Nuclear matter effects on jet production at electron-ion colliders

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Abstract

In these proceedings we report recent progress on understanding hadron and jet production in electron-nucleus collisions at the future Electron-Ion Collider [1, 2]. These processes will play an essential role in the exploration of the partonic structure of nuclei and the study of parton shower evolution in strongly-interacting matter. We employ the framework of soft-collinear effective theory, generalized to include in-medium interactions, to present the first theoretical results for inclusive hadron and jet cross sections, as well as the jet charge modification in deep inelastic scattering on nuclei. We further demonstrate how to separate initial-state and final-state effects.

1 Introduction

The future high-luminosity and high-energy Electron-Ion collider (EIC) will help answer questions central to nuclear science. These include the 3D structure of the nucleon, the origin of mass, the properties of the high density gluon saturation regime, and the physics of hadronization in strongly-interacting matter [3]. Among these topics the physics of light and heavy hadron and jet production in deep inelastic scattering (DIS) on nuclei is, perhaps, the least developed. In these proceedings we report the first calculations of inclusive hadron and jet production and the jet charge in electron-nucleus collisions at the EIC and investigate the impact of initial-state and final-state cold nuclear matter effects. To develop the electron-nucleus (e+A) jet physics program at the EIC, we find it useful to place emphasis on observables that have been the most illuminating in the case of heavy-ion collisions. At the same time, the kinematics in DIS is very different relative when compared to heavy-ion collisions (A+A). In the latter case the hard parton and the associated shower propagate in a quark-gluon plasma that is, to first approximation, static in the frame where the jet momentum is transverse to the collision axis. On the other hand, at the EIC even at forward rapidity in the proton / nucleus going direction the energy of the jet is dominated by the longitudinal momentum component in the rest frame of the nucleus. It is important to establish a theoretical approach for calculating jet and hadron production and to be able to predict the magnitude of nuclear modification relative to the electron-proton (e+p) case. Furthermore, to address the physics of parton and particle transport in matter and the physics of gluon saturation, it is essential to be able to separate initial-state and final-state effects. We have developed strategies to accomplish this

task and discuss them here. Last but not least, quenching of jet cross sections in cold nuclear matter is complemented by a modification of the jet substructure. We illustrate this using the jet charge observable.

2 Theoretical formalism

In QCD factorization, the inclusive hadron and jet cross sections can be expressed as follows [1,2],

$$E_{h/J} \frac{d^3\sigma^{lN \to h/JX}}{d^3 P_{j/J}} = \frac{1}{S} \sum_{i,f} \int_0^1 \frac{dx}{x} \int_0^1 \frac{dz}{z^2} f_{i/N}(x,\mu) \hat{\sigma}^{i \to f}(s,t,u,\mu) O_f(z,\mu), \tag{1}$$

where $f_{i/N}$ is the PDF of parton i in nucleon N. $\hat{\sigma}^{i \to f}$ is the partonic cross section with initial-state parton i and final-state parton f, which we take up to NLO and account for the resolved photon contribution. For hadron production $O_f(z,\mu) \equiv D_{h/f}(z,\mu)$ is the fragmentation function, and for jet production $O_f(z,\mu) \equiv J_f(z,p_T R,\mu)$ is the semi-inclusive jet functions (SiJFs) initialed by parton f. When the jet radius R is small, potentially large logarithms of the type $\ln R$ are resummed via time-like DGLAP evolution.

Jet substructure on the other hand is sensitive to the radiation pattern inside a given jet and is governed by a smaller intrinsic scale. One such observable is the average jet charge defined as the transverse momentum p_T^i weighted sum of the charges Q_i of the jet constituents,

$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^\kappa} \sum_{i \in \text{jet}} Q_i \left(p_T^i\right)^\kappa, \quad \kappa > 0, \tag{2}$$

where κ is a free parameter that must be positive for infrared safety. The jet charge is strongly correlated with the electric charge of the parent parton and can be used to separate quark jets from anti-quark jets and to determine their flavor origin.

In reactions with nuclei the factorization formula Eq. (1) receives in-medium corrections [1, 2]. If the leading-twist distributions of partons in nuclei are modified relative to the nucleon, they can be accounted for through nuclear PDFs. Our main focus, however, is on the effect of final-state interactions. The full fragmentation function evolution in the presence of nuclear matter is given by

$$\frac{d}{d \ln \mu^2} D^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z} D^{h/j}\left(\frac{x}{z},\mu\right) \left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\text{med}}(z,\mu)\right), \tag{3}$$

where in Eq. (3) P_{ji}^{med} are the medium corrections to the splitting functions. Their derivation with emphasis on DIS can be found in [4] and they lead to broader and softer parton showers than the vacuum ones [1]. The SiJFs, on the other hand, receive a medium induced contribution at NLO that can be written as

$$J_f(z,p_T R,\mu) = J_f^{\text{vac}}(z,p_T R,\mu) + J_f^{\text{med}}(z,p_T R,\mu), \tag{4}$$

where the vacuum contributions are calculated at the LL accuracy, while only the fixed-order medium corrections are included consistently. It is important to note that $J_f^{\text{med}}(z,p_T R,\mu)$ can be expressed in terms of the in-medium splitting functions [2]. The factorization formula for the jet charge observable Eq. (2) also receives corrections from final-state interactions. Thus, we expect to see differences between the substructure of jets in e+p and e+A reactions, although smaller than in the case of heavy ion reactions.

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[1] Higher order corrections do not qualitatively change this picture [5].
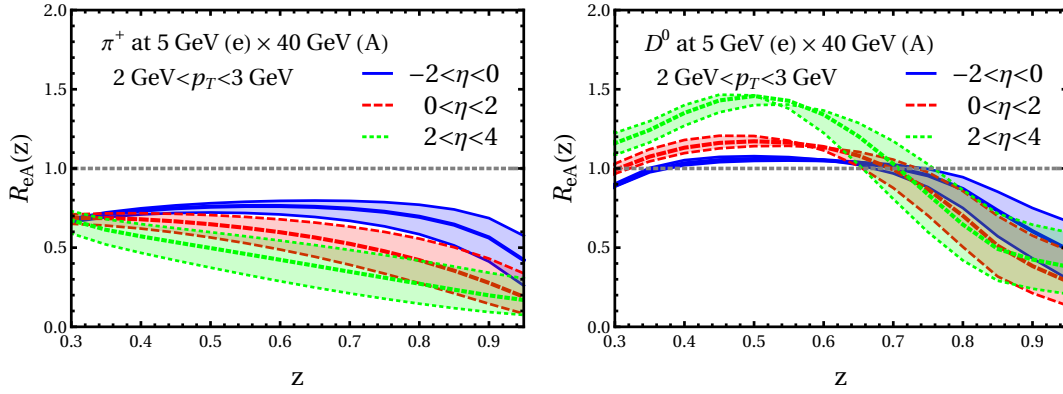
Figure 1: Left: in-medium corrections for π^+ production as a function of z at the EIC in three rapidity regions. Blue bands (solid lines), red bands (dashed lines), and green bands (dotted lines) correspond to -2< η <0, 0< η <2 and 2< η <4, respectively. Right: the same in-medium corrections, but for D^0 at the EIC in the same rapidity regions.

3 Selected results

To investigate the nuclear medium effects, we study the ratio of the cross sections in electron-gold (e+Au) collision to the one in e+p collision. When looking at hadron production, we use the cross section of inclusive jet production for normalization that minimizes the effect of nuclear PDFs,

$$R_{eA}^h(p_T, \eta, z) = \left.\frac{N^h(p_T, \eta, z)}{N^{\text{inc}}(p_T, \eta)}\right|_{e+Au} \bigg/ \left.\frac{N^h(p_T, \eta, z)}{N^{\text{inc}}(p_T, \eta)}\right|_{e+p}. \tag{5}$$

The transport properties of cold nuclear matter can be constrained to a certain extent from HERMES data [6]. Light hadron production in DIS on nuclei at HERMES, however, has not been able to differentiate between competing models of parton energy loss and hadronization in cold nuclear matter, see Ref. [7] for review. This is one area where the EIC with its electron-nucleus program and center-of-mass energies sufficient to copiously produce D-mesons and B-mesons can make a major contribution. We show our results for $R_{eA}^h(p_T, \eta, z)$ in Fig. 1 for 5 GeV(e) × 40 GeV(A) collisions where nuclear effects are most significant. Suppression for pions in three rapidity intervals is shown in the left panel and is largest in the nucleus-going direction, however it is qualitatively similar to the one observed in HERMES data. In contrast to light flavor, the modification of open heavy flavor in DIS reactions with nuclei is much more closely related to the details of hadronization. The $R_{eA}(z)$ in the right panel of Fig. 1 is qualitatively consistent with the effective modification of fragmentation functions in that there is a significant suppression for large values of z, but it quickly evolves to enhancement for $z < 0.65$ for D-mesons. This is an unambiguous signal of final-state partonic interactions.

For reconstructed jets, nuclear effects in e+A reactions can be studied through the ratio

$$R_{eA}(R) = \frac{1}{A}\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+A} \bigg/ \int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+p}. \tag{6}$$

We found that the modification of jets of moderate radius $R = 0.5$ is significant, but mixes initial-state and final-state effects. To isolate jet quenching effect in matter we propose to measure the ratio of the suppression with different jet radii, $R_{eA}(R)/R_{eA}(R = 1)$. Results are shown in the left panel of Fig. 2 and the red, blue, and green bands denote ratios with $R = 0.3, 0.5, 0.8$, respectively. The suppression is stronger for smaller center-of-mass energies
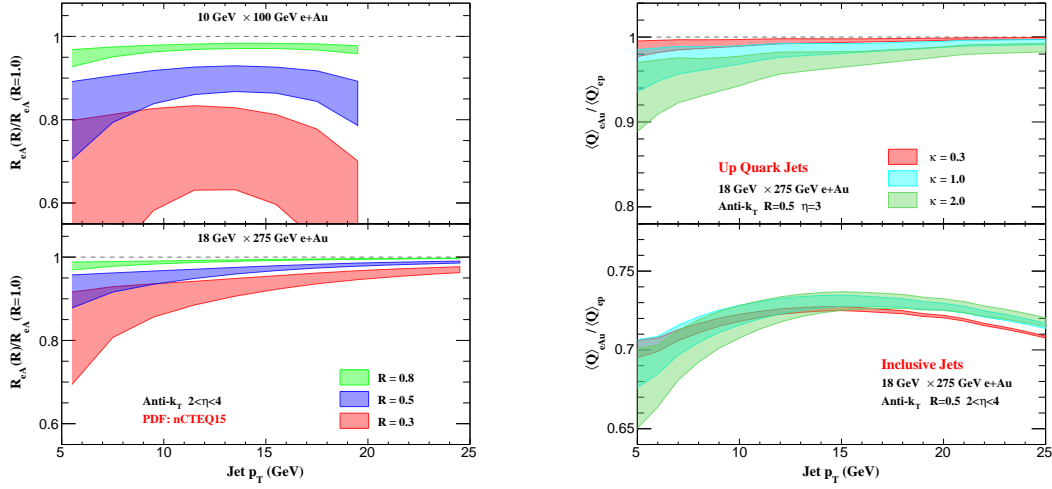
Figure 2: Left: ratio of jet cross section modifications for different radii $R_{\rm eA}(R)/R_{\rm eA}(R=1.0)$ in 10×100 GeV (upper) and 18×275 GeV (lower) e+Au collisions, where the smaller jet radius is R=0.3, 0.5, and 0.8, and the jet rapidity interval is $2 < \eta < 4$. Right: modifications of the jet charge in e+Au collisions. The upper panel is the modification for up-quark jet with $\eta = 3$ in the lab frame. The lower panel is the results for inclusive jet with $2 < \eta < 4$ in 18×275 GeV e+Au collisions.

and for 10 GeV(e) $\times$ 100 GeV(A) collisions it is very significant - close to a factor of two and similar to what has been observed in heavy-ion collisions. The separation in the magnitude of the effect as a function of R is also very clear, the reason being that medium-induced parton showers are broader than the ones in the vacuum. In the right panel of Fig. 2 we present the ratio of the jet charge in e+A relative to the one in e+p collisions. The red, blue and green bands correspond to the jet charge parameter $\kappa = 0.3, 1.0, 2.0$, see Eq. (2). If jets are separated based on their flavor, for example up quark jets, $\langle Q_{\kappa,q}^{\rm eA} \rangle / \langle Q_{\kappa,q}^{\rm ep} \rangle$ is a direct measure of medium-induces scaling violations in QCD - of order 10%. On the other hand, the modification of the average charge for inclusive jets behaves differently because there is a cancellation between contributions from jets initiated by up quarks and down quarks. In nuclei the partonic composition is different because of the neutron contribution. The modification is about 30% and measurement of the charge for inclusive jets can help constrain isospin effects and the up/down quark PDFs in the nucleus.

4 Conclusion

To summarize, hadron and jet physics in e+p and e+A collisions is an important part of the EIC program. It can provide constraints on nuclear PDFs, the physics of hadronization, and the transport of energy and matter in the nuclear environment. We presented calculations of light hadron and jet cross sections, and also jet substructure in e+p and e+A with transport parameters constrained by HERMES experimental measurements. Our results show that to access the physics of hadronization and particle propagation in matter, lower CM energies, forward rapidity, and high luminosity will be very beneficial. Heavy flavor is the key to differentiating between models of hadron suppression in large nuclei. To differentially study parton shower formation in matter, we presented results for reconstructed jets. Using measurements with different jet radii, we developed strategies to separate initial-state from final-state effects. We

further showed, on the example of the jet charge, that jet substructure is also modified in e+A versus e+p reactions and can be used to study medium-induced scaling violations in QCD. Upcoming results on charm jets and bottom jets at the EIC [8] are also promising. They point to the opportunity for heavy flavor tomography of cold nuclear matter and to novel ways to study the mass hierarchy of jet quenching effects on jet substructures. It will also be interesting to study sub-eikonal effects on jet observables related to inhomogeneities in the medium density and fluctuations in the strength of the underlying gluon fields [9].

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