Heavy meson tomography of cold nuclear matter at the electron-ion collider

Hai Tao Li, Ze Long Liu, Ivan Vitev
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, 87545, USA

Abstract
An important part of the physics program at the future electron-ion collider is to understand the nature of hadronization and the transport of energy and matter in large nuclei. Open heavy flavor production in deep inelastic scattering provides a new tool to address these critical questions. We present the first calculation of $D$-mesons and $B$-meson cross sections in electron-nucleus collisions at the EIC by including both next-to-leading order QCD corrections and cold nuclear matter effects. Our formalism employs generalized DGLAP evolution to include the contribution of in-medium parton showers, and is based on methods developed in soft-collinear effective theory with Glauber gluons that describe inclusive hadron production in reactions with nucleons and nuclei. The comprehensive study summarized here allows us to identify the optimal observables, center-of-mass energies, and kinematic regions most sensitive to the physics of energy loss and hadronization at the EIC.

1. Introduction
A high-luminosity electron-ion collider (EIC), which recently received mission need approval from the US Department of Energy, can address fundamental questions about nucleons and nuclei. These include the origin of mass, the internal landscape of hadrons, the phenomenon of gluon saturation, and the physics of hadronization [1]. The production and propagation of heavy flavor in deep inelastic scattering (DIS) are a unique and critical part of this planned decade-long research program. Studies in this direction have so far focused on charm production that can constrain the gluon and strangeness content of the nucleon/nucleus [2, 3, 4], especially at moderate and high values of Bjorken-$x$.

In this letter we investigate semi-inclusive open heavy meson cross sections in electron-proton ($e+p$) and electron-nucleus ($e+A$) collisions to address a different set of questions - how energy and matter are transported through a strongly interacting quantum mechanical environment. The possibility to study the physics of hadronization and energy loss of partons in cold nuclear matter has been investigated by the HERMES Collaboration at HERA using fixed nuclear targets and an electron beam of energy $E_{\text{beam}} = 27.6$ GeV [5, 6]. In these experiments suppression of the multiplicities of light hadrons in $e+A$ versus $e+p$ collisions has been clearly established. Theoretical interpretations of the data predominantly fall within two classes of models. The parton energy loss approach assumes that fragmentation occurs outside of the nucleus and evaluates the attenuation of the quarks and gluons that produce the final-state hadrons, or, equivalently, the effective modification of fragmentation as a function of the transport properties of large nuclei [7, 8, 9]. The hadron absorption model argues that hadronization can take place on length scales smaller than the nuclear size and final-state particle can be absorbed in the medium [10, 11]. We note that phenomenology that uses elements of
both elastic parton scattering and hadron absorption has been developed [12]. Transport models have also been employed to investigate the HERMES data [13].

The HERMES Collaboration e+A results have advanced our understanding of particle production in the nuclear environment, but a number of open questions still remain. The transport coefficients extracted from data using different energy loss approaches differ by up to an order of magnitude [8,9]. More importantly, fundamentally different assumptions about the time scales involved in the process of hadronization and the nature of nuclear attenuation - inelastic parton scattering versus hadron absorption - give equally good description of the light meson multiplicities’ quenching [9,11]. With this in mind, we turn to open heavy meson production as a new probe of cold nuclear matter effects at the EIC, where the semi-inclusive cross sections can be readily measured. Since the shape of charm and beauty quark fragmentation functions (FFs) into D-meson and B-meson is very different from the shape of light parton fragmentation into pions and kaons, carefully chosen observables may be much more sensitive to the nature of nuclear attenuation [14]. A number of center-of-mass (CM) energies are expected to be available at the EIC, with multiple distinct kinematic domains for the final-state particles for each electron-proton/nucleon energy combination. Thus, we further aim to identify the CM energies and rapidity intervals that are most sensitive to the nuclear modification of hadron production from final-state interactions, which may facilitate operation planning and optimize detector coverage for the EIC.

In describing heavy meson production in DIS on nuclei we go beyond the traditional energy loss approach. The evolution of FFs is determined by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations. Recently, soft-collinear effective theory (SCET) [15,16,17,18] has been employed to describe interactions between jets and a QCD medium via Glauber gluon exchange [19,20]. This allowed for the derivation of the full set of 1 → 2 medium-induced splitting kernels for massless and massive partons [21,22]. With EIC applications in mind, these results were verified using a lightcone wavefunction approach and a formalism to calculate higher order corrections in the opacity of nuclear matter was developed [23,24]. The medium-induced splitting kernels can be used to understand the evolution of FFs in cold nuclear matter - a technique which was successfully developed in heavy ion collisions [25,26]. In this letter, we employ the QCD evolution-based method to encode the cold nuclear matter effects on hadron production at the EIC and to present the results of our analysis.

The rest of our letter is organized as follows. In section 2, we briefly introduce the theoretical framework for the next-to-leading order (NLO) QCD corrections to hadron production in DIS and in-medium QCD evolution based on SCET_G. In section 3, we compare theoretical predictions with HERMES measurement and demonstrate the validity of our approach for hadron production in reactions with heavy nuclei. Section 4 is dedicated to the detailed study of pion, D and B mesons production at the EIC. We conclude in section 5.

2. Theoretical Framework

2.1. Hadron Production in DIS

In collinear leading-twist perturbative QCD the inclusive cross section for the production of hadron $h$ is factorized as follows:

$$E_h \frac{d^3 \sigma^{N\rightarrow hX}}{d^3 P_h} = \frac{1}{S} \sum_{i,f} \int_0^1 dx \int_0^1 dz \frac{d \hat{\sigma}^{i\rightarrow f}}{z^2} f^{i/N}(x,\mu) \times D^{h/f}(z,\mu) \left[ \hat{\sigma}^{i\rightarrow f} + f_{\text{ren}}^{i/f} \left( \frac{-t}{s+u},\mu \right) \hat{\sigma}^{i\rightarrow f} \right]. \quad (1)$$

Here, $f^{i/N}$ is the parton distribution function (PDF) of parton $i$ in nucleon $N$ and $D^{h/f}$ is the conventional FF from parton $f$ to hadron $h$. $\hat{\sigma}^{i\rightarrow f}$ is the partonic cross section for lepton-parton scattering with initial-state parton $i$ and final-state parton $f$. $s, t, u$ are the partonic Mandelstam variables defined as $s = (k+l)^2$, $t = (k-p)^2$ and $u = (l-p)^2$, where $p$,
k' and p' are the momenta of incoming lepton, incoming parton and fragmenting parton, respectively. When the lepton scattering angle is small, the hard process can be described by an incoming quasi-real photon scattering: $\gamma g \rightarrow q(g)$. $\gamma g \rightarrow g(\bar{q})$, which contribute to the cross section starting at order $\alpha^2_{\text{EM}}$. In this case, the incoming lepton is regarded as a source of quasi-real photons. The well known Weizsäcker-Williams (WW) distribution provides an accurate description for photons in leptons by perturbative distribution functions $f_{\text{ren}}^{\gamma/(l)}(y, \mu)$ [27, 28, 29, 30]. The analytical expressions for $\bar{\sigma}^{i\rightarrow f}$, $\bar{\sigma}^{i\rightarrow f}$ and $f_{\text{ren}}^{\gamma/(l)}(y, \mu)$ have been known up to $O(\alpha^2_{\text{EM}})$ for a while, and can be found in [31].

In the numerical calculations that follow we use CT10lo PDF sets [32] and the associated strong coupling provided by LHAPDF6 [33]. Fragmentation functions into light hadrons, for example $\pi$, are taken from Ref. [34]. The boundary condition for heavy quark fragmentation into the various D-meson and B-meson states at a scale $\mu = 2m_Q$ can be calculated perturbatively using heavy quark effective theory (HQET), as shown in Refs. [35, 36]. The FFs obey the DGLAP evolution equations, which can be written as

$$\frac{d}{d \ln \mu^2} D_{hij}(x, \mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_s(\mu)) D_{hj}(\frac{x}{z}, \mu), \tag{2}$$

where $P_{ji}$ is the Altarelli-Parisi (AP) splitting functions describing $i \rightarrow j + X$ splitting and $z$ is the longitudinal momentum fraction of $j$ relative to $i$. We make use of HOPPET [37] to solve the Eq. (2) numerically to LO.

To understand the feasibility of heavy flavor measurements at nominal EIC luminosity and to assess the magnitude of higher order corrections we first turn to the calculation of hadron cross sections in e+p collisions. The vacuum splitting functions are used to perform the RG evolution of the FFs. Both the renormalization scale and factorization scale are chosen as the energy of the initial parton fragmenting to a hadron in the rest frame of the proton. This is motivated by the need for consistency with e+A calculations where the energy of the parent quark or gluon in nuclear matter plays a key role in determining the strength of the medium-induced parton shower. Selected results for the expected multiplicities of light, charm, and beauty mesons, exemplified by $\pi^+$, $D^0$ and $B^0$, are shown in Table 1 for integrated luminosity of 10 fb$^{-1}$. We consider three combinations of electron and proton beam energies: 5 GeV (e) × 40 GeV (p), 10 GeV (e) × 100 GeV (p), and 10 GeV (e) × 100 GeV (p) and integrate over the pseudorapidity interval $-2 < \eta < 4$. The NLO QCD corrections are obtained from Eq. (1), including the contribution from quasi-real photon scattering. They lead to a $K$-factors in the range of 1.5 to 2.5. For $\pi$ meson production, the quasi-real photon scattering contributes about 40% to 50% to NLO corrections.
while for $D$-mesons and $B$-mesons the quasi-real photon contribution is even more dominant. The NLO corrections are sizable and when it comes to absolute cross sections they should be considered for reliable theoretical predictions.

2.2. Cold Nuclear Matter Effects

When partons propagate in strongly-interacting matter they scatter and radiate. The medium-induced parton shower will modify the evolution of the FFs, and has been investigated in the framework of SCET\textsubscript{M,G} [20, 22]. These modifications were first introduced as corrections to the DIS hadronization process [38] and, more recently, implemented in medium-modified DGLAP evolution. This theoretical framework has been used extensively in Refs. [9, 25, 26, 22, 39, 40, 41] to carry out resummation in cold and hot QCD medium numerically, and to describe hadron production and observables sensitive to the fragmentation process. We will solve the medium-corrected DGLAP evolution equations to take account of the radiation induced by a large nucleus, as shown in Fig. 1.

The full fragmentation function evolution in the presence of nuclear matter is given by:

$$
\frac{d}{d\ln \mu^2} D_{ji}(x, \mu) = \sum_f \int_x^1 \frac{dz}{z} D_{ji}(\frac{x}{z}, \mu) \\
\times \left( P_{ji}(z, \alpha_s(\mu)) + P^\text{med}_{ji}(z, \mu) \right). \tag{3}
$$

In Eq. (3) $P^\text{med}_{ji}$ are the medium corrections to the splitting functions. It has been demonstrated that the full splitting kernel is a direct sum of its vacuum and medium-induced components and the corrections are gauge-invariant. We will make use of the form of in-medium branching processes derived in [20, 21, 23, 24]. Equivalent to the vacuum splitting functions, the real contribution can be written as

$$
P^\text{med,real}_{i\rightarrow jk}(z, k_\perp) = 2\pi \times k_\perp^2 \int dN^\text{med}_{i\rightarrow jk}. \tag{4}
$$

The full splitting functions can be expressed as proportional to the vacuum ones with a medium induced correction that depends both on the longitudinal momentum fraction $z$ and the intrinsic transverse momentum of the branching $k_\perp$. This is because in-medium parton showers are broader and softer than the ones in the vacuum.

The full set of medium corrections to the splitting functions can be written as

$$
P^\text{med}_{qq}(z, k_\perp) = [P^\text{med,real}_{q\rightarrow qg}(z, k_\perp)]^+, \tag{5}
$$

$$
P^\text{med}_{gq}(z, k_\perp) = [P^\text{med,real}_{g\rightarrow qg}(z, k_\perp)]^+, \tag{6}
$$

$$
P^\text{med}_{gg}(z, k_\perp) = \left[ \left( \frac{2z - 1}{1 - z} + \frac{z(1 - z)}{z} \right) h_{gg}(z, k_\perp) \right]^+ \\
+ \frac{h_{gg}(z, k_\perp)}{z} + B(k_\perp) \delta(1 - z), \tag{7}
$$

where

$$
h_{gg}(z, k_\perp) = \frac{P^\text{med,real}_{g\rightarrow gg}(z, k_\perp)}{\frac{1}{z} - x + \frac{z(1 - z)}{z}}, \tag{8}
$$

and $B(k_\perp)$ can be obtained through momentum sum rules. The definition of the splitting function in QCD medium can be also found in Refs. [25, 26, 22].
Note that in Eq. (3) the scale of the medium-induced splitting function is set to be $k_\perp$ which characterizes the intrinsic scale of the collinear splitting. The evolution for heavy flavor can similarly be written down and the splitting kernels associated with massive quarks can be found in Refs. [22, 24].

The medium-induced splitting functions for massive quarks are defined in a similar way as the ones in Eq. (5). They reduce to the massless case for large scales, while the mass effects can play an important role for small scales.

An example of how in-medium evolution can alter the fragmentation pattern of partons into hadrons is given in Fig. 2. It presents the ratio of the FFs for the case of a gold (Au) nucleus evolved from the boundary condition to a scale $\mu = 30 \text{ GeV}$ to the ones in the vacuum, denoted $D_{\text{Med}}/D_{\text{Vac}}$. The dotted blue lines, dashed red lines and solid green lines represent the fragmentation of $u \to \pi^-$, $c \to D^0$ and $b \to B^0$, respectively. We have averaged the parent parton production point over the nuclear geometry in evaluating the splitting kernels that enter the evolution equations. The nominal transport coefficient of cold nuclear matter we take to be $(k_\perp^2) / \lambda_g = 0.12 \text{ GeV}^2/\text{fm}$. Here, $(k_\perp^2)$ is the mean momentum transfer squared in two dimensions per scattering and $\lambda_g$ is the gluon scattering length. The bands correspond to varying the transport parameter up and down by a factor of two. The effect of the medium-induced shower is to further soften fragmentation relative to the vacuum. We can see that the FFs for $\pi^+$ are always suppressed, except for very small values of $z$. The fragmentation pattern of heavy flavor is modified in a distinctly different way, the suppression only happens in the large-$z$ region. For $c \to D^0$ and $b \to B^0$, the in-medium corrections enhance very significantly FFs with $z < 0.6$ and $z < 0.85$, respectively. In addition, the modification due to cold nuclear matter effect is larger at lower energy scales, which opens the door toward fruitful phenomenology at the future EIC. An essential task that we face is to identify the optimize phase space regions that are most sensitive to the effect of in-medium parton showers and where semi-inclusive DIS measurements can provide constraints on the transport properties of large nuclei.

### 3. Comparison with HERMES data

In order to provide theoretical predictions for heavy flavor modification at the EIC, it is useful to get some guidance from existing DIS measurements on nuclei. The HERMES collaboration at HERA has collected such data on light hadron production, albeit at much lower center-of-mass energies. With this limitation in mind, we use the opportunity to test the validity of our theoretical framework of cold nuclear effects on hadronization. Let us define the modification of semi-inclusive pion production as follows:

$$R_{\pi A}(\nu, Q^2, z) = \left. \frac{N_{\pi}(\nu, Q^2, z)}{N_{\pi}(\nu, Q^2, z)_{D}} \right|_{\text{A}},$$

where $N_{\pi}(\nu, Q^2, z)$ and $N_{\pi}(\nu, Q^2, z)_{D}$ is the event number for hadron production ($\pi^+$) and the total number of inelastic events determined by measuring the scattered lepton, respectively. The kinematic variables are defined as $\nu = E - E'$. $Q^2 = -(k - k')(\nu)$, where $E(k)$ and $E'(k')$ are the energies (momenta) of the incoming and outgoing electron in the target rest frame, respectively. Subscripts $A=$Kr, Xe, ... and $D=$deuteron

![Figure 2: The ratio of fragmentation functions for the case of a Au nucleus to the ones in vacuum at a scale $\mu = 30 \text{ GeV}$. Blue band (dotted lines), red band (dashed lines), and green band (solid lines) correspond to light parton to pion, $c$-quark to $D$-meson, and $b$-quark to $B$-meson fragmentation, respectively.](image-url)
denote the target nuclei. The energy of incoming electrons is 27.6 GeV. Here, we employ the same kinematic cuts as in the HERMES measurements: \(Q^2 > 1 \text{ GeV}^2, \quad W = \sqrt{2M\nu + M^2 - Q^2} > 2 \text{ GeV}\) and \(y = \nu/E < 0.85\) [6]. The idea behind normalizing by the number of DIS events is to both account for the large number of nucleons in the nucleus and to minimize effects strictly due to PDFs.

Figure 3 presents comparisons between the theoretical predictions and the HERMES measurements of pion production in DIS on Kr and Xe targets. The bands correspond to the nuclear matter transport parameter and its variation described in the previous section, but the splitting kernels and evolution are for the Kr and Xe nuclei. The theoretical predictions and HERMES data are in good agreement in a range of energy values \(\nu\). Pion production is more suppressed with at lower scales and already hints that it will be more beneficial to study cold matter effects at lower energy \(e^+A\) collision. In addition, we can also see that there is a stronger suppression on heavier nuclear targets.

4. Hadron Production at the EIC

In this section, we move to the main result of this work - hadron and, especially, heavy meson cross section modification at the EIC. Here, we consider three benchmarks energy combinations for electron-proton collisions, for electron-nucleus collision the beam energy is per nucleon: 5 GeV (e) \(\times 40 \text{ GeV} (\text{A}), 10 \text{ GeV} (\text{e}) \times 100 \text{ GeV} (\text{A})\) and 18 GeV (e) \(\times 275 \text{ GeV} (\text{A})\). To investigate the nuclear medium effects, we study the ratio of the cross sections in electron-gold \((e^+\text{Au})\) collision to the one in \(e^+p\) collision. We use the cross section of inclusive jet production for normalization that minimizes the effect of nuclear PDFs.

\[
R_{hA}^{eA}(p_T, \eta, z) = \frac{N^{h(\ln, \eta, z)}_{e^+\text{Au}}}{N^{h(\ln, \eta, z)}_{e^+p}}. \tag{8}
\]

Here, \(N^{\text{inc}}_{(p_T, \eta)}\) denotes the cross section of large radius jet production with transverse momentum \(p_T\) and rapidity \(\eta\). As we only aim to eliminate the differences between proton and nuclear PDFs, result for the inclusive jet production to lowest order are enough for this purpose. In fact, we can reasonably estimate those numbers from the number of scattered electrons in calculable \(p_T\) and backward rapidity bins.

We first turn to the production of hadrons as a function of the transverse momentum \(p_T\) in the laboratory frame. The in-medium shower corrections induced by the interactions between the final-state parton and the nucleus vary with the parton energy in the nuclear rest frame, where the lower energy parton receives the larger medium corrections. One way to study this effect is to vary the CM energy as shown in Fig. 4. The left column of panels is for 5 GeV \(\times 40 \text{ GeV} e^+\text{Au} \) collision and the right left column of panels is for 10 GeV \(\times 100 \text{ GeV} e^+\text{Au} \) collision.
Figure 4: Medium modification of $\pi^+$, $D^0$ and $B^0$ production on a gold (Au) nucleus at the EIC as a function of transverse momentum in three pseudo-rapidity regions for the hadrons. The left column of figures is for 5 GeV (e) $\times$ 40 GeV (p) collisions and the right column of figures is for 10 GeV (e) $\times$ 100 GeV (p) collisions, respectively. The pseudorapidity regions from top to bottom are $-2 < \eta < 0$, $0 < \eta < 2$ and $2 < \eta < 4$.

The dotted blue line, dashed red line and solid green lines denote the result for $\pi^+$, $D^0$ and $B^0$, respectively. We find that not only is the magnitude of the nuclear modification $R_{eA}(p_T)$ larger, but the sensitivity to the transport properties of nuclei, illustrated by the width of the theory bands is also enhanced at the lower CM energy. We also performed calculations for 18 GeV $\times$ 275 GeV e+Au collision and found that the medium effects at those energies are smaller than the ones at 10 GeV $\times$ 100 GeV. Hence, we don’t show them here.

Another way to vary the parent parton energy $\nu$ in the rest frame of the nucleus is to use different rapidity ranges. For given hadron $p_T$, the medium
corrections will be larger for smaller relative rapidity $|\eta - \eta_A|$, with hadron rapidity $\eta$ and nuclear rapidity $\eta_A$ in the lab frame\footnote{In the lab frame $\eta_A \approx 4.4$ and $5.4$ in $5 \text{ GeV} \times 40 \text{ GeV}$ and $10 \text{ GeV} \times 100 \text{ GeV} + A$ collisions, respectively.}. The horizontal sets of panels in Fig. 4 presents $R_{eA}^D$ values in three rapidity bins $-2<\eta<0$, $0<\eta<2$ and $2<\eta<4$. The in-medium corrections are the largest in the forward hadron rapidity region $2<\eta<4$ as expected. The study of the transverse momentum distribution of hadrons can provide a first glimpse of jet quenching effects in reactions with nuclei at the EIC. This is especially clear for the suppression of pions. Even for heavy flavor, at low CM energies and forward rapidities we are beginning to see a hierarchy of suppression patterns and transition from small enhancement at low $p_T$ to sizable suppression at large $p_T$. At the same time, to investigate the nature of hadronization, more differential observables are needed. This is especially true for heavy flavor which in many cases shows little or no nuclear modification. The physics reason is that away from the edges of kinematic acceptance the range of fragmentation fractions $z$ that give sizable contributions to hadron production is limited. For heavy quarks fragmenting into heavy mesons it is in the range $z = 0.55 - 0.90$ and is harder for $b$ quarks in comparison to $c$ quarks. This is precisely the range of momentum fractions where the medium-induced modification to $D$-meson and $B$-meson FFs transitions from suppression at large $z$ to enhancement at small $z$, see Fig. 2. Consequently, for most energy and rapidity combinations we find $R_{eA}^D \approx R_{eA}^B \approx 1$. We finally remark that since $R_{eA}$ is a ratio of cross sections, there is practically no difference in the calculated nuclear modification with LO and NLO hard parts.

To exploit the differences in the hadronization patterns between light hadrons and heavy mesons and use them to discriminate between theoretical models of nuclear modification we turn to more differential observables. Specifically, we fix the $p_T$ bin and look at the momentum fraction distribution $z$, which we extract from our calculation. This corresponds to the variation of $\nu$ which in experiment can be constrained by the kinematics of the scattered electron. Figures 5 and 6 present $R_{eA}^D$ result as a function of $z$. Our predictions in rapidity regions $-2<\eta<0$, $0<\eta<2$ and $2<\eta<4$ are represented by the blue solid lines, red dashed lines, and green dotted lines, respectively. We choose the $p_T$ range $2 \text{ GeV} < p_T < 3 \text{ GeV}$ where the cross sections at lower $z$ values (e.g. $z \sim 0.3$) are sizable. With the same $p_T$ range fixed, we can identify larger in-medium effects at $5 \text{ GeV} \times 40 \text{ GeV}$ e$+A$ collision than at $10 \text{ GeV} \times 100 \text{ GeV}$ collisions. Additionally, hadron productions at forward
rapidity region $2 < \eta < 4$ receive the largest in-medium corrections. For $\pi^+$ production, $R_{eA}$ is always smaller than one in the region of momentum fractions that is accessible with the largest quenching seen at large $z$, see Fig. 5.

In contrast, the modification of open heavy flavor in DIS reactions with nuclei, such as the one for $D^0$ mesons and $B^0$ mesons shown in Fig. 6 is much more closely related to the details of hadronization. The observed $R_{eA}(z)$ is qualitatively consistent with the effective modification of fragmentation functions seen in Fig. 2 even after their convolution with the PDFs and the hard part. There is a significant suppression for large values of $z$, but it quickly evolves to enhancement for $z < 0.65$ and $z < 0.8$ for $D$-mesons and $B$-mesons, respectively. The effect is most pronounced at forward rapidities and we find that $R_{eA}$ as a function of $z$ is a more suitable observable for cold nuclear matter tomography at the EIC than the transverse momentum distributions’ modification for hadrons in the laboratory frame alone. We note that as we go toward small values of $z$ (e.g., $z = 0.3$) the enhancement can be compensated by suppression that arises from the normalization factor $N_{pA}^{inc}(p_T, \eta)/N_{A}^{inc}(p_T, \eta)$. The exact interplay of these effects depends on the rapidity region of interest.

5. Conclusions

In summary, we presented first predictions for heavy $D$-mesons and $B$-meson production in $eA$ collisions at the EIC including NLO corrections and cold nuclear matter effects. The much higher CM energies energies relative to HERMES and, correspondingly, larger parent parton energies in the rest frame of the nucleus boost hadron formation times. This motivates a detailed theoreti-
cal study of in-medium effects arising from final-state parton-level interactions inside large nuclei. The effective modification of open heavy flavor fragmentation functions was obtained by solving the generalized DGLAP evolution equations with in-medium splitting kernels derived in the framework of SCET. This theoretical approach, when applied to light hadron production, shows good agreement with HERMES measurements and allows us to set a range of nuclear transport properties and make projections for the future EIC.

To demonstrate the utility of heavy flavor for cold nuclear matter tomography we carried out a comprehensive study of the production of various $D$-mesons and $B$-meson states at different center-of-mass energies and different rapidity ranges at the EIC. We found that the modification of light and heavy flavor hadron cross sections in reactions with nuclei is sizable and depends on the electron and proton/nucleus beam energy combinations and the rapidity gap between the produced hadron and the target nucleus. Our numerical results show that the 5 GeV × 40 GeV scenario followed by the 10 GeV × 100 GeV case and the forward proton/nucleus going rapidity region $2 < \eta < 4$ produce the largest nuclear effects. Conversely, semi-inclusive hadron production at large center-of-mass energies, e.g. 18 GeV × 275 GeV, and backward rapidities, e.g. $-2 < \eta < 0$, exhibits only small modification in eA reactions relative to e+p ones. Such kinematics is better suited to explore shadowing and the phenomenon of gluon saturation.

Last but not least, we looked for experimental observables that are most sensitive to the details of hadronization. While $p_T$ distributions in the laboratory frame can provide initial information on the quenching of hadrons in cold nuclear matter, a more differential observable such as the fragmentation fraction $z$ distribution measured by HERMES is a much better choice, especially for open heavy flavor. The clear transition from enhancement to suppression at moderate to large values of $z$ will be an unambiguous and quantitative measure of parton shower formation in large nuclei. In conclusion, we expect that this work will be useful in guiding the future heavy flavor tomography program at the EIC.

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