LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Forward Physics Facility Theory Workshop
CERN, September 18-19, 2023

Hadronic Physics in Neutrino Interactions and Complementarities to the EIC

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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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U.S. DEPARTMENT OF ENERGY

September 19, 2023

NNSA
National Nuclear Security Administration

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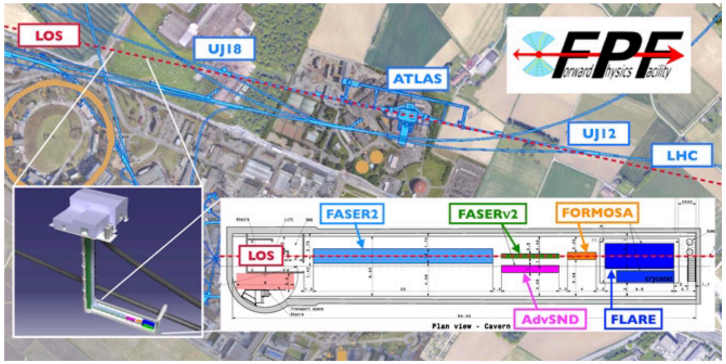
Outline of the talk

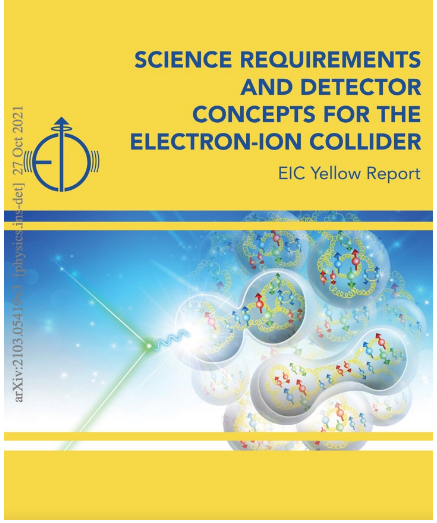
I will tell you about the physics and you decide what is relevant to FPF

- **Dynamical shadowing effects in neutrino-nucleus interactions**
- **In-medium DGLAP and renormalization group analysis of modifications to hadronization**
- **Jets and separation of initial-state and final-state effects**
- **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



For more information on the EIC



SCIENCE REQUIREMENTS
AND DETECTOR
CONCEPTS FOR THE
ELECTRON-ION COLLIDER
EIC Yellow Report

arXiv:2103.05419v3 [physics.ins-det] 27 Oct 2021

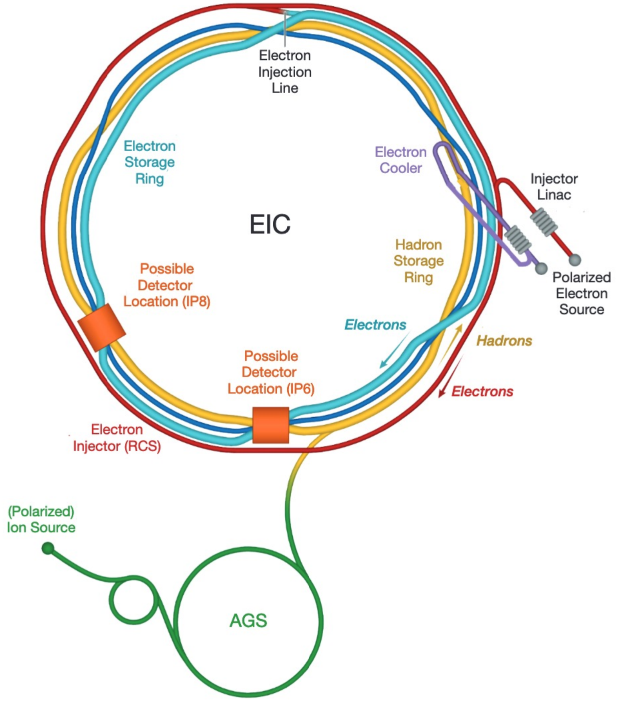
R. Abdul-Khalek et al. (2021)

A FPF newcomer's perspective

I learned a lot from yesterday's talks. As a newcomer I apologize for any misinterpretation

- **For most of this talk (final-state physics) the differences between electron-proton/nucleus and neutrino-proton/nucleus reactions won't matter**
- **Coupling constants, CKM matrix elements, W boson mass affect the hard part/overall normalization**

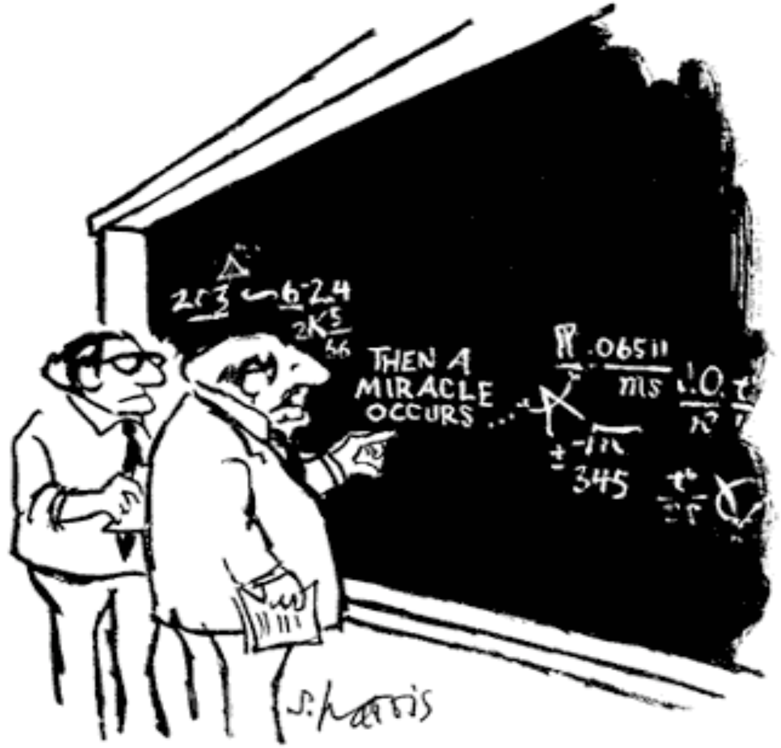
Depending who you ask (collinear NLO vs k_T factorization, neutrino flavor) energy normalized cross sections peak at ~ 2 TeV. Assume that broad distribution (x1/4, x4). CM energy ~ 60 GeV (x1/2, x2) **Ideal complementarity to the EIC**



The future EIC

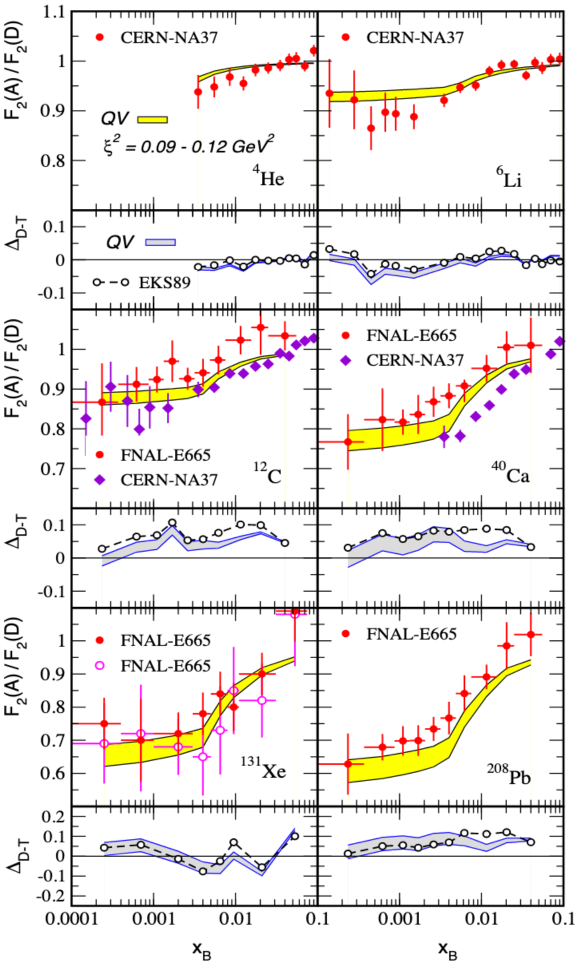
Variable e+p center-of-mass energies from 20−100 GeV, upgradable to 140 GeV

Inclusive DIS



"I think you should be more explicit here in step two."

A quick remark on inclusive νA



J. Qiu et al. (2003), (2004)

- **The physical origin of shadowing effects remains an open question**
- **We have calculated and resummed higher twist corrections in the structure functions for small-x**
- **Physics interpretation – generation of dynamical parton mass in the background gluon field of the nucleon/nucleus**

$$x_M = \frac{M^2}{2p\cdot q} = x_B \frac{M^2}{Q^2} \qquad x_{\rm HT} = x_B \frac{\xi^2}{Q^2}(A^{1/3}-1)$$

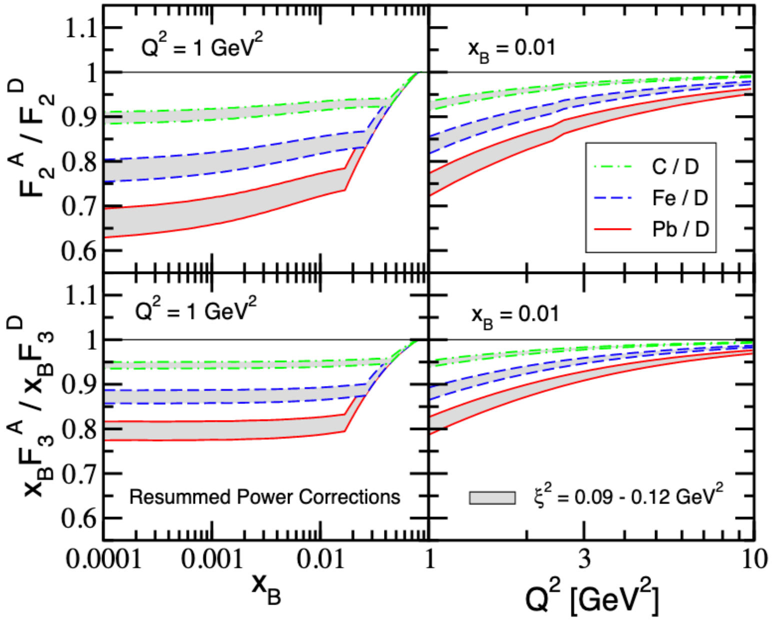
$$\frac{1}{A}F_{1,3}^{\nu A}(x_B,Q^2) \approx \{2\}\left(\sum_{D,U}|V_{DU}|^2\phi_D^A\left(x_B+x_{\rm HT}+x_{M_U},Q^2\right) \pm \sum_{\bar U,\bar D}|V_{\bar U\bar D}|^2\phi_{\bar U}^A\left(x_B+x_{\rm HT}+x_{M_{\bar D}},Q^2\right)\right)$$

$$\frac{1}{A}F_{1,3}^{\bar\nu A}(x_B,Q^2) \approx \{2\}\left(\sum_{U,D}|V_{UD}|^2\phi_U^A\left(x_B+x_{\rm HT}+x_{M_D},Q^2\right) \pm \sum_{\bar D,\bar U}|V_{\bar D\bar U}|^2\phi_{\bar D}^A\left(x_B+x_{\rm HT}+x_{M_{\bar U}},Q^2\right)\right)$$

$$\begin{aligned}\frac{1}{A}F_L^{\nu A}(x_B,Q^2) &\approx F_L^{(\rm LT)}(x_B,Q^2) + \sum_{D,U}|V_{DU}|^2\left[\frac{M_U^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_U^2}{Q^2+M_U^2}\right)^2\right]\phi_D^A\left(x_B+x_{\rm HT}+x_{M_U},Q^2\right)\\ &+ \sum_{\bar U,\bar D}|V_{\bar U\bar D}|^2\left[\frac{M_{\bar D}^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_{\bar D}^2}{Q^2+M_{\bar D}^2}\right)^2\right]\phi_{\bar U}^A\left(x_B+x_{\rm HT}+x_{M_{\bar D}},Q^2\right)\ ,\\ \frac{1}{A}F_L^{\bar\nu A}(x_B,Q^2) &\approx F_L^{(\rm LT)}(x,Q^2) + \sum_{U,D}|V_{UD}|^2\left[\frac{M_D^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_D^2}{Q^2+M_D^2}\right)^2\right]\phi_U^A\left(x_B+x_{\rm HT}+x_{M_D},Q^2\right)\\ &+ \sum_{\bar D,\bar U}|V_{\bar D\bar U}|^2\left[\frac{M_{\bar U}^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_{\bar U}^2}{Q^2+M_{\bar U}^2}\right)^2\right]\phi_{\bar D}^A\left(x_B+x_{\rm HT}+x_{M_{\bar U}},Q^2\right)\ .\end{aligned}$$

Areas of interest in νA at the FPF

- **Hierarchy in F_2 and F_3 dynamical shadowing**



$$R^{A/A'}_{sea/val.}(x_B,Q^2) = \frac{F_2^A(x_B,Q^2)}{F_2^{A'}(x_B,Q^2)} \Bigg/ \frac{F_3^A(x_B,Q^2)}{F_3^{A'}(x_B,Q^2)}$$

$$= 1 - (\alpha_{sea} - \alpha_{val.})(A^{1/3} - A'^{1/3})\xi^2/Q^2 + \cdots$$

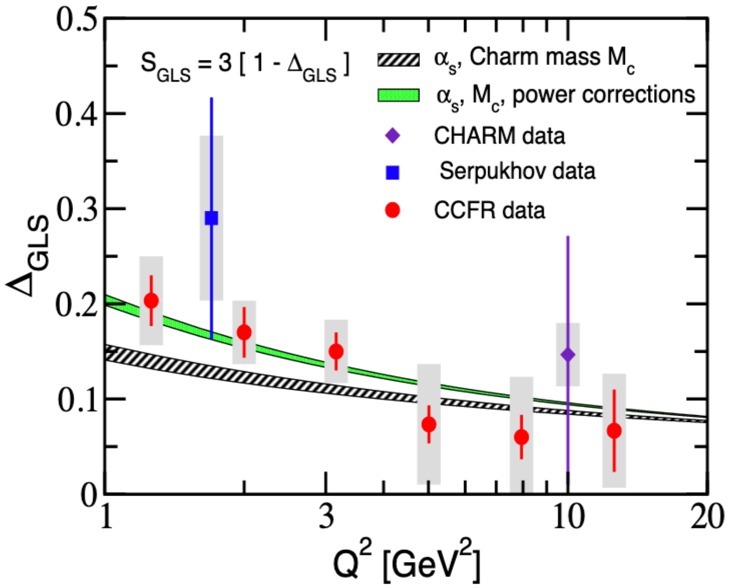
J. Qiu et al. (2004)

- **Gross-Llewellyn Smith (GLS) sum rule**

$$S_{\rm GLS} = \int_0^1 dx_B \, \frac{1}{2x_B} \left(x_B F_3^{\nu A} + x_B F_3^{\bar{\nu} A}\right)$$

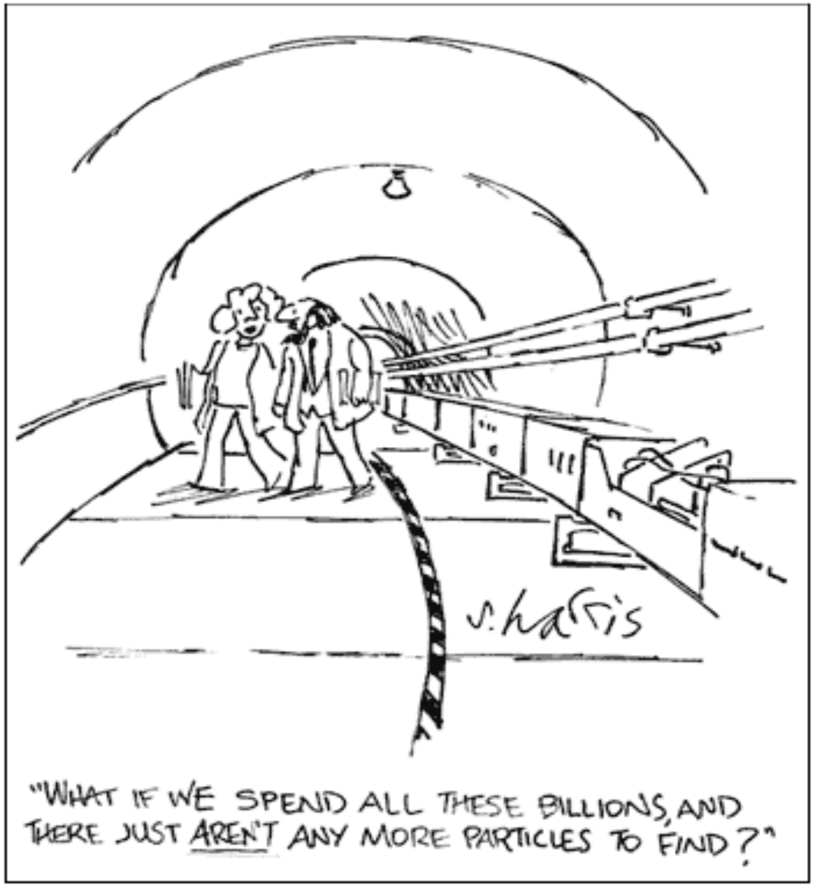
At tree level counts the number of valance quarks

$$\Delta_{\rm GLS} \equiv \frac{1}{3}(3 - S_{\rm GLS}) = \frac{\alpha_s(Q^2)}{\pi} + \frac{\mathcal{G}}{Q^2} + \mathcal{O}(Q^{-4})$$



- **Inclusion of high twist effects as boundary conditions for evolution**

Hadronic final states

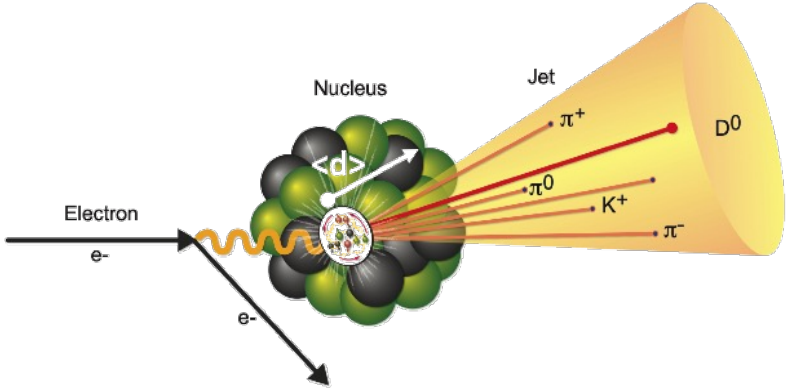


Hadronic physics in lepton-nucleon/nucleus scattering

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

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

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



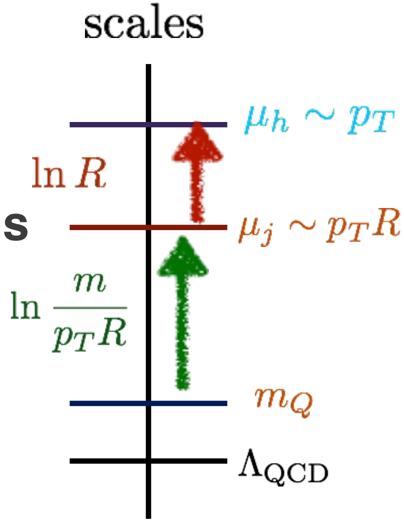
Z. Kang et al. (2016)

- **New theoretical approach using semi-inclusive jet functions**

The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu)\end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1\frac{dz}{z}\begin{pmatrix} P_{qq}(z) & 2P_{gq}(z) \\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu)\end{pmatrix}$$

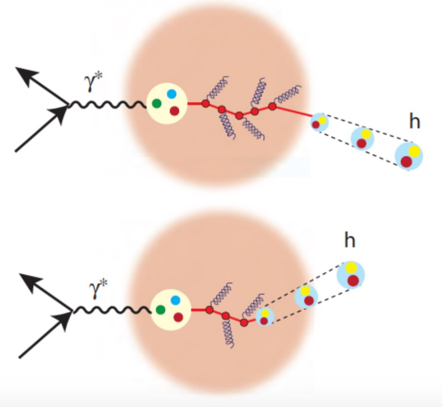
$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar{Q}}(p_T R, m) = 2\sum_{l=g,Q}\bar{K}_{l/g}(p_T R, m,\mu_F)\bar{D}_{Q/l}(m,\mu_F)$$



L. Dai et al. (2016), (2018)

Open questions about hadronization

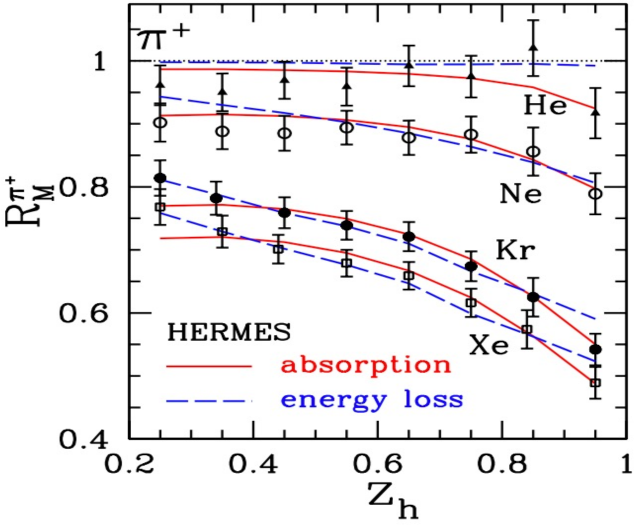
- **Open questions about the nature of hadronization – independent fragmentation, string fragmentation, cluster hadronization**
- **The space-time picture of hadronization is unknown, but critical for e+A**
- **Competing physics explanations of HERMES hadron suppression data based on energy loss and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



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

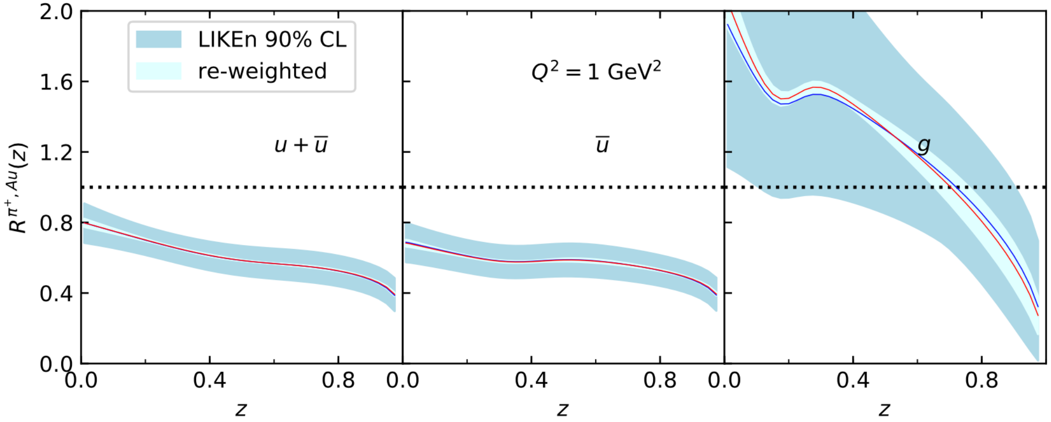
Light hadron measurements cannot differentiate between competing mechanisms

A. Accardi et al. (2009)

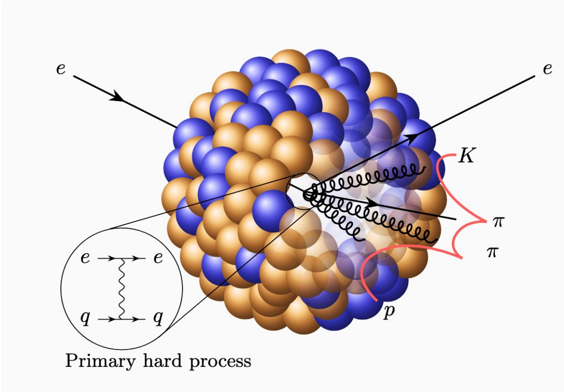


Ideas to parametrize nFFs assuming universality

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



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

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

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

In-medium evolution of fragmentation functions

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

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

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

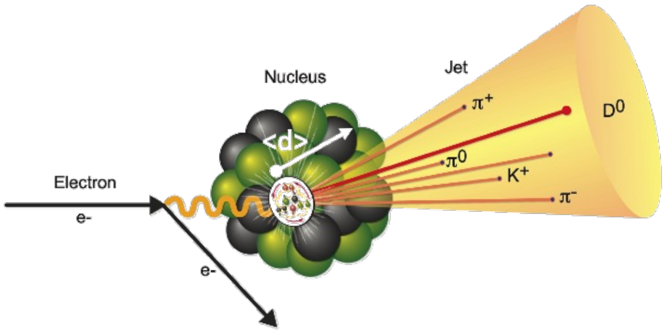
$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right.$$

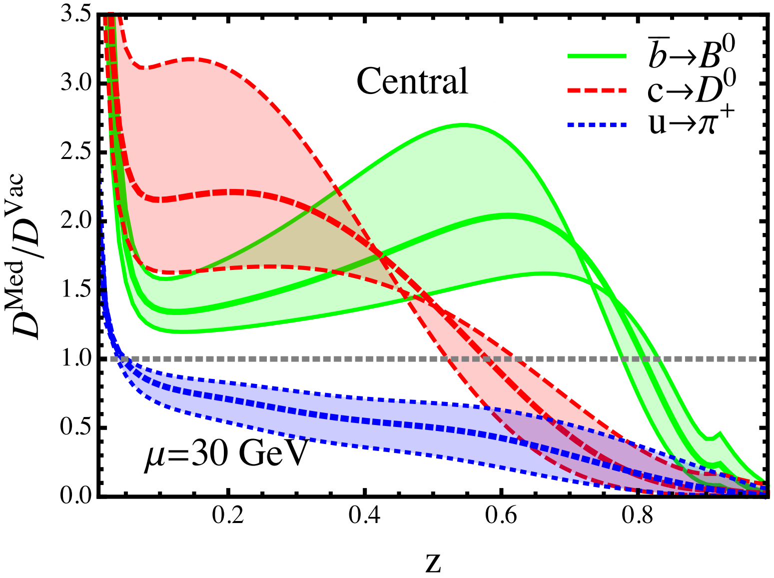
$$\left. + P_{g\to q\bar{q}}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + f_{\bar{q}}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

- **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**

N. Chang et al. (2014)

Z. Kang et al. (2014)





H. Li et al. (2020)

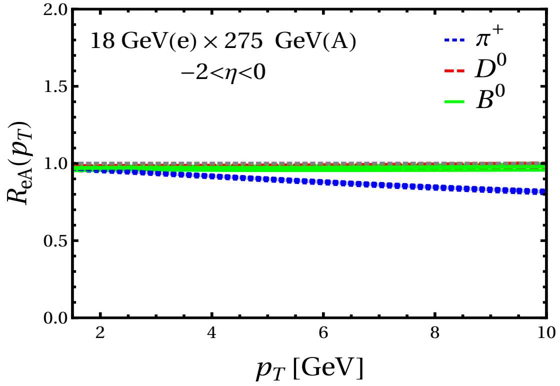
Phenomenological results - hadrons

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

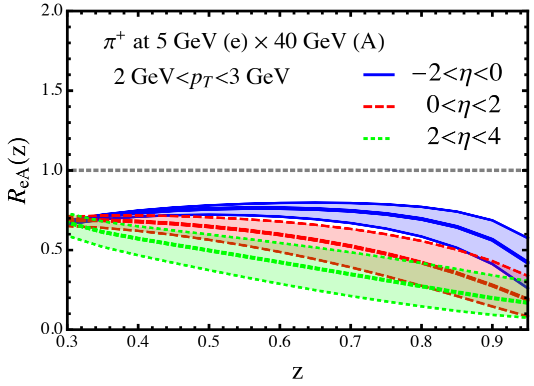
$$R^h_{eA}(z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{eA}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{ep}}$$

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

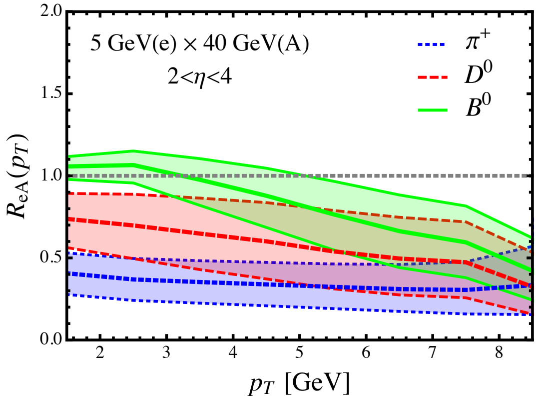
Backward rapidity, large C.M. energy



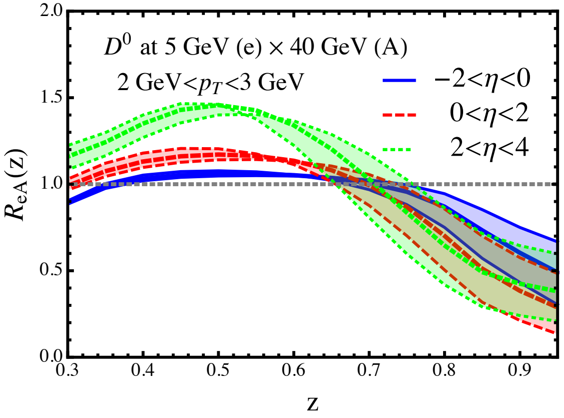
Light pions



Forward rapidity, small C.M. energy



Heavy flavor



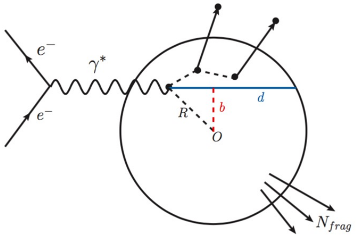
Differential in p_T

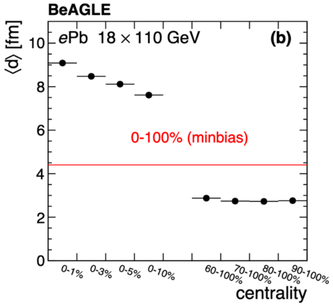
Differential in p_T and z

Centrality dependence of hadron cross sections

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

H. Li et al. (2023)



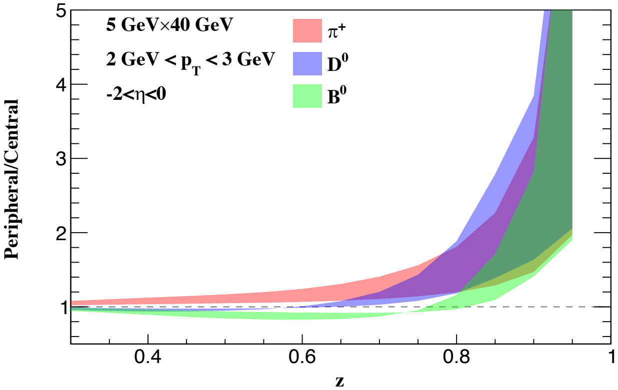


W. Chang et al. (2022)

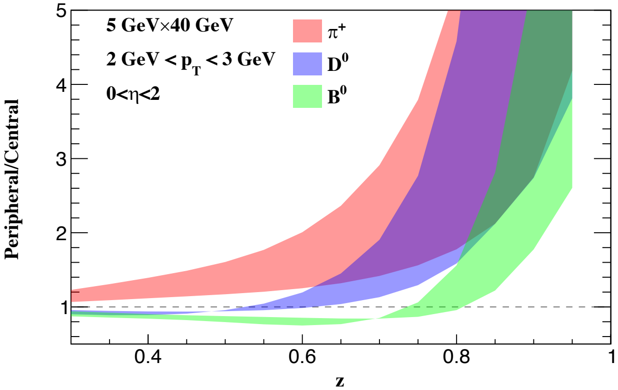
$$\frac{\text{Peripheral}}{\text{Central}}(h) = \frac{R^h_{eA}(z)|_{\text{eA,Peri.}}}{R^h_{eA}(z)|_{\text{eA,Cent.}}}$$

- 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

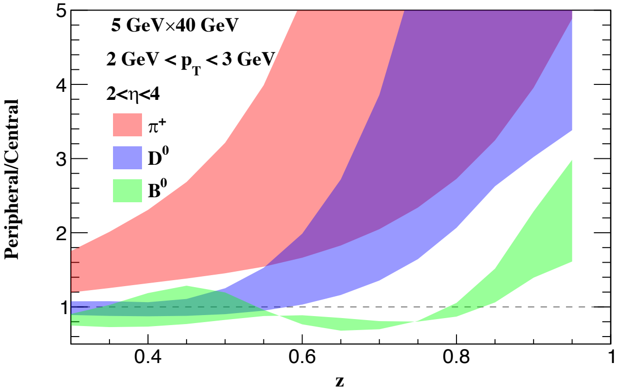
Backward rapidity



Near mid rapidity

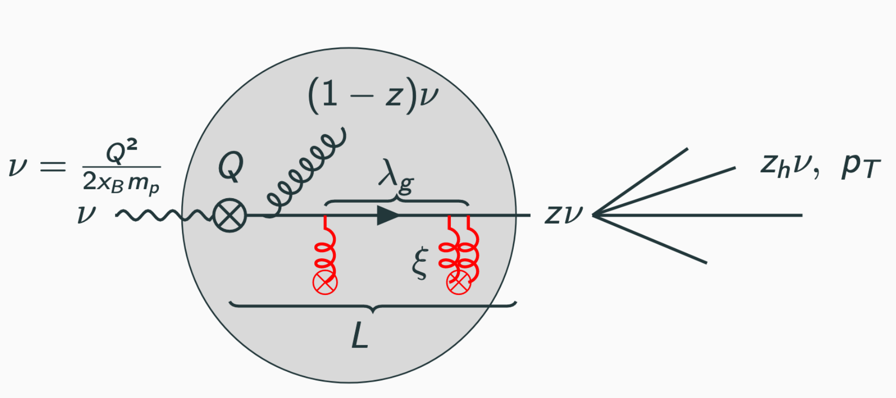


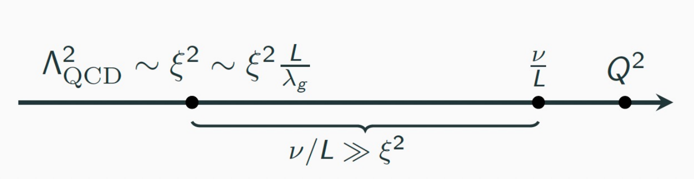
Forward rapidity



Scales in the in-medium parton shower problem

In-medium DGLAP does not tell us what kind of large logs are being resummed





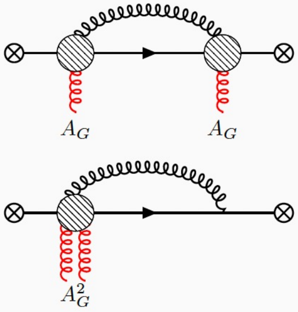
- **We encounter many ratios of scales in DIS on nuclei**
- **Will resum large logarithms of Q/Qo and E/ξ^2L**

- **Consider differential hadron production in ep and eA**

W. Ke et al. (2023)

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

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



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

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

Emergent analytic understanding of the in-medium shower

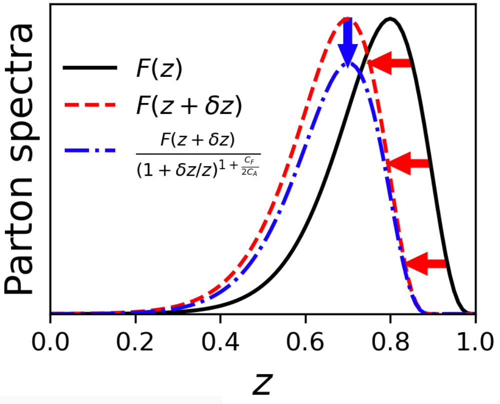
- **We were able to identify a simple analytic limit of the splitting functions integrate the transverse degrees of freedom using dim. reg. and isolate the endpoint divergences**

Color non-singlet distribution as an example

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

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

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



$$\Delta F_{\rm NS}(z) = A(\alpha_s, \cdots) \left(\frac{1}{2\epsilon} + \ln \frac{\mu^2 L}{\chi z \nu} \right) 2C_F [\underbrace{2C_A \left(-\frac{d}{dz} + \frac{1}{z} \right)}_{\text{from } x\to1} + \underbrace{\frac{C_F}{z}}_{x\to0}] F_{\rm NS}(z) + \text{F.O.}$$

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

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

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

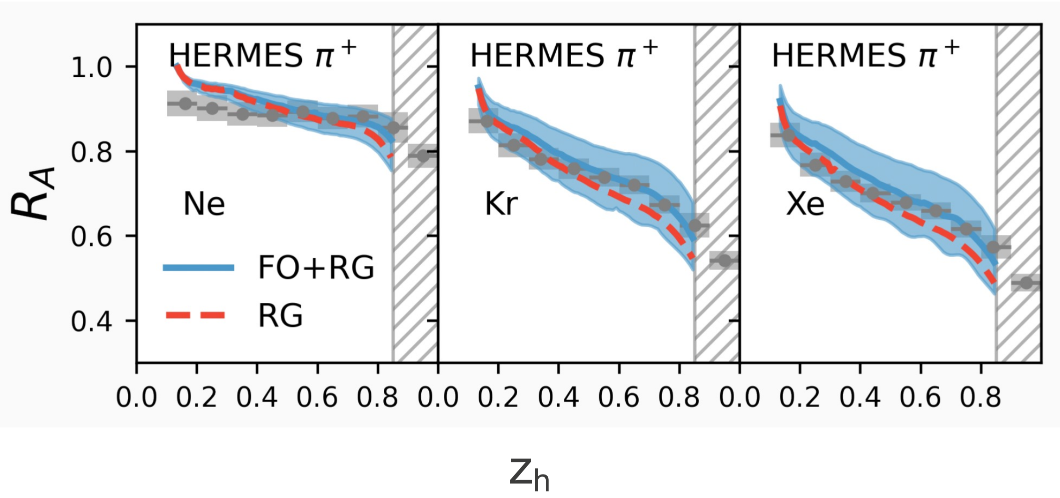
$$\frac{\partial F_g}{\partial \tau} = \left(4C_A^2 \frac{\partial}{\partial z} - \frac{2N_f C_F}{z} \right) F_g + 2C_F^2 \sum_f \frac{F_f}{z}.$$

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

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

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

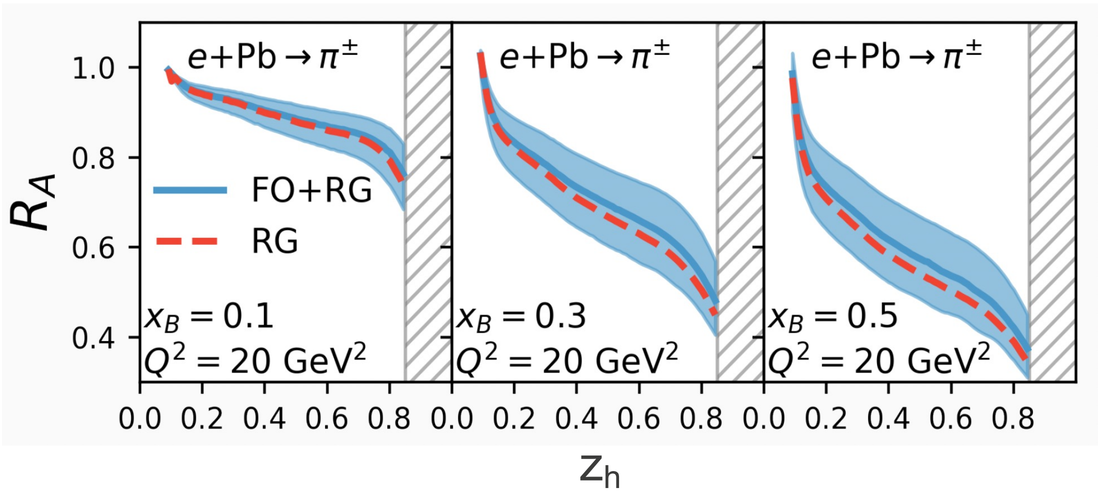
$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

- **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**

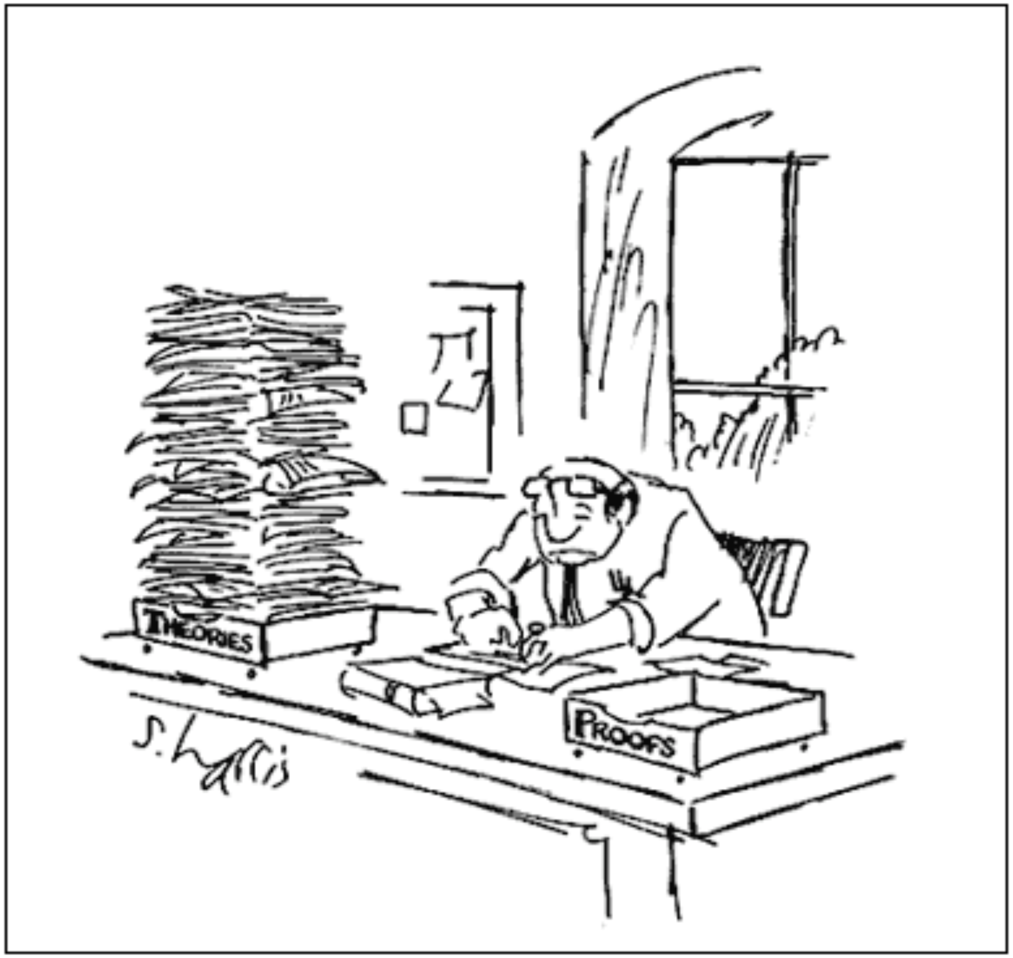
W. Ke et al. (2023)

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**

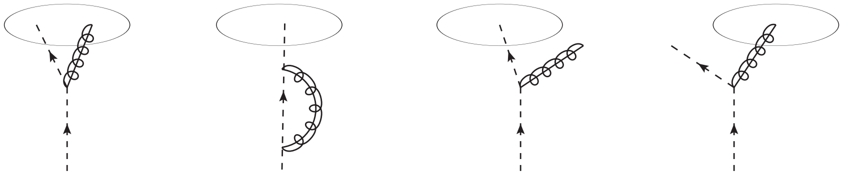


Jets and jet substructure

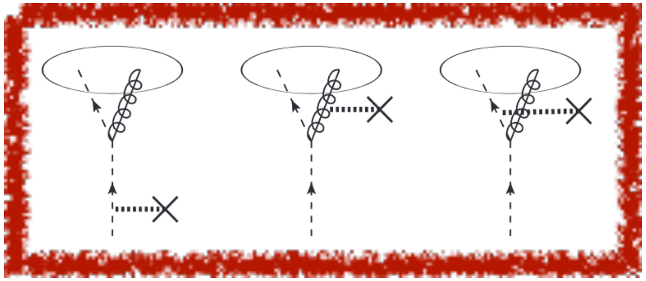


Final-state in-medium jet cross section modification

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

The medium NLO contributions to SiJF

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

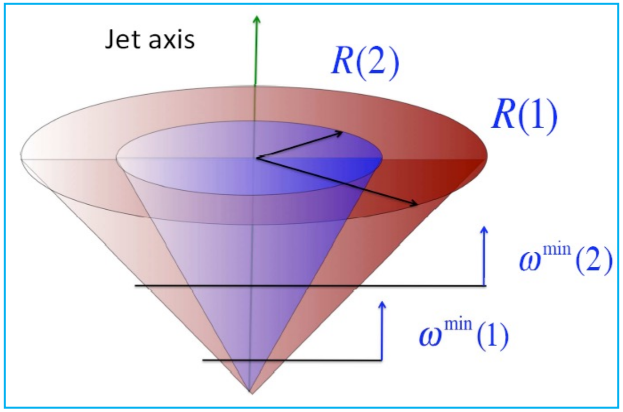
$$\begin{aligned}J_g^{\rm med}\left(z,p_TR,\mu\right)=&\left[\int_{z(1-z)p_TR}^{\mu}d^2\mathbf{k}_\perp\left(h_{gg}\left(z,\mathbf{k}_\perp\right)\left(\frac{z}{1-z}+z(1-z)\right)\right)\right]_+\\&+n_f\left[\int_{z(1-z)p_TR}^{\mu}d^2\mathbf{k}_\perp f_{g\to q\bar{q}}\left(z,\mathbf{k}_\perp\right)\right]_+\\&+\int_{z(1-z)p_TR}^{\mu}d^2\mathbf{k}_\perp\left(h_{g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

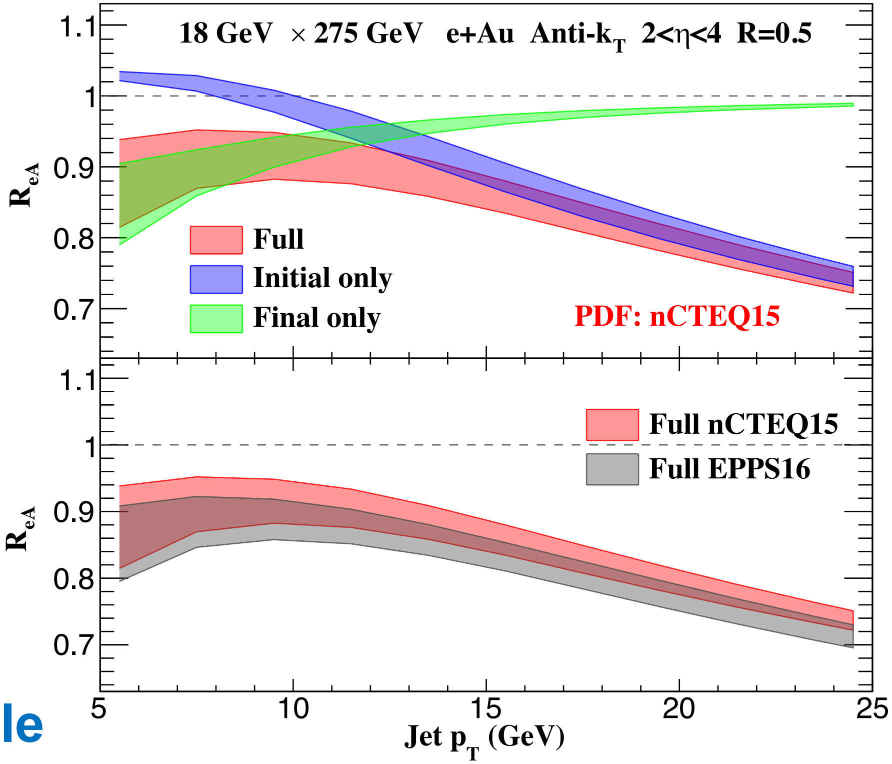
Z. Kang et al. (2017) *H. Li et al. (2021)*

Jet results at the EIC

- The physics of reconstructed jet modification

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





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

H. Li et al., (2020)

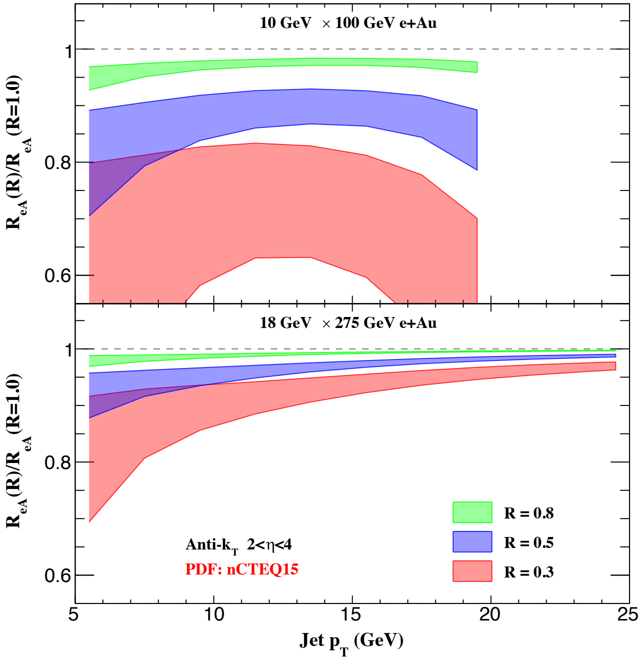
Separating initial-state and final-state effects with jets in DIS

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)

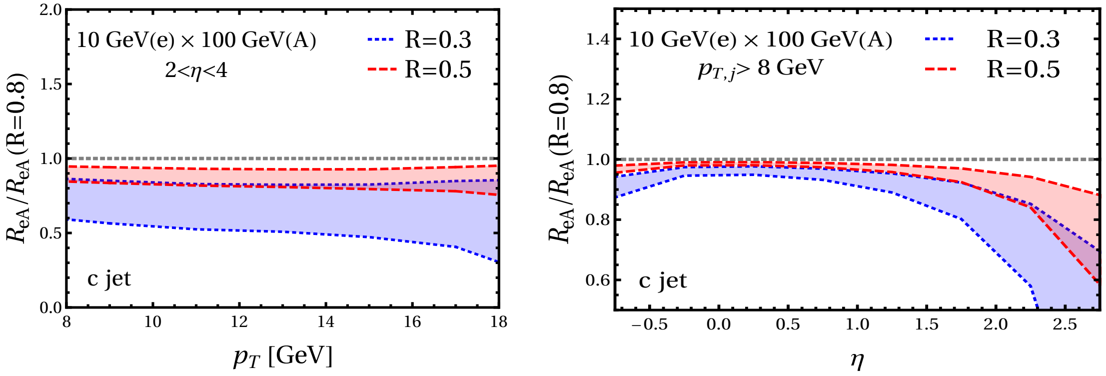
$$R_R = R_{eA}(R)/\ R_{eA}(R=1)$$

- 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)



Initial-state effects are successfully eliminated

H. Li et al., (2020)



The suppression is similarly large for heavy flavor jets

H. Li et al., (2021)

The jet charge in ep/pp and eA/AA

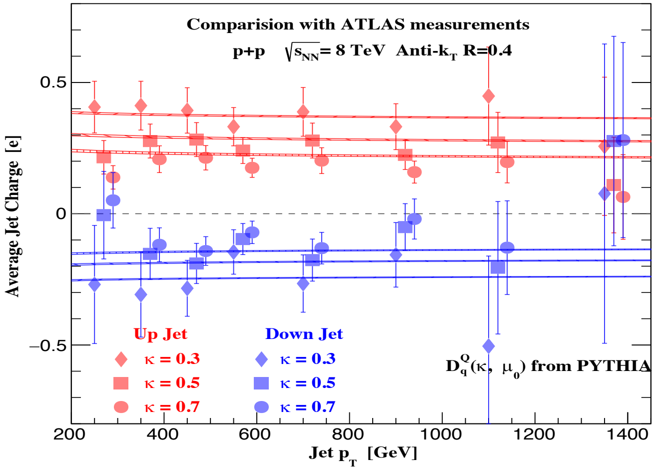
Definition

R. Field et al., (1978)

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

D. Krohn et al., (2012)

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

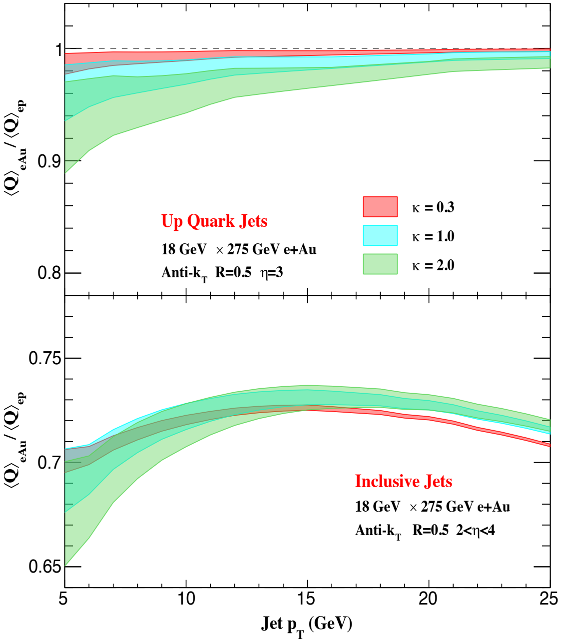


H. Li et al., (2019)

- 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 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

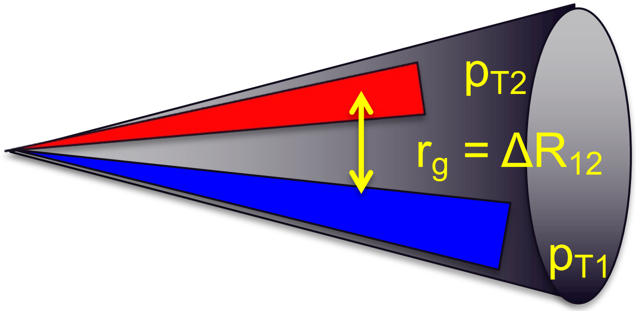


H. Li et al., (2020)

Jet momentum sharing distributions

Soft dropped momentum sharing distributions

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



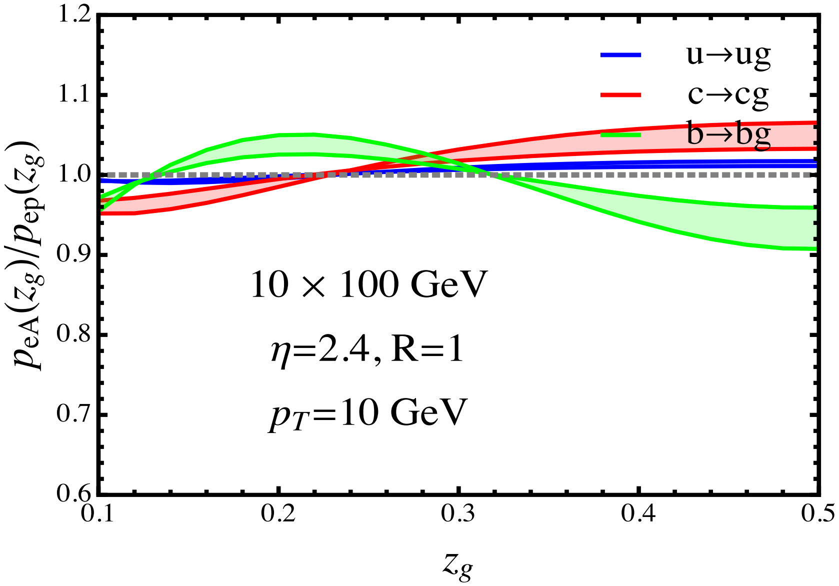
There is a contribution from the medium. The softer in-medium branching was observed in HIC!

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

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

H. Li et al., (2018)

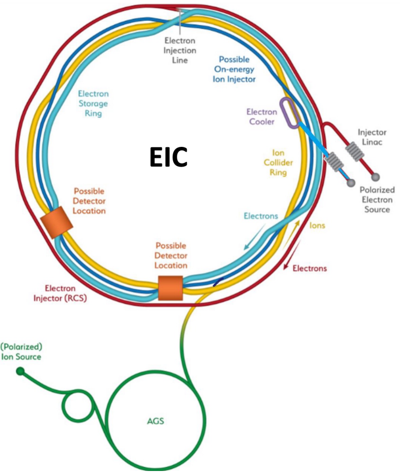
$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz\, d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov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

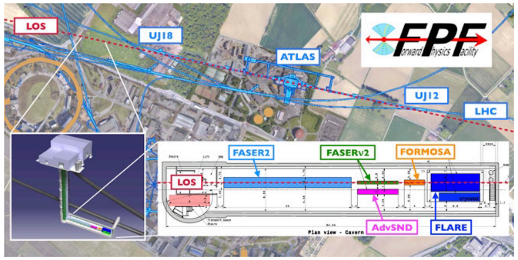


- **Modification of both c-jets and b-jets substructure in eA is relatively small**
- **It is dominated by limited phase space**

Conclusions

- There is great complementarity between FPF and EIC
- In neutrino-nucleus DIS there is opportunity to better understand the physics behind shadowing, sum rules and structure functions
- FPF and EIC, especially with an ν(e)A program can answer fundamental questions about hadronization, many-body QCD, transport properties of matter, the effects of heavy quark mass on parton showers
- There are opportunities for new QCD theory developments, observables and techniques





How much of this physics program can be implemented at FPF will depend on detector capabilities. Still I hope I have given you ideas how one can expand and strengthen the case for FPF

Thank you

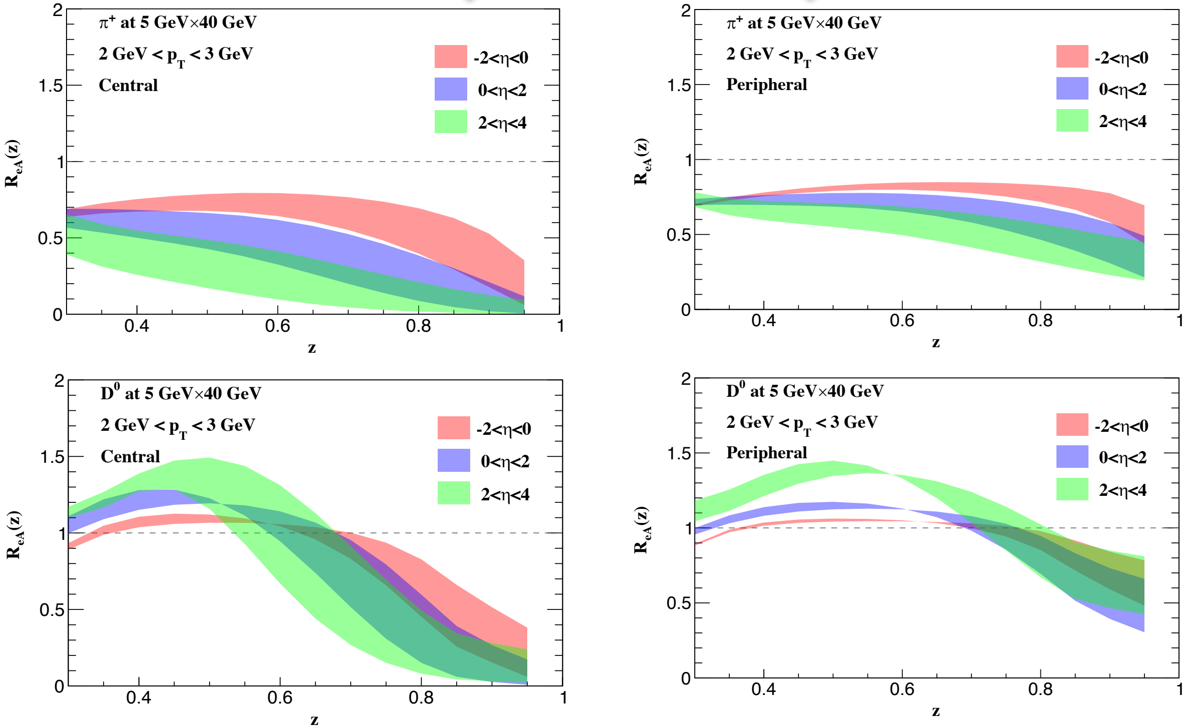
Phenomenological results – light and heavy mesons and hadronization

The observable (normalized by a large radius 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**
- **Modifications to hadronization for light and heavy mesons is very different**

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

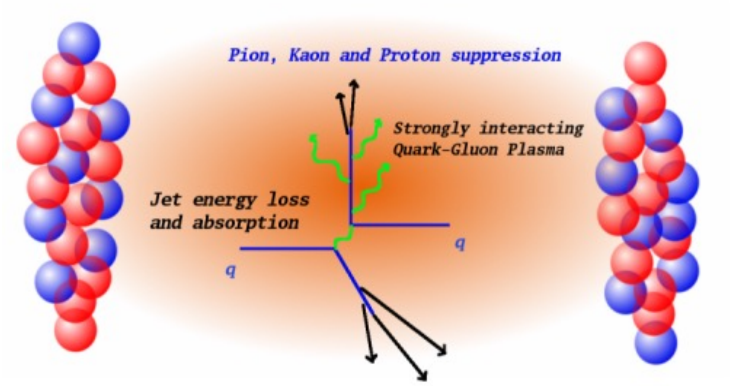


Central **Peripheral**

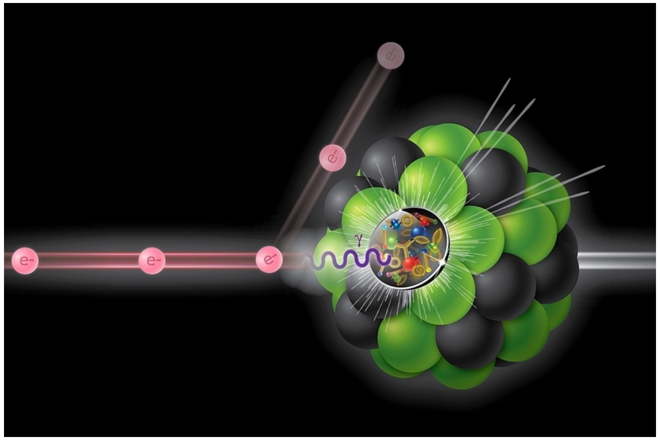
Analysis of light and heavy mesons and centrality will differentiate all 3 paradigms of modifications to hadronization

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**



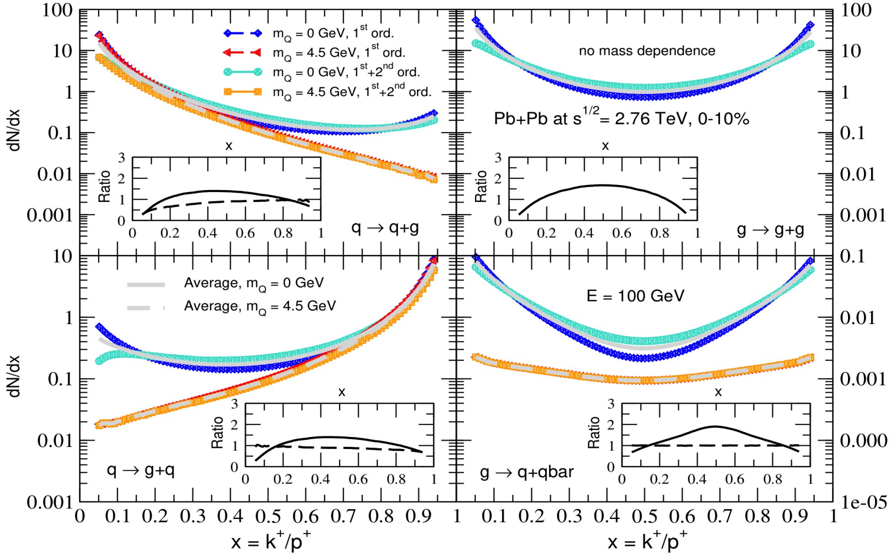
- **Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)**
- **Largest effects at midrapidity**
- **Higher C.M. energies correspond to larger plasma densities**



- **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)**

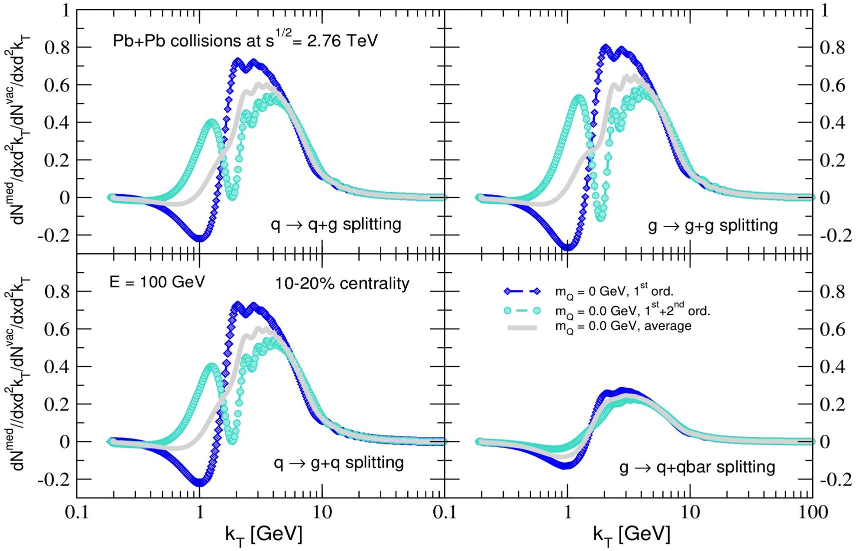
Properties of in-medium showers

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

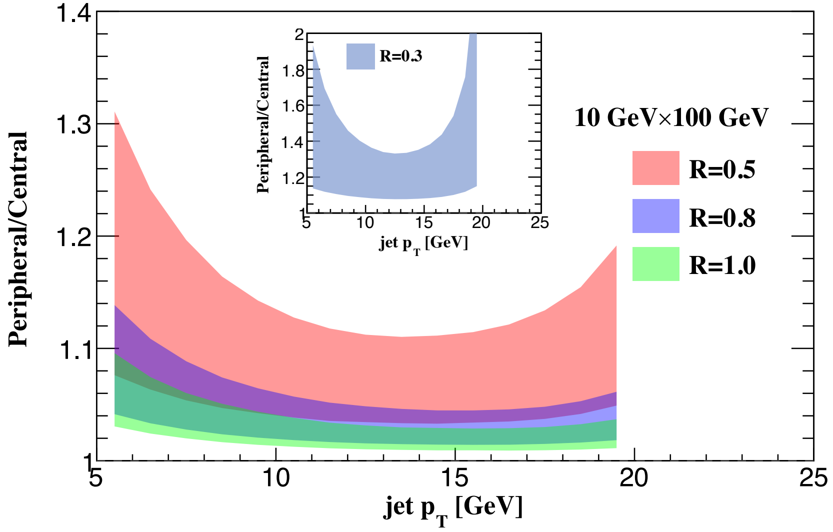
$$2\frac{\mu_D^2}{\lambda q} = 0.053\frac{GeV^2}{fm} \quad (vary \times 2,/2) \qquad 2\frac{\mu_D^2}{\lambda g} = 0.12\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$

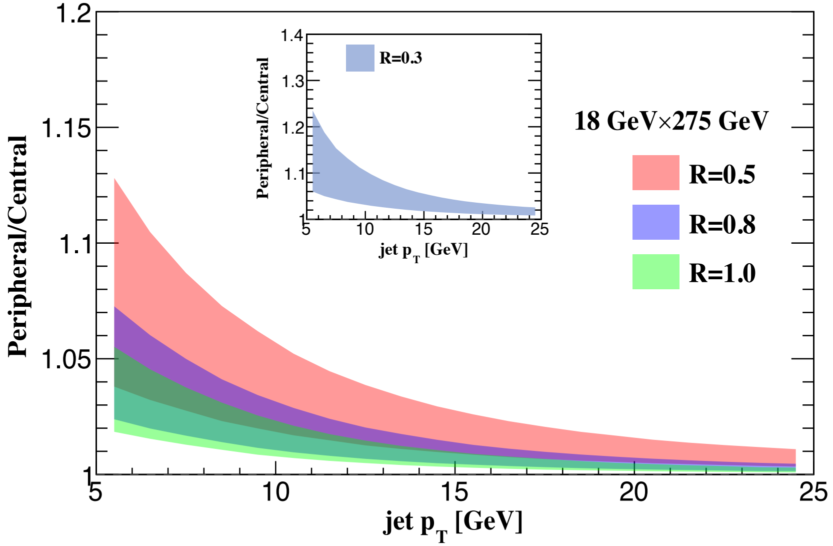
Centrality dependence of jet cross sections

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

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

- 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)

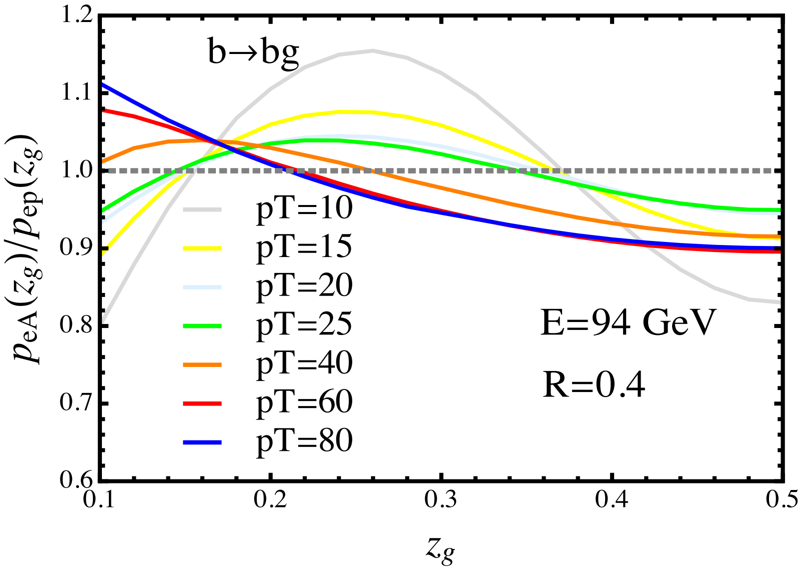
Jet splitting functions for light and heavy flavor jets in eA for EIC

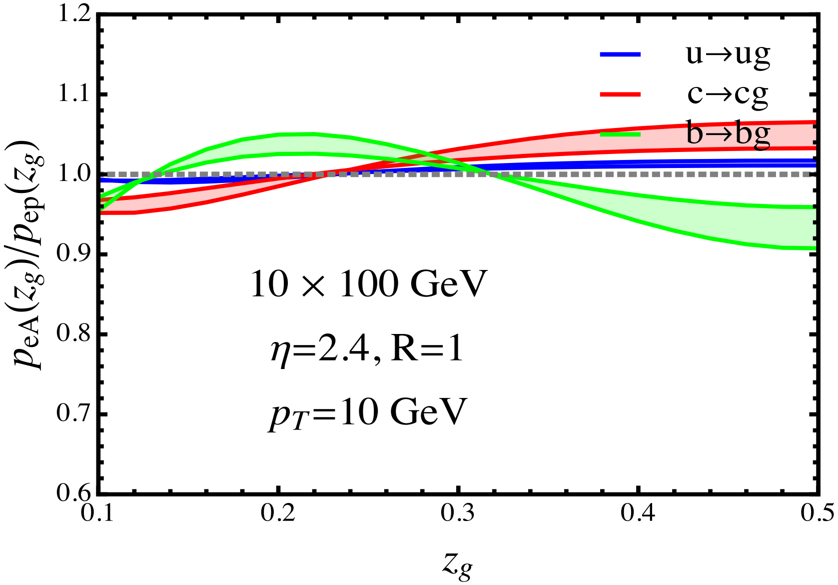
Jet substructure modification at the EIC is quite different that jet substructure modification in HIC

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