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Nuclear matter effects on jet production at electron-ion colliders

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Los Alamos
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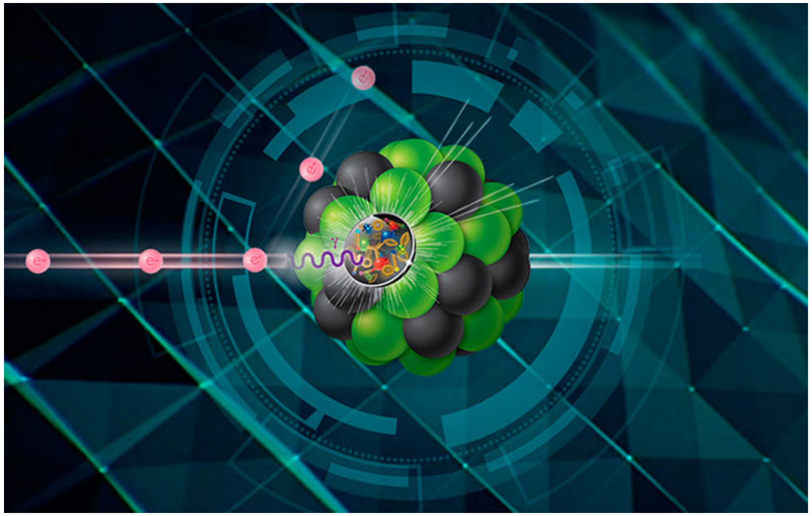
Outline of the talk



- Parton propagation in CNM
- Meson production HERMES constraints
- Jets in e+A at the EIC
- Comment of other proposed EIC fcilities

Light mesons: ArXiv:2007.10994
Jets and substructure in e+A: ArXiv:2010.05912

Work with H. Li (and Z. Liu for the meson part)

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

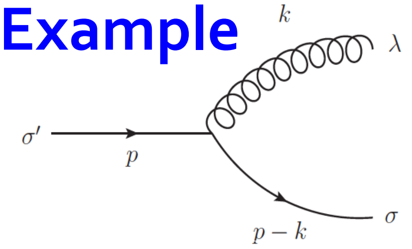
TMD Collaboration

LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

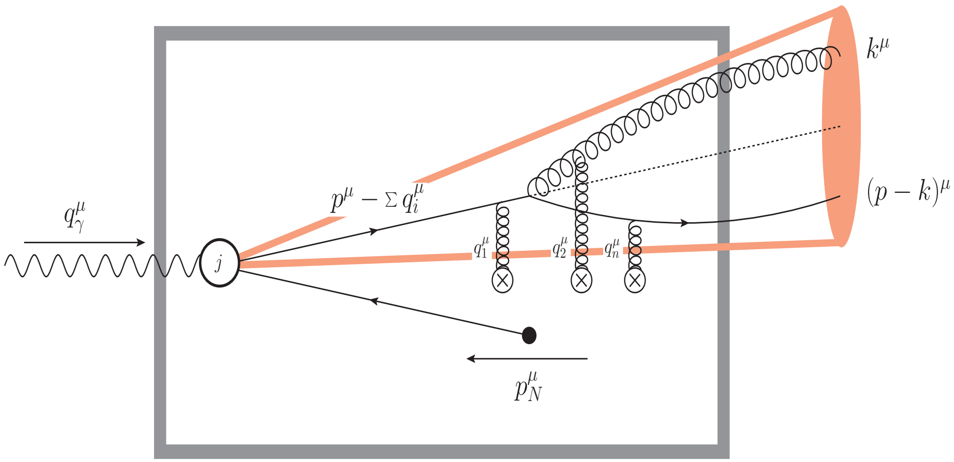
Lightcone wave functions and parton branchings

M. Sievert et al . (2018)

Example



- The technique of lightcone wavefunctions



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

$$= \frac{g x(1-x)}{(\underline{k} - x\underline{p})_T^2 + x^2 m^2} \left\{ \frac{2-x}{x\sqrt{1-x}} \left(\underline{\epsilon}^*_\lambda \cdot (\underline{k} - x\underline{p})\right) \left[\mathbb{1}\right]_{\sigma\sigma'} + \frac{\lambda}{\sqrt{1-x}} \left(\underline{\epsilon}^*_\lambda \cdot (\underline{k} - x\underline{p})\right) \left[\tau_3\right]_{\sigma\sigma'} + \frac{i m x}{\sqrt{1-x}} \underline{\epsilon}^*_\lambda \times \left[\underline{\tau}_\perp\right]_{\sigma\sigma'} \right\}.$$

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

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

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

- 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)

M. Sievert et al . (2019)

- Direct sum

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

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

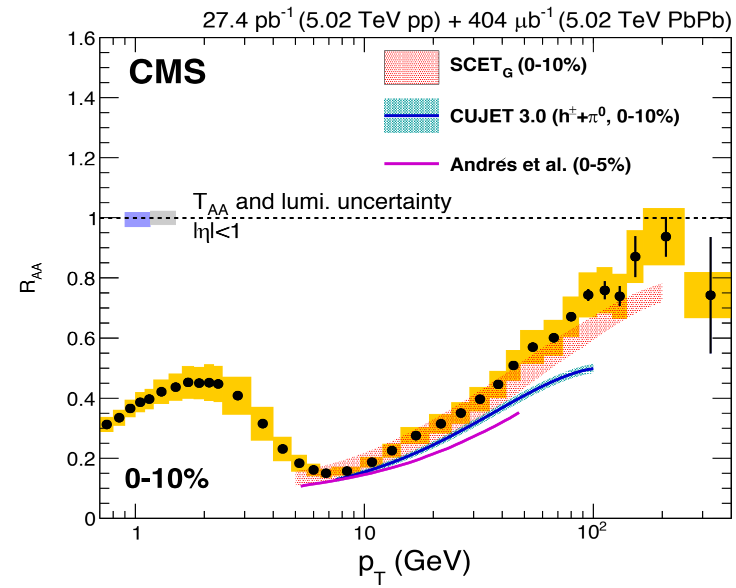
$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}\Bigg[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\pe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

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

Softer, broader

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

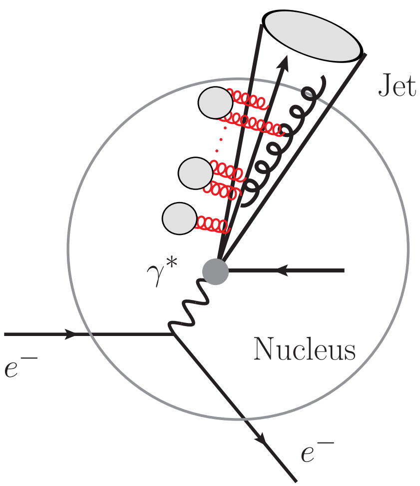
Z. Kang *et al.* (2015)



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

Modification of light hadrons at HERMES

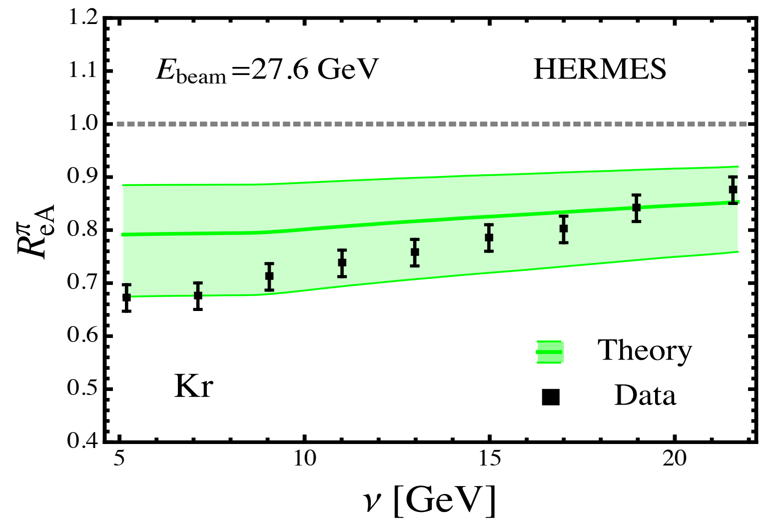
- Account for nuclear geometry, i.e. the production point and the path length of propagation of the hard parton, NLO

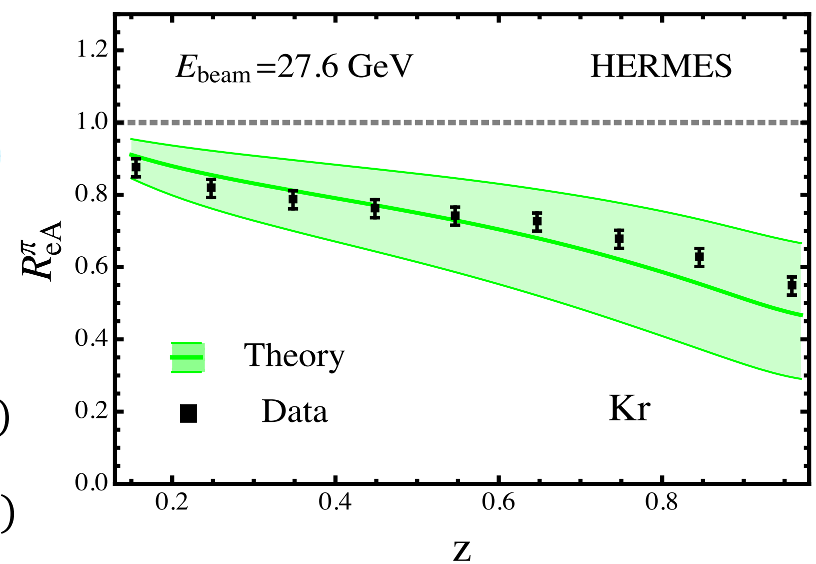


$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

In-medium evolution of fragmentation functions

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





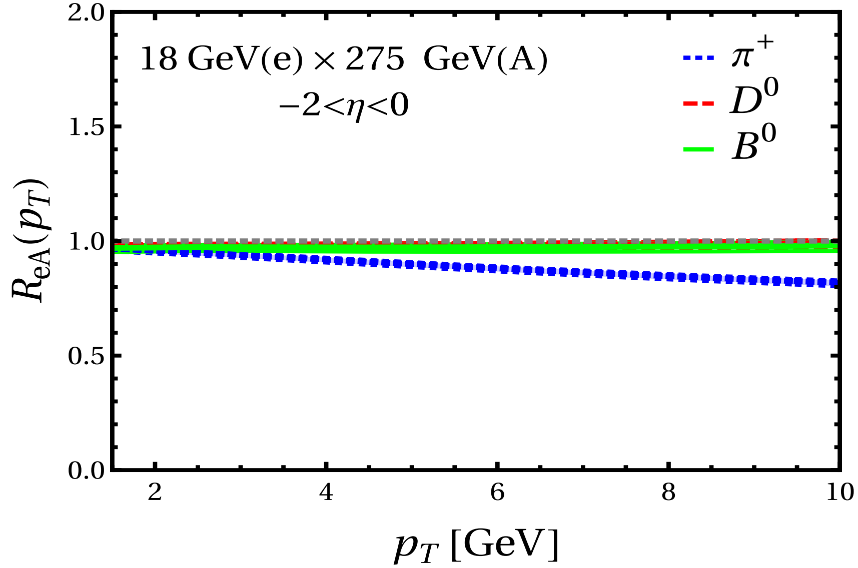
- We constrain a range of transport properties to explore from HERMES

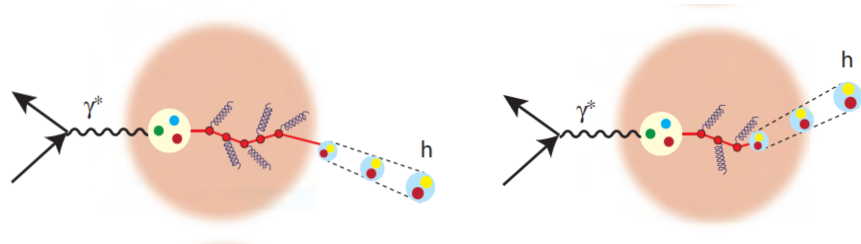
Transport properties:

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

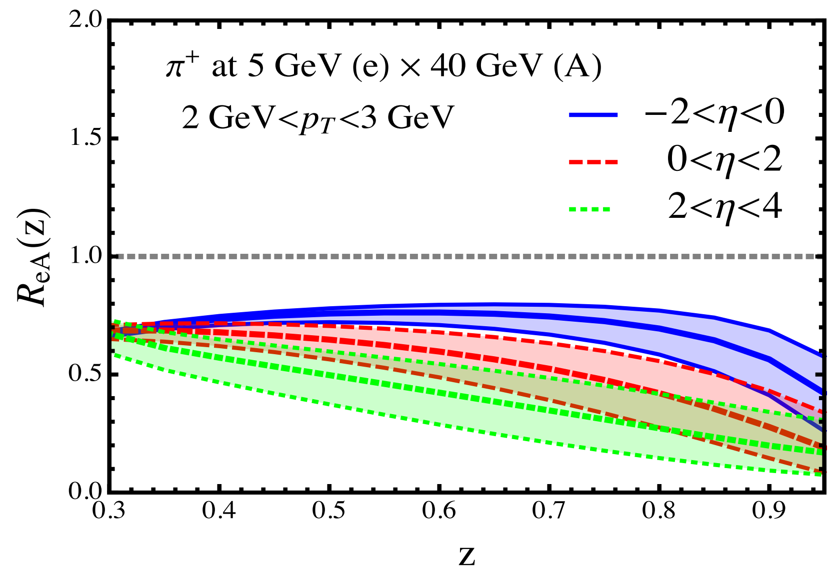
$$q-hat(q) = 0.05\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$

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



H. Li et al . (2020)

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

This is to study in-medium evolution / energy loss

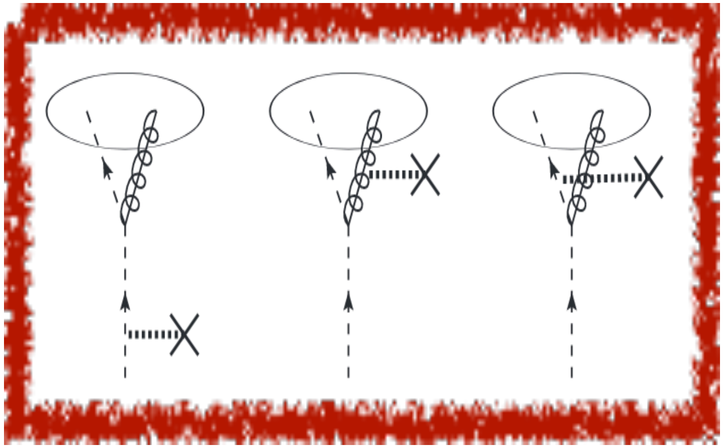
- This is the region where we will concentrate with jets

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

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

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

- Stable in numerical implementation
- Similarly for gluon jets

In-medium jet functions

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

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

H. Li et al. (2020)

Cross section contribution

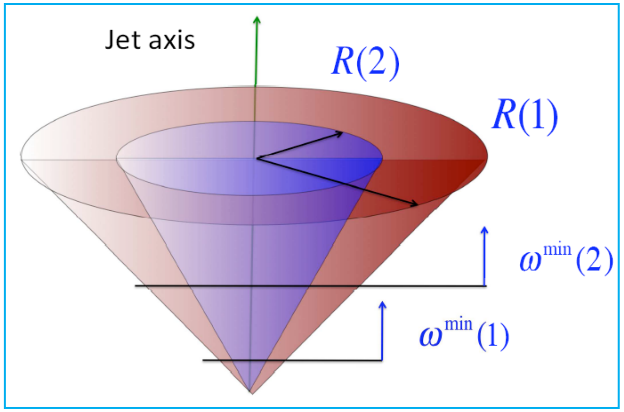
$$d\sigma^{\rm jet,med} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\rm med}$$

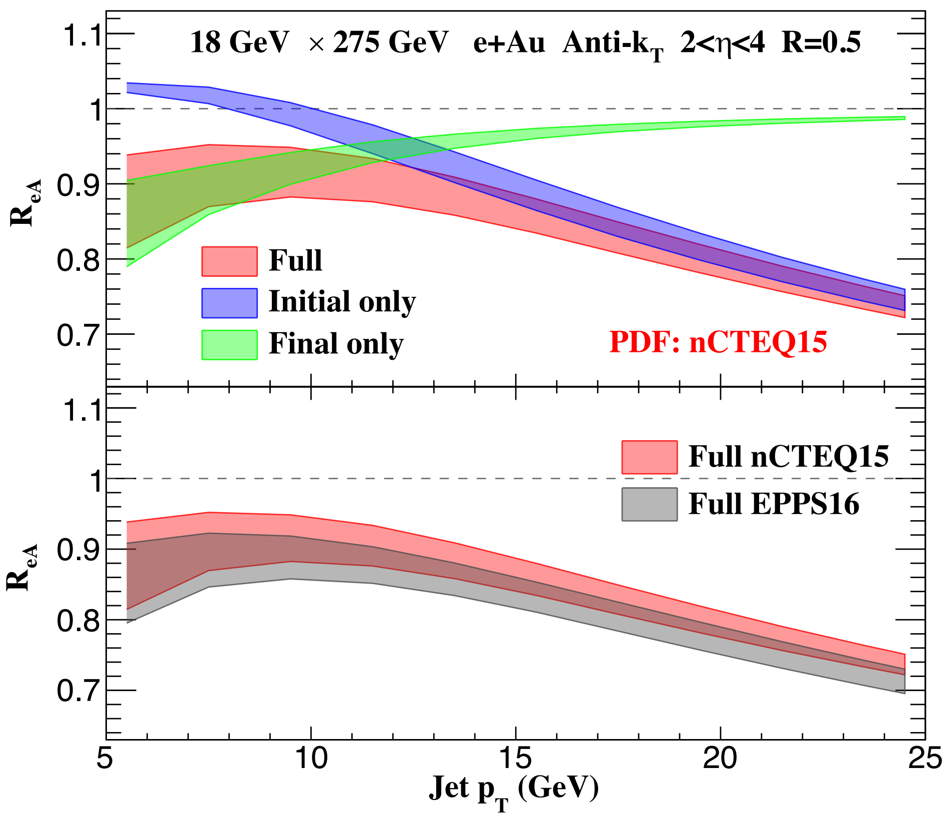
Jet results at the EIC

- The physics of reconstructed jet modification

H. Li et al. (2020)

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





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

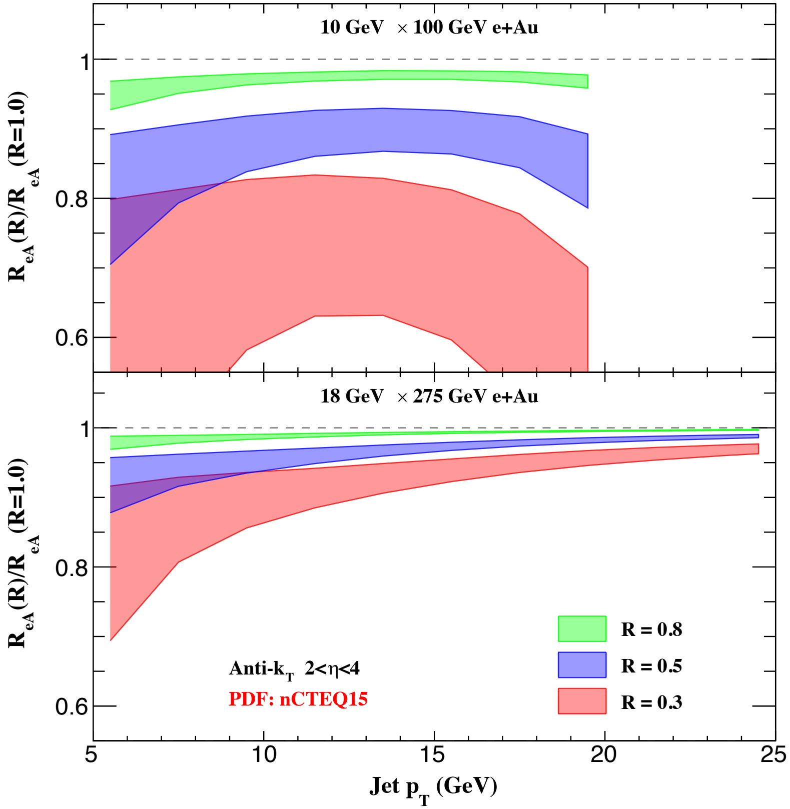
Separating initial-state from final-state effects at EIC

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)



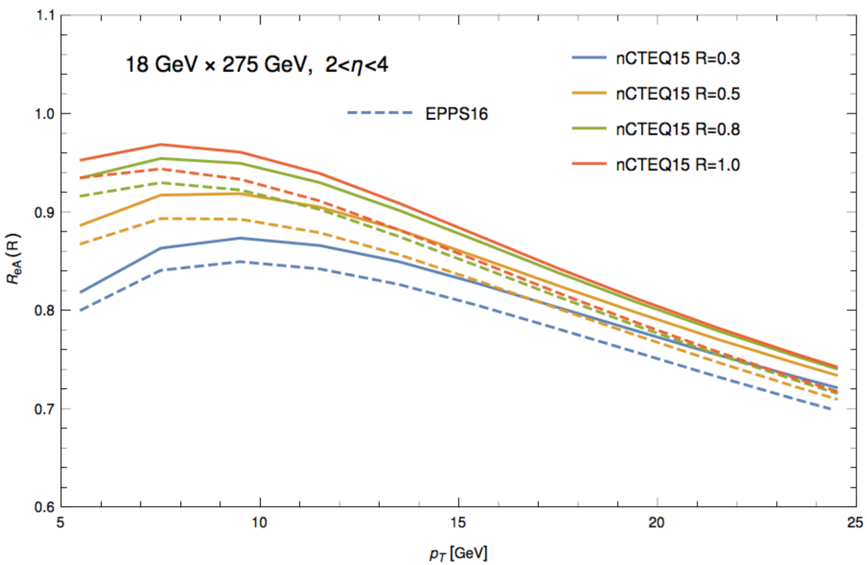
H. Li et al. (2020)

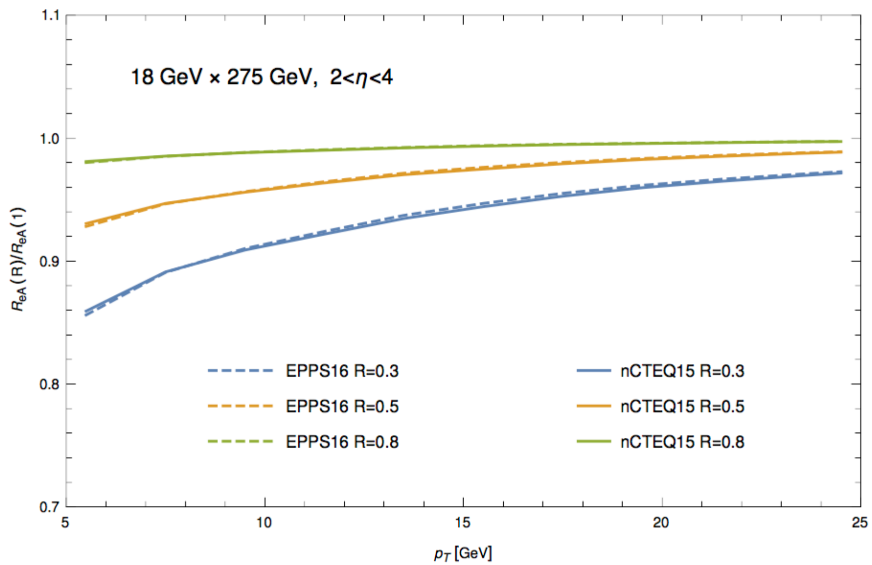
Initial-state effects are successfully eliminated

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

The difference between different nPDF parametrizations is invisible

NB: PDF/nPDF sets have to be carefully chosen

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)

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

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

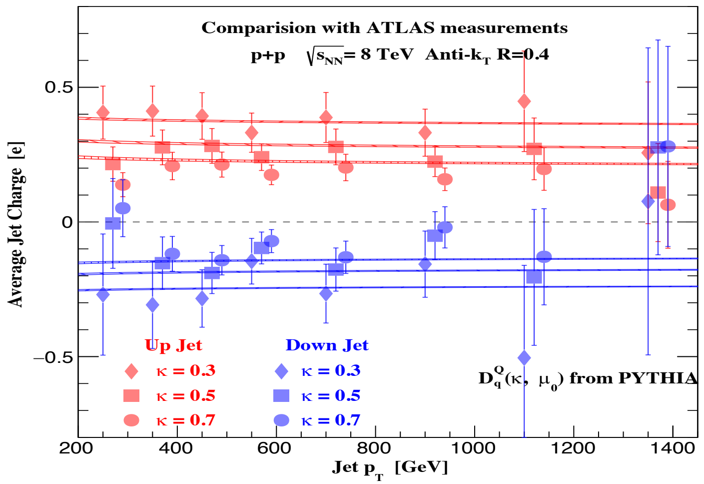
- Has been used extensively to determine the partonic origin of jets
- Renewed interest in the past 10 years as it has been computed more precisely in SCET

D. Krohn et al. (2012)

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

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

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



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

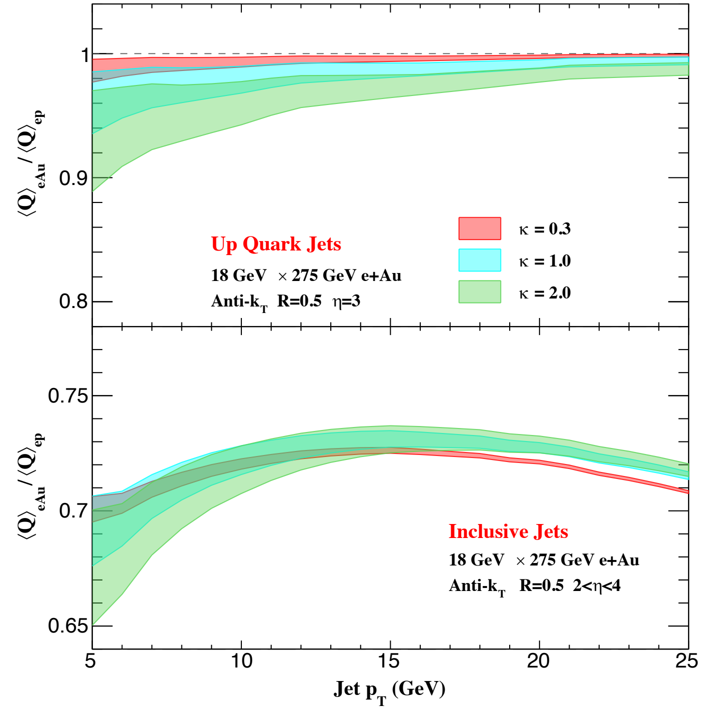
The components of he factorization formula receive in-medium corrections

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

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

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

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

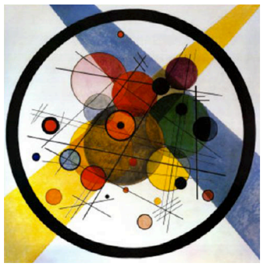


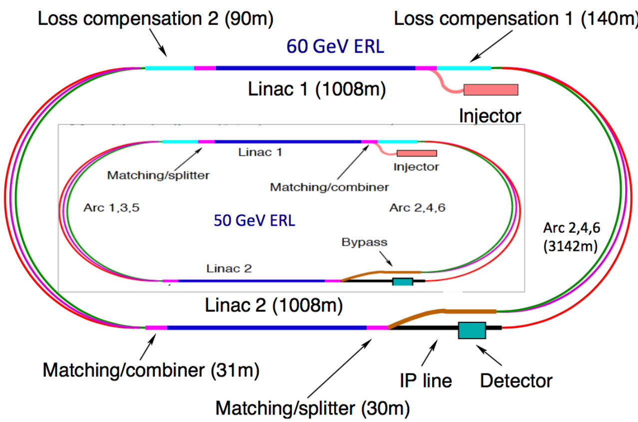
H. Li *et al.* (2020)

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

Other electron-ion colliders

LHeC – large hadron electron collider



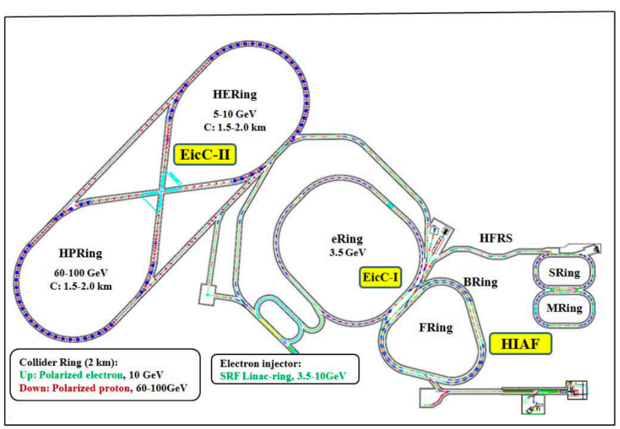


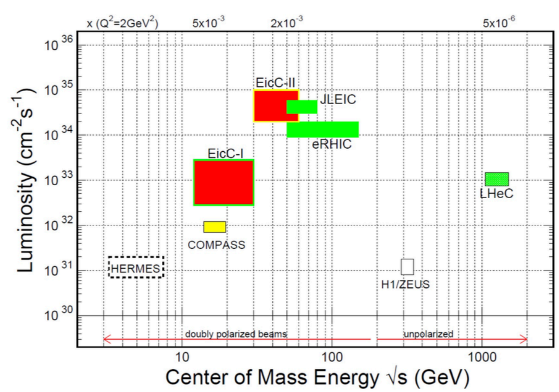
Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

C.M. energies of order TeV at the LHeC will eliminate medium-induced parton-shower effects and the facility will be best suited to study nuclear PDFs and small-x physics

P. Augostini *et al.* (2020)

EicC - electron ion collider in China





EicC would have ideal C.M. energies to study hadronization and energy loss (I), nuclear effects on jets (II). Limited reach for saturation physics.

X. Chen *et al.* (2018)

Conclusions

- Jet physics in e+p and e+A collisions is an important part of the EIC program. It 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 presented calculations of light hadron and jet production, and also jet substructure, in e+p and e+A. The nuclear modification is significant and measurable at the EIC.
- We successfully developed strategies to separate initial-state from final state effects to facilitate both the extraction of nPDFs and cold nuclear matter tomography. We showed how the jet charge can facilitate flavor separation, and in-medium scaling violation studies
- EIC occupies the ideal middle ground – allowing studies of paton energy los and hadronization as well as gluon saturation. LHeC has vary high CM energies – only gluon saturation. EicC – Ideal for studies of hadronization but can't access the small x-regime.

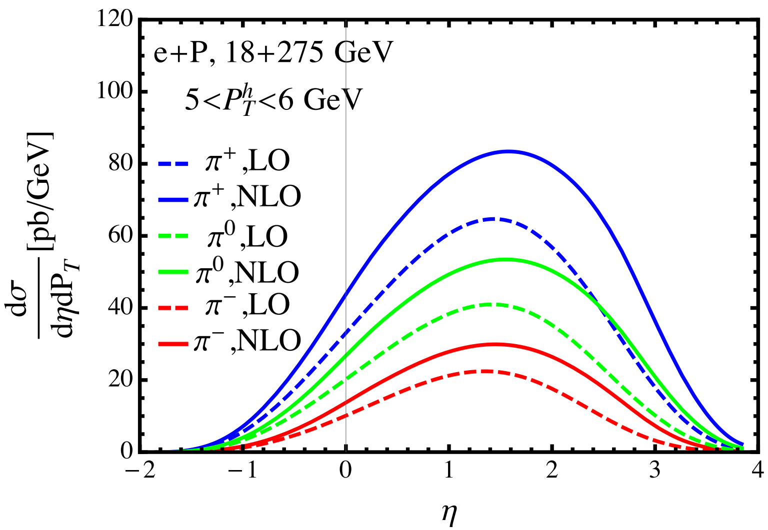
Results in e+p, NLO corrections

Factorization formula

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

		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 < η < 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