Parton distribution functions at the Electron-Ion Collider[1]

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Abstract

High-statistics deep-inelastic scattering at the EIC can elucidate several open questions about the structure of nucleons and nuclei that cannot be answered solely by measurements at the Large Hadron Collider. These questions include flavor composition of PDFs; nuclear correction factors; effect of isospin violation on the PDFs; and behavior of the longitudinal structure function F_L at the boundary between nonperturbative and perturbative QCD domains.

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1.1 Introduction

The Electron-Ion Collider (EIC) will operate at the time when the Large Hadron Collider (LHC) establishes a new "gold standard" for perturbative QCD by measuring a variety of hard-scattering processes. High-luminosity EIC measurements will be very complementary to those at the LHC, as they will accurately probe various aspects of hadronic structure using independent experimental techniques. In the next few years, when next-to-next-to-leading order (NNLO) accuracy of QCD calculations becomes the norm, a variety of perturbative and nonperturbative effects needs to be taken into account to match the precision of multi-loop radiative contributions. Some of these effects can be constrained solely by the LHC data; others need independent measurements, not affected by systematical uncertainties present at the LHC. With the luminosity 10 fb^{-1} or more, the EIC will disentangle many such effects, including modification of the nucleon structure within heavy-nuclei targets, flavor dependence of parton distribution functions (PDFs), and QCD dynamics at very large or small x.

By performing deep inelastic scattering (DIS) both on proton and heavy-nuclei targets, the EIC can distinguish between intrinsic properties of the proton and those of the extended nuclear medium. To highlight this point, figure 1 displays the $\{x, Q^2\}$ kinematic reach of the EIC. As compared with previous lepton–nucleus experiments (fig. 1-b), the EIC will probe to smaller x values with high precision. Here, the ability to use heavy-ion beams, such as Ca or Au, will allow exploration of the quark saturation region at low x and low Q^2 as a function of the atomic number A. In contrast to the HERA ep collider, which explores the same $\{x, Q^2\}$ region (fig. 1-a), heavy-ion scattering will achieve much higher partonic densities that are a prerequisite for the onset of saturation. It will help delineate the kinematical boundary between the DGLAP factorization and saturated dynamics in the nuclear medium and, more broadly, map out the A-dependence of nuclear PDFs.

The Q^2 range of the EIC will cover the transition region from the perturbative to the non-perturbative regime. Here, we wish to learn how the perturbative parton-scattering picture valid at large momentum transfers matches on nonperturbative models describing the strongly-coupled resonance region. Understanding of this region is important for hadronic experiments at the intensity frontier.

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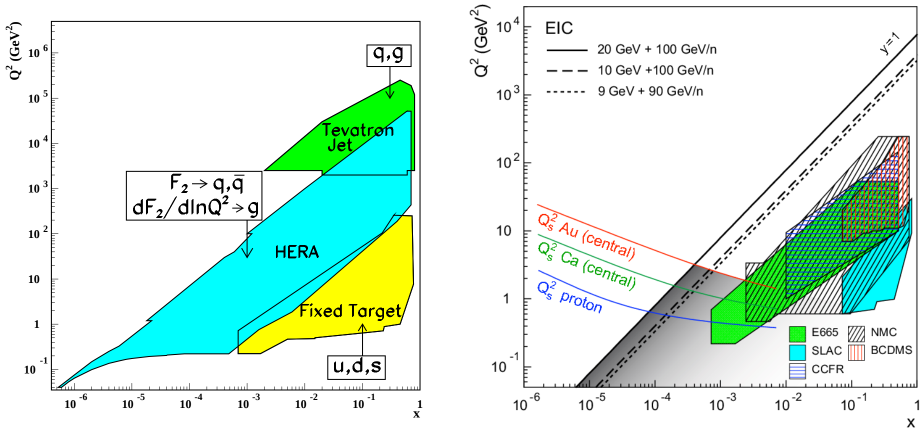

Figure 1: (a) Kinematic domains in x and Q^2 probed by fixed-target and collider experiments, shown together with the PDFs that are most strongly constrained by the indicated regions [39]. (b) Kinematic acceptance in the $\{x, Q^2\}$ plane for proposed EIC energies and in the past eA, μA, and νA experiments, from Ref. [46]. Dashed lines indicate the quark saturation scale Q_s^2 for protons, Ca, and Au nuclei.

1.2 Open Questions

Several questions about PDFs will likely remain open at the time of the EIC operation.

Nuclear PDFs. The A-dependent nuclear correction factors have not been exhaustively studied as a function of x and Q^2. Their uncertainty can be a limitation in present analyses. A high-intensity EIC could use a variety of nuclear beams to map these A-dependent nuclear correction factors in the $\{x, Q^2\}$ kinematic plane. Some possibilities are discussed in Sec. 1.3. Ion-ion scattering at the LHC will constrain some flavor combinations of nuclear PDFs, but DIS at the EIC would provide independent information necessary for reliable flavor separation.

Better constraints on the strangeness PDF. Despite extensive investigation, there remain large uncertainties in flavor differentiation of sea-quark PDFs both in the proton and nuclei. In particular, the strange quark+antiquark distribution in the proton, $s_+(x) = s(x)+\bar{s}(x)$, and its asymmetry, $s_-(x) = s(x)-\bar{s}(x)$, are still poorly known [40, 33, 34, 36, 8], despite their significance for understanding of the nucleon structure. Existing constraints on the strangeness come predominantly from neutrino (semi-)inclusive DIS [47, 45]. At the EIC, both $s_+(x)$ and $s_-(x)$ can be probed in semi-inclusive DIS production of kaons. This measurement will rely on understanding of fragmentation functions, which will be known much better by the time the EIC is turned on.

The d/u ratio at large x. Because of its intermediate energy and high beam intensity, the EIC is ideal for studying parton distributions at large Bjorken x ($x > 0.1$), where separation of parton flavors is not fully understood despite many years of experiments. For example, even the ratio $d(x, Q)/u(x, Q)$ of the dominant up and down quark proton PDFs at $x > 0.3$ has been recently put in doubt by contradicting constraints from DIS on deuteron targets [11, 5] and charged lepton asymmetry at the Tevatron [2, 1]. While the PDF analysis groups labor to understand these differences [36, 34, 9] (and new clean LHC measurements of the d/u ratio in *proton* scattering are in the queue), the EIC will help to resolve this controversy by extracting the ratio $F_2^n(x, Q)/F_2^p(x, Q)$ from DIS data on various nuclear targets. Such measurement will help to separate several types of kinematical and nuclear corrections ([3], and references therein) that influence the F_2^n/F_2^p ratio derived from nuclear-target DIS.

Gluon PDF in the proton and charm production at large x. Even more uncertainty exists in the gluon PDF $g(x,Q)$ at large x, where it can be larger than the down-quark $d(x,Q)$ at $x > 0.5$ in some recent parametrizations for proton PDFs [41]. This ambiguity will be reduced by upcoming jet production at the LHC, but significant systematic limitations of both experimental and theoretical nature may persistent at the largest x, where the EIC could independently contribute. Production of heavy-quark (c, b) pairs or heavy mesons ($J/\psi, \Upsilon$) in deep-inelastic scattering could accurately probe the large-x gluon PDF. The EIC detectors will have excellent charm tagging efficiency, in a relatively clean scattering environment as compared to the LHC.

Inclusive charm production is interesting in its own right, given that large radiative contributions are known to exist near the heavy-quark production threshold, *i.e.*, at Q comparable to charm mass and $x > 0.1$. The rate for this process can be increased by up to an order of magnitude by nonperturbative **intrinsic charm** production suggested by light-cone models [15, 16]. An EIC will be a unique opportunity to cleanly test for the presence of intrinsic charm contributions in the observable future [24].

Transition to the high-density regime. There is a long-standing question of partonic saturation and recombination in the small-x region. As a related phenomenon, BFKL [31, 32, 7] effects from large $\ln[1/x]$ contributions may supersede the usual DGLAP evolution in the small-x regime. The EIC should be capable of probing the transition from DGLAP factorization to BFKL/saturation dynamics, particularly using heavy nuclei beams in order to produce large partonic densities.

Perturbative-nonperturbative QCD boundary. The general kinematic parameters of an EIC would span across both the perturbative (large Q^2) region and the non-perturbative (small Q^2) region. The theoretical description of the physics in these two regions is very different, and precise EIC data might enable us to better connect these two disparate theoretical descriptions.

The longitudinal structure function F_L is of special interest, in view that its leading term vanishes according to the Callan-Gross relation. It is sensitive to helicity violating effects (of order m^2/Q^2) and higher order correction (proportional to $\alpha_s\, g(x,Q)$). An EIC could make precise measurements of F_L in a kinematic range that overlaps both the fixed-target and HERA collider data; see Sec. 1.4.

Electroweak contributions to proton PDFs. Some, if not all, NLO electroweak effects will be included in the future PDF analysis, as their magnitude is comparable to the size of NNLO QCD radiative contributions that will be routinely included. The QCD+EW PDFs require additional experimental input to constrain nonperturbative parametrizations for photon PDFs, as well as charge asymmetry effects (**isospin violation**) between PDFs for up-type quarks and down-type quarks at the initial scale $Q \approx 1$ GeV. An EIC has the potential to contribute toward improving limits on electroweak PDF terms either directly or in combination with neutrino DIS measurements. See Sec. 1.5 for details.

1.3 Nuclear corrections to proton PDFs

In the remainder, we focus on select opportunities for testing QCD at the EIC, starting with DIS on nuclear targets. The DIS differential cross section is given in terms of structure

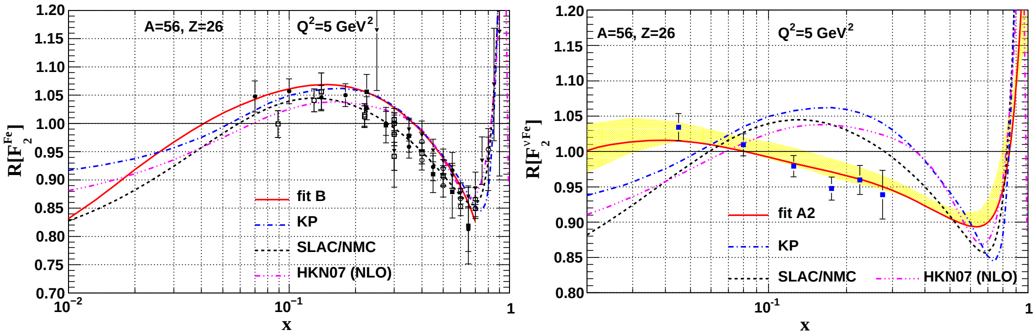

Figure 2: The computed nuclear correction ratio (R), F_2^{Fe}/F_2^D, as a function of x for $Q^2 = 5\,\mathrm{GeV}^2$. Figure-a) shows the fit to $\ell^\pm A$ DIS and DY data (fit B from Ref. [44]), whereas Figure-b) shows the fit to νA DIS data (fit A2 from Ref. [43]). Both fits are compared with the SLAC/NMC parametrization, as well as Kulagin-Petti [29, 30] and Hirai et *al.* [26] fits. The data points in Figure-a) are from SLAC and BCDMS measurements (see Ref. [44] for details), and those in Figure-b) come from the NuTeV experiment [45].

functions $\{F_1, F_2, F_3\}$ by [39]

$$\frac{d^2\sigma^{\ell N}}{dx\;dy} \sim \frac{4\pi\alpha^2}{xyQ^2}\left[y^2 xF_1 + (1-y)\,F_2 \pm \left(y - \frac{y^2}{2}\right) xF_3\right],$$

where the sign in front of the parity-violating F_3 term is *plus* for $\{e^-, \nu\}$ beams and *minus* for $\{e^+, \bar{\nu}\}$ beams. In the context of the QCD-improved parton model, the structure functions can be decomposed into hard-scattering coefficient functions and quark and gluon PDFs.

Various combinations of leptonic projectiles ($e^\pm$, ν) and proton and nuclear targets are generally needed to separate contributions from different parton flavors. Free-nucleon PDFs are modified if a nuclear target is used. Several groups extract nuclear PDFs and their uncertainties by analyzing the global data on nuclear targets [44, 27, 43, 29, 30, 26, 19, 22, 20, 25, 21]. In their studies, they find that the nuclear corrections depend on the type of the nucleus (its atomic number A), flavor of the probed parton, and even the type of the probing boson.

For example, it was found recently [43, 27] that the nuclear correction factors preferred by the νFe DIS data by NuTeV are surprisingly different from predictions based on the $\ell^\pm$Fe charged-lepton results. Figure 2 displays the extracted nuclear correction factors in neutral-current (NC) and charged-current (CC) DIS. They are clearly distinct, suggesting that the NC and CC nuclear correction factors are not exactly the same even for a *universal* set of nucleon PDFs. Some models in the literature predict differences between reactions in NC and CC DIS [17], but the magnitude and shape of the actually observed differences (in particular, the absence of shadowing in νFe DIS at $x \approx 0.02$) turns out to be quite surprising.

The EIC could clarify the behavior of nuclear corrections to NC DIS by studying their A dependence and flavor dependence with several beam types. Such information is of importance for determining the proton PDFs, in particular, the strange quark PDF that is constrained largely from the above NuTeV data. The nuclear correction affects the uncertainty in $s(x, Q)$, which is large at present and may limit the precision of electroweak studies in W and Z boson production at the LHC [38].

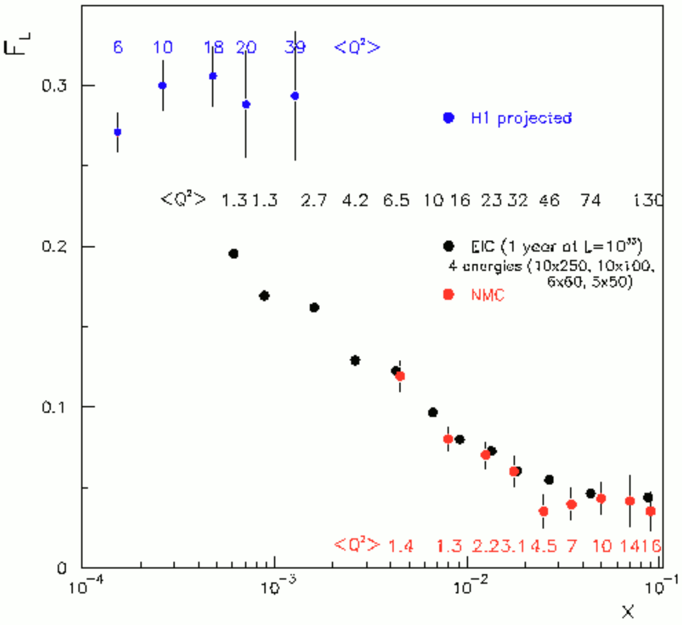

Figure 3: Projected accuracy for EIC determination of F_L on the proton [18].

1.4 Longitudinal Structure Function

The EIC can make precise measurements of the longitudinal structure function, $F_L = F_2 - 2xF_1$. This structure function is particularly interesting, because the leading-order contribution vanishes in the limit of zero mass due to the Callan-Gross relation. Schematically, F_L is given by

$$F_L \sim \frac{m_Q^2}{Q^2}\, q(x) + \alpha_s \left\{ c_g \otimes g(x) + c_q \otimes q(x) \right\}, \tag{1}$$

so that a non-zero value of F_L comes from two sources. The first term of Eq. (1) is a helicity-violating contribution which is necessarily proportional to m_Q^2/Q^2. To describe this contribution, we must properly incorporate heavy-quark masses m_Q. The second term is a next-to-leading-order contribution, proportional to α_s and dominated by the $\gamma^* g$ scattering term.

Thus, F_L is sensitive both to heavy-quark mass effects and higher-order contributions, particularly from the gluon PDF. Figure 3 compares projected accuracy for the measurement of F_L at an EIC with that at other facilities. Not only will the EIC have good statistics, but the kinematic region will nicely overlap with the HERA ep collider and fixed-target experiments.

1.5 Isospin Violation

When extracting information about the proton PDFs from scattering on nuclear targets, we generally make use of isospin symmetry to relate the proton and neutron PDFs via a $u \leftrightarrow d$ interchange. While the isospin symmetry is elegant, it is nonetheless approximate and can be violated at the level of a few percent [14, 10, 28, 37, 13, 12, 6, 43, 4]. Violation of the exact $p \leftrightarrow n$ isospin symmetry, or charge symmetry violation (CSV), invalidates the parton model relations that reduce the number of independent nonperturbative distributions; *e.g.*, $u^n(x) \not\equiv d^p(x)$ and $u^p(x) \not\equiv d^n(x)$. It is important to be aware of the potential magnitude of isospin symmetry violation and its consequences for flavor separation of proton PDFs.

It is noteworthy that isospin symmetry is automatically violated both perturbatively and nonperturbatively. This is because the photon couples to the up quark distribution $u^p(x)$ differently than to the down quark distribution $d^n(x)$. These terms can be comparable to the NNLO DGLAP evolution effects [35, 42, 23].

Some combinations of structure functions, such as $\Delta F_2 \equiv \frac{5}{18} F_2^{CC}(x,Q^2) - F_2^{NC}(x,Q^2)$ and $\Delta x F_3 = x F_3^{W^+} - x F_3^{W^-}$, can be particularly sensitive to isospin violations, and an EIC can contribute to their measurement. For example, the EIC is capable of measuring precisely the structure function F_2^{NC} mediated by the neutral-current γ/Z exchange processes. Measurement of F_2^{CC}, mediated by the charged-current $W^\pm$ exchange, would rely on compensating the M_W^2/Q^2 suppression of the W boson propagator with high intensity of the beams.

In separate experiments, $\Delta x F_3$ can be measured precisely via the neutrino-nucleon DIS process; as these measurements are performed with heavy nuclear targets, the nuclear correction factors can be the limiting factor as to the derived CSV constraint. Since an EIC will use a variety of nuclear targets, it can obtain very precise nuclear correction factors; this information could, in principle, be used together with the neutrino-nucleon DIS data to extract improved CSV limits.

The structure functions ΔF_2 and $\Delta x F_3$ receive contributions from both heavy flavors as well as CSV contributions; improved understanding of the heavy-quark components (discussed previously) can indirectly contribute to better CSV limits [4].

The combination of high-statistics EIC measurements and constraints could thus yield important information on the fundamental charge symmetry.

1.6 Acknowledgments

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