Heavy quark production at an Electron-Ion Collider

E Chudakov[1], D Higinbotham[1], Ch Hyde[2], S Furletov[1], Yu Furletova[1], D Nguyen[1,3], M Stratmann[4], M Strikman[5], C Weiss[1]

[1] Jefferson Lab, Newport News, VA 23606, USA
[2] Old Dominion University, Norfolk, VA 23529, USA
[3] University of Virginia, Charlottesville, VA 22904, USA
[4] Tübingen University, 72076 Tübingen, Germany
[5] Pennsylvania State University, University Park, PA 16802, USA

E-mail: weiss@jlab.org

Abstract. An Electron-Ion Collider (EIC) with center-of-mass energies $\sqrt{s_{eN}} \sim$ 20–100 GeV and luminosity $L \sim 10^{34}$ cm^{-2} s^{-2} 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 large x (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 identification using next-generation detector capabilities (π/K identification, vertex reconstruction). The results can be used also for other physics applications of heavy quark production at EIC (fragmentation functions, jets, heavy quark propagation in nuclei).

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 [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 [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) [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 $x_{\mathrm{B}} < 0.01$, using various methods of charm/beauty identification (see below) [6, 7]. Open charm production was also observed at the COMPASS μN fixed-target experiment [8]. The EIC luminosity is two orders-of-magnitude higher than that of HERA and would permit measurements of open

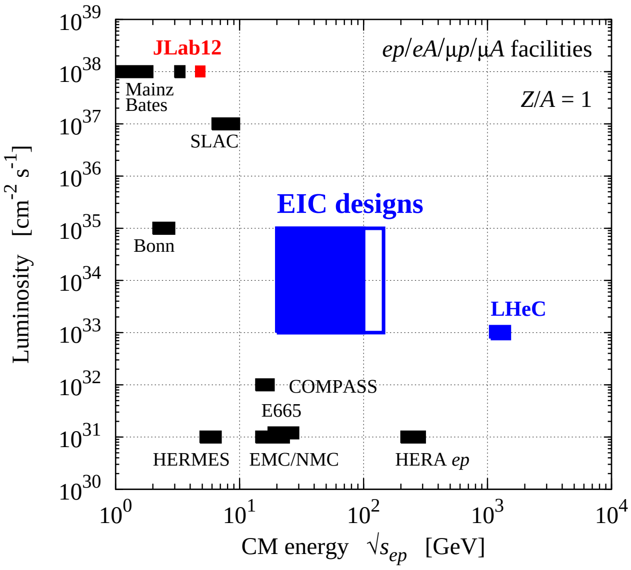

Figure 1. CM energies and luminosities of experimental facilities for electromagnetic scattering at multi–GeV energies ($ep/eA/\mu p/\mu A$; past, present, and future). The coverage of the EIC designs is indicated by the blue box ($ep, Z/A = 1$).

charm/beauty production with much higher rates, extending the kinematic coverage to the region of large x_B (~ 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 π/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.

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 $x > ax_{\mathrm{B}}$ (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 Ref. [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 been 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.

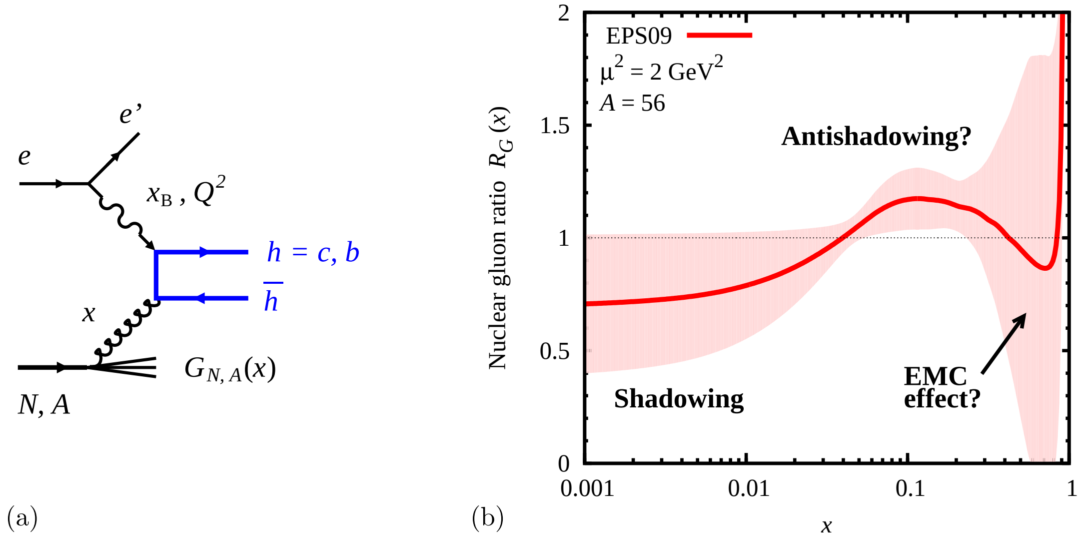

Figure 2. (a) Heavy-quark production in DIS at LO (photon-gluon fusion). (b) The nuclear gluon density ratio $R_G(x,\mu^2) = G_A(x,\mu^2)/[AG_N(x,\mu^2)]$ and its uncertainty at a scale $\mu^2 = 2$ GeV^2, obtained from the EPS09 analysis of nuclear PDFs [12].

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; (b) studying the angle and momentum distributions of the heavy mesons and their decay products; (c) exploring new methods of charm reconstruction appropriate for large x_B using the EIC detector capabilities; (d) quantifying the impact on nuclear gluons and the theoretical uncertainties. 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).

Charm production rates. Charm production rates in DIS at EIC have been estimated using QCD expressions and the HVQDIS code [15] (see figure 3). Simulations show that the charm rates drop rapidly above $x_{\rm B} \sim 0.1$ due to the decrease of the gluon density. The fraction of DIS events with charm production changes from $\sim 10\%$ at $x_{\rm B} \sim 0.01$ to $\sim 1\%$ at $x_{\rm B} \sim 0.1$ (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 $x_{\rm B} \sim 0.01$ (~ 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 ~ 100 times larger.

Charm angle and momentum distributions. The typical nucleon momenta in the medium-energy EIC proton/ion beam are $\sim$ few 10 GeV; e.g., collisions of 10 GeV electrons on 50 GeV nucleons at $s_{eN} = 2000$ GeV^2. With this setup the charm quarks produced in DIS at $x_{\rm B} \sim 0.1$ typically emerge with large angles in the lab frame (which approximately coincides with the virtual photon–gluon CM frame) and carry momenta of $\sim$ several GeV. The actual charm angle and momentum distributions exhibit a complex dependence on $x_{\rm B}$ 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 (π, K, p). Detection capabilities

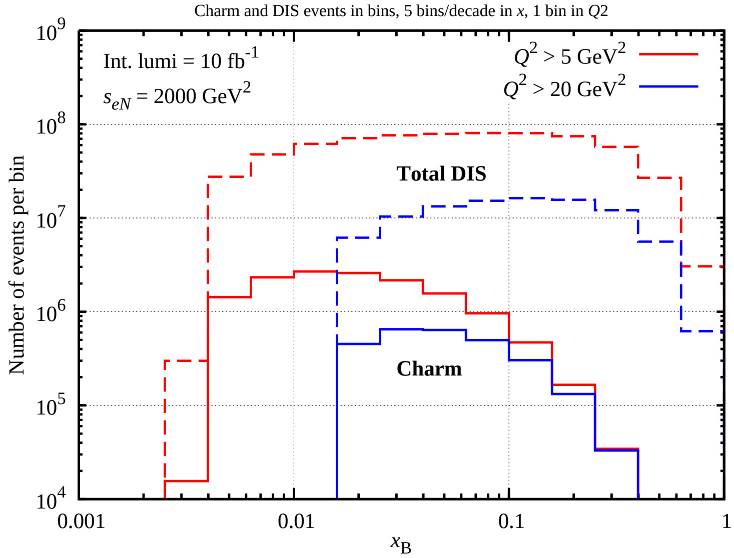

Figure 3. Estimated number of DIS events (dashed lines) and charm events (solid lines) in DIS at EIC (CM energy $s_{eN} = 2000$ GeV^2, integrated nucleon luminosity 10 fb^{-1}). The bins in $x_{\rm B}$ are 5 per decade as indicated on the plot. Q^2 is integrated from the lower value indicated (5 or 20 GeV^2) to the kinematic limit at the given x_B.

h_c	f	Decay	BR
D^0	59%	$K^-\pi^+$	3.9%
		$K^-\pi^+\pi^+\pi^-$	8.1%
D^+	23%	$K^-\pi^+\pi^+$	9.2%
D^{*+}	23%	$(K^-\pi^+)_{D0}\ \pi^+_{\rm slow}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{\rm slow}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%

Table 1. Channels for charm reconstruction with charged hadronic final states. Columns: 1) charmed hadron h_c; 2) fragmentation fraction $f(c \to h_c)$; 3) significant charged decay channels; 4) branching ratio. The fragmentation fractions are from ZEUS γp; for uncertainties and comparison with other results see Ref. [7]. They do not add up to 100% because D^0 is also produced through D^{*+} decays.

for these hadrons need to be provided in the relevant angle and momentum ranges. A major advantage of the medium-energy EIC is that the hadrons emerge at large angles and moderate momenta $\sim$ few GeV, where good particle identification (PID) can be performed. 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.

Charm reconstruction. Charm events are identified by reconstructing the charmed hadrons (D mesons, Λ_c baryons) that are produced by charm quark fragmentation and subsequently decay into $\pi/K/p$. A summary of the channels with significant decays into charged hadrons is given in table 1. The theoretical reconstruction efficiency is determined by the product of the fragmentation ratio into the charmed hadron and the branching ratio for the hadronic decay. Experiments at HERA [6] made extensive use of the D^{*+} channel, which exhibits a distinctive two-step decay $D^{*+} \to D^0\pi^+_{\rm slow}$, $D^0 \to K^-\pi^+$, and can be reconstructed without PID or vertex detection. However, this channel offers an overall reconstruction efficiency of only $\sim 1\%$, which may not be sufficient for gluon measurements at $x_{\rm B} \sim 0.1$. The EIC detector will provide vastly improved PID capabilities, especially for charged π/K separation, and allows one to use other channels for charm reconstruction. Combining the charged decay channels 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. The feasibility of this method of charm reconstruction with EIC and its optimization are objects of on-going R&D [13].

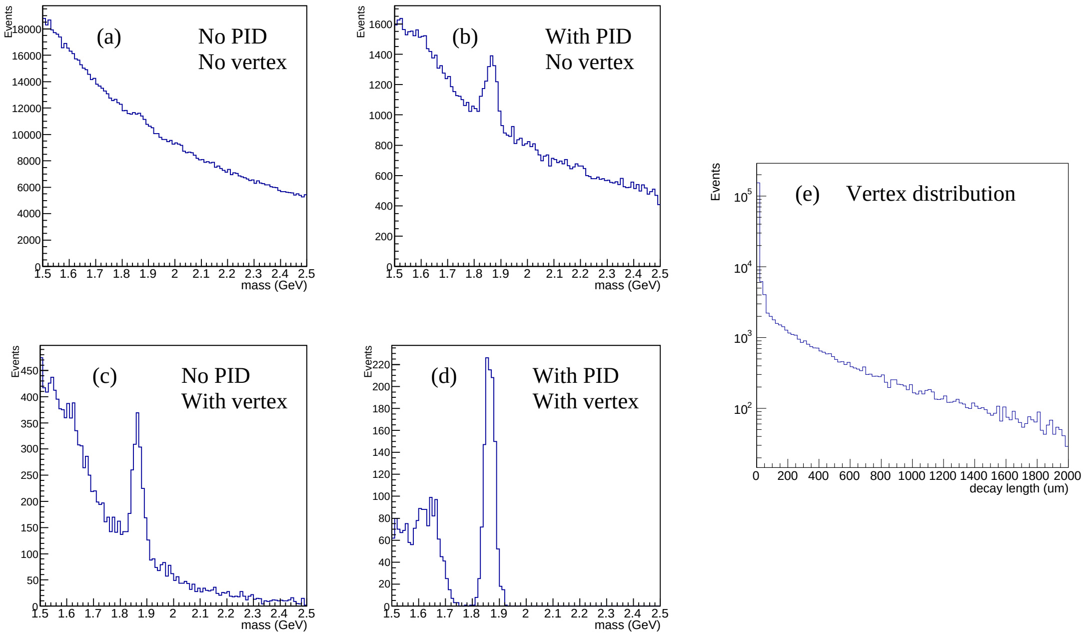

Figure 4. Impact of PID and vertex cuts on D^0 meson reconstruction from the $K^-\pi^+$ decay. Plots (a)–(d) show the invariant mass spectrum of two charged tracks/mesons in a sample of charm events with $Q^2 > 10$ GeV^2 and $x_B > 0.05$ (arbitrary normalization, no other DIS background). (a) No PID (charged tracks), no vertex cut; (b) with PID (K^-, π^+), 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 200 μm.

Vertex reconstruction. Reconstruction of the displaced decay vertex of the charmed hadron can substantially improve the signal/background ratio in charm reconstruction, by eliminating much of the combinatorial background. However, the method also reduces the overall charm reconstruction efficiency because it rejects events with a short decay length. Vertex detection was/is extensively used in charm production at HERA at $x_B < 0.01$ and at LHC experiments, where the charm production rates are large and the decay lengths are boosted by the large D meson momenta. The method can certainly be applied to charm experiments at EIC. However, in DIS at at $x_{\mathrm{B}} \sim 0.1$ the charm cross section will be $\sim 1\%$ of the total cross section, and it is imperative to maximize the overall efficiency of charm reconstruction. At the same time the vertex displacements generally will be smaller than in the high-energy experiments. The benefits of vertex detection for the specific purpose of large–x gluon measurements need to be explored. As an example, figure 4 illustrates the impact of PID and vertex cuts on the reconstruction of D^0 through the $K^-\pi^+$ decay (see table 1).

High–p_T charm pairs. 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. Whether nuclear ratio measurements would be feasible with such final states is a topic for further R&D [13].

Nuclear ratio measurements. The application of charm production at EIC to the study of the nuclear modification of 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].

In sum, 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 %. 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.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177. The work of M.S. was supported by the same agency under award DE-FG02-93ER40771.

References

[1] U.S. Department of Energy Office of Science, Reaching for the horizon: The 2015 Long Range Plan for Nuclear Science, available at `http://science.energy.gov/np/nsac`
[2] Accardi A *et al.* 2016 Eur. Phys. J. A **52** 268
[3] For current information on the EIC machine designs, see: `https://eic.jlab.org/wiki/` (JLab) and `https://wiki.bnl.gov/eic/` (BNL).
[4] Accardi A, Guzey V, Prokudin A and Weiss C 2012 Eur. Phys. J. A **48** 92
[5] Boer D *et al.* 2011 Gluons and the quark sea at high energies: Distributions, polarization, tomography, *Preprint* arXiv:1108.1713 [nucl-th].
[6] Aaron F D *et al.* [H1 Collaboration] 2011 Eur. Phys. J. C **71** 1509 Abramowicz H *et al.* [ZEUS Collaboration] 2014 JHEP **1409** 127; Abramowicz H *et al.* [H1 and ZEUS Collaborations] 2013 Eur. Phys. J. C **73** 2311
[7] Abramowicz H *et al.* [ZEUS Collaboration], 2013 JHEP **1309** 058
[8] Adolph C *et al.* [COMPASS Collaboration], 2012 Eur. Phys. J. C **72**, 2253; 2013 Phys. Rev. D **87** 052018 [arXiv:1211.6849 [hep-ex]].
[9] Gluck M, Reya E and Stratmann M, 1994 Nucl. Phys. B **422** 37
[10] Baines J et al. 2006 Heavy quarks (Working Group 3): Summary Report for the HERA-LHC Workshop Proceedings, *Preprint* hep-ph/0601164.
[11] Malace S, Gaskell D, Higinbotham D and Cloet I, 2014 Int. J. Mod. Phys. E **23** 1430013
[12] Eskola K J, Paukkunen H and Salgado C A, 2009 JHEP **0904** 065
[13] Weiss C et al., JLab LDRD Project LD1601: Nuclear gluons with charm at EIC, `https://wiki.jlab.org/nuclear_gluons/`
[14] Chudakov E *et al.* 2016 Probing nuclear gluons with heavy quarks at EIC *Preprint* arXiv:1608.08686 [hep-ph].
[15] Harris B W and Smith J, 1998 Phys. Rev. D **57** 2806 (1998)