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Centrality-dependent jet and hadron cross sections in eA reactions at the EIC

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based on ArXiv: 2303.14201

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Outline of the talk

- Centrality in eA reactions
- Parton showers in matter
- Theory and phenomenology of jet production
- Theory and phenomenology of hadron fragmentation
- Conclusions

i) R. Dupre for suggesting the centrality-dependent calculation
ii) P. Zurita for bringing early EMC measurements to our attention
iii) W. Chang and M. Baker on centrality determination in DIS. W. Chang for the effective interaction lengths in eA from BeAGLE
iv) Conveners for the opportunity to present the results

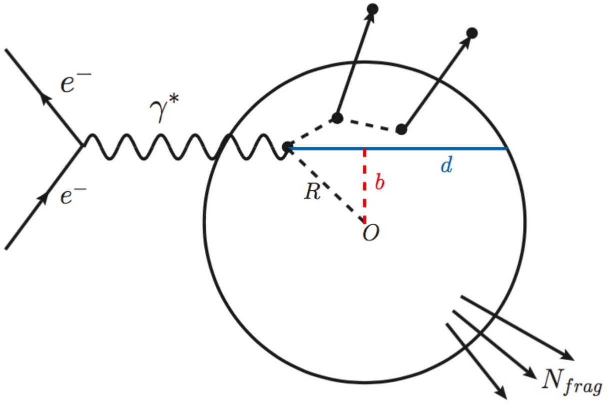
Why centrality?

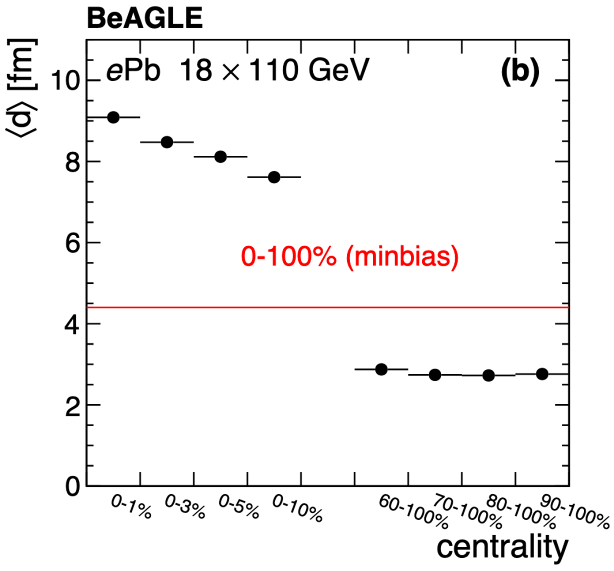
- The goal is to understand QCD in the nuclear environment. Find **corrections to factorization**

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

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

Z. Kang et al. (2016)

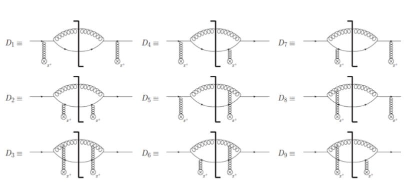




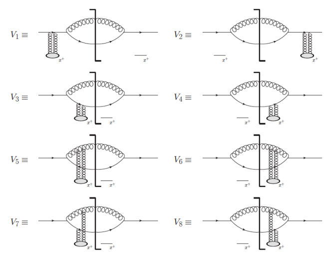
W. Chang et al. (2022)

- 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

EFTs for parton showers in matter



Single Born



Double Born

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

$$A_\perp = k_\perp,\ B_\perp = k_\perp + x q_\perp,\ C_\perp = k_\perp - (1-x) q_\perp,\ D_\perp = k_\perp - q_\perp.$$

$$\Omega_1 - \Omega_2 = \frac{B_\perp^2+\nu^2}{p_0^+ x(1-x)},\ \Omega_1 - \Omega_3 = \frac{C_\perp^2+\nu^2}{p_0^+ x(1-x)},\ \Omega_4 = \frac{A_\perp^2+\nu^2}{p_0^+ x(1-x)},$$

Kinematic variables and mass dependence

$$\begin{aligned} \nu &= m \qquad && (g \to Q\bar{Q}), \\ \nu &= x\, m && (Q \to Qg), \\ \nu &= (1-x)\, m && (Q \to gQ), \end{aligned}$$

- Evaluated using EFT approaches - $\mathrm{SCET}_{\mathrm{G}}$, $\mathrm{SCET}_{\mathrm{M,G}}$
- 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

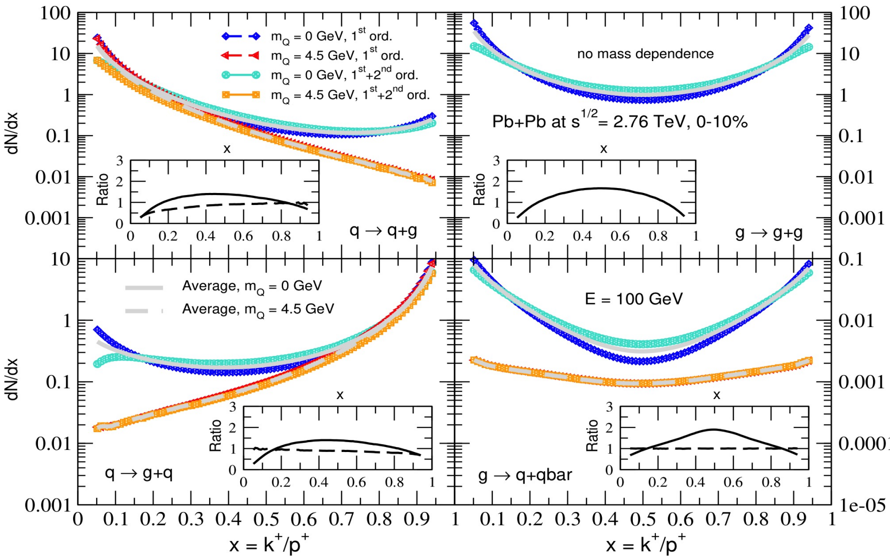
Quark to quark splitting function example

$$\begin{aligned} \left(\frac{dN^{\mathrm{med}}}{dx d^2k_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2 q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\mathrm{med}}}{d^2 q_\perp} \Bigg\{ \left(\frac{1+(1-x)^2}{x}\right) \Bigg[\frac{B_\perp}{B_\perp^2+\nu^2} \\ &\times \left(\frac{B_\perp}{B_\perp^2+\nu^2} - \frac{C_\perp}{C_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{C_\perp}{C_\perp^2+\nu^2} \cdot \left(2\frac{C_\perp}{C_\perp^2+\nu^2} - \frac{A_\perp}{A_\perp^2+\nu^2} \right. \\ &\left. - \frac{B_\perp}{B_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{B_\perp}{B_\perp^2+\nu^2} \cdot \frac{C_\perp}{C_\perp^2+\nu^2} (1-\cos[(\Omega_2-\Omega_3)\Delta z]) \\ &+ \frac{A_\perp}{A_\perp^2+\nu^2} \cdot \left(\frac{D_\perp}{D_\perp^2+\nu^2} - \frac{A_\perp}{A_\perp^2+\nu^2} \right) (1-\cos[\Omega_4 \Delta z]) - \frac{A_\perp}{A_\perp^2+\nu^2} \cdot \frac{D_\perp}{D_\perp^2+\nu^2} (1-\cos[\Omega_5 \Delta z]) \\ &+ \frac{1}{N_c^2} \frac{B_\perp}{B_\perp^2+\nu^2} \cdot \left(\frac{A_\perp}{A_\perp^2+\nu^2} - \frac{B_\perp}{B_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) \Bigg] \\ &+ x^3 m^2 \left[\frac{1}{B_\perp^2+\nu^2} \cdot \left(\frac{1}{B_\perp^2+\nu^2} - \frac{1}{C_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots \right] \Bigg\} \end{aligned}$$

G. Ovanesyan et al. (2011) *Z. Kang et al. (2016)* *M. Sievert et al. (2019)*

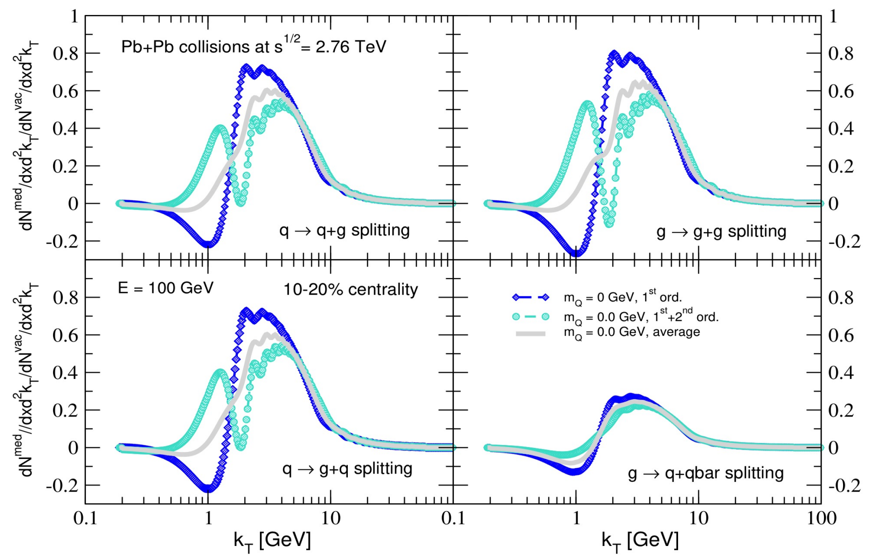
Properties of in-medium showers

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**

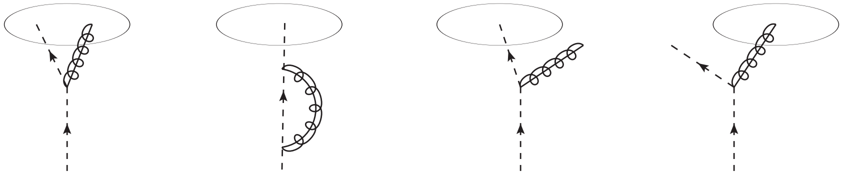
B. Yoon et al. (2019)

Same behavior in cold nuclear matter

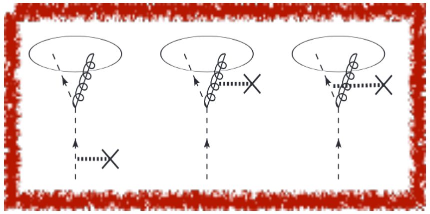
$$2\frac{\mu_D^{\,2}}{\lambda q} = 0.053\frac{GeV^2}{fm} \quad (vary \times 2,/2) \qquad 2\frac{\mu_D^{\,2}}{\lambda g} = 0.12\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$

Final-state in-medium jet cross section modification

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

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

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

Phenomenological results - jets

- **Define nuclear modification**

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

- **Eliminate initial-state effects (to a few %**

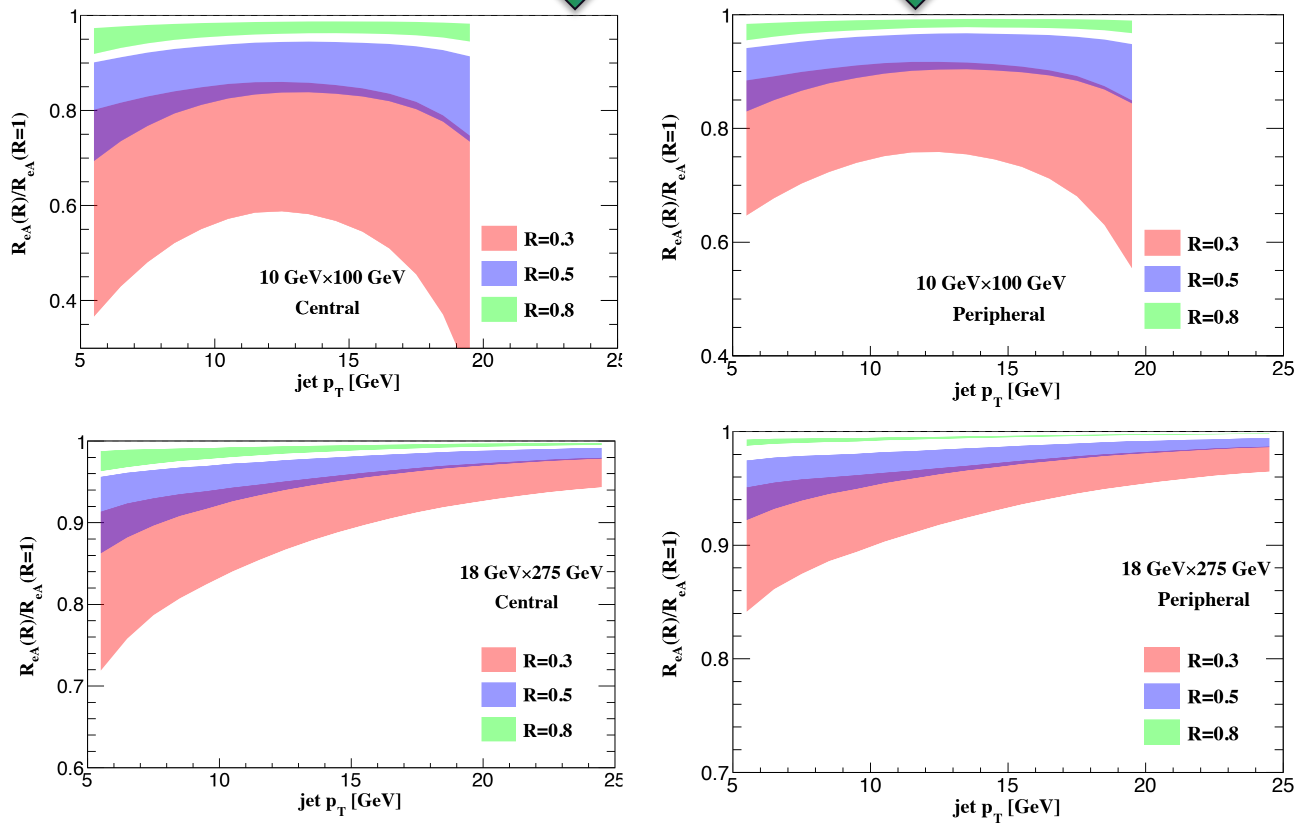
$$R_R = R_{eA}(R)/\, R_{eA}(R=1)$$

H. Li et al. (2021)

- **Larger suppression at smaller C.M. energies. Can reach a factor of two**
- **Pronounced jet radius dependence. Smaller radius jets exhibit the largest suppression**

Selected centrality classes

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
$\langle d \rangle / \langle d \rangle_{\mathrm{min.bias}}$	2.07	1.93	1.73	0.65	0.62	0.62	1.00

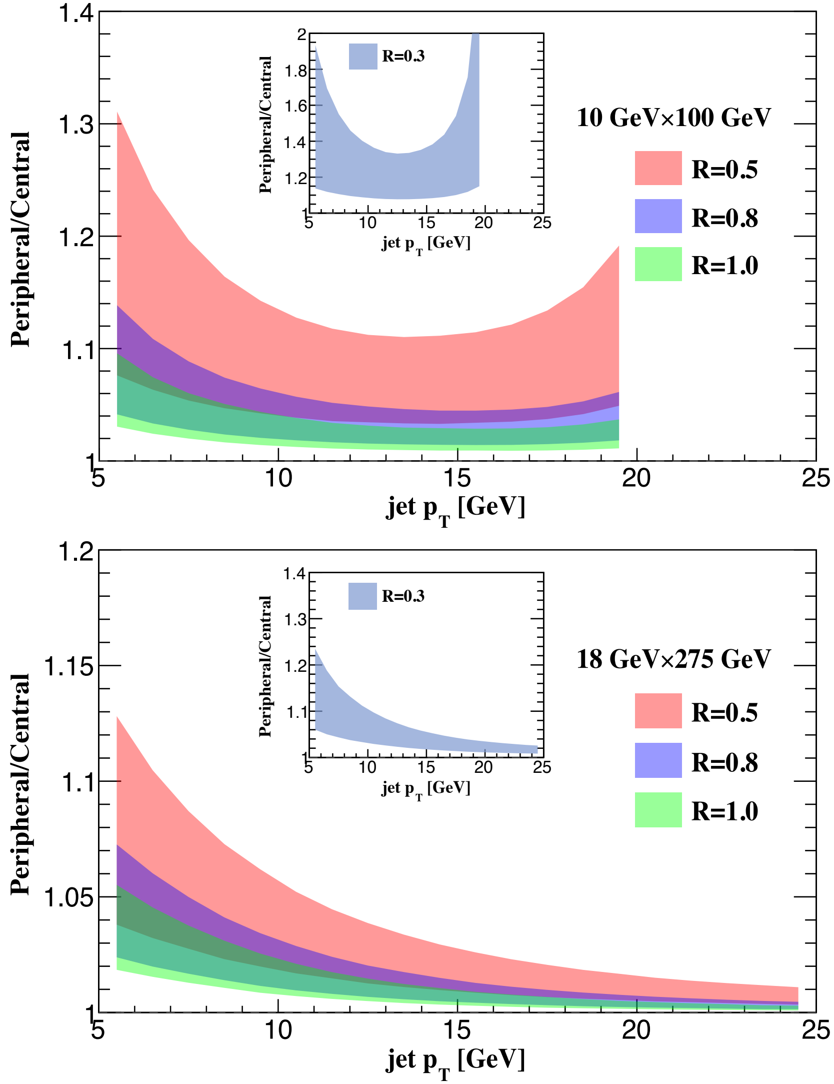


Centrality dependence of jet cross sections

- 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>



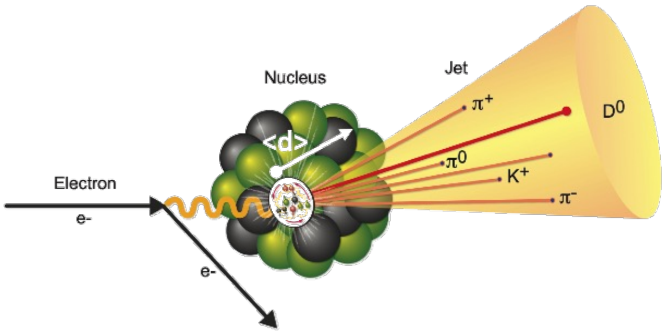
H. Li et al. (2023)

In-medium evolution of fragmentation functions

- **Medium-induced splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs**

N. Chang et al. (2014)

Z. Kang et al. (2014)

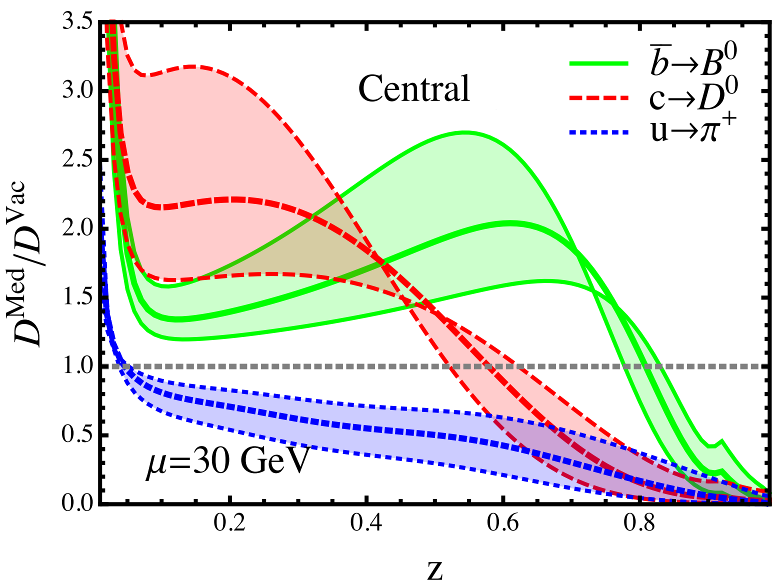


$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

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

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

- **Enhancement at small z but for pions (light hadrons) at very small values – mostly suppression**
- **Very pronounced differences between light and heavy flavor fragmentation.**
- **Related to the shape of fragmentation functions**



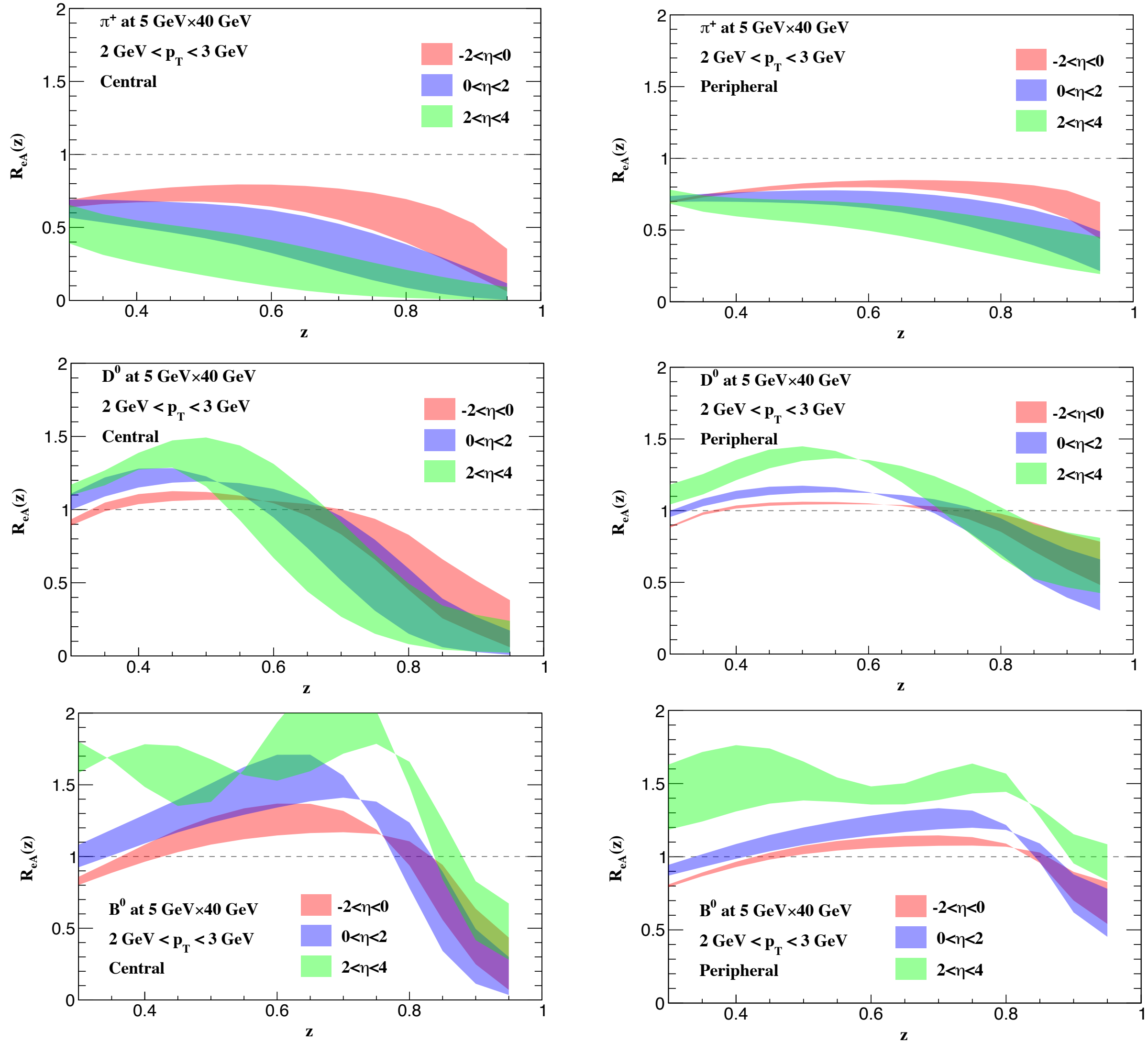
H. Li et al. (2020)

Phenomenological results - hadrons

- Differential hadronization cross sections **normalized** by the cross section for R=1 jet

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

- Modifications to hadronization **grow form backward to forward** rapidity
- Transition from **enhancement to suppression for heavy flavor**
- Larger effects than for inclusive jets



Central

Peripheral

Centrality dependence of hadron cross sections

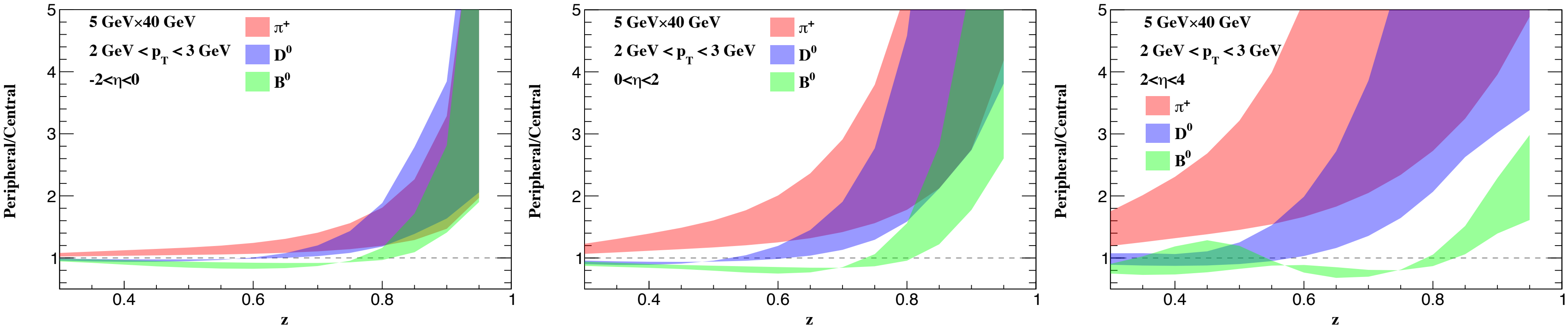
- Similar to jets - quantify the path-length dependence of the per-nucleon jet cross section modification

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

- 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



Analytic insight and comparison to RG evolution

- In numerically evaluated splitting functions the non-perturbative scale in the medium regulates endpoint divergences
- We can isolate explicitly divergences and in the limit that medium effects are localized in finite parts of phase space

For simplicity: fixed coupling, focus on the soft gluon emission region

- Resums matter-induced logarithms of the type $\ln[E/(L\mu_D^2)]$

- Directly comparable to renormalization group analysis results

See talk by Weiyao Ke later in this session

Parton shower approach – distribution of quark and gluon energies relative to the E transfer

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

$$\frac{\partial F_{\rm NS}}{\partial \ln \mu^2} = 4C_F C_A A_0 \int_0^{1-\frac{\mu_D^2}{\mu^2}} \frac{4}{\pi}\frac{\Phi(u)}{u} \frac{\frac{x}{z}F_{\rm NS}(\frac{z}{x}) - \frac{F_{\rm NS}(z)}{z}}{(1-x)^2} dx$$

$$\approx \frac{4}{\pi}\frac{\Phi(u)}{u} 4C_F C_A A_0 \left[\frac{\partial F_{\rm NS}}{\partial z} - \frac{F_{\rm NS}}{z}\right] \ln \frac{\mu^2}{\mu_D^2}$$

$$\approx \delta\left(\mu^2 - \frac{2\pi E}{L}\right) 4C_F C_A A_0 \left[\frac{\partial F_{\rm NS}}{\partial z} - \frac{F_{\rm NS}}{z}\right] \ln \frac{\mu^2}{\mu_D^2}$$

A traveling wave solution

$$F_{NS}^{+}(z) = \frac{F_{NS}^{-}(z + 4C_F C_A \tau_{\rm fix})}{1 + 4C_F C_A \tau_{\rm fix}/z}$$

$$\tau_{\rm fix} = A_0 \ln \frac{2\pi E}{\mu_D^2 L} \qquad A(\mu_2^2, E, w_{\rm max}) = \alpha_s^2(\mu_2^2) L^2 B(w_{\rm max}) \rho_G/(8E)$$

W. Ke et al., (2023)

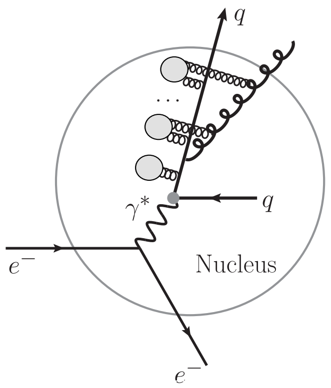
Conclusions

- The ability to determine centrality in eA collisions will open new possibilities to study QCD in cold nuclear matter
- Focused on final state interactions and path-length dependence of in-medium parton showers. Useful to differentiate between theoretical models of in-medium effects
- Calculated the modification to jet and hadron cross sections in eA relative to ep. Showed that the centrality dependence is very significant for differential hadron distributions. It is still there, but more subtle for inclusive jets
- A new analytic understanding of the properties of parton showers in matter has emerged, the types or logarithms that are being resummed by in-medium DGLAP, and connection to RG analysis

Thank you

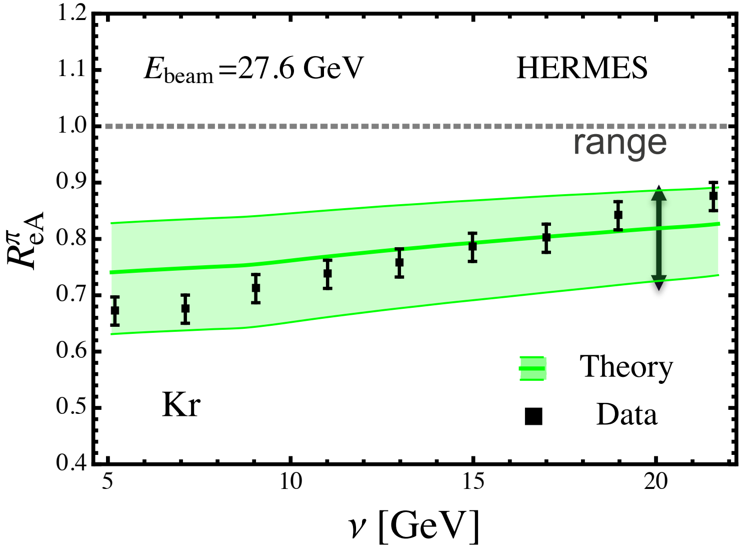
Modification of light hadrons at HERMES

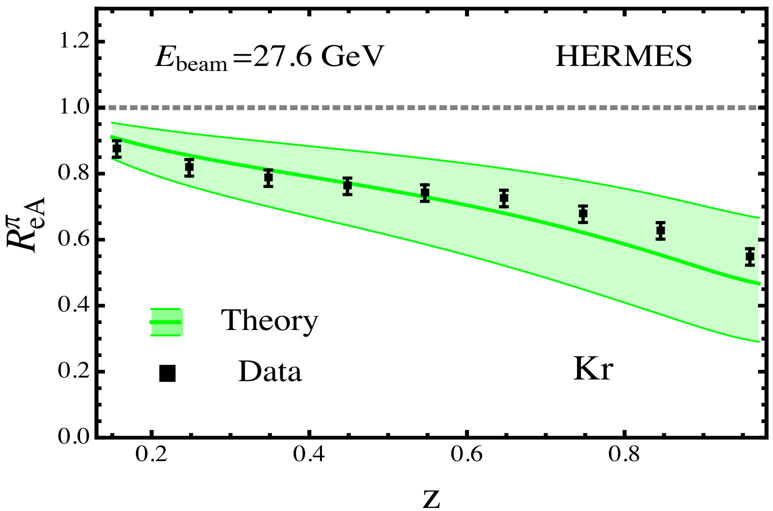
- **Account for nuclear geometry, i.e. the production point and the path length of propagation of the hard parton in minimum bias collisions**



Normalization by an inclusive process is useful

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





Goal is to get generous band to allow for reasonable projections for EIC

CNM transport properties for numerics

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

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