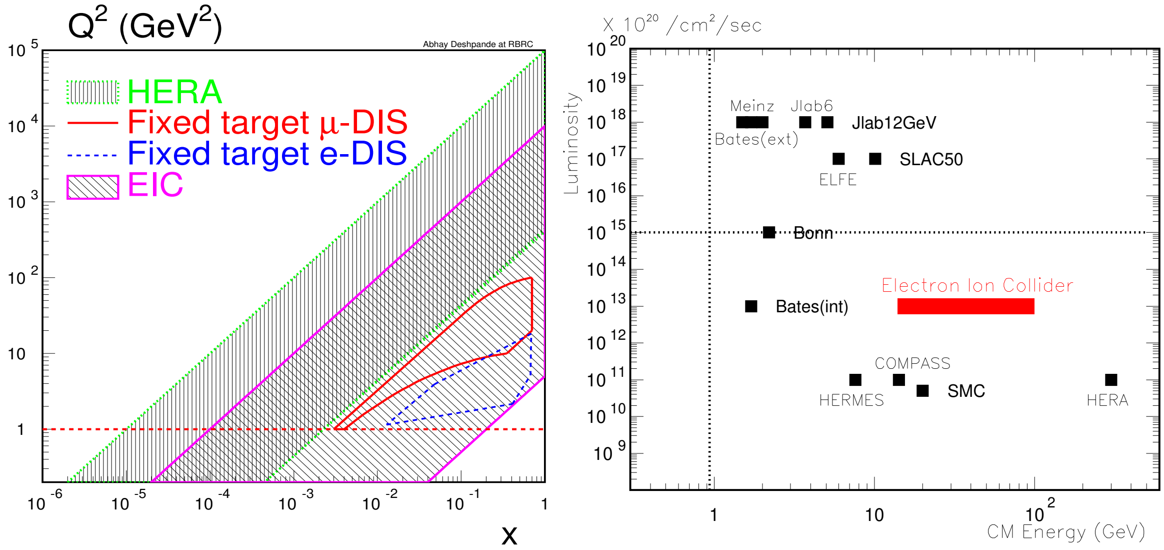

Figure 1: (a) The $x - Q^2$ range possible with EIC in comparison with the presently explored kinematic region by fixed target experiments and by HERA. (b) The plot of CM vs. Luminosity for EIC in comparison with the other experimental facilities around the world.

1.1 Polarized $\vec{e} \cdot \vec{p}$ studies with EIC

Much of our knowledge of the nucleon spin structure is based on the deep inelastic scattering (DIS) experiments carried out over the past three decades using charged lepton beams and fixed targets. These measurements were mainly *inclusive* in nature which determined the valence quark contribution to the nucleon spin precisely, but left the questions of the gluon spin (ΔG), and the angular momentum (L_q+L_G) contributions to the nucleon spin almost completely open.

After exploring the inclusive DIS, the recent fixed-target experiments produced semi-inclusive measurements that for the first time allowed quark-flavor decomposition of the nucleon spin. However, the "fixed target" geometry of these measurements inhibits full acceptance of the target fragments, and makes tagging on specific quark flavors difficult. Such semi-inclusive measurement do not necessarily require high beam energies, but they need good detector acceptance, excellent particle identification, and high luminosity. The approved next-generation DIS fixed-target experiments (HERMES (II) at DESY, COMPASS at CERN) represent improvements in this direction. But only DIS measurements in a collider geometry with almost 4π acceptance of a detector capable of excellent particle identification will overcome all present limitations.

1.1.1 EIC Physics at low CM energies

A program at low energies will use the high luminosity and collider geometry to perform semi-inclusive and exclusive processes with high precision and much more detail than hitherto possible.

- Effect of the parton's intrinsic transverse momentum in current fragmentation.
- Mechanism of polarization transfer from incoming lepton to the final hadronic states, from both polarized fragmentation functions and "fracture" function.
- How does removal of a certain parton from a nucleon affects probability that residue decays into a particular hadron? Including spin, this would examine how the polarization of the initial state affects the quantum numbers of the final hadron.
- Comparison of the relative number of baryons and meson states in target fragmentation with those in the current fragmentation, a region dominated by mesons. Polarizability of both beams allows investigations on how spin affects these ratios.

A polarized electron-hadron collider with high luminosity is uniquely able to address the question: *How do partons evolve into hadrons?*. The collider geometry allows clear separation of the current ("beam") and target fragments. The study of fragments provides a window in to the evolution of quarks into hadrons. Topics of interest are:

- Model independent studies of the parton structure of the neutron over a wide kinematic range using "tagged" structure functions, through the process $e+D \to e'+p+X$.

This technique can obtain accurate measurements of $d^p(x)/u^p(x)$ at large x, as well as proton and neutron spin asymmetries $A_1^n(x)$.

- Measurements of the π^+ structure function could be made by observing forward neutrons in the reaction $e + p \rightarrow e' + n + X$, determining the effects of sea quarks and gluons in the pion, and nuclear medium effects on meson structure functions. Similarly kaon structure functions could be obtained by observing Λ hyperons arising from the $e - p$ collisions.

- Transversity, the last unmeasured spin related structure function, could be obtained using the azimuthal asymmetry of pion production.

- Hard exclusive processes using deeply virtual Compton scattering (DVCS) and meson electro production provide access to the generalized parton distributions (GPD's), which are a topic of intense current interest and debate.

- Comparison of elastic processes with inelastic excitations to the $N^\star$ or the hyperon provides information about spin-flavor correlations.

1.1.2 Physics at high CM Energies

Every time the DIS experiments (including those related to spin) have moved into new $x - Q^2$ territory by increasing beam energies there have been surprises with respect to the structure of the nucleon. Figure 1shows that the $x - Q^2$ range of a 250-GeV proton on 10-GeV electron polarized collider increases by more than an order of magnitude over fixed target experiments in both x and Q^2. This allows one to address questions like: *what is the role of sea quarks and gluons in the nucleon's spin?* and *what is the quark-gluon structure of the photon?*

Specific inclusive and semi-inclusive measurements at high collider energies are:

- Spin structure functions $g_1^{\mathrm{p/n}}$ could be measured with high precision down to $x \sim 10^{-4}$ and at high enough Q^2 so that pQCD could be reliably applied.

- Low x measurement with very good accuracy will reduce the present 10% uncertainty in the test of the fundamental Bjorken sum rule to significantly less than 1%.

- Perturbative QCD analysis at next-to-leading order of the spin structure function results in the first moment of the polarized gluon distribution ΔG. Measurement of ΔG has been the principle motivation for the proposals and construction of major experimental facilities at CERN, DESY and BNL. EIC would reduce the uncertainty on this quantity by factors of 3-5.

- The ΔG in the nucleon can also be accessed through partonic processes where the gluon appears at LO. The photon gluon fusion process is one such example. Using the EIC data on di-jet production, the uncertainty in gluon distribution can further be reduced by factors of 3 or more.

- if this method of constraining $\Delta G(x)$ is coupled with the pQCD analysis method mentioned before, the effective improvement factor is estimated to be about 10 or higher.
- At high energies the virtual photon can resolve itself into its partonic contents. Unpolarized structure functions of the photon have been measured at HERA. A polarized EIC would do the same for the polarized photon. This would be a unique measurement not planned at any other future approved facility.
- Measurements of $W^{\pm}$ production (charged current events) give access, at intermediate x and high Q^2, to the parity violating spin structure functions $g_5^{\pm}$. These would be unique measurements no other experimental facility plans to measure them.
- Inclusive measurements made with EIC with very low Q^2 values determine the contributions to the Drell-Hearn-Gerasimov spin sum rule integral in the high energy regime. This would be complementary to the JLAB measurements. Although the integral contribution in this kinematics is small, the data constrain the extrapolations that are necessary to evaluate the full sum rule.

The RHIC spin program at RHIC, the first high energy collider with two polarized proton beams will overcome some of the obstacles of the fixed target experiments and will pursue some of the same physics goals of the polarized electron-hadron collider in a complementary way. An elegant test of universality of QCD and perturbative QCD (pQCD) dynamics would be that the final results from both facilities agree.

1.2 $e \cdot A$ with EIC

DIS off large nuclei at high energies is ideal for studying QCD properties at small x. Following the discovery of asymptotic freedom in the early 70's, perturbative QCD has been enormously successful in describing the physics of very high momenta that probe phenomena at wavelengths that are small compared to the QCD scale: $Q^2 \gg \Lambda_{QCD}$. However, these very high Q^2 processes comprise only a small fraction of the total cross–section at high energies. The vast bulk of the cross–section, corresponding to soft and semi–hard processes, is still poorly understood in QCD.

Note that for a fixed momentum transfer Q^2, the high energy limit $s \longrightarrow \infty$ is also the limit $x \longrightarrow 0$ since $x \propto Q^2/s$. The physics of high energy soft and semi–hard processes in QCD is therefore also the physics of small x. Understanding these small-x processes within the framework of QCD is an outstanding challenge to both theory and experiment. In fact it is in this regime that entirely new many-body manifestations of QCD may become apparent.

In a large nucleus, there are $A^{1/3}$ more partons per unit transverse area and the struck quark will sample them all. Due to this nuclear amplification, the parton densities reached in eA collisions at RHIC energies will be comparable to parton densities reached in ep collisions at $\sqrt{s} \approx 30$ TeV!! Thus EIC would have the same saturation scale Q_s as might an *ep* collider at LHC energies! EIC therefore provides an outstanding capability to answer the question: *How does partonic matter behave at extremes of low x.*

At very small x, the density of partons per unit area is large, and is characterized by a scale large compared to the QCD scale: $Q_s(x, Q^2) \gg \Lambda_{QCD}$. For x and Q^2 values beyond this scale, parton distributions saturate. The properties of these saturated distributions are predicted to be those of a *Colored Glass Condensate*. *Colored* because of because it is a manifestation of QCD, *Glass* because the infrared behavior of these parton distributions bears a formal resemblance to that of a spin glass, and *Condensate* because the occupation number of gluons in the saturated state is large. Such a state has not yet been seen, and it lies in a regime of QCD that has yet to be explored.

The properties of matter in the colored glass condensate can be probed both in inclusive and exclusive processes. In this regime, for instance, one expects hard diffractive events (a hard final state accompanied by a rapidity gap that is not exponentially suppressed) to comprise about 30% to 40% of the total cross–section. It is a particularly attractive feature of DIS experiments with a collider with tunable energies of the proton and nuclear beams that the longitudinal structure function (in the small x region) can be measured for the first time. This will provide a reliably gluon distribution at small x. Knowing the gluon distribution to high accuracy is very important for many applications.

EIC will be also very important for understanding the detailed properties of the hot and dense partonic matter (called a quark gluon plasma) that may be produced at RHIC and LHC. Sophisticated simulations now show that the multiplicity and final state properties of partons produced in heavy ion collisions sensitively depend on the bulk scale Q_s of the colored glass condensate. In heavy ion collisions the colored glass condensate is destroyed, resulting in large color field strengths that finally relax to form the plasma. Thus both heavy ion collisions, and deep-inelastic lepton scattering off nuclei provide crucial complementary information about a new regime of QCD. In this regime the coupling is weak, albeit the physics is non–perturbative, thus allowing accurate calculations. The study of the small-x regime in e-A collisions can resolve the long standing mystery of multi–particle production in QCD.

1.3 Accelerator & Detectors

The collider being proposed for the physics program above has exacting, but technically realistic, properties.

- It must be able to collide polarized electrons with polarized protons as well as light nuclei and heavy ions, with a center-of mass-energy range $\sqrt{s}$ from $14 \rightarrow 100$ GeV for polarized protons and ≥ 63 GeV/A for ions.
- The luminosity is to be $\geq 10^{33}\text{cm}^{-2}\text{sec}^{-1}$ per nucleon over the entire energy range.

While this luminosity is unprecedented for such a collider and drives the machine design, it is achievable with a focused R&D program, and may in practice be exceeded with clever detector integration into the machine lattice.

Many details of the collider configuration need to be decided in a dialogue between experiment and accelerator designers:

- What electron/proton(nucleus) energy tuning range is required to address the full panoply of QCD studies?
- What is the minimum bunch spacing and what clear length in the interaction region is required for a detector?
- How can the synchrotraon radiation incident on the interaction region be accomodated?

1.3.1 Accelerator physics issues

The high luminosities mentioned above will drive some design parameters, e.g. the electron current, to extremes (although the modern B factories have demonstrated that it can be done). Synchrotron radiation in a high current high energy electron storage ring is a serious limitation on magnet design. It is also important in the e-p/A collision region and determines the minimum radius with which the beams can be joined.

Two options have been evaluated for the collision geometry: The *Ring-Ring option* draws on established technology and the experience of the B-factory. The *Electron Linac-Ring* option offers several important advantages, but pushes existing technology in terms of electron current ($\geq$ 200mA) and requires full beam energy recovery along the lines of the FEL accelerator now operating at Jefferson Laboratory. For the proton and ion ring RHIC demonstrates the required ring capability covering the full energy range. RHIC does have available suitable interaction points and collisions between an electron ring or linac have been studied. It appears that e-A and A-A operation would be entirely transparent to each other. However, achieving the large luminosity requires that any proton/ion ring design (including RHIC) will require electron cooling at colliding energy (except for the highest energy protons).

Electron cooling at these energies has not yet been demonstrated. An R&D effort will be required to address several technical challenges:

- Need high precision manufacturing and alignment of a long superconducting solenoid
- Need to operate a 50 MeV high current ($\sim$ 100 mA) electron linac with full energy recovery.
- Must generate, transport and match a “magnetized” beam without continuous magnetic field.
- Need to de-bunch (then re-bunch) the beam to obtain low energy spread
- An interesting question for the electron cooled collider: Will the electron cooling permit an increase in the tune shift parameter which would further increase the luminosity?

- Need to resolve issues regarding high polarization, polarization time in the ring, and the strength of polarized sources, which have to be increased significantly above the presently achieved levels.

1.3.2 Detector issues

The development of detectors for EIC collisions can build upon the experience gained at Hermes for low energies, and at HERA for high energies. Some straw detectors have been developed. The geometry is of course highly asymmetric, consisting of a "hadronic component " detecting reaction products emitted along the p/A beam direction, a central "parton detector" detecting transverse hadrons and DIS electrons, and a lepton side in the direction of the electron beam. Both forward elements will need to be incorporated into the collider magnetic lattice elements and the electron inflection magnets. The energy variability of the EIC electron beam makes it possible to tune the reaction so that the central detector may be quite modest. These aspects may reduce the costs of such detectors, but require a vigorous R&D program in tracking detectors and calorimeters that are suitable for operation close to the beam and must accommodate strong synchrotron radiation.

1.4 Summary

An electron-nucleon/nucleus collider with an energy range from 30 to 100 GeV and operating with high luminosity will provide a world-wide unmatched capability to study QCD as a fundamental theory and its manifestations in the nuclear environment.

EIC will make possible precision studies of the partonic structure of mesons, nucleons and nuclei, and the evolution from partons to hadrons. It will also provide an unmatched capability to explore gluon saturation at low momenta, and to search for new many-body phenomena, such as the *Color Glass Condensate* predicted by QCD.

First studies indicate that such a facility can be built at reasonable cost. A vigorous R&D program over 3 to 5 years will be required in order to prepare a full conceptual design.

- It is proposed that this R&D program begin in the immediate future with the goal to construct EIC at the turn of the decade.