Semi–inclusive and exclusive measurements with EIC: 
The advantages of lower energies

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Exploring the nucleon’s sea quark and gluon structure is a prime objective of a future electron–ion collider (EIC). Many of the key questions require accurate differential semi–inclusive (spin/flavor decomposition, orbital motion) and exclusive (spatial distributions of quarks/gluons) DIS measurements in the region $0.01 < x < 0.3$ and $Q^2 \sim \text{few} \times 10 \text{GeV}^2$. Such measurements could ideally be performed with a high–luminosity collider of moderate CM energy, $s \sim 10^8 \text{GeV}^2$, and relatively symmetric configuration, e.g. $E_e/E_p = 5/30–60 \text{GeV}$. Specific examples are presented, showing the advantages of this setup (angular/energy distribution of final–state particles, large–$x$ coverage) compared to typical high–energy colliders.

One of the most fascinating aspects of the partonic description of nucleon structure at short distances is that the nucleon becomes a many–body system, whose wave function has components with very different number of particles. Depending on the excitation energy (or the Bjorken variable, $x$) DIS experiments can map the particle distributions in these different components, and thus provide much interesting information about the effective dynamics governing these degrees of freedom (see Fig. 1a and b). Measurements at $x > 0.1$ probe mostly the valence quark component of the nucleon, for which a dynamical description as a few–body system, in the spirit of nuclear physics, seems to be appropriate. At higher energies, $x < 0.1$, one observes the quarks and antiquarks in the “sea” which are created by non–perturbative QCD vacuum fluctuations; their distributions carry quantum numbers (spin/flavor) and depend in a delicate way on the character of these vacuum fluctuations and their coupling to the valence quarks. Some of these $q\bar{q}$ pairs in the sea develop into the nucleon’s pion cloud, which makes a distinctive contribution to the partonic structure at transverse distances $\sim 1/M_\pi$ and is governed by chiral dynamics. Also in this region of $x$, gluons become an essential part of the nucleon’s structure. At even higher energies, $x \ll 0.01$, the relevant degrees of freedom are radiatively generated gluons and singlet quarks, and the main dynamical questions concern the dominant characteristics of the radiation processes and the role of unitarity in the regime of high parton densities.

Mapping the nucleon’s valence quark distributions is the objective of the Jefferson Lab 12 GeV Upgrade; in particular, it will allow one to access the unexplored region of $x \to 1$, and to map the transverse spatial distribution of the valence quarks (generalized parton distributions, or GPDs) through high–$Q^2$ exclusive processes [2]. Exploring the nucleon’s sea quark and gluon structure will be the domain of a future EIC. Most of the interesting non–singlet sea quark distributions, which are largely unaffected by perturbative QCD radiation (evolution) and directly testify to the non–perturbative structure of the nucleon and the QCD vacuum, are localized in the region of moderately small $x$, $0.01 < x < 0.3$. As an example, Fig. 1c shows the antiquark flavor asymmetry $x [\bar{d} - \bar{u}] (x)$ measured in Drell–Yan pair production, as well as its polarization predicted by a dynamical model of nucleon structure. Exploration of such details of the sea quarks’ spin and flavor distributions is possible with semi–inclusive DIS measurements. Equally fundamental are their transverse spatial
Figure 1: (a) Kinematic coverage for DIS measurements with JLab 12 GeV and a medium–energy EIC (s = 1000 GeV²). (b) Components of the nucleon wave function probed in DIS experiments at different x. (c) Examples of non-singlet sea quark distributions. Top: Flavor asymmetry \(x(\bar{d}-\bar{u})\). Bottom: Polarized flavor asymmetry \(x(\Delta \bar{u} - \Delta \bar{d})\).

distributions, which are probed in exclusive processes. Gluons at \(x > 0.01\), including their substantial density in the region \(x > 0.1\), are another essential — and largely unexplored — part of nucleon structure. They are probed in semi–inclusive production of heavy quarks (open charm etc.), and their spatial distributions are revealed in exclusive \(J/\psi\) production.

Semi–inclusive and exclusive measurements require high luminosity (low rates at high \(p_T\) / high \(Q^2\), several kinematic dependences) and the capability to analyze the final state (exclusivity, particle ID, momentum resolution). Furthermore, in order to test the partonic reaction mechanism and extract information about nucleon structure it is essential to perform fully differential measurements, in which the kinematic dependences on \(x\) and the final–state variables (\(z\) and \(p_T\) in semi–inclusive, \(t\) in exclusive DIS) are measured at fixed \(Q^2\), without correlations between the variables. Realizing such measurements with an EIC poses a major challenge for the accelerator as well as detector and interaction region design.

The EIC designs discussed so far have mostly focused on high CM energies (eRHIC: \(E_e/E_p = 10/100–250\) GeV [3], ELIC: \(E_e/E_p = 3–7/30–150\) GeV [4]), driven primarily by the desire to reach the saturation regime in \(eA\) collisions, and also to extract the polarized gluon density from the \(Q^2\)–dependence of inclusive DIS data. Similar to HERA, the proton energy is 10–20 larger than the electron energy in these collider designs. While the region of interest for sea quarks in nucleon structure, \(0.01 < x < 0.3\) and \(Q^2 \sim \text{few} \times 10 \text{GeV}^2\),
is formally within the kinematic coverage, significant restrictions for semi–inclusive and exclusive measurements appear when taking into account detector coverage and resolution. Recent studies show that such measurements can be performed much more efficiently with a collider of lower, more symmetric energies. In this note we summarize two of the pertinent considerations: (a) $x–Q^2$ coverage and final–state particle energies in semi–inclusive DIS; (b) angular distributions and $t$–resolution in exclusive processes. The arguments presented here are general and do not assume a specific detector; they are intended to provide guidance for the detector design and eventual more detailed simulations.

**Semi–inclusive DIS.** Semi–inclusive DIS is an essential tool for the flavor decomposition of the nucleon’s polarized valence and sea quark distributions. It is also used to study quark orbital motion and QCD final–state interactions through $p_T$–dependent observables (single–spin asymmetries, etc.) which sit mostly at $x > 0.1$. Both types of studies require fully differential measurements in $x, Q^2, z$ (and $p_T$) in the region $0.01 < x < 0.3$. The ability to measure kinematic dependences at fixed $Q^2$ is particularly important for testing the partonic reaction mechanism (separating leading and higher twist), and to make contact with the fixed–target results for these observables (JLab 12 GeV).

In a high–energy collider, the kinematic reach for DIS measurements at large $x$ is limited by the experimental limits on the $y$ variable, $y = Q^2/(xs) > y_{\text{min}}$, which implies that large values of $x$ are accessible only at high $Q^2$. If the electron variables are used for event reconstruction the resolutions in $y$ and $x$ diverge for $y \to 0$; using methods with hadronic variables $y_{\text{min}} \approx 0.005$ was reached in inclusive measurements at HERA (see Fig. 2), albeit with considerable uncertainties. A medium–energy collider, providing high luminosity over a range of $s$ around $\sim 1000$ GeV$^2$ (e.g., $E_e/E_p = 3–7/30–60$ GeV) could cover the region $0.01 < x < 0.3$ at $Q^2 \sim$ few $\times$10 GeV$^2$ with comfortable values of $y$ (see Fig. 1b), enabling precise and fully differential SIDIS measurements at fixed $Q^2$. Studies show that e.g. the flavor separation of polarized quark distributions at $x > 0.01$ can be performed much more efficiently at $s \sim 10^3$ GeV$^2$ than at $10^4$ GeV$^2$, as the lower CM energy permits measurements at lower $Q^2$ where the cross sections are larger.

Another important issue in SIDIS is particle identification (PID). An advantage of the
lower CM energy is that final–state particles are produced at lower energies, so that the range where good PID is available, $E_h = 1–10$ GeV, matches the $z$–range of physical interest, $z > 0.1$. Energy resolution is likewise improved.

**Exclusive processes.** Exclusive processes $eN \rightarrow e'MN$ ($M = \text{meson, } \gamma, \ldots$) at $Q^2 \sim \text{few } \times 10$ GeV$^2$ reveal the transverse spatial distribution of quarks and gluons in the nucleon and its change with $x$ (“nucleon tomography”). It is encoded in the $t$–dependence of the GPDs, which can be extracted from that of the differential cross sections. In order to resolve interesting details of the quark/gluon spatial distribution, such as the contribution of the pion cloud, accurate measurements in the range $|t| \ll 1$ GeV$^2$ are needed. Measurements of exclusive processes are among the most demanding applications of a future EIC. Besides the need for high luminosity (small cross sections, fully differential measurements), the challenges are to ensure exclusivity of the events and to achieve high resolution in $t$ at small $|t|$. Both are greatly aided by choosing collider energies appropriate to the $x$–range in question.

As an example, Fig. 3 shows a simulation of exclusive $\pi^+$ production, $ep \rightarrow e'\pi^+n$ in DIS kinematics, which provides interesting information about the nucleon’s partonic structure in the region $x > 0.01$ (non-diffractive process) and about the pion form factor. It compares the angular distributions of the produced pion and the recoiling neutron for an ep collider with $E_e/E_p = 5/30$ GeV and 10/250 GeV. With the lower–energy collider the pions are distributed over a wide angular range and could be detected with a central detector; with the high–energy collider they are kinematically boosted forward and appear under very small angles. Similarly, with the lower–energy collider the recoiling neutron emerges at larger angles (several degrees), allowing for much better $t$–resolution with an appropriate forward detector. The relation between $|t|$ and $\theta_n$ at small angles is $|t| \approx E_p^2(\theta_n - \pi)^2$, i.e., at the same CM energy, a more symmetric collider with lower proton energy offers much better prospects for good $|t|$–resolution. Similar conclusions apply to other meson production processes, e.g. exclusive $J/\psi$ production, which maps the transverse spatial distribution of gluons in the nucleon, as well as to deeply–virtual Compton scattering.

**A high–luminosity medium–energy EIC for nucleon structure.** A design for a high–luminosity medium–energy EIC for nucleon structure measurements is being developed at JLab [6]. This ring–ring collider, which uses the upgraded CEBAF complex for electron acceleration, would operate with energies in the range $E_e/E_p = 3–11/12–60$ GeV and can achieve luminosities of up to few $\times 10^{34}$ cm$^{-2}$s$^{-1}$ over a broad range of CM energies, $s = \text{few } 100–2600$ GeV$^2$. The envisaged proton/ion complex uses an SRF linac and a pre–booster ring for acceleration and cooling. The figure–8 design of the electron and proton/ion storage rings (circumference $\sim 600$ m) guarantees optimal beam polarization and allows for up to 4 interaction regions. An upgrade to the high–energy ELIC ($s \sim 10^4$ GeV$^2$, $L \sim 10^{15}$ cm$^{-2}$s$^{-1}$) would be possible with larger rings. The medium–energy EIC would offer unprecedented capabilities for exploring the nucleon’s sea quark and gluon structure through semi–inclusive and exclusive measurements, and for studying the structure of nuclei with novel short–distance probes. It supports a physics program distinct from that of the high–energy stage, and would thus add considerably to the overall potential of an EIC.

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Figure 3: Combined angular and momentum distribution of the $\pi^+$ (top row), and angular and $|t|$-distribution of the recoil $n$ (bottom row), in exclusive production $ep \rightarrow e'\pi^+n$ with two different $ep$ colliders: $E_e/E_p = 5/30$ GeV (left column), and 10/250 GeV (right column). A lab angle of 0° corresponds to the electron, 180° to the proton direction. Shown are the results of simulations based on a specific model of the exclusive cross section.

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