LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

1st Workshop on 2nd Detector
Temple University
Philadelphia, PA
May 17-19, 2023

Hadronization and Jet Substructure Analysis in eA and ep

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Largely based on the following papers
2303.14201 [hep-ph] 2301.11940 [hep-ph]
2108.07809 [hep-ph] 2010.05912 [hep-ph]
2007.10994 [hep-ph]

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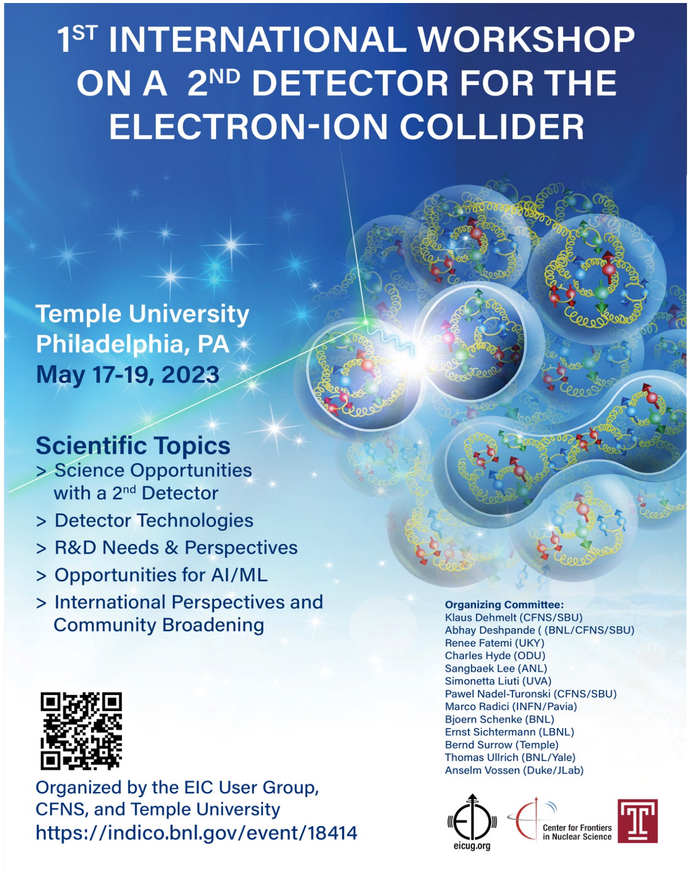
Outline of the talk

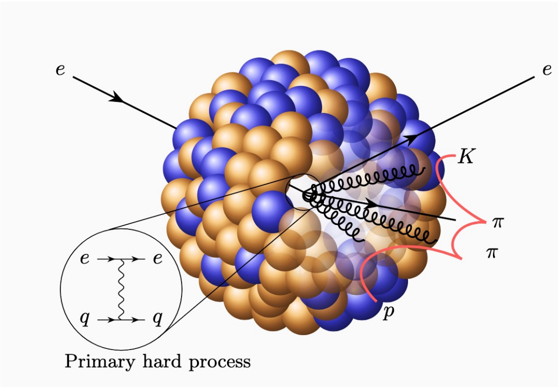
I will tell you about the physics and you decide what is relevant to second IR/Detector

- **Parton showers in cold nuclear matter**
- **Renormalization group analysis of modifications of hadronization**
- **Centrality dependent light and heavy meson (and jet) production in eA**
- **Jet substructure modification in eA (charge and momentum sharing distributions)**
- **Conclusions**



i) Thanks to the organizers for the invitation to give this talk
ii) Credit for the work presented goes to my collaborators W. Ke, H. Li, Z. Liu
iii) We thank W. Chang and M. Baker on centrality determination in DIS. W. Chang for the effective interaction lengths in eA from BeAGLE

EFTs for parton showers in matter



- Evaluated using EFT approaches - SCET$_G$, SCET$_{M,G}$
- Cross checked using light cone wavefunction approach
- Factorize from the hard part
- Gauge invariant
- Contain non-local quantum coherence effects (LPM)
- Depend on the properties of the nuclear medium

G. Ovanesyan et al. (2011)

- Compute analogues of the Altarelli-Parisi splitting functions
- Enter higher order and resumed calculations

Quark to quark splitting function example

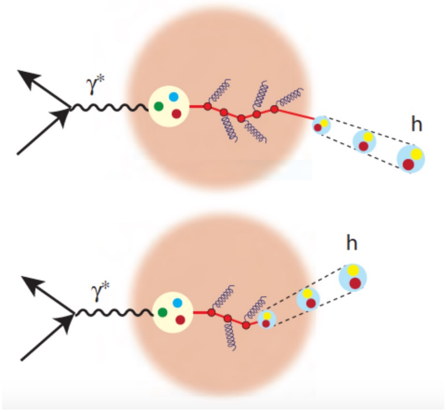
$$
\begin{aligned}
\left(\frac{dN^{\rm med}}{dx\, d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \Bigg\{ \left(\frac{1+(1-x)^2}{x}\right) \Bigg[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \\
&\times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right. \\
&\left. - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) \\
&+ \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z]) \\
&+ \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) \Bigg] \\
&+ x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\Bigg\} \qquad (2.51)
\end{aligned}
$$

Z. Kang et al. (2016) *M. Sievert et al. (2019)*

- **In-medium parton showers are softer and broader than the ones in the vacuum**
- **New contributions to factorization theorems and evolution**

Open questions about hadronization

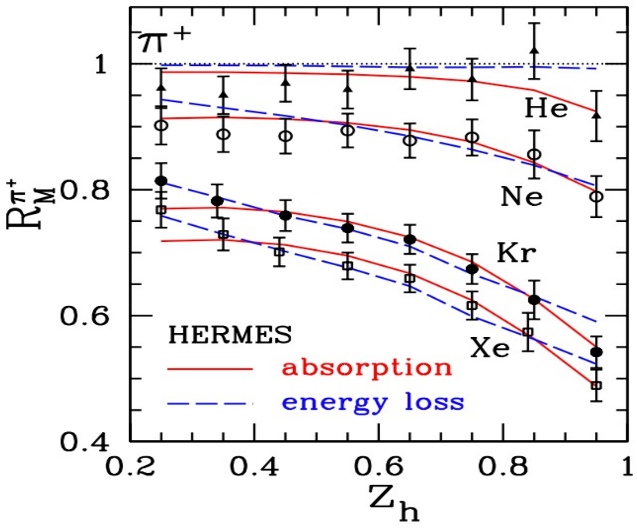
- Open questions about the nature of hadronization – independent fragmentation, string fragmentation, cluster hadronization
- The space-time picture of hadronization is unknown unknown, but critical for e+A
- Competing physics explanations of HERMES hadron suppression data based on energy loss and absorption



W. Wang et al. (2002) *B. Kopeliovich et al. (2003)*

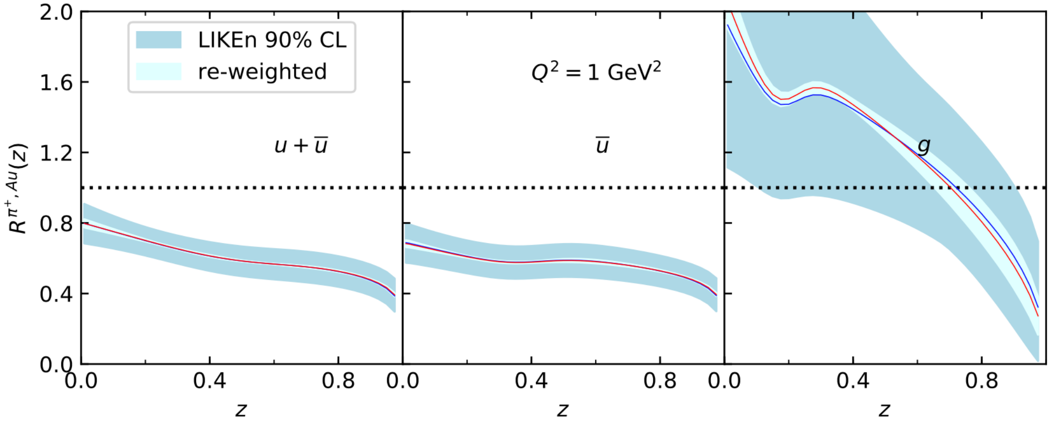
Light hadron measurements cannot differentiate between competing mechanisms

A. Accardi et al. (2009)

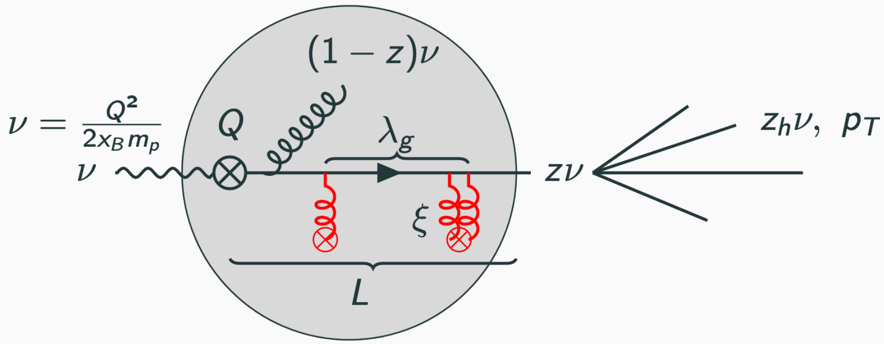


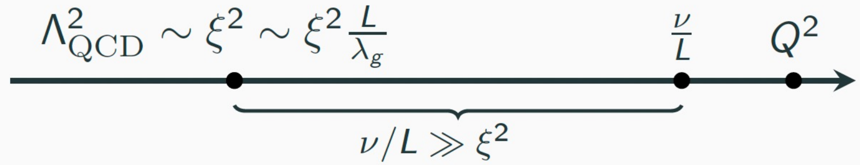
Ideas to parametrize nFFs assuming universality

Effect of 10 fb-1 EIC data *P. Zurita et al. (2021)*



Scales in the in-medium parton shower problem



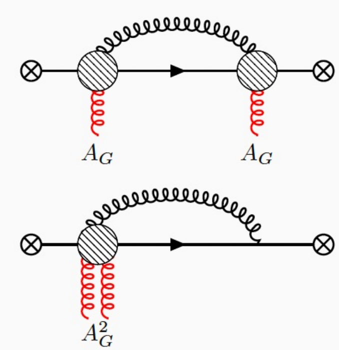


- **We encounter many ratios of scales in DIS on nuclei**
- **Will resum large logarithms of Q/Qo and $E/\xi^2 L$**

- **Consider differential hadron production in ep and eA** *W. Ke et al. (2023)*

$$\frac{d\sigma_{ep\to h}}{dx_B\, dQ^2\, dz_h} = \frac{2\pi\alpha_e^2}{Q^4}\sum_{i,j} \underbrace{e_q^2 f_{i/A}(x_B)\otimes C_{ij}^h(x,z)}_{F_{ij}(z)} \otimes d_{h/j}(z_h)$$

$$\frac{d\sigma_{eA\to h}}{dx_B\, dQ^2\, dz_h} = \sum_{i,j}\frac{2\pi\alpha_e^2}{Q^4}\left[F_{ij}(z) + \Delta F_{ij}^{\mathrm{med}}(z)\right]\otimes d_{h/j}(z_h)$$



- **The distribution of partons in the shower receives contributions proportional to the in-medium splitting functions**

$$\Delta F_{ij}^{\mathrm{med}}(z) = F_{ik}^{(0)} \otimes P_{kj}^{\mathrm{med}(1)}$$

Emergent analytic understanding of the in-medium shower medium

- **We were able to identify a simple analytic limit of the splitting functions integrate the transverse degrees of freedom using dim. reg. and isolate the endpoint divergences**

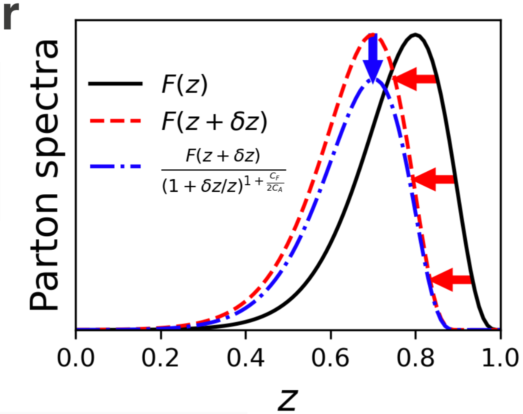
Color non-singlet distribution as an example

$$\Delta F_{\rm NS}^{\rm med}(z) = \int_z^1 \frac{dx}{x} F_{\rm NS}\Big(\frac{z}{x}\Big) P_{qq}^{\rm med(1)}(x) \quad + \quad \text{virtual term.}$$

$$P_{qq}^{\rm med(1)}(x) = A(\alpha_s, \cdots) \cdot \frac{P_{qq}^{vac(0)}(x)}{[x(1-x)]^{1+2\epsilon}} \cdot \left[\frac{\mu^2 L}{\chi z \nu}\right]^{2\epsilon} \cdot C_n \Delta_n(x)$$

- **Divergences are cancelled by the soft-collinear sector**

$$\Delta F_{\rm NS}(z) = A(\alpha_s, \cdots) \left(\frac{1}{2\epsilon} + \ln \frac{\mu^2 L}{\chi z \nu}\right) 2C_F [\underbrace{2C_A \left(-\frac{d}{dz} + \frac{1}{z}\right)}_{\text{from } x\to 1} + \underbrace{\frac{C_F}{z}}_{x\to 0}] F_{\rm NS}(z) + \text{F.O.}$$



- **Derived a full set of RG evolution equations. The NS distribution has a very elegant traveling wave solution**

$$\frac{\partial F_{\rm NS}(\tau, z)}{\partial \tau} = \left(4C_F C_A \frac{\partial}{\partial z} - \frac{4C_F C_A + 2C_F^2}{z}\right) F_{\rm NS}$$

$$\frac{\partial F_f}{\partial \tau} = \left(4C_F C_A \frac{\partial}{\partial z} - \frac{4C_F C_A + 2C_F^2}{z}\right) F_f + 2C_F T_F \frac{F_g}{z},$$

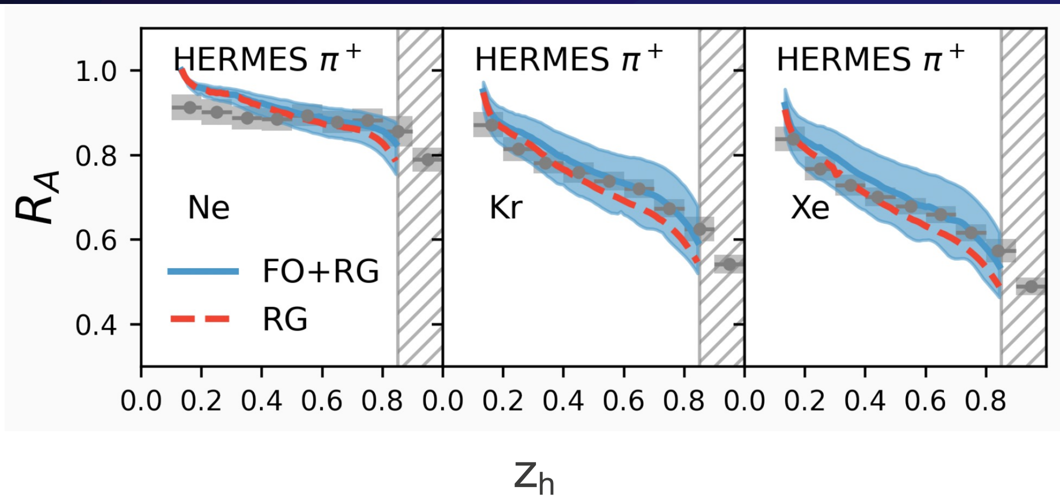
$$\frac{\partial F_g}{\partial \tau} = \left(4C_A^2 \frac{\partial}{\partial z} - \frac{2N_f C_F}{z}\right) F_g + 2C_F^2 \sum_f \frac{F_f}{z}.$$

$$\tau(\mu^2) = \frac{\rho_G L^2}{\nu} \frac{\pi B}{2\beta_0} \left[\alpha_s(\mu^2) - \alpha_s\left(\chi \frac{z\nu}{L}\right)\right]$$

$$F_{\rm NS}(\tau, z) = \frac{F_{\rm NS}(0, z + 4C_F C_A \tau)}{(1 + 4C_F C_A \tau / z)^{1 + C_F/(2C_A)}}$$

Can directly identify parton energy loss, the nuclear size dependence of the modification, etc

Phenomenological applications of the new RG analysis



Observable chosen to eliminate initial-state effects

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

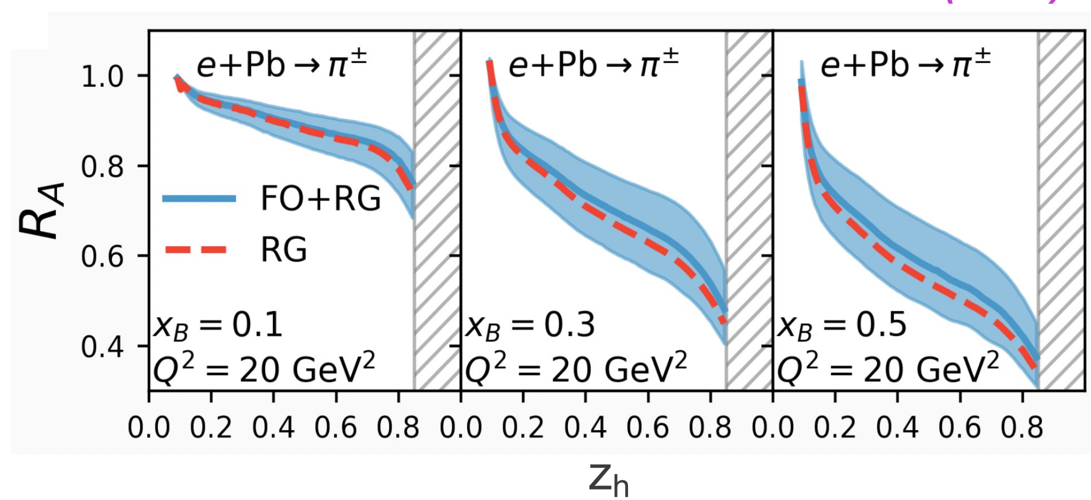
- **RG evolution gives a good description of the data at small to intermediate z_h .**
- **Fixed order corrections improve the agreement at large z_h**

W. Ke et al. (2023)

- **Working on second order in opacity corrections analytically**

Results for EIC

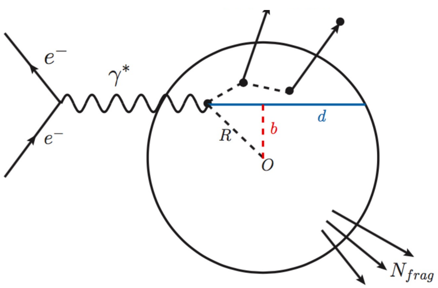
- **The modifications to hadronization at EIC depends on kinematics x_B,Q^2 (which affects the)**
- **At large x_B and (forward rapidities) the modification can be very significant**



Why centrality?

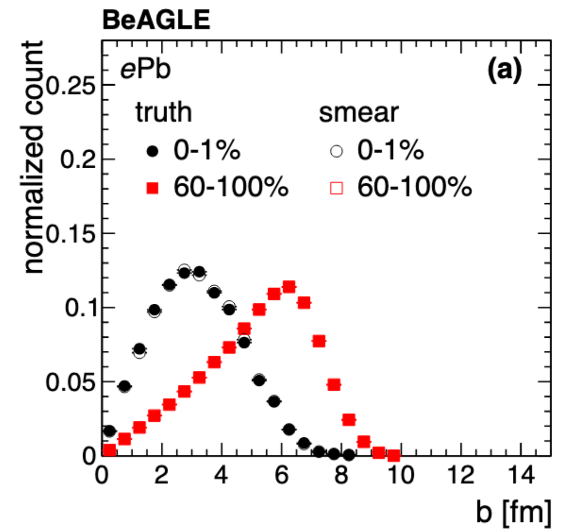
- Further understand QCD in the nuclear environment. Find corrections to factorization

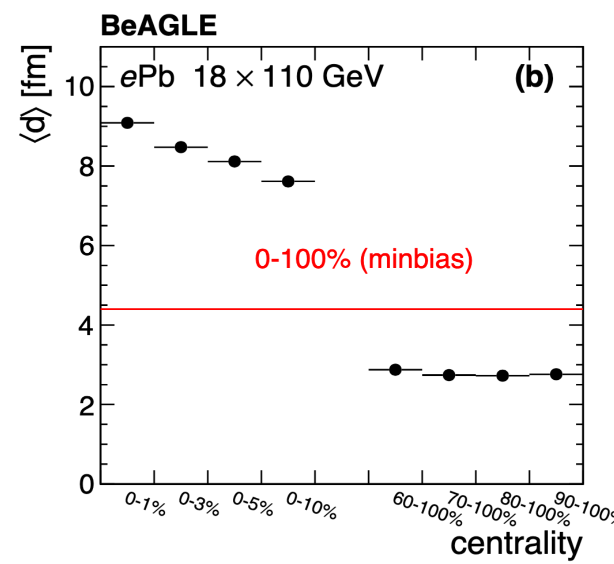
$$
\begin{aligned}
\frac{d\sigma^{\ell N\to hX}}{dy_h d^2\mathbf{p}_{T,h}} = & \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \\
& \times\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right] \\
& \times D^{h/f}(z,\mu)\,,
\end{aligned}
$$



Z. Kang et al. (2016)

W. Chang et al. (2022)





- Centrality dependent measurements emphasize the dynamical nature of nuclear effects
- BeAGLE – centrality can be determined from the neutrons detected in the ZDC, <d>
- Robust with respect to nuclear effects – shadowing, particle formation times

mDGLAP and RG evolution

N. Chang et al. (2014) *Z. Kang et al. (2014)*

- More traditional: numerically evaluate splitting functions the non-perturbative scale in the medium regulates endpoint divergences

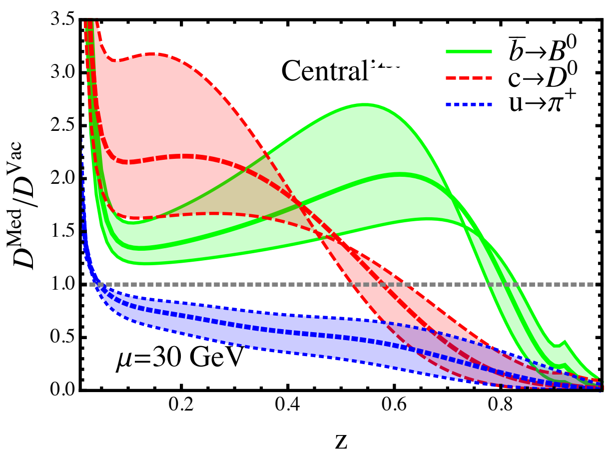
$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q}=\frac{\alpha_s(Q^2)}{\pi}\int_z^1\frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right)+P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

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

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

H. Li et al. (2020)

$$\left.+P_{g\to q\bar q}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right)+f_{\bar q}\left(\frac{z}{z'},Q\right)\right)\right\}.$$



- We can isolate explicitly divergences and in the limit that medium effects are localized in finite parts of phase space

$$\frac{\partial F_{\mathrm{NS}}(z)}{\partial\ln\mu^2}=\int_0^1\mathbf{k}^2\frac{d[P_{qq}(x,\mathbf{k}^2)+P^{(1)}_{qq}(x,\mathbf{k}^2)]}{dxd\mathbf{k}^2}\times\left[F_{\mathrm{NS}}\left(\frac{z}{x}\right)-F_{\mathrm{NS}}(z)\right]dx\,,$$

$$\frac{\partial F_{\mathrm{NS}}}{\partial\ln\mu^2}=4C_FC_AA_0\int_0^{1-\frac{\xi^2}{\mu^2}}\frac{4\Phi(u)}{\pi u}\frac{\frac{x}{z}F_{\mathrm{NS}}(\frac{z}{x})-\frac{F_{\mathrm{NS}}(z)}{z}}{(1-x)^2}dx$$
$$\approx\frac{4\Phi(u)}{\pi u}4C_FC_AA_0\left[\frac{\partial F_{\mathrm{NS}}}{\partial z}-\frac{F_{\mathrm{NS}}}{z}\right]\ln\frac{\mu^2}{\xi^2}$$
$$\approx\delta\left(\mu^2-\frac{2\pi E}{L}\right)4C_FC_AA_0\left[\frac{\partial F_{\mathrm{NS}}}{\partial z}-\frac{F_{\mathrm{NS}}}{z}\right]\ln\frac{\mu^2}{\xi^2},$$

$$A(\mu_2^2,E,w_{\max})=\alpha_s^2(\mu_2^2)L^2B(w_{\max})\rho_G/(8E)$$

- Directly comparable to renormalization group analysis results – resumms the same logs $\ln(E/L\xi^2)$.

W. Ke et al., (2023)

Phenomenological results – light and heavy mesons and hadronization

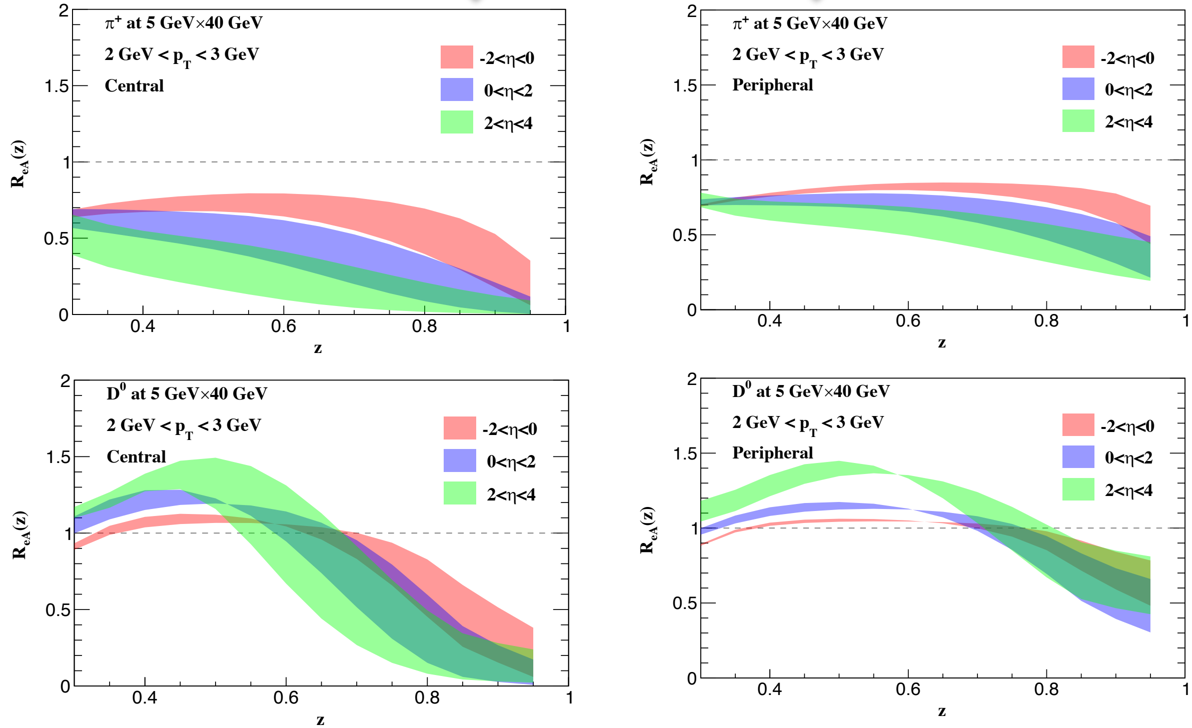
Centrality	$0-1\%$	$0-3\ \%$	$0-10\ \%$	$60-100\ \%$	$80-100\ \%$	$90-100\ \%$	$0-100\ \%$
$\langle d\rangle[fm]$	9.09	8.48	7.61	2.88	2.71	2.71	4.40
$\langle d\rangle/\langle d\rangle_{\text{min.bias}}$	2.07	1.93	1.73	0.65	0.62	0.62	1.00

The observable (normalized by a large radius jet)

$$R^h_{eA}(z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{eA}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{ep}}$$

- **Modifications to hadronization grow form backward to forward rapidity**
- **Transition from enhancement to suppression for heavy flavor**

- **Modifications to hadronization for light and heavy mesons is very different**



Central **Peripheral**

Analysis of light and heavy mesons and centrality will differentiate all 3 paradigms of modifications to hadronization

Centrality dependence of hadron cross sections

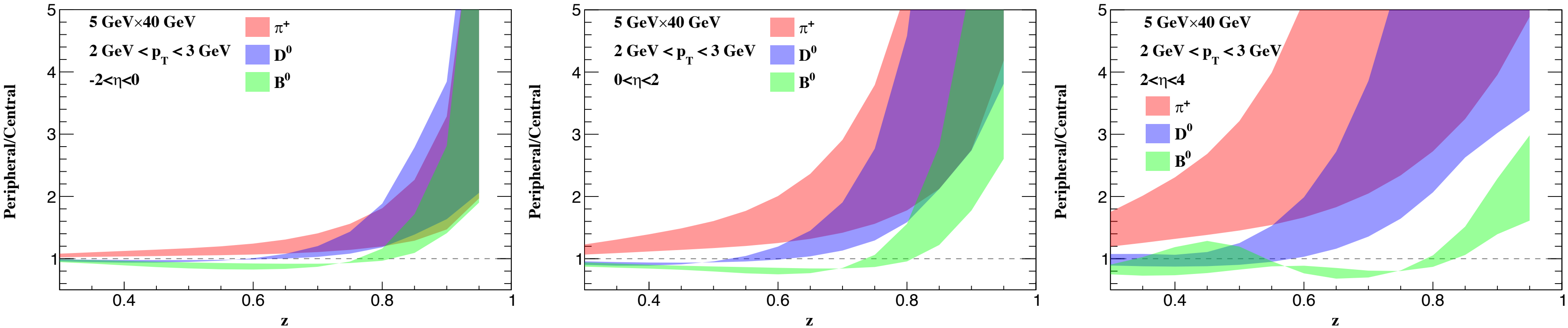
- Similar to jets - quantify the path-length dependence of the per-nucleon jet cross section modification

$$\frac{\text{Peripheral}}{\text{Central}}(h) = \frac{R^h_{eA}(z)|_{\mathrm{eA,Peri.}}}{R^h_{eA}(z)|_{\mathrm{eA,Cent.}}}$$

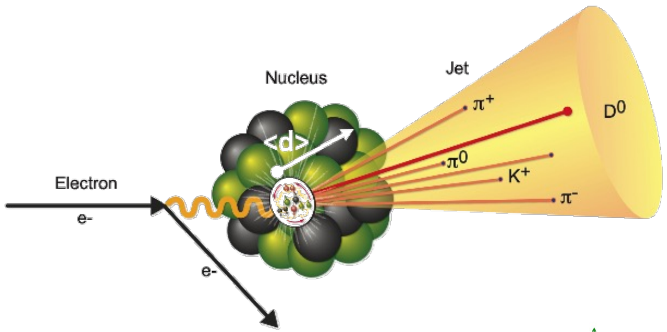
- At large values of the hadronization fraction z the per-nucleon nuclear effects are very significant
- At forward rapidities the centrality-dependence progresses toward intermediate z and differences can reach an order of magnitude – this is larger than the differences in <d>
- For heavy mesons peripheral/central can be < 1
- Sensitivity to final-state parton shower vs centrality

H. Li et al. (2023)

Backward rapidity — Near mid rapidity — Forward rapidity

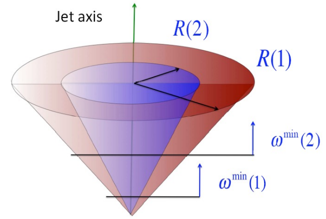


Jets and jet substructure at the EIC

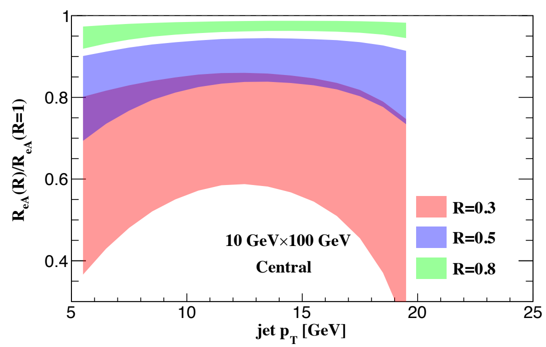


- **Before we go to jet substructure we should recognize the modification of the jet cross sections in eA vs ep**
- **We have made progress in understanding how to separate initial-state and final-state effects**

The physics is the loss of the in-medium (broader) parton shower outside of the jet cone



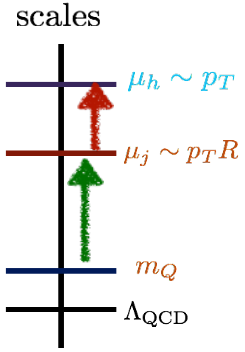
$$R_R = R_{eA}(R)/\, R_{eA}(R=1)$$



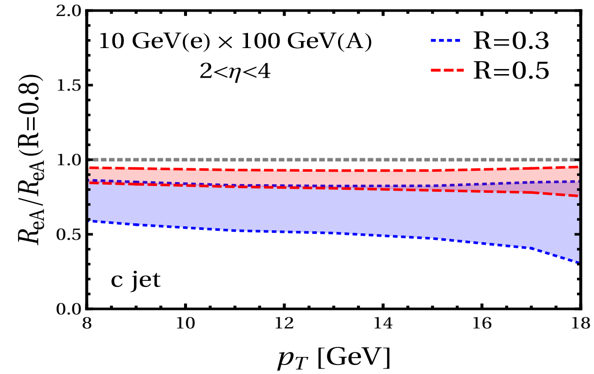
Factor of 2 suppression for light flavor jets. 30-50% extra from centrality selection

The technique is the one of semi-inclusive jet functions

$$\frac{d\sigma^{\ell N\to JX}}{dy_J d^2\mathbf{p}_{T,J}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right] \times J_f(z,p_T R,\mu)\,.$$



The suppression is similarly large for heavy flavor jets



Z. Kang et al. (2017) *H. Li et al. (2021)*

The jet charge in ep/pp and eA/AA

Definition

R. Field et al., (1978)

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

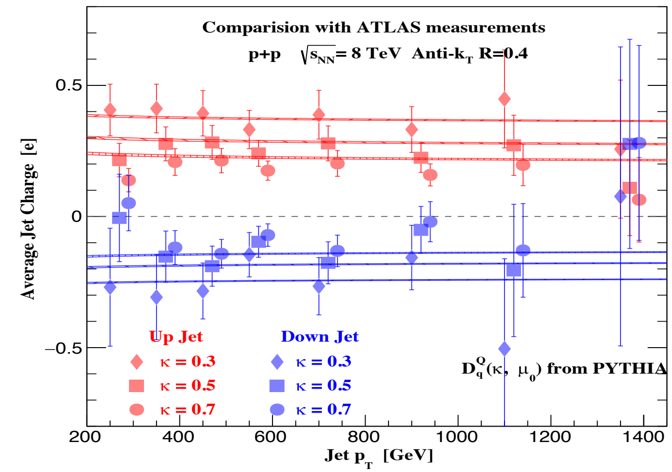
$$\langle Q_{\kappa,q} \rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu)$$

- Advances in the past decade based on SCET have rekindled interest in the jet charge
- Flavor separation of jets at the LHC

D. Krohn et al., (2012)

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

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



H. Li et al., (2019)

- The factorization formula ingredients receive contributions
- Can be computed with the in-medium splitting functions

In the case of collisions that involve a nucleus

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

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

H. Li et al., (2020)

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

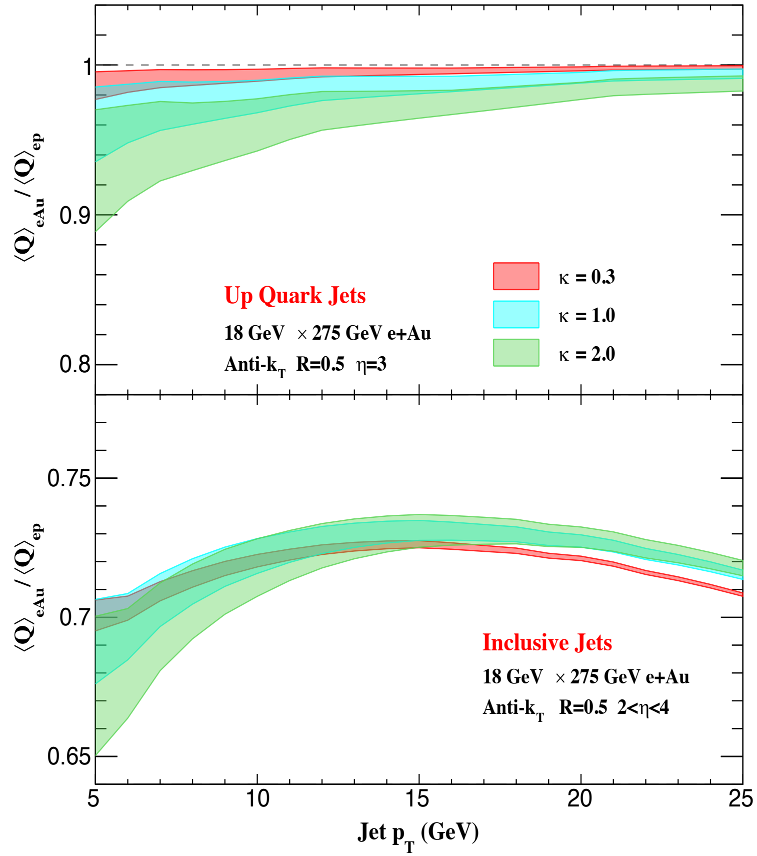
Phenomenological results for EIC

Individual jet charges have been used separate different flavor jets at the LHC. It can be very useful tool for the EIC

- The difference between e+A and e+p can tell **us directly about medium-induced scaling violations**
- Effects are enhanced by a larger jet parameter κ which enhances the role of soft radiation

For inclusive jets there is cancelation of contributions between different flavor jets (especially up and down)

- Can be particularly useful to determine the parton content of nuclei, look for violations of isospin symmetry

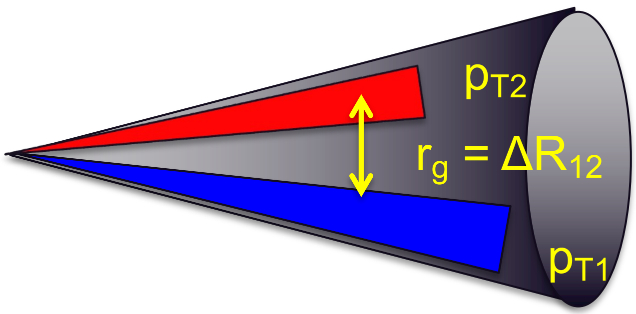


H. Li et al., (2020)

Jet momentum sharing distributions

Soft dropped momentum sharing distributions

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



H. Li et al., (2018)

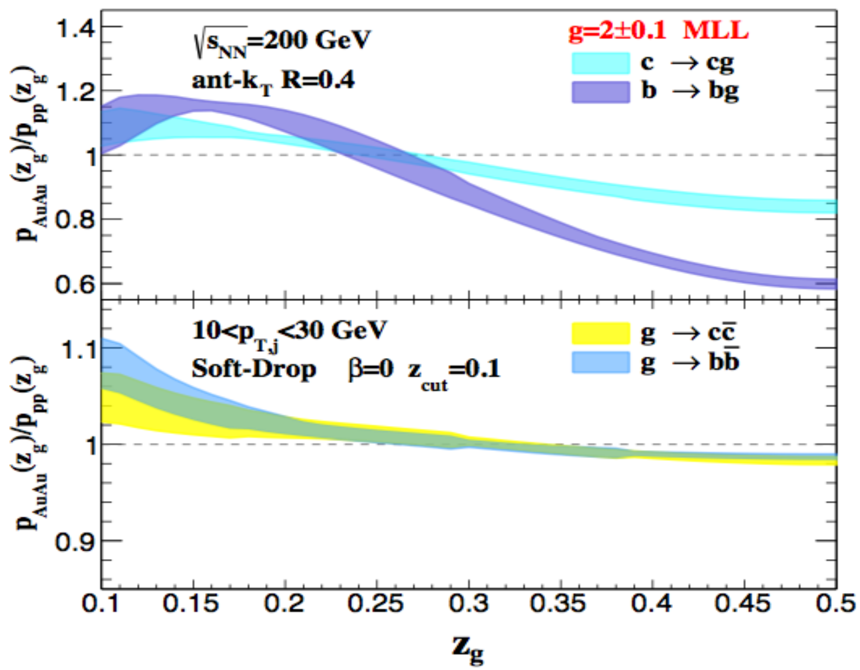
$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$

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

There is a contribution from the medium. The softer in-medium branching was observed in HIC!

- **The most significant manifestation of the "dead cone" effect – role of heavy quark mass in parton showers**

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



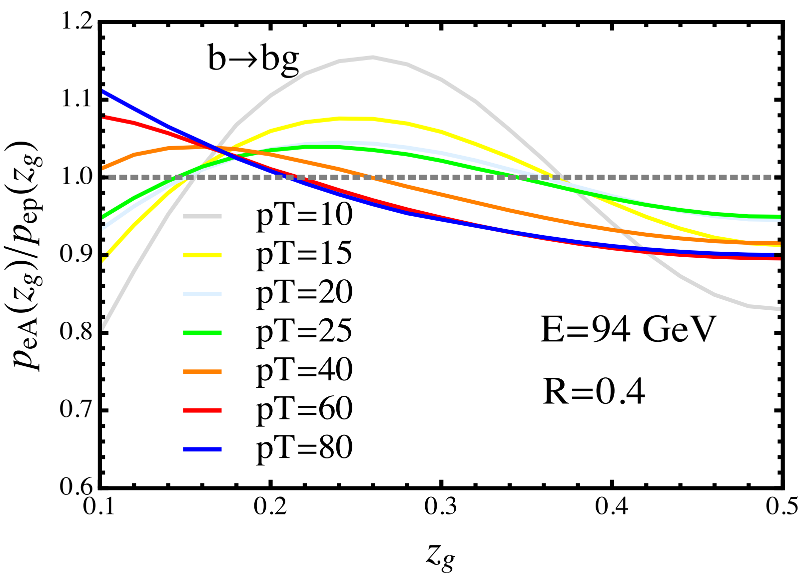
Jet splitting functions for light and heavy flavor jets in eA for EIC

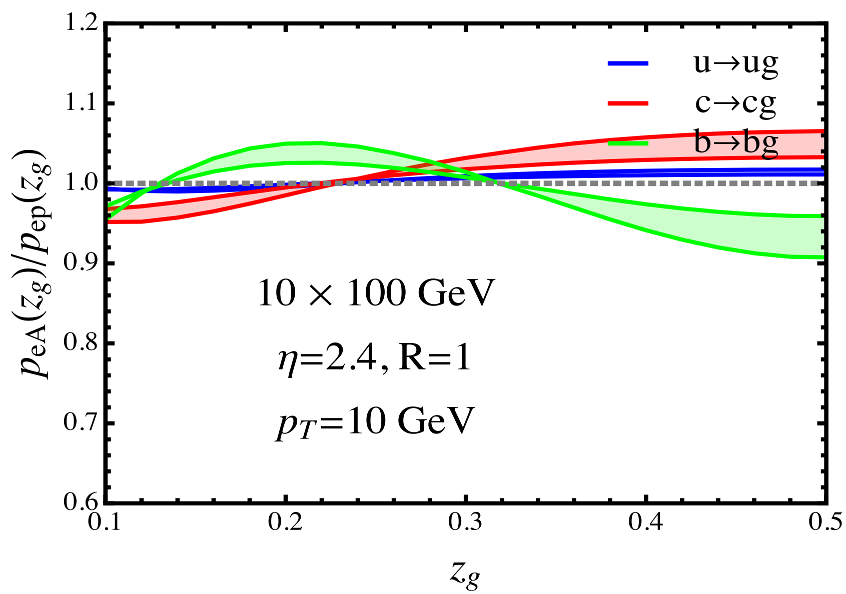
Jet substructure modification at the EIC is quite different that jet substructure modification in HIC

H. Li 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**

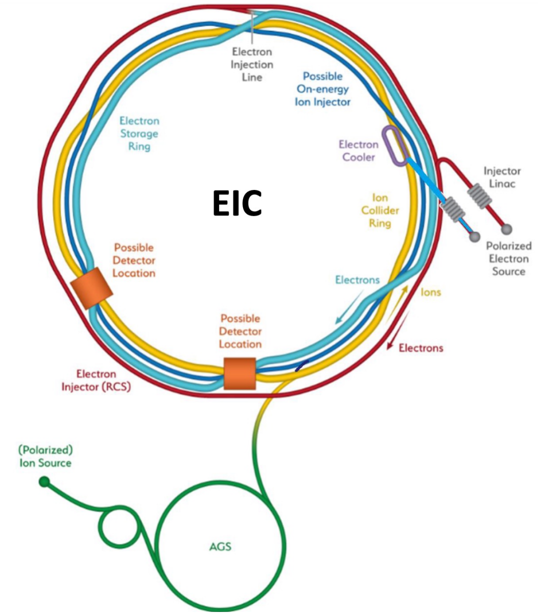




All jet substructure observables in eA so far have been done for minimum bias eA. If we make use of centrality in most central collisions we expect (naively) a factor of 2 enhancement an O(20%) effects

Conclusions

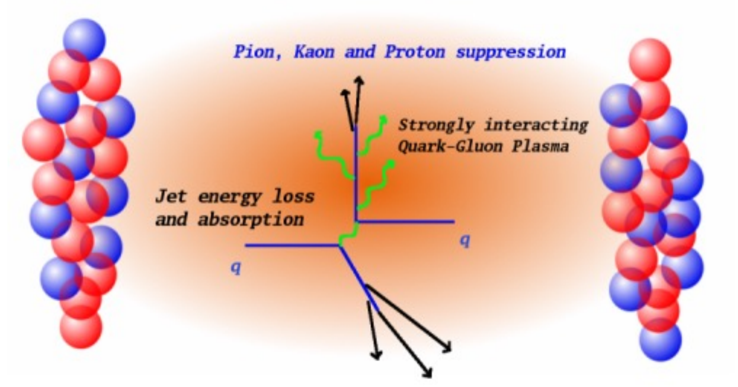
- For details and technical summaries, please consult the papers. I'll just call out new theory developments (RG analysis) and the interplay between theory and simulation (centrality dependence)
- To have second IR/Detector (and even first) a strong physics program is needed and support for research/theory
- EIC and especially its eA program can answer fundamental questions about hadronization, many-body QCD, transport properties of matter, the effects of heavy quark mass on parton showers
- Many of those questions are best answered at forward rapidity (p/A going direction) intermediate and smaller center of mass energies

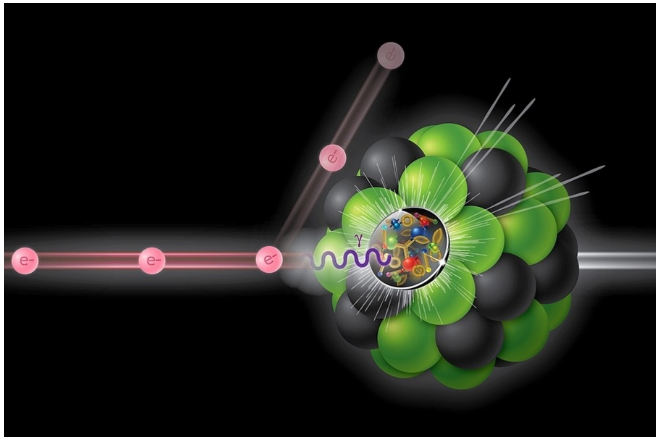


Thank you

Differences between AA and eA

- AA and eA collisions are very different. Due to the LPM effect the “energy loss” decreases rapidly. The kinematics to look for in-medium interactions / effects on hadronization very different



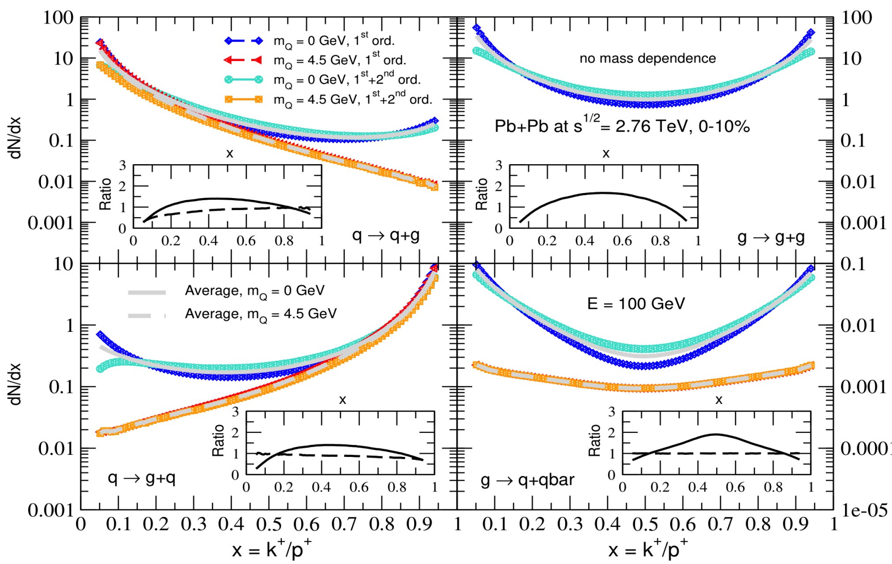


- Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)
- Largest effects at midrapidity
- Higher C.M. energies correspond to larger plasma densities

- Jets are in the nuclear rest frame Longitudinal momentum matters
- Largest effects are at forward rapidities
- Smaller C.M. energies (larger only increase the rapidity gap)

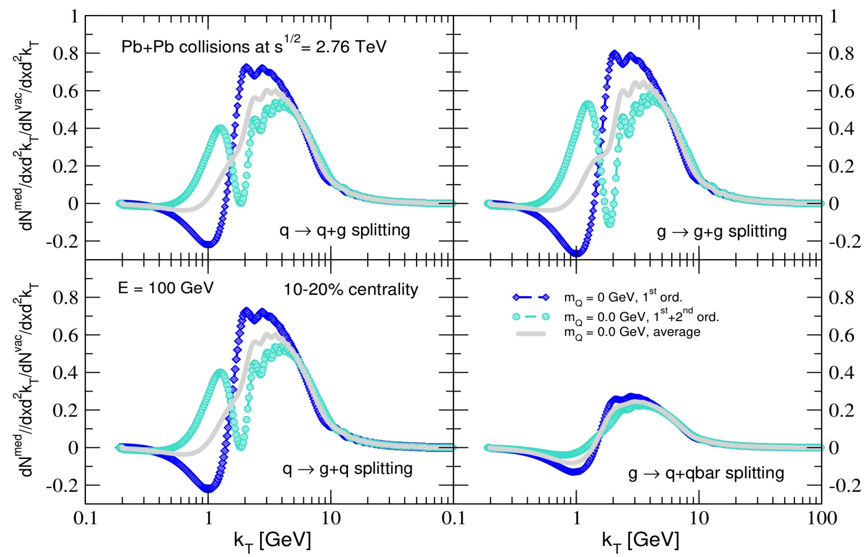
Properties of in-medium showers

Longitudinal (x) distribution



- In-medium parton showers are **softer and broader** than the ones in the vacuum
- There is even more matter-induced **soft gluon emission** enhancement

Angular (k_T) distribution – relative to vacuum



- **Enhancement of wide-angle radiation**, implications for reconstructed jets and jet substructure
- Limited to specific kinematic regions
- **Medium-induced scaling violations, new contributions to the jet function**

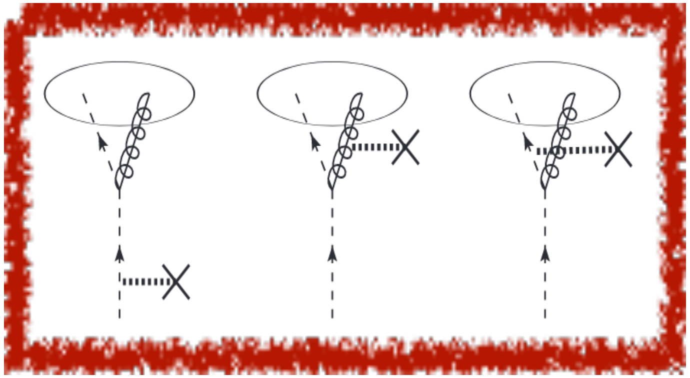
B. Yoon et al. (2019)

Same behavior in cold nuclear matter

$$2\frac{{\mu_D}^2}{\lambda q} = 0.053\frac{GeV^2}{fm} \quad (vary \times 2,/2) \qquad 2\frac{{\mu_D}^2}{\lambda g} = 0.12\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$

Other Electron Ion Colliders

Note: Labels of some expressions are pp and AA, same expressions for eP, eA. It's a final-state observable



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

- Modifications to jet matching coefficient, jet function and FF evolution

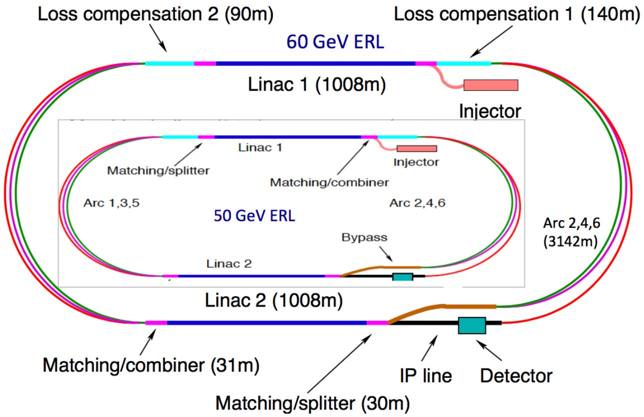
$$\frac{d}{d\ln\mu}\tilde{D}^{Q,\,{\rm full}}_q(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\Big(\tilde{P}_{qq}(\kappa) + \tilde{P}^{\rm med}_{qq}(\kappa,\mu)\Big)\tilde{D}^{Q,\,{\rm full}}_q(\kappa,\mu)$$

- The charge-weighted Mellin moment of the fragmentation function is obtained using the Mellin moment of the medium-induced splitting kernel
- Jet matching coefficient in matter is evaluated with the help of the medium-induced spitting kernels

$$\begin{aligned}\mathcal{J}^{\rm med}_{qq}(E,R,x,\mu) =\\ &\frac{\alpha_s(\mu)}{2\pi^2}\Bigg[-\delta(1-x)\int_0^1 dz\int_0^\mu \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P^{\rm med}_{q\to qg}(z,\mathbf{k}_\perp)\\ &+\int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P^{\rm med}_{q\to qg}(x,\mathbf{k}_\perp)\Bigg]\\ &=\frac{\alpha_s(\mu)}{2\pi^2}\int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P^{\rm med}_{q\to qg}(x,\mathbf{k}_\perp)\end{aligned}$$

Other heavy ion colliders

LHeC – large hadron electron collider

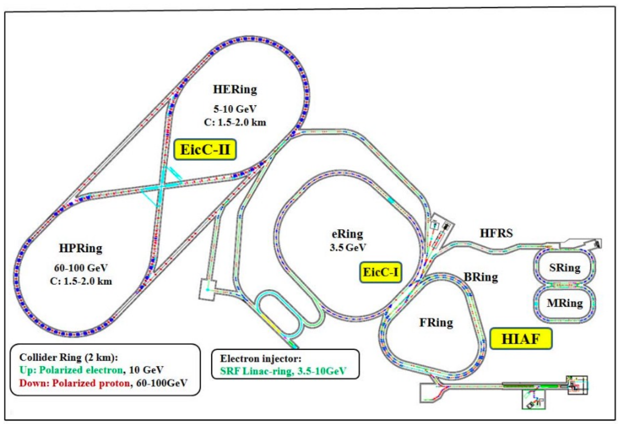


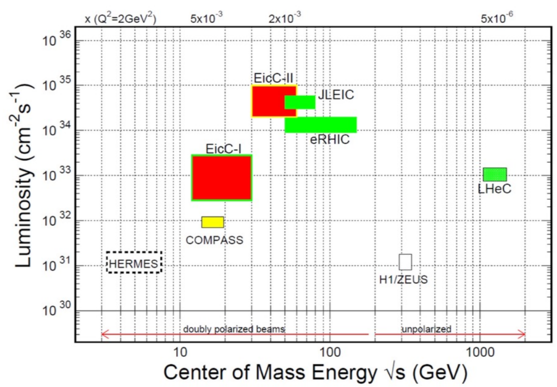
P. Augostini et al., (2020)

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	$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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

EicC - electron ion collider in China

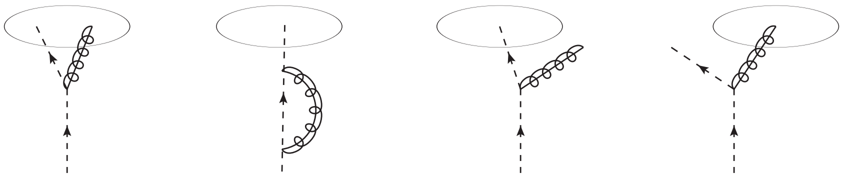




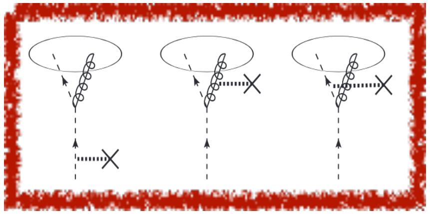
EicC would have ideal C.M. energies to study hadronization and energy loss (I), nuclear effects on jets (II). Limited reach for saturation physics.

X. Chen et al., (2018)

Diagrams that contribute to the SiJF at NLO



Medium contributions to the first diagram



- **The medium contribution to the jet functions can be expressed in terms of the in-medium splitting functions**
- **Included at fixed order - NLO level**
- **Suitable for numerical implementation**

Z. Kang et al. (2017) *H. Li et al. (2021)*

- **Resummation for small-radius jets in vacuum**

$$\frac{d}{d\log\mu^2}\begin{pmatrix}J_S(z,\omega_J,\mu)\\ J_g(z,\omega_J,\mu)\end{pmatrix} = \frac{\alpha_s(\mu)}{2\pi}\begin{pmatrix}P_{qq}(z) & 2N_f P_{gq}(z)\\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\otimes\begin{pmatrix}J_S(z,\omega_J,\mu)\\ J_g(z,\omega_J,\mu)\end{pmatrix}$$

The medium NLO contributions to SiJF

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

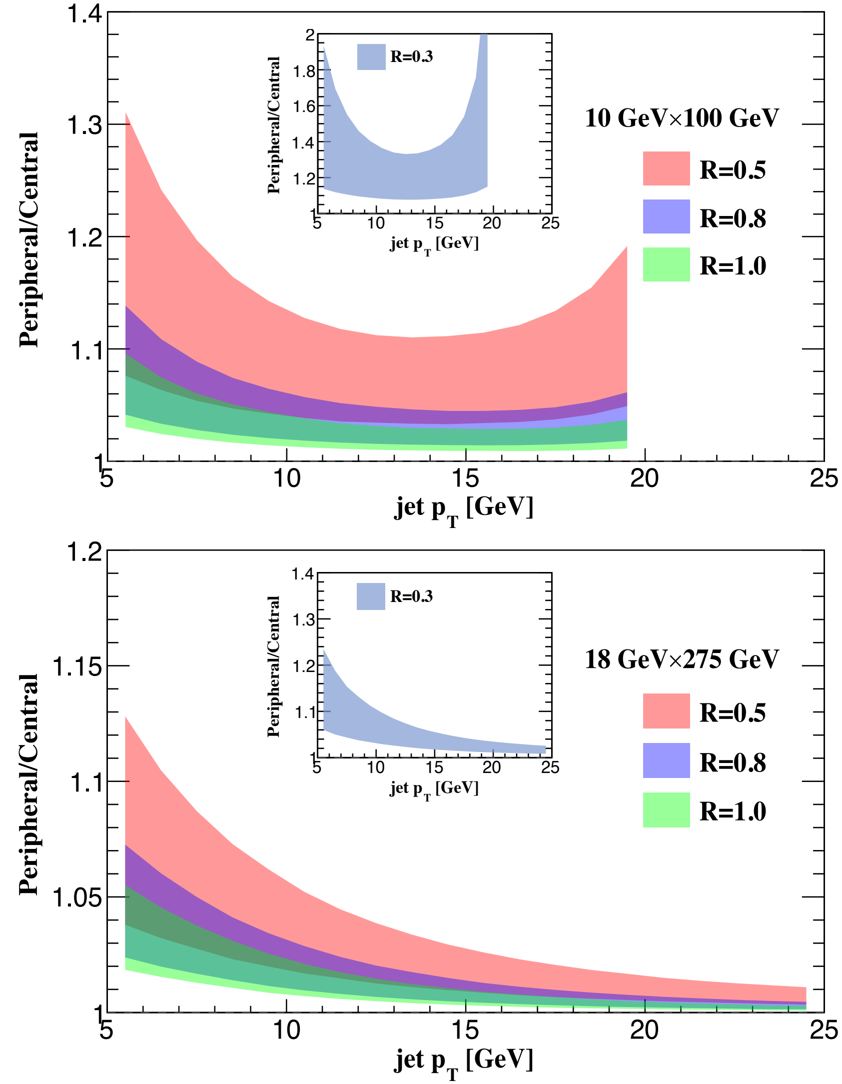
$$\begin{aligned}J_g^{\rm med}(z,p_T R,\mu) = &\left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(z,\mathbf{k}_\perp)\left(\frac{z}{1-z}+z(1-z)\right)\right)\right]_+ \\ &+ n_f\left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{g\to q\bar{q}}(z,\mathbf{k}_\perp)\right]_+ \\ &+ \int_{z(1-z)p_T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

Centrality dependence of jet cross sections

- To quantify the path-length dependence of the per-nucleon jet cross section modification

$$\frac{\text{Peripheral}}{\text{Central}}(J) = \frac{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}\Big|_{eA,\text{Peri.}}}{\frac{1}{\Delta_b T_A(b)} \int_{\eta 1}^{\eta 2} \frac{d\sigma}{d\eta dp_T}\Big|_{eA,\text{Cent.}}}$$

- Enhancement implies less cross section suppression in peripheral vs central collisions
- The difference is proportional to the cross section “quenching” itself
- At small CM energies the differences are few % to 10-20% for the smallest jet radius R=0.3
- At moderate CM energies from 20% to almost a factor of two – differences clearly identified but smaller than the differences in <d>



H. Li et al. (2023)