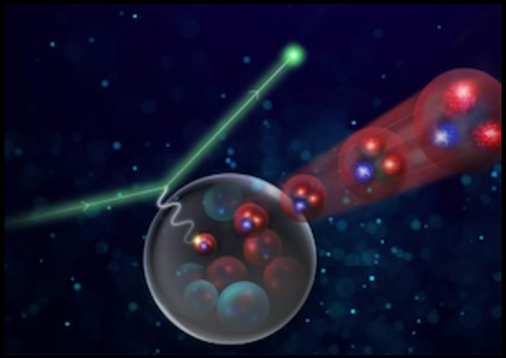
Ivan Vitev

Jets and Heavy Flavor at the EIC



The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond,
Virtually on line, June 7-8, 2021

Los Alamos
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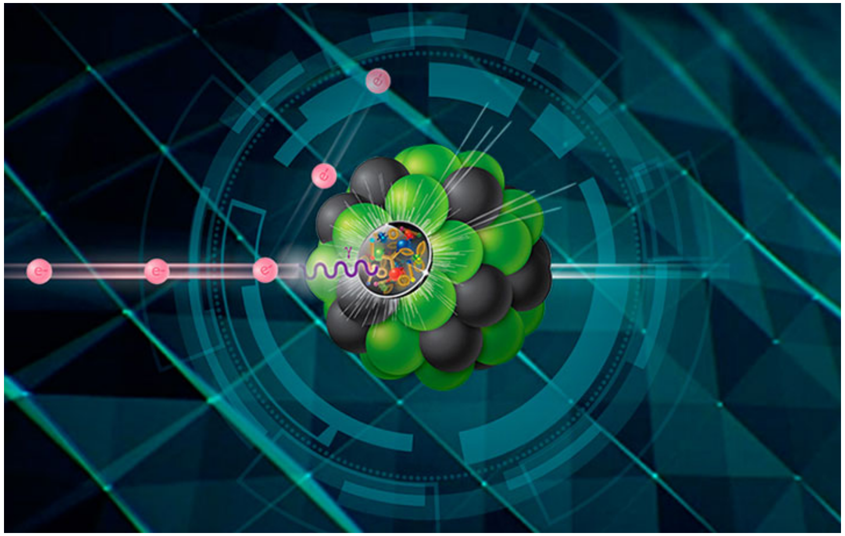
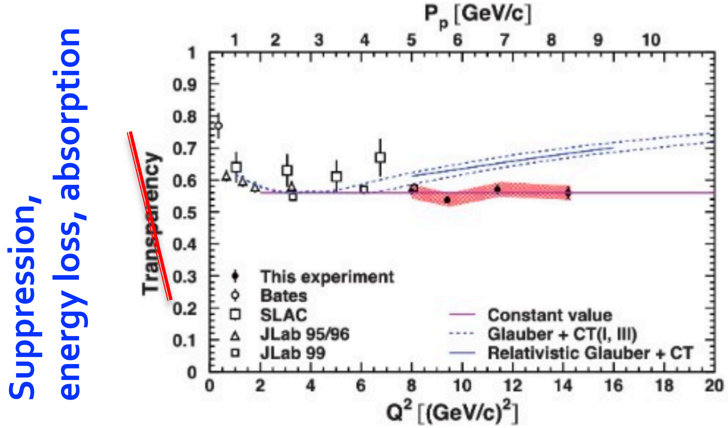
Outline of the talk



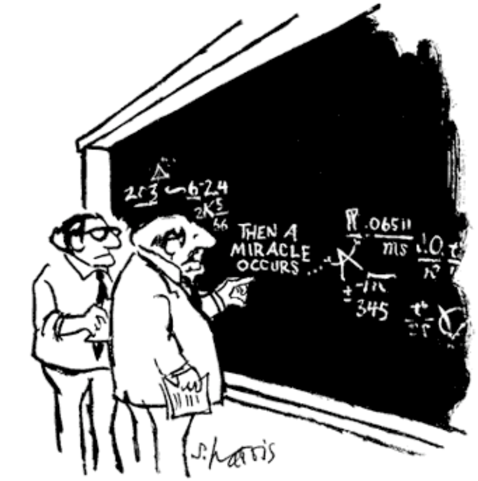
- Theoretical underpinnings
- Hadron production
- Jets and jet substructure
- Heavy Flavor

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

What we have seen is hadron suppression – energy loss and absorption

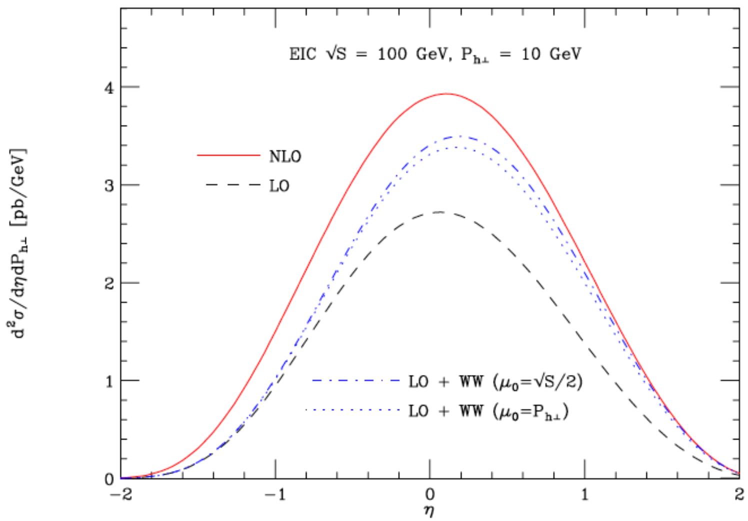


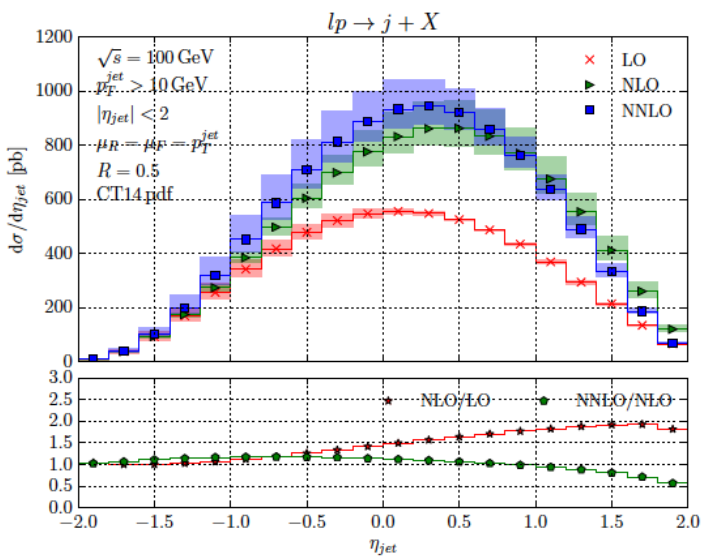
I. Theoretical underpinnings



"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

Hadrons

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

Jets

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

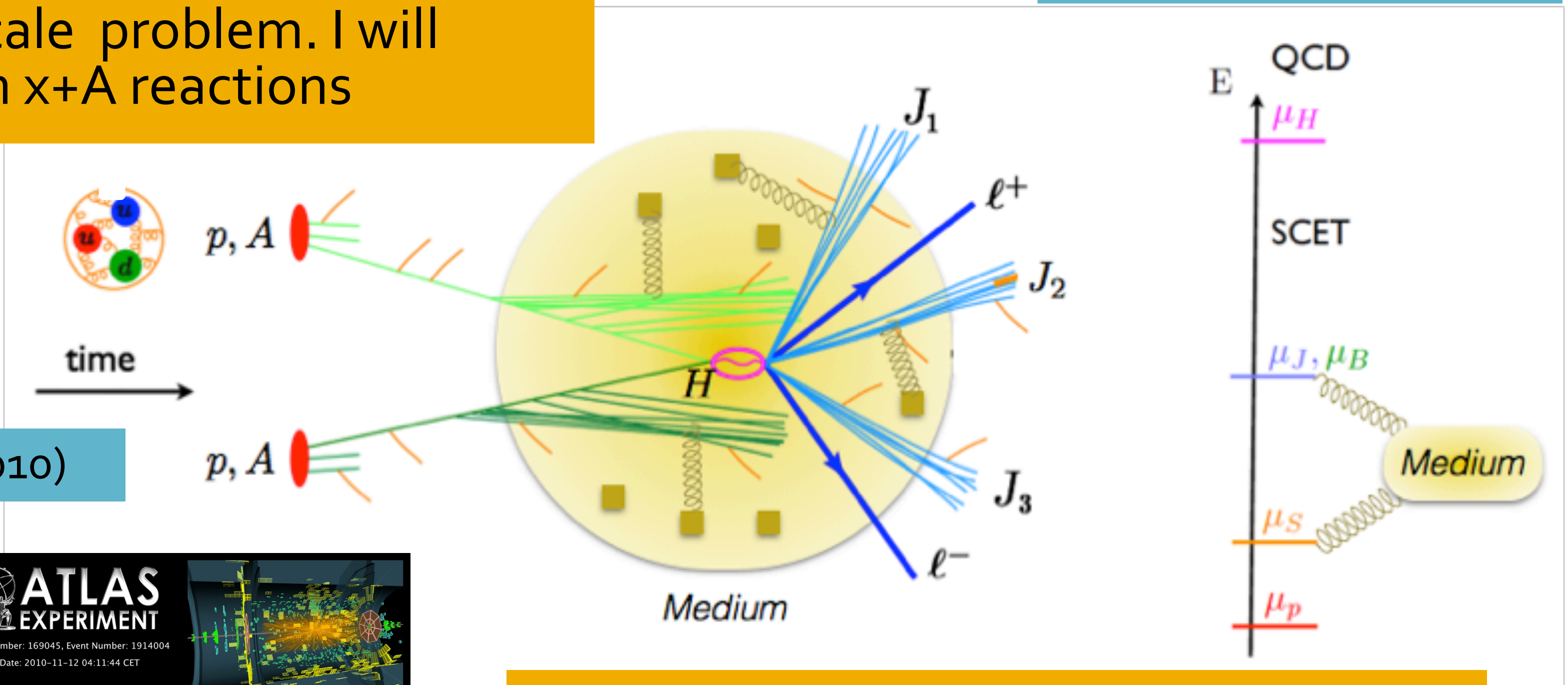
P. Hinderer et al. (2015)

G. Abelof et al. (2016)

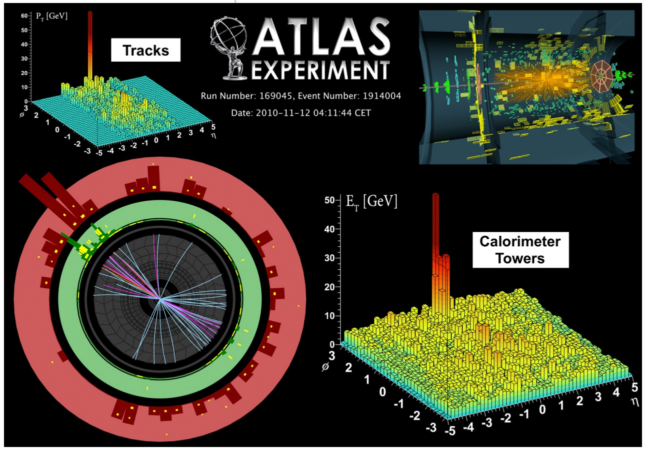
Nucelei and interactions of hard probes in matter

- 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

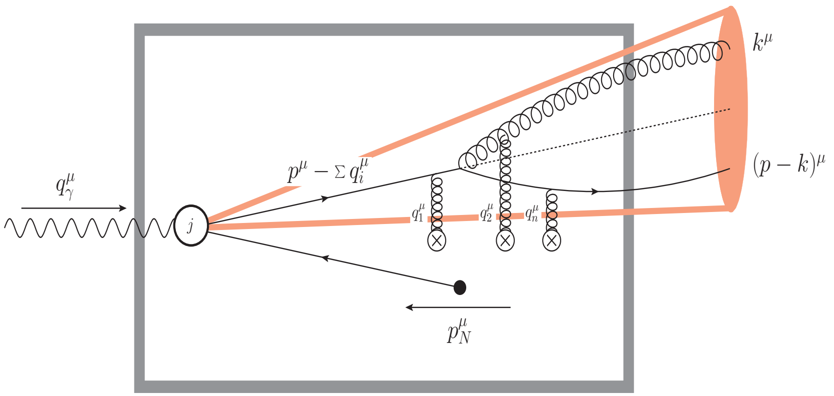
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

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

G. Ovanesyan et al . (2012)

Z. Kang et al . (2016)

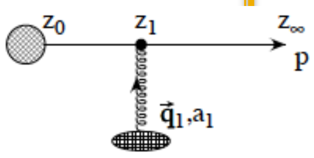
M. Sievert et al . (2018)



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

Develop specific EFTs for particle propagation in matter

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

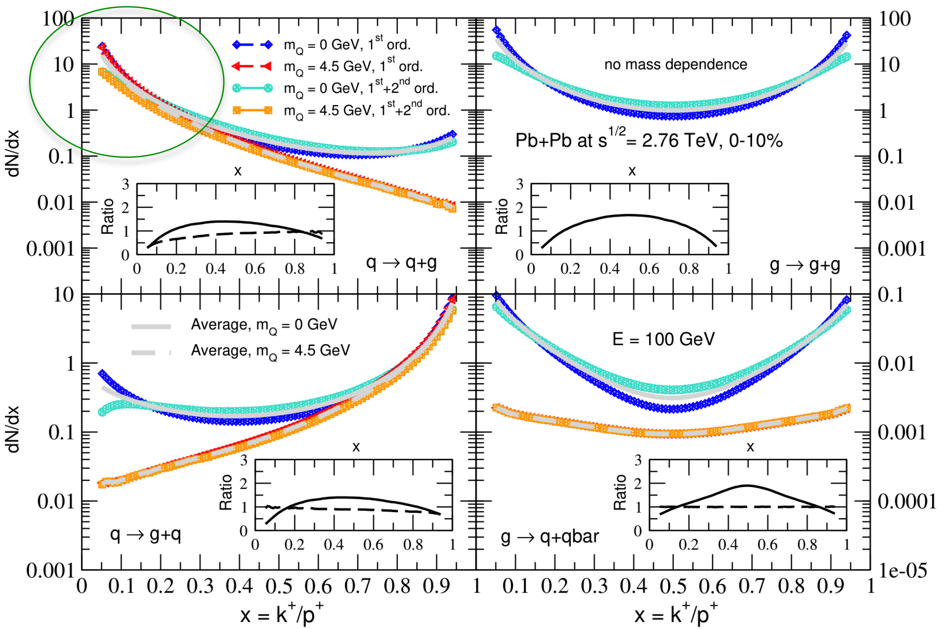


- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

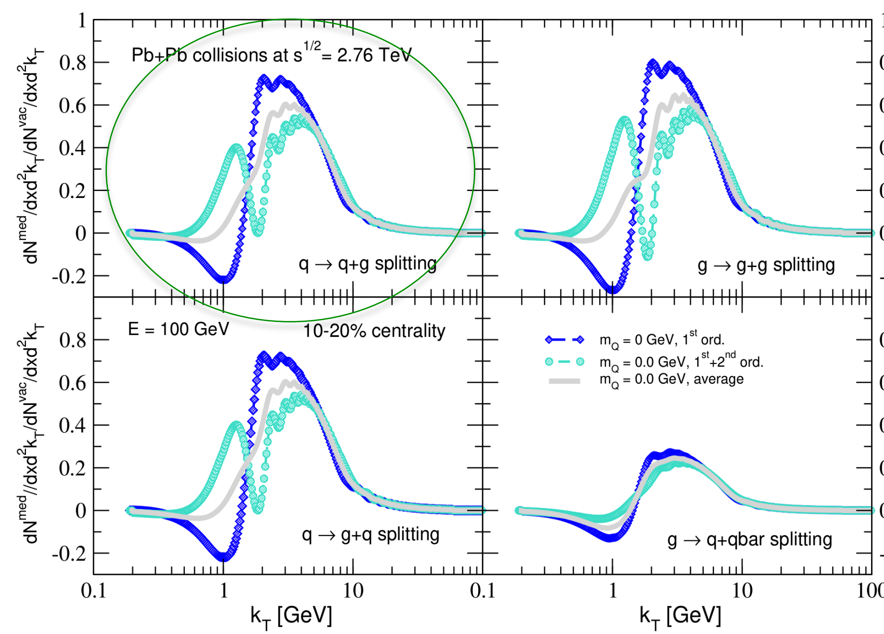
Often used in saturation calculations. Can get on one shot massless and massive splitting functions

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

Differential branching spectra

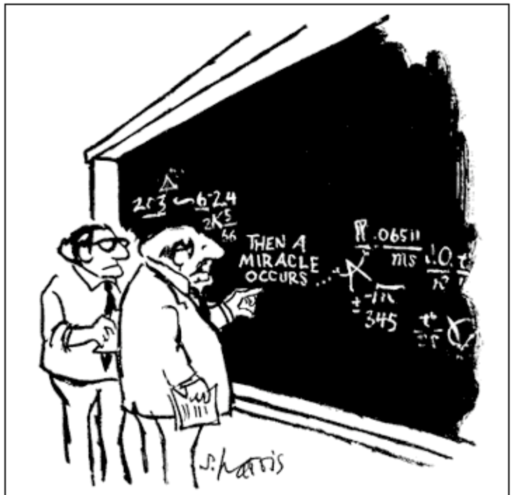


- Production of hadrons and jets can be understood from the broader and softer splitting functions
- Holds to higher orders in opacity



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

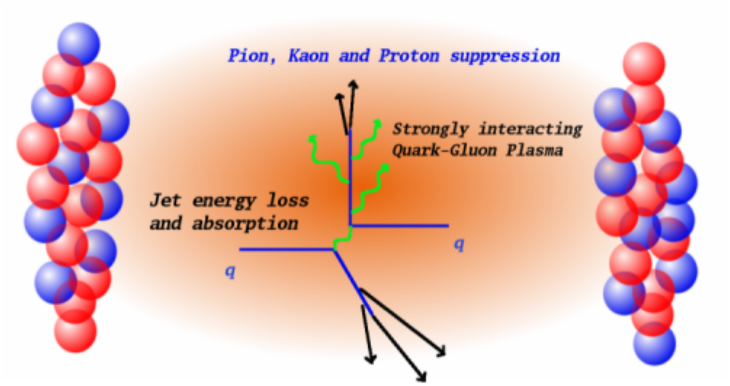
II. Hadron production

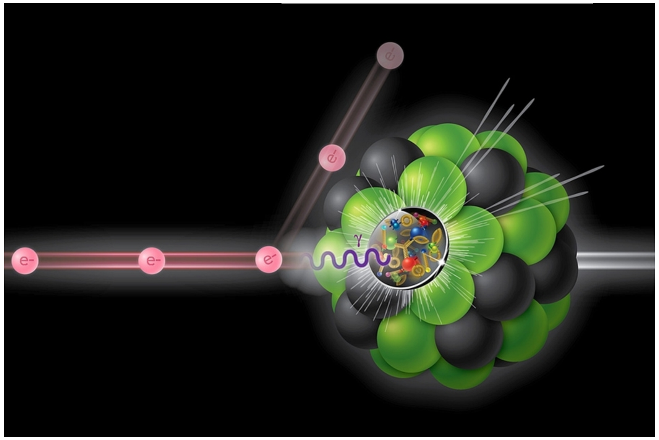


"I think you should be more explicit here in step two."

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



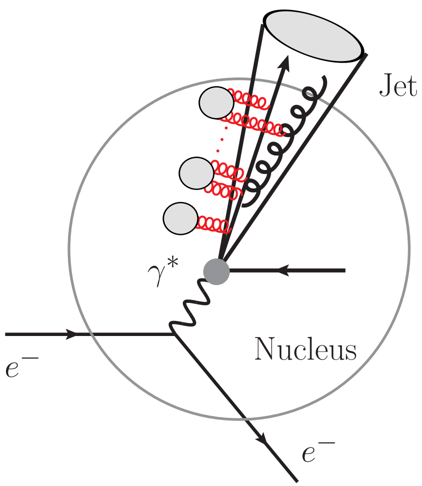


- Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)
- Largest effects at midrapidity
- Higher C.M. energies correspond to larger plasma densities

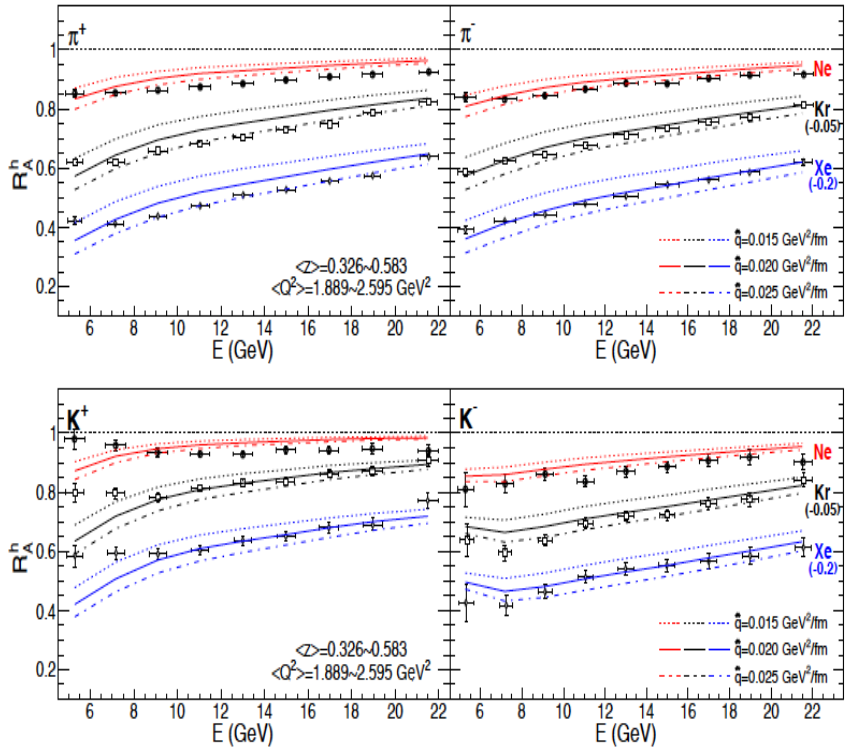
- Jets are on the nuclear rest frame. Longitudinal momentum matters
- Largest effects are at forward rapidities
- Smaller C.M. energies (larger only increase the rapidity gap)

Modification of light hadrons at HERMES

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



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



N. Chang et al. (2014)

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

Transport properties:

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

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

NB: this is our extraction of transport properties - others vary up/down by a factor of 2

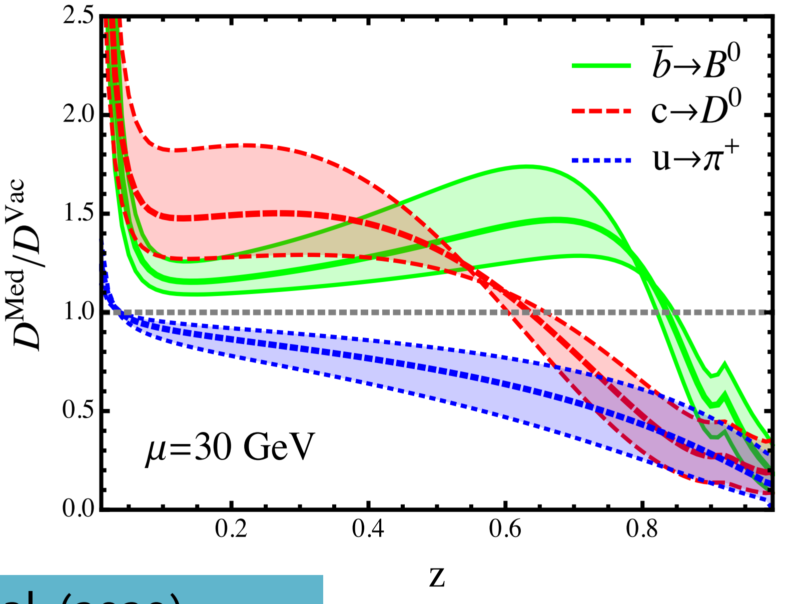
Modification of FFs

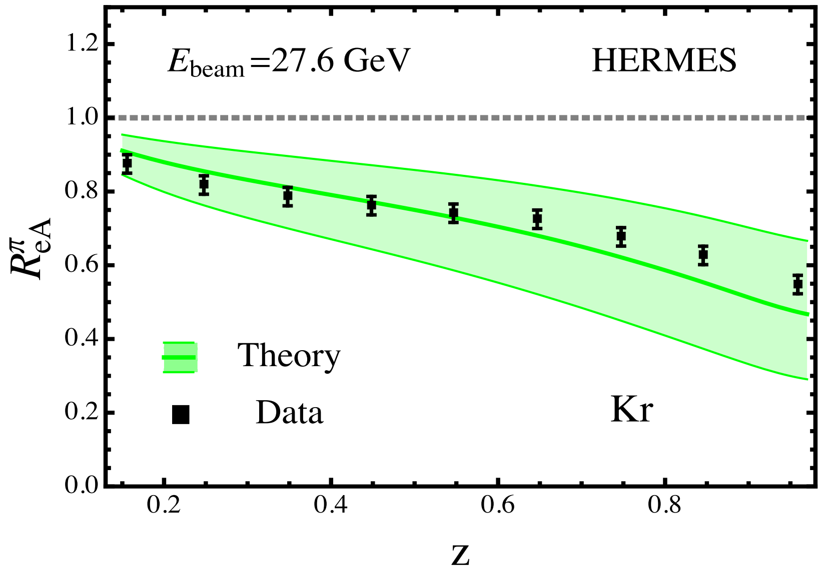
Vacuum splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs

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

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

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

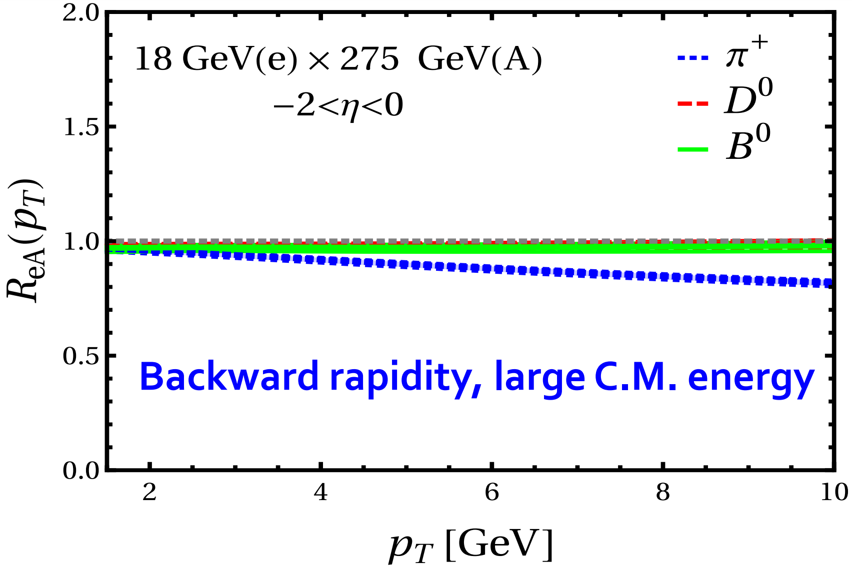


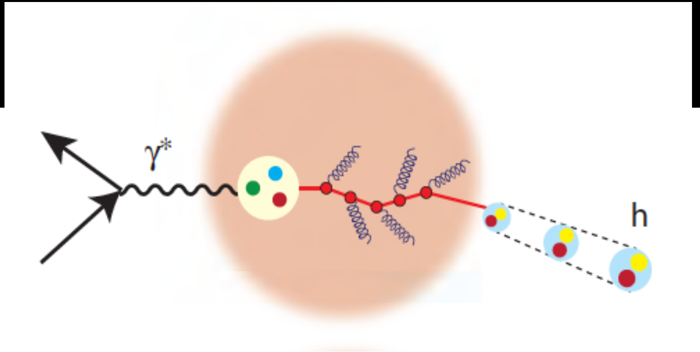


Z. Liu et al. (2020)

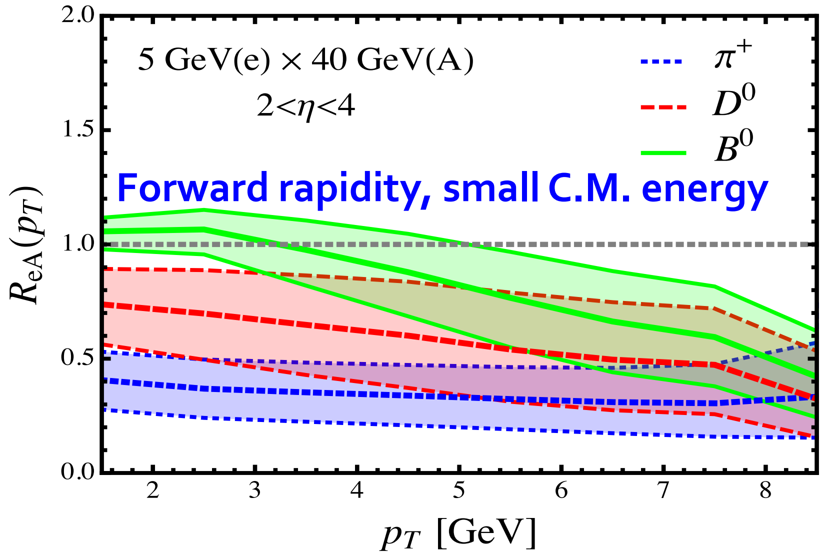
- Always enhancement at small z but for pions (light hadrons) at very small values – mostly suppression
- Very pronounced differences between light and heavy flavor fragmentation

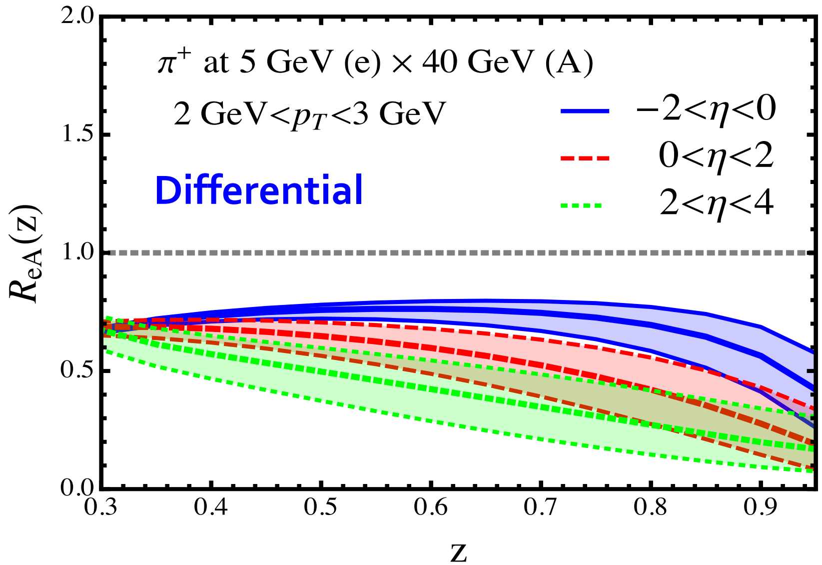
Light flavor suppression at the EIC





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



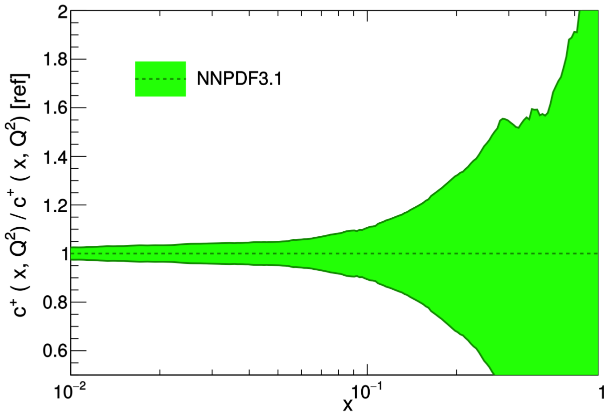


H. Li et al . (2020)

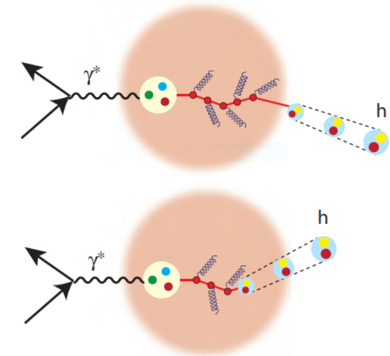
Heavy flavor hadrons at the EIC

Multiple uses of heavy flavor

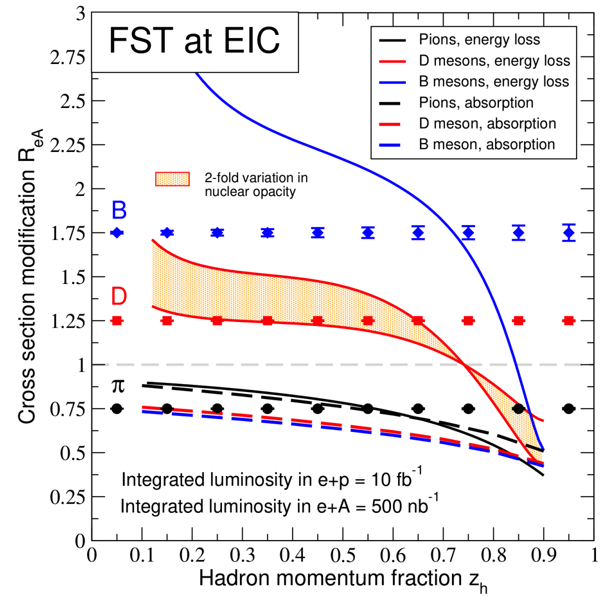
- Constrain gluon and c/b distributions. Look for intrinsic charm



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 cross sections

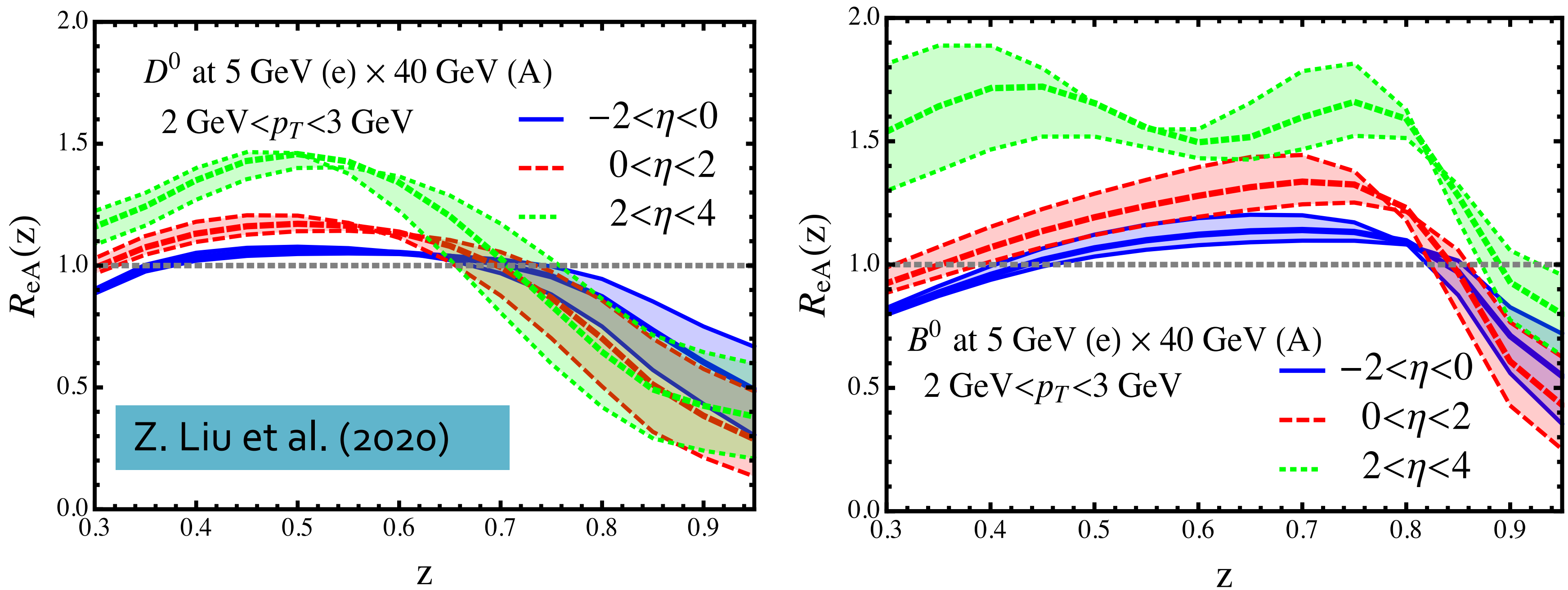
A more differential ratio vs the momentum fraction of the hadron

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

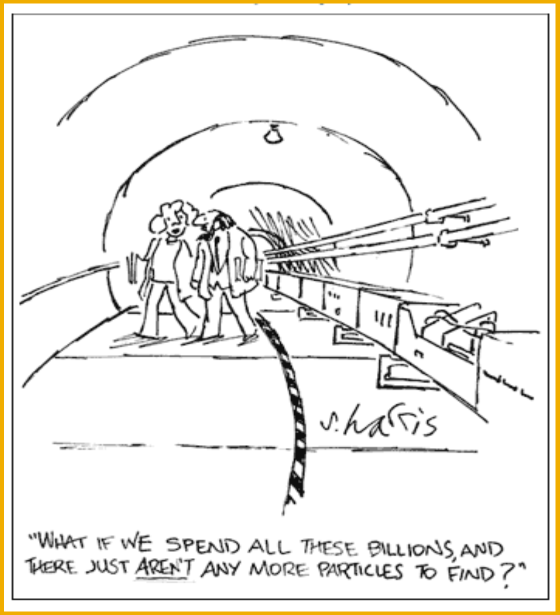
Detailed and constrained predictions for the EIC

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

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



III. Jet production

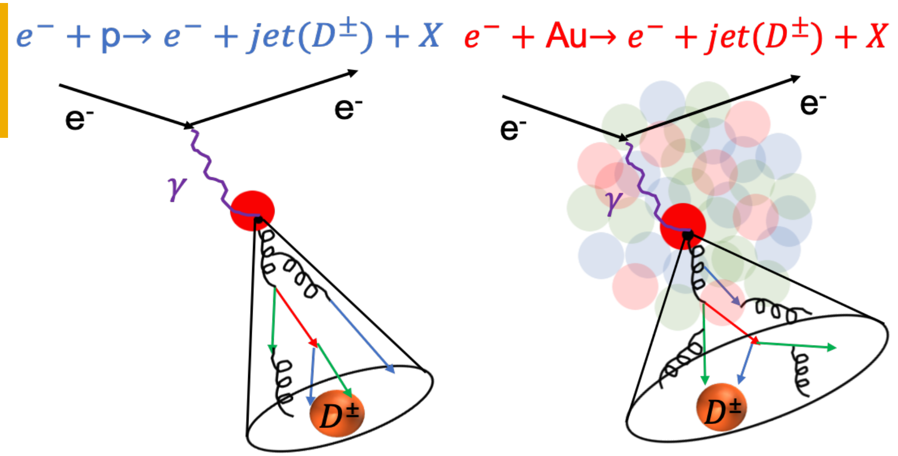


Jet production

Z. Kang et al. (2016)

L. Dai et al. (2016)

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



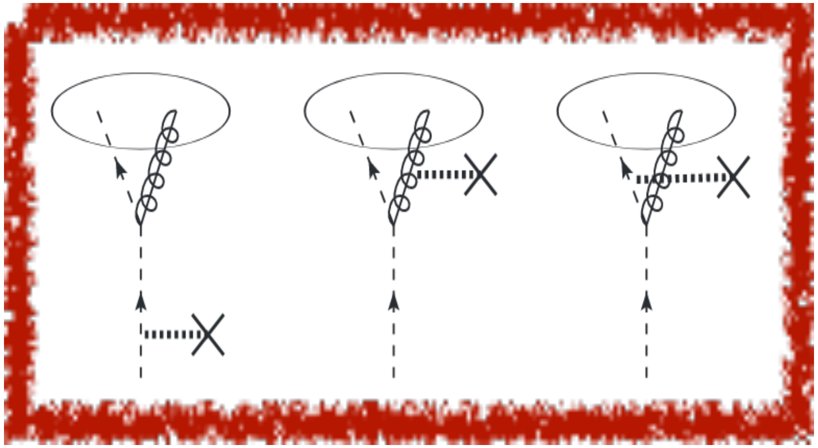
Factorization formula

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

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

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

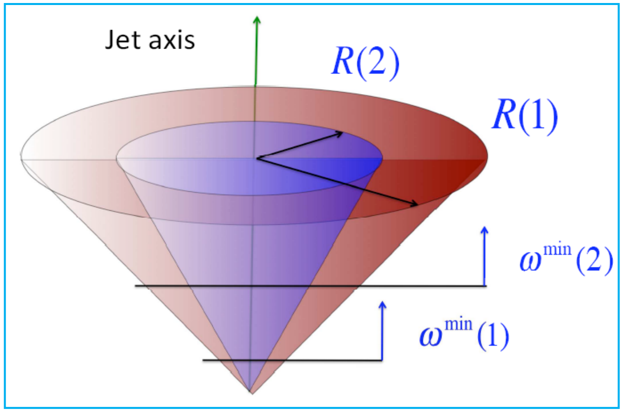
$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$$

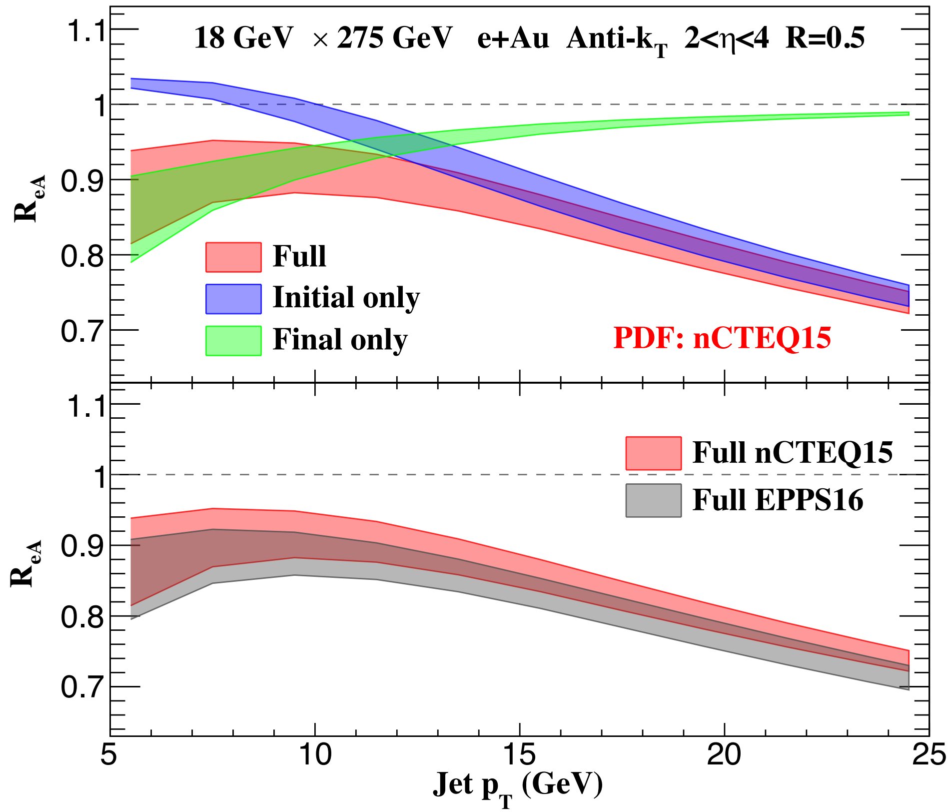
Jet results at the EIC

- 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

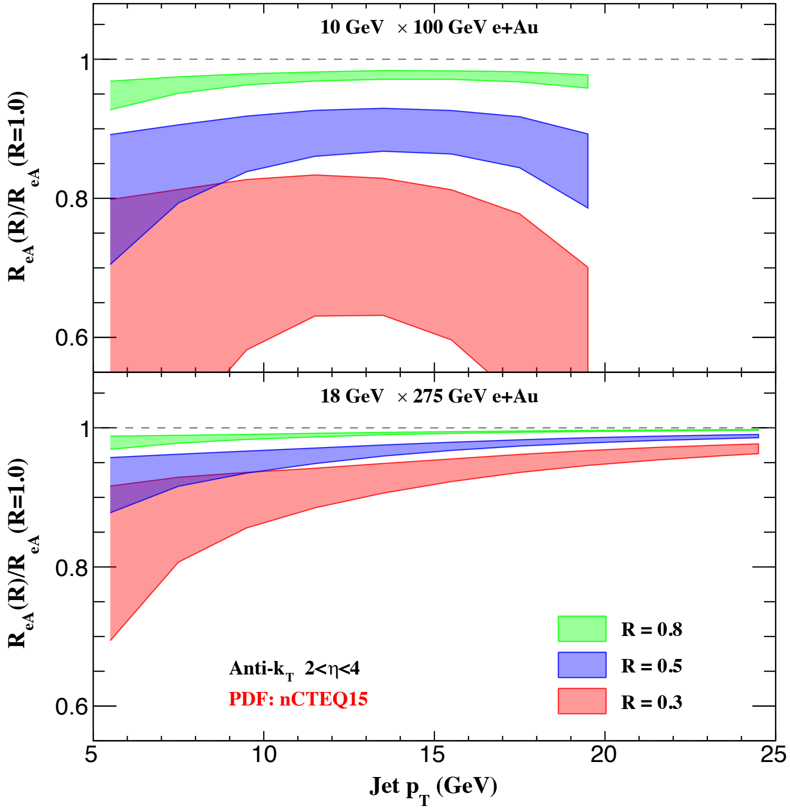
Separating initial-state from final-state effects at EIC

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)

$$Q_{\kappa,\,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^\kappa} \sum_{\text{h in jet}} Q_h \left(p_T^h\right)^\kappa \qquad \langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)}\tilde{D}_q^Q(\kappa,\mu)$$

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

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

The components of he factorization formula receive in-medium corrections

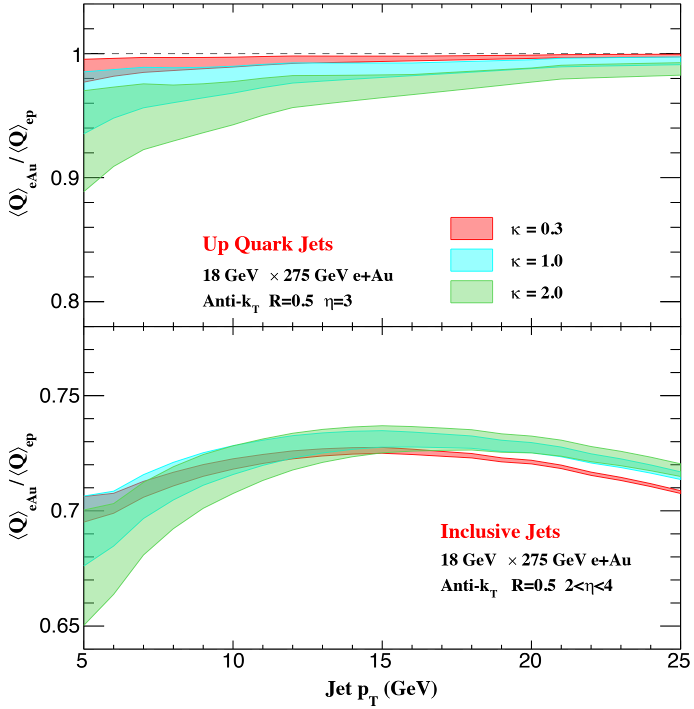
$$\langle Q_{q,\kappa}^{\text{pp}}\rangle \left(1+\tilde{\mathcal{J}}_{qq}^{\text{med}} - J_q^{\text{med}}\right)\exp\left[\int_{\mu_0}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}}\frac{\alpha_s(\bar{\mu})}{\pi}\tilde{P}_{qq}^{\text{med}}\right] + \mathcal{O}\left(\alpha_s^2,\chi^2\right)$$

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

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

SCET approach

D. Krohn et al. (2012)

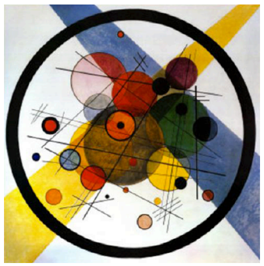


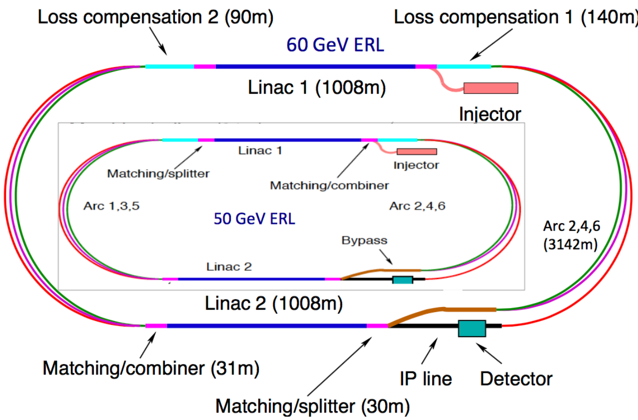
H. Li *et al.* (2020)

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

Other electron-ion colliders

LHeC – large hadron electron collider



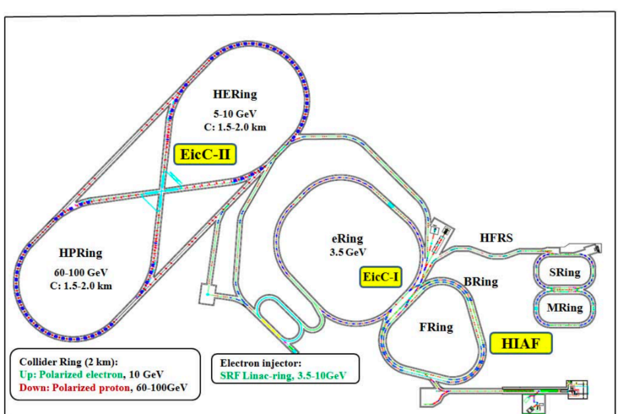


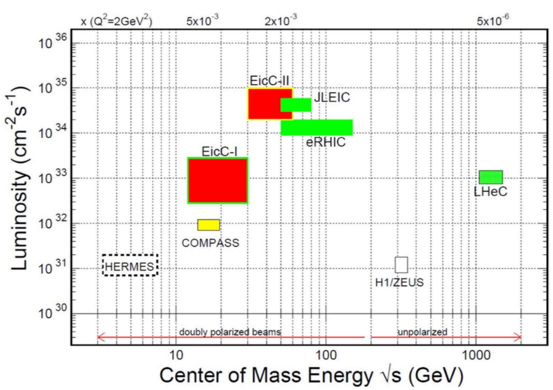
Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7	14	35

C.M. energies of order TeV at the LHeC will eliminate medium-induced parton-shower effects and the facility will be best suited to study nuclear PDFs and small-x physics

P. Augostini *et al.* (2020)

EicC - electron ion collider in China

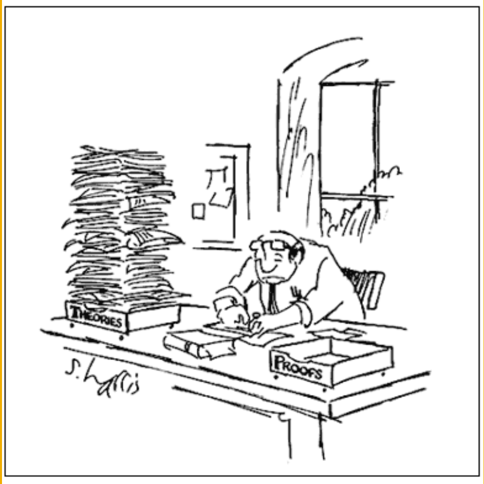




EicC would have ideal C.M. energies to study hadronization and energy loss (I), nuclear effects on jets (II). Limited reach for saturation physics.

X. Chen *et al.* (2018)

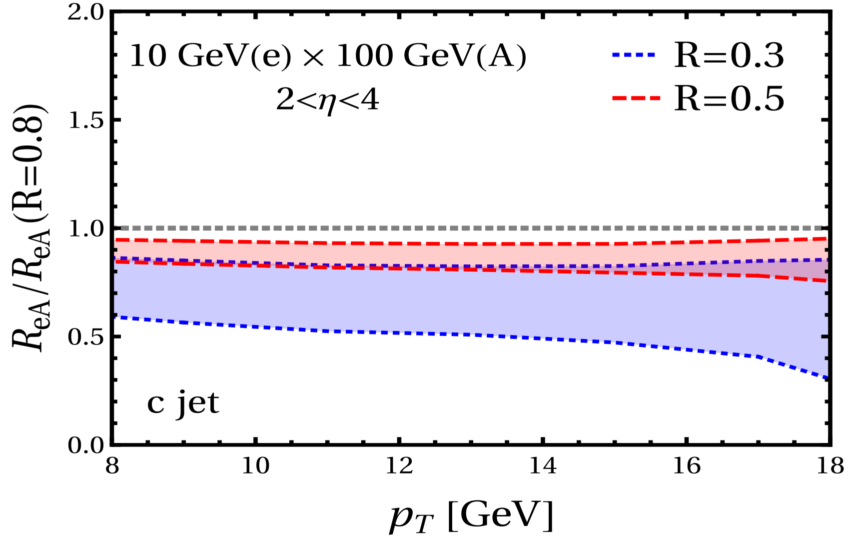
IV. Heavy flavor Jets and quarkonia



Heavy flavor jets at EIC

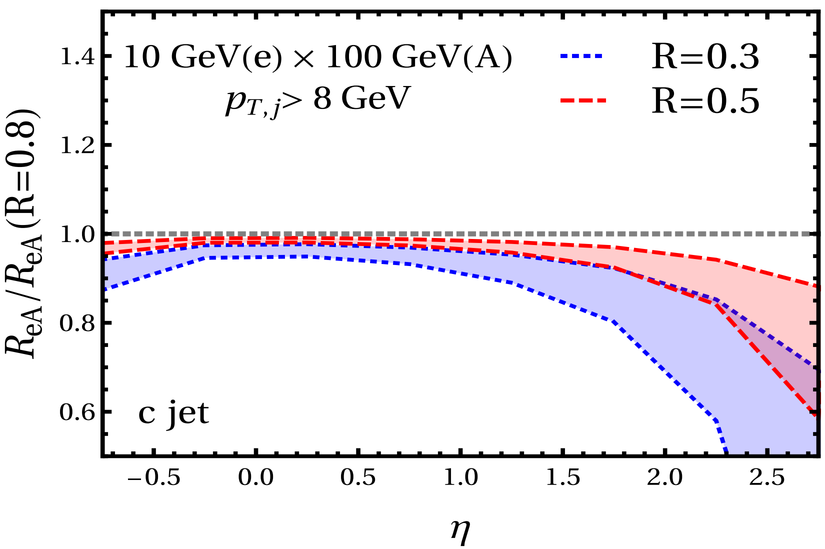
PRELIMINARY

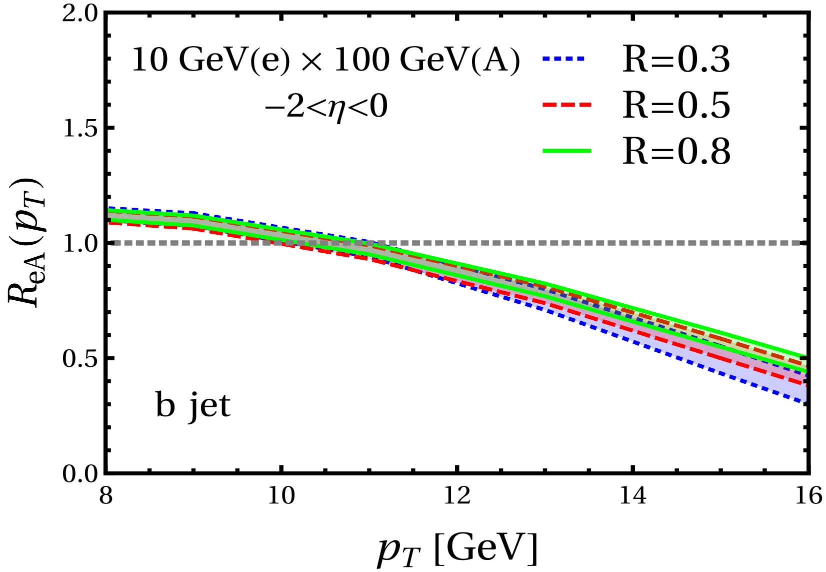
Z. Liu et al. (2021)



- 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

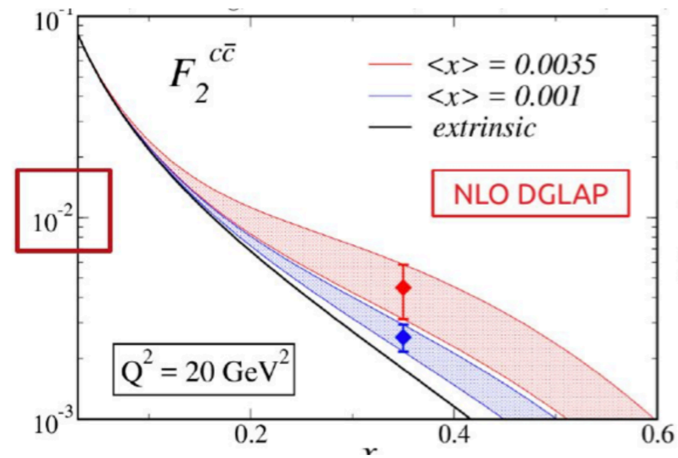




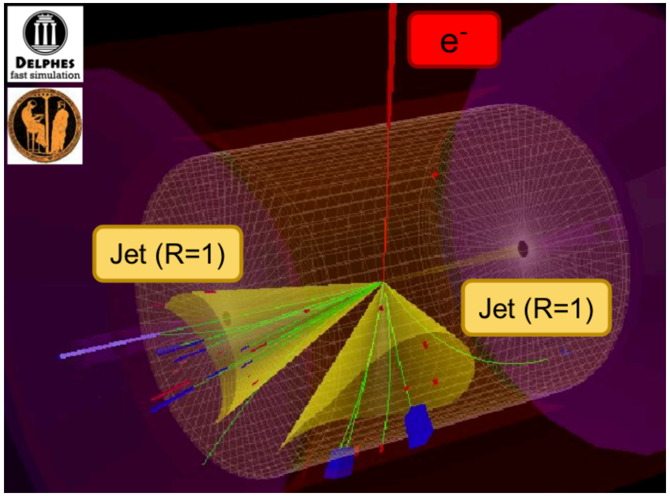
Intrinsic charm and strangeness at the EIC

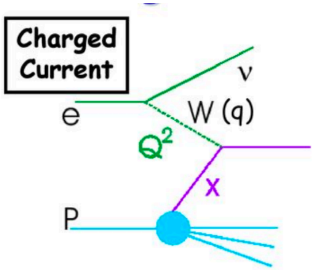
EIC will finally have the precision to answer long standing questions about large-x structure – strangeness and intrinsic charm

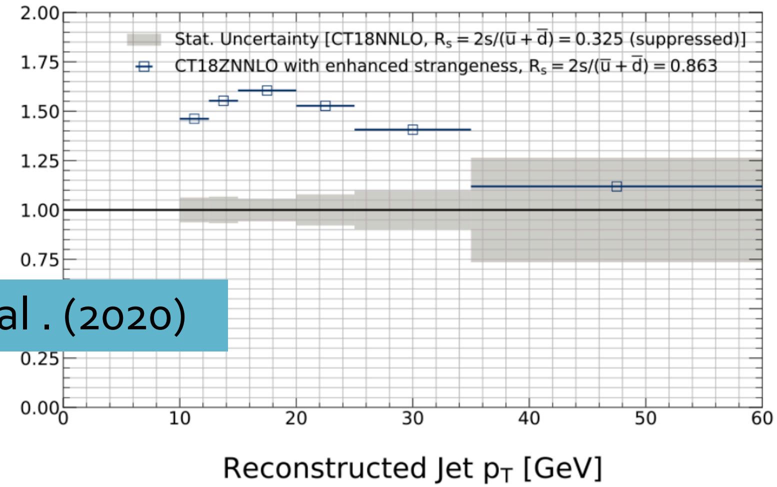
- Intrinsic charm – genuine non-perturbative contribution to the proton wave function – can affect HQ schemes, masses, global fits
- Strangeness – can be accessed via CC reactions. Requires high statistics, can look for enhanced strangeness



T. Hobbs et al . (2017)







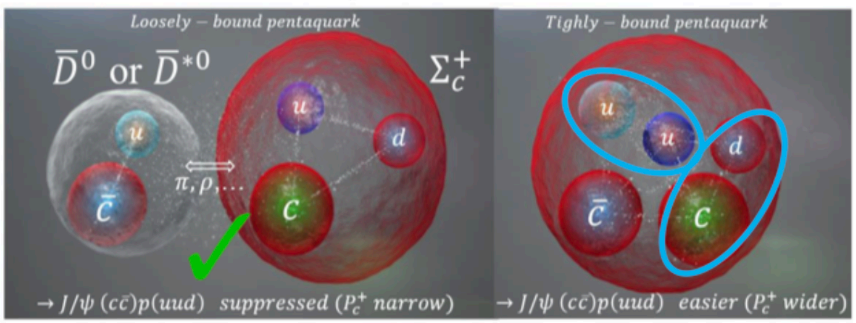
M. Arratia et al . (2020)

Double charm jet NC event

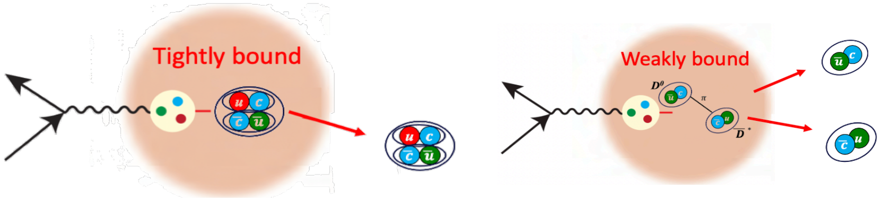
Heavy exotic states at the EIC

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

S. Olsen *et al.*, *R*MP(2018)



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

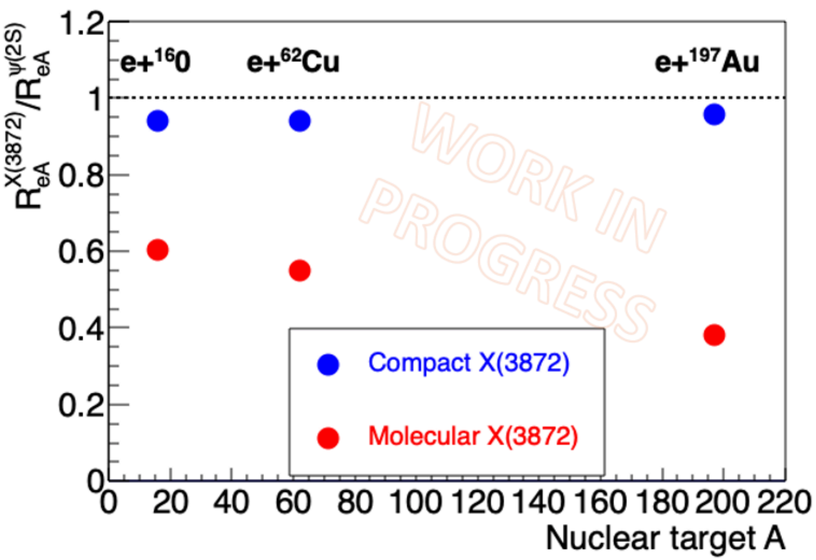


Use the nucleus as a "filter" for the heavy states

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)

Conclusions

- The future of color transparency is hadron and jet suppresson –energy loss, in-medium showers, absorption
- 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. 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 (Forward rapidity, smaller CM energies.)
- 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). 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. 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. In eA provide clean constraints on NRQCD LDMEs