THE SCIENCE OF ELECTRON ION COLLIDERS

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Abstract

There is substantial international interest in a high energy-energy, high-luminosity polarized Electron Ion Collider (EIC). The EIC could explore unique aspects of interactions amongst quarks and gluons in hadrons and in nuclei and help us understand some of the most fundamental and universal aspects of Quantum Chromo-Dynamics (QCD). The impact of data at a future EIC would go beyond the reach of existing or other planned facilities including possible discovery of a new state of partonic matter, understanding the spin structure of the nucleon. I will review the goals of the proposed EIC and comment on the plans for its realization.

INTRODUCTION

Most of what we know about the hadron structure in terms of its quark-gluon (together called "partons") is a result of scattering experiments performed with neutrino, electron or muon beams (probe) off nucleons (target). Early 1960s the probe energies were insufficient to resolve the hadron structure (called "elastic scattering"), but later when the probe energies increased (multiple tens of GeV) the internal structure of the nucleons was discovered (Deep Inelastic Scattering, DIS) at SLAC and the field of QCD took a giant leap. Ever since then higher and higher energies of collisions have enabled deeper investigations of hadronic matter.

EIC PROPOSALS UNDER CONSIDERATION

Four Electron Ion Collider (EIC) proposals are currently under considerations: two in the US, and two in Europe. All four of them utilize existing, operating or planned facilities to be augmented or upgraded to realize these future collier proposals. In the US the two proposals: **e**RHIC at Broohaven National Laboratory (BNL)[1] and **EL**ectron **I**on **C**ollider (ELIC) at Thomas Jefferson National Laboratory (JLab) [2] propose to utilize their existing RHIC and about-to-be-upgraded 12-GeV CEBAF, respectively. eRHIC would be built by augmenting RHIC with an electron beam facility (Energy Recovery LINAC) and ELIC by building a hadron beam facility next to CEBAF, to accomplish the US EIC proposals. In Europe, the high-energy proposal entails adding an high energy ER LINAC complex to CERN's LHC, hence called the LHeC [3]. A second proposal Electron Nucleon Collider (ENC) [4], a low energy collider proposal involves adding a polarized electron beam facility to the future HESR ring at FAIR/GSI to collide with polarized protons. The machine parameters and other high level characteristics of interest are given in Table 1.

Table 1: EIC Proposals Under Consideration

Proposal	Center of Mass Energy (GeV)	Luminosity ($cm^{-2}sec^{-1}$)	Pol. of beams & nuclei	IR & detector
ENC	14	10^{32}	Pol: e, p, D	1 new detector: possible to use modified PANDA
ELIC	30-160 (Variable)	few $x10^{33-34}$	e, p, D Nuclei: up to Gold	Up-to 3 new detector
eRHIC	30-200 (Variable)	few $x10^{33-34}$	e, p, ^{3}He Nuclei up-to Uranium	Up-to 3, 1 new and two upgraded existing detectors
LHeC	1200	10^{33}	Pol: e Nuclei up-to Lead	1, new detector

The Kinematics and the Science of EIC

In DIS, four variables are commonly used: x, y, Q^2 and s. The variable x, called "Bjorken x" represents the fractional momentum carried by the struck quark in a certain frame of reference. The variable Q^2 represents the momentum transfer between the leptonic probe and the quark, typically a virtual photon carries this momentum. The resolving power of the experiment is defined by Q: The resolution of the experiment $\lambda = h/(2\pi Q)$. Variable y is a measure of inelasticity whether the collision was elastic (y~0) or inelastic (y~1). Last but not the least, "s" is the square of the center of mass energy of the lepton-proton collision. The four variables are related by a simple relation: Q^2=sxy.

The proposals listed in Table 1 are generally categorized in to three different center of mass energy settings; the lowest one being the ENC, and the highest one being the LHeC. The ELIC and eRHIC proposals are aimed at approximately 100 GeV in center of mass. Based on these and whether polarized beams are available, they have a somewhat complementary physics scope. For a fixed value of Q^2 and y, larger the value of s, allows exploration of lower values of x, the parton's momentum fraction. Hence the highest center of mass machine ENC, is intended for exploration of large x region

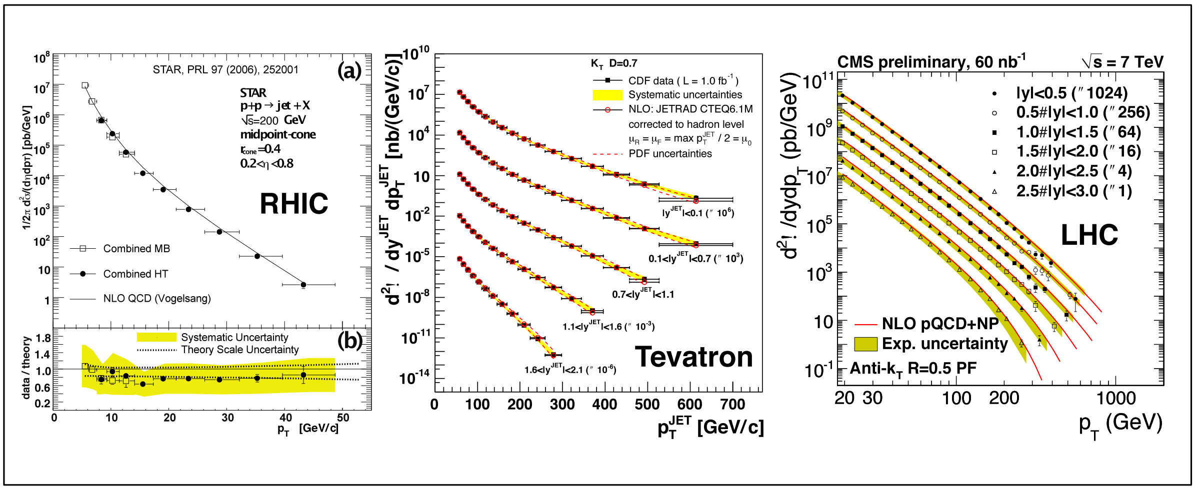

Figure 1: Comparison of data and NLO calculations of single inclusive jet cross-section. Data were measured at 200, 2000 and 7000 GeV in center of mass at three different hadron-hadron collisions facilities, namely, at RHIC, Tevetron and the LHC.

where (mostly) the quarks reside. The ELIC and eRHIC are designed to explore (mainly) the region of x< 0.1 going all the way to about 10^{-4}. They would also study polarization effects using their polarized lepton and hadron beams. They will also equipped to study nuclei at very low values of x using the idea that packing many nucleons in the nuclei allows one to explore many partons (gluons in this case due to high center of mass energy) at a time, coherently, with the virtual photon. Finally the LHeC with its highest energy among theses proposals, will allow exploration of even smaller values of x compared to the US EIC proposals by about 2 orders of magnitude.

QCD is without doubt the correct theory of Strong Interaction. Realization that the strong interaction constant behaves very differently (than the EM counterpart) and changes very significantly as function of the scale at which interactions occur has been a remarkable discovery of the last century which resulted the three proponents (D. Gross, H.D. Politzer, F. Wilczek) of the asymptotic freedom receiving the Nobel Prize in 2004. There has been enormous effort over the last two decades, experimental as well theoretical, to explore and test our understanding of QCD. We have not found any situation in which it, or its perturbative calculable formalism fails. Next to Leading Order (NLO) or Next-to-Next-Leading Order (NNLO) calculations based on our best knowledge of $F_2(x,Q^2)$ structure function of the proton measured at HERA seems to fit experimental data over a wide range of energies. Figure 2 shows a comparison of inclusive single jet cross sections calculated using the F_2 structure functions and our best knowledge of perturbative QCD (and some apparently valid assumptions regarding factorization of cross section formulae) at three different center of mass energies 200, 1800 and 7000 GeV. All seem to do extremely well. We hence know that at high energies perturbative QCD works.

Fig. 2 shows the calculation of mass spectrum of hadrons using lattice QCD with only three inputs masses: those of p, K and S. Also shown overlaid are the experimental data on the masses of the hadrons. Clearly the comparison is excellent indicating we can indeed calculate the masses based on the knowledge of QCD hard and soft interactions to a good degree of satisfaction.

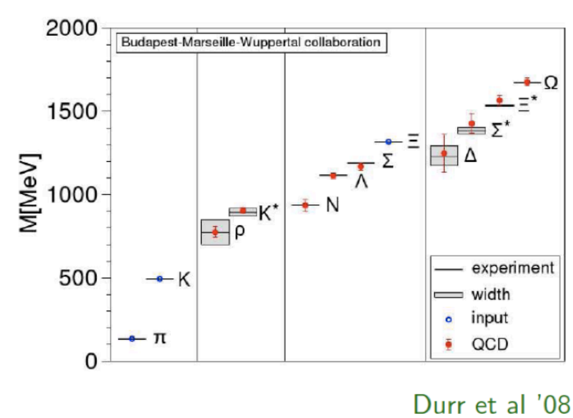

Figure 2: Calculation of mass of hadrons using lattice QCD and three masses as input (π, K, Σ). The rest of the calculations compare extremely well with the observed masses of the hadrons.

Based on such favorable facts and comparisons, one might be compelled to think, that it would mean we understand QCD fully and are able to calculate and understand all intricacies of the theory beyond any concern.

Unfortunately, this is not the case. For example, although can indeed calculate most of the mass spectrum of hadrons, we cannot calculate their spins based on the knowledge of interactions. Where is the proton's spin? How is it constituted based on contributions from quarks, gluons and their orbital motions contribute? The nucleon spin has been an open question, indeed an enigma, since the investigations began in the mid 1980s. One of the most important contributions the future polarized EIC could make would be to address this, one of the most fundamental and yet unanswered question in QCD.

The knowledge of longitudinal spin constitution of the nucleon is one of the original mysteries we have been after, however, its investigations have led to other, richer aspects of the nucleon structure that were not of interest just a decade ago, but have become "hot" topic now. They are now often categorized as "transverse spin phenomena" in the nucleon and fall in to two distinct categories: one, the transverse spatial distribution of partons in the nucleon and its correlation with the longitudinal momentum distribution, widely known as Generalized Parton Distribution functions (GPDs). The second category is the transverse momentum distribution (TMDs) of the partons. Clearly, the finite size of the nucleons over all dictates that the partons have some sense of boundaries of the nucleon; they know where they can and can not go, technically known in QCD as "confinement", one of the unknown or un-understood aspect of the QCD at low energy. The possibility of learning something about confinement as we learn more about the spatial and transverse position and momentum distribution of partons inside the nucleon has motivated a very large number of people in this field of QCD to study and explore these effects, systematically [5].

Over the past 10 years a consensus has developed that allows us a clear, theoretically understood way to address and measure the GPDs. The preferred methods seem to be electron-hadron scattering called Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Vector Meson Scattering (DVVMS). In these, the high Q virtual photon interacts with the partons inside the nucleon, excites them and the de-excitation may involve emission of a real photon (DVCS) or a vector meson (DVVMS). DVVMS necessarily involves gluonic interactions inside the nucleon, as such allows measurements of gluon GPDs. The formalism that has been developed promises ultimately that we could estimate the orbital angular motion of quarks and gluons quantitatively, initially, in a model dependent way, but hopefully later to evolve in to a model-independent evaluation. Considerations of finite size of the nucleon, and such knowledge of orbital motion of partons may be interconnected. As such the full understanding of spin and spatial structure of the nucleon may give us valuable understanding of the "confinement" in QCD, a yet un-understood but a true feature of QCD.

Another unknown in QCD is the behavior of gluons when their momentum fractions become extremely small. It is known from HERA, that at very low values of x, the gluon distribution function is presently unconstrained, i.e. it tends to go to infinity. The number of gluons increases indefinitely in this region. Physicists don't like infinities. Whether the infinite rise in the gluon distribution function extracted from the HERA data is an artifact of our lack of knowledge of non-linear QCD (multi-gluon dynamics which was never needed so far to explain data, and hence ignored), or there is something else that is wrong about our knowledge of QCD? This is not quite understood. To explore this question one would have to achieve energies significantly higher than those at HERA in an e-p collider in the future. This is possible at the LHeC, which would allow explorations at about 1.2 TeV in center of mass. Alternatively, one could use a very wise and insightful observation: that instead of building a higher energy e-p collider which could be prohibitively expensive, why not use the existing *nuclear* beams of RHIC and perform DIS at the highest possible energy (allowed by cost considerations). The nuclear enhancement factor for the Q^2 that has been suggested [5,6] is

$$Q^2_s\,(x,Q^2,A) = f(Q)*(A/x)^{1/3} \qquad (1)$$

The boundary of such a surface, a new saturation scale, is shown in Figure 3. If such an EIC with nuclear beams could be realized, one could explore a unique new form of matter that is predicted, which has shown to have very unique properties. The name given to this form of gluonic matter, at extreme low values of x, is the Color Glass Condensate (CGC). Discovery and study of this new form of gluonic matter, is one of the most exciting aspects of the EIC proposals [5,6].

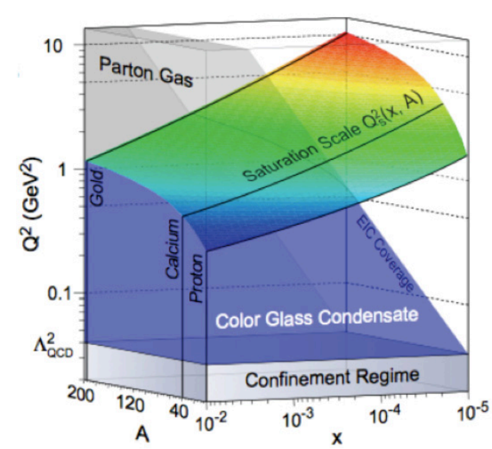

Figure 3: x,Q2,A dependence of Qs, the saturation scale and possible (accessible) region of exploration of Color Glass Condensate.

Another important aspect of the exploration of the nuclei at highest possible energy is that they form the initial stage of the collisions currently being pursued at RHIC as part of the Heavy Ion Collision Program, which discovered the Quark Gluon Plasma. QGP has been called one of the most interesting discoveries of the last decade. The scientists are embarking upon a new set of measurements over the next decade that will characterize the QGP with multiple new probes and detector upgrades. However, no amount of new measurements will allow us to fully understand the time line of evolution of the cold nuclear matter (CGC or other form of saturation) in to the QGP, as direct measurements of the initial state would do. As such measurements with EIC would form a very fundamental aspect of QCD studies in the next decade to be pursued at RHIC or at LHC with nuclear beams.

Coming back to the exploration possibilities of the four EIC proposals in the US and Europe. The low-x physics discussed above could be the principle topics of interest for the LHeC and the EIC (highest energy eRHIC) proposal. In addition to the low-x physics of saturation, and CGCs, there are numerous other aspects of nuclear structure that are yet unknown. An eRHIC with a rather range of nuclei in its arsenal of investigation could be an ideal machine for these investigations. LHeC would be a natural place for these studies as well, due to the shear high energy it could achieve. The nucleon spin studies require that both beams are polarized to the highest possible degree. Low x could be attained by both proposals of EIC (ELIC and eRHIC) up to about 10^{-4} in x, still restricting its exploration in perturbative QCD region with moderate-to-high values of Q. The ENC proposal in Europe is squarely aimed at the high x region, to study the quark sector in the best possible way, with both beams polarized. This would allow a complete exploration of GPDs and TMDs beyond the current experimental efforts at CERN by the COMPASS experimental collaboration and the JLab12 GeV upgrade being constructed and expected to run in the present decade.

TIMELINES AND REALIZATION

While it is extremely difficult to predict when exactly any of these future facilities will be realized, the time-lines and the hurdles that these proposals need to over come are being defined: The ENC proposal depends on successful completion and operation of the FAIR facility at GSI. The timeline for this is presently being discussed in the European nuclear and hadronic physics communities. The US EIC community consisting of the Jefferson Laboratory and BNL user communities are now coming together under the umbrella of US EIC collaboration to make the case for this future collider to the Nuclear Science Advisory Committee (NSAC) when it meets next, possibly in 2013 to make its next 5-year long range plan. In the last such meeting held in 2007, the EIC got rather favorable comments and funding for machine and detector R&D was funded. The US EIC community will ask in 2013 to go forward, and build such a facility in the US, either at BNL as eRHIC or ELIC at Jefferson Laboratory. In either case, the possible time for first collisions at a US EIC would be around the turn of the decade (~2020). The LHeC proponents are aggressively pursuing a timeline that would also bring LHeC in to collisions around the same time.

SUMMARY AND OUTLOOK

Contrary to popular belief, much remains to be understood about QCD, both at low and high energies. While we understand the basic interactions in QCD, the many body aspects of the QCD interactions, and dynamics of the partons including origin of spin are still unknown. The future of QCD investigations and the EIC proposals in the US and in Europe are driven by these fundamental questions.

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