Lepton-Hadron Collider Physics and Detectors : Electron Ion Collider (EIC) ep at $\sqrt{s} > 1$ TeV

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Abstract

Consider the physics opportunities of a lepton-hadron collider and how these opportunities might be realized in a possible polarized eRHIC facility and an e-p collider as part of a staged or final version VLHC. Detector challenges should be considered including possible physics opportunities in the forward direction. Contrast these opportunities with the physics likely from existing facilities and identify *R&D* needs for a realization of future programs.

1 Introduction

The Deep Inelastic Scattering (DIS) process, in which an electron (or any lepton) is used to destructively probe a hadron has proven to be one of the best ways to study hadronic structure and the nature of the strong interactions between its fundamental constituents (quarks and gluons). Over the past 30 years, the theory of color interactions of quarks and gluons, Quantum Chromodynamics (QCD), has been validated to distances at least 10 times smaller than the size of the proton. A future e-p collider has the following attractive advantages :

- The (pointlike) electron probe is ideal for examining proton structure.
- It is tunable over a wide range in hard scattering scale.
- QCD parameters and properties can be studied in a relatively background free environment.
- Some unique couplings may exist to new physics at high energy.

The first three points, taken together, define an e-p collider as a "QCD Factory" where all aspects of the strong interaction can be investigated, including short- to long-distance interactions between quarks and gluons, low- to high-density partonic states, and detailed measurements of the proton structure and its evolution.

2 Electron-Ion Collider (EIC)

At 2 recent Town Meetings held at JLAB in December 2000 and at BNL in January 2001, it was recommended to the Nuclear Sciences Advisory Committee (NSAC) that a high-luminosity electron-ion collider covering CM energies in the range of 30-100 GeV be built as the next generation facility for the study of electromagnetic and hadronic physics [1]. The purpose of this collider would be to answer the following questions :

- What is the structure, both flavor and spin, of hadrons in terms of their quark and gluon constituents?
- How do quarks and gluons evolve into hadrons via the dynamics of confinement?
- How do quarks and gluons reveal themselves in the structure of atomic nuclei?

In addition to these questions, the Electron-Ion Collider will contribute to a fundamental understanding of QCD by testing its predictions and parameters in extreme conditions and at the limits of its expected applicabilities. In particular, parton distributions will be measured in regions of parameter space in which non-linear effects are expected to dominate. Tests of QCD in regions where many-body effects between strongly-interacting matter are expected will be done. An even more fundamental question is whether nuclei can be used to study partonic matter under extreme conditions.

2.1 EIC Parameters

The EIC should be built with the following characteristics :

- Capable of collisions between electrons (positrons) and protons, light and heavy nuclei
- Provide high luminosity $L \geq 10^{33} cm^{-2} s^{-1}$ per nucleon
- Operate in a wide range of CM energies $E_{cm} = 15\ GeV \rightarrow 100\ GeV$
- Polarization of electron and proton spins
- Two interaction regions with dedicated detectors

2.2 EIC Physics Priorities

The following list of physics topics related to QCD can be addressed at the EIC :

Flavor and Spin Structure of the Nucleon : It will be possible to measure the pdfs of light quarks and the gluon by tagging final states in inclusive

DIS. For example, by tagging kaons, both momentum and spin pdfs of strange quarks can be determined with high precision down to $x \simeq 10^{-3}$. In general, the spin structure of the nucleon can be determined to lower x than is presently known, leading to a better understanding of the contribution of the sea to the total spin of the nucleon. Finally, a complete understanding of the partonic structure of a nucleon requires not only momentum and spin contributions, but also those from, for example, parton-parton correlations. These fall into a class of structure functions called Generalized Parton Distributions, many of which can be accessed at the EIC.

Partonic Substructure of Mesons and Hyperons : Very little is known about the structure of hyperons and mesons, despite their role as the glue that holds nuclei together. At the EIC, measurements of the quark and gluon structure of these particles can be compared to those in the nucleon. Since mesons and hyperons are the Goldstone bosons of spontaneously broken chiral symmetry, fundamental questions of the role of quarks and gluons in transition from partonic degrees of freedom to their Goldstone modes can also be addressed.

Hadronization : At the EIC, complete final states of the hard scattering process can be detected and reconstructed, allowing studies to be done of the transformation by colored quarks and gluons into color neutral hadrons. This non-perturbative process must be measured experimentally in order to understand the long-range dynamics of confinement. Using flavor tagging and jet reconstruction, studies of the transfer of spin from quarks to hadronic final states can also be done.

Role of Quarks and Gluons in Nuclei : Comparisons of collisions involving both light and heavy nuclei at the EIC can illustrate possible effects of nuclear matter on the parton distributions, for example, the effects of nuclear binding, expressed as exchanged mesons, on the underlying quarks and gluons in nucleons. The large range in x at the EIC allows the x-dependence of these and other nuclear effects to be determined. Also, the initial conditions for relativistic heavy ion collisions can be determined, helping to fill in missing pieces of the transition from cold, partonic matter to a hot, dense quark-gluon plasma.

High Density QCD at Low x : At HERA, the scaling dependence of F_2 at low x indicates that the gluon density increases very steeply as x decreases. Unitarity bounds on the gluon distribution predict that this steep rise must eventually saturate, at around $x \simeq 10^{-6}$ for $Q^2 = 10\ GeV^2$. Across this boundary, non-linear evolution of parton distributions occurs, leading to a new state of color-saturated high-density QCD. Since the parton densities in nuclei are enhanced by a factor of $A^{1/3}$, these effects might be seen in nuclei at lower energies than in protons. The EIC could be the first place to see this new state of partonic matter, if nuclear effects are negligible or non-existent in the low x region.

3 ep at $\sqrt{s} > 1$ TeV

There are presently no e-p colliders planned at $\sqrt{s} > 1$ TeV. A possible upgrade to HERA, THERA [2], in which 250 GeV electrons from TESLA [3] are collided with 900 GeV protons from HERA, has been studied. This option (at $\sqrt{s} \sim 1$ TeV) can only be realized if TESLA is built at DESY, if the accelerators are made to match at an appropriate IP, and if luminosity is taken from the TESLA program and provided for THERA.

At the Snowmass 2001 workshop, studies were made of an e-p option in which electrons from a future e^+e^- linear collider are collided with protons from a future VLHC [4]. Our "standard" option was defined as a 250 GeV e^- interacting with a 20 TeV proton, corresponding to Stage I of the VLHC (epVLHC). The corresponding CM reach of this option is $\sqrt{s} \sim 4.5$ TeV. The ratio of incoming beam energies is $E_p/E_e = 80$, more than twice the asymmetry at HERA. As an alternative, one of the THERA options, 800 GeV e x 800 GeV p was studied as an example of a symmetric collider. Both the asymmetry of the beams and the physics requirements affect the design of detectors at a future e-p facility.

3.1 Physics Priorities

In the early planning for HERA, it was thought that new physics beyond the Standard Model was within range. HERA would see at least some of the following : leptoquarks, excited electrons, contact interactions indicating quark substructure, SUSY, and others. Now we know that the Standard Model is alive and well at HERA. However, HERA has expanded our knowledge of the proton structure by several orders of magnitude in both hard scattering scale, Q^2, and longitudinal momentum fraction, x. It has shown that the inclusive proton structure function, F_2, rises steeply as x decreases. This steep rise has been linked to a large increase in the gluon distribution in the proton at low x. HERA has also discovered that hard diffractive scattering contributes a significant amount to the total DIS cross section. Also, at HERA, extensive inclusive and exclusive measurements have been made to test the limits of perturbative QCD and to study the transition to the non-perturbative regime.

So, we have learned that e-p at HERA is an ideal place to study the dynamics of perturbative QCD. We have, therefore, taken this lesson from HERA and applied it to our determination of physics priorities at a future e-p collider. We believe that the following ordered physics priorities should form the basis of the physics case for a future e-p collider.

3.1.1 Perturbative QCD Dynamics at Low x

Th evolution of partons in the proton is normally described by a set of linear equations where the number of partons evolves as a function of either Q^2

(DGLAP evolution), x (BFKL evolution), or a combination of both Q^2 and x evolution (DLLA). The following table summarizes the forms of linear parton evolution :

	DGLAP	DLLA	BFKL
Resummed terms	$(\alpha_s \ln Q^2)^n$	$(\alpha_s \ln Q^2 \ln 1/x)^n$	$(\alpha_s \ln 1/x)^n$
Region	High/medium x	low x	small x limit
Program	Fixed target DIS	HERA/THERA	epVLHC

Outstanding questions remain about the form of the linear evolution processes seen in the HERA DIS data. At HERA, DGLAP alone can describe the full range of inclusive F_2 data as long as enough gluons are included in the proton at a low scale. Some more exclusive measurements, e.g., final state multiplicities in the current region of the Breit frame, are consistent with DLLA evolution, and from forward jets and hadrons, it also appears that DGLAP alone is unable to describe the data. The tunability of the electron probe is a distinct advantage in measurements of this type, since it allows for selection of extreme kinematic regions where one evolution scheme is expected to dominate over the others.

A future e-p collider at very high energy can access the very small x region where BFKL evolution should apply. At some point, DGLAP should fail to describe the data when large longitudinal distances are being probed (very small x). As the number of partons increases, which is evident at HERA with no signs of stopping, eventually parton-parton interactions should start to occur. The eventual trade-off between parton evolution and parton-parton recombination "saturates" the cross section and the steep rise becomes flat. The complete description of parton evolution would then require the addition of non-linear terms. This should occur when the number of gluons is $xg \sim Q^2/\alpha_s(Q^2)$. HERA has had much success in mapping the low-x growth in F_2, but has not yet seen effects that could be interpreted as saturation of the proton structure function. Extrapolating with GRV pdfs, at $Q^2 = 10\ GeV^2$, the saturation boundary would occur at $x \simeq 10^{-6}$.

At Snowmass, simulated events were generated using the CASCADE Monte Carlo program [5] which incorporates the CCFM parton evolution model. This model should be a good choice at a future e-p collider since it allows for x-evolution of the partons (BFKL) in the small x limit. Figure 1 shows the e-p scattering kinematic plane in x and Q^2 comparing HERA with THERA and epVLHC. A minimum scattering angle for the electron of 10^o was required for each option and shows up as the high x, low Q^2 limit of the events generated for THERA and epVLHC. The low x, high Q^2 limit is the kinematic constraint, $y \leq 1$. The red shaded region denotes the part of the region where $ln\ 1/x$ is at least a factor of 5 larger than $ln\ Q^2$. For $Q^2 = 10\ GeV^2$, this is where saturation effects should occur.

The onset of saturation is also affected by the twist level (higher order

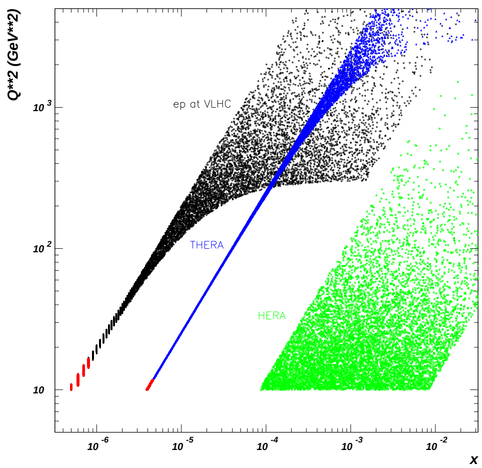

Figure 1: *Kinematics at HERA, THERA, and epVLHC, indicating where saturation is expected to occur.*

$(1/Q^2)^n$ terms of the evolution equations. Current measurements of F_2 are well-described by twist-2 evolution equations, but even after considering higher-order corrections these equations do not lead to saturation as $x \to 0$. However, with appropriate choices of pdfs and screening radius (size of the region in the proton in which parton-parton interactions begin to occur), twist-4 contributions to the evolution equations predict the onset of saturation at around $x = 10^{-7}$.

At even lower x, beyond the saturation boundary, perturbation theory breaks down even if α_s is small, because the non-linear effects are large. The physical state of quarks and gluons in this region has been described as a Color-Glass Condensate, named from the type of equations used to describe high-density concentrations of the colored gluons. If this state exists, it should be seen at a future e-p collider with $\sqrt{s}$ in the few TeV range.

3.1.2 Proton Structure and Flavor Decomposition

In addition to measurements of inclusive proton structure functions, an e-p collider is also an ideal place to decompose the inclusive F_2 measurement into individual flavor pdfs. In searches for new physics at p-p machines, e.g., at the LHC and VLHC, it will be important to know the contribution to cross section measurements from the heavy quark content of the proton. As is the case today, all measurements of the b quark cross section, including those at HERA, are larger than the predicted theoretical values, and without a precise measure of the b content of the proton, this difference is hard to interpret as new physics.

Comparisons between HERA, THERA, and epVLHC for heavy quark distributions were examined in MC simulated events. The following plots show the light and heavy quark distributions in pseudorapidity (η) for the three e-p options. A minimum p_T requirement of 6 GeV was made on the quarks. For

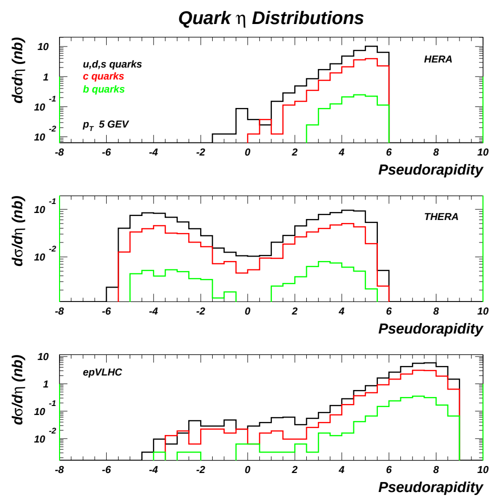

Figure 2: *η distributions of quarks at HERA, THERA, and epVLHC.*

both HERA and epVLHC, the quarks are forced into the forward (proton direction) region, requiring a detector which would look more like a fixed target detector than a collider detector. However, for the symmetric case of THERA, the quarks are scattered closer to the central region. A "standard" symmetric collider detector with vertex detector and some extended coverage in the forward region might work for this configuration.

3.1.3 Beyond the Standard Model (BSM)

Although the opportunities for studying exotic physics at a future e-p facility are potentially rich and varied, we did not attempt any predictive studies at Snowmass. However, the following discussion summarizes the current state of some BSM investigations and indicates where a future e-p collider could contribute.

Leptoquarks (LQ) and squarks : An e-p collider is ideal for the production of new bosons possessing both leptonic and baryonic quantum numbers, e.g., leptoquarks and squarks in SUSY with R-parity violation. HERA has set limits on the production of these particles that are competitive with comparable limits set at the Tevatron. If LQs are discovered in a hadron-hadron collider (e.g. LHC), a future e-p collider would be the best place to study their properties : the angular distribution of the final-state lepton can discriminate between scalar and vector resonances; the LQ fermion number is determined by comparing the signal cross section in e^+p and e^-p collisions; the chirality structure of the LQ coupling can be determined by the polarisation of the incoming lepton beam. Further constraints on the LQ coupling can be made by polarizing the proton beam as well. At an e-p facility at the VLHC, s-channel LQ resonances in the mass range up to $\sim 4.5\ TeV$ could be seen directly, as well as higher mass states by parametrisation as a contact interaction.

Contact Interactions : In addition to very high mass LQs, generic four-fermion contact interactions can also signal new physics processes, e.g., by interfering with the observed NC DIS cross section. If contact interactions were seen, e-p collisions would give a unique insight into the chiral structure of the interactions by exploiting the lepton beam polarization.

Excited Leptons : Although the LHC will be able to discover e^* and ν^* by pair production independent of coupling, some processes involving these particles are better done at an e-p collider. For example, searches for ν^* can take advantage of the large u-quark density in the proton and the helicity nature of the charged-current interaction.

Large Extra Dimensions : The t-channel exchange of Kaluza-Klein gravitons in models with large extra dimensions affects the Q^2 distribution of NC DIS events. While the LHC again can probe very large compactification scales, some models predict that fermions with different gauge quantum numbers are localised on different branes. A future e-p machine could provide complementary information on fermion localization, since the two-gluon final state would dominate the cross section at the LHC.

3.2 Detector Considerations

Since it is easier to accelerate protons to higher energy than electrons and positrons, the highest $\sqrt{s}$ e-p machines would be highly asymmetric in incoming beam energies. At HERA, the proton beam energy is $\sim 30\times$ that of the lepton beam. At the VLHC, with 20 TeV protons colliding with e^+e^- linear collider electrons of 250 GeV, the asymmetry factor is ~ 80. Therefore, the detector must be highly asymmetric with most of the detection capability far forward in the proton direction. The detection of scattered electrons would also require calorimetry in the opposite direction to the proton. For studies of QCD dynamics and non-linear evolution effects, an asymmetric detector would suffice, including good angle and energy measurement of the scattered electron and the capbility of hadron/jet reconstruction in the far forward region. Since the objective is an inclusive measurement at extremely low x, a split detector of this type would be necessary at such a highly asymmetric collider facility.

For measurements of flavor pdfs, a more symmetric configuration would be desirable, however, as already mentioned, this would come at the expense of $\sqrt{s}$. Even with symmetric beam energies, the heavy quarks populate the forward region of the detector, so forward detection is still important. Detectors for more symmetric beams look more like traditional collider detectors.

For studies of possible BSM processes, it is important to have a hermetic 4π detector. This is very difficult to do with highly asymmetric beams, so specific BSM searches would be chosen at the detector design stage. This limits the effectiveness of a future e-p machine as a BSM search device, hence our lower priority for this type of physics.

4 Conclusions

We have attempted to understand the important physics issues for possible future e-p colliders. Both the low $\sqrt{s}$ (EIC) and high energy options (epVLHC) are seen primarily as QCD "Factories" which utilize the advantages of a point-like, well-defined probe to measure the parameters and dynamics of QCD theory. Our aim was to provide a general, first view of future e-p options, so that if, at some future date, an e-p collider configuration becomes viable, specific physics and detector studies can build on our ideas as contained here.

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