Ivan Vitev

Hadron and jet production in e+A collisions at the EIC

IR2@EIC workshop, CFNS & Argonne
Online, March 17 - 19, 2021

Los Alamos
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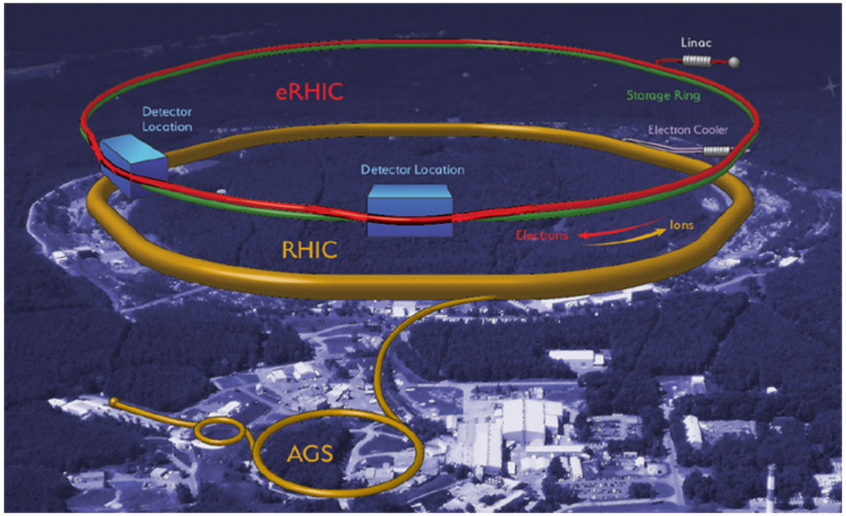
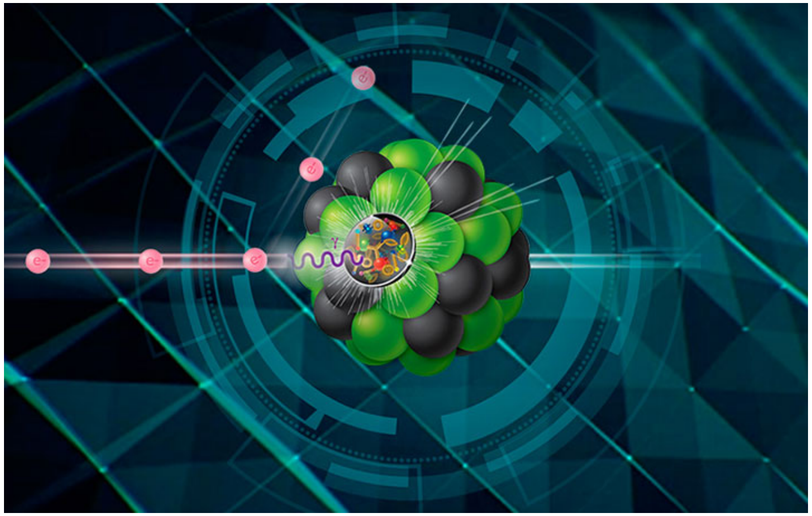
Outline of the talk





What can be done at somewhat smaller CM energies and higher luminosity?

- Parton propagation in CNM
- Meson production, HERMES constraints
- Jets in e+A at the EIC

Work with H. Li, Z. Liu, A. Sadofyev, M. Sievert

This work is supported by the TMD topical collaboration and the LANL LDRD program

Splitting functions at EIC: ArXiv:1903.06170
Light mesons: ArXiv:2007.10994
Jets and substructure in e+A: ArXiv:2010.05912

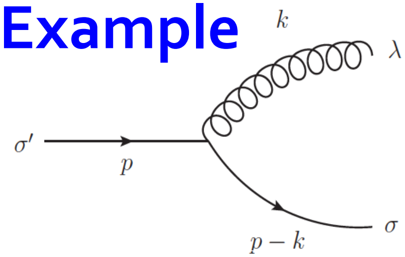
TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Lightcone wave functions and parton branchings

M. Sievert et al . (2018)

Example



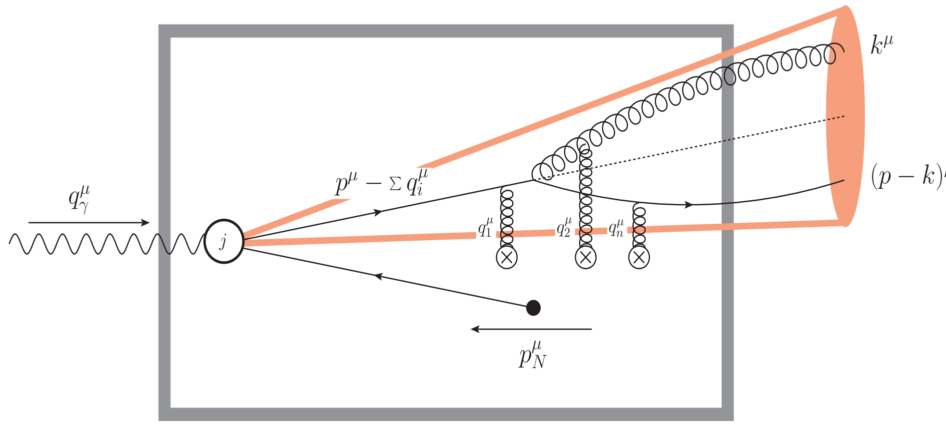
- The technique of lightcone wavefunctions

$$\psi(x, \underline{k}-x\underline{p}) \equiv \frac{1}{2p^+}\frac{1}{p^- - (p-k)^- - k^-}\overline{U}_\sigma(p-k)\left[-g\not{\epsilon}^*_\lambda(k)\right]U_{\sigma'}(p)$$

$$= \frac{gx(1-x)}{(\underline{k}-x\underline{p})_T^2 + x^2m^2}\left\{\frac{2-x}{x\sqrt{1-x}}\left(\underline{\epsilon}^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\mathbb{1}\right]_{\sigma\sigma'}\right.$$

$$\left. + \frac{\lambda}{\sqrt{1-x}}\left(\underline{\epsilon}^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\tau_3\right]_{\sigma\sigma'} + \frac{im\,x}{\sqrt{1-x}}\underline{\epsilon}^*_\lambda\times\left[\underline{\tau}_\perp\right]_{\sigma\sigma'}\right\}.$$

$$\langle\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle \equiv \sum_{\lambda=\pm1}\frac{1}{2}\mathrm{tr}\left[\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\right]$$



Branchings depending on the intrinsic momentum of the splitting $\underline{\kappa} = \underline{k - xp}.$

$$xp^+\frac{dN}{d^2k\,dx\,d^2p\,dp^+}\bigg|_{\mathcal{O}(\chi^0)} = \frac{\alpha_s C_F}{2\pi^2}\frac{(k-xp)_T^2\left[1+(1-x)^2\right]+x^4m^2}{\left[(k-xp)_T^2+x^2m^2\right]^2}\times\left(p^+\frac{dN_0}{d^2p\,dp^+}\right)$$

- Certain advantages – can provide in "one shot" both massive and massless splitting functions
- Have checked that results agree for massless and massive DGLAP splittings

In-medium parton splitting functions

Ovanesyan et al. (2012)

- Direct sum

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

$$\begin{aligned}\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm medium}}{d^2\mathbf{q}_\perp} \Bigg[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2 + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right) \\ \times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) \\ + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\right)\cos[\Omega_4\Delta z] \\ + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\cos[\Omega_5 \Delta z] + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\Bigg].\end{aligned}$$

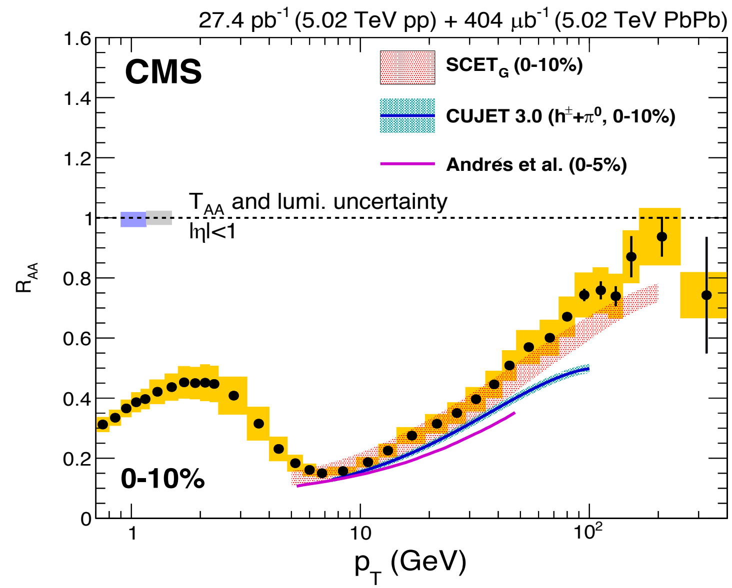
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

$$N.B.\ \ x \to 1-x \qquad A,..D,\Omega_1..\Omega_5 - functions(x,k_\perp,q_\perp)$$

Softer, broader

Y.T.Chien *et al.* (2014)

Z. Kang *et al.* (2015)



Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions Theory and predictions verified

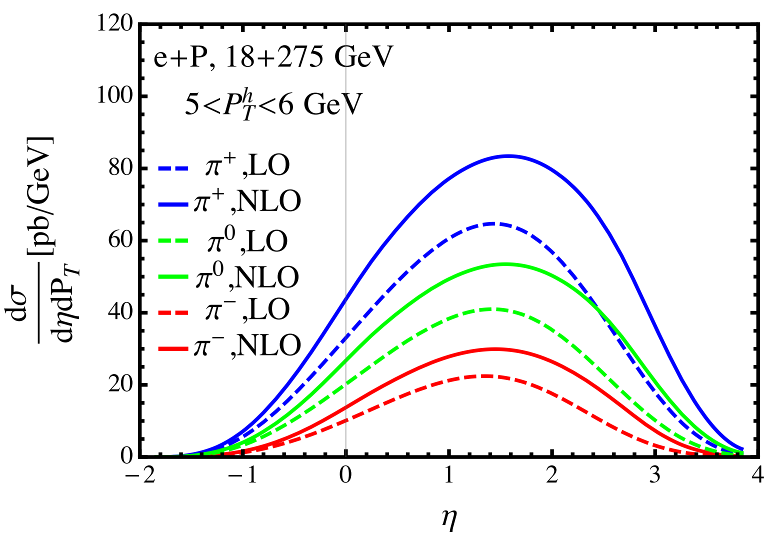
Results in e+p, NLO corrections

Factorization formula

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

		5 GeV×40 GeV		10 GeV×100 GeV		18 GeV×275 GeV	
p_T^h [GeV]		[2,3]	[5,6]	[2,3]	[5,6]	[2,3]	[5,6]
π^+	LO	5.3×10^6	24260	1.4×10^7	3.0×10^5	2.9×10^7	9.6×10^5
	NLO	1.1×10^7	69473	2.8×10^7	6.1×10^5	5.6×10^7	1.9×10^6
D^0	LO	1.4×10^6	3242	8.6×10^6	89952	3.1×10^7	6.6×10^5
	NLO	3.7×10^6	8536	2.1×10^7	2.1×10^5	7.2×10^7	1.5×10^6
B^0	LO	3.7×10^5	1171	2.4×10^6	28413	9.0×10^6	2.0×10^5
	NLO	1.1×10^6	3333	6.2×10^6	72329	2.1×10^7	4.7×10^5

Example of light, charm, and bottom hadron multiplicities at the EIC in selected pT bins to lowest and next-to-leading order. We have integrated over the hadron pseudo-rapidity is the interval $-2 < \eta < 4$ and used a typical one year integrated luminosity of 10 fb^{-1} in e+p collisions



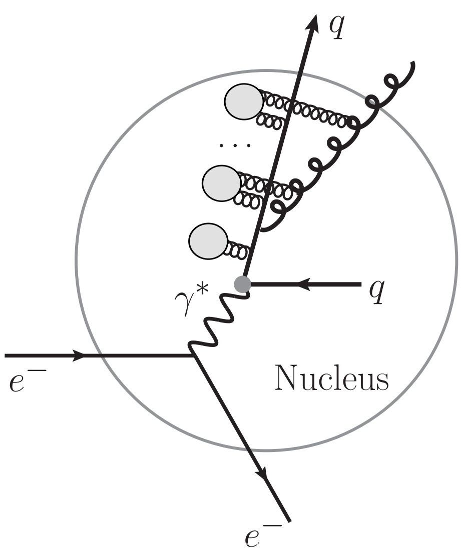
The WW contribution not included
In the figure

The resolved photon contribution (with WW photons) gives a large contribution - 40-50% of the NLO correction

Generally production is at more forward rapidities. Most pronounced for pions. Differences are attributed to parton distributions

Modification of light hadrons at HERMES

- Account for nuclear geometry, i.e. the production point and the path length of propagation of the hard parton, NLO



$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

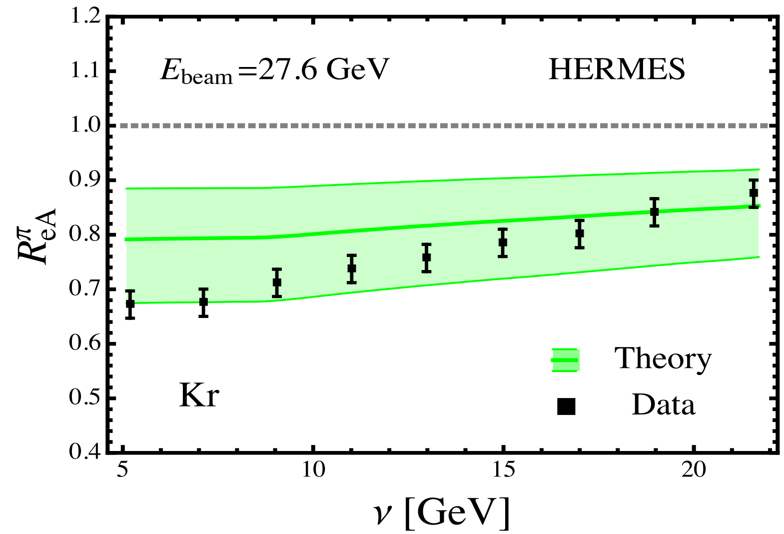
In-medium evolution of fragmentation functions

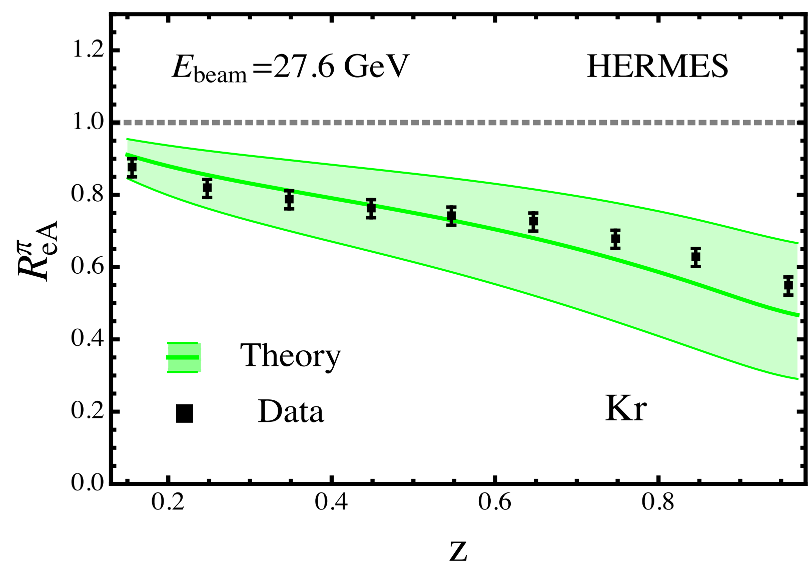
$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right) \times \left(P_{ji}(z,\alpha_s(\mu)) + P^{\rm med}_{ji}(z,\mu)\right)$$

- We constrain a range of transport properties to explore from HERMES

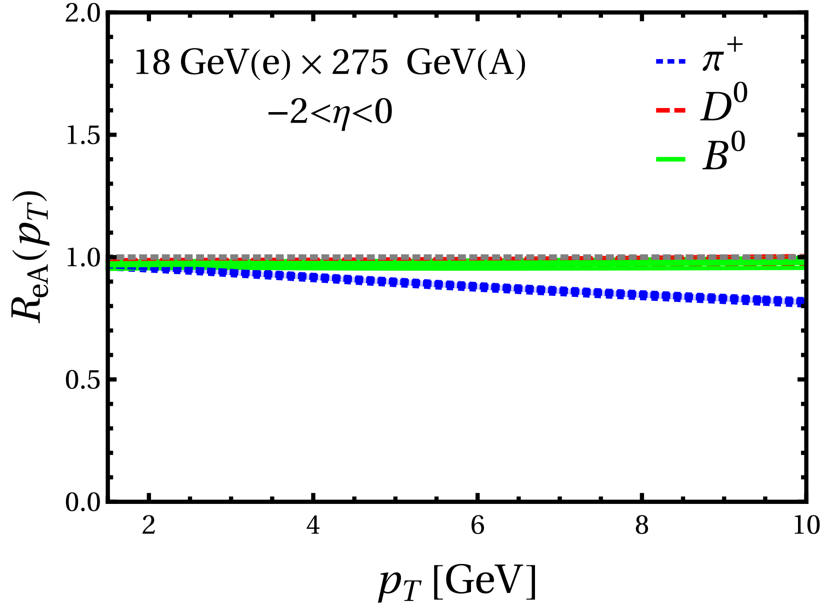
Transport properties:

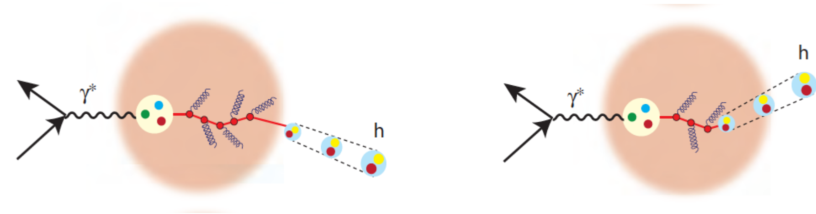
$$2\frac{\mu^2}{\lambda g} = 0.12\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$



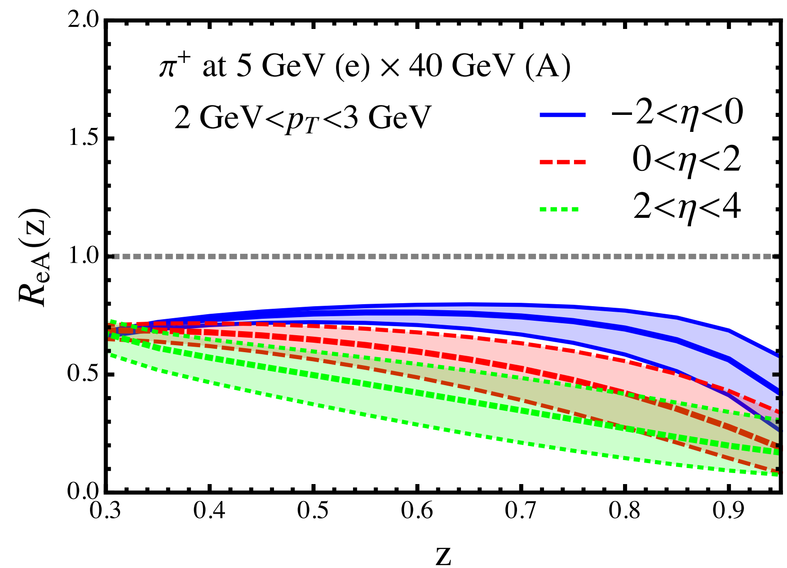


Light flavor suppression at the EIC





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



- This is the figure that illustrates the usefulness of smaller CM energies and forward rapidities.

This is to study in-medium evolution / energy loss

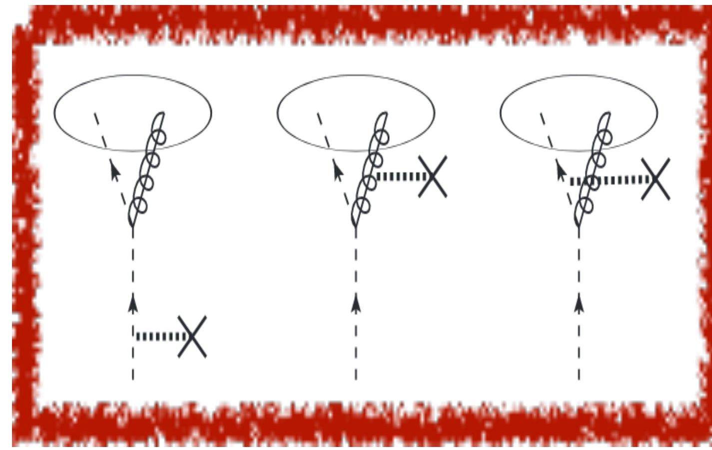
H. Li et al . (2020)

Jet production

Z. Kang et al. (2016)

L. Dai et al. (2016)

A useful modern way (though not unique) to calculate jet cross sections



Factorization formula

$$E_J \frac{d^3\sigma^{lN\to jX}}{d^3P_J} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f_{i/N}(x,\mu) \times \hat{\sigma}^{i\to f}(s,t,u,\mu) J_f(z, p_T R, \mu) \,,$$

$$\mu_J = \omega_J \tan\frac{R}{2} = (2p_T\cosh\eta)\tan\left(\frac{R}{2\cosh\eta}\right) \approx p_T R$$

- Stable in numerical implementation
- Similarly for gluon jets

In-medium jet functions

$$\begin{aligned} J_g^{\mathrm{med}}(z, p_T R, \mu) = & \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(z,\mathbf{k}_\perp)\left(\frac{z}{1-z} + z(1-z)\right)\right)\right]_+ \\ & + n_f \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{g\to q\bar{q}}(z,\mathbf{k}_\perp)\right]_+ \\ & + \int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(x,\mathbf{k}_\perp)\left(\frac{1-z}{z} + \frac{z(1-z)}{2}\right) \right. \\ & \left. + n_f f_{g\to q\bar{q}}(z,\mathbf{k}_\perp)\right) \end{aligned}$$

$$J_q^{\mathrm{med},(1)}(z,\omega R,\mu) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp$$

H. Li et al. (2020)

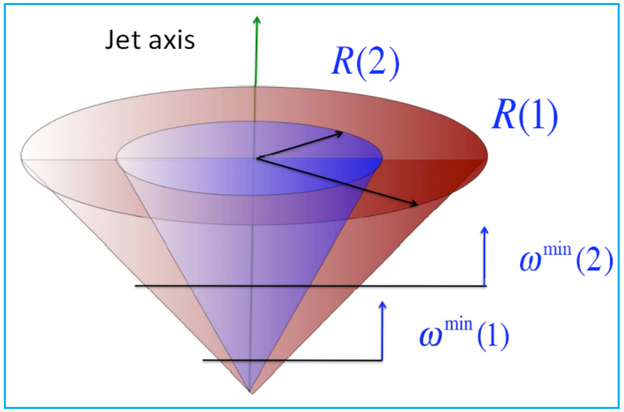
Cross section contribution

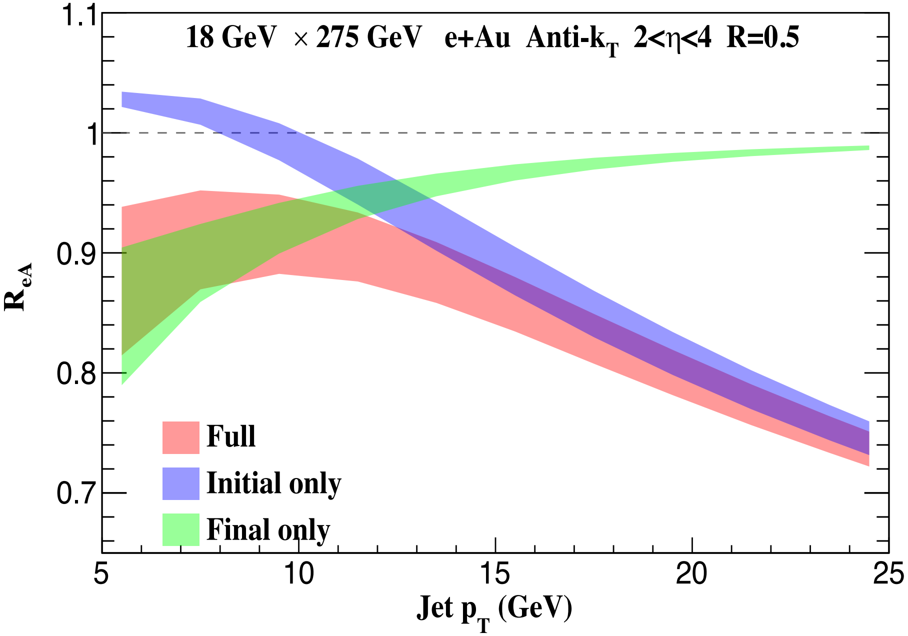
$$d\sigma^{\mathrm{jet,med}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$$

Jet results at the EIC

- The physics of reconstructed jet modification

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





H. Li et al. (2020)

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**

- Net modification 20-30% even at the highest CM energy
- E-loss has larger role at lower p_T. The EMC effect at larger p_T

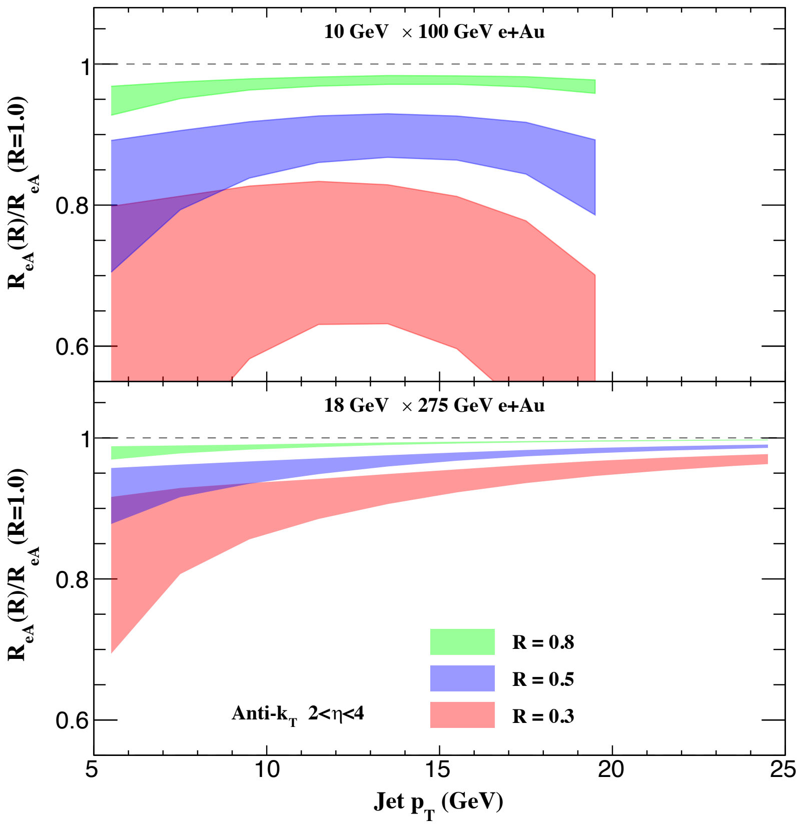
Separating initial-state from final-state effects at EIC

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)

$$R_R = R_{eA}(R) / R_{eA}(R = 1)$$

- 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)



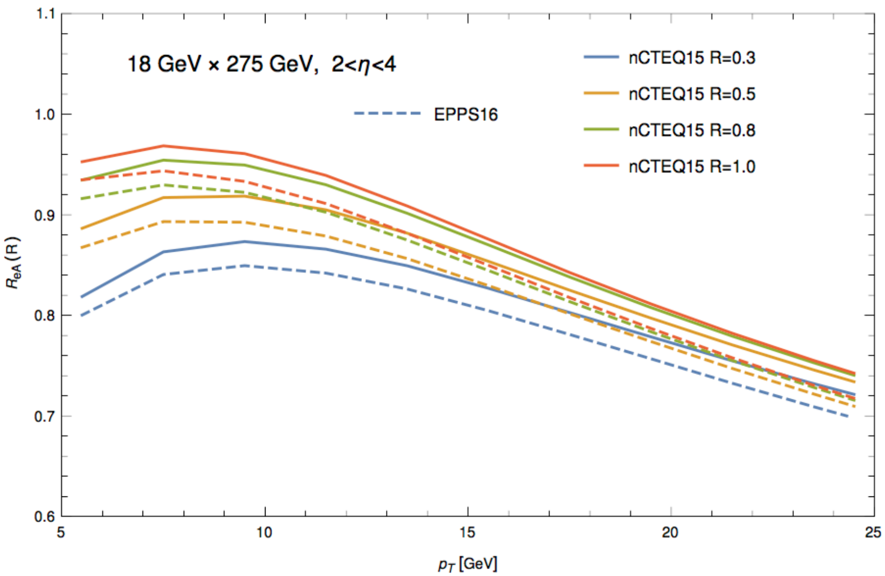
H. Li et al. (2020)

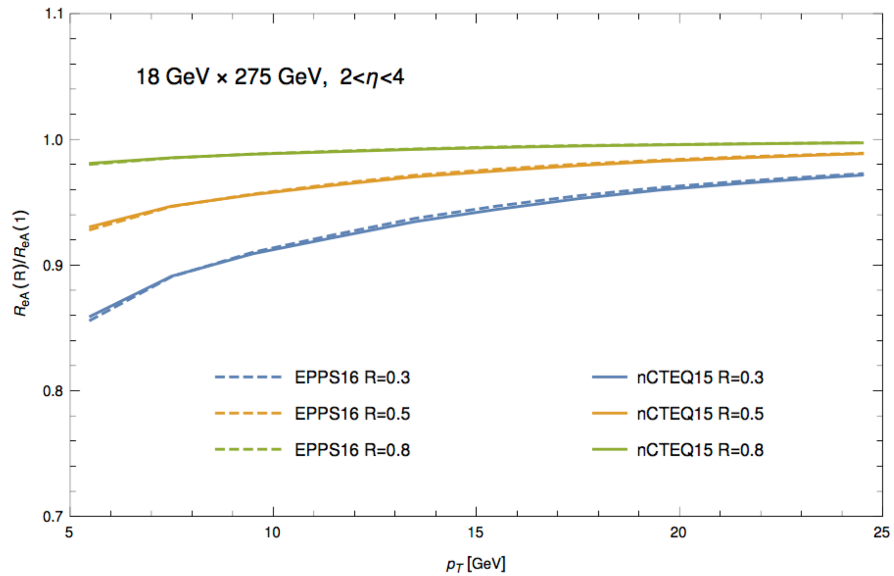
Initial-state effects are successfully eliminated

nPDF Effects and effectiveness of initial/final separation

H. Li et al. (2020)

- We further checked the effectiveness of such initial / final state effect separation. Used nCTEQ15 and EPPS16 – in the double ratios the difference is invisible
- When we look at the absolute cross section we see that the differences are and they are surprisingly small.
- The physics will be readily accessible at the EIC





Even the absolute cross section modification is very similar between different PDF sets

Initial-state effects are successfully eliminated

Jet substructure at the EIC – the jet charge

A fundamental prediction of the theory of jets in reactions with nuclei is that inclusive and tagged cross section modifications are related to substructure modification *Substructure is a modern way of saying – jet shapes, jet fragmentation functions, jet charge, etc*

The jet charge

R. Field *et al.* (1978)

$$Q_{\kappa,\,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{\text{h in jet}} Q_h \left(p_T^h\right)^{\kappa}$$

$$\langle Q_{\kappa,q} \rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu)$$

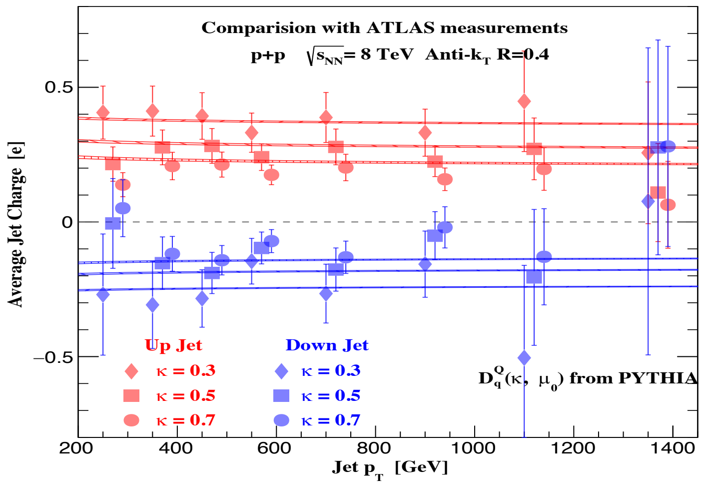
Note that gluons do not contribute to the jet charge *on average*. We will need quark jet and fragmentation functions and matching coefficients

$$\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu) = \int_0^1 dz\; z^{\kappa} \mathcal{J}_{qq}(E,R,z,\mu)\;,$$

$$\tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\; z^{\kappa} \sum_h Q_h D_q^h(z,\mu)$$

- Has been used extensively to determine the partonic origin of jets
- Renewed interest in the past 10 years as it has been computed more precisely in SCET

D. Krohn et al. (2012)



Jet charge in e+A at the EIC

Jet substructure – jet shapes, splitting functions, fragment. functions, charge … can improve the understanding of the role of heavy quark mass, dead cone effect, etc

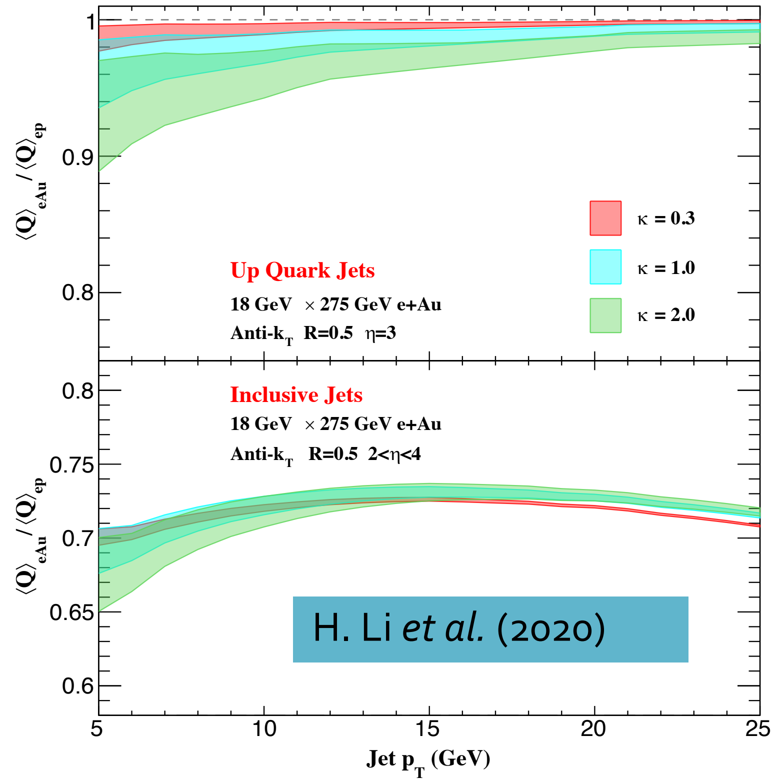
The components of he factorization formula receive in-medium corrections

$$
\begin{aligned}
J_q^{\rm med}(E,R,\mu) &= \int_0^1 dx\, x\left(\mathcal{J}_{qq}^{\rm med}(E,R,x,\mu)+\mathcal{J}_{qg}^{\rm med}(E,R,x,\mu)\right)\\
&= \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\left(xP^{\rm med,real}_{q\to qg}(x,\mathbf{k}_\perp)+xP^{\rm med,real}_{q\to gq}(x,\mathbf{k}_\perp)\right)\\
&= \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P^{\rm med,real}_{q\to qg}(x,\mathbf{k}_\perp)\,,
\end{aligned}
$$

$$
\langle Q^{\rm pp}_{q,\kappa}\rangle\left(1+\tilde{\mathcal{J}}^{\rm med}_{qq}-J^{\rm med}_q\right)\exp\left[\int_{\mu_0}^{\mu}\frac{d\bar\mu}{\bar\mu}\frac{\alpha_s(\bar\mu)}{\pi}\tilde{P}^{\rm med}_{qq}\right]+\mathcal{O}\left(\alpha_s^2,\chi^2\right)
$$

$$
\tilde{\mathcal{J}}^{\rm med}_{qq}-J^{\rm med}_q=\frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx\,(x^\kappa-1)\int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P^{\rm med,real}_{q\to qg}(x,\mathbf{k}_\perp)
$$

- Medium-induced scaling violation of the individual flavor and average jet charge



First calculation of the jet charge at EIC – understand medium-induced scaling violations and isospin symmetry braking in nuclei

Conclusions

- e+A collisions are an important part of the EIC program. They can provide information about nuclear PDFs, the physics of hadronization, and transport of energy and matter in the nuclear environment
- To study the physics of hadronization, particle propagation in matter lower CM energies, forward rapidity and high luminosity are very beneficial
- We have derived in-medium slitting functions and developed codes to evaluate them numerically
- Based on these, fist calculations of light/heavy flavor production, jets, and jet substructure are available. We successfully developed strategies to separate initial-state from final state effects to facilitate both the extraction of nPDFs and cold nuclear matter tomography