Journal Club

---[Nuclear Matter Effects on Jet Production at Electron-Ion Colliders]

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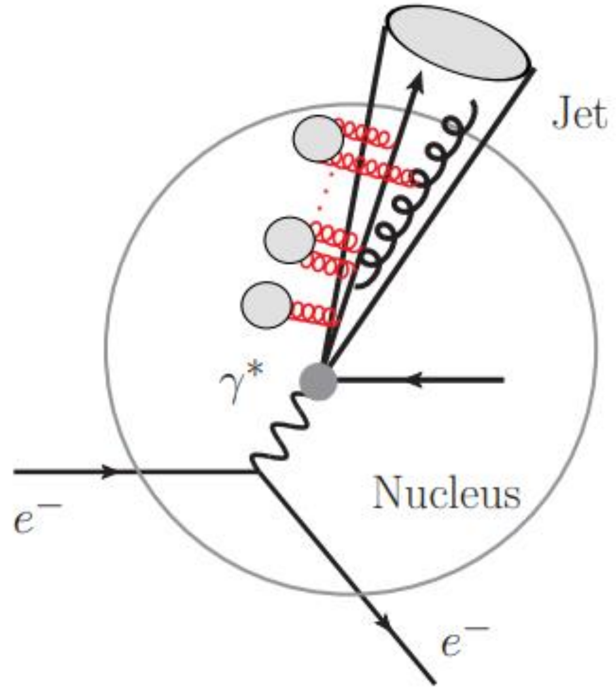
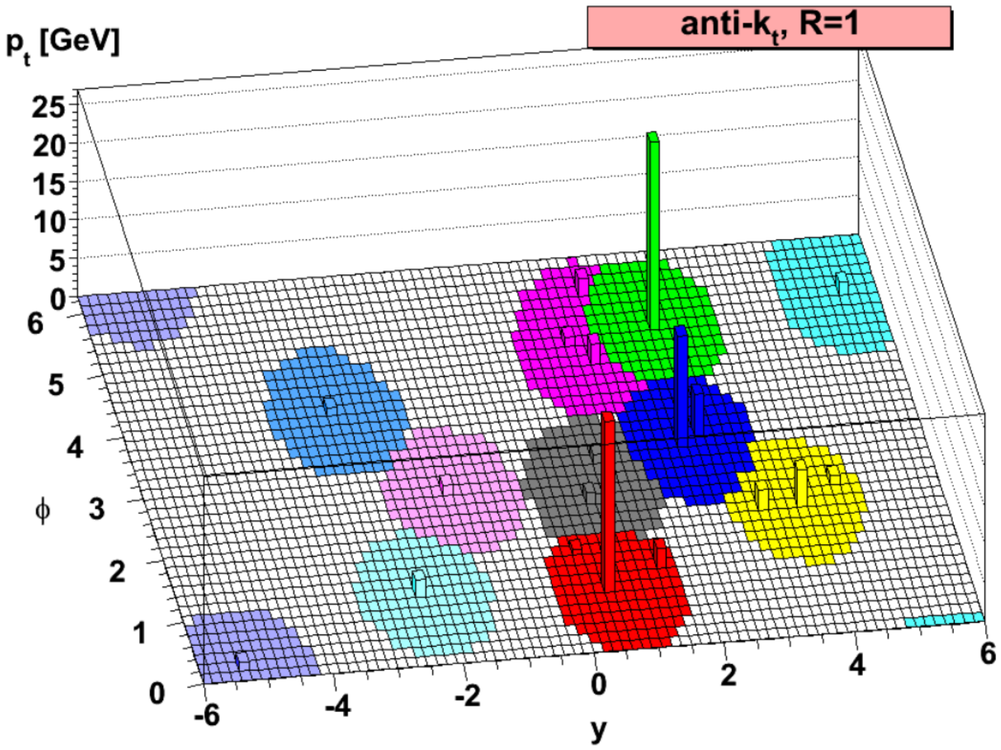
Introduction





- A jet is a narrow cone of hadrons and other particles produced by the hadronization of a quark or gluon.
- At EIC, a photon hit a parton. Then the parton creates colored objects around it to form colorless objects.
- EIC has the much cleaner DIS environment to avoid HI background.

Initial State Effects

Final State Effects

Jet Definiton

- Distance(no dimension):

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$anti - k_T$ algorithm (p=-1 in this paper)

$$d_{1i} = \min(1/k_{t1}^2, 1/k_{t1}^2)\Delta_{1i}^2/R^2 < R$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

In this article

- Inclusive jets in electron-nucleus are calculated.
  - Inclusive jet production
  - Jet Charge: $Q_{\kappa,jet} = \frac{1}{(p_T^{jet})^\kappa} \Sigma_{i\in jet} Q_i \left(p_T^i\right)^\kappa (\kappa > 0)$

-- Jet Substructure

- the radiation pattern inside a given jet

- Two observables are studied.
  - Jet Ratio:

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

  - Jet Double Ration: $R_{eA}(R)/R_{eA}(R=1)$
  - Jet charge ratio: $\langle Q\rangle_{eAu}/\langle Q\rangle_{ep}$
  - Ability to disentangle initial- and final-sate effects

Theoretical Framework—Initial state effect

- Inclusive jet cross section: factorized form

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

Initial State Effect

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 next-to-leading order (NLO) in QCD [27]. J_f is the SiJF initialed by parton f; it

SiJF: semi-inclusive jet function

Initial State Effect:

- Included through global-fit nuclear PDFs
- Isospin symmetry is implemented.
  A=Z+N will change the density of up and down quarks in nucleus.

What does isospin symmetry mean here?

- Neutron(udd, $I = 1, I_3 = -1$) and proton(uud, $I = 1, I_3 = 1$)
- There is isospin sysmmetry between neutron and proton.
  $f_{u/N}(x, Q^2) = f_{d/p}(x, Q^2), f_{d/N}(x, Q^2) = f_{u/p}(x, Q^2)$

Theoretical Framework—Final State Effect

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

Final State Effect

- Spltting function:

$$f_{i\to jk}(z, \boldsymbol{k}_\perp) = dN_{i\to jk}/d^2\boldsymbol{k}_\perp \mathrm{d}z$$

$$f^{\mathrm{tot}}_{i\to jk}(z, \mathbf{k}_\perp) = f^{\mathrm{vac}}_{i\to jk}(z, \mathbf{k}_\perp) + f^{\mathrm{med}}_{i\to jk}(z, \mathbf{k}_\perp)$$

i: identified initial state
j: final-state parton
If $z \to 1$ *and* $i = j$, f^{tot}_{i-jk} is splitting kernel.

In analogy to vacuum SiJFs,

Insdie jet cone

$$J_q^{\mathrm{med}}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f^{\mathrm{med}}_{q\to qg}(z, \mathbf{k}_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f^{\mathrm{med}}_{q\to gq}(z, \mathbf{k}_\perp),$$

Outsdie jet cone

$$J_g^{\mathrm{med}}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(z, \mathbf{k}_\perp)\left(\frac{z}{1-z} + z(1-z)\right)\right)\right]_+ + n_f\left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{g\to q\bar{q}}(z, \mathbf{k}_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(x, \mathbf{k}_\perp)\left(\frac{1-z}{z} + \frac{z(1-z)}{2}\right) + n_f f_{g\to q\bar{q}}(z, \mathbf{k}_\perp)\right). \quad (5)$$

In the high p_T and forward rapidity EIC kinematics, gluon contribution to jet is insignificant. Neglect this term.

When $z \to 1$, SiJFs singularities are regularized by

$$\int_0^1 dz g(z)[f(z)]_+ = \int_0^1 dz[g(z) - g(1)f(z)$$

Theoretical Framework—Jet Charge for Electron-Proton

where $J_q(E,R,\mu)$ is a jet function and $\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)$ is the $(\kappa+1)$th Mellin moment of the Wilson coefficient for matching the quark fragmenting jet function onto a quark fragmentation function. The perturbative NLO jet function

- Quark fragmenting jet function: the probability of a quark fragmenting into a jet of particles with a certain energy and direction
- Quark fragmentation function: the probability of a quark producing a particular hadron with certain momentum

$$Q_{\kappa,jet} = \frac{1}{(p_T^{jet})^{\kappa}} \Sigma_{i\in jet} Q_i (p_T^i)^{\kappa} (\kappa > 0)$$

- Both Q_i and p_T^i are used to describe hadron in the jet cone.
- But all that have been calculated are about jets, not hadrons in the jets cones.
- Parton-to-hadron processes have a smaller intrinsic scale than parton-to-jet. To relate them, a scale conversion should be done here by renormalization group(RG). And Wilson coefficient appears when RG resummation is done.

For each jet flavor the average jet charge only depends on one nonperturbative parameter $\tilde{D}_q^Q(\kappa)$, which is obtained from PYTHIA.

$$\langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa) \times \exp\left[\int_{1\,\mathrm{GeV}}^{\mu} \frac{d\mu'}{\mu'} \frac{\alpha_s(\mu')}{\pi} \tilde{f}_{q\to qg}^{\mathrm{vac}}(\kappa)\right]$$

$\tilde{f}_{q\to qg}^{vac}(\kappa)$ is the $(\kappa+1)$ th Mellin moment of the splitting function $f_{q\to qg}^{vac}$

- Mellin transformation:

$$\{\mathcal{M}f\}(s) = \varphi(s) = \int_0^{\infty} x^{s-1} f(x)\,dx.$$

Theoretical Framework—Jet Charge for Electron-Nucleus

Here, the exponential term comes from the medium-modified Dokshitzer-Gribov-Lipatov-Altarelli-Parisi e vol-ution from $\mu_0 \approx \Lambda_{\mathrm{QCD}}$ to the jet scale and $\tilde{f}^{\mathrm{med}}_{q\to qg}(\kappa,\mu) = \int_0^1 dx(x^\kappa - 1) f^{\mathrm{med}}_{q\to qg}(x,\mu)$. Finally, from the second line of

Jet Charge at electron-proton

$$\langle Q^{eA}_{\kappa,q}\rangle = \langle Q^{ep}_{\kappa,q}\rangle \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \frac{\alpha_s(\mu')}{2\pi^2} (2\pi\mu'^2) \tilde{f}^{\mathrm{med}}_{q\to qg}(\kappa,\mu')\right] \times (1 + \tilde{\mathcal{J}}^{\mathrm{med}}_{qq} - J^{\mathrm{med}}_{q}) + \mathcal{O}(\alpha_s^2). \quad (6)$$

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

- DGLAP for jet

$$\frac{\partial}{\partial \ln Q^2} D_i^h(x,Q^2) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{4\pi} P_{ji}\left(\frac{x}{z},Q^2\right) D_j^h(z,Q^2)$$

- DGLAP for Parton Density

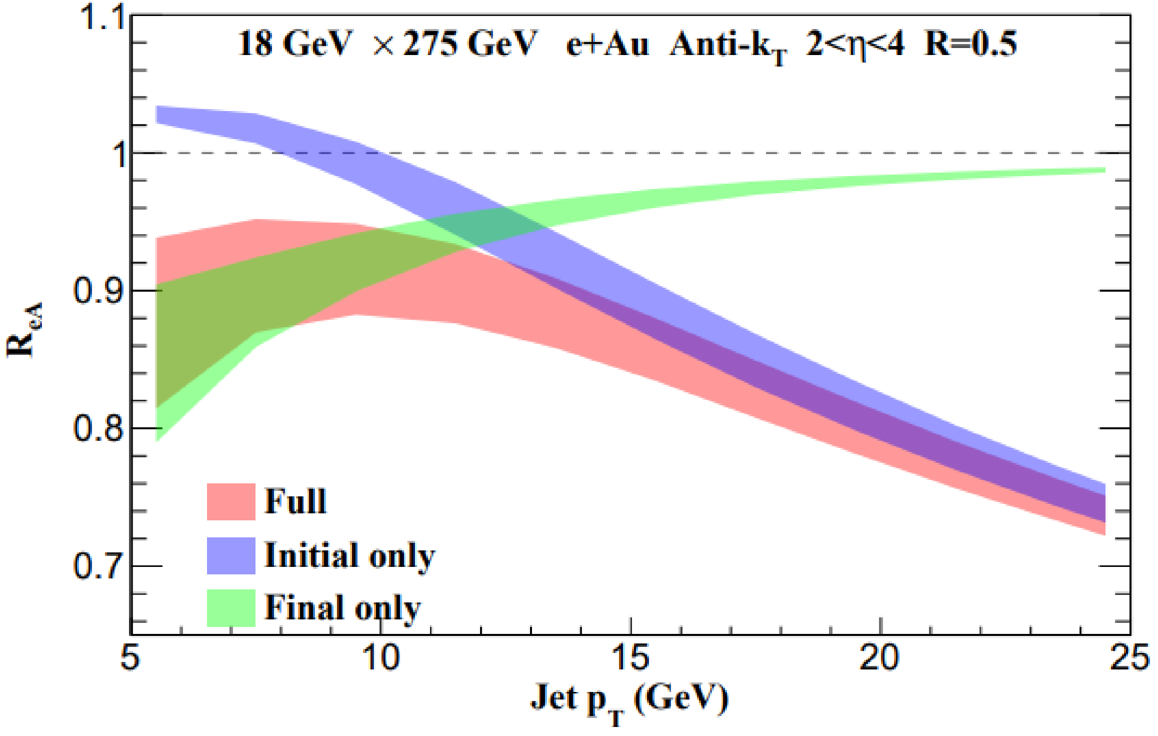
$$\frac{\partial f(x,Q^2)}{\partial lnQ^2} = \alpha_s(Q^2) \int_x^1 \frac{dz}{z} \left[P(z)\, f\left(\frac{x}{z},Q^2\right)\right]$$

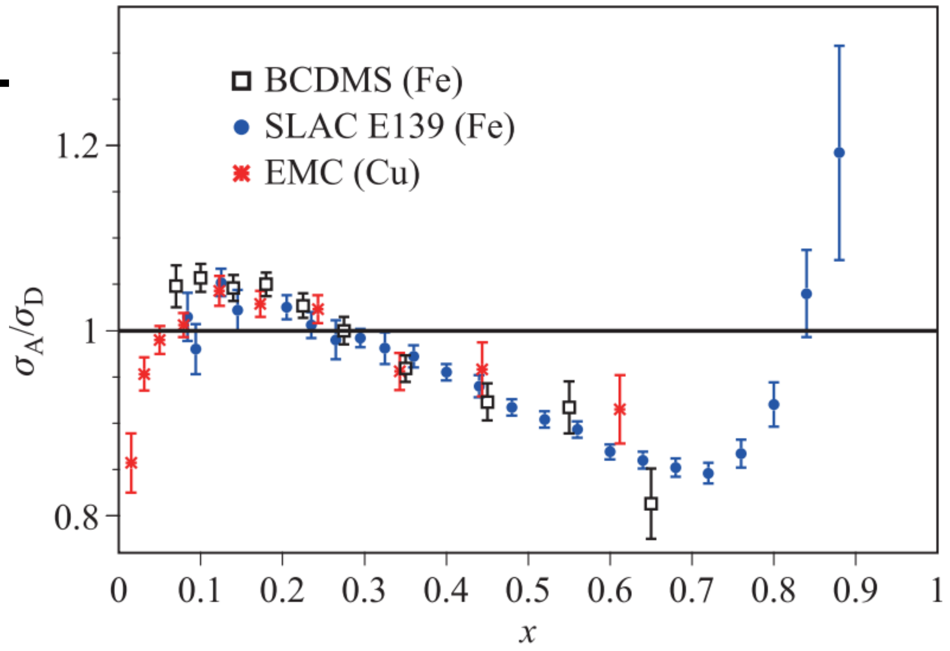
Numerical Resluts

- CT14nlo PDF for proton and nCTEQ15FullNuc for nucleus(Au)
- Fix the nominal transport coefficient of cold nuclear matter $\langle k_\perp^2 \rangle / \lambda_g = 0.12 GeV^2/fm$ and averag
over the nuclear geometry
- In nuclear rest frame, the lower energy the parton has, the larger medium corrections it receives.
- Calculation focus on $2 < \eta < 4$, where the jet energy is lower in the nuclear rest frame.

Jet Ratio-Total Nuclear Effects

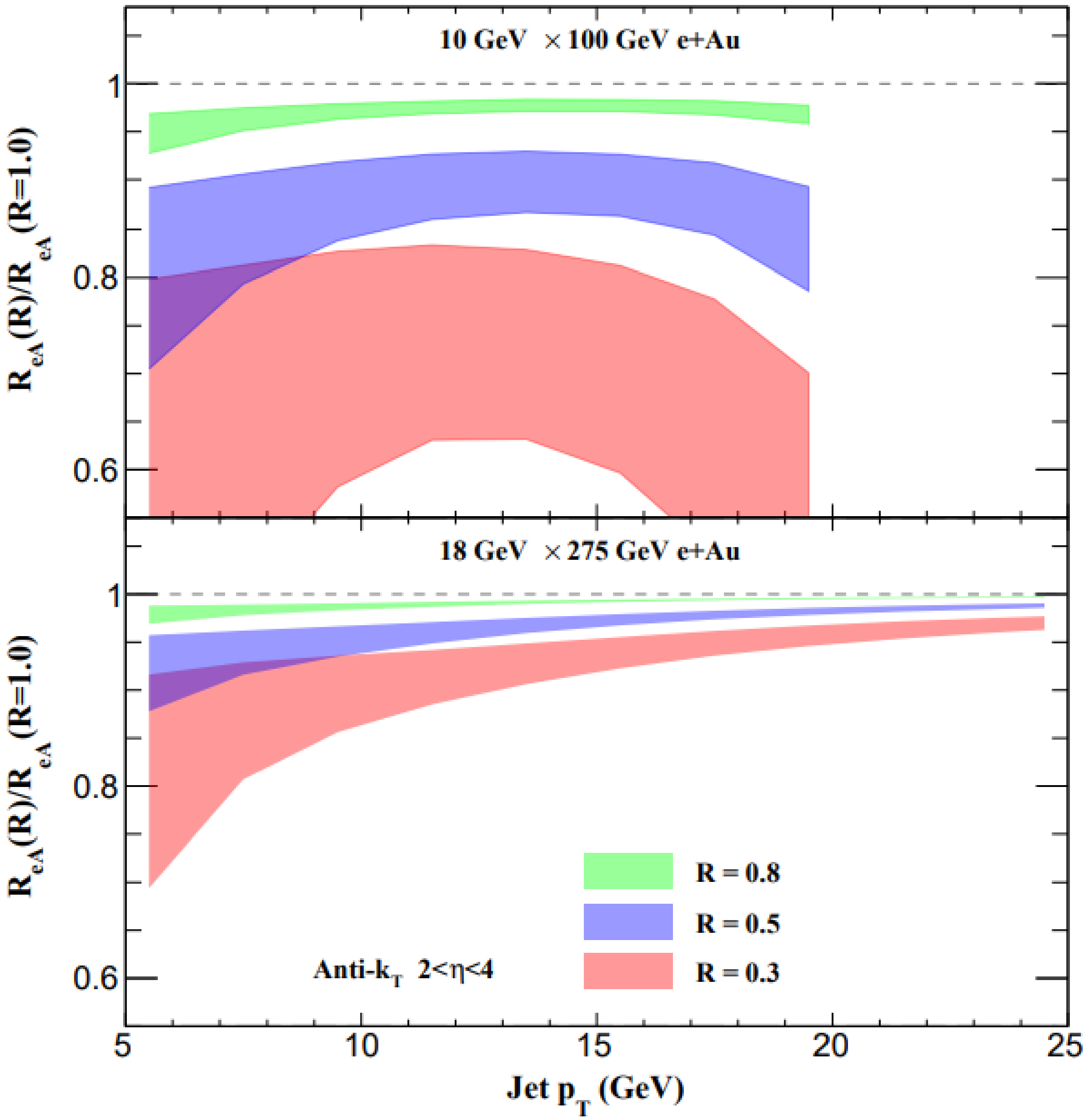
$$R_{eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+p}}$$





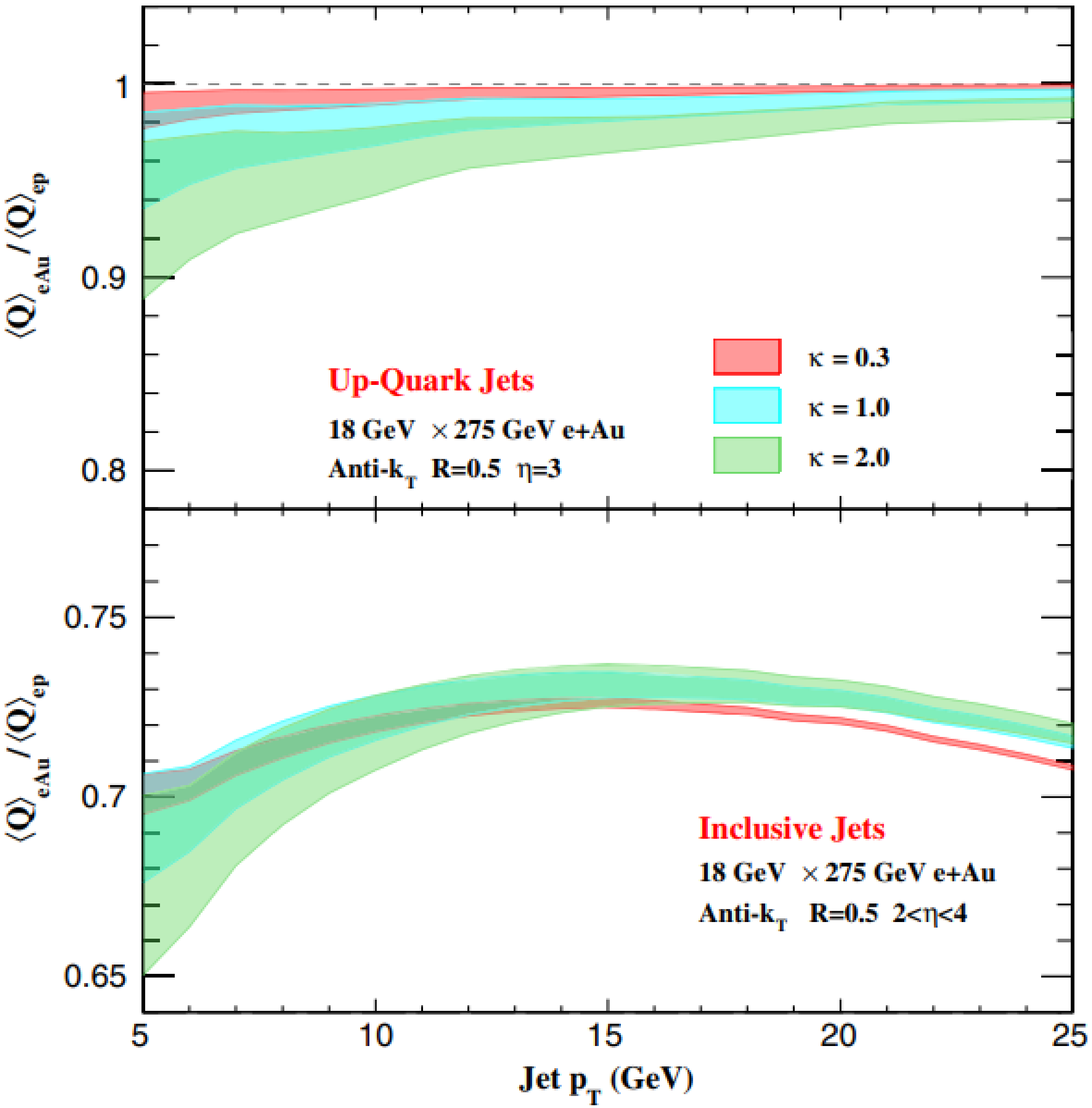
- Bands:
  - Varying the factorization scale and the jet scale by a factor of two independently
- $p_T \in [5,25] GeV, x \in [0.09, 0.43]$ corresponding to the anti-shadowing and EMC regions of nuclear PDFs
- Initial State Effect only, enhancement at lower p_T(anti-shadowing) and suppression at Higher p_T(EMC)
- Final State Effect Only: higher p_T, lower modification and then lower suppression

Jet Double Ratio—$R_{eA}(R)/R_{eA}(R=1)$



- To reduce the initial-state effect
  - Medium-induced parton showers are broader than the ones in the vacuum.
  - Smaller jet radii the suppression from final-state interactions is more significant.
  - Indeed eliminating initial-state effects
- Different $\sqrt{s}$
  - Even though the scale uncertainties also grow, the suppression magnitude is further significantly enhanced.

Jet Charge Ratio—$\langle Q \rangle_{eAu} / \langle Q \rangle_{ep}$



- Different κ
  - Medium enhancement for soft-gluon radiation is the largest.
  - Larger κ, it is more sensitive to soft-gluon emission.
- Flavor Tagged or Inclusive
  - They behaves very differently.
  - For inclusive jets, there is a cancellation between contributions from jets initialed by different flavor partons.
- Constrain isospin effects

Conclusions

- This article calculates the production of the inclusive jet and its substructure at EIC.
- Several observables have been studied to examine their sensitivity to
  - Jet Ratio:

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

    Total initial- and final-state effects

  - Jet Double Ratios: $R_{eA}(R)/R_{eA}(R=1)$

    Final-state effects

  - Jet charge ratio: $\langle Q \rangle_{eAu}/\langle Q \rangle_{ep}$

    Isospin effects