Hadronic Physics with a Polarized Electron-Ion Collider

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Abstract. A high luminosity polarized Electron-Ion Collider (EIC) can provide precise and complete data essential to the ultimate understanding of the microscopic structure of matter. With a luminosity in excess of $10^{33} \cdot \frac{1}{A}$ cm^{-2} s^{-1} and a variable center-of-mass energy in the range of 30 to 100 GeV, EIC would be a powerful new microscope to probe the partonic structure of matter. The scientific highlights motivating the machine are summarized.

INTRODUCTION

It has now been over twenty-five years since the formulation of Quantum Chromodynamics (QCD), the theory which identifies colored quarks and gluons as the basic constituents of matter, and which provides an understanding of the strong interactions in terms of the basic forces between these nucleonic constituents. In the intervening decades, we have learned a great amount of information about the partonic (quark and gluon) structure of hadronic matter. However, our knowledge is still far from complete. Some 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 into hadrons?
- What is the role of quarks and gluons in the structure of atomic nuclei?

The answer to these questions is the missing 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 would be the ideal machine to address the above questions. The collider should have a high luminosity, greater than $10^{33} \cdot \frac{1}{A}$ cm^{-2} s^{-1}, and have a variable center-of-mass energy in the range of 30 to 100 GeV.

A "NEXT-GENERATION" FACILITY FOR PARTONIC PHYSICS

Measurements of deep inelastic scattering (DIS) carried out over the past 25 years have determined single-quark probability densities with great precision [1]. However, in inclusive DIS with charged lepton beams, one is unable to distinguish between quark and antiquark contributions to structure functions, and it is difficult to separate contributions from different quark flavors. Recently, semi-inclusive deep inelastic scattering has been used to differentiate between contributions from quarks and antiquarks, and to identify the quark flavors participating in partonic reactions. In the past year or two, there has been great interest in the physics insights which can be obtained from hard exclusive reactions; the proof of factorization theorems, and studies of generalized parton distributions, have made this an exciting area of research.

As a result, there is great interest in using semi-inclusive and exclusive processes to probe new features of the quark-parton structure of matter. The HERMES experiment at HERA used semi-inclusive measurements to determine the contributions of different quark flavors, and quark vs. antiquark effects, in the spin of the proton [2]. They have also obtained first measurements of exclusive (technically, "semi-exclusive") processes. Measurement of such processes is also a significant aspect of the proposed 12 GeV upgrade at Jefferson Laboratory [3].

These facilities, together with the upcoming COMPASS experiment at CERN, will provide a tantalizing first look at these reactions. However, experimental conditions at these facilities (see Fig. 1) are not optimally suited to studies of partonic physics. They typically operate at rather low Q^2 values, where higher-twist contributions could be substantial. They also have a limited range in both x and Q^2, which makes it difficult to observe the evolution of these distributions. As a consequence, it would appear that a dedicated facility, designed from the outset to probe the essential $x - Q^2$ region, and with the detection capabilities required to access this physics, should be the highest priority for a "next-generation" facility in the field of electromagnetic and hadronic physics.

What are the features of a facility necessary to address these issues? First, it must have sufficiently high energy that the cross-sections are dominated by the leading amplitudes. Next, it should have optimal control of spin-flavor degrees of freedom. It should allow full kinematic coverage; in particular, to observe both the fast current jets, and the slow target fragments. Furthermore, it should provide full azimuthal coverage, since azimuthal asymmetries highlight key aspects of quark/parton structure. In addition to continued inclusive measurements, such a facility will concentrate on both semi-inclusive and hard exclusive processes, which require both high luminosity and effective coincidence detection.

To address these issues, we propose an "*E*lectron-*I*on *C*ollider", or *EIC* facility. This would be an asymmetric collider, with an electron beam colliding with a beam of protons or ions. For the lightest ions (p, D and ^{3}He), both beams would

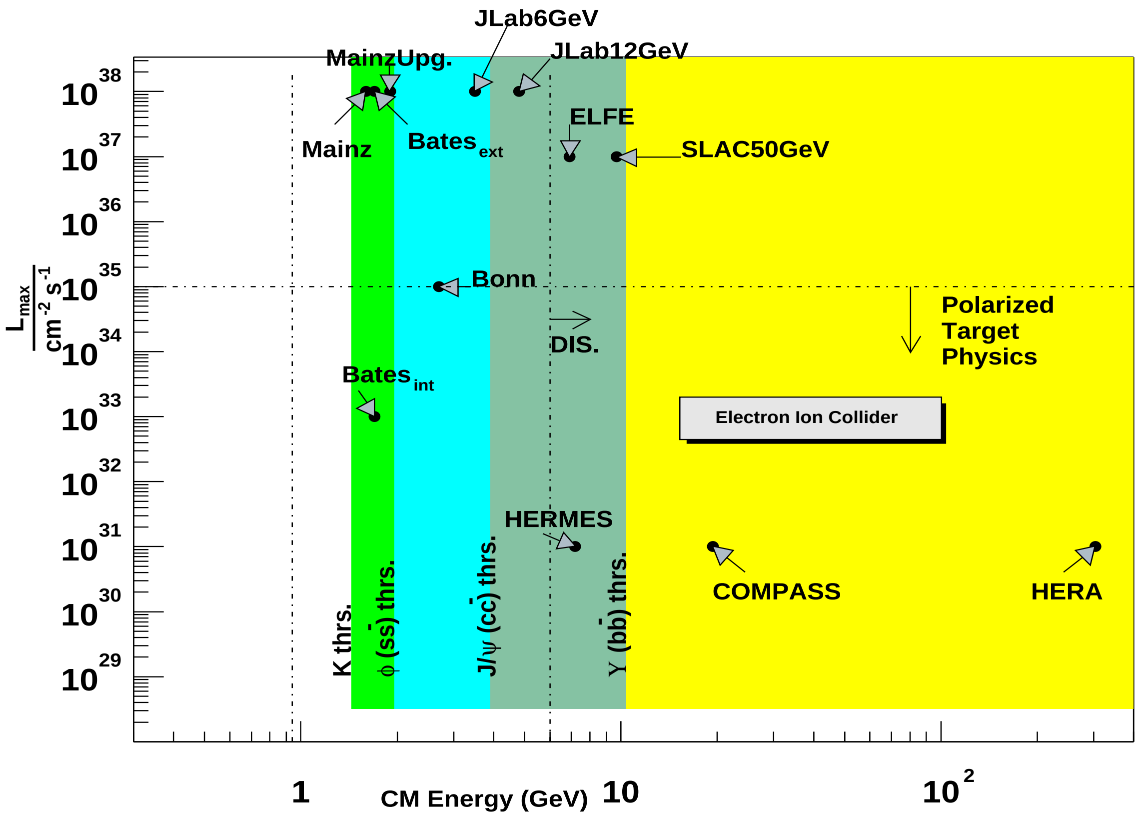

FIGURE 1. A plot of maximum luminosity vs. CM energy for a selection of existing and proposed facilities worldwide using lepton scattering. The shaded area denotes the proposed EIC parameters.

be polarized, in order to provide maximal control of the spin and flavor degrees of freedom. The collider CM energies would be substantially greater than at fixed target facilities such as Jefferson Lab or SLAC, and well below the high energy range of HERA. Such a facility would provide high luminosity (an $e-p$ luminosity of at least 10^{33} cm^{-2}s^{-1}) to enable the study of semi-inclusive and exclusive reactions. Variable CM energy will allow the study of hard exclusive processes, where detection of all final-state particles is easier at lower energies. For inclusive measurements and heavy-nucleus collisions higher energies, up to $\sqrt{s} \sim 100$ GeV, are desirable. The asymmetric collider geometry would allow both current fragment and target fragmentation events to be measured and kinematically separated. Fig. 1 shows the luminosity vs. CM energy for a series of existing and proposed electron facilities. To date, facilities cluster into high luminosity but relatively low CM energy machines, and high energy but low luminosity facilities. Clearly, the EIC collider would occupy a unique regime.

For partonic physics at moderate x, in semi-inclusive and exclusive measurements, a large solid-angle detector is required with excellent particle identification and tracking capabilities. The luminosity and particle ID requirements necessitate that the accelerator and detector design be closely correlated. We request an aggressive R&D effort over the next few years, in order to evaluate competing accelerator designs, and to demonstrate that the luminosity and detector requirements can be simultaneously satisfied.

The physics potential of such a collider has been reviewed in a series of conferences and workshops. The first of these were held in Germany beginning in 1997 [4]. These were followed by a series of workshops on electron colliders [5–7] held in the US. Obviously it is impossible in such a short document to review all physics topics; we refer to the workshop proceedings for a more complete list.

SEMI-INCLUSIVE MEASUREMENTS OF PARTON STRUCTURE

In semi-inclusive measurements induced by leptons, one measures both the scattered lepton, and a fast outgoing final hadron. The resulting cross section is given by

$$\sigma \sim \sum_q e_q^2 \, q(x) \, D_q^h(z)$$

In addition to the quark probability $q(x)$, the cross section contains the "fragmentation function" $D_q^h(z)$, which describes the probability that quark q will fragment to final hadron h with fractional energy z.

The EIC facility could probe parton spin distributions at an order of magnitude smaller x than can be measured at HERMES. Figure 2 shows the precision which could be obtained for spin probabilities for various quark flavors, with one month's running at the EIC projected luminosity [8]. One can obtain impressive statistical measurements, in a kinematic region clearly complementary to that probed at Hermes.

Another possibility is model-independent studies of neutron structure using the technique of *spectator tagging*. With a deuteron beam, one can measure protons in coincidence with the scattered electron in the process $e + D \to e' + p + X$. The spectator proton will move forward with momentum $k_p \sim k_D/2$. The neutron structure function can thus be measured on-shell, over the kinematic range $1 < Q^2 < 200$ GeV^2. With this technique, one can obtain accurate measurements of $d^p(x)/u^p(x)$ at large x. Since deuteron Fermi motion, binding and relativistic effects are all significant at large x, this quantity is surprisingly poorly known. In addition, with either polarized deuteron or ^{3}He beams, one can obtain accurate measurements of proton and neutron spin asymmetries A_1^N at large x, as measurements of this quantity appear to be crucial tests of QCD models. Spectator tagging could also be used to extend measurements of the neutron spin structure function $g_1^n(x)$ to

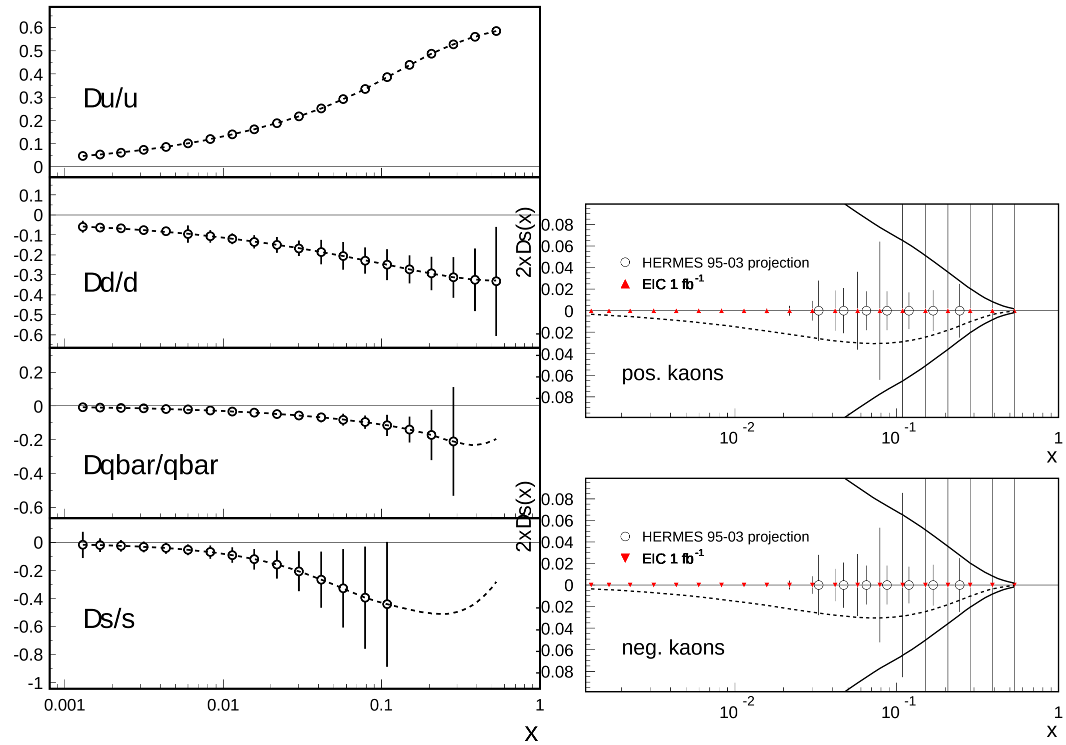

FIGURE 2. Left: statistical errors and range of x which could be covered by EIC collider for quark spin densities. Right: statistical accuracy which could be reached by EIC in one month of running at design luminosity, for strange quark spin distribution, if spin densities of non-strange quarks were accurately determined [8].

lower values of x. The additional information would be very useful in decreasing experimental errors in the determination of the Bjorken sum rule.

An electron collider would also allow precise measurements of pion and kaon structure functions. At present, pion valence quark distributions are reasonably well known in the region $x_\pi \geq 0.2$, but poorly known for smaller x. With the collider, we could obtain accurate values through the reaction $e + p \rightarrow e' + n + X$. Forward neutrons are detected in $e - p$ scattering. The photon scatters from a virtual π^+ which is very near its mass shell, and the resulting cross section is proportional to $F_\pi(x_\pi)$. Simulations by Holt and Reimer [9], in Fig. 3 show that F_π can be determined with excellent precision in the region $0.01 \leq x_\pi \leq 0.9$. At low x, one can answer the question, *"Are sea quarks and gluons as important for pions at low x as for the nucleon?"* One could then repeat these experiments with a nuclear target to determine *"How does F_π vary in the nuclear medium?"* Finally, one could obtain accurate measurements of the kaon structure functions using the reaction $e + p \rightarrow e' + \Lambda + X$. Only very sketchy information is known about the kaon structure function to date.

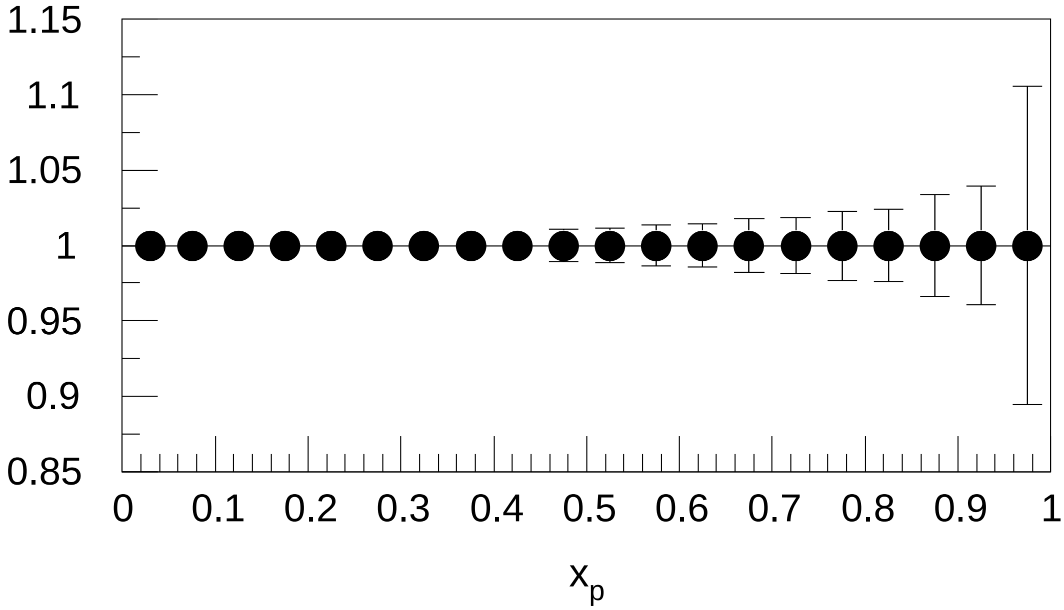

FIGURE 3. Expected precision in determination of the pion structure function F_π as a function of x_π, which could be obtained from less than one month's collider measurements of forward neutrons in $e-p$ collisions [9].

A polarized EIC facility would be able to make definitive studies of *transversity*, a third leading-twist structure function. The transversity $h_1(x)$ is proportional to $\delta q(x)$, the transverse spin difference for nucleons. One reason that transversity is interesting is that, unlike the longitudinal spin distribution g_1, gluons do not contribute to h_1. Consequently, h_1 should evolve much more like the valence quark polarization than the longitudinal spin structure function g_1, which is believed to have a very large contribution from polarized glue. The first moment of h_1 is equal to the nucleon's tensor charge, a quantity which may be calculable with lattice QCD.

As h_1 is a chiral-odd operator, it is inaccessible in inclusive DIS, but in semi-inclusive processes (e.g., $e+\vec{p} \to e' + \pi + X$) this effect could be observed by measuring the azimuthal asymmetry of leading pions. The asymmetry will be proportional to $A \sim h_1(x)\, H_1^\perp(z) \sin\phi$. Consequently, one measures the product of the transversity distribution times the so-called Collins fragmentation function $H_1^\perp$, another chiral-odd operator. With sufficiently precise data, one could separately determine the x-dependence of h_1 and the z-dependence of $H_1^\perp$, and hence determine h_1 to within an overall normalization. Transversity can be accessed by measuring single-spin asymmetries in semi-inclusive electroproduction on a transversely polarized target. Both HERMES and COMPASS will make exploratory

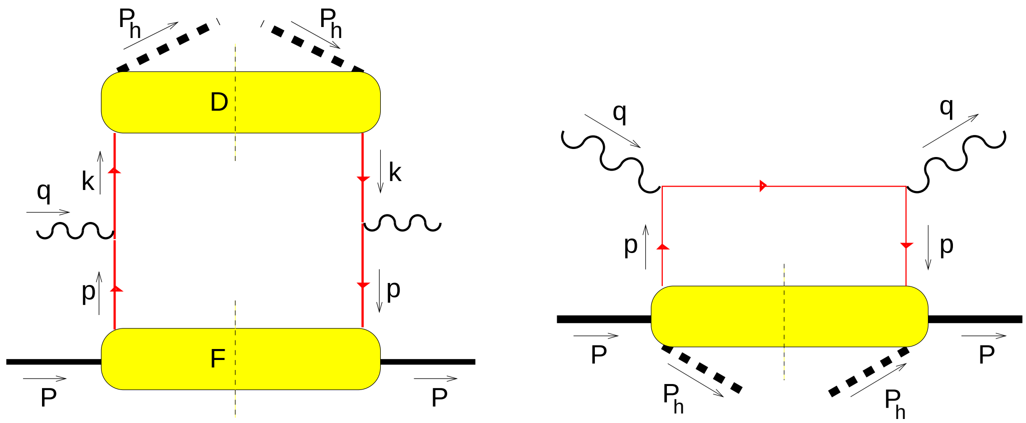

FIGURE 4. Leading contribution to fragmentation processes, in which quark q evolves to final hadron h. Left: current fragmentation; Right: target fragmentation, where the quark is struck by a virtual photon while baryon remnants fragment to final hadron.

measurements of this quantity; however the collider geometry is optimal for this type of study, since in a collider one can detect the full hadronic final state, both current and target fragmentation regimes are accessible, and one can measure complete angular distributions and hence extract moments of the parton distributions.

Parton Evolution into Hadrons: Fragmentation

An interesting partonic phenomenon which could be studied with a polarized electron-ion collider in the EIC energy regime is the *fragmentation* of quarks into hadrons. In such studies, a quark makes a transition into a final hadron which is detected. The ability of the collider to detect all final hadrons will allow detailed studies of the properties of fragmentation. The most commonly studied process is that of *current fragmentation*, shown schematically on the left in Fig. 4. In this process, the quark struck by the virtual photon decays to a final hadron h. There is also the *target fragmentation* process, where a quark is struck with a virtual photon in a lepton-induced reaction, and one observes the subsequent decay of the nucleon remnants. The kinematic situation for target fragmentation is shown schematically on the right-hand side of Fig. 4.

Target fragmentation is a largely unexplored regime of QCD. Observing such processes requires a detector capable of measuring decay fragments separated from the current jet by a large interval in rapidity. As a result, the collider geometry is probably essential for studies of the target fragmentation region. In Fig. 5 we show a plot by Mulders [10] of rapidity vs. fragmentation energy fraction z, for a $\gamma^* N$ invariant mass $W = (1-x)ys = 20$ GeV. Our experience from the EMC results suggests that both current and target fragmentation regions extend over a CM rapidity range $\Delta\eta \approx 2$, where the rapidity is defined by $\eta = 0.5 \ln(P_h^-/P_h^+)$. Fig. 5 shows the z values above which current and target fragmentation could be

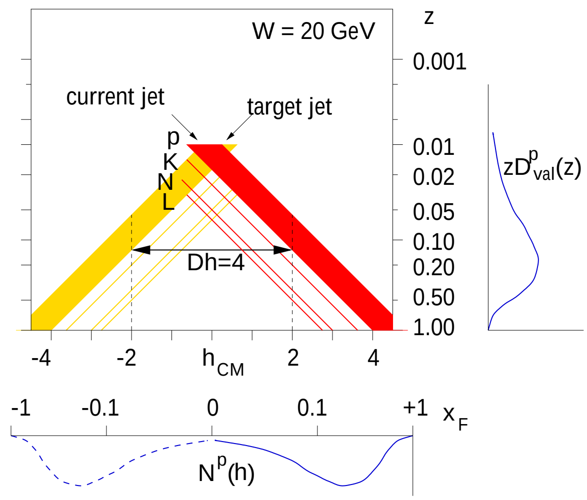

FIGURE 5. Relation between z-values in fragmentation and CM rapidity for $W = 20$ GeV. Roughly speaking, for regions separated by at least four units in CM rapidity, current and target fragmentation can be kinematically separated.

kinematically separated; for $W = 20$ GeV, these regions can be separated for all $z \geq 0.01$. Increases in W greatly lower those z-values, and demonstrates that a collider, with the properties which we have defined, has the capability of accessing and separating both the current and target fragmentation regimes.

There are two types of target fragmentation. In the first case, the momentum fraction x carried by the struck parton is small. The momentum fraction of the remnant, $1-x$, is large. In this case the subsequent decay is not correlated with the initial parton. Trentadue and Veneziano [11] described target fragmentation processes in terms of *fracture functions*. A fracture function represents the probability of finding a parton of a certain flavor i, together with a hadron h, in the target nucleon. One can subsequently determine how the fracture function evolves in Q^2, in analogous fashion to the DGLAP evolution equations for parton distributions. As the fracture functions are universal, they can be measured in other processes, for example diffraction. There exists some first experimental data for these processes from HERA. EIC could investigate this regime in detail. As this field is largely unexplored, the discovery potential is quite high. With both polarized leptons and hadrons, one could measure the extent to which the polarization of the initial state affects the quantum numbers of the final hadron h. In the current fragmentation regime, a quark which has participated in a hard scattering event evolves into a hadron. This region is "meson-rich," since the quark can become a meson by picking up a single antiquark. Naively, one expects the target fragmentation region to be relatively "baryon-rich", since after removal of a single quark the two remaining valence quarks can decay to a baryon by picking up a single quark.

There is another kinematic regime, as yet unexplored, for which an asymmetric electron-ion polarized collider at these energies would be a uniquely capable facility.

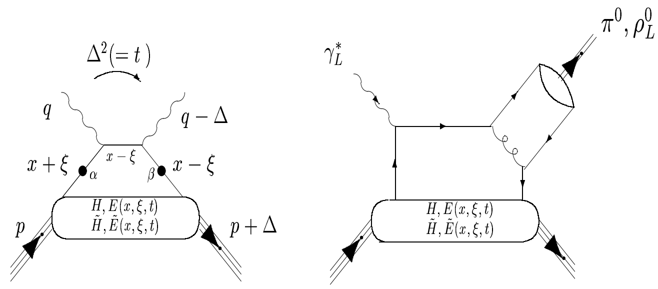

FIGURE 6. Leading order diagrams for DVCS (left) and for longitudinal electroproduction of mesons (right).

This is the regime of large x for the struck parton in target fragmentation (right side of Fig. 4). In this case the momentum fraction $1-x$ of the hadronic remnants is small. At higher-energy facilities like HERA, these slower-moving fragments cannot be analyzed as they proceed down the beam pipe. The subsequent remnant decay is correlated with the struck parton, and does not evolve with Q^2.

HARD EXCLUSIVE PROCESSES AT A COLLIDER

An asymmetric polarized beam collider provides the opportunity to study the correlations between partons in nucleons and nuclei. A particularly promising area is the study of hard exclusive processes. One of the leading terms in the amplitude for a hard exclusive process is shown schematically in Fig. 6. In this process, a virtual photon γ^* from the lepton produces either a real photon (Deeply Virtual Compton Scattering, or DVCS) or a meson (meson electroproduction). The amplitude depends on the quantity x, related to the momentum fraction carried by the parton, the "skewedness" ξ which measures the different momentum fractions carried by initial and final partons, and the four-momentum transfer $\Delta^2 = t$ at the upper vertex.

Amplitudes for this process depend upon four *generalized parton distributions* or GPD's, which are functions of the aforementioned three kinematic variables. The GPD's *interpolate* between the quantities measured in inclusive deep inelastic scattering, and the particle form factors traditionally measured in nuclear physics processes [12,13]. For example, in the forward direction, characterized by $\xi = \Delta^2 = 0$, two of the GPD's reduce to the helicity-averaged and helicity-dependent single-parton densities, the quantities measured in inclusive DIS reactions. The first moment of the GPD's with respect to x, at fixed four-momentum transfer, gives the nucleon form factors. Fig. 7 shows the kinematic range accessible for DVCS [14] by an $e-p$ collider with $\sqrt{s} = 30$ GeV, with the restriction that $|t| < 1$ GeV^2.

An asymmetric collider, which is capable of measuring all final hadrons in exclusive reactions, has the possibility of directly sampling effects of partonic correlations. One promising area would be to compare amplitudes for elastic processes,

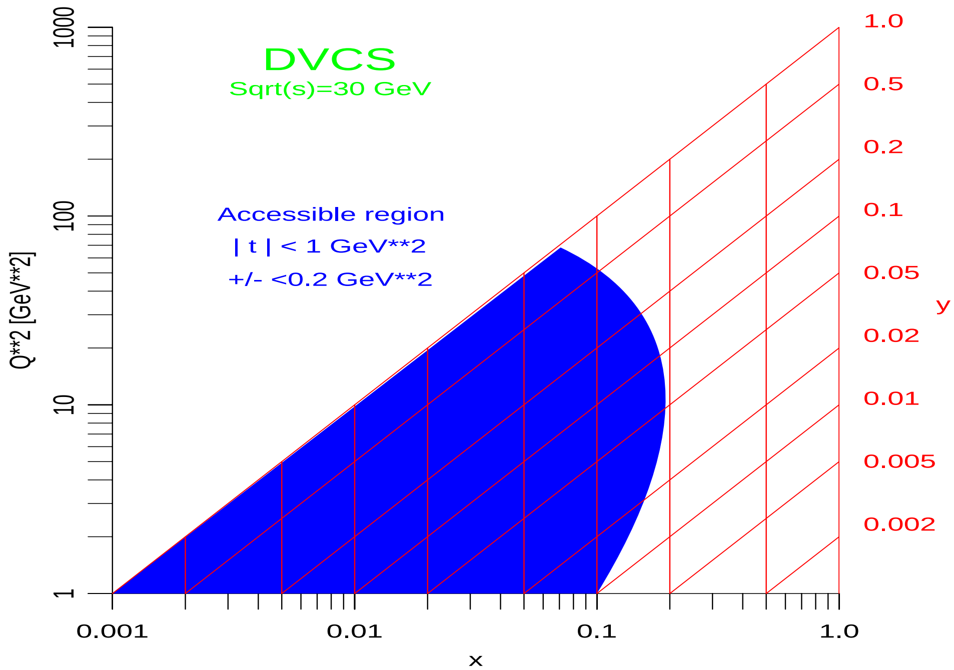

FIGURE 7. Expected kinematic range, x vs. Q^2, for DVCS processes in an $e-p$ collider with $\sqrt{s} = 30$ GeV.

where the struck nucleon remains in its ground state, with inelastic excitations resulting in a final N^*, Δ or hyperon. This would enable us to answer the question, *what is the partonic structure of light baryons?* For example, valence-quark models of baryons would suggest that diquark correlations are more important in octet than in decuplet baryons. The reasoning is that one expects a very strong attraction between quarks in the spin-isospin zero channel. In contrast, in chiral models which employ an expansion about the large-N_C limit of QCD, the octet and decuplet baryons are different rotational excitations of the same soliton, and one would not expect significant differences from diquark correlations.

The ability to control both lepton and hadron polarizations at the collider is an important element in the ability to extract information on partonic correlations. The ability to measure flavor effects in final state baryons and mesons is also important, since through the Pauli principle spin effects become correlated with flavor physics. In this regard Λ hyperon production can be extremely useful because of the self-analyzing nature of the Λ. Comparison of hyperon, octet and decuplet baryon production can answer the question, *Is SU(3) flavor symmetry valid for baryon structure?* Because u, d and s quarks are relatively light, and partly because of a paucity of experimental information on strange quark production, it is common to use SU(3)-based arguments to infer relate strange and non-strange hadronic processes. However, it is quite possible that large flavor-dependent effects may be found in parton distributions and fragmentation functions.

The area of GPD's is quite new. In 1997 Collins, Frankfurt and Strikman proved that under certain conditions factorization occurs in hard exclusive processes. Consequently such processes can be described as the product of a hard scattering term calculable from pQCD, times a soft amplitude (the GPD's) which are universal but not calculable from QCD. Both theoretical and experimental work in this area is only a few years old, but extremely rapid progress is being made in this field. Some preliminary experimental studies are being carried out at HERA and HERMES, and are proposed for Jefferson Lab at 12 GeV. In addition, theoretical studies are needed to determine which experiments most directly reveal the important physical information accessible with hard exclusive processes, e.g.: *How does the transverse momentum of partons influence the GPD amplitudes?*, and *Which observables are most sensitive to quark-quark correlations?*

HADRONIC PHYSICS WITH NUCLEI

With the addition of nuclear beams at a collider, there are a number of important questions which can be addressed:

- Measurement of the pion structure function (as described above) can also be considered for a pion in flight in a nucleus. This can answer the question, *"What role do pions play in nuclear binding?"*. Studies of nuclear effects on pion structure functions can also check measurements of nuclear anti-quark distributions, which found no enhancement over anti-quark probabilities in a nucleon [15].

- Measurement of the gluon distribution in nuclei would be relatively straightforward at EIC via charm production. One would look for the expected medium modification of the gluon distribution. Only scant data exist at present [16].

- There are indications that gluon densities, at high partonic density and low x, undergo significant change. It has been suggested that experiments in this region will reveal a *"Colored Glass Condensate"*, a collective gluonic Bose condensate analogous to effects seen in spin glasses.

- A number of important partonic phenomena can be explored with nuclei, e.g.: color transparency, color coherence, parton energy loss, hadronization in nuclei.

The physics prospects for an $e-A$ collider have been covered in detail in previous "e-RHIC" workshops; we refer the reader to the workshop proceedings for a more complete summary [6,7].

CONCLUSIONS

The scientific motivation to pursue realization of an Electron-Ion Collider is very strong. Previous experiments using hard processes indicate the essential need for a machine with a large kinematic range, high luminosity and optimal control of spin and flavor for a decisive study of hadron structure. The collider geometry offers the crucial and unique capability of complete event reconstruction in hard scattering. The collider should be available in a timely fashion to build upon the insights gained from existing programs at BNL, CERN, DESY, and SLAC. It is our strong desire that the collider concept be endorsed by the nuclear physics community in the United States and that it receive vigorous R&D funding over the next several years.

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