

Probing nuclear gluons with heavy quarks at EIC

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We explore the feasibility of direct measurements of nuclear gluon densities using heavy-quark production (open charm, beauty) at a future Electron-Ion Collider (EIC). We focus on the regions $x > 0.3$ (EMC effect) and $x \sim 0.05-0.1$ (antishadowing), where the nuclear modifications of the gluon density offer insight into non-nucleonic degrees of freedom and the QCD structure of nucleon-nucleon interactions. We describe the charm production rates and momentum distributions in nuclear deep-inelastic scattering (DIS) at large x_B , and comment on the possible methods for charm reconstruction using next-generation detectors at the EIC (π/K identification, tracking, vertex detection).

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Nuclear parton densities (PDFs) describe the basic quark-gluon structure of the nucleus in QCD. They represent the expectation value of the leading-twist QCD operators in the nuclear ground state and can be measured in high-energy, high-momentum transfer processes such as DIS or dilepton production. The comparison of the nuclear PDFs to that of a system of unbound protons and neutrons ($A = Z + N$) offers unique insight into the QCD structure of nucleon interactions and the microscopic origin of nuclear binding. Distinct dynamical mechanisms are expected to cause nuclear modifications in different regions of x : modified single-nucleon structure and non-nucleonic degrees of freedom in nuclei ($x > 0.3$), exchange interactions between nucleons ($x \sim 0.1$, antishadowing), and the appearance of coherent gluon fields associated with multiple nucleons ($x < 0.01$, shadowing) [1].¹ Suppression of the nuclear quark densities in the valence region $x > 0.3$ has been observed in inclusive DIS (EMC effect) and is the object of intense theoretical study [2]. Some information on nuclear sea quarks is available from dilepton production.

Much less is known about the nuclear modifications of gluons (see Fig. 1). Basic questions remain to be answered: (a) Is the nuclear gluon density suppressed at $x > 0.3$ (gluonic EMC effect)? This would provide insight into the change of quark-gluon configurations of the nucleon due to nuclear binding. (b) Are nuclear gluons enhanced at $x \sim 0.1$ (gluon antishadowing)? This would reveal the gluonic structure of nucleon-nucleon interactions at average distances in the nucleus. A recent theoretical analysis [4] of data in J/ψ production in ultraperipheral AA collisions at LHC [5] confirms substantial gluon shadowing at $x < 0.01$, which suggests large compensating antishadowing at $x \sim 0.1$ to conserve the overall light-cone momentum carried by gluons.

The nuclear modifications of gluons at $x \gtrsim 0.1$ have so far been studied only indirectly, through the Q^2 dependence of inclusive nuclear DIS cross sections (DGLAP evolution). Results could be improved by extending such measurements over a larger range of Q^2 and W , and separating transverse and longitudinal nuclear structure functions. Much more incisive could be measurements with probes coupling directly to gluons at a fixed scale.

Heavy quark production in DIS provides a direct probe of the gluon density in the target. At leading order (LO) in the perturbative QCD expansion the heavy quark pair is produced through

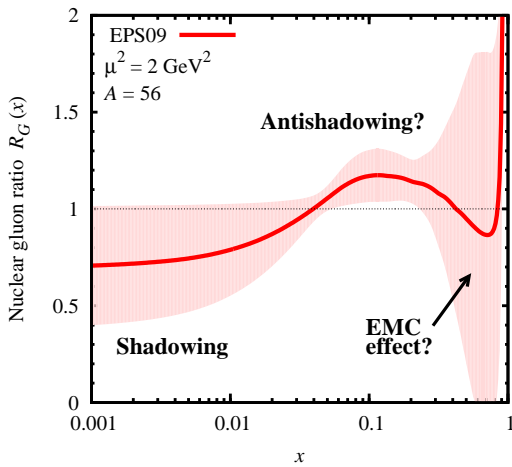


Figure 1: The nuclear gluon density ratio $R_G(x, \mu^2) = G_A(x, \mu^2)/[AG_N(x, \mu^2)]$ and its uncertainty at a scale $\mu^2 = 2 \text{ GeV}^2$, obtained from the EPS09 analysis of nuclear PDFs [3].

¹Here x refers to the light-cone momentum fraction of the parton relative to a nucleon in the nucleus ($0 < x < 1$).

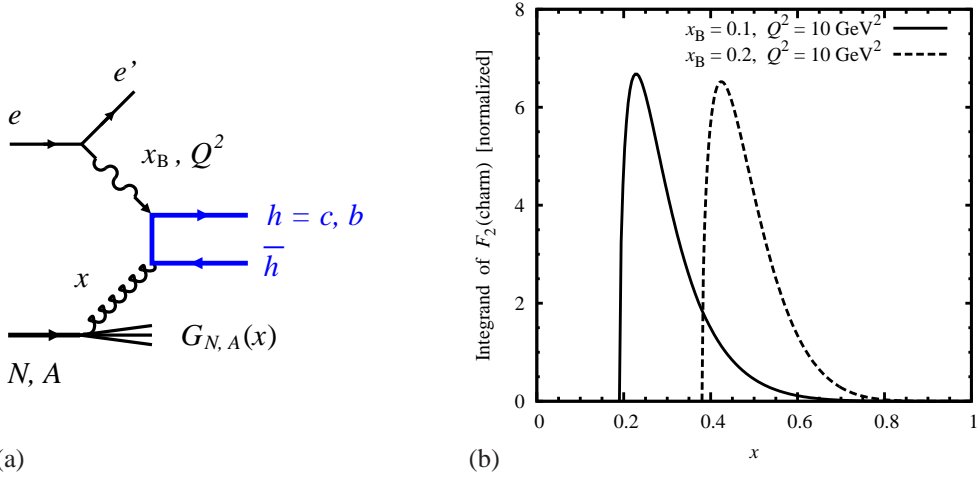


Figure 2: (a) Heavy-quark production in DIS at LO (photon-gluon fusion). (b) Distribution of gluon momentum fractions x in the convolution integral defining the charm structure function $F_2(\text{charm})$ at given x_B and Q^2 (values see plot). The distributions are shown normalized to unit integral.

the photon-gluon fusion process (see Fig. 2a). The heavy quark structure function is given by a convolution integral over the gluon density extending over $x > x_B$, where x_B is the Bjorken variable defined by the electron kinematics, and $a = 1 + 4m_h^2/Q^2$ (m_h is the heavy quark mass). The process effectively probes the gluon density in a region of x strongly localized above x_B (see Fig. 2b), and at a scale $\mu^2 \approx 4m_h^2$ [6]. Next-to-leading order (NLO) QCD corrections have been calculated [7], and the theoretical uncertainties have been quantified [8]. Extensive measurements of charm and beauty production have been performed at the HERA ep collider at $x_B < 0.01$, using various methods of charm/beauty identification (see below), and found good agreement with QCD predictions [9]. Open charm production was also studied at the COMPASS μN fixed-target experiment [10].

The proposed Electron-Ion Collider (EIC) [11, 12] would enable the first direct measurements of nuclear gluons at intermediate and large x using heavy quark probes and could qualitatively advance our understanding of the gluonic structure of nuclei. The electron-nucleon squared center-of-mass energy in the range $s_{eN} \equiv s_{eA}/A \sim 200\text{--}2000 \text{ GeV}^2$ would provide wide coverage in Q^2 in DIS at $x_B > 0.01$. [We quote the s_{eN} values for eA collisions, which are lower than those for ep by the factor $Z/A \approx 0.5(0.4)$ for light (heavy) nuclei.] The luminosity of the order $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (per nucleon) would give reasonable charm production rates even at $x_B \gtrsim 0.1$. The next-generation detectors (π/K identification, tracking, vertex detection) would open up new methods of charm reconstruction with greater efficiency than those used at HERA. Here we report about results of an R&D project [13] aiming to explore the feasibility of such measurements on nuclei and to quantify their physics impact (for a general overview of nuclear physics with EIC, see Refs. [14, 15]).

Charm production rates in nuclear DIS at EIC have been estimated using QCD expressions and the HVQDIS code [16] (see Fig. 3). One observes that: (a) the charm rates drop rapidly above $x_B \sim 0.1$, due to the drop of the gluon density; (b) charm rates of few $\times 10^5$ can be achieved at $x_B \sim 0.1$ with 10 fb^{-1} integrated luminosity; (c) the fraction of DIS events with charm production at $x_B \sim 0.1$ is $\sim 1\%$ at $Q^2 > 10 \text{ GeV}^2$ ($\sim 3\%$ at $Q^2 > 50 \text{ GeV}^2$). Thus large- x charm samples of $O(10^4)$ could be obtained if charm events could be identified with an overall efficiency of $\sim 10\%$.

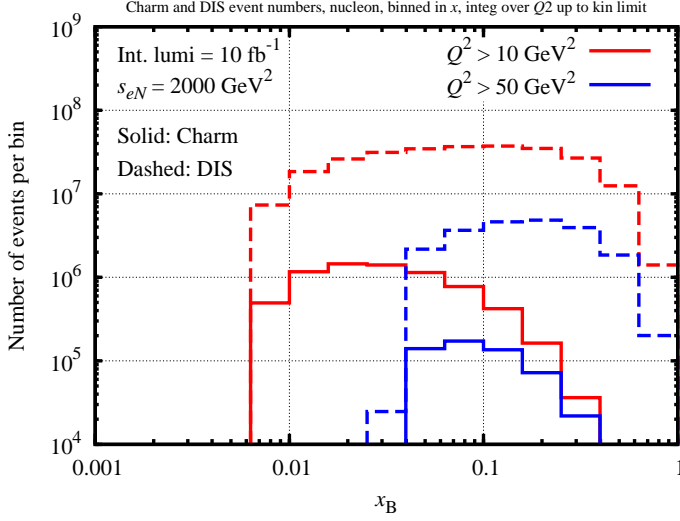


Figure 3: Solid lines: Estimated number of charm events in DIS at EIC (CM energy $s_{eN} = 2000 \text{ GeV}^2$, integrated nucleon luminosity 10 fb^{-1}). The bins in x_B are 5 per decade as indicated on the plot. Q^2 is integrated from the lower limit indicated (10 or 50 GeV^2) to the kinematic limit. Dashed lines: Total number of DIS events in the same bins

At an EIC with ion momenta \sim few 10 GeV (per nucleon) the charm quarks produced in DIS at $x_B \sim 0.1$ typically emerge with large angles in the lab frame, and carry momenta of \sim several GeV. (The actual distribution is determined by the transformation from the collinear frame, where the momentum transfer \vec{q} and the ion momentum \vec{p}_A are collinear, to the lab frame and exhibits a complex dependence on x_B and Q^2 .) The charm angular and momentum distributions are imparted on the produced D mesons and their final decay hadrons (π, K). Detection capabilities for these hadrons need to be provided in the relevant angle and momentum ranges. An advantage of the moderate ion beam energies \sim few 10 GeV (per nucleon) is that the hadrons are produced at large angles and momenta \sim few GeV, where good particle identification (PID) can be performed.

Charm events are identified by reconstructing the D mesons that are produced by charm quark fragmentation and subsequently decay into π and K . Experiments at HERA [9] made extensive use of the D^* channel, which exhibits a distinctive two-step decay $D^{*+} \rightarrow D^0 \pi^+$ (slow), $D^0 \rightarrow K^- \pi^+$, and can be reconstructed without PID or vertex detection. However, this channel offers an overall reconstruction efficiency of only $\lesssim 1\%$ (given by the product of the fragmentation function and the branching ratios) and will likely not be sufficient for nuclear gluon measurements at $x_B \sim 0.1$. The EIC detector will provide vastly improved PID capabilities, especially for charged π/K separation, and allows one to use other decay channels to reconstruct D mesons through charged π/K tracks (see Fig. 4). A survey of decay channels shows that this method could potentially permit charm reconstruction with an efficiency of $\sim 10\%$, which would significantly expand the physics reach at large x_B . Simulating charm reconstruction with this method and optimizing its performance are objects of on-going R&D [13].

Reconstruction of the displaced decay vertex of the D meson can substantially improve the signal/background ratio in charm/beauty reconstruction, by eliminating much of the combinatorial background. However, the method reduces the overall charm/beauty reconstruction efficiency, because it rejects events with a short decay length. Vertex detection was/is extensively used in high-energy experiments (HERA, LHC), where the charm production rates are large and the decay lengths are boosted by the large D meson momenta. In DIS at EIC at $x_B \sim 0.1$ the charm cross

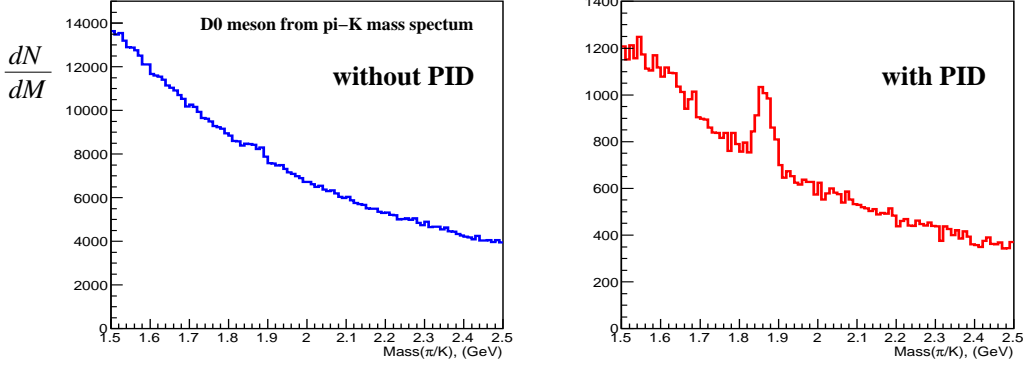


Figure 4: Impact of PID on D^0 meson reconstruction from charged π/K decays. The plots show the invariant mass spectrum of charged meson pairs, dN/dM , in a sample of charm events without and with PID (arbitrary normalization, no DIS background included). The peak represents the $D^0 \rightarrow K^- \pi^+$ decay.

section will be $\sim 1\%$ of the total cross section, so that it is imperative to maximize the overall efficiency of charm reconstruction. At the same time the vertex displacements will be smaller than in the high-energy experiments. The benefits of vertex detection in this context need to be explored.

Another possible strategy for large- x gluon measurements with charm is to focus on exceptional $c\bar{c}$ pairs with large transverse momenta $p_T \sim Q$. While they are produced with a small cross section, such configurations represent a very distinctive final state that is practically free from hadronic background. Whether nuclear ratio measurements would be feasible with such final states is a topic for further R&D [13].

Measurements of nuclear ratios of charm production with EIC require good control of the relative nuclear luminosity of the different ion beams. One possible method is to normalize the luminosity through measurement of the inclusive nuclear DIS structure function ratio F_2^A/F_2^D at $x_B \sim 0.2 - 0.3$ and $Q^2 \sim \text{few GeV}^2$, where the nuclear modification was measured in fixed-target experiments and is known to be very small (“double ratio method”).

It is also necessary to analyze the theoretical uncertainties associated with nuclear charm production measurements. The uncertainties related to the QCD subprocess (higher-order corrections, effective scale) cancel when taking nuclear ratios, making such measurements more robust than those of the absolute gluon density. The effects of nuclear final-state interactions on the observed D -meson spectrum can be separated from initial-state modifications of the nuclear gluon density by using the different A -dependence of the two mechanisms. Finally, the impact of the charm production pseudodata on the nuclear PDFs can be quantified using reweighting methods [17].

In sum, direct measurements of nuclear gluons at $x > 0.1$ could significantly advance our understanding of nucleon interactions in QCD. A medium-energy EIC with ion beam energies \sim several 10 GeV (per nucleon) and luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is ideally suited for this purpose. Large- x gluon measurements will be limited by rates (luminosity) and the efficiency of charm reconstruction. An overall efficiency of up to $\sim 10\%$ could possibly be achieved using the PID capabilities of the EIC detector. Further R&D is needed to demonstrate the method [13].

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