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Heavy Quark Production at an Electron-Ion Collider

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Abstract. An Electron-Ion Collider (EIC) with center-of-mass energies $\sqrt{s_{\text{ee}}} \sim 20–100$ GeV and luminosity $L \sim 10^{34}$ cm$^{-2}$ s$^{-1}$ would offer new opportunities to study heavy quark production in high-energy electron or photon scattering on protons and nuclei. We report about an R&D project exploring the feasibility of direct measurements of nuclear gluon densities at $x > \sim 0.1$ (gluonic EMC effect, antishadowing) using open charm production at EIC. We describe the charm production rates and angle-momentum distributions at large $x$ and discuss methods of charm reconstruction using next-generation detector capabilities ($\pi/K$ identification, vertex reconstruction). The results could be used also for other physics applications of heavy quark production at EIC (fragmentation functions, jets, heavy quark propagation in nuclei).

1. Electron-Ion Collider

An Electron-Ion Collider (EIC) is being developed as a next-generation facility for nuclear physics and has been recommended for future construction in the 2015 U.S. Department of Energy’s Long-Range Plan \cite{1}. The present EIC designs envisage electron-proton ($ep$) center-of-mass (CM) energies $\sqrt{s_{ep}} \sim 20–100$ GeV, with possible extensions to higher energies, and aim to deliver luminosities $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$ over the full energy range \cite{2, 3}. Acceleration of a wide variety of nuclear beams would be possible, ranging from the deuteron ($A = 2$) to heavy ions ($A \sim 200$). In electron-nucleus ($eA$) scattering at the collider the CM energy per nucleon is lower compared to $ep$ by a factor $\sqrt{Z/A} \approx 0.7 (0.6)$ for light (heavy) nuclei, and the luminosity per nucleon is approximately the same as in $ep$. Such a facility would significantly expand the “energy-luminosity frontier” in electromagnetic scattering (see figure 1), particularly for nuclei, and enable qualitative advances in exploring short-range structure and Quantum Chromodynamics. The EIC physics program includes studies of the nucleon’s three-dimensional partonic structure (gluon spin, quark spin flavor decomposition, transverse momentum, spatial structure, correlations), the dynamics of color fields in nuclei (quarks/gluon densities in nuclei, nuclear shadowing, physics of high gluon densities), and the conversion of color charge to hadrons (color transparency, parton propagation in medium, hadronization) \cite{4, 5}.

The EIC would vastly expand the capabilities for studying heavy quark production in electromagnetic scattering as compared to present facilities. Measurements of open charm and beauty electro- and photoproduction were performed at the HERA $ep$ collider at $x_B < 0.01$, using various methods of charm/beauty identification; see \cite{6, 7} and references therein.
Open charm production was also observed at the COMPASS $\mu N$ fixed-target experiment [8]. The EIC luminosity is two orders-of-magnitude higher than that of HERA and would permit measurements of open charm/beauty production with much higher rates, extending the kinematic coverage to the region of large $x_B$ ($\sim 0.1$) and rare processes such as high-$p_T$ jets. Heavy quark production with electromagnetic probes could for the first time be measured on nuclear targets and used to study the gluonic structure of nuclei and the propagation of heavy quarks through cold nuclear matter with full control of the initial state. Next-generation detection capabilities at the EIC — tracking, vertex detection, and especially $\pi/K$ identification — would open up new channels for charm/beauty reconstruction compared to HERA and further boost the rate of identified heavy quarks for physics purposes. The study of possible EIC applications to heavy quark production therefore deserves special attention. Here we consider heavy quark production as a new method for measuring the gluon densities in nuclei.

2. Heavy quarks as probe of nuclear gluons

Heavy quark production in DIS can serve as a direct probe of the gluon density in the target. At leading order in perturbative QCD the heavy quark pair is produced through photon-gluon fusion (see figure 2a) and samples the gluon density at momentum fractions $x > ax_B$ ($x_B$ is the Bjorken variable, $a = 1 + 4m_h^2/Q^2$, and $m_h$ is the heavy quark mass), at an effective scale $\mu^2 \approx 4m_h^2$; see [9] and references therein. Higher-order QCD corrections are known and theoretical uncertainties have been quantified [10]. The HERA results have shown good agreement with the QCD predictions [6]. With the EIC heavy quark production could thus become a practical tool for measuring the gluon densities in the nucleon and in nuclei.

Of particular interest is the gluon density in nuclei at large $x$. Measurements of inclusive DIS have shown that the valence quark densities in nuclei are suppressed at $x > 0.3$ (EMC effect) and inspired numerous theoretical studies of QCD in nuclei [11]. The nuclear modifications of gluons are largely unknown at present, and basic questions remain to be answered (see figure 2b): Is the nuclear gluon density suppressed at $x > 0.3$ like the valence quarks (gluonic EMC effect)? Is the nuclear gluon density enhanced at $x \sim 0.1$ (gluon antishadowing)? The answers to these questions would offer insight into the change of the nucleon’s gluonic structure due to nuclear binding and the QCD structure of nucleon-nucleon interactions. Information on the nuclear gluons at $x > 0.1$ can be obtained indirectly from the $Q^2$ dependence of inclusive nuclear DIS
cross sections (DGLAP evolution), but the reach of the present fixed-target data is very limited. EIC would improve the situation by extending the inclusive measurements over a larger $Q^2$ and $W$ range and separating longitudinal and transverse structure functions. A much more powerful method would be direct measurements of the nuclear gluon density at a fixed scale using heavy quark production.

Here we report about an R&D project studying the feasibility of direct measurements of large-$x$ nuclear gluons using heavy quark production at EIC [13, 14]. The tasks include (a) estimating the charm production rates at EIC and the angle-momentum distributions of the heavy mesons and their decay products; (b) exploring new methods of charm reconstruction appropriate for large $x_B$ using the EIC detector capabilities; (c) quantifying the impact on nuclear gluons and the theoretical uncertainties. We note that a detailed design of the JLab EIC detector has yet to be completed, and that simulations of charm reconstruction methods at this stage are necessarily at the generic level. While the studies of charm/beauty production reported here focus on the specific application to large-$x$ nuclear gluons, many of the results are more general and can be used for other physics studies with heavy quarks at EIC (heavy quark fragmentation functions, jets, propagation and hadronization in nuclei).

3. Charm production in DIS at EIC

Charm production rates in DIS at EIC have been estimated using QCD expressions and the HVQDIS code [15] (see figure 3). The charm rates drop rapidly above $x_B \sim 0.1$ due to the decrease of the gluon density. The fraction of DIS events with charm production changes from $\sim 10\%$ at $x_B \sim 0.01$ to $\sim 1\%$ at $x_B \sim 0.1$ (exact numbers depending on $Q^2$). The charm fraction increases with $Q^2$ at fixed $x_B$ as expected for a gluon-dominated process. With an integrated luminosity of $10$ fb$^{-1}$ charm production numbers of $\sim 10^6$ ($\sim 10^5$) can be achieved in DIS at $x_B \sim 0.01$ ($\sim 0.1$). Higher charm rates could be achieved by lowering the $Q^2$ cutoff and/or including charm photoproduction. These numbers define the starting point for charm physics analysis. The challenge in gluon measurements at $x_B \sim 0.1$ will be to identify charm events with an efficiency of $\sim$ few $\%$, in the presence of a DIS background that is $\sim 100$ times larger.
The nucleon momenta in the medium-energy EIC proton/ion beams are \( \sim \) few 10 GeV; e.g., collisions of 10 GeV electrons on 50 GeV nucleons at \( s_{eN} = 2000 \text{ GeV}^2 \). With this setup the charm quarks produced in DIS at \( x_B \sim 0.1 \) typically emerge with large angles in the lab frame (which approximately coincides with the virtual photon-gluon CM frame) and carry moderate momenta \( \sim < 10 \text{ GeV} \). (The actual charm angle and momentum distributions exhibit a complex dependence on \( x_B \) and \( Q^2 \) and have to be determined by kinematic transformations.) The charm quark distributions are imparted on the produced charmed hadrons and their final decay hadrons (\( \pi, K, p \)). A major advantage of the medium-energy EIC design is that these hadrons emerge at large angles and moderate momenta, where good particle identification (PID), tracking, and vertex detection capabilities can be provided by the central detector. In contrast, with a high-energy collider (HERA) the hadrons from large-\( x_B \) charm decays would appear at forward angles and with much larger momenta, rendering their detection more difficult.

4. Toward charm reconstruction at EIC

Charm events in DIS have to be identified through the charmed hadrons (\( D \) mesons, \( \Lambda_c \) baryons) that are produced by charm quark fragmentation and subsequently decay into \( \pi/K/p \), using either exclusive decay channels or inclusive modes (jets).

A summary of significant exclusive decays of \( D/\Lambda_c \) into charged \( \pi/K/p \) is given in table 1. The theoretical reconstruction efficiency in this method is determined by the product of the fragmentation ratio into the charmed hadron and the branching ratio for the exclusive decay. HERA experiments made extensive use of the \( D^{*+} \) channel, which exhibits a distinctive two-step decay \( D^{*+} \rightarrow D^0\pi^+ \), \( D^0 \rightarrow K^-\pi^+ \), and can be reconstructed without PID or vertex detection. However, this channel offers an overall reconstruction efficiency of only \( \sim 1\% \), which is not sufficient for gluon measurements at \( x_B \sim 0.1 \). The EIC detector will provide PID capabilities for charged \( \pi/K \) separation and permit use of other exclusive channels for charm reconstruction (see the example of \( D^0 \) reconstruction through the \( K^-\pi^+ \) decay in figure 4). Combining the charged exclusive decays in table 1 one could achieve a theoretical charm reconstruction efficiency of up to \( \sim 10\% \), which would significantly expand the physics reach at large \( x_B \). Vertex detection can substantially improve the signal/background ratio in charm reconstruction through exclusive decays (see figure 4), but it reduces the overall reconstruction efficiency, because it rejects events with a short decay length. The optimization of charm reconstruction with exclusive decays for

![Figure 3. Estimated number of DIS events (dashed lines) and charm events (solid lines) 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 value indicated (5 or 20 GeV\(^2\)) to the kinematic limit at the given \( x_B \).](image-url)
Table 1. Channels for charm reconstruction through exclusive decays into charged hadronic final states. Columns: 1) charmed hadron $h_c$; 2) fragmentation fraction $f(c \rightarrow h_c)$; 3) significant charged decay channels; 4) branching ratio. The fragmentation fractions are from ZEUS $\gamma p$ [7]. They do not add up to 100% because $D^0$ is also produced through $D^*$ decays.

| $h_c$ | $f$ | Decay | BR |
|------|-----|-------|----|
| $D^0$ | 59% | $K^-\pi^+$ | 3.9% |
|       | 0%  | $K^-\pi^+\pi^+\pi^-$ | 8.1% |
| $D^+$ | 23% | $K^+\pi^+$ | 9.2% |
| $D^{**}$ | 23% | $(K^-\pi^+)D_0\pi^+_{\text{slow}}$ | 2.6% |
|       |     | $(K^-\pi^+\pi^-\pi^-)D_0\pi^+_{\text{slow}}$ | 5.5% |
| $D_s^+$ | 9%  | $(K^+K^-)\phi \pi^+$ | 2.3% |
| $\Lambda_c^+$ | 8%  | $pK^-\pi^+$ | 5.0% |

the purpose of gluon measurements at $x_B \sim 0.1$ at EIC is the object of on-going R&D [13].

Charm production in DIS can also be identified through inclusive modes, by selecting jet events with a displaced secondary vertex indicating a $D$ meson decay. A selection method based on the decay length significance distribution was used in the last HERA experiments at $x_B < 0.01$ [6]. Such methods can in principle achieve much larger charm reconstruction efficiencies than exclusive channels, especially when combined with PID ($\sim 30\%$ was assumed in the EIC simulations in [2]). Their feasibility for gluon measurements at $x_B \sim 0.1$, where the fraction of charm events is only $\sim 1\%$ of DIS, needs to be explored further. Note that this assessment requires detailed assumption about the performance of the EIC vertex detector.

Another possible strategy for large-$x$ gluon measurements with charm is to focus on exceptional $c\bar{c}$ pairs with large transverse momenta $p_T \gg 1$ GeV. While they are produced with a small cross section, such configurations represent a very distinctive final state that is practically free from hadronic background.

5. Nuclear ratio measurements

The application of charm production at EIC to the study of nuclear gluons at large $x$ also requires analysis of the uncertainties specific to nuclear ratio measurements [14]. This includes (a) controlling the relative nuclear luminosity in measurements with different ion beams through physics processes; (b) separating effects of nuclear final-state interactions on the observed meson spectrum from initial-state modifications of the nuclear gluon density using the different $A$-dependence of the two mechanisms; (c) quantifying the impact of the charm production pseudodata on the nuclear gluon densities. Results will be reported in due course [13].

6. Summary

A medium-energy EIC would offer excellent opportunities for measurements of charm/beauty production in $ep/eA$ and $\gamma p/\gamma A$ scattering through a unique combination of energy, luminosity, and next-generation detection capabilities. The charm rates appear sufficient to constrain nuclear gluons at $x > 0.1$, if charm reconstruction could be performed with an overall efficiency of $\sim$ few %. Practical methods to achieve such efficiency are being investigated. Heavy quark production at EIC could of course also be used for other physics purposes (e.g. heavy quark fragmentation functions, jets, propagation and hadronization in nuclei), which may impose less stringent requirements. Simulating such measurements would elucidate other aspects of charm production/reconstruction with EIC and provide further impulses for detector development.

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Figure 4. Impact of PID and vertex cuts on $D^0$ meson reconstruction from the $K^-\pi^+$ exclusive decay. Plots (a)–(d) show the invariant mass spectrum of two charged tracks/mesons in a sample of charm events with $Q^2 > 10$ GeV$^2$ and $x_B > 0.05$ (PYTHIA 6 simulation, arbitrary normalization of event sample, background from non-charm DIS events not included). (a) No PID (charged tracks), no vertex cut; (b) with PID ($K^-$, $\pi^+$), no vertex cut; (c) no PID, with vertex cut; (d) with PID and vertex cut. Plot (e) shows the vertex distribution of the $D^0$ decay in the sample. The vertex cut was applied at 100 $\mu$m.

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