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Heavy flavor and jet studies for the future Electron-Ion Collider to explore the hadronization process

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Abstract

Heavy flavor production at the future Electron-Ion Collider (EIC) will allow us to precisely determine the quark/gluon fragmentation processes in vacuum and the nuclear medium especially within the poorly constrained kinematic region. Heavy flavor hadron and jet reconstructions with the recent EIC detector design have been studied in simulation. Results of corresponding physics projections such as the flavor dependent hadron nuclear modification factor R_{eA} in electron+nucleus collisions will be shown. The statistical precision obtained by these proposed heavy flavor measurements for the future EIC provides a strong discriminating power in separating different theoretical predictions.

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1 Introduction

One of the EIC science drivers is to explore how quarks and gluons form colorless hadrons, which is known as the hadronizaiton process. Such process can not be directly calculated by the perturbative Quantum Chromodynamics (pQCD) theory, and it relies on the extrapolation of global fits on experimental measurements. The future EIC will operate high luminosity electron+proton and electron+nucleus collisions with a variety of different nuclear species (mass number from 2 to 208) at center of mass energies from 20 to 140 GeV. A cleaner environment can be provided by the EIC compared to heavy ion collisions for exploring the hadronization process within both vacuum and a nuclear medium. Heavy flavor quarks (i.e. charm and bottom quarks) have different production mechanisms from light flavor quarks and are expected to experience different hadronization processes due to their mass differences ($m_{c,b} > \Lambda_c > m_{u,d,s}$) [1]. Heavy flavor nuclear modification factor R_{eA} can help extracting the information about the hadronization in medium especially when the final state hadron carries a large momentum fraction relative to the parent parton. Simulation studies of reconstructed D-mesons and B-mesons with the help of a proposed forward silicon vertex/tracking detector together with the associated physics projections at the future EIC [2] will be discussed.

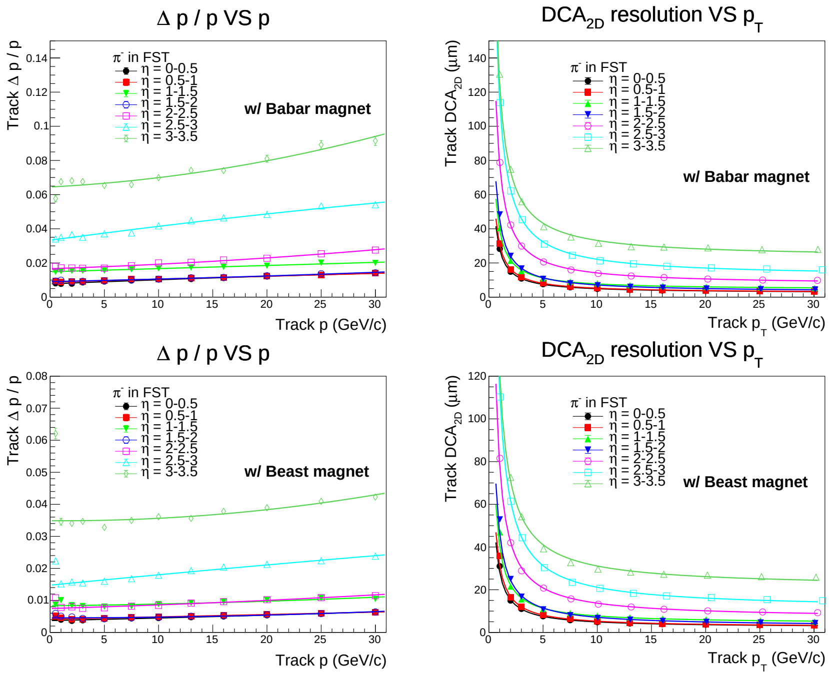

Figure 1: Performances of an integrated silicon tracking system with the Babar magnet for the future EIC [2] are shown in the top and the results with the Beast magnet are shown in the bottom. The track momentum resolutions versus track momentum in different pseudorapidities are shown in the left and the pseudorapidity dependent track transverse distance of closet approach (DCA_{2D}) resolutions versus transverse momentum are illustrated in the right.

2 Heavy Flavor Hadron and Jet Reconstruction in e+p Simulation

To identify particles from heavy flavor decay in the hadron beam going direction at the EIC, a proposed Forward Silicon Tracker (FST), which can provide precise track reconstruction and Distance of Closest Approach (DCA) determination in the $1.0 < \eta < 3.5$ region, is under design and detector R&D [3]. The performance of the proposed FST and other EIC detector sub-systems [2, 4] has been included in the simulation framework, which contains the event generation in PYTHIA8 [5], beam remnant background and the hadron/jet reconstruction chain. The tracking performances with two magnet options: Babar and Beast have been studied in GEANT4 [6] within the Fun4All framework. Figure 1 shows the momentum dependent tracking momentum resolutions and transverse momentum dependent transverse DCA ($\mathrm{DCA}_{2\mathrm{D}}$) resolutions in different pseudorapidity regions.

According to the factorization mechanism, cross section of the hadron with a flavor b in $e+p$ collision can be described as Equation 1.

$$\frac{d\sigma^{b}_{e+p}}{dp_T d\eta} = \sum_a f_a(x_{BJ}, Q^2) \cdot \sigma_{\gamma^* a \to b} \cdot D_b(z_h, \nu), \tag{1}$$

where $f_a(x_{BJ}, Q^2)$ is the parton distribution function of a parton with flavor a that carries the longitudinal momentum fraction x_{BJ} relative to the parent proton, $\sigma_{\gamma^* a \to b}$ is the deeply inelastic scattering partonic process which can be precisely calculated by pQCD and $D_b(z_h, \nu)$ is the fragmentation function of a parton with flavor b that produces a final hadron carrying the momentum fraction z_h relative to the parton. Reconstructed hadrons with different flavors/masses or within different pseudorapidities in $e+p$ collisions are sensitive to quark and gluon Parton Distribution Functions (PDF) in different Bjorken-x (x_{BJ}) regions. Fragmentation functions of partons with different flavors and within different hadron momentum fraction z_h regions can be accessed as well.

For the heavy flavor hadron reconstruction, a series of topological cuts, which include the charged track transverse displaced vertex matching and minimum track transverse momentum cut ($p_T > 0.2$ GeV/c), which is constrained by the proposed Babar magnet, have been applied in simulation. The invariant mass distributions of reconstructed heavy flavor hadrons with the detector performance using the Babar magnet in 10 fb^{-1} electron+proton ($e+p$) collisions at 63.2 GeV center of mass energy are illustrated in Figure 2. Good signal over background ratios have been obtained for reconstructed $D^{\pm}$, $D^0(\bar{D}^0)$, $D_s^{\pm}$, $\Lambda_c^{\pm}$, $B^{\pm}$, $B^0(\bar{B}^0)$ and $B_s^0(\bar{B}_s^0)$. A better mass resolution and slightly higher signal over background ratios can be obtained for the heavy flavor hadron reconstruction with the Beast magnet [3]. Figure 3 shows the reconstructed $D^0(\bar{D}^0)$ within four different pseudorapidity regions from -2 to 3.5 in 10 fb^{-1} 10 GeV electron and 100 GeV proton collisions with the same simulation configuration applied in Figure 2.

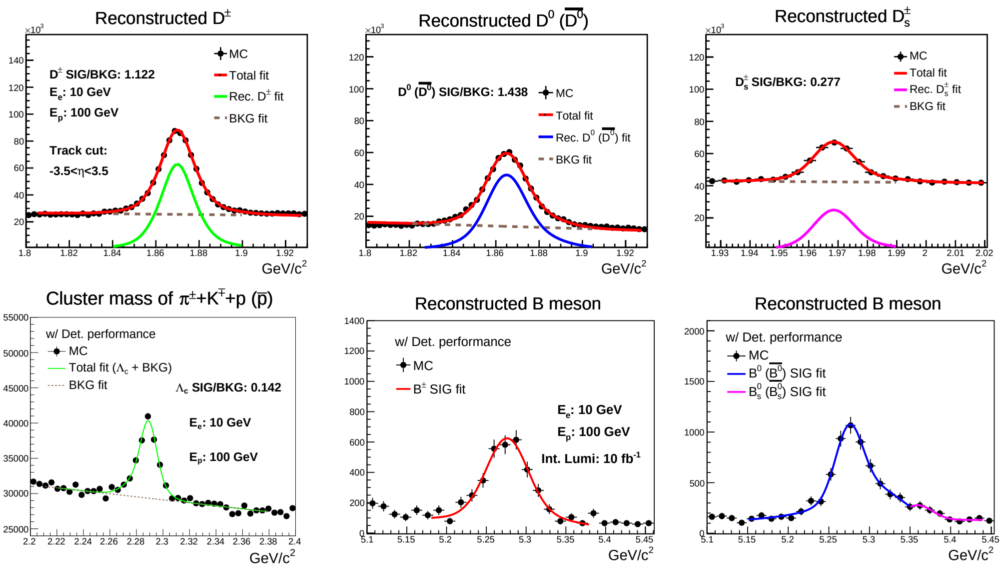

Figure 2: Reconstructed heavy flavor hadron mass spectrums with the evaluated silicon tracking detector performance using the Babar magnet (shown in the top row of Figure 1)) in 63.2 GeV $e+p$ collisions with integrated luminosity of 10 fb^{-1}.

Jets are reconstructed via the anti-k_T algorithm [7] with the cone radius ($R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$) set at 1.0 in $e+p$ simulation. The detector response defined in [2] has been included in the simulation. Jet flavor is tagged when a fully reconstructed light/heavy flavor hadron is within the jet cone or a jet contains multiple tracks from a charm/bottom hadron decay. The transverse momentum (p_T) distributions of reconstructed jets with different flavors in 10 fb^{-1} $e+p$ collisions at 63.2 GeV are illustrated in Figure 4.

3 Nuclear Modification Factor R_{eA} Projection

In order to explore the sensitivity to the hadronization in nuclear medium through the proposed heavy flavor hadron and jet measurements at the future EIC, we have carried out simulation studies of flavor dependent nuclear modification factor R_{eA}, which is defined in Equation

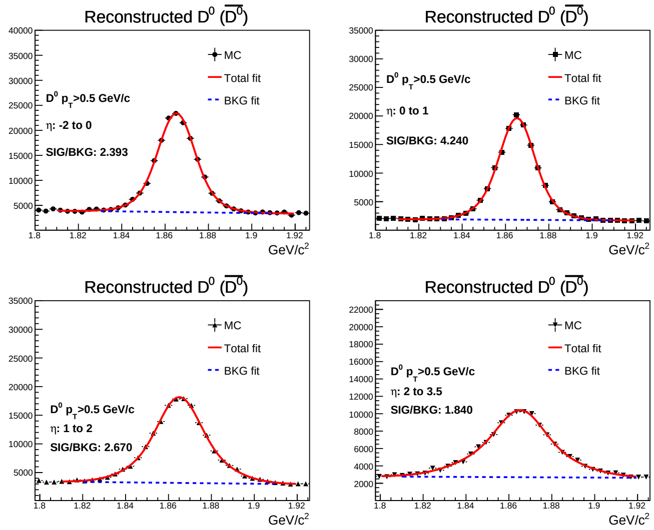

Figure 3: Reconstructed $D^0(\bar{D^0})$ mass spectrums in four different pseudorapidity regions with the evaluated silicon tracking detector performance using the Babar magnet (shown in the top row of Figure 1) in 63.2 GeV $e+p$ collisions with integrated luminosity of 10 fb^{-1}.

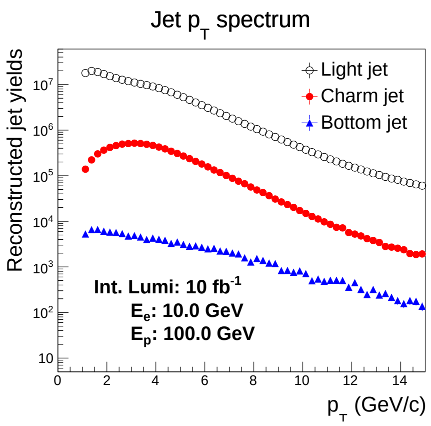

Figure 4: Reconstructed light, charm, and bottom jet transverse momentum (p_T) dependent yields in 10 GeV electron and 100 GeV proton collisions with the integrated luminosity of 10 fb^{-1}. Reconstructed light flavor jet p_T spectrum is shown in open black circles, reconstructed charm jet p_T spectrum is shown in red solid circles and reconstructed bottom jet p_T spectrum is shown in blue solid triangles.

2, in 10 GeV electron and 100 GeV proton/gold collisions.

$$R_{eA} = \frac{1}{A}\frac{d\sigma_{e+A}/dp_T d\eta}{d\sigma_{e+p}/dp_T d\eta}. \tag{2}$$

Hadron yields in $e+p$ collisions, $d\sigma_{e+p}/dp_T d\eta$, are extracted from reconstructed heavy/light flavor hadron mass spectrums discussed in Section 2. The yields in $e+Au$ collisions, $d\sigma_{e+Au}/dp_T d\eta$, are scaled from the corresponding cross-section in $e+p$ collisions at the same collision energy by the nuclear mass number A. The left panel of Figure 5 illustrates the statistical projection of hadron momentum fraction z_h, which is the ratio of reconstructed hadron momentum over associated jet momentum, dependent nuclear modification factor R_{eAu} for reconstructed $\pi^{\pm}$, $D^{\pm}$ and $B^{\pm}$ in 10 fb^{-1} $e+p$ collisions and 500 pb^{-1} $e+Au$ collisions at 63.2

GeV center of mass energy.

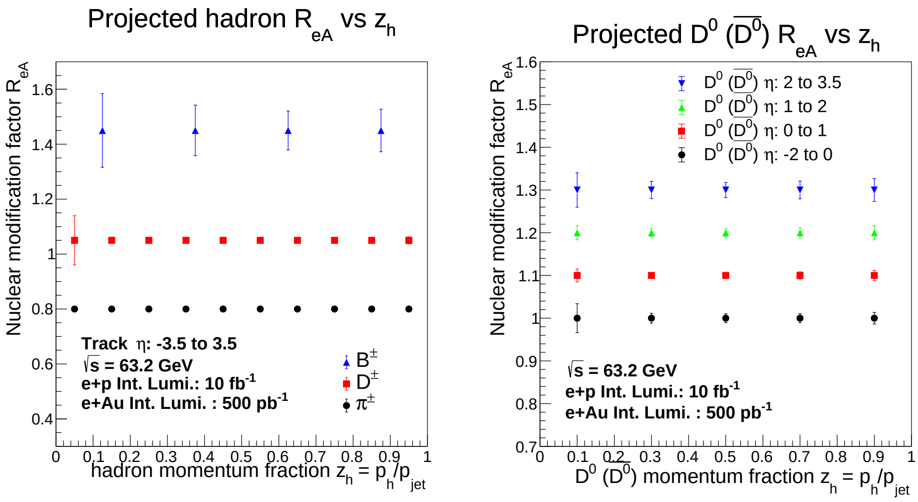

Figure 5: Projected statistical accuracies of flavor dependent nuclear modification factor R_{eAu} for reconstructed hadrons with different flavors (left) and pseudorapidity separated reconstructed $D^0(\bar{D}^0)$ R_{eAu} (right) in 10 fb^{-1} e+p collisions and 500 pb^{-1} e+Au collisions at $\sqrt{s} = 63.2$ GeV. The reconstructed hadron yields are extracted from PYTHIA simulations with the proposed silicon vertex/tracking detector performances using the Babar magnet.

The projected statistical uncertainties of hadron momentum fraction dependent R_{eAu} for reconstructed $D^0(\bar{D}^0)$ in pseudorapidity regions of -2 to 0, 0 to 1, 1 to 2 and 2 to 3.5 using 10 fb^{-1} $e+p$ collisions and 500 pb^{-1} $e+Au$ collisions at $\sqrt{s} = 63.2$ GeV are shown in the right panel of Figure 5. Less than 10% statistical uncertainties can be obtained by reconstructed heavy flavor R_{eAu} measurements with around one year EIC operation. These proposed measurements will provide better constraints on the probed nuclear PDFs and fragmentation functions in nuclear medium in a wide kinematic region.

4 Conclusion

The future EIC will create an ideal QCD environment to explore the hadronization process in vacuum and the nuclear medium through a series of heavy flavor and jet measurements. Various heavy flavor signals have been obtained in simulation studies with the performance of the proposed EIC detector conceptual design, which includes a high precision silicon vertex/tracking subsystem. Good precisions of the proposed flavor dependent and pseudorapidity separated heavy flavor nuclear modification factor measurements at the EIC will provide a strong discriminating power in separating different model predictions for the hadronization process in nuclear medium [8].

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