Probing nuclear gluons with heavy flavor production at EIC

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The nuclear modifications of the parton densities in different regions of x (EMC effect, antishadowing, shadowing) reveal aspects of the fundamental QCD substructure of nucleon interactions in the nucleus. We study the feasibility of measuring nuclear gluon densities at large x using open heavy flavor production (charm, beauty) in DIS at EIC. This includes (a) charm production rates and kinematic dependences; (b) charm reconstruction at large x_B using exclusive and inclusive modes, enabled by particle identification and vertex detection; (c) impact of inclusive charm data on nuclear gluon density.

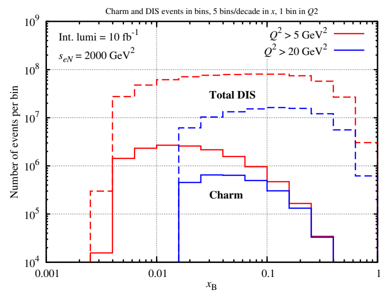
Keywords: Heavy flavor production in DIS, nuclear gluon densities, EMC effect

1. Introduction

Measurements of nuclear parton densities are an essential part of the EIC physics program.[1] The nuclear modifications in different regions of x (EMC effect, antishadowing, shadowing) reveal aspects of the fundamental QCD substructure of nucleon interactions in the nucleus. Of particular interest are the modifications of the nuclear gluon densities at large x, i.e., their possible suppression at $x > 0.3$ (gluonic EMC effect) or enhancement at $x \sim 0.1$ (gluon antishadowing). Nuclear gluon densities at $x > 0.1$ have so far been determined only indirectly, through the Q^2 dependence of inclusive nuclear DIS cross sections (DGLAP evolution).

Open heavy flavor production (charm, beauty) in DIS provides a direct probe of the gluon density in the target. At leading order (LO) in the pQCD expansion the heavy quark pair is produced through the photongluon fusion process (see Fig. 1a); higher-order QCD corrections have been and are under good theoretical control (uncertainties, stability).[2] Extensive measurements of open charm and beauty production have been performed at HERA in ep DIS at $x_B < 10^{-2}$ and found good agreement with the QCD predictions.[3,4]

The EIC would make it possible to use heavy flavor production as a probe of nuclear gluon densities. The EIC luminosity of $\sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ per nucleon ($\sim 10^2$ times higher than HERA) would substantially increase the heavy flavor production rates and allow one to extend such measurements to $x_B \gtrsim 0.1$. Next-generation detection capabilities (particle identification or PID, vertex detection) would enable new methods of charm reconstruction at large x_B using exclusive and inclusive modes. Altogether such measurements could significantly advance knowledge of nuclear gluon densities at large x_B. Their feasibility and impact should therefore be studied with high priority and inform the detector design.[5,6] Here we report some results of the study of Ref.[5] and on-going efforts.



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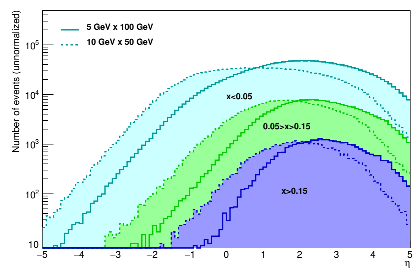

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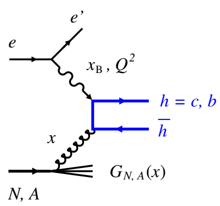


(a)

Fig. 1. (a) Charm production in DIS in LO QCD. (b) Estimated number of DIS events (dashed lines) and charm events (solid lines) in DIS at EIC (CM energy $s_{eN} = 2000$ GeV^2, integrated nucleon luminosity 10 fb^{-1}). The bins in $x_{\rm B}$ are 5 per decade as indicated on the plot. Q^2 is integrated from the lower value indicated (5 or 20 GeV^2) to the kinematic limit at the given x_B. (c) Rapidity distribution of $c\bar{c}$ pairs produced in in DIS events with $x_B = 0.1$, for electron/nucleon beam energies 5×100 GeV and 10×50 GeV.

2. Charm production at large x_B.

Charm production rates in eN DIS have been estimated using QCD cross sections and phase space integration (LO formulas, HVQDIS LO/NLO code[7]). Figure 1b shows the charm rates differentially in x_B (5 bins per decade) and integrated over Q^2 (two different lower limits), for an integrated luminosity of 10 fb^{-1}; it also shows the total DIS rates in the same bins. One observes: (a) The charm production rates decrease rapidly above $x_{\rm B} \sim 0.1$, due to the drop of the gluon density. Nevertheless charm rates of few $\times 10^5$ are achieved at $x_{\rm B} \sim 0.1$ with 10 fb^{-1} integrated luminosity. (b) The fraction of DIS events with charm production at $x_{\rm B} \sim 0.1$ is $\sim 1\%$ for $Q^2 > 5$ GeV^2 ($\sim 2\%$ for $Q^2 > 20$ GeV^2). These observations define the baseline requirements for charm reconstruction at large x_B with EIC: the charm reconstruction efficiency should be $\gtrsim$10%, and the reconstruction methods have to work in an environment where charm events constitute only ~1% of DIS events.

Fig. 1c shows the rapidity distributions of the produced $c\bar{c}$ pairs in collider experiments. As an example it shows the distributions for two different electron/nucleon beam energies, 5×100 GeV and 10×50 GeV, corresponding to the same CM energy $s = 2000$ GeV^2. One sees that charm pairs at $x_B \sim 0.1$ are produced at central rapidities, where good PID and vertex detection is provided by the central detector.

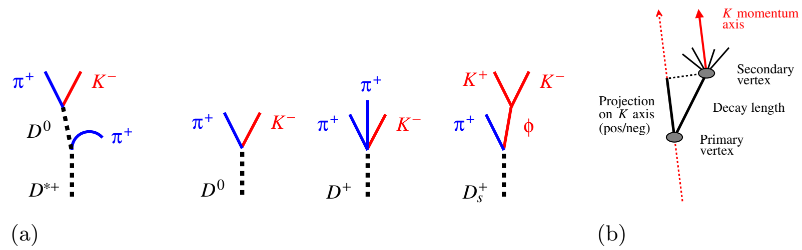


Fig. 2. (a) Exclusive D meson decays into charged π/K final states. (b) Charm reconstruction using the decay length significance distribution in inclusive D-meson decays.

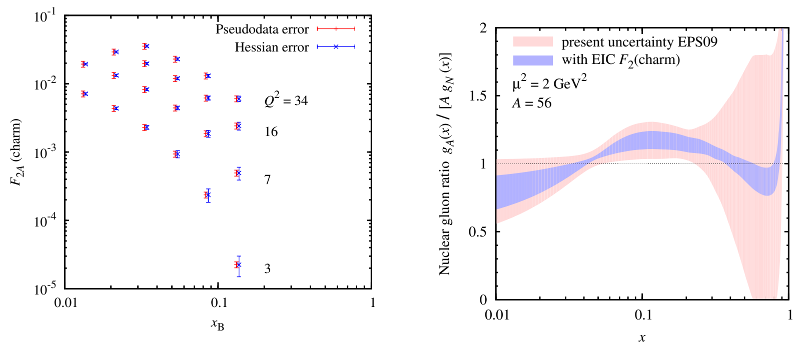
3. Charm reconstruction at large x_B with EIC

Charm events are identified by reconstructing the D mesons that are produced by charm quark fragmentation and subsequently decay into π and K. Charm reconstruction at large x_B relies essentially on the PID and vertex detection capabilities of the EIC detectors and has been simulated using a schematic detector model[5]. Two different methods are being considered:
(a) *Exclusive method*, in which individual D mesons are reconstructed from exclusive decays into charged hadrons (see Fig. 2a). Experiments at HERA-I made extensive use of the D^* channel, which exhibits a distinctive two-step decay $D^* \to D^0\pi^+(\text{slow}), D^0 \to K^-\pi^+$, and can be reconstructed without PID or vertex detection, but provides a reconstruction efficiency of only $\sim$1%.[4] At EIC the PID and vertex capabilities allow one to use also other D-meson decays (D^0, D^+, D_s^+); summing these channels increases the overall efficiency to $\sim$6%.[4]
(b) *Inclusive method*, in which D mesons are identified through inclusive decays with a displaced vertex using the decay length significance distributions (hadronic and semileptonic decays, see Fig. 2.[3] This technique was used at HERA-II for charm reconstruction at $x_B < 10^{-2}$. At EIC the combination with PID and improved vertex detection would make it possible to use this method at larger x_B. The overall efficiency achievable with this method is estimated at $\sim$25%.

Both charm reconstruction methods are expected to be applicable in the high-background environment of DIS at $x_B \gtrsim 0.1$. The overall efficiency would be sufficient for F_{2c} measurements and large-x gluon density extraction. Systematic uncertainties need to be studied with a detailed detector design.

4. Impact on large-x nuclear gluons

The impact of open charm measurements at EIC on the nuclear gluon densities has been studied using a Monte-Carlo reweighting method[8]. Figure 3a shows a sample set of pseudodata for the nuclear charm structure function $F_{2A}^c(x, Q^2)$; the errors in the measured region are dominated by systematics and estimated at $\sim$10%. (The F_{2A}^c measurements could be extended to larger x_B, where statistical errors dominate.) Figure 3b shows the impact of the pseudodata on the nuclear gluon



(a) (b)

Fig. 3. (a) Sample set of pseudodata in the nuclear charm structure function F^c_{2A} used in the impact study. The two error bars show the assumed pseudodata errors and the theory error estimated with the Hessian uncertainty of the nuclear gluon PDF parametrization (EPS09 LO[9]). (b) Impact of charm pseudodata on the nuclear gluon PDF.

density (here EPS09 LO;[9] NLO simulations are in progress). One sees that the charm data substantially reduce the gluon uncertainties at $x > 0.1$ and would allow one to establish the presence of a "gluonic EMC effect."

5. Summary

A high-luminosity EIC with next-generation detectors would offer excellent opportunities for measurements of open heavy flavor production in ep/eA scattering. The charm production rates appear sufficient to constrain nuclear gluons at $x > 0.1$, if charm reconstruction could be performed with an overall efficiency $> 10\%$. Heavy quark production at EIC could also be used for other physics studies, such as heavy quark fragmentation functions, jets physics, and heavy quark propagation and hadronization in nuclei.

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