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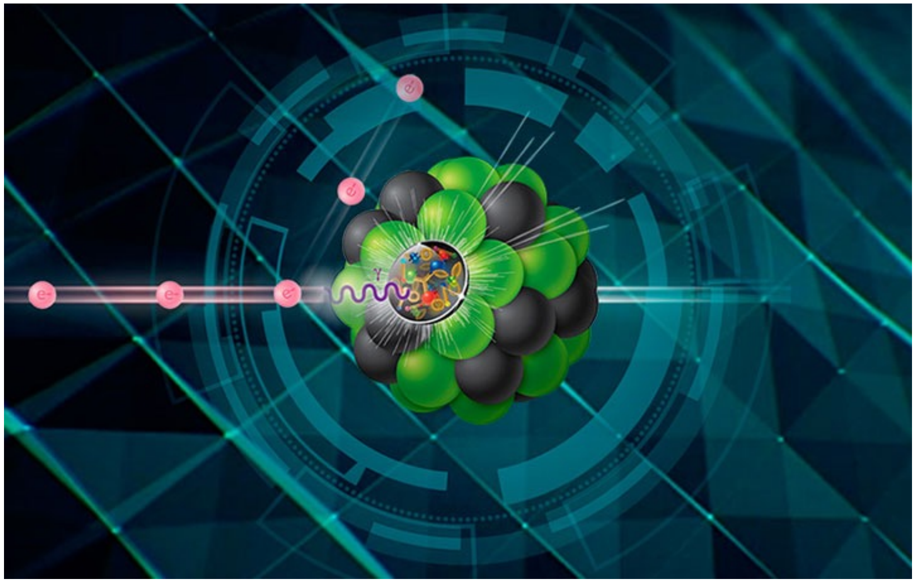
Heavy flavor jet production and substructure in electron-nucleus collisions

DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Santiago de Compostela, Spain, May 2-6

Los Alamos NATIONAL LABORATORY

Outline of the talk



- Heavy flavor branching processes in matter
- Heavy flavor jet cross sections
- Heavy flavor jet substructure

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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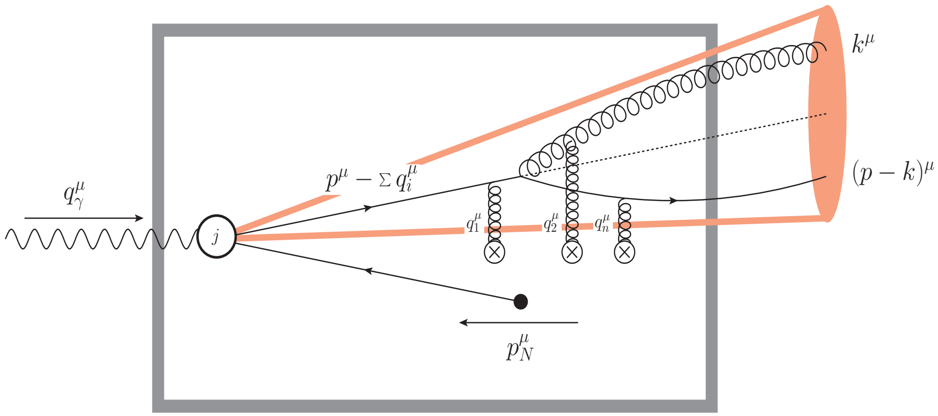
- e-Print: [2108.07809](2108.07809) [hep-ph]

Full in medium splitting for heavy flavor

- Full massless and massive in-medium splitting functions now available to first order in opacity
- SCET-based effective theories and lightcone wavefunction approach give the same result



Representative example

$$\left(\frac{dN^{\rm med}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right.\right.$$
$$\times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$
$$\left. - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left. +\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\}$$

Done of course for all splitting functions

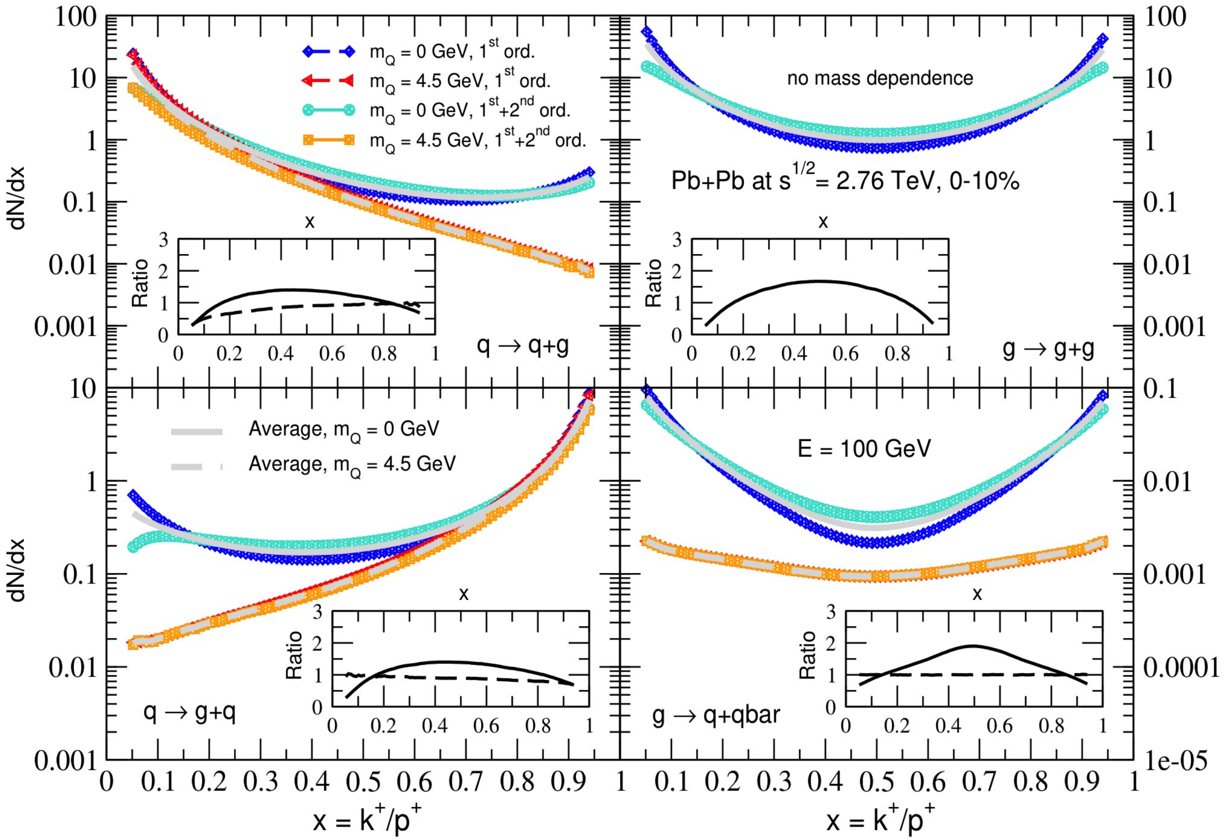
Direct sum of vacuum and medium contributions

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as corrections to Altarelli-Parisi

Differential branching spectra

In-medium parton showers are softer and broader than the ones in the vacuum. There is even more soft gluon emission – medium induced scaling violations, enhancement of soft branching



There us also more wide-angle emission (which implies out-of-cone radiation for jet physics)

- There are significant differences due to the heavy quark mass between massless and massive splitting functions
- Higher orders in opacity have minimal effect on heavy flavor splitting

Hadron production in eA

In-medium splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs

$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

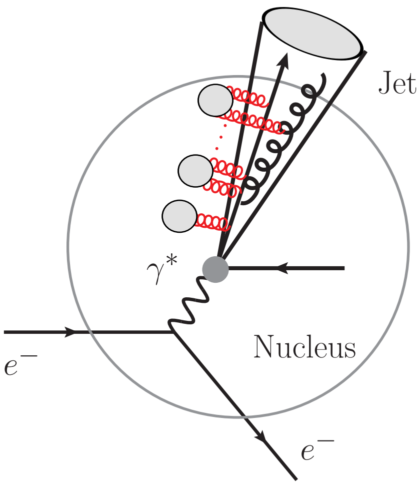
$$\frac{\mathrm{d}D_{\bar{q}}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar{q}}\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right) + P_{g\to q\bar{q}}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + f_{\bar{q}}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

Medium induced scaling violations

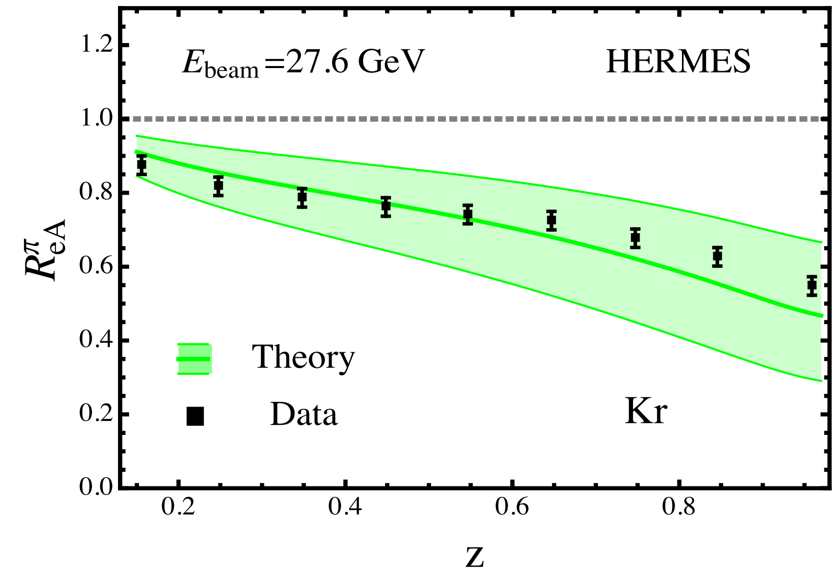
$$q-hat(q) = 0.05\,\frac{GeV^2}{fm}\quad (vary\ \times 2,/2)$$

$$q-hat(g) = 0.12\,\frac{GeV^2}{fm}\quad (vary\ \times 2,/2)$$

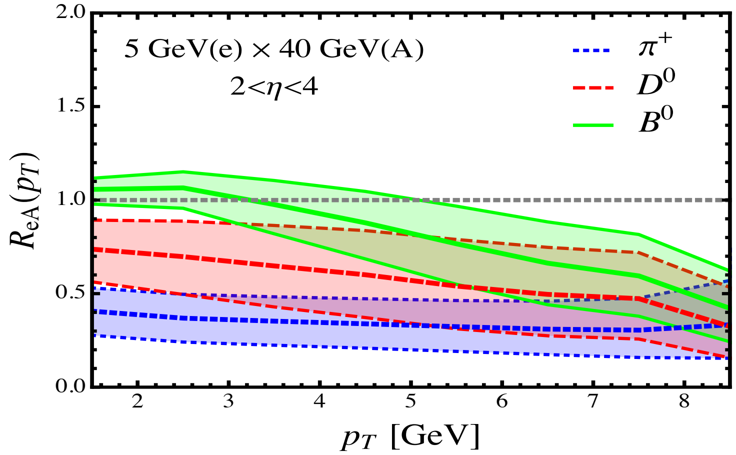


Z. Liu et al. (2020)

hermes



Light and heavy flavor suppression at the EIC

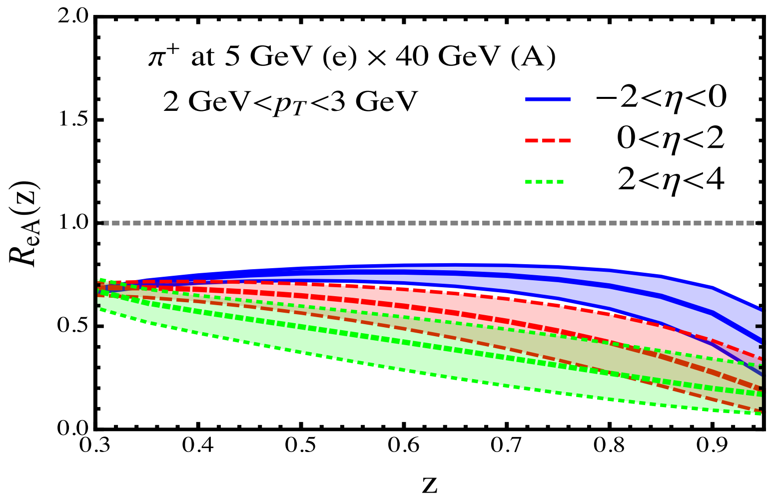


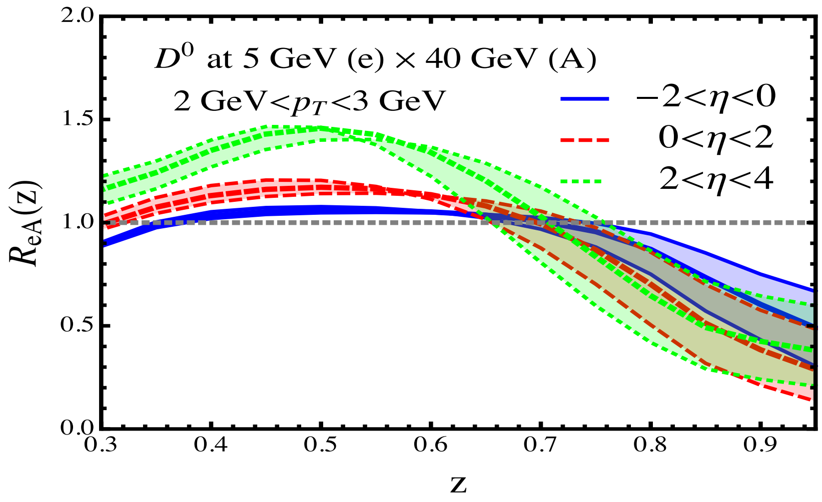
$$R^{h}_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{inc}(p_T,\eta)}\right|_{e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{inc}(p_T,\eta)}\right|_{e+p}}$$

Effects are the largest at forward rapidities (p/A going)

Light pions show the largest nuclear suppression at the EIC. However to differentiate models of hadronization heavy flavor mesons are necessary

Z. Liu et al . (2020)





The differential fragmentation fraction measurements (vs z) of heavy flavor are the most revealing about the

Charm and beauty jet production

- Recent advances are based in SCET – precision theory for small radius jets and heavy flavor jets based on semi-inclusive jet functions

$$E_J \frac{d^3\sigma}{d^3P_J} = \frac{1}{S} \sum_{i,f} \int_0^1 \frac{dx}{x} \int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu)\, J_{J_Q/f}(z, p_T R, m, \mu) \left[\hat{\sigma}_{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u}, \mu\right) \hat{\sigma}^{\gamma i \to f}\right]$$

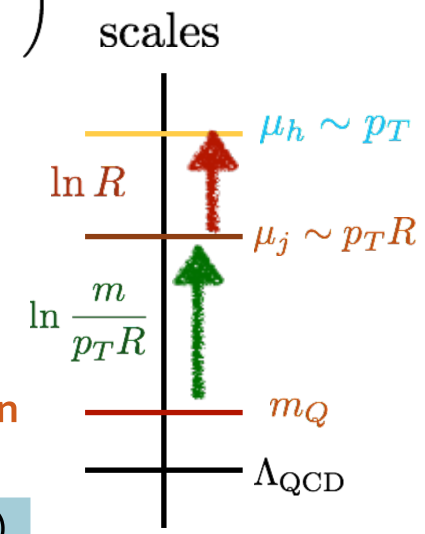
The SiJFs Evolve according to DGLAP-like equations

Resums $\ln \mu/p_T R$

$$\frac{d}{d\ln\mu^2} \begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu) \end{pmatrix} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{qq}(z) & 2P_{gq}(z) \\ P_{qg}(z) & P_{gg}(z) \end{pmatrix} \begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu) \end{pmatrix}$$

Resums $\ln p_T R/m$

$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar{Q}}(p_T R, m) = 2 \sum_{l=g,Q} \bar{K}_{l/g}(p_T R, m, \mu_F)\, \bar{D}_{Q/l}(m, \mu_F)$$



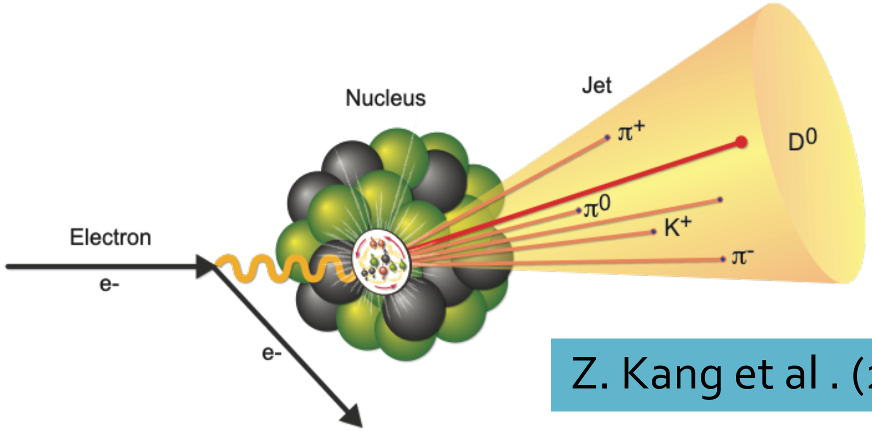
The integrated perturbative kernel at the jet typical scale

The integrated parton fragmentation function from parton *l* to parton *Q*

C. Bauer et al. (2013)

L. Dai et al (2016), (2018)

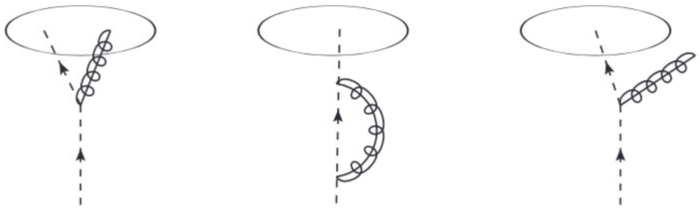
Heavy flavor jet production



Z. Kang et al . (2016)

The semi-inclusive jet function theory can be generalized to jet production in matter

For the heavy quark example



Medium corrections to the NLO jet function are written in terms of integrals over splitting functions. First developed for light jets

After summing over all diagrams

H. Li et al . (2018)

Z. Liu et al . (2021)

$$J^{\mathrm{med},(1)}_{J_Q/Q}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{QQ}(z, m, q_\perp) \right]_+$$

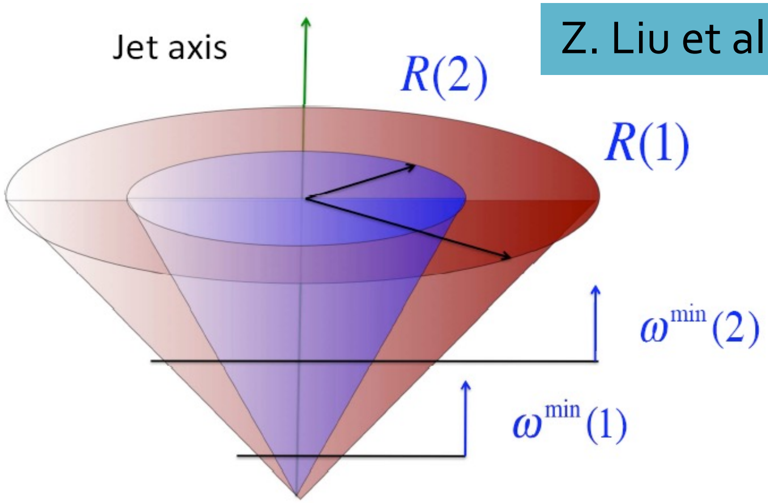
$$J^{\mathrm{med},(1)}_{J_s/g}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp) \right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp)$$

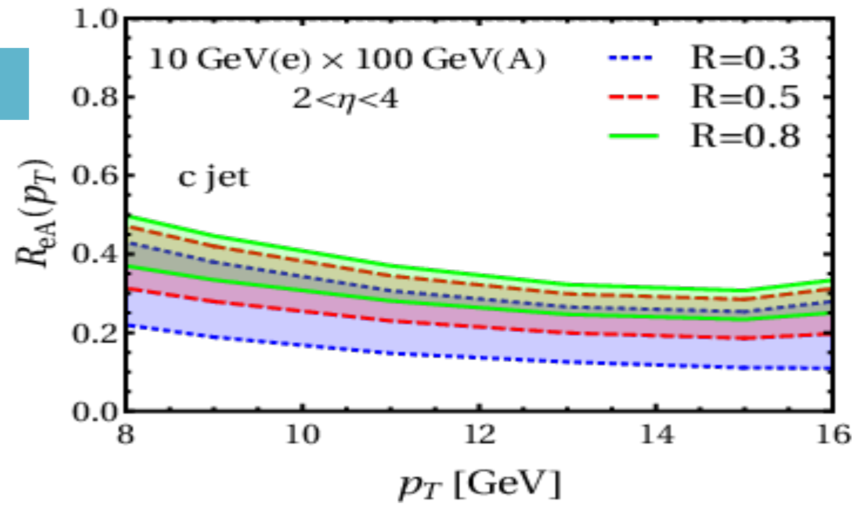
Heavy flavor jet quenching at EIC

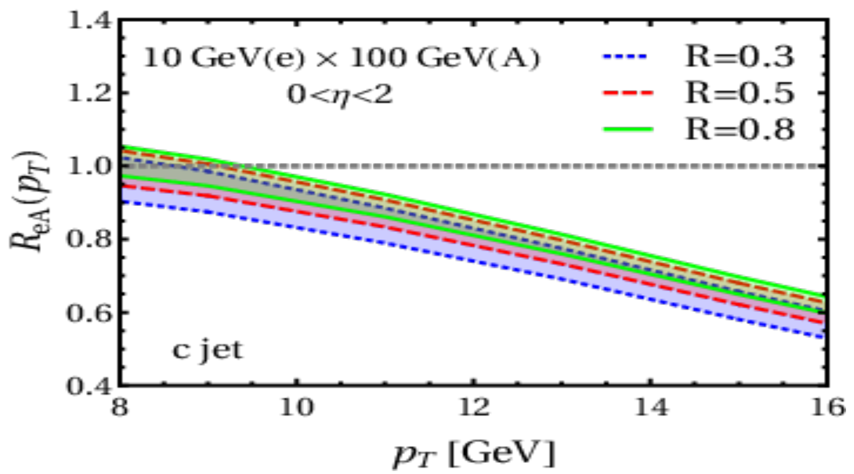
Very strong modification – sensitive to the gluon contribution. Pronounced rapidity dependence

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

Z. Liu et al. (2021)



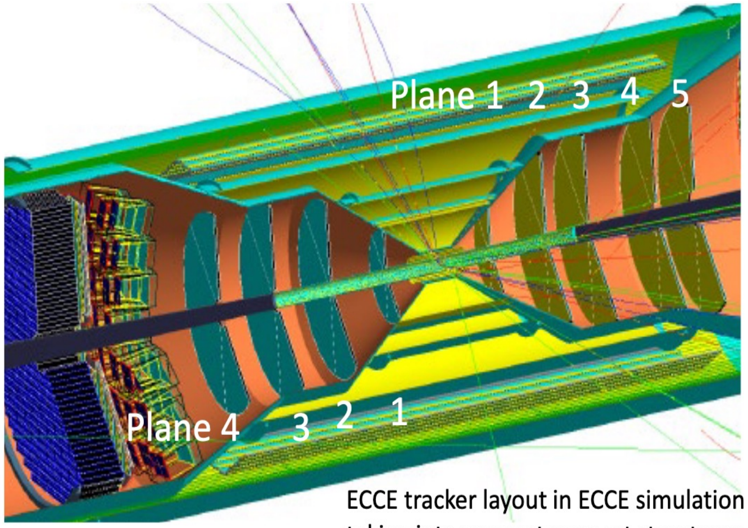




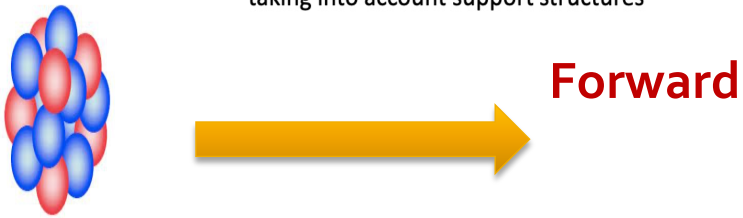
Two types of nuclear effect play a role

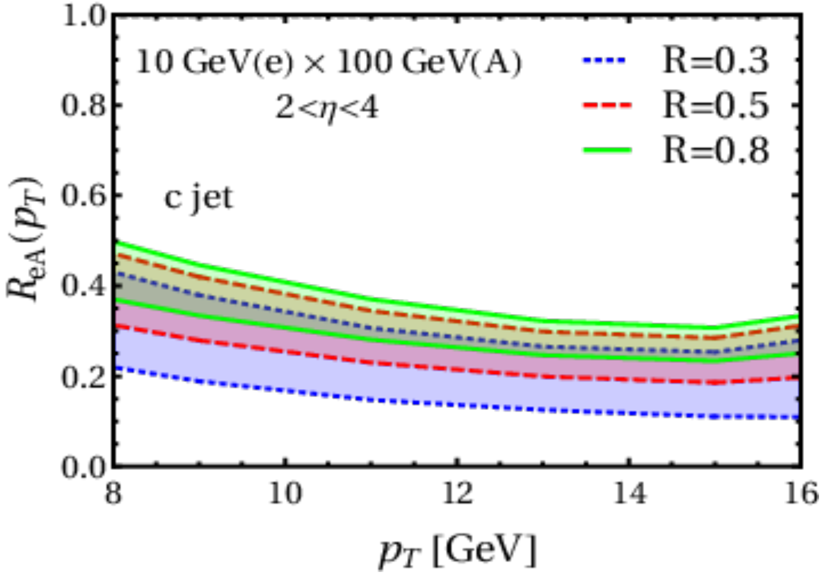
- Initial-state effects parametrized in nuclear parton distribution functions or nPDFs
- Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers and jet energy loss

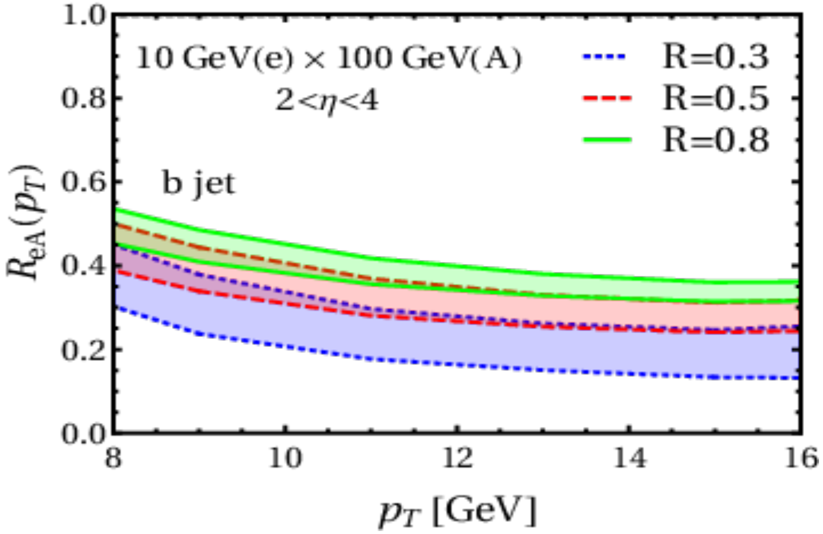
Flavor (mass) dependence



ECCE tracker layout in ECCE simulation taking into account support structures







Even at forward rapidity the parton energy in the rest frame of the nucleus is relatively large. The differences in the quenching of the b-jets and c-jets are small

Heavy flavor jets at EIC

Z. Liu et al. (2021)

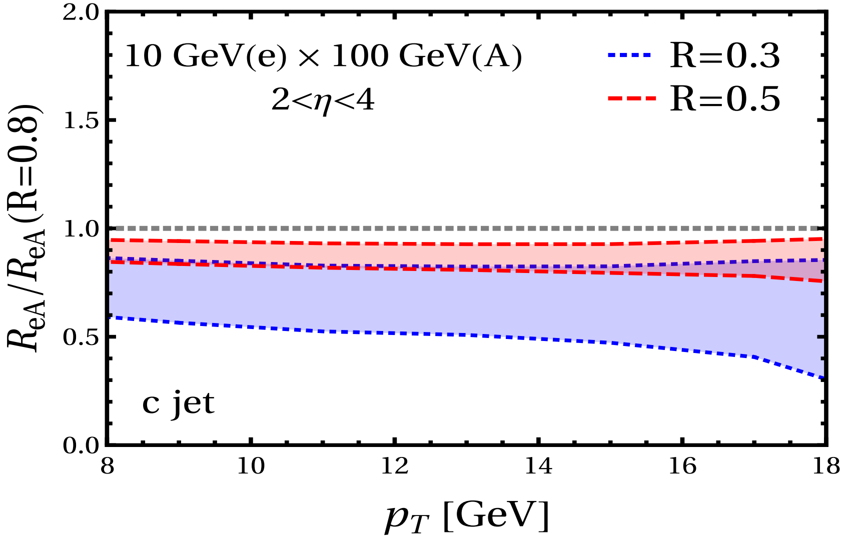
A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

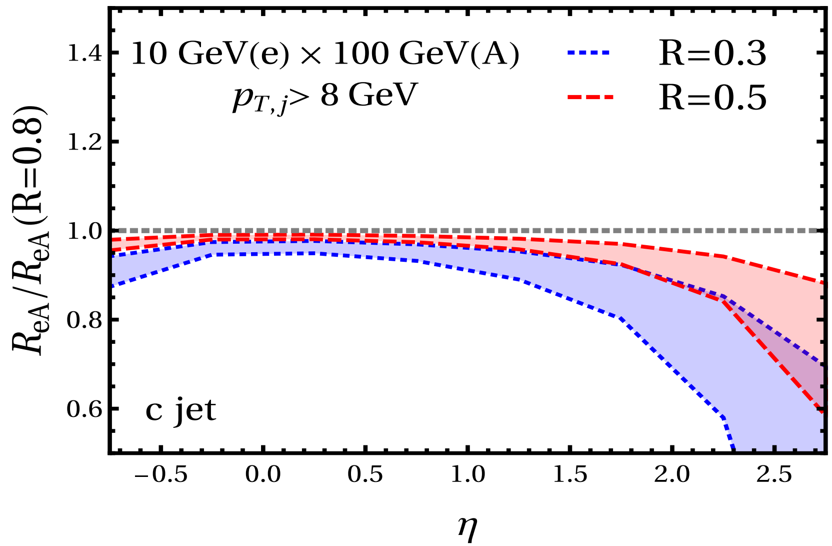
Define the ratio of modifications for 2 radii (it is a double ratio)

$$R_R = R_{eA}(R) / R_{eA}(R = 0.8)$$

- Jet energy loss effects are larger at smaller center of mass energies (electron-nuclear beam combinations)
- Effects can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)

Results are similar for b-jets





Jet substructure – splitting functions

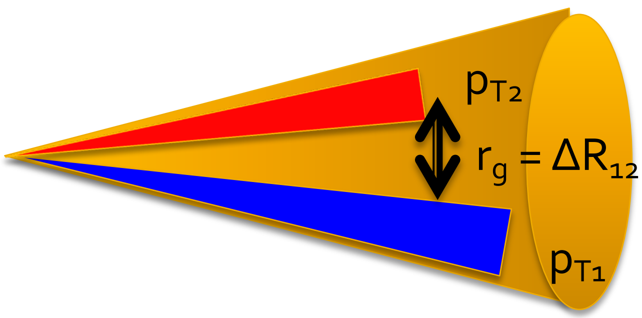
A. Larkoski et al. (2015)

$$\frac{dN_j^{\mathrm{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\mathrm{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\mathrm{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\mathrm{vac}}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$

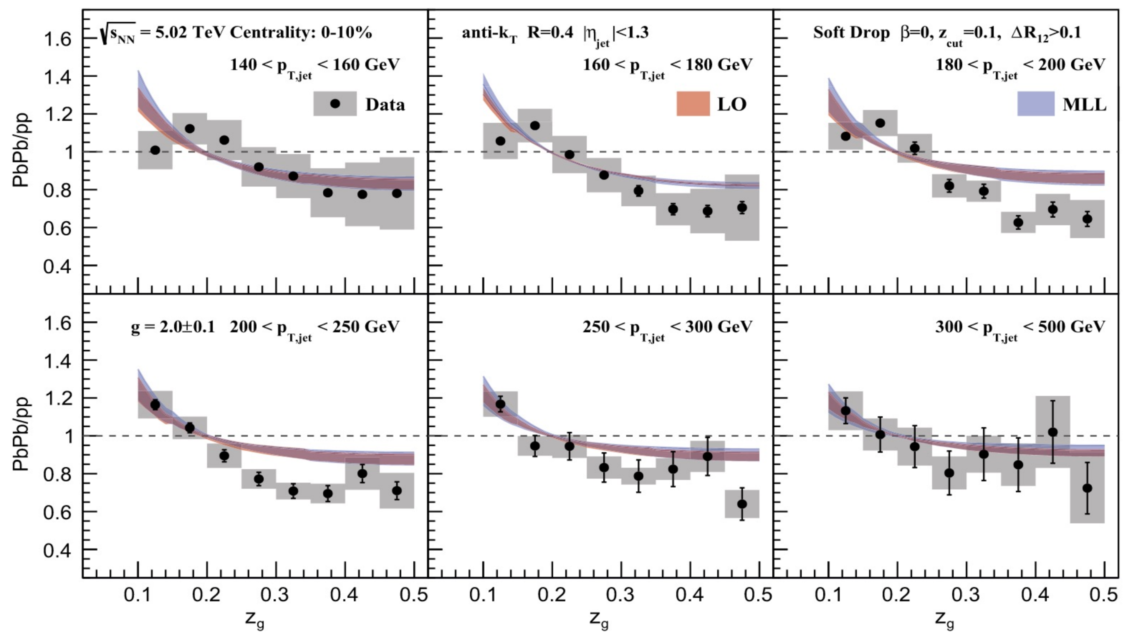
In-medium splitting functions can be measured directly through observables

Soft dropped momentum sharing distributions

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



H. Li et al. (2018)



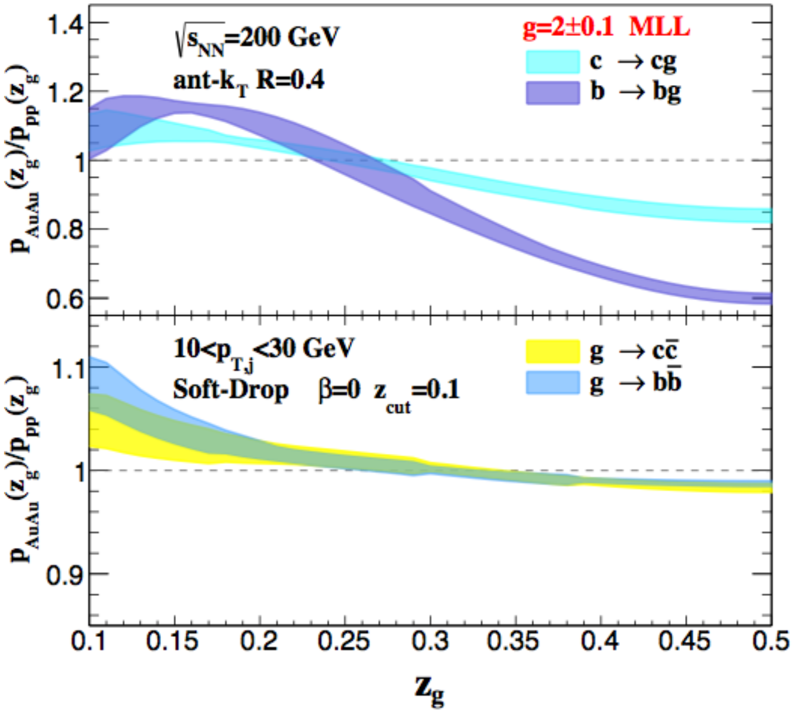
Directly proportional to the splitting functions, + resummation for small angles

The softer in-medium branching is directly observed!

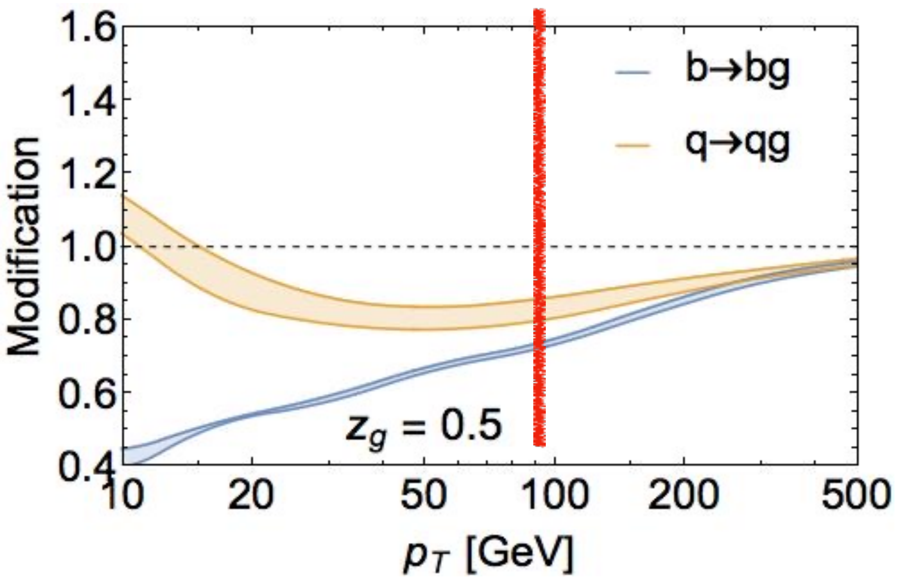
Heavy flavor jet substructure

Analytic predictions for low jet momenta

$$\frac{p_{med}^{Q\to Qg}(z_g)}{p_{pp}^{Q\to Qg}(z_g)} \sim \frac{1}{z_g^2}, \quad \frac{p_{med}^{j\to i\bar{i}}(z_g)}{p_{pp}^{j\to i\bar{i}}(z_g)} \sim \frac{1}{z_g}, \quad \frac{p_{med}^{g\to Q\bar{Q}}(z_g)}{p_{pp}^{g\to Q\bar{Q}}(z_g)} \sim \text{const.}$$



We can see the mass effects even for the b-jet with p_T~50 GeV and a bit beyond



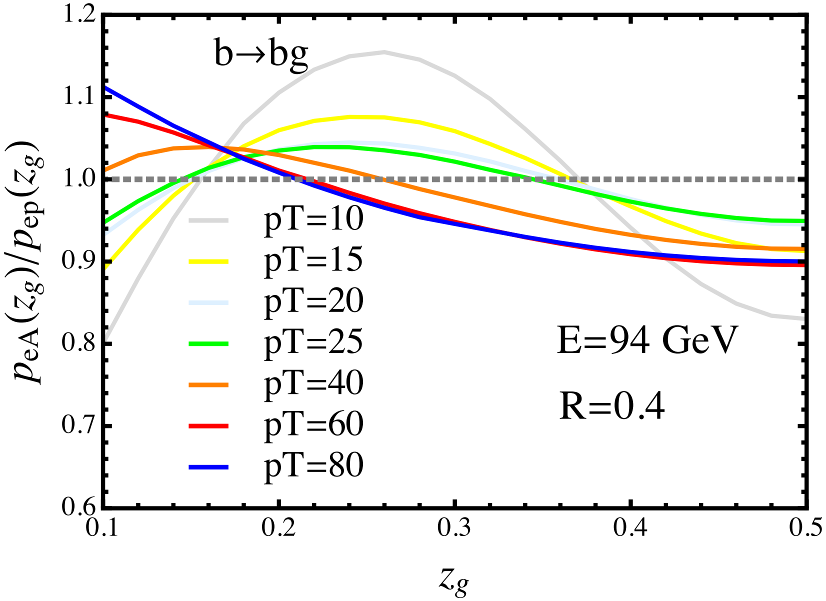
- A unique inversion of the mass hierarchy of jet quenching effects,
- Can be used to constrain the still not well understood dead cone effect in the QGP
- It is measurable at RHIC and LHC

Heavy flavor jet substructure in DIS

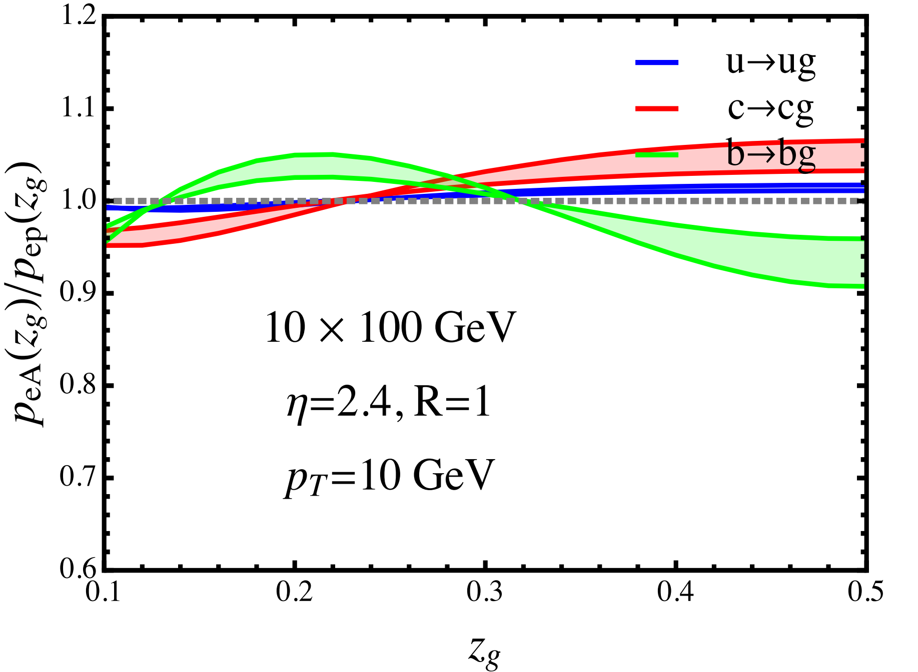
Jet substructure modification at the EIC is quite different that jet substructure modification in HIC

Z. Liu et al. (2021)

Illustrative study: Kinematically not possible in DIS but illustrates very well the difference with HIC



- Modification of both c-jets and b-jets substructure in eA is relatively small
- It is dominated by limited phase space



Conclusions

- At the EIC heavy flavor provides complementary probe of the transport properties of cold nuclear matter and can reveal the dynamics of hadronization
- Open heavy flavor production has been calculated at NLO, in-medium evolution of fragmentation understood. We have detailed and differential predictions of D and B meson cross section modification, which can differentiate between energy loss and hadron absorption
- Calculations of open heavy flavor jets in e+A collisions are complete. Results are very promising – large suppression of c-jets and even b-jets. Heavy jet substructure in reactions with nuclei quite different from HIC, exhibits new features that could be studied at the EIC