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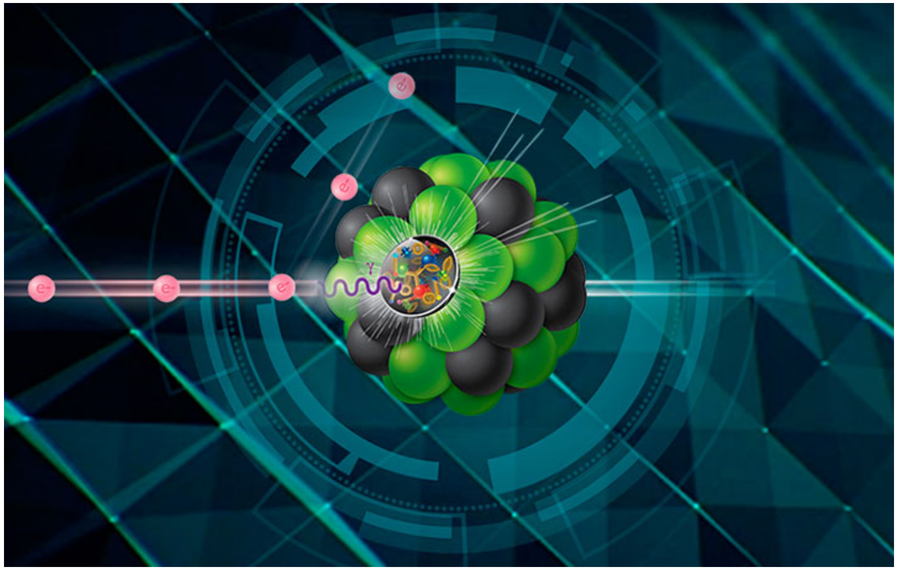
Theory of Hard Probes from RHIC to EIC

Center for Frontiers in Nuclear Science

RHIC Science Programs Informative Toward EIC in the Coming Years, CFNS, Stony Brook, NY
Online, May24-26, 2021

Los Alamos NATIONAL LABORATORY EST.1943

Outline of the talk



- Theoretical underpinnings
- Hadron production
- Jets and jet substructure
- Heavy Flavor

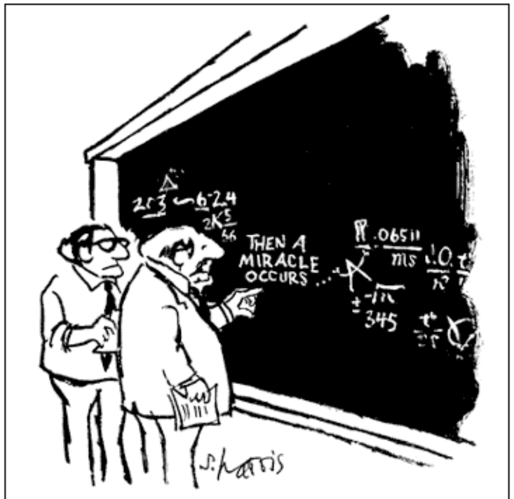
This work is supported by the TMD topical collaboration and the LANL LDRD program

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

I understood the request as the the direct RHIC -> EIC evolution. There is another line RHIC <-> LHC with complementarity of physics and measurements. I did not understand this to be the charge for the talk – few LHC examples

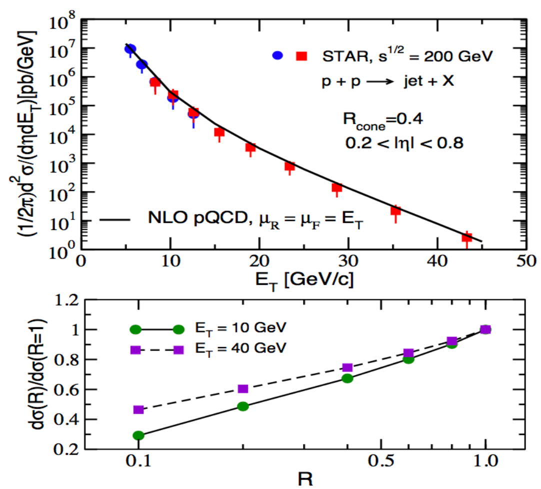
I. Theoretical underpinnings



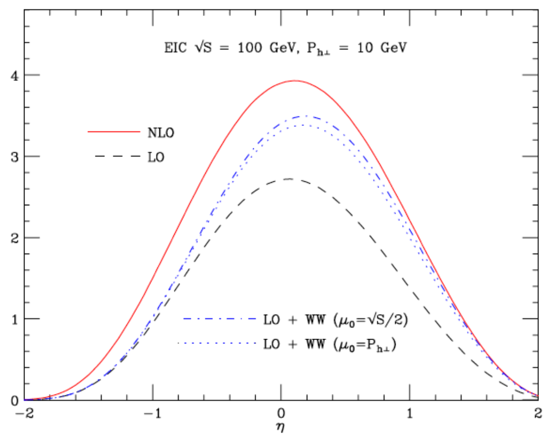
“I think you should be more explicit here in step two.”

Production of hard probes

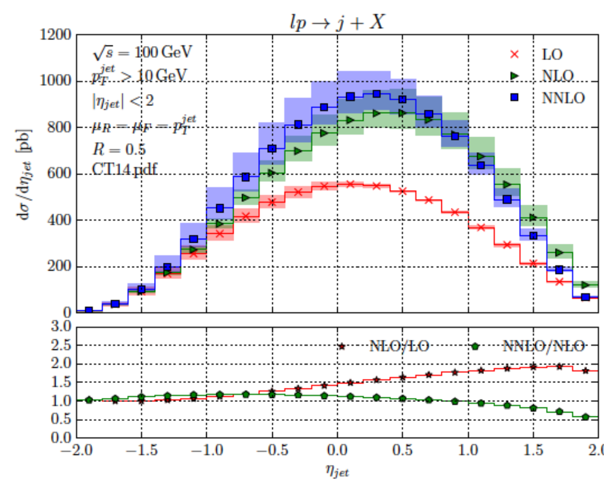
Based on QCD / SCET factorization. Calculations at next-to-leading order (and resummation where applicable) are standard. Calculations at NNLO also exist but still time consuming



I. Vitev et al. (2009)



P. Hinderer et al. (2015)



G. Abelof et al. (2016)

Examples (ep)

Hadrons

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

Similarly pp

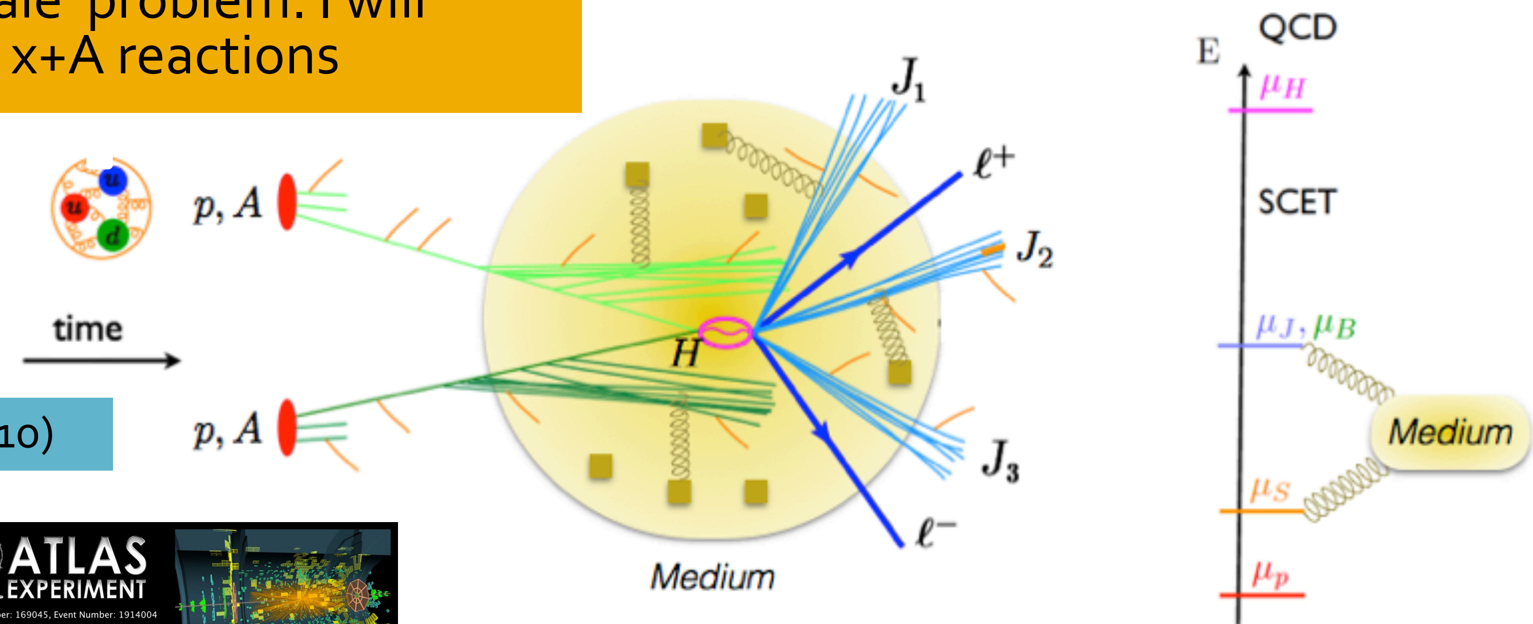
Jets

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

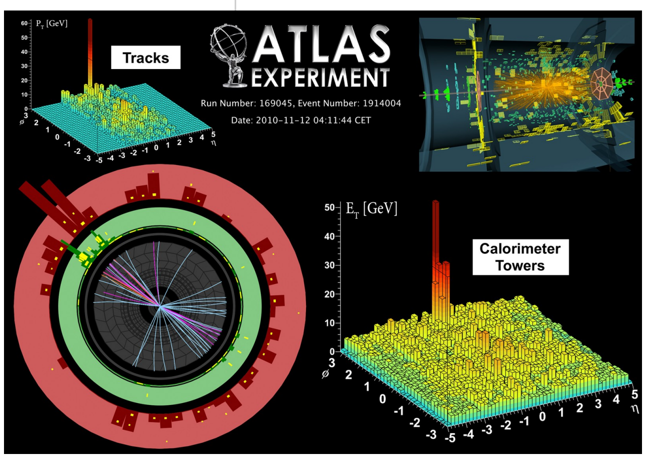
Interaction of hard probes in matter

- QCD in the medium remains a multi-scale problem. I will focus on x+A reactions

Ovanesyan et al. (2011)



Aad et al. (2010)



- Factorization, with modified J (jet), B (beam), S (soft) functions

$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

SCET$_{(M),G}$ and LCWF

G. Ovanesyan et al . (2012)

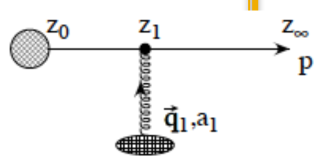
Z. Kang et al . (2016)

M. Sievert et al . (2018)

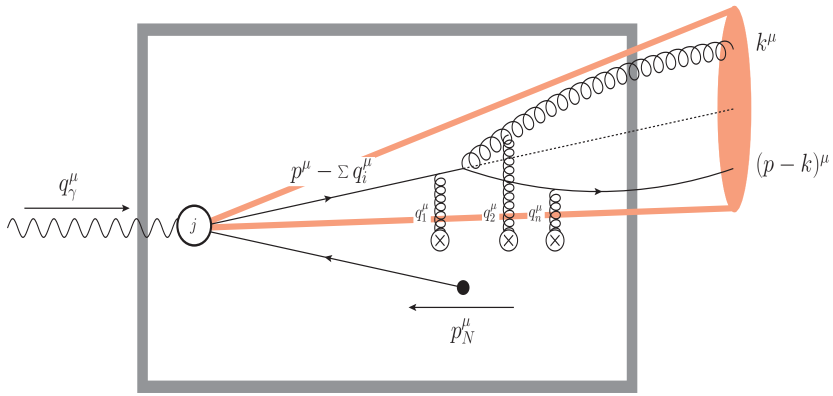
In-medium splitting functions necessary for higher order and resumed calculations

Develop specific EFTs for particle propagation in matter

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



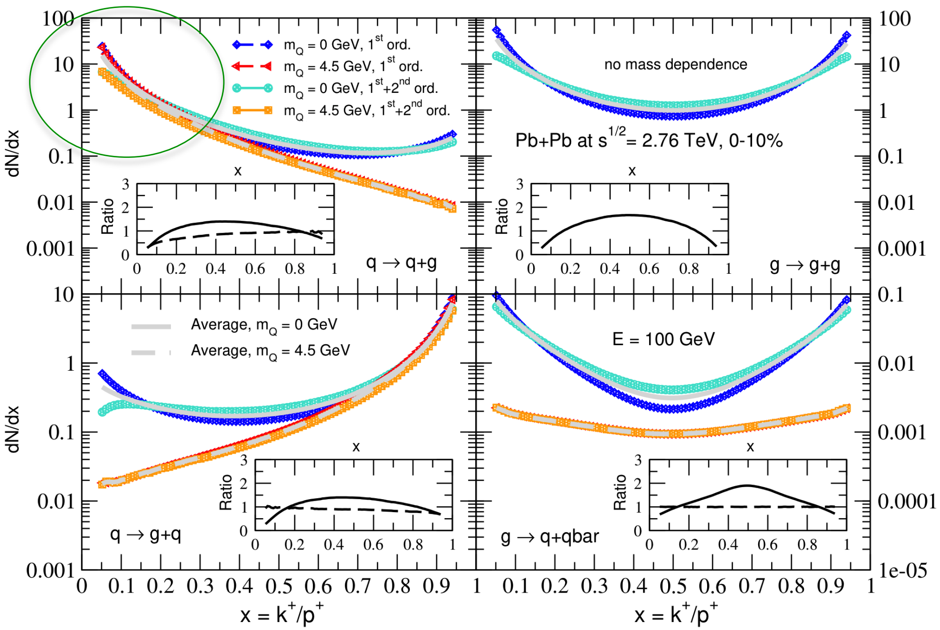
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi



Often used in saturation calculations. Can get on one shot massless and massive splitting functions

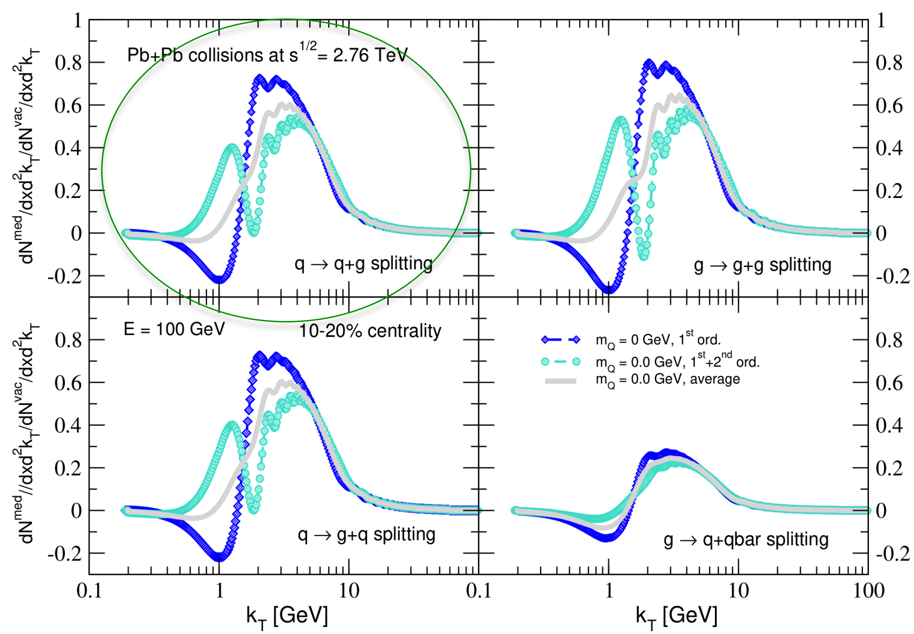
$$\begin{aligned}\left(\frac{dN}{dxd^2\mathbf{k}_\perp}\right)_{q\to qg} &= \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp}\left[-\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\right)^2+\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp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

Differential branching spectra



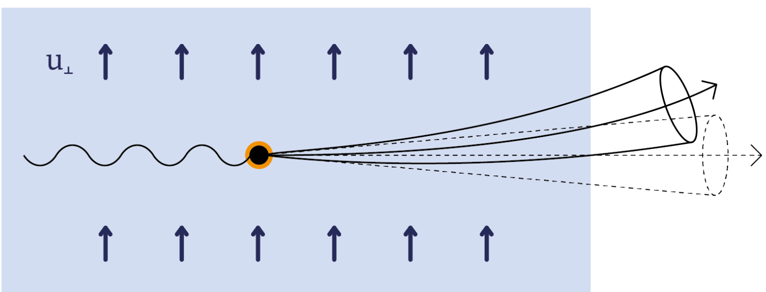
- Production of hadrons and jets can be understood from the broader and softer splitting functions
- Holds to higher orders in opacity

Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions

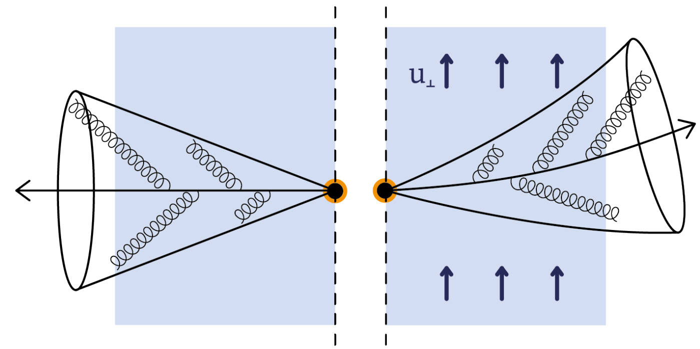


Effect of medium motion and inhomogeneities

- In the QGP - transverse and longitudinal expansion, rotation at non-zero impact parameter, fluctuations
- Cold nuclear matter – orbital motion of nucleons, breakup of the nucleus, color charge fluctuations



Effects on broadening and radiation



- Several selected results

Scattering

$$\langle \boldsymbol{p}_\perp \rangle = 3 \frac{\boldsymbol{u}_\perp}{(1-u_z)} \frac{L}{\lambda} \frac{\mu^2}{E} \ln \frac{E}{\mu}$$

$$E \frac{dN^{(1)}}{d^2k_\perp \, dx \, d^2p_\perp \, dE} = \frac{\alpha_s N_c}{\pi^2 x} \left(E \frac{dN^{(0)}}{d^2p_\perp \, dE} \right) \int_0^L dz \, \rho \int d^2q_\perp \bar{\sigma}(q_\perp^2)$$
$$\times \left\{ \frac{2\boldsymbol{k}_\perp \cdot \boldsymbol{q}_\perp}{k_\perp^2 (k-q)_\perp^2} \left(1 - \cos\left(\frac{(k-q)_\perp^2}{2xE} z \right) \right) + \frac{q_\perp^2}{k_\perp^2 (q_\perp^2 + \mu^2)} \frac{\boldsymbol{u}_\perp \cdot \boldsymbol{k}_\perp}{2(1-u_z)xE} \right\}$$

Radiation

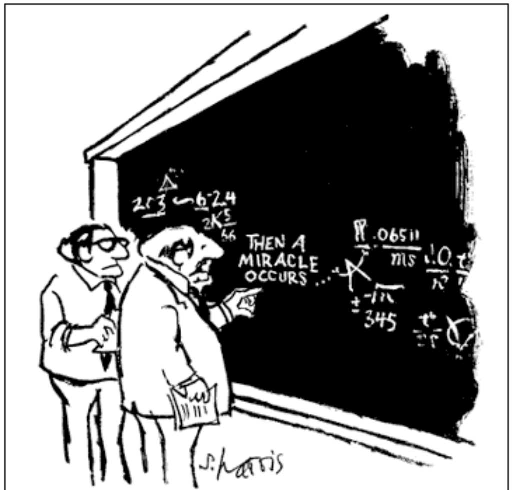
$$\left\langle \frac{\boldsymbol{k}_\perp}{k_\perp^2} \right\rangle = \frac{N_c}{C_F} \frac{L}{\lambda} \frac{\boldsymbol{u}_\perp}{8(1-u_z)xE}$$

MC by boosting to local rest frame

Y. He et al . (2020)

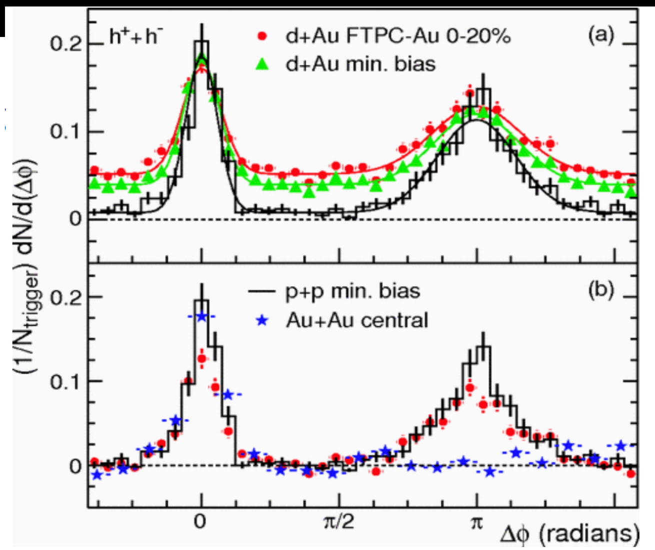
A. Sadofyev et al . (2021)

I. Hadron production



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

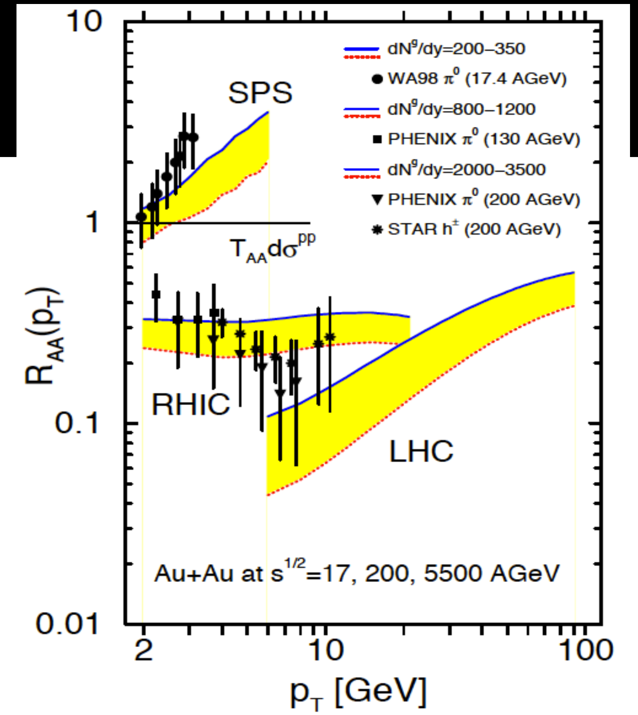
Hadron suppression and correlations



I. Vitev et al. (2002)

Adams et al. (2003)

Discovery of jet quenching



- Inclusive hadron production and di-hadron correlations has played a definitive role in the discovery and verification of jet quenching

Energy loss approaches

Zakharov (1995)

Baier et al. (1997)

Gyulassy et al. (2000)

Guo et al. (2001)

Alford et al. (2003)

Accounting for multiple gluon emission

$$P(\epsilon) = \sum_{n=0}^{\infty} P_n(\epsilon) \,, \qquad P_0(\epsilon) = e^{-\langle N_g \rangle} \delta(\epsilon) \,,$$

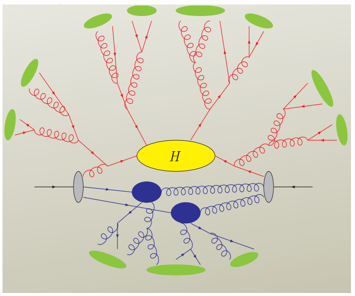
$$P_n(\epsilon) = \frac{1}{n} \int_0^{\epsilon} d\epsilon' \; P_{n-1}(\epsilon - \epsilon') \frac{dN_g}{d\epsilon'}(\epsilon' = \omega/E)$$

$$\int_0^1 d\epsilon \; P(\epsilon) = 1 \,, \quad \int_0^1 d\epsilon \; \epsilon \, P(\epsilon) = \left\langle \frac{\Delta E}{E} \right\rangle$$

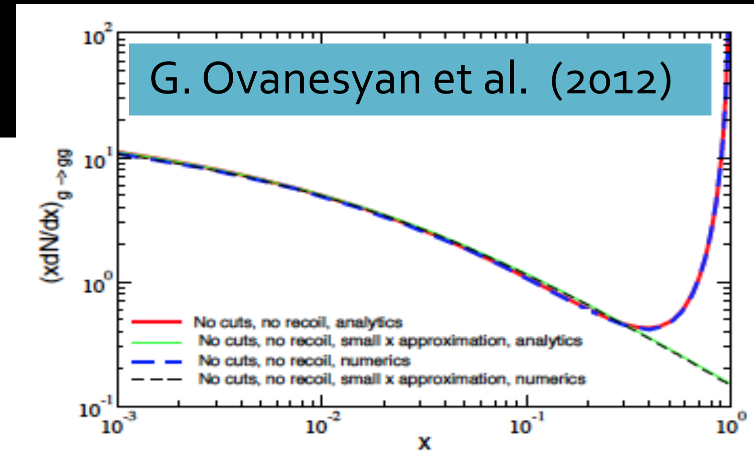
***Effective* modification of fragmentation**

$$D_{h/c}(z) \;\Rightarrow\; \int_0^{1-z} d\epsilon \; P(\epsilon) \, \frac{1}{1-\epsilon} D_{h/c}\left(\frac{z}{1-\epsilon}\right) + \int_z^1 d\epsilon \, \frac{dN^g}{d\epsilon}(\epsilon) \, \frac{1}{\epsilon} D_{h/g}\left(\frac{z}{\epsilon}\right) \quad .$$

QCD evolution in the soft gluon energy loss limit



Advances in understanding in-medium parton showers. Beyond energy loss



$$\frac{df_q(x,Q)}{d\ln Q} = P_{q\to qg}\otimes f_q + P_{g\to q\bar{q}}\otimes f_g$$

$$\frac{df_g(x,Q)}{d\ln Q} = P_{g\to gg}\otimes f_g + \sum_{q,\bar{q}} P_{q\to gq(\bar{q})}\otimes f_q$$

$$P_{q\to qg} = \frac{2C_F}{x_+} + \left(\frac{2C_F}{x}\, g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to gg} = \frac{2C_A}{x_+} + \left(\frac{2C_A}{x}\, g[x,Q,L,\mu]\right)_+ ,$$

$$P_{g\to q\bar{q}} = 0, \qquad P_{q\to gq} = 0,$$

- If a connection is to be found between the energy loss and the evolution approach, it is in the soft gluon limit

Analytic solution to DGLAP evolution

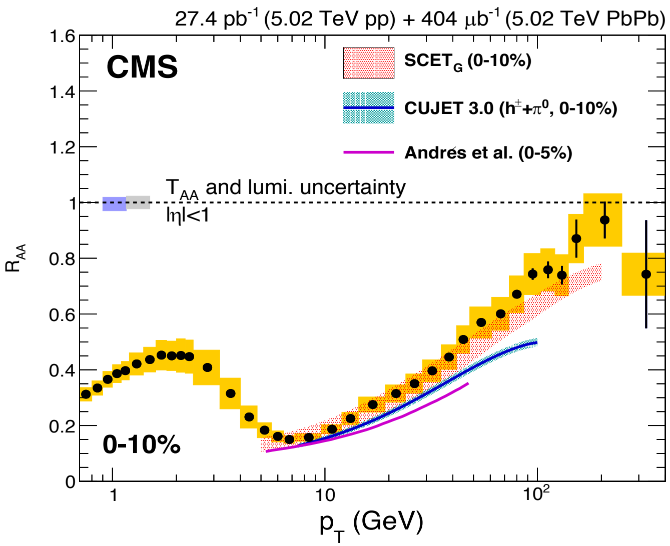
$$D_{h/c}^{\rm med.}(z,Q) = D_{h/c}(z,Q)\, e^{-[n(z)-1]\left\langle \frac{\Delta E}{E}\right\rangle_z - \langle \tilde{N^g}\rangle_z} .$$

- *The main result*: direct relation between the evolution and energy loss approaches first established here

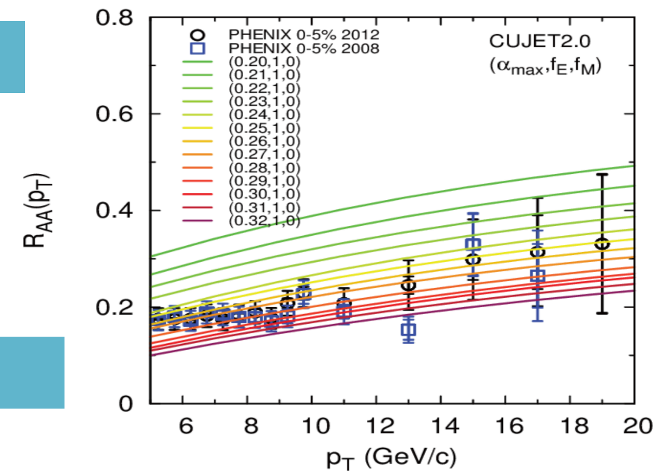
Z. Kang et al. (2014)

Comparison of energy loss and QCD evolution approaches

- The in-medium QCD evolution approach works over a wide variety of energies. This is, of course, expected because we have an analytic proof of the relation between QCD evolution and energy loss



Y.T. Chien et al. (2015)

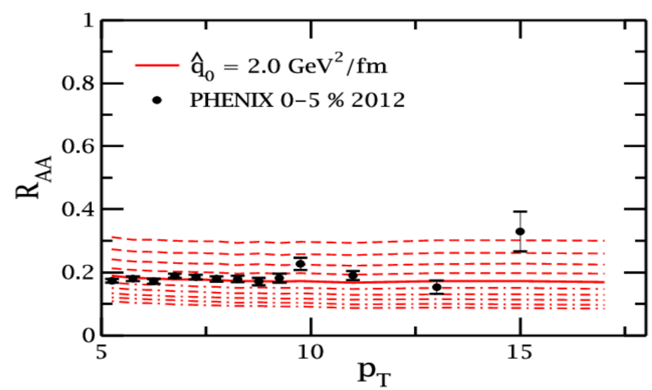


K. Burke et al. (2015)

- RHIC: Extend calculations to high p_T
- Understand QGP vs cold nuclear matter effects
- Compare e-loss, evolution and MC approaches
- Further constrain transport properties

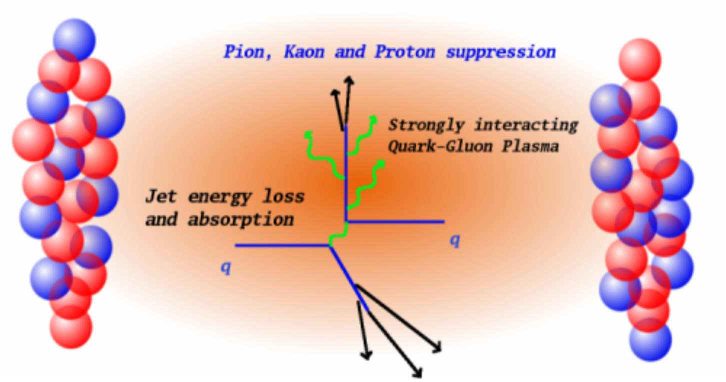
Also other Monte Carlo approaches

JETSCAPE

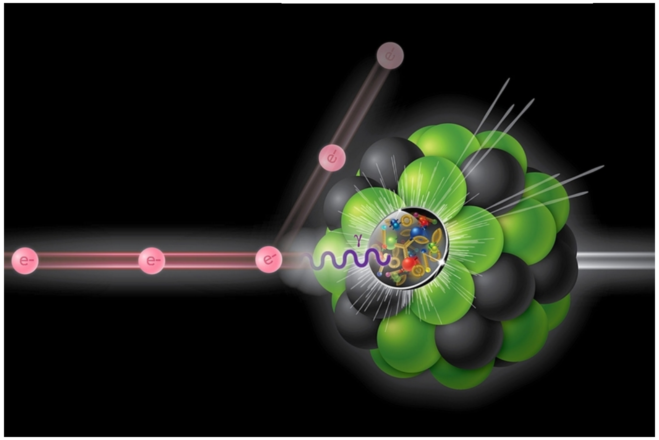


Differences between AA and eA

- 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



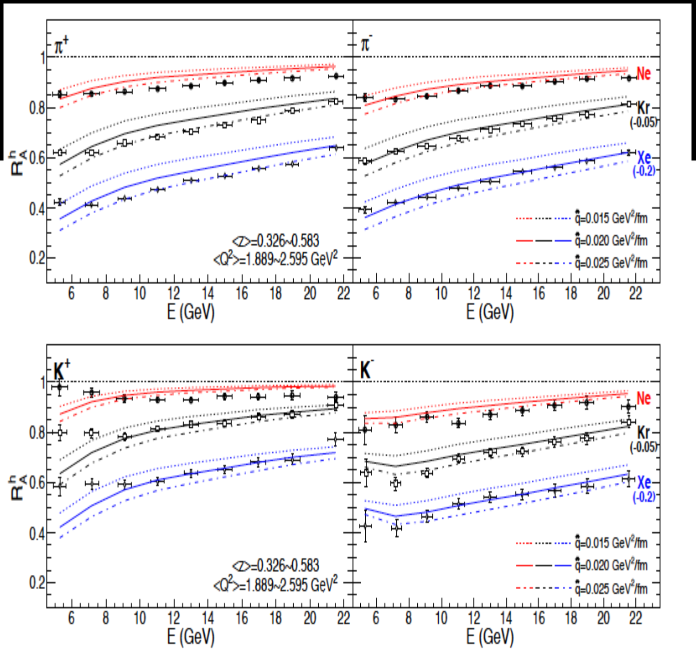
- **Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)**
- **Largest effects at midrapidity**
- **Higher C.M. energies correspond to larger plasma densities**



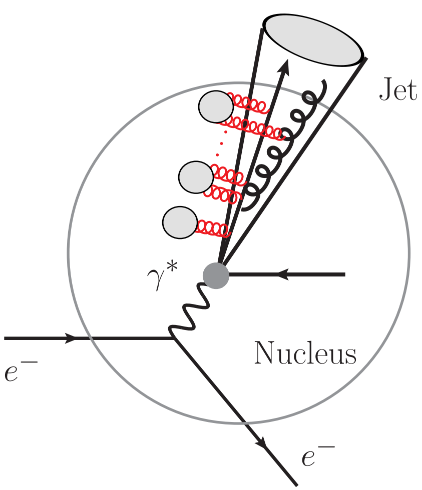
- **Jets are on the nuclear rest frame. Longitudinal momentum matters**
- **Largest effects are at forward rapidities**
- **Smaller C.M. energies (larger only increase the rapidity gap)**

Modification of light hadrons at HERMES

N. Chang et al. (2014)



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

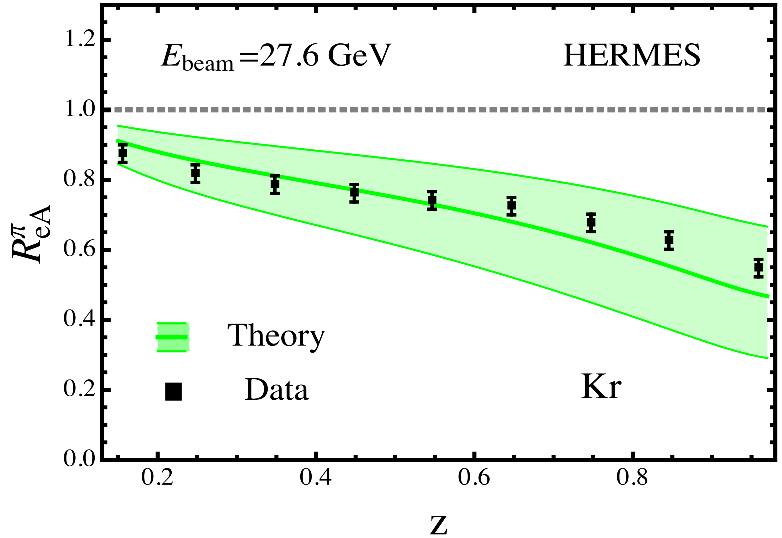


$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

In-medium evolution of fragmentation functions

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

Z. Liu et al. (2020)



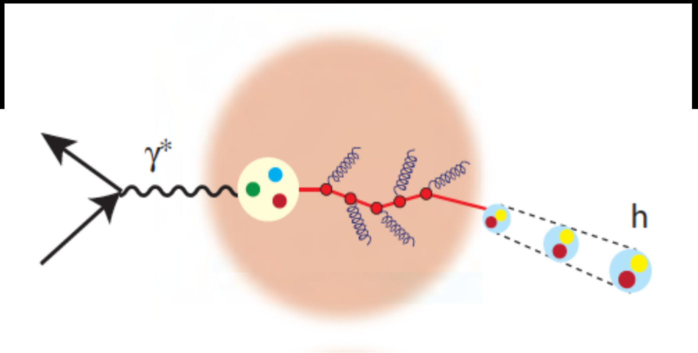
- We constrain a range of transport properties to explore from HERMES

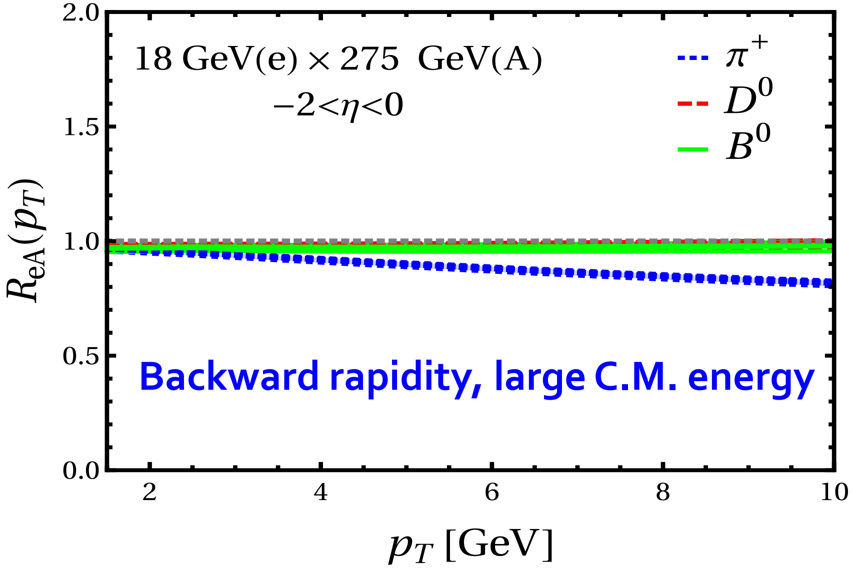
Transport properties:

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

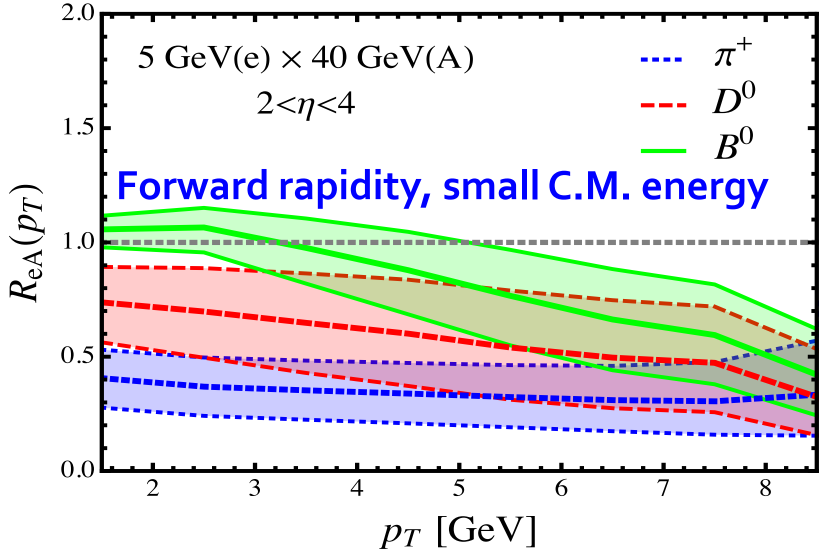
$$q-hat(q) = 0.05\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$

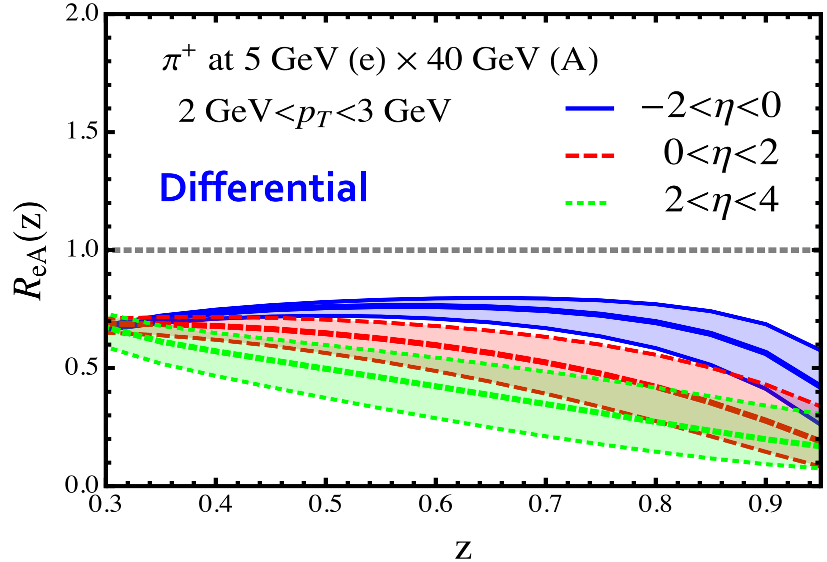
Light flavor suppression at the EIC





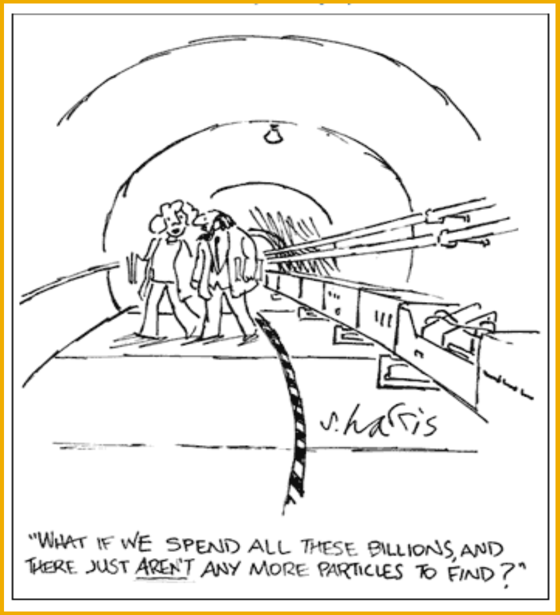
Light pions show the largest nuclear suppression at the EIC. However to differentiate models of hadronization heavy flavor mesons are necessary





H. Li et al . (2020)

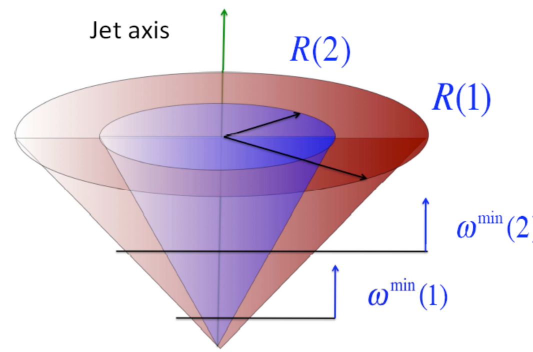
II. Jet production



Jets – the next step in understanding the QCD with nuclei

- One can leverage the differences between the vacuum parton showers, the medium-induced showers and the medium response to jets to experimental signatures of parton interaction in matter
- Need NLO/resummed calculations

I. Vitev et al. (2008)



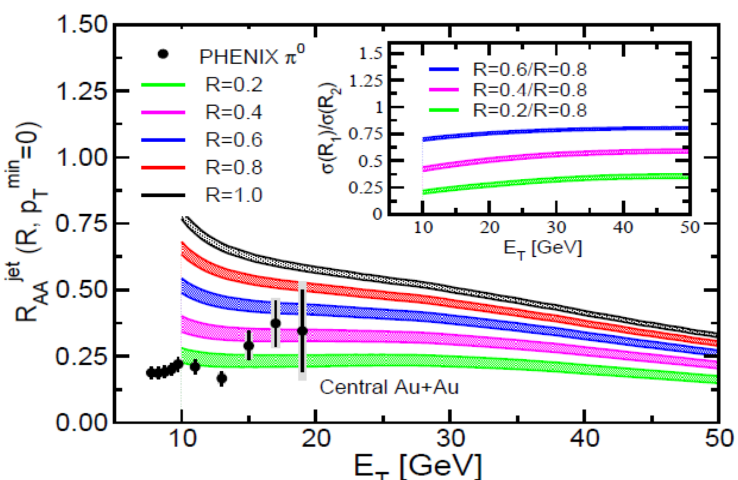
Mechanism	Signature
Dissociative	~ Constant $R_{AA}^{jet}=1$ (No suppression)
Radiative	Continuous variation of R_{AA}^{jet} with R, w_{min}
Collisional	~ Constant $R_{AA}^{jet}= R_{AA}^{particle}$ (Large suppression)

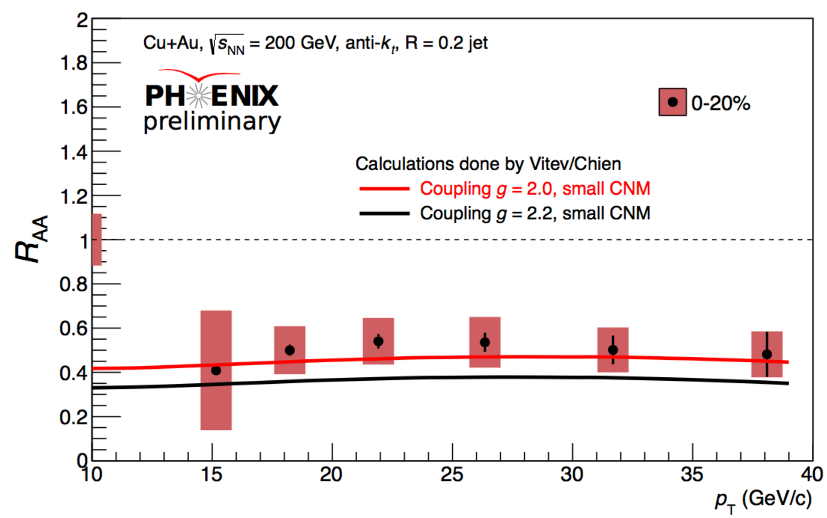
$$|J_i(\epsilon_i)| = 1/\left(1 - [1 - f(R_i, p_{T\,i}^{\min})_{q,g}]\epsilon_i\right)$$

$$\frac{\sigma^{AA}(R,\omega^{\min})}{d^2E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^2} \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2E'_T dy}$$

I. Vitev et al. (2009)

A. Timilsina et al. (2016)





Dijets and gamma-jets

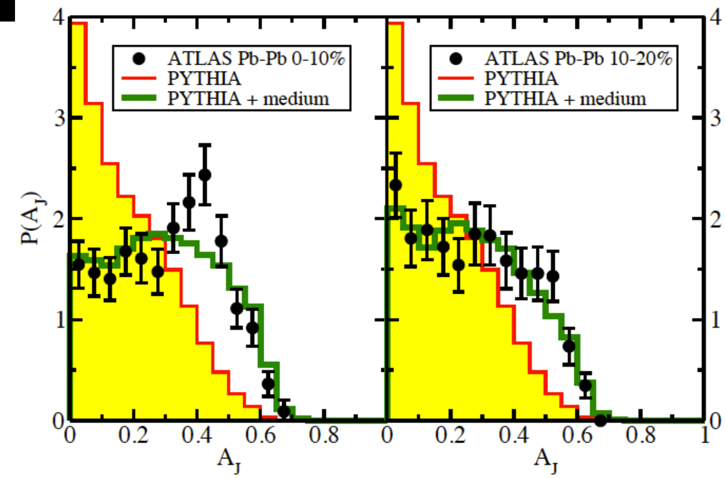
First measurements of jet modification were not of inclusive jets but di-jet correlations

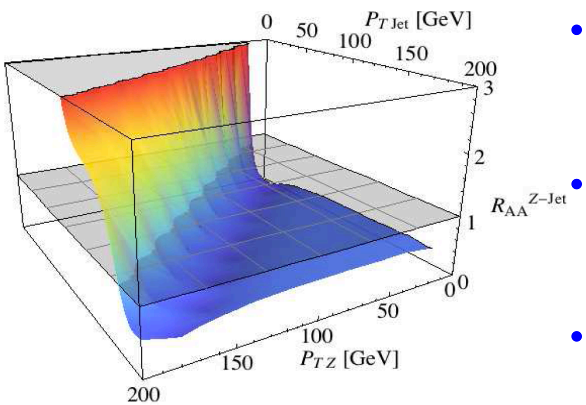
$$\frac{d\sigma}{dA_J} = \int_{y_{1\,\min}}^{y_{1\,\max}} dy_1 \int_{y_{2\,\min}}^{y_{2\,\max}} dy_2 \int_{E_{T\,2\,\min}}^{E_{T\,1}} dE_{T\,2}\, \frac{2E_{T\,2}}{(1-A_J)^2} \times \frac{d\sigma[E_{T\,1}(A_J, E_{T\,2})]}{dy_1 dy_2 dE_{T\,1} dE_{T\,2}}\,,$$

$$A_J = \frac{E_{T\,1} - E_{T\,2}}{E_{T\,1} + E_{T\,2}}$$

Y. Quin et al. (2011)

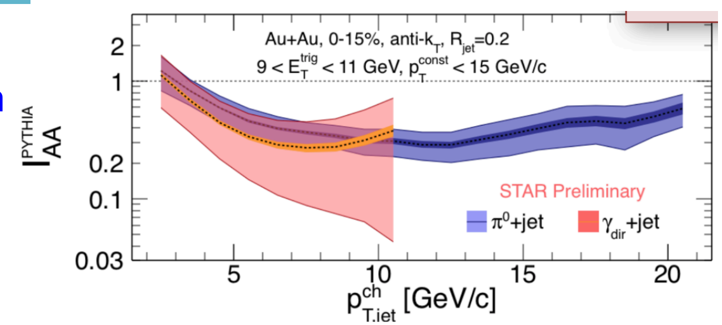
C. Young et al. (2011)

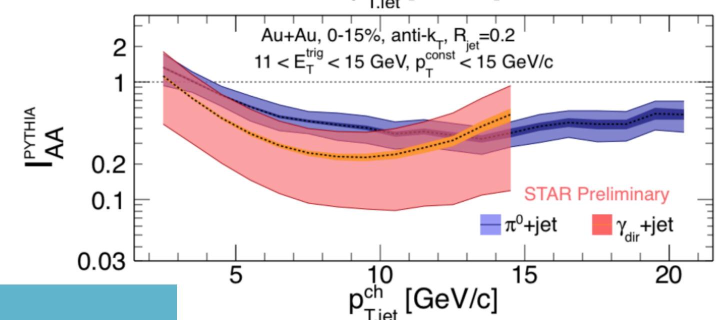




System	$\langle z_{J\gamma}\rangle_{\mathrm{LHC}}$	$\langle z_{J\gamma}\rangle_{\mathrm{RHIC}}$
p+p	0.94	0.90
A+A, CNM	0.94	0.89
A+A, $g_{med} = 1.8$,Rad.+Col	0.84	0.78
A+A, $g_{med} = 2.0$,Rad.+Col	0.80	0.74
A+A, $g_{med} = 2.2$,Rad.+Col	0.71	0.70

- **Gamma-jets give cleaner constraints on the E-loss of jets**
- **Transition from enhancement to suppression**
- **STAR measurements some tension with theory**
- **Future sPHENIX measurements**





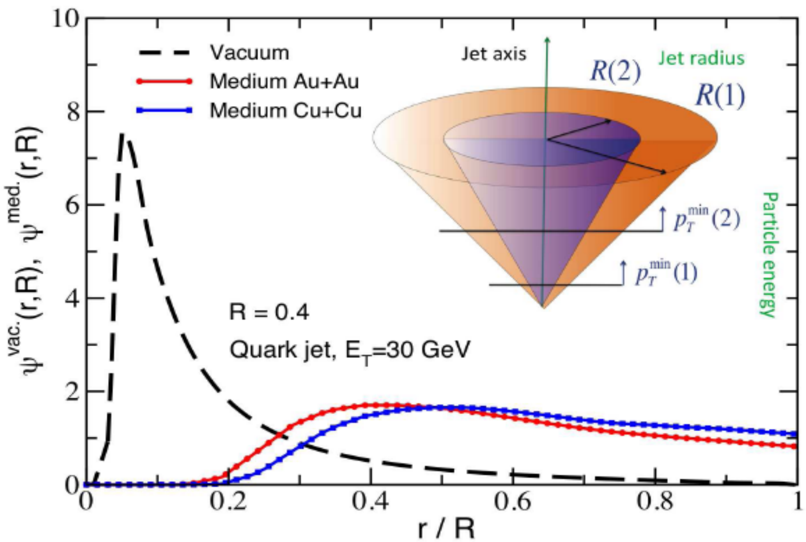
STAR (2018+)

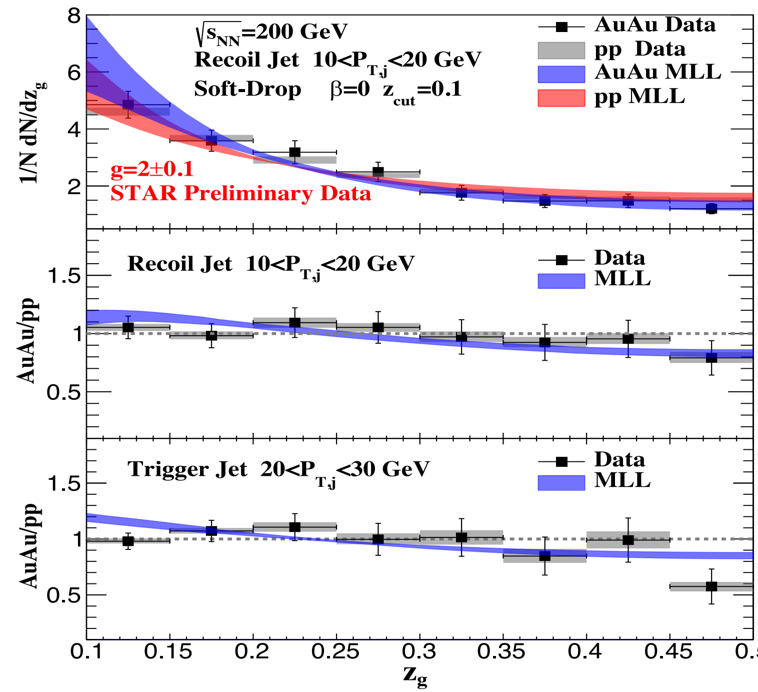
Jet substructure modification

- Direct access to the characteristics of the in-medium parton showers. LHC has led the way. It will be very useful to measure jet shapes and fragmentation functions at RHIC

H. Li et al. (2018)

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





$$\Psi_{\mathrm{int}}(r;R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\mathrm{jet}})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\mathrm{jet}})_i)},$$

$$\psi(r;R) = \frac{d\Psi_{\mathrm{int}}(r;R)}{dr}.$$

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

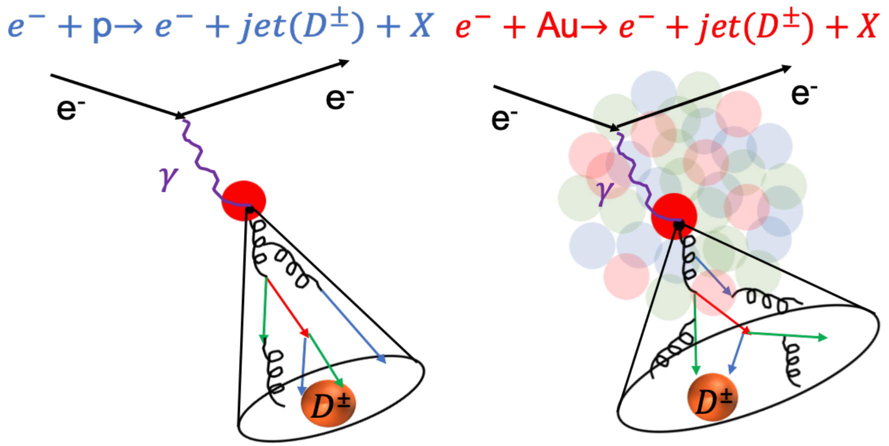
There is also modelling effort to include "medium response"

Jet production

Z. Kang et al. (2016)

L. Dai et al. (2016)

A useful modern way (though not unique) to calculate jet cross sections



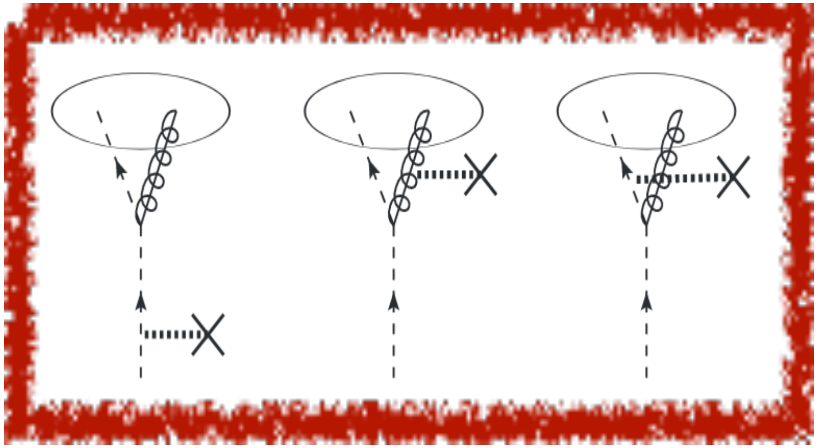
Factorization formula

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

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

In-medium jet functions

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



- Stable in numerical implementation
- Similarly for gluon jets

H. Li et al. (2020)

Cross section contribution

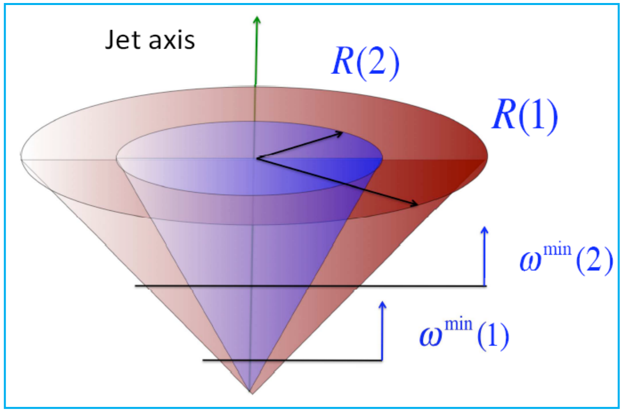
$$d\sigma^{\mathrm{jet,med}}_{\mathrm{PbPb}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$$

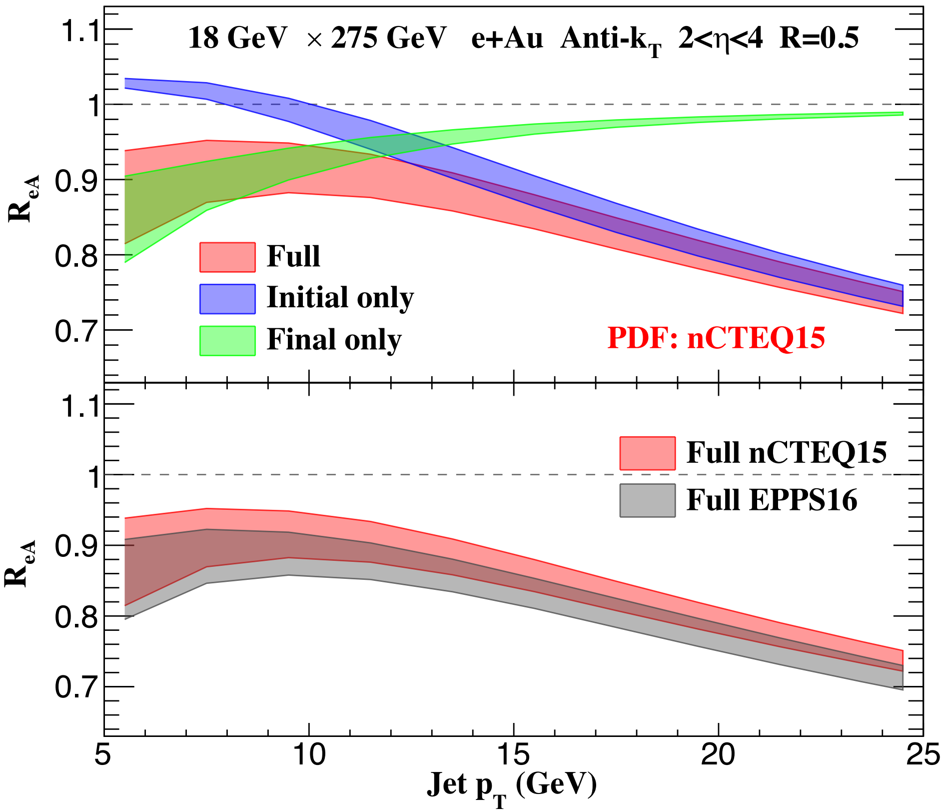
Jet results at the EIC

- The physics of reconstructed jet modification

H. Li et al. (2020)

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





Two types of nuclear effect play a role

- **Initial-state effects parametrized in nuclear parton distribution functions or nPDFs**
- **Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers and jet energy loss**

- Net modification 20-30% even at the highest CM energy
- E-loss has larger role at lower p_T. The EMC effect at larger p_T

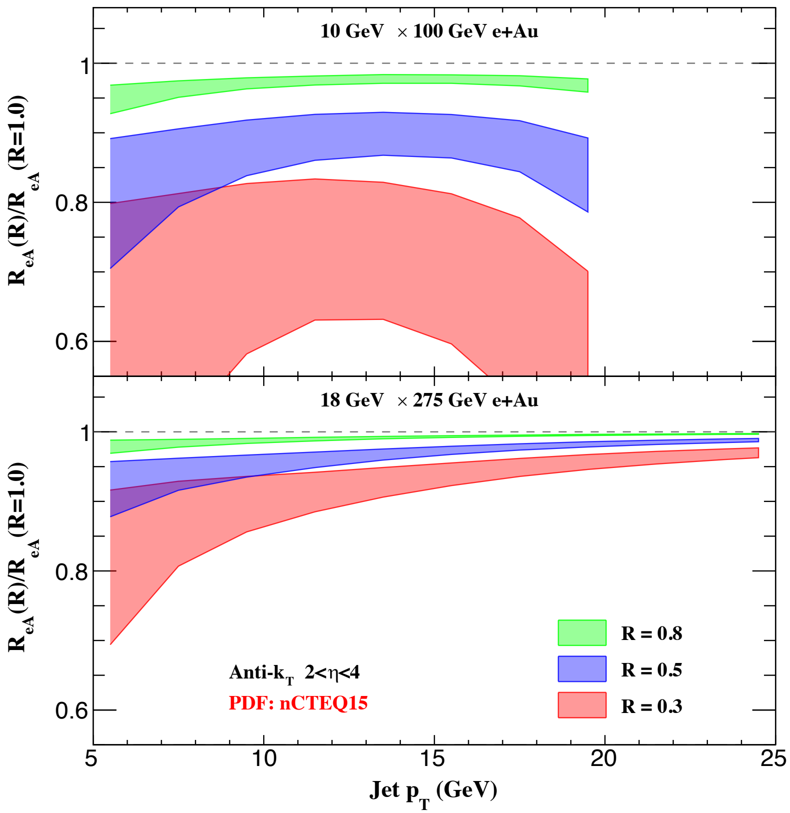
Separating initial-state from final-state effects at EIC

A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

Define the ratio of modifications for 2 radii (it is a double ratio)

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

- Jet energy loss effects are larger at smaller center of mass energies (electron-nuclear beam combinations)
- Effects can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)



H. Li et al. (2020)

Initial-state effects are successfully eliminated

Jet charge in e+A at the EIC

The jet charge

R. Field *et al.* (1978)

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

SCET approach

D. Krohn et al. (2012)

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

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

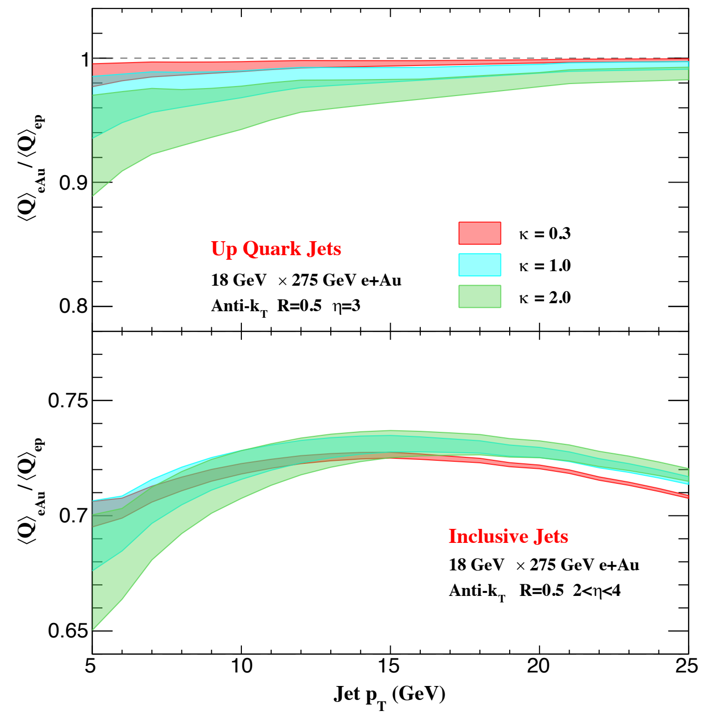
$$\tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\; z^{\kappa} \sum_h Q_h D_q^h(z,\mu)$$

The components of he factorization formula receive in-medium corrections

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

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

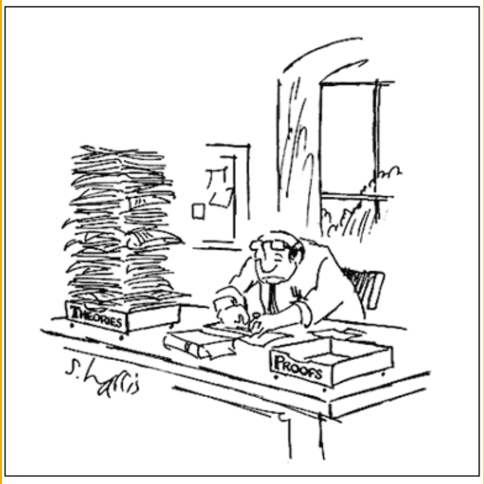
- Medium-induced scaling violation of the individual flavor and average jet charge



H. Li *et al.* (2020)

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

III. Heavy flavor production



Transport approaches and hadronization

- Where heavy flavor/heavy quarks come into their own is by providing a mass scale and in the physics of hadronization

Transport approaches

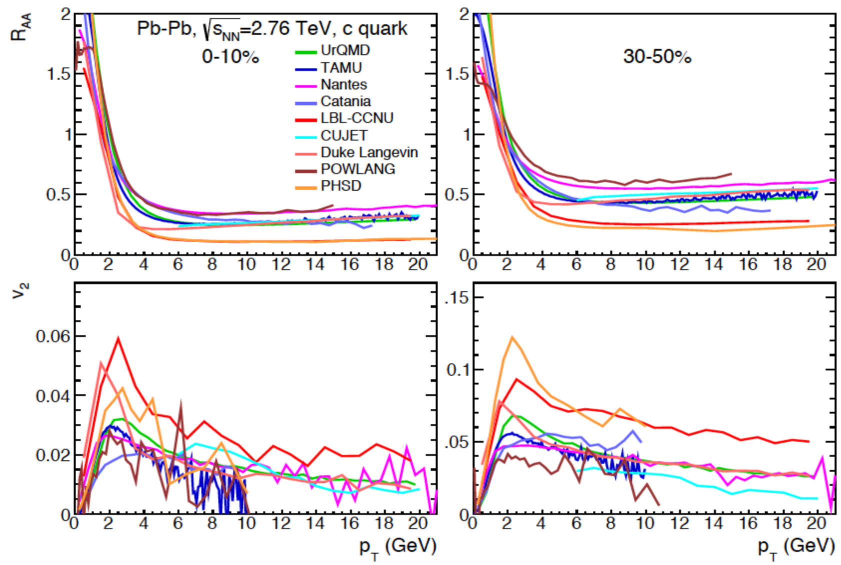
Van Hees et al. (2004)

G. Moore et al. (2005)

$$\frac{dx}{dt} = F(x) + \eta(t) \quad \langle \eta(t)\eta(t') \rangle = \Delta\delta(t-t')$$

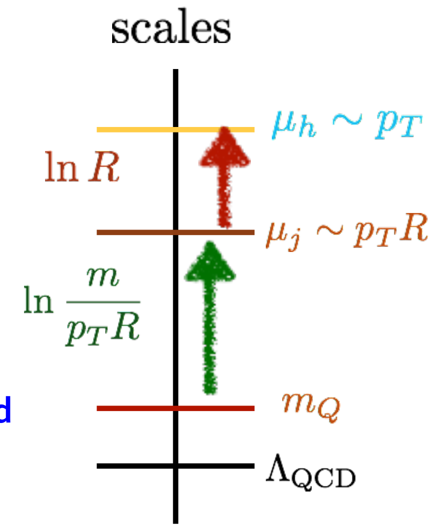
$$\frac{\partial P}{\partial t} = -\frac{\partial}{\partial x}(FP) + \frac{1}{2}\Delta\frac{\partial^2}{\partial x^2}P$$

R. Rapp et al. (2018)



Perturbative approaches

Inclusion of mass in perturbative calculations and effect of mass on parton showers / "dead cone effect" (vacuum and medium) is understood



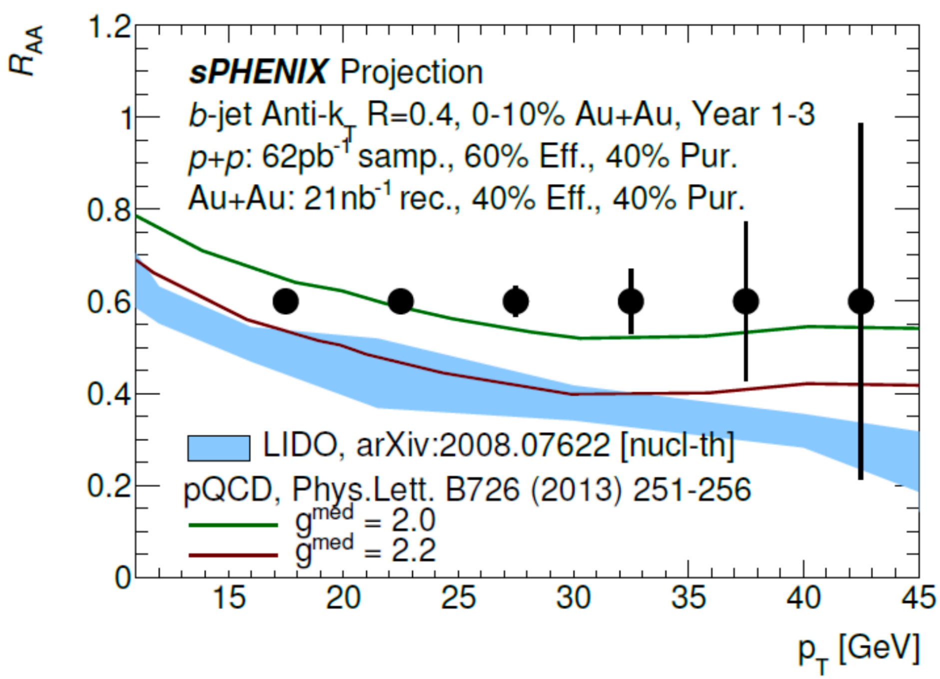
$$\left(\frac{dN^{\rm med}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \Bigg\{ \left(\frac{1+(1-x)^2}{x}\right) \Bigg[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}$$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

Inverting the mass hierarchy of jet quenching effects

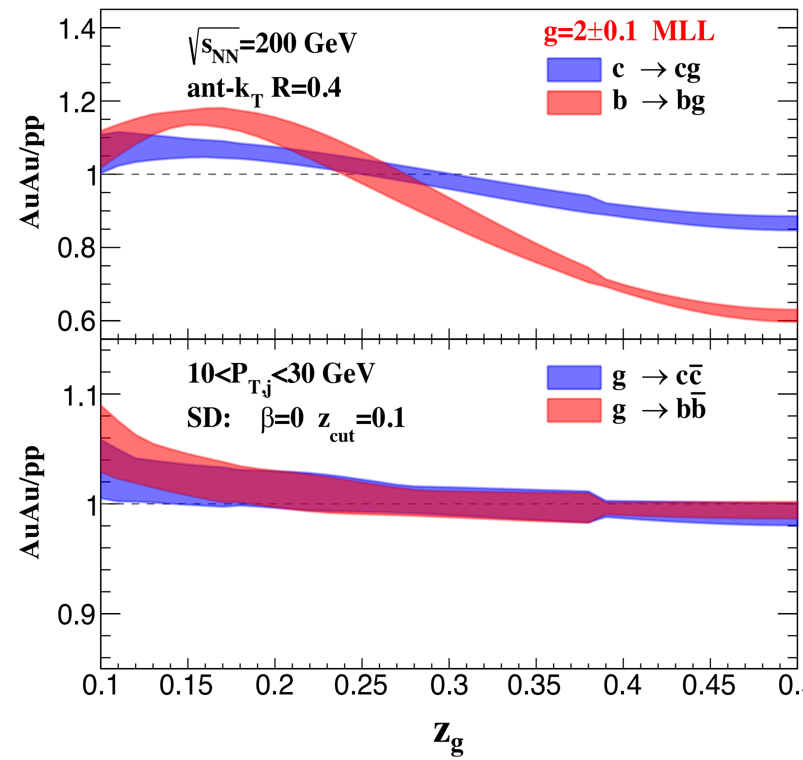
H. Li et al . (2018)

sPHENIX will heave excellent reach to measure heavy flavor jets. It will be very important to complement such measurements with heavy flavor jet substructure

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



Z. Shi et al. / sPHENIX (2021)

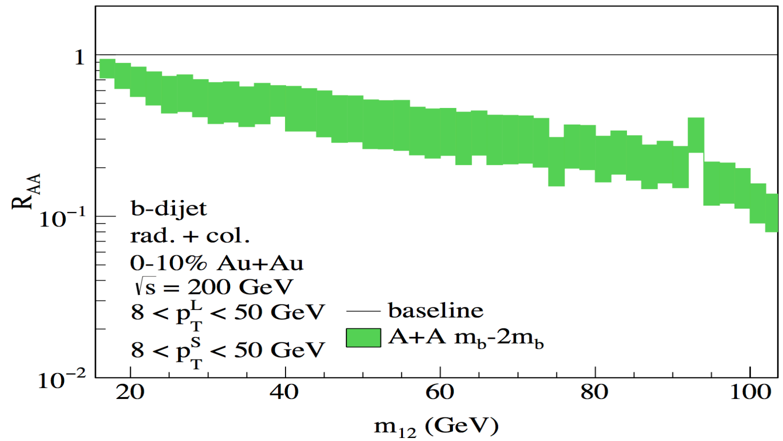


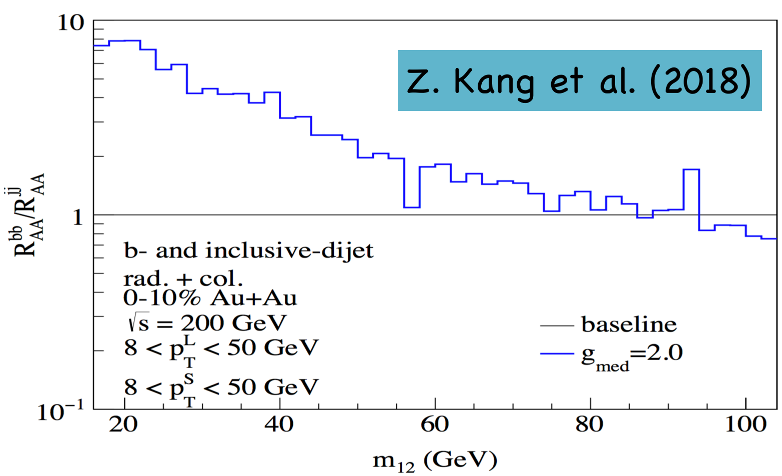
At RHIC jet energies, and at lower jet energies at the LHC there is a unique reversal of the mass hierarchy effecets on b > c >= u,d. (Single B,D meson tag)

Dijet mass modification

Great way to study the effect of mas on parton energy loss

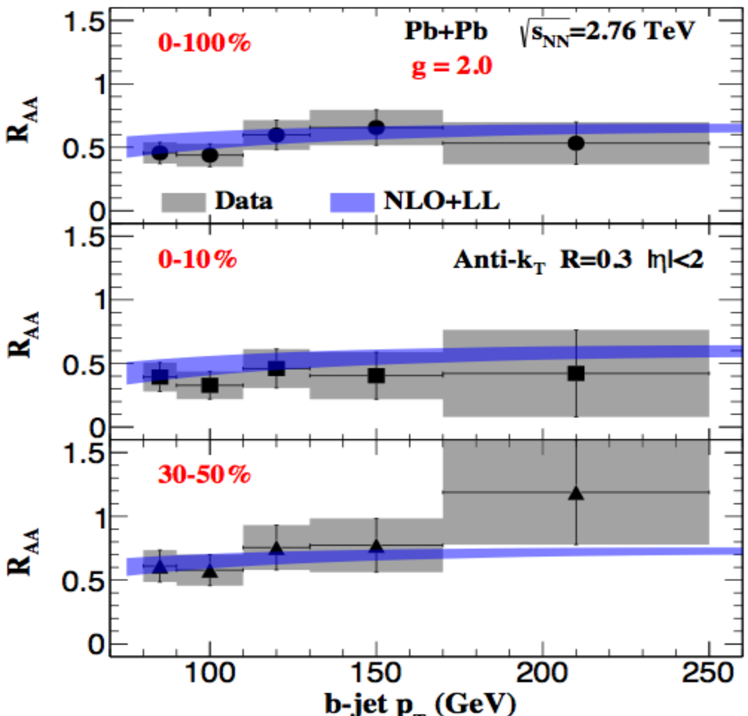
$$m_{12}^2 = m_1^2 + m_2^2 + 2\left[m_{1T}m_{2T}\cosh(\Delta\eta) - p_{1T}p_{2T}\cos(\Delta\phi)\right]$$





Z. Kang et al. (2018)

- Calculations shown in the energy loss limit. Full in-medium parton showers implemented in SCET calculations. First on the example of LHC b-jets

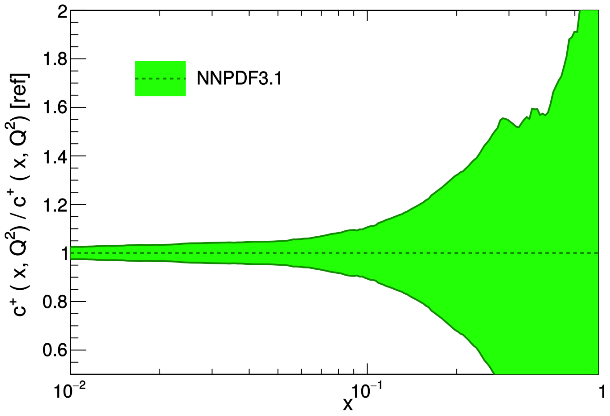


H. Li et al . (2018)

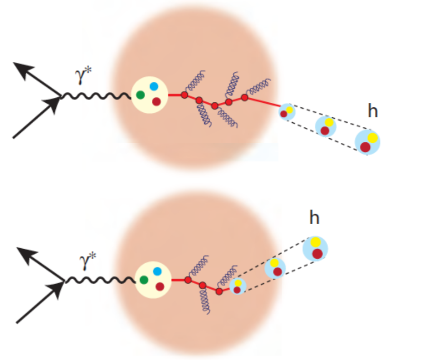
Heavy flavor at the EIC

Multiple uses of heavy flavor

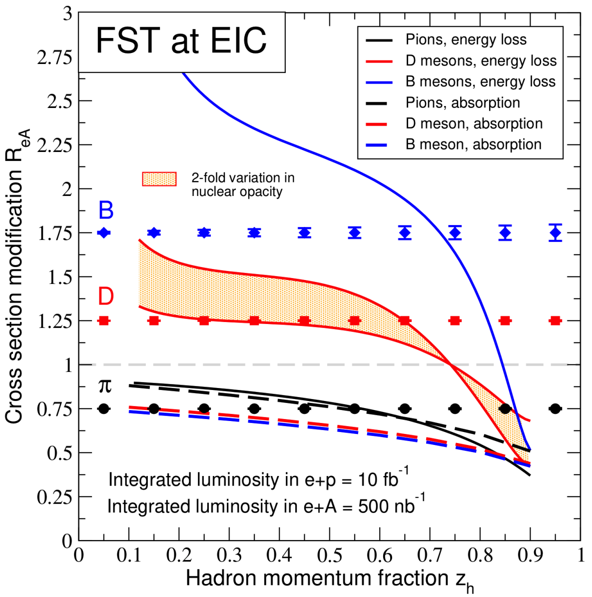
- Constrain gluon and c/b distributions. Look for intrinsic charm



R. Ball et al. (2016)

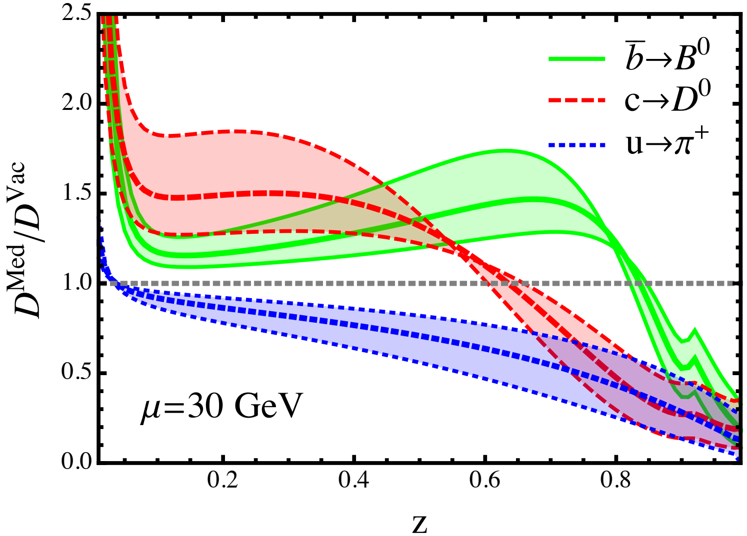


- Constrain the transport properties of cold nuclear matter
- Shed light on the picture of hadronization, differentiate between energy loss and hadron absorption
- Go beyond energy loss phenomenology at the EIC



X. Li et al. (2020)

Modification of heavy flavor FFs



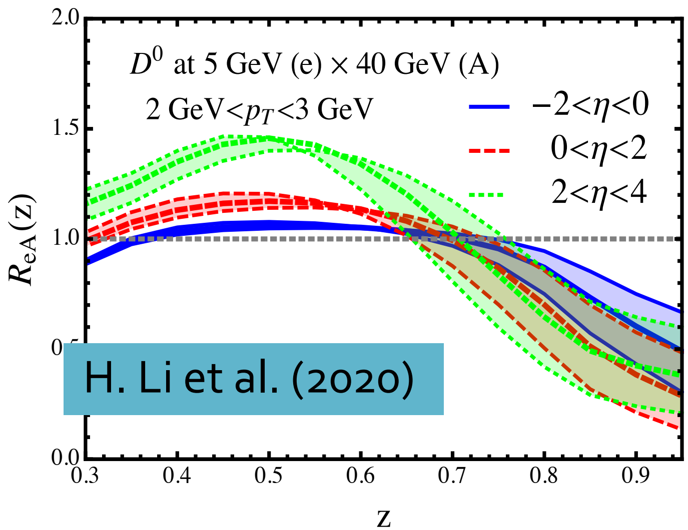
Detailed and constrained predictions for the EIC

A more differential ratio vs the momentum fraction of the hadron

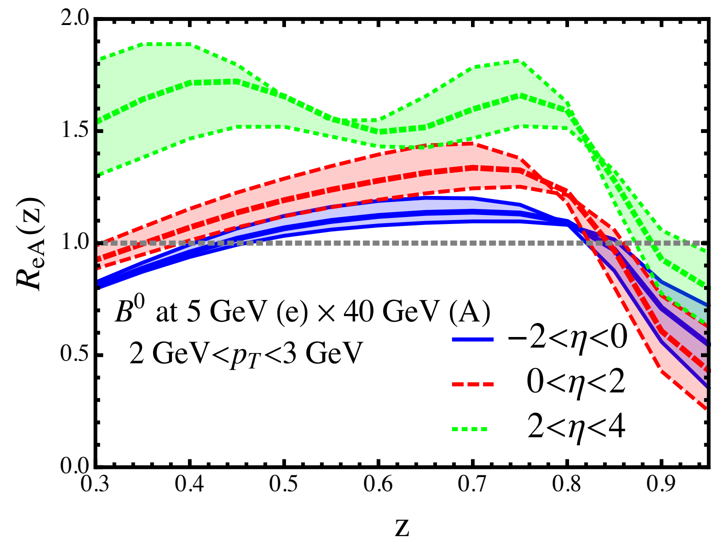
The difference in the suppression pattern of pions and D, B mesons is characteristic of the in-medium evolution/energy loss approach

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

Normalized by inclusive large radius jet production. To LO equivalent inclusive normalization



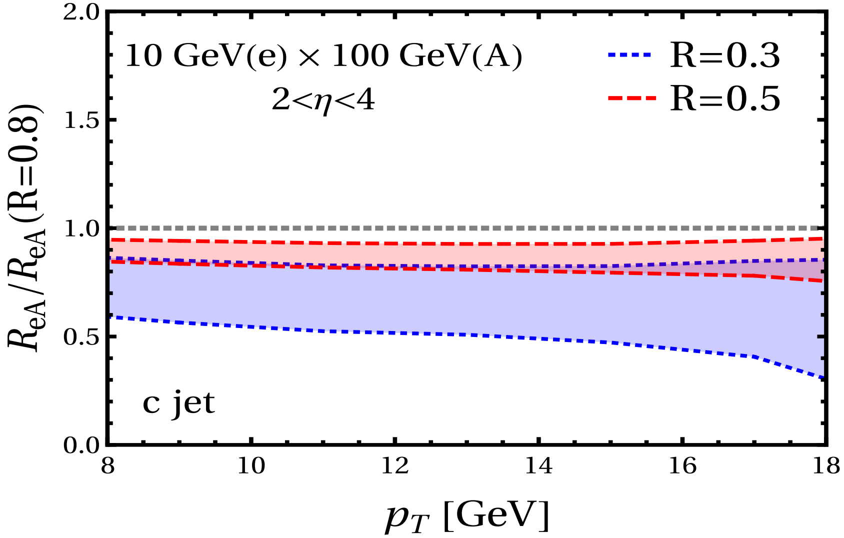
H. Li et al. (2020)



Heavy flavor jets at EIC

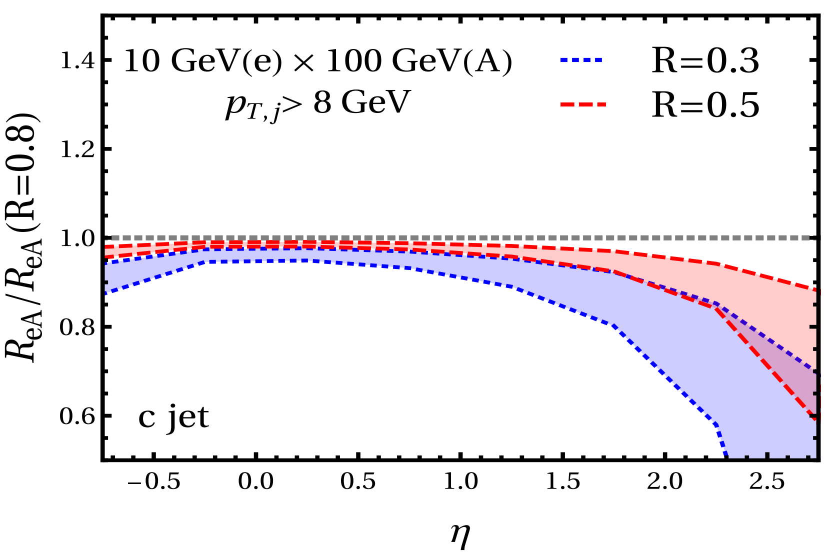
PRELIMINARY

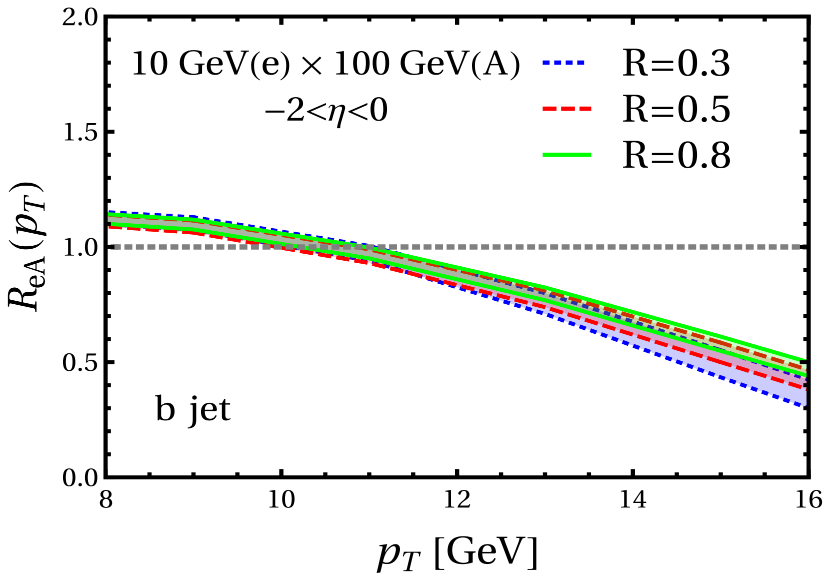
Z. Liu et al. (2021)



- Heavy flavor jet calculations are underway at the LHC

Very strong modification – sensitive to the gluon contribution. Pronounced rapidity dependence.
Results for both c-jets and b-jets upcoming.
Interesting to study their substructure in eA

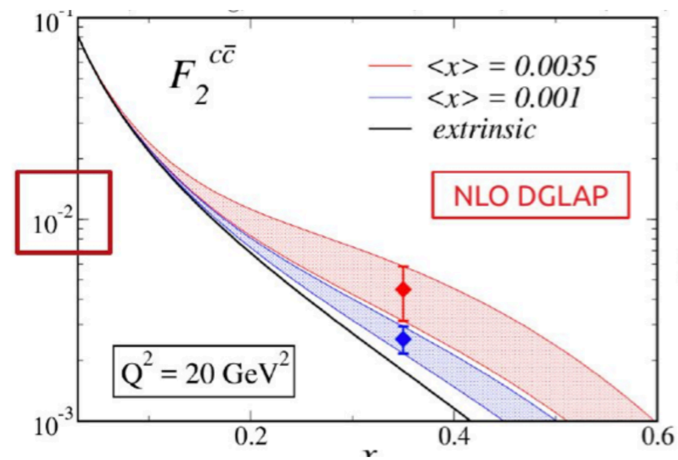




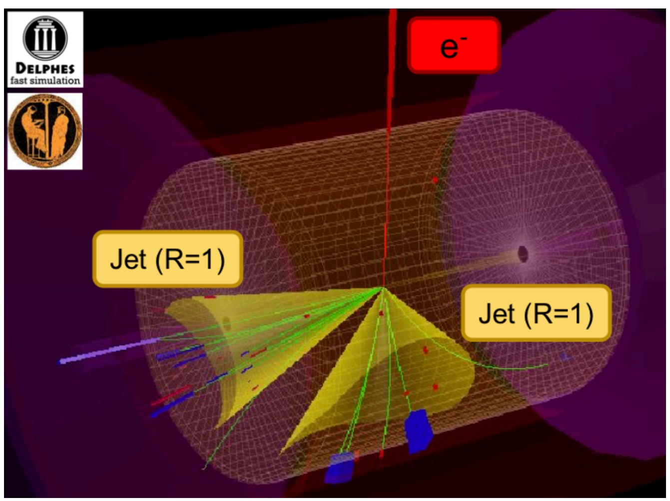
Intrinsic charm and strangeness at the EIC

EIC will finally have the precision to answer long standing questions about large-x structure – strangeness and intrinsic charm

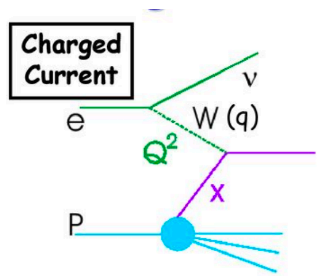
- Intrinsic charm – genuine non-perturbative contribution to the proton wave function – can affect HQ schemes, masses, global fits
- Strangeness – can be accessed via CC reactions. Requires high statistics, can look for enhanced strangeness

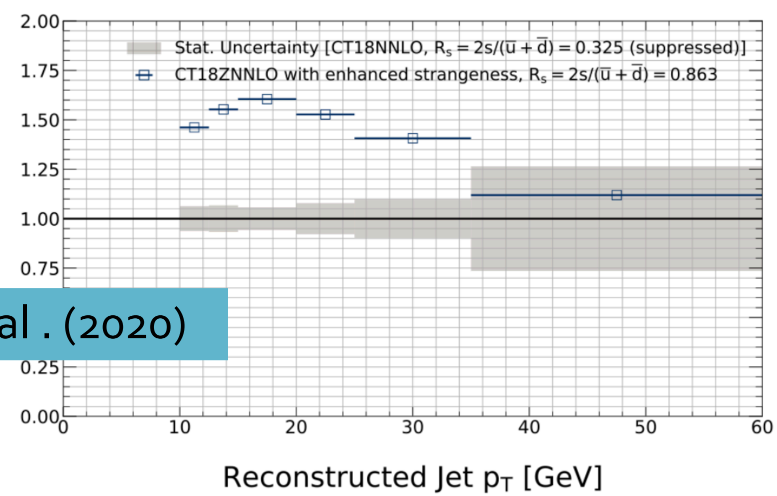


T. Hobbs et al . (2017)



Double charm jet NC event





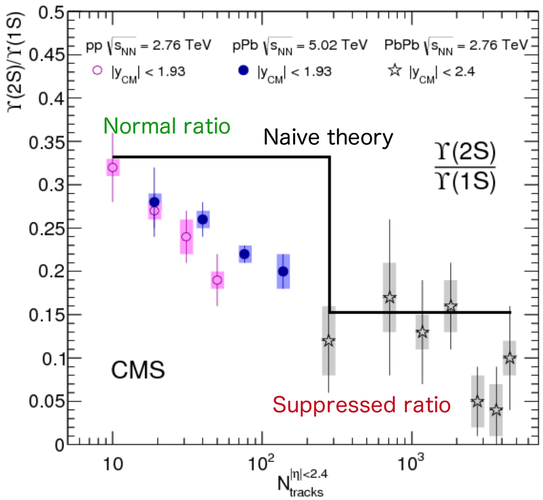
M. Arratia et al . (2020)

Conclusions

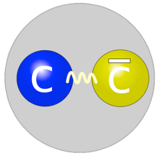
- Important progress has been made in the theory of hard probes (QCD, SCET, NRQCD) – precise high order and resumed calculations standard. X+A collisions provide new opportunities to study many-body QCD, emergence of EFTs in matter. Progress toward medium motion effects, gradient corrections – leading subeikonal effects
- Hadron production has been instrumental instrumental in the discovery of jet quenching and jet tomography. Modern QCD / SCET techniques in matter (evolution, NLO) first developed here. The mix of nuclear matter effects more pronounced at. RHIC. At EIC hadrons are the first line of study for cold nuclear matter tomography and to check the fundamental theoretical understanding of nuclear effects. Effects are large and measurable
- Jet production and substructure are the next step in jet quenching studies (with predictions just like for hadrons before exp. measurements). Require precise theoretical control on parton showers. Novel SCET techniques developed for both cross sections and substructure (which can be understood from first principles). Inclusive and tagged jet theory can be improved at RHIC in anticipation of upcoming measurements. EIC results already available with strategies developed how to separate initial nPDF effects form CNM parton showers and how to use jet substructure to address emerging questions such as isospin symmetry violation at large Bjorken-x
- Heavy flavor comes in its own right by providing a new mass scale ("dead cone effect", extraction of diffusion coefficients in transport models) and the physics of hadronization. Predictions for heavy flavor jets quenching exist, but more importantly heavy jet substructure modification (momentum sharing distributions) can show different mass hierarchy of nuclear effects at moderate p_T . Dijet mass calculations have shown that this observable can enhance more subtle jet quenching effects. At the EIC heavy meson production can shed light on the physics of hardonization / differentiate between competing paradigms of DIS nuclear attenuation. Heavy flavor jets calculations are underway
- There are also important developments in the theory of quarkonium production, stochastic equations for evolution from open quantum systems and the formulation of NRQCD in matter. Upsilon measurements at RHIC will help constrain theory and the EIC relative contribution of collisional breakup vs thermal dissociation. In eA provide clean constraints on NRQCD LDMEs

Quarkonium production in reactions with nuclei

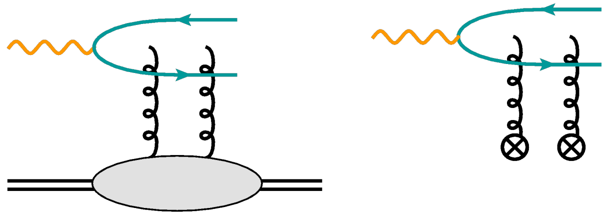
Excited Upsilon suppression



Similar dissociation behavior in A+A, p+A and even in p+p (where QGP is not expected)



NRQCD with Glauber Gluons



$$\mathcal{L}_{\mathrm{NRQCD}_G} = \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A^{\mu,b}_{s}, A^{\mu,a}_{G/C}) + \psi \longleftrightarrow \chi$$

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},q_T} \psi^{\dagger}_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^{0}_{G/C}\Big)\psi_{\mathbf{p}} \quad (collinear/static/soft).$$

Microscopic description of dissociation

Y. Makris et al . (2019)

The EIC will also offer the opportunity to observe quarkonium production in eA collisions where one can study the interactions with nuclear matter and the formation of quarkonia in a nuclear medium.

Open quantum systems

$$H = H_S + H_E + H_I\,, \qquad \frac{\mathrm{d}\rho^{(\mathrm{int})}(t)}{\mathrm{d}t} = -i[H_I^{(\mathrm{int})}(t), \rho^{(\mathrm{int})}(t)]$$

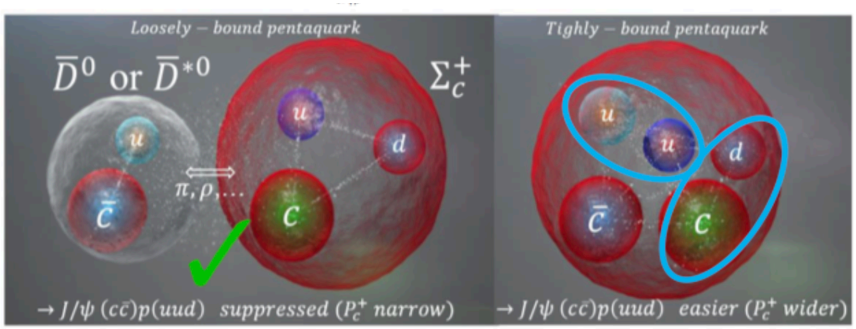
Akamatsu et al . (2014)

Yao et al . (2020)

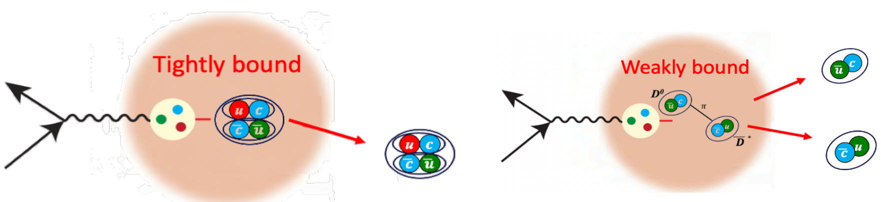
Heavy exotic states at the EIC

Many exotic states – mesons (tetraquarks) and baryons (pentaquarks) being observed

S. Olsen *et al.*, RMP(2018)



Masses expected near $\bar{D}^{(*)}\Sigma_c^+$ thresholds

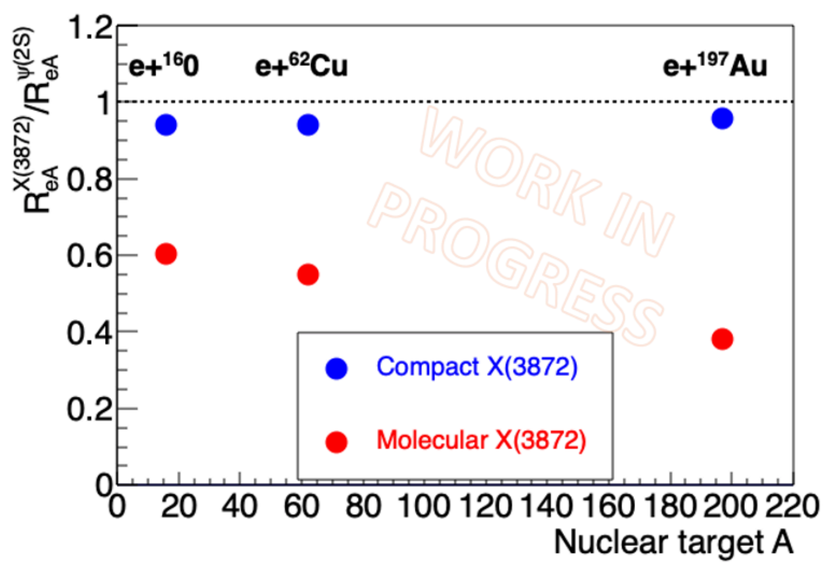


Use the nucleus as a "filter" for the heavy states

New physics observables

Structure and formation process of new exotic hadrons, e.g. X(3872) can be explored by measuring their suppression in e+A collisions.

Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV



Arleo *et al.*, PRC, 61 054906 (2000)