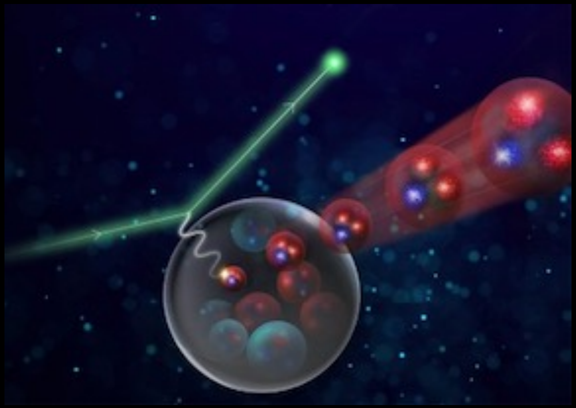
Ivan Vitev

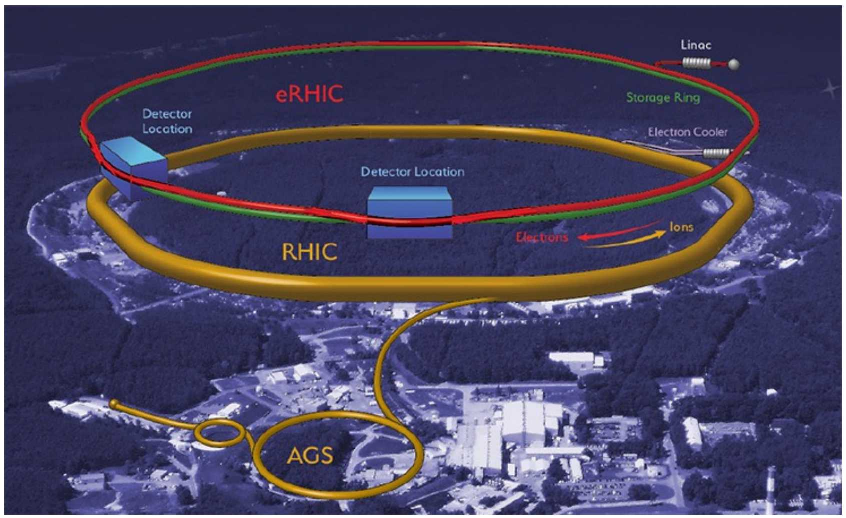
Heavy Flavor at the EIC

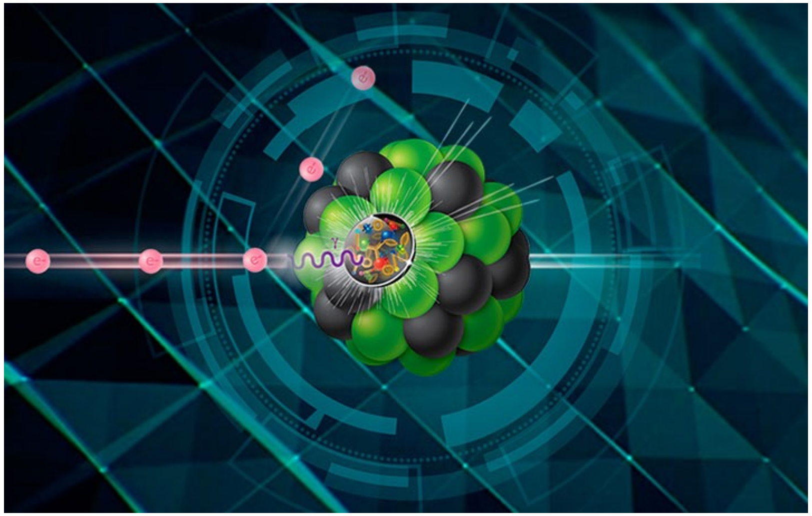


A Virtual Tribute to Quark Confinement and Hadron Spectra,
August 2-6, 2021

Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline of the talk





- Theory and heavy flavor probes of QCD dynamics
- Open heavy flavor hadron production
- Heavy flavor jets and jet substructure
- Quarkonium production and exotics

H. Li, Z. Liu, I.V., Phys. Lett. B 816, 136261 (2021)

H. Li, I.V., Phys. Rev. Lett. 126, 252001 (2021)

H. Li, Z. Liu, I.V., in preparation

I. Olivant, I.V., in preparation

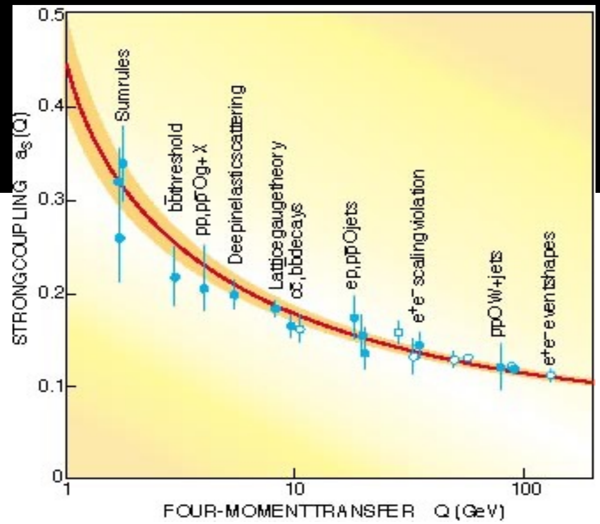
For expert-level comprehensive discussion of HF@EIC topics see https://indico.bnl.gov/event/9273/

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Confinement and hadronization

- Does QCD predict confinement? Yes
- Do we fully understand the static properties of confinement? Not fully
- Do we understand dynamically how confinement occurs? No



- Perturbative hadronization

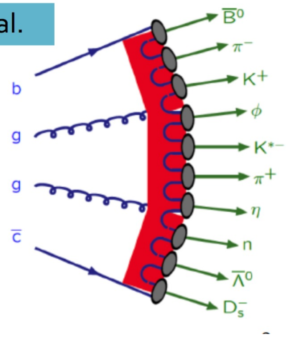
J. Collins et al. (1982)

C. McNeile et al. (2013)

- Hadronization in event generators

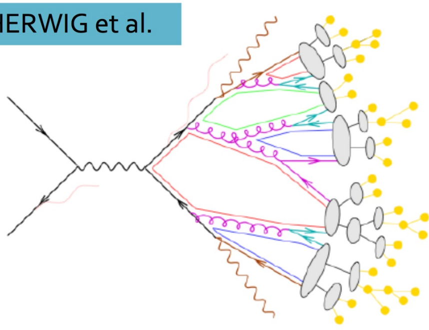
String fragmentation

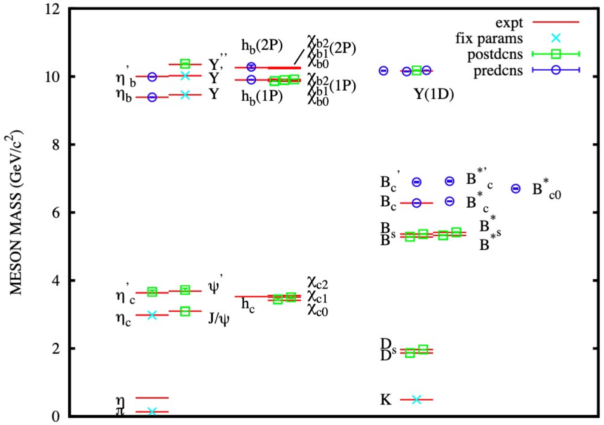
PYTHIA et al.



Cluster hadronization

HERWIG et al.





- Hadronization in the nuclear environment - in can provide insights into the dynamics and the space-time picture of hadronization

Total HF cross sections and lessons from HERA data

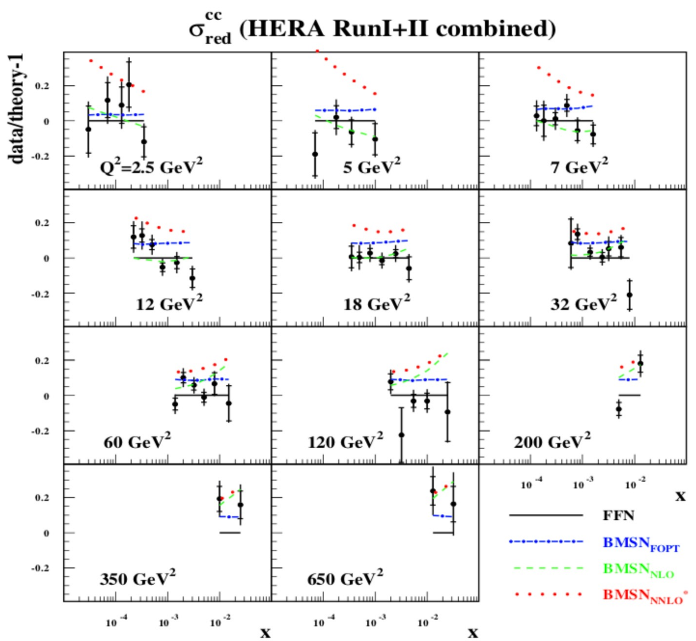
Realistic evaluations combine FFNS and VFNS, subtraction of double counting is required

$$F_{2,h}^{FFN} = \sum_{k=1}^{\infty} a_s^k(n_f) \sum_{i=q,g} H_{2,i}^{(k)}(n_f) \otimes f_i(n_f),$$

$$F_{2,h}^{ZMVFN} = \sum_{k=0}^{\infty} a_s^k(n_f+1) \sum_{i=q,g,h} C_{2,i}^{(k)}(n_f+1) \otimes f_i(n_f+1)$$

- Transitions between FFN and VFS
- Depending on order/prescription, Q2 – good description of DIS data

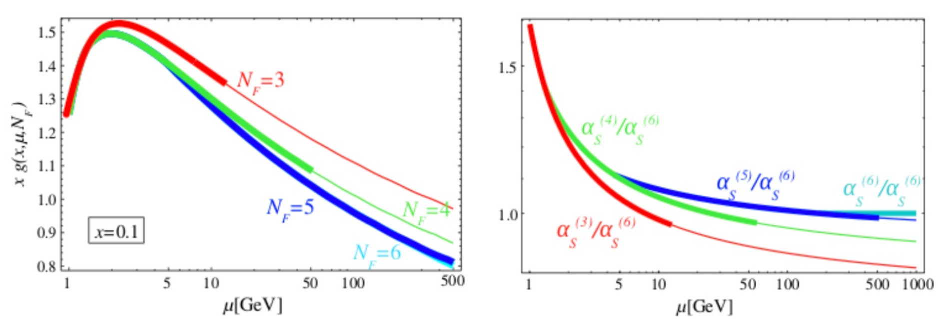
S. Alekhin et al . (2020)



Confronting HF schemes with HERA data

Hybrid variable flavor number scheme

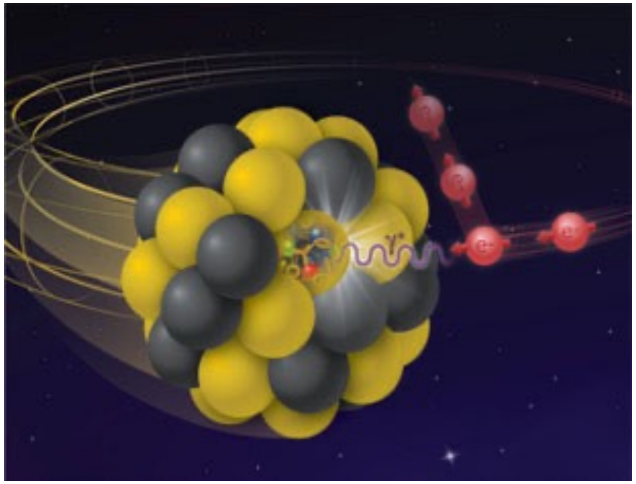
- Different choices of matching mass values. It allows the user, for example to use Nf=4 above Mb scale for example



V. Bertone et al . (2018)

Heavy flavor in polarized reactions at the EIC

The EIC is a polarized machine – will constrain precisely the spin content of nucleons and nuclei and their 3D landscape



Hadrons (DD-bar)

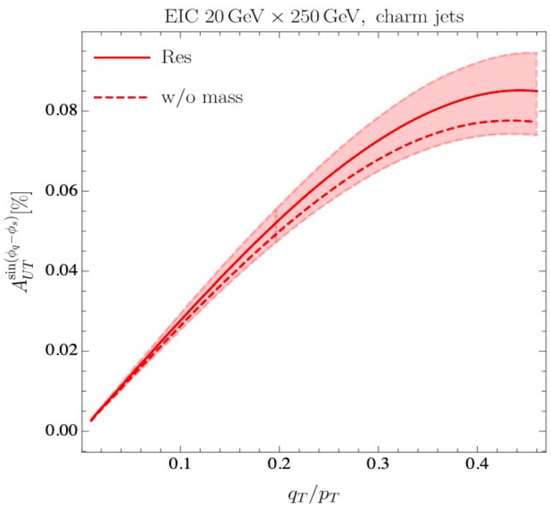
L. Zheng et al. 2018

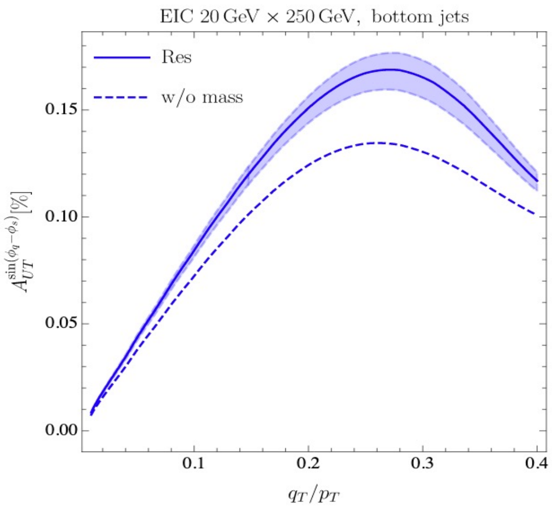
$$\frac{d\sigma^{UT}(\boldsymbol{S}_T)}{dQ^2 dy d^2\boldsymbol{q}_T dy_J d^2\boldsymbol{p}_T} = \sin(\phi_q - \phi_s)\, H(Q, y, p_T, y_J, \mu_h) \int_0^\infty \frac{b^2 db}{4\pi} J_1(b\, q_T) f_{1T, g/N}^{\perp, f}(x, \mu_{b*})$$
$$\times \exp\left[-\int_{\mu_{b*}}^{\mu_h} \frac{d\mu}{\mu}\Gamma^h(\alpha_s) - 2\int_{\mu_{b*}}^{\mu_j} \frac{d\mu}{\mu}\Gamma^{j_Q}(\alpha_s) - \int_{\mu_{b*}}^{\mu_{cs}} \frac{d\mu}{\mu}\left(\bar{\Gamma}^{cs_Q}(\alpha_s) + \bar{\Gamma}^{cs_{\bar{Q}}}(\alpha_s)\right)\right]$$
$$\times \exp\left[-S_{\rm NP}^{\perp}(b, Q_0, n\cdot p_g)\right].$$

Jets

Z. Kang et al. 2020

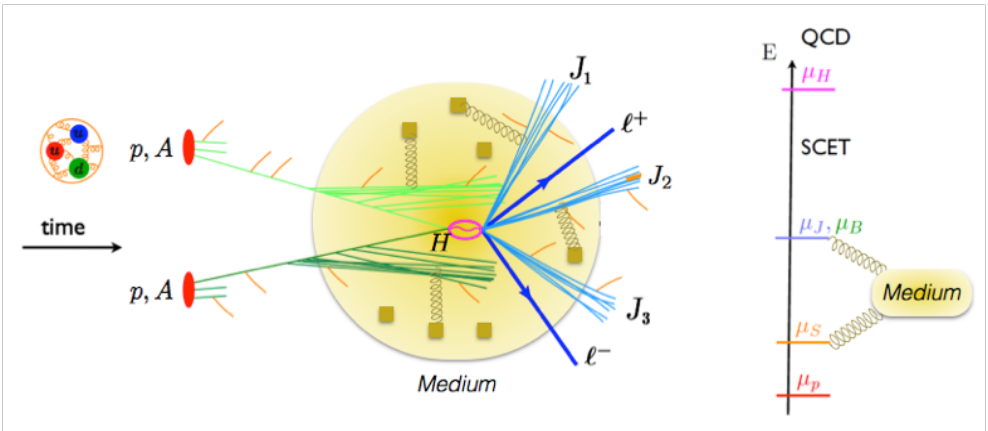
See talk by E. Aschenauer





Rather significant asymmetries. Hadronization reduced the asymmetry. Experimental feasibility studies have also been performed (on charm meson)

Production of semi-inclusive hadrons and jets



C. Bauer et al. (2001)

D. Pirol et al. (2004)

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

In the medium we still have a multi-scale problem

A. Idilbi et al . (2008)

G. Ovanesyan et al . (2011)

Hadrons

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

In the medium: factorization, with modified J (jet), B (beam), S (soft) functions

Jets

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

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

G. Ovanesyan et al . (2012)

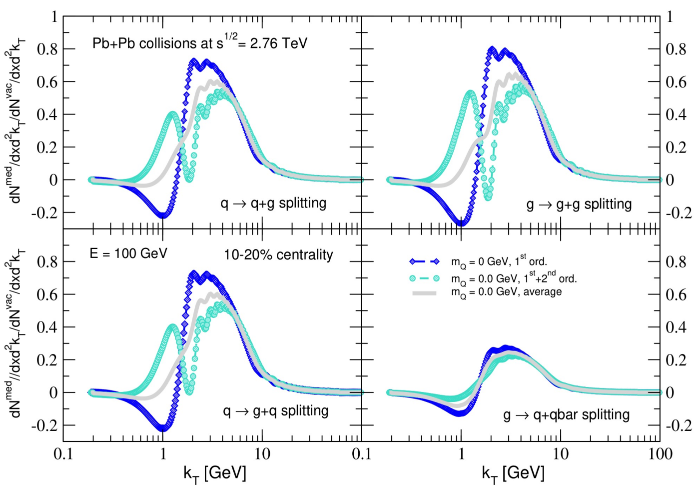
Z. Kang et al . (2016)

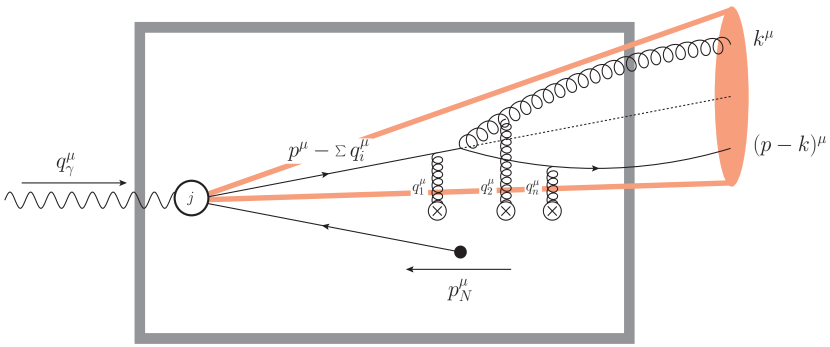
M. Sievert et al . (2018)

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

Develop specific EFTs for particle propagation in matter

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





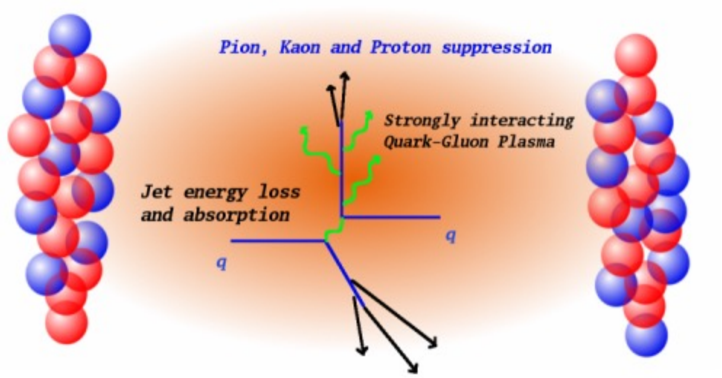
Often used in saturation calculations. Can get on one shot massless and massive splitting functions

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

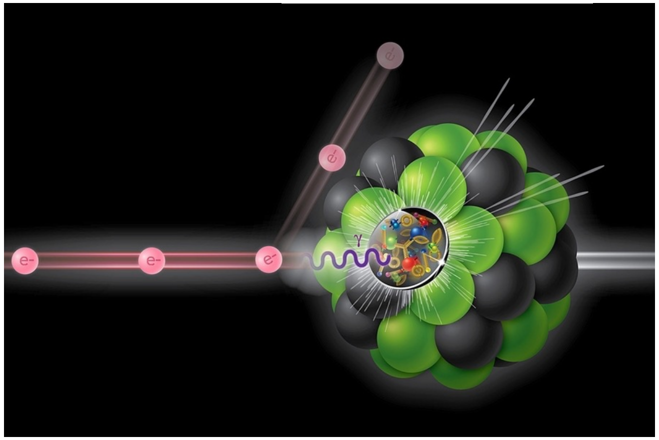
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

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**

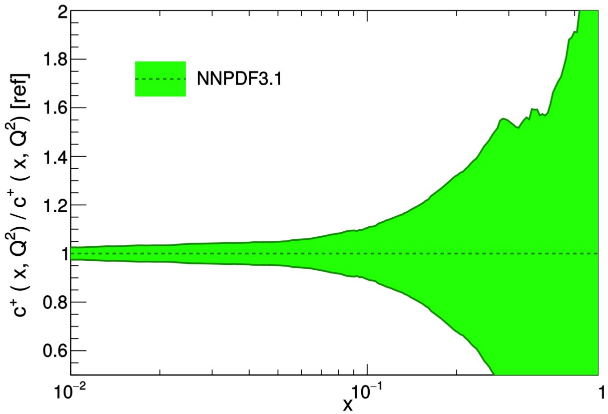


- **Jets are on the nuclear rest frame. Longitudinal momentum matters**
- **Largest effects are at forward rapidities**
- **Smaller C.M. energies (larger only increase the rapidity gap)**

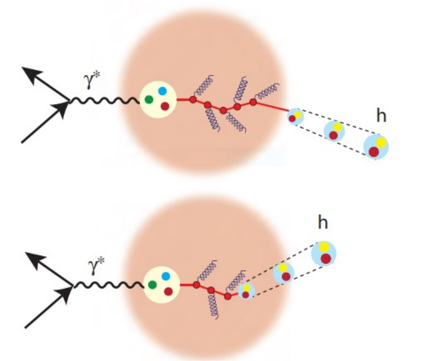
Heavy flavor hadrons at the EIC

Multiple uses of heavy flavor

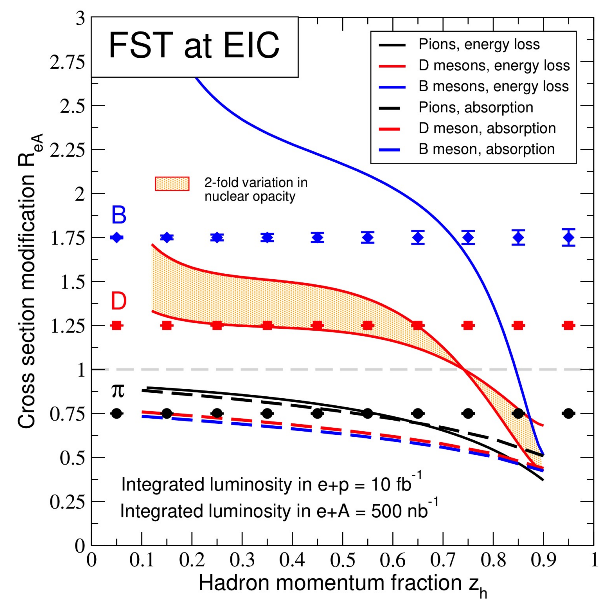
- Constrain gluon and c/b distributions. Look for intrinsic charm



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 FFs

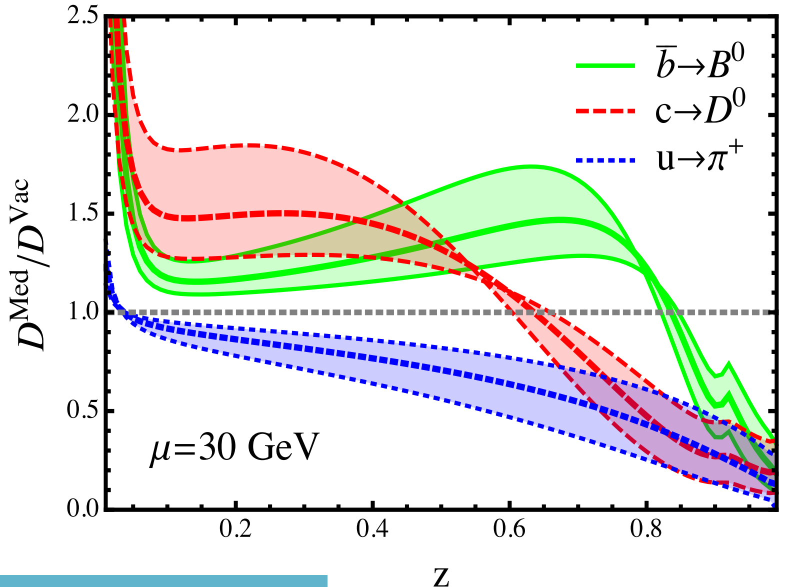
Vacuum splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs

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

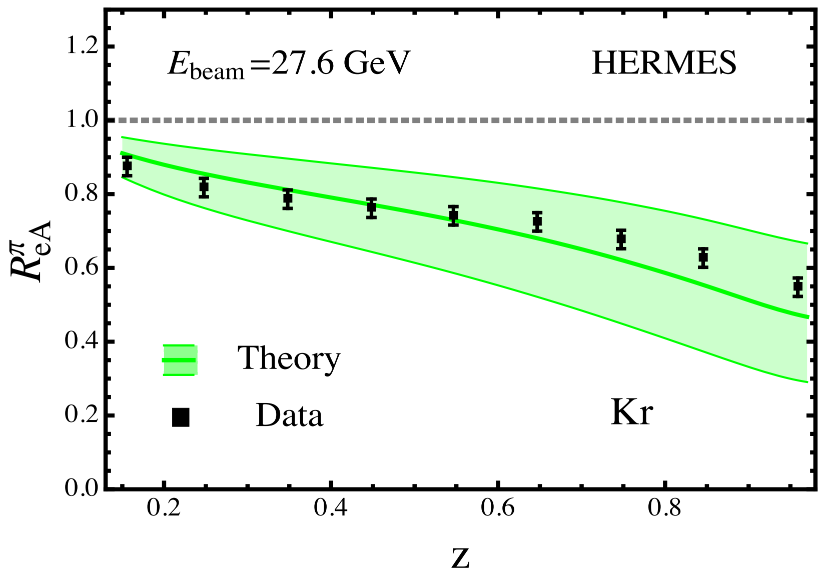
$$\frac{\mathrm{d}D_{\bar q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar q}\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

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

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

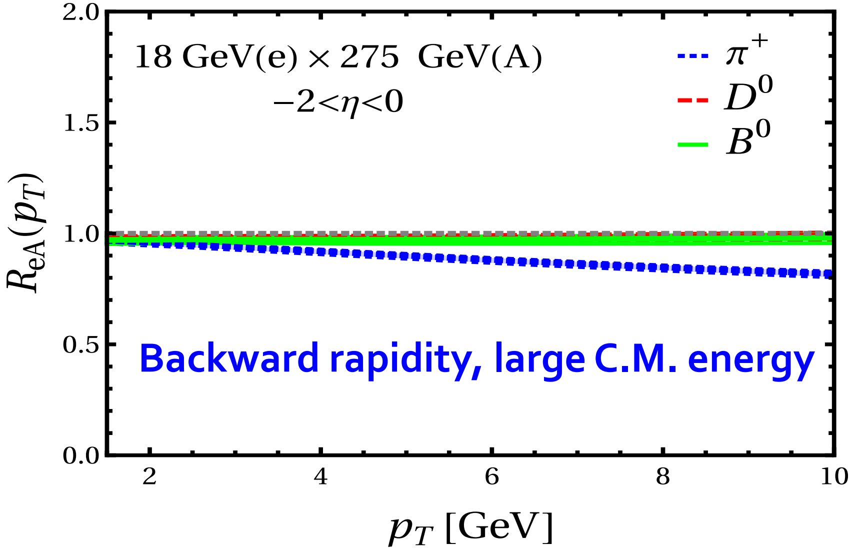


Z. Liu et al. (2020)

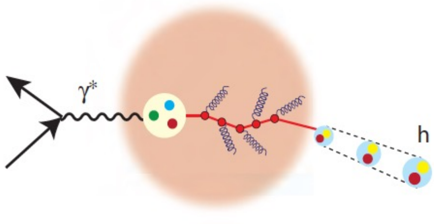


- Always enhancement at small z but for pions (light hadrons) at very small values – mostly suppression
- Very pronounced differences between light and heavy flavor fragmentation

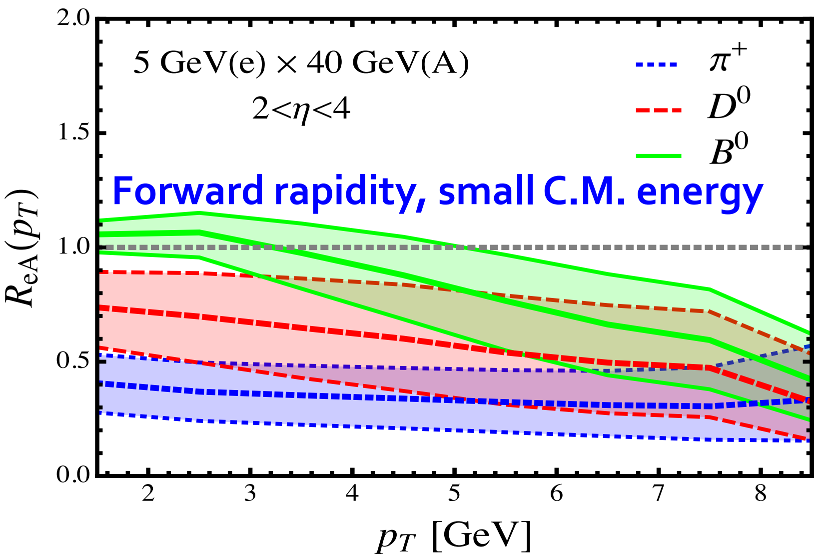
Light and heavy flavor suppression at the EIC

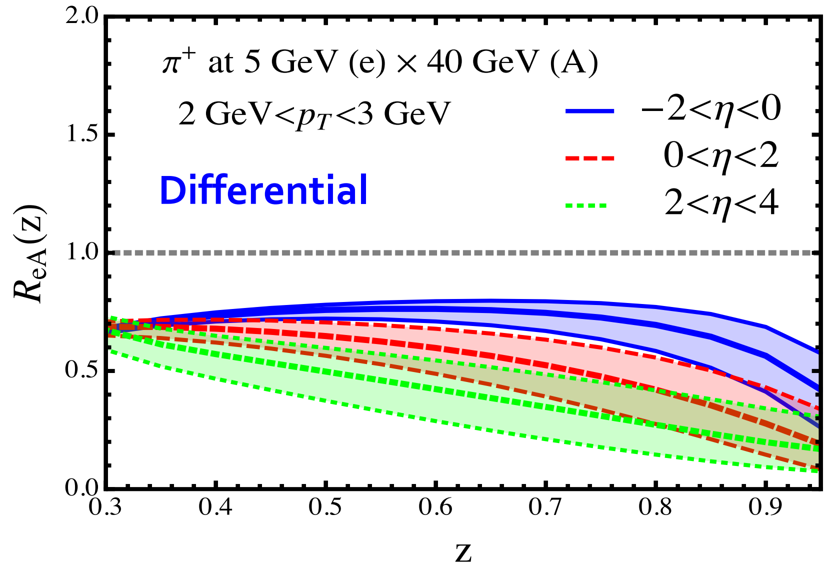


Given the much larger C.M. energy that at HERMES this is the picture to study first



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)

Modification of heavy flavor cross sections

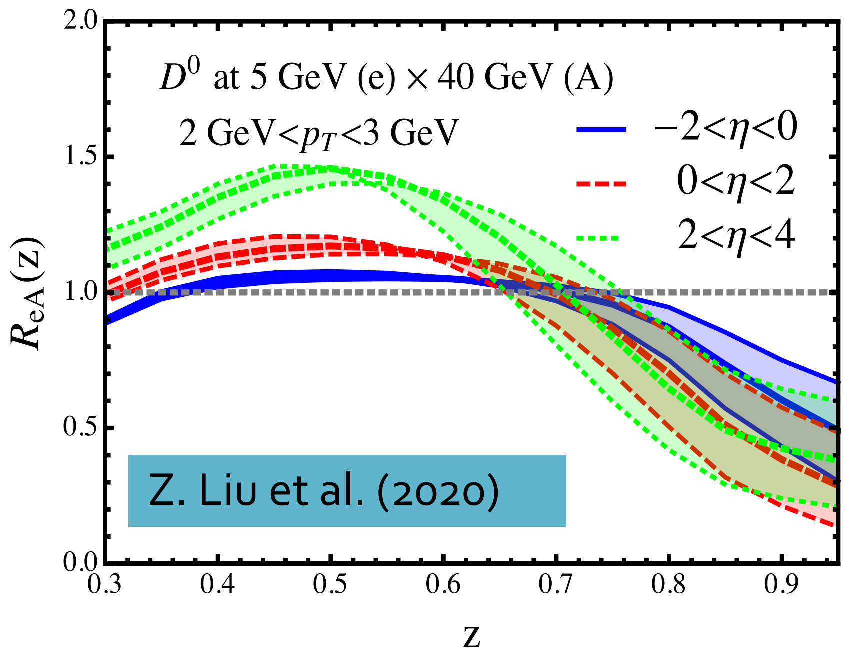
A more differential ratio vs the momentum fraction of the hadron

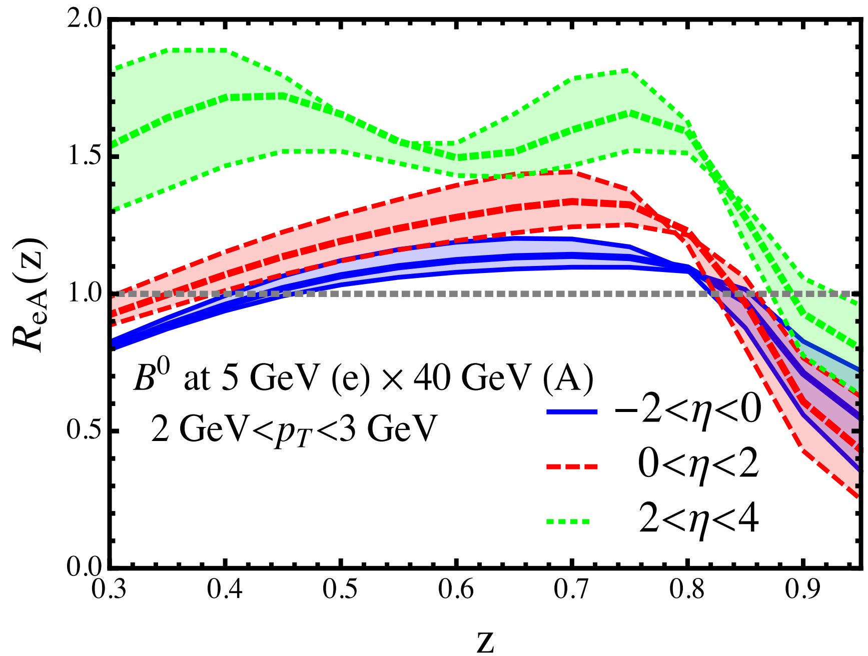
The difference in the suppression pattern of pions and D, B mesons is characteristic of the in-medium evolution/energy loss approach

Detailed and constrained predictions for the EIC

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

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



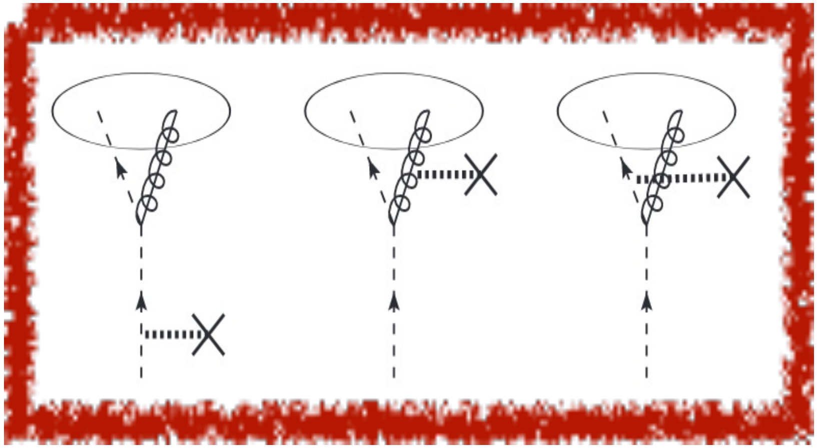


Jet production

Z. Kang et al. (2016)

L. Dai et al. (2016)

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



Factorization formula

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

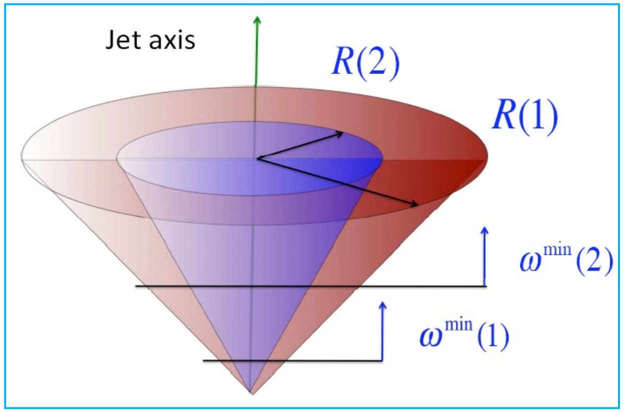
$$\mu_J = \omega_J \tan\frac{\mathcal{R}}{2} = (2p_T\cosh\eta)\tan\left(\frac{\mathcal{R}}{2\cosh\eta}\right) \approx p_T \mathcal{R}$$

Cross section contribution

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

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

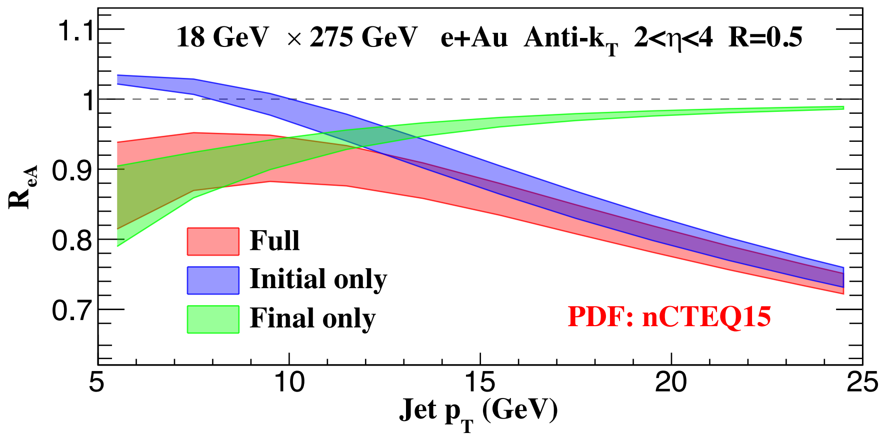
H. Li et al. (2020)

The physics of in-medium jet modification

Jet results at the EIC

H. Li et al. (2020)

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

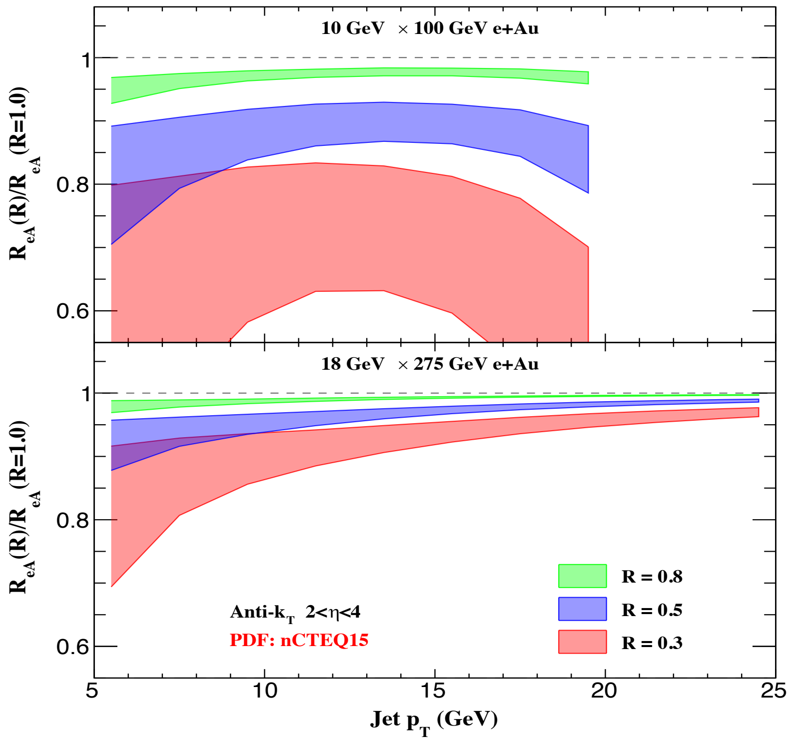


Two types of nuclear effect play a role

- 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

How to separate them? Define the ratio of modifications for 2 radii (it is a double ratio)

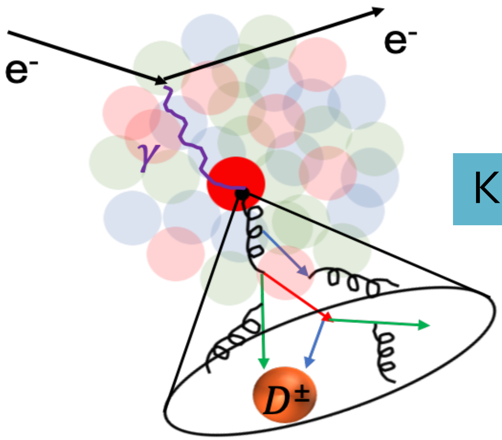
$$R_R = R_{eA}(R)/\, R_{eA}(R=1)$$



- Jet energy loss effects are larger at smaller C.M. energies
- Remarkably, effects can be almost a factor of 2!

Inclusive heavy jet production

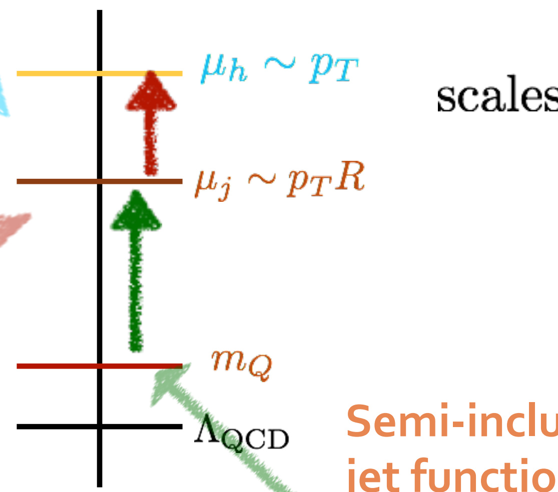
$e^- + \text{Au} \to e^- + jet(D^\pm) + X$



Heavy flavor jets introduce a new mass scale that requires careful treatment SiJF

K. Kovarik et al. (2018)

nPDFs



Semi-inclusive jet function

$$J_{J/c}(z_c, w_J \tan(R'/2), m_Q, \mu)$$

$$E_J \frac{d^3\sigma}{d^3P_J} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times J_{J_Q/f}(z,\mu)\left[\hat{\sigma}_{i\to f} + f^{\gamma/\ell}_{\rm ren}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right]$$

L. Dai et al. (2018)

H. Li et al. (2019)

Hard scattering kernel

P. Hinderer et al. (2018)

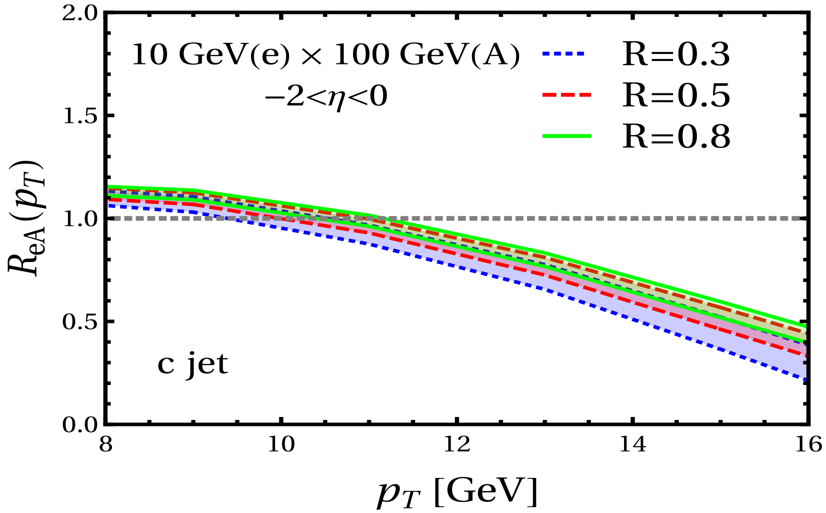
In eA collisions there is an in-medium contribution to the SiJFs

Furthermore, there can be a significant Weiszacker-Williams photon contribution

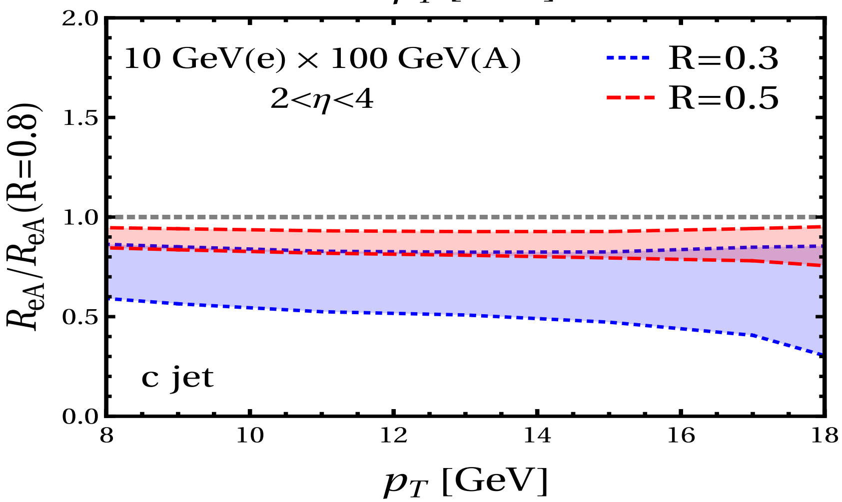
Heavy flavor jets at EIC

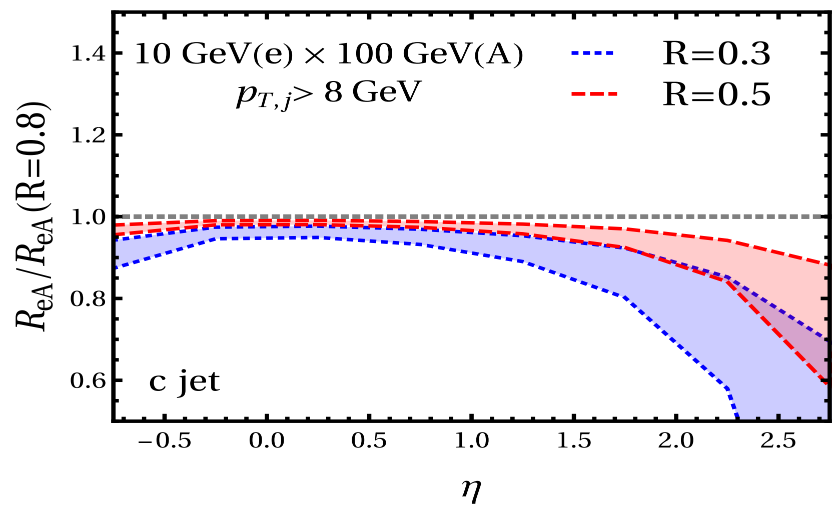
PRELIMINARY

Z. Liu et al. (2021)



- The modification of heavy flavor jets in eA is significant
- There is much larger sensitivity to the gluon distributions but initial-state and final-state effects can still be separated
- There is a pronounced rapidity dependence of the heavy flavor jet suppression





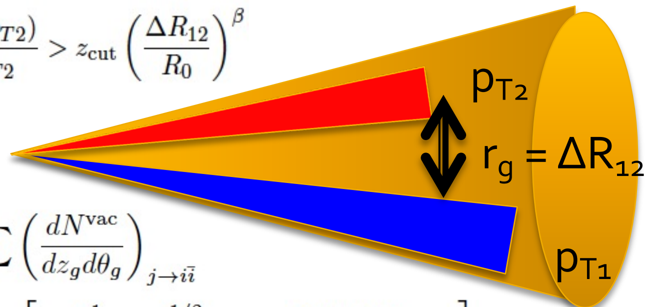
We have also done the calculation for b-jets and slightly smaller, but still significant modification

Heavy flavor jets substructure in DIS

PRELIMINARY

Z. Liu et al. (2021)

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

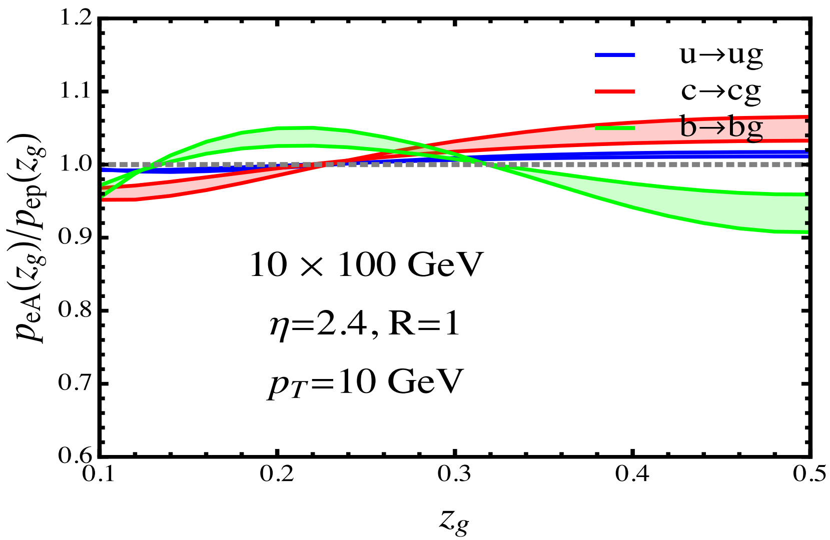


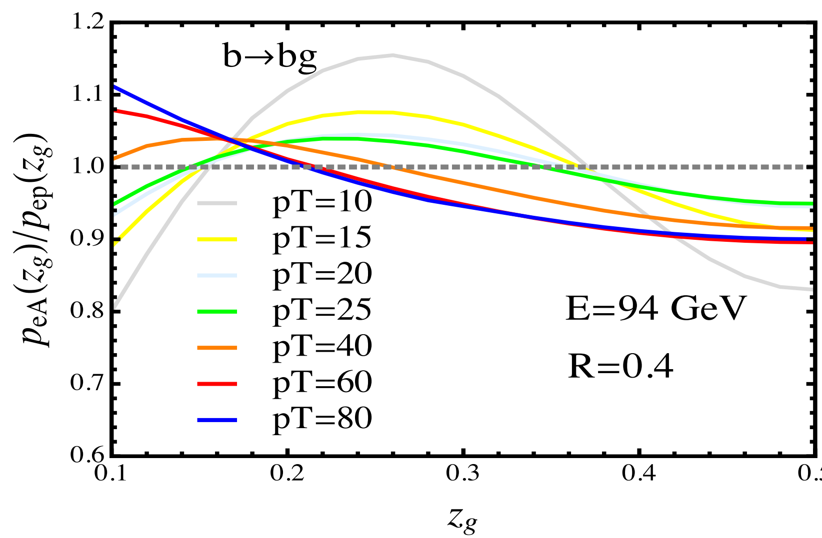
$$\frac{dN_j^{\rm vac,MLL}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\rm vac}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\rm cut}}^{1/2} dz \sum_i \left(\frac{dN^{\rm vac}}{dz\, d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$

$$p(\theta_g, z_g)\big|_j = \frac{\frac{dN_j^{\rm vac,MLL}}{dz_g d\theta_g}}{\int_0^1 d\theta \int_{z_{\rm cut}}^{1/2} dz \frac{dN_j^{\rm vac,MLL}}{dz d\theta}}$$

Related to the modification of jet cross sections is the modification of jet substructure. Example - Soft dropped momentum sharing distributions

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



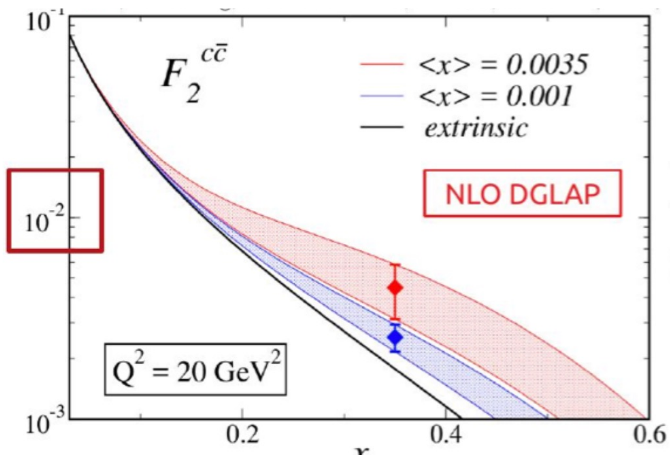


Kinematically not possible in DIS but illustrates very well the difference with HIC

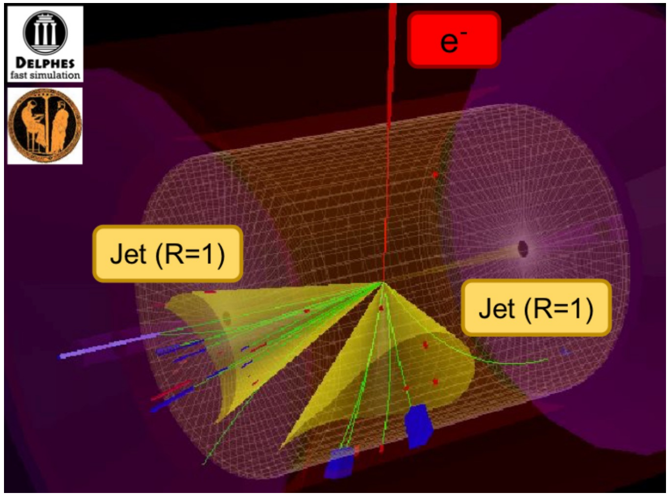
Intrinsic charm and strangeness at the EIC

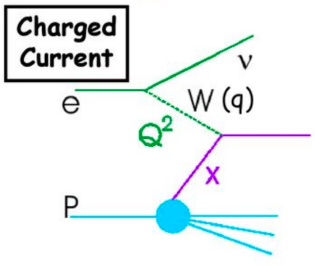
EIC will finally have the precision to answer long standing questions about large-x structure – strangeness and intrinsic charm

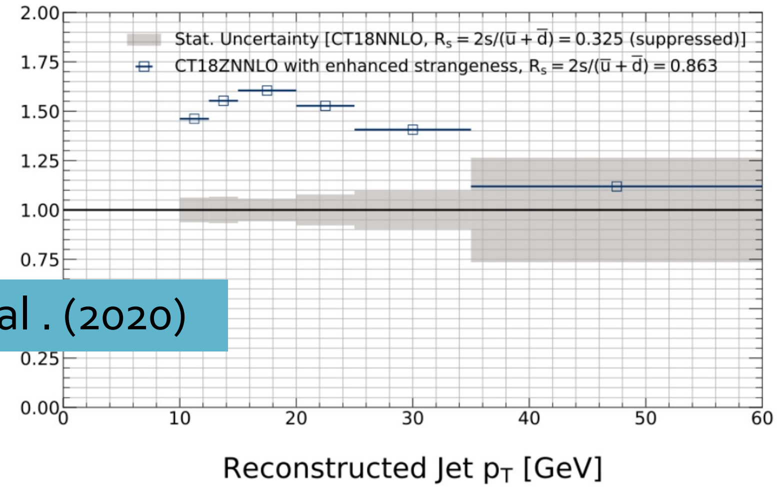
- Intrinsic charm – genuine non-perturbative contribution to the proton wave function – can affect HQ schemes, masses, global fits
- Strangeness – can be accessed via CC reactions. Requires high statistics, can look for enhanced strangeness



T. Hobbs et al . (2017)







M. Arratia et al . (2020)

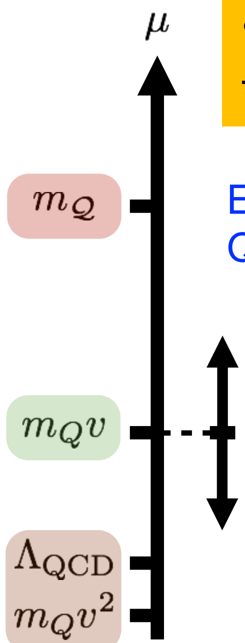
Double charm jet NC event

Production of quarkonia

• Non-Relativistic QCD (NRQCD) -a particular type of effective theory (EFT)

Bodwin *et al.* (1995)

Cho *et al.* (1996)



Explores all regimes of QCD

Perturbative

Non-Perturbative

$b\bar{b}: \quad v^2 \sim 0.1$

$c\bar{c}: \quad v^2 \sim 0.3$

Ultra-soft

$p_s^\mu \sim m_Q v(1,1,1,1)$

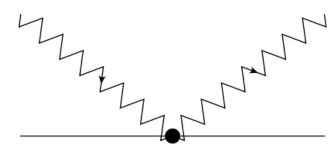
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

$$\mathcal{L}_{\text{NRQCD}} = \mathcal{L}_{\text{light}} + \psi^\dagger\Big(iD_0 + \frac{\mathbf{D}^2}{2M}\Big)\psi + \chi^\dagger\Big(iD_0 - \frac{\mathbf{D}^2}{2M}\Big)\chi$$

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO



typical momentum if heavy quark: $|\mathbf{p}_Q| \sim m_Q v$

typical kinetic energy if heavy quark: $K_Q \sim m_Q v^2$

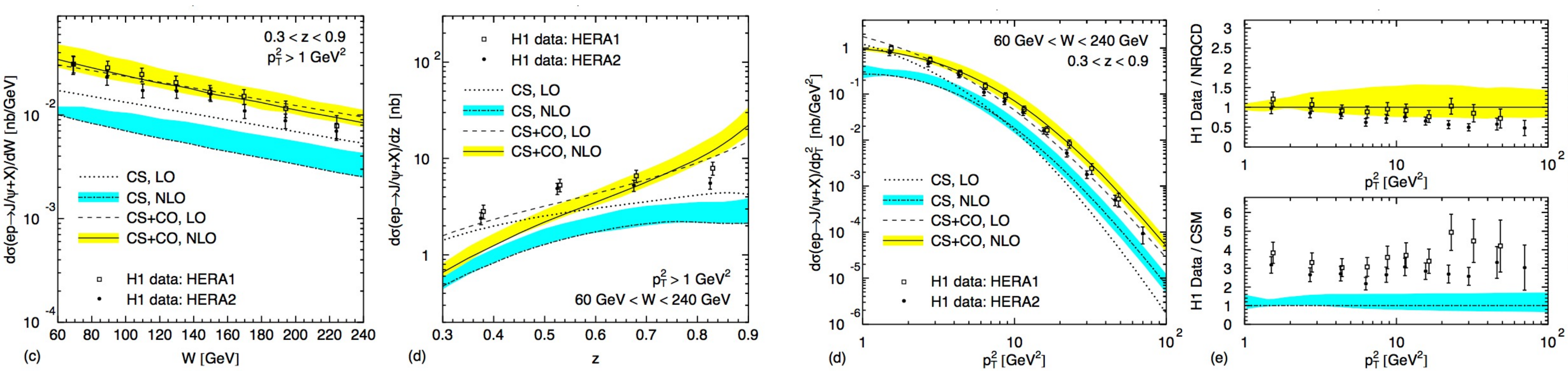
• NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

$$d\sigma(a+b \to \mathcal{Q}+X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

Results in DIS and EIC specifics

• Data and photoproduction theory at HERA

M. Butenchoen *et al.* (2010)



• Good description of cross sections can can be achieved but still some tensions remain in understanding polarization, especially at low p_T

• At EIC we have lower CM energies than HERA. Production at low p_T can probe gluon TMDs and universal Shape functions

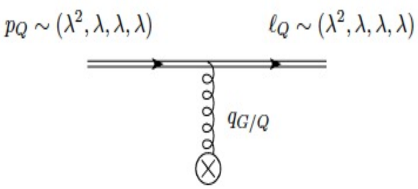
$$\frac{d\sigma}{d^2\mathbf{q}} = \sigma_0([n])\, H(2m_Q, \mu; [n]) \int d^2\mathbf{k}\, \mathbf{F_{g/P}}(\mathbf{x}, \mathbf{k})\, \mathbf{Sh}(\mathbf{q} - \mathbf{k}; [\mathbf{n}])$$

S. Fleming *et al.* (2019)

Low transverse momentum gluon production

NRQCD with Glauber Gluons

- At the level of the Lagrangian



Possible scaling for the virtual gluons interacting with the heavy quarks

$$\begin{array}{ll} & \quad 0 \;\; 1 \;\; 2 \;\; 3 \qquad + \; - \; \perp \\ (1) & q_G \sim (\lambda^2, \lambda^1, \lambda^1, \lambda^2) \sim (\lambda^2, \lambda^2, \boldsymbol{\lambda}_\perp)_n \\ (2) & q_C \sim (\lambda^2, \lambda^1, \lambda^1, \lambda^1) \sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_\perp)_n \end{array}$$

- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

Background field method	Perform a shift in the gluon field in the NRQCD Lagrangian then perform the power-counting
Hybrid method	From the full QCD diagrams for single effective Glauber/Coulomb gluon perform the corresponding power-counting, read the Feynman rules
Matching method	Full QCD diagrams describing the forward scattering of incoming heavy quark and a light quark or a gluon. We also derive the tree level expressions of the effective fields in terms of the QCD ingredients

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

Y. Makris *et al.* (2019)

- Calculated the leading power and next to leading power contributions 3 different ways

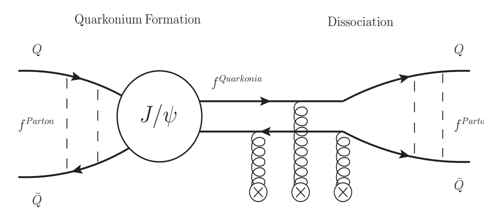
$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^0_{G/C}\Big)\psi_{\mathbf{p}} \quad (collinear/static/soft).$$

$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\big[(\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})A^{\mathbf{n}}_G\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = 0 \quad (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2\mathbf{A}_C\cdot\boldsymbol{\mathcal{P}} + [\boldsymbol{\mathcal{P}}\cdot\mathbf{A}_C] - i\big[\boldsymbol{\mathcal{P}}\times\mathbf{A}_C\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (soft)$$

Phenomenological applications



See talks by Y. Akamatsu & A. Viaro

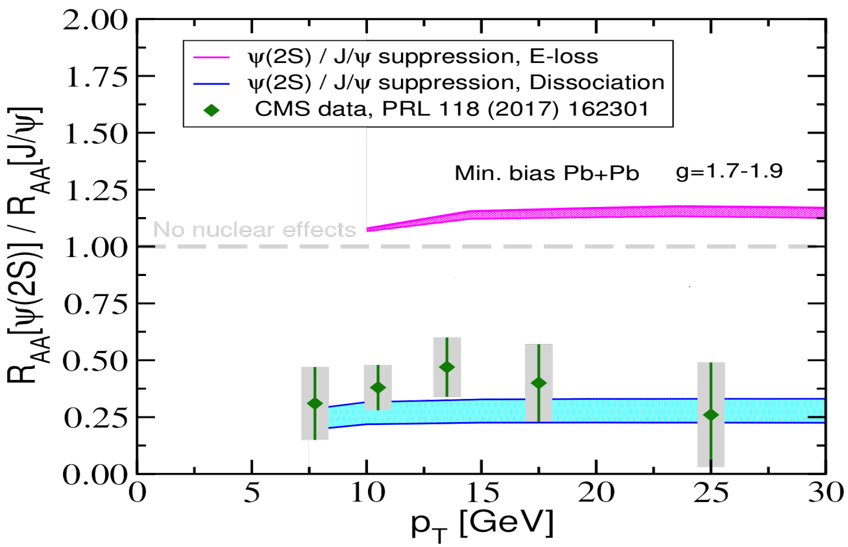
Phenomenology with $NRQCD_G$

At the moment data exists in heavy ion collisions (as far as nucleus A is involved)

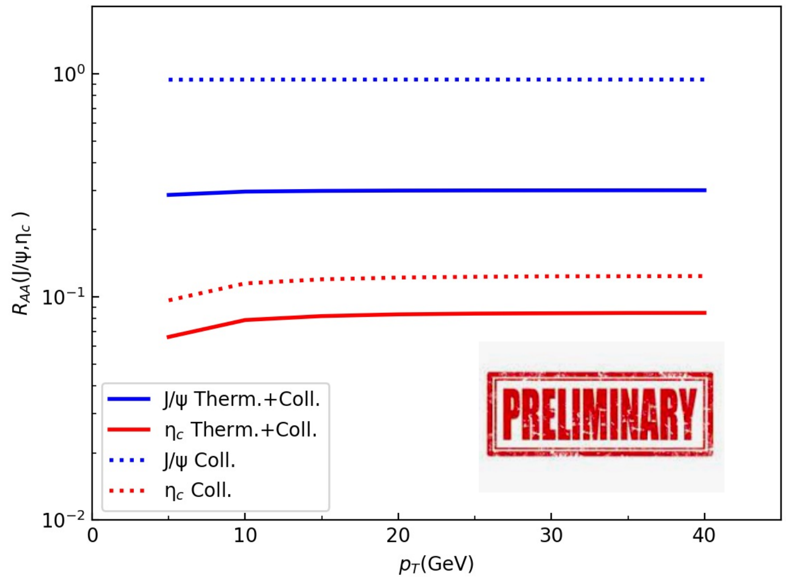
- Correct hierarchy of excited and ground state suppression

- QGP – thermal effect on the wavefunction and collisional dissociation
- EIC – only CNM collisional effects

Y. Makris *et al.* (2019)



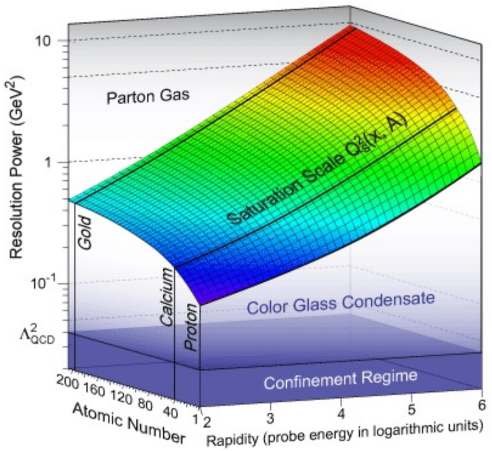
Collisional interactions



Work to extend this to e+A is under way. Cold nuclear matter vs QGP, lower transverse momenta

I. Olivant *et al. in progress*

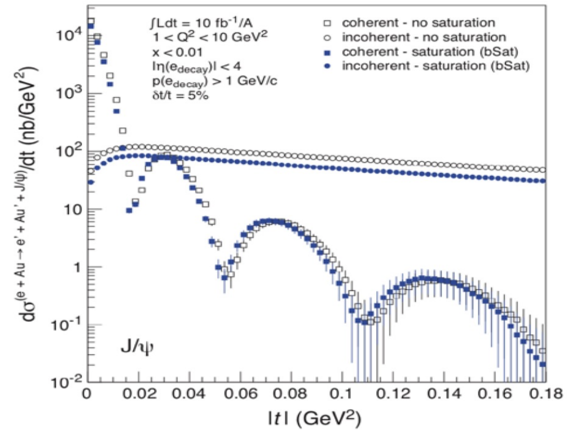
Quarkonia and small-x physics



The EIC will probe the small-x gluon saturation regime. The connection between CGC and TMD physics is actively explored. It is first important to unambiguously establish the saturation regime

Abdulkhalek et al. 2021

Coherent and incoherent J/ψ photo production

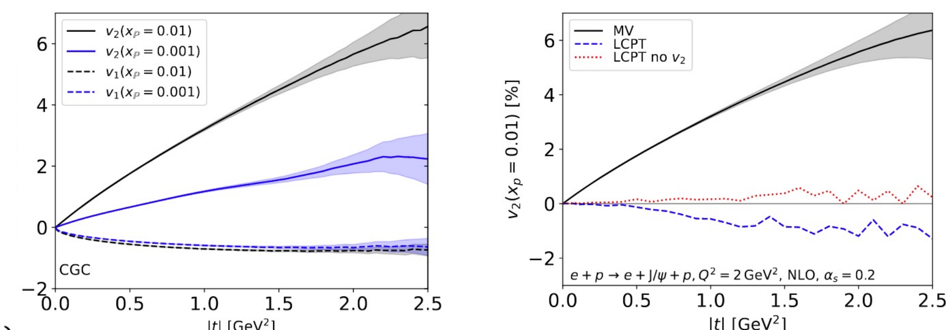


More differential observables such as the asymmetries of exclusive J/ψ production

A. Dumitru et al. 2021

$$v_n = \frac{\int_0^{2\pi} \mathrm{d}\phi_{k\Delta} e^{ni\phi_{k\Delta}} \mathrm{d}\sigma^{e+p\to e+p+V}/\mathrm{d}t\mathrm{d}\phi_{k\Delta}\mathrm{d}Q^2\mathrm{d}x_{\mathbb{P}}}{\int_0^{2\pi} \mathrm{d}\phi_{k\Delta}\mathrm{d}\sigma^{e+p\to e+p+V}/\mathrm{d}t\mathrm{d}\phi_{k\Delta}\mathrm{d}Q^2\mathrm{d}x_{\mathbb{P}}}$$

$$\begin{aligned}\frac{\mathrm{d}\sigma^{eA\to eAV}}{\mathrm{d}x_{\mathbb{P}}\mathrm{d}Q^2\mathrm{d}|t|\mathrm{d}\phi_{k\Delta}} = \frac{\alpha_{em}}{32\pi^3 Q^2 x_{\mathbb{P}}} \sum_{\lambda'=0,\pm1} \Bigg\{ &(1-y)\left|\left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{0,\lambda'}\right\rangle_Y\right|^2 \\ &+\frac{1}{4}\left[1+(1-y)^2\right]\sum_{\lambda=\pm1}\left|\left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{\lambda,\lambda'}\right\rangle_Y\right|^2 \\ &-\frac{\sqrt{2}}{2}(2-y)\sqrt{1-y}\sum_{\lambda=\pm1}\mathrm{Re}\left(\left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{0,\lambda'}\right\rangle_Y \left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{\lambda,\lambda'}\right\rangle^*_Y\right)\cos(\phi_{k\Delta}) \\ &+(1-y)\mathrm{Re}\left(\left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{+1,\lambda'}\right\rangle_Y \left\langle \widetilde{\mathcal{M}}^{\gamma^*A,V}_{-1,\lambda'}\right\rangle^*_Y\right)\cos(2\phi_{k\Delta})\Bigg\}\end{aligned}$$



(a) Dependence on $x_{\mathbb{P}}$.

(b) MV model compared to the LCPT dipole.

Conclusions

- Heavy flavor production is an essential part of the EIC science. For expert level discussion of various experimental and theoretical aspects see https://indico.bnl.gov/event/9273/ HF can shed light on the dynamical aspects of confinement

- Heavy flavor provides complementary probe of the TMD stricture of nucleons/nuclei, small-x saturation physics, parton distributions, and transport properties of cold nuclear matter

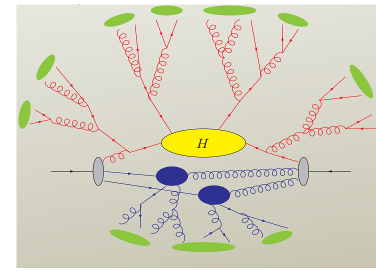
- Open heavy flavor production has been calculated at NLO, in-medium evolution of fragmentation understood. We have detailed and differential predictions of D and B meson cross section modification, which can differentiate between energy loss and hadron absorption

- Calculations of open heavy flavor jets in e+A collisions are near complete. They require more careful treatment of energy/mass scales. Preliminary results are promising – large suppression of c-jets. Heavy jet substructure in reactions with nuclei quite different from HIC, exhibits new features that could be studied at the EIC

- Quarkonium production, as described by NRQCD, can be further constrained at EIC. New developments are theories of quarkonium production in matter ($NRQCD_G$), low P_T and gluon TMDs at the EIC. e+A collisions can shed light on the structure of heavy exotics

Confinement and hadronization

- Do we understand dynamically how confinement occurs? No



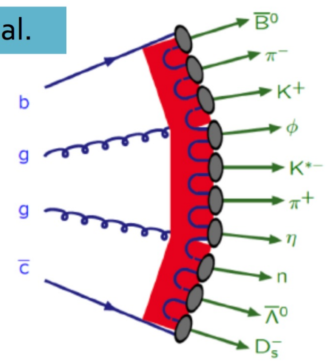
- Perturbative hadronization
- Hadronization in event generators

$$\mathcal{P}_{A/j}(z, P_T) = \frac{1}{2z(2\pi)^3} \int dx^- \, d^2x_T \, e^{ik^+x^- - ik_T \cdot x_T}$$
$$\times \frac{1}{3} \mathrm{tr}_{\mathrm{color}} \frac{1}{2} \mathrm{tr}_{\mathrm{Dirac}} \{\gamma^+ \langle 0|\psi(x) a_A^\dagger(P^+, 0) a_A(P^+, 0) \bar{\psi}(0)|0\rangle\}$$

J. Collins et al. (1982)

String fragmentation

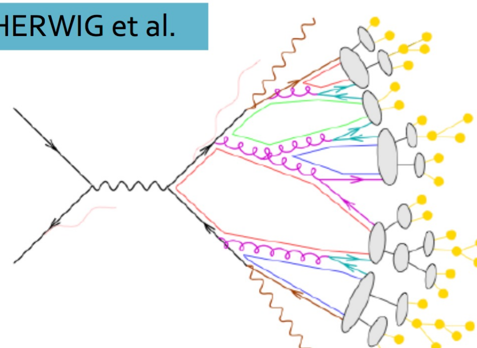
PYTHIA et al.



$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

Cluster hadronization

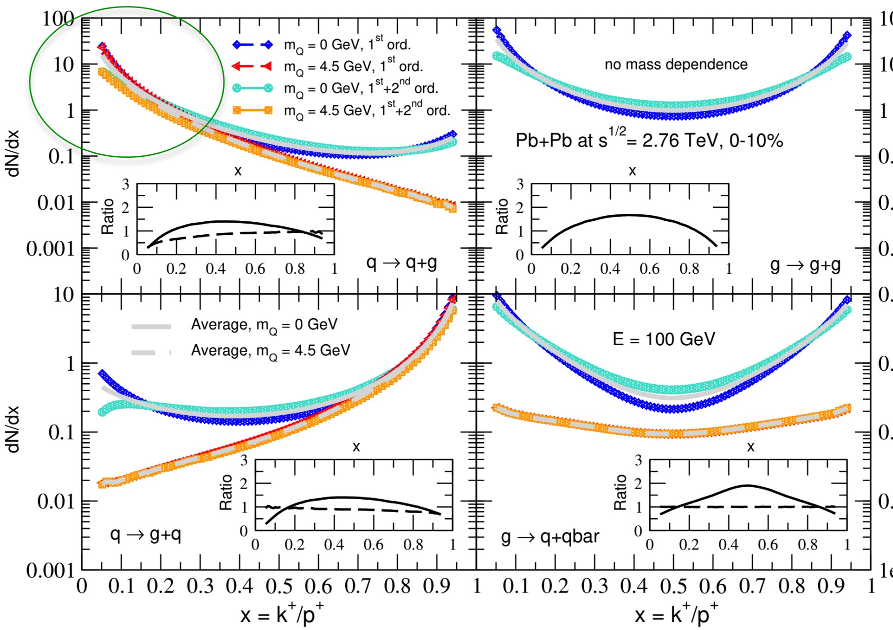
HERWIG et al.



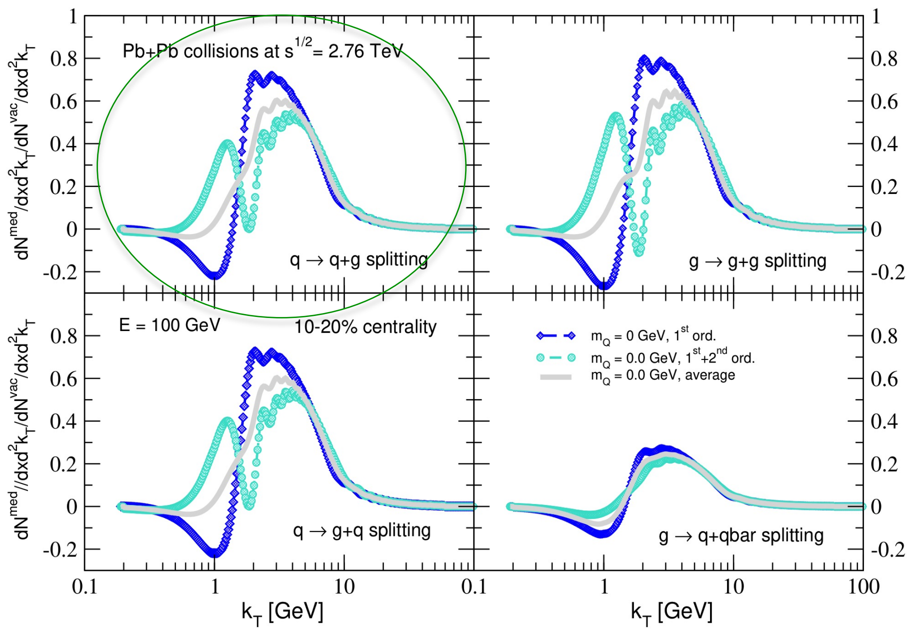
program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful predictive	simple unpredictive
parameters	few	many
flavour composition	messy unpredictive	simple in-between
parameters	many	few

- Hadronization in the nuclear environment - in can provide insights into the dynamics and the space-time picture of hadronization

Differential branching spectra



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



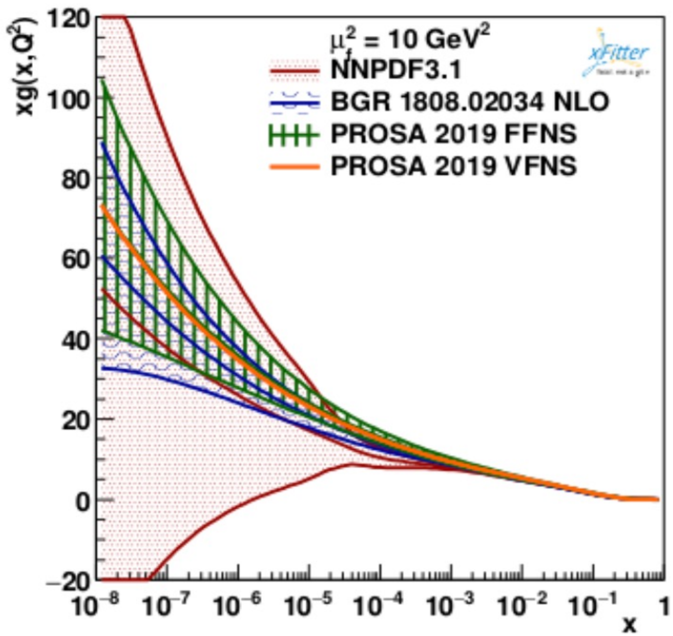
Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions

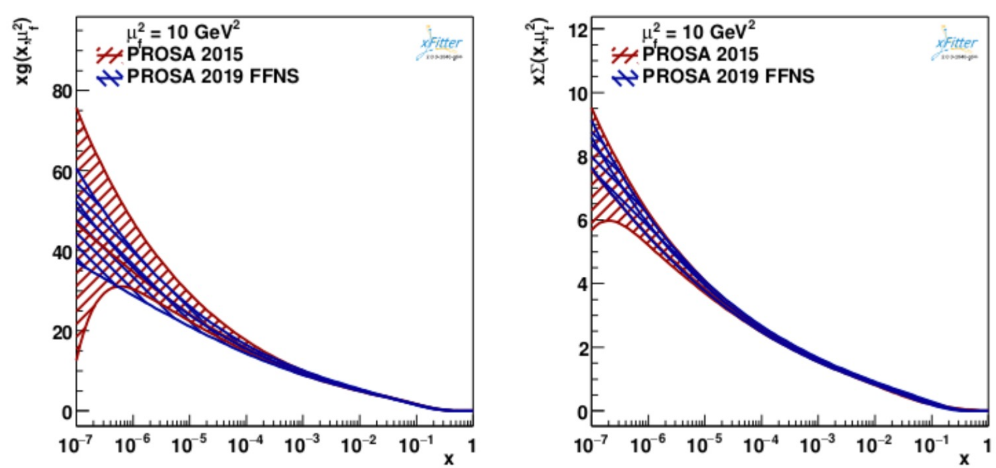
Use of LHC data to constrain heavy favor PDFs – PROSA collaboration

O. Zenaiev et al . (2018)

- Adding LHCb and ALICE data to the heavy flavor data from HERA

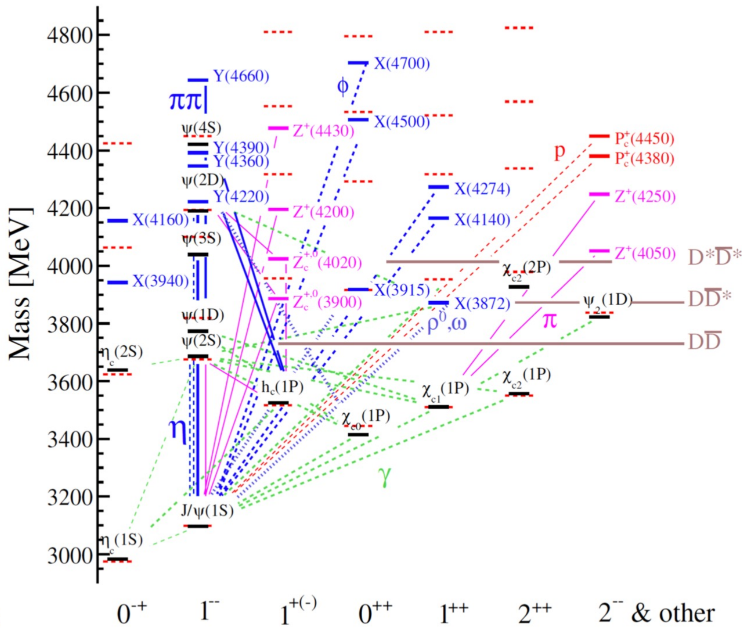
Inclusion of heavy flavor reduces PDF uncertainties for sea quarks and gluons at small x, especially FFNS





Important to do combined analysis at the EIC

Exotics states at the EIC



T. Skwarnicki et al. (2018)

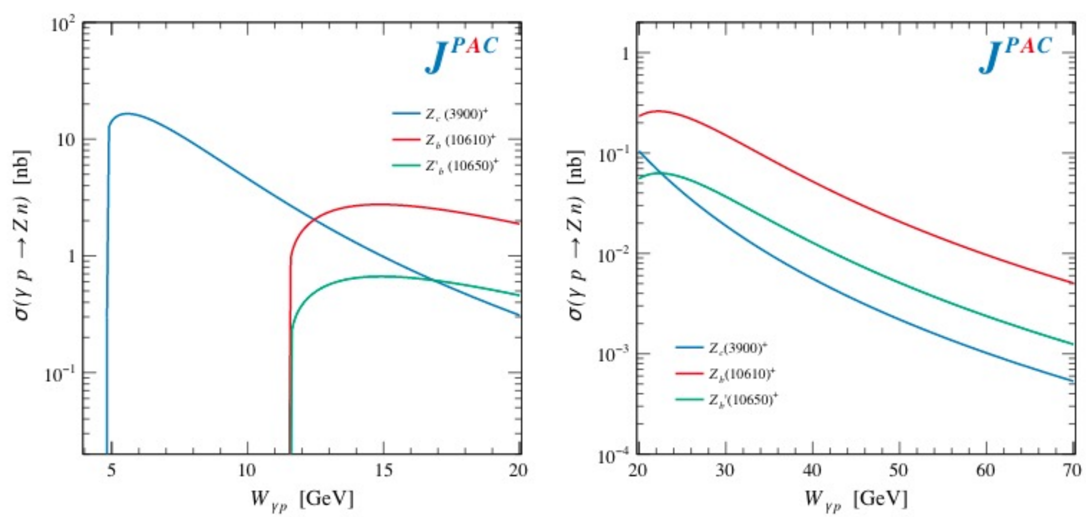
In addition to quarkonia, we have a large number of heavy quark exotic hadrons

- *Photoproduction through photon-Pomeron fusion lead predominantly to $J^{PC}=1^{--}$ states like the J/ψ, etc., so is only sensitive to exotic with those quantum numbers*
- *Photon-Reggeon fusion leads to states with a wider range of spin, parity and even charge*

$$\sigma(ep \to eX^+n) = \int \frac{dk}{k} dQ^2 \frac{d^2N_\gamma(k,Q^2)}{dkdQ^2} \times \sigma_{\gamma^* p \to X^+ n}(W,Q^2),$$

$$\sigma_{\gamma^* p \to X^+ n}(W,Q^2) = \left(\frac{M_X^2}{M_X^2+Q^2}\right)^\eta$$

$$\sigma_{\gamma p \to X^+ n}(W,Q^2=0) f(M_X),$$



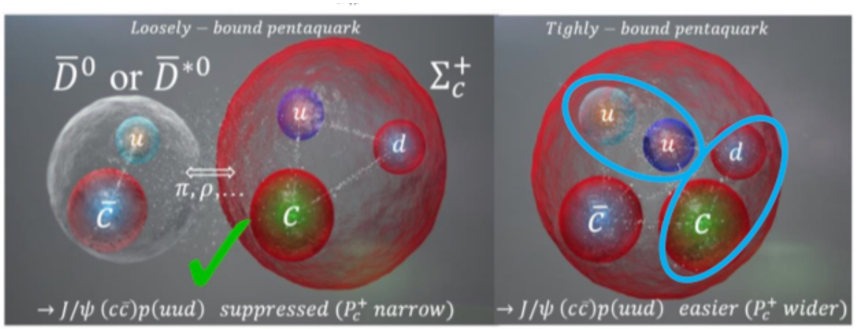
M. Albaladejo et al. (2018)

Heavy exotic states at the EIC

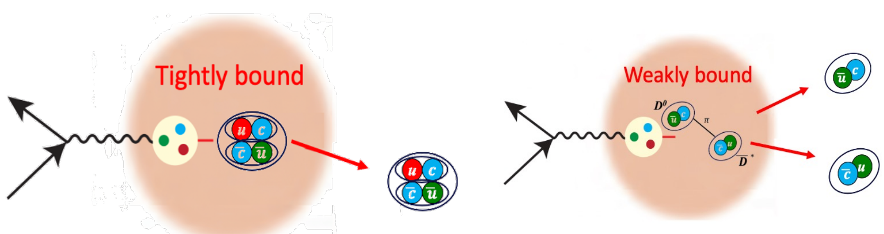
See talk by E. Braaten

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

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



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

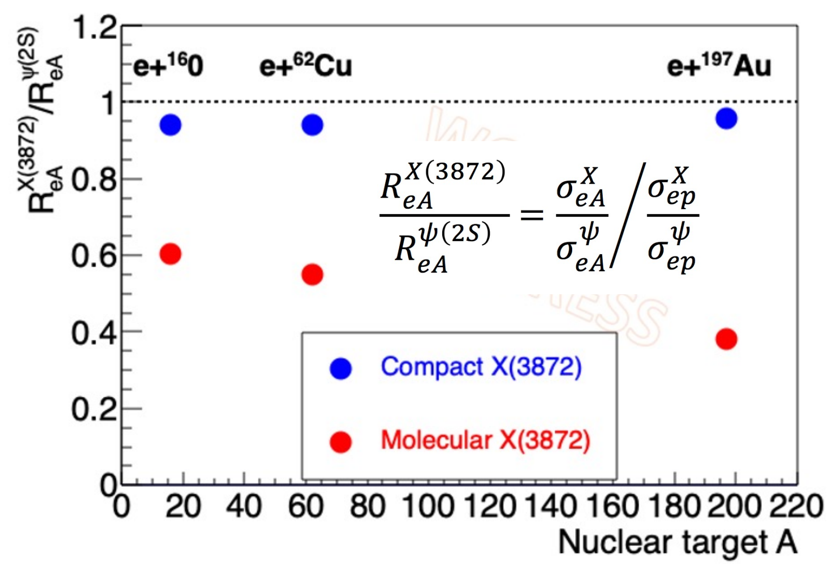


Use the nucleus as a "filter" for the heavy states

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

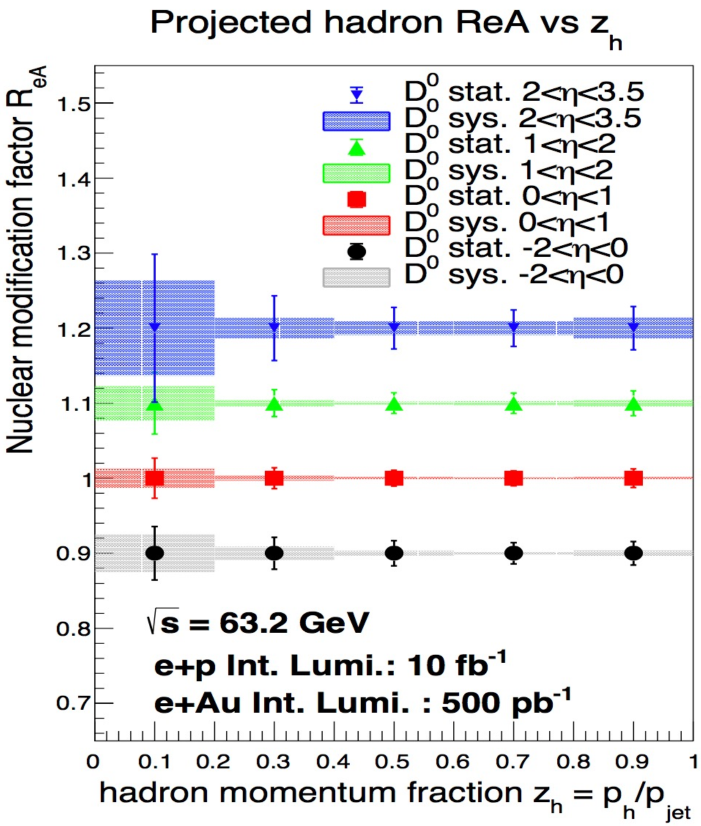


Arleo *et al.*, PRC, 61 054906 (2000)

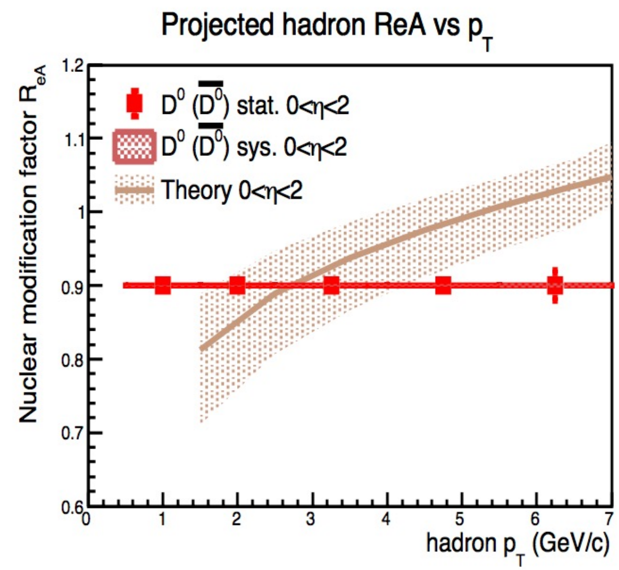
Can this be measured?

Yes it can. Quite accurately on top of that

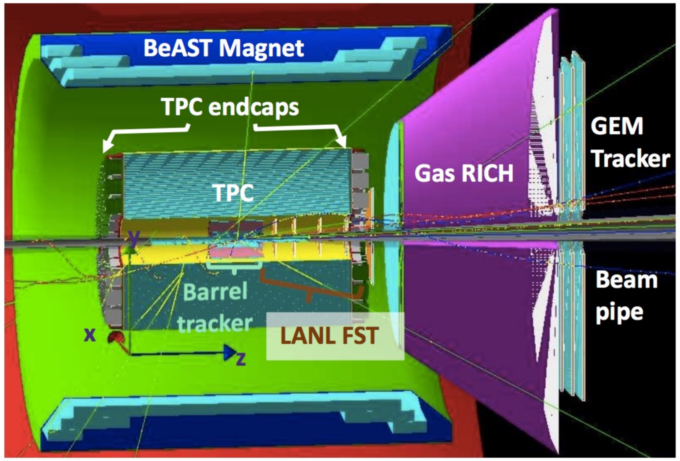
Differentially vs rapidity and momentum fraction



- Can constrain the transport properties to about 30%



- Based on realistic detector concepts,
- Full Fun4All framework Geant

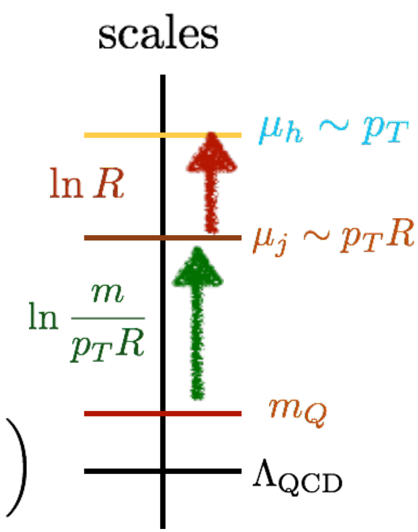


X. Li et al . (2021)

R. Abhdul Khalek et al . (2021)

Resummation

- Jet production is one of the cornerstonoe processes of QCD. Light jets have been studied for a long time.
- Recent advances are based in SCET – precision theory for small radius jets and heavy flavor jets



The SiJFs Evolve according to DGLAP-like equations

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

We use the Mellin moment space approach to solve this equation

Resums ln $\mu/p_T R$

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

Resums ln $p_T R/m$

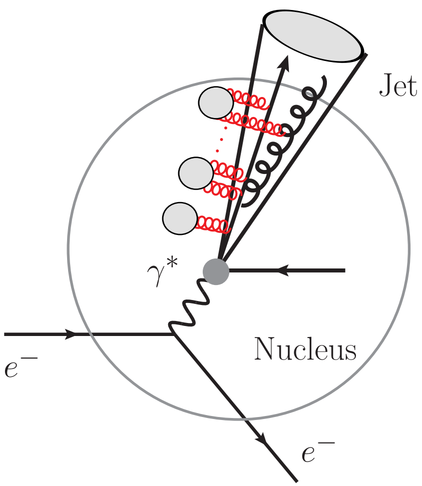
The integrated perturbative kernel at the jet typical scale

The integrated parton fragmentation function from parton *l* to parton *Q*

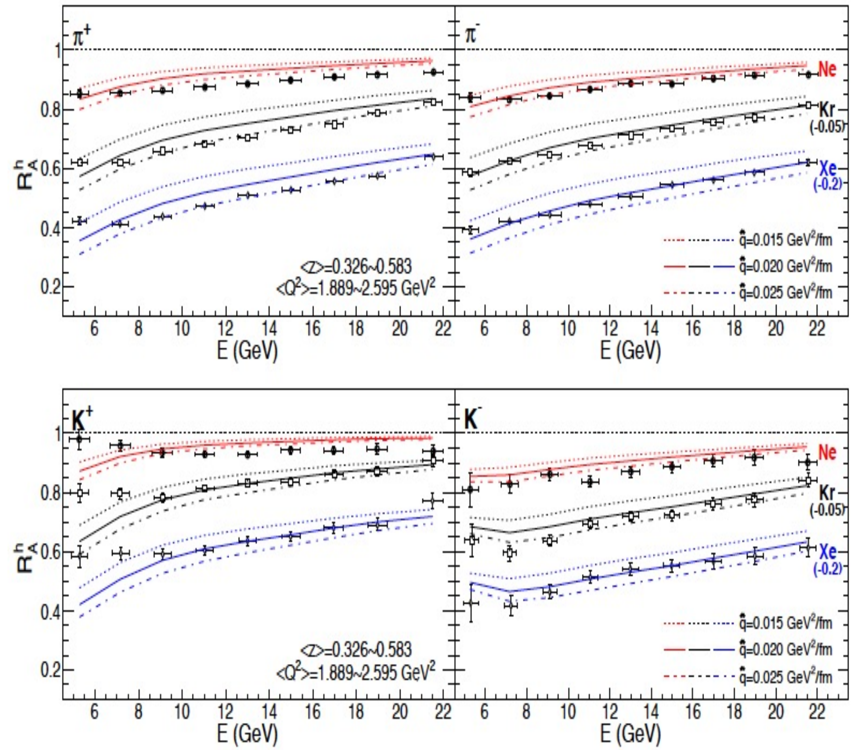
Bauer, Mereghetti 2013, Dai, Kim, Leibovich 2016, 2018

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