Ivan Vitev

Open heavy flavor and quarkonium physics at the EIC

IR2@EIC workshop, CFNS & Argonne
Online, March 17 - 19, 2021

Los Alamos
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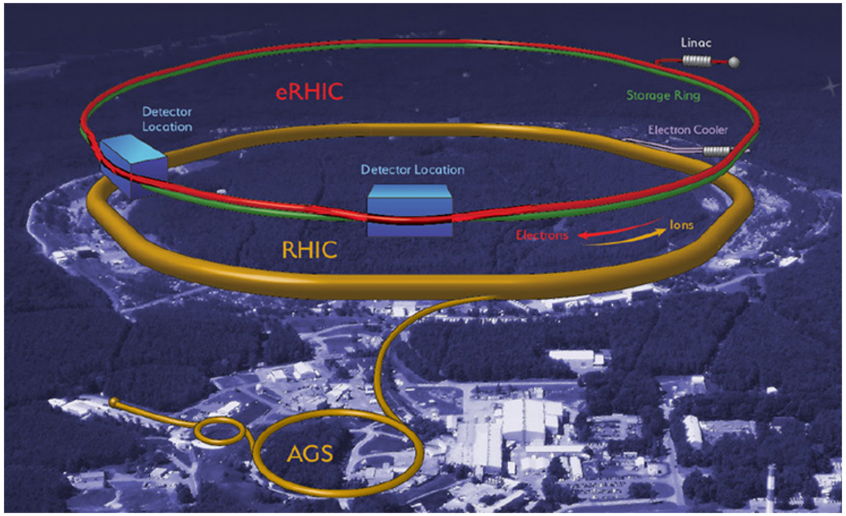
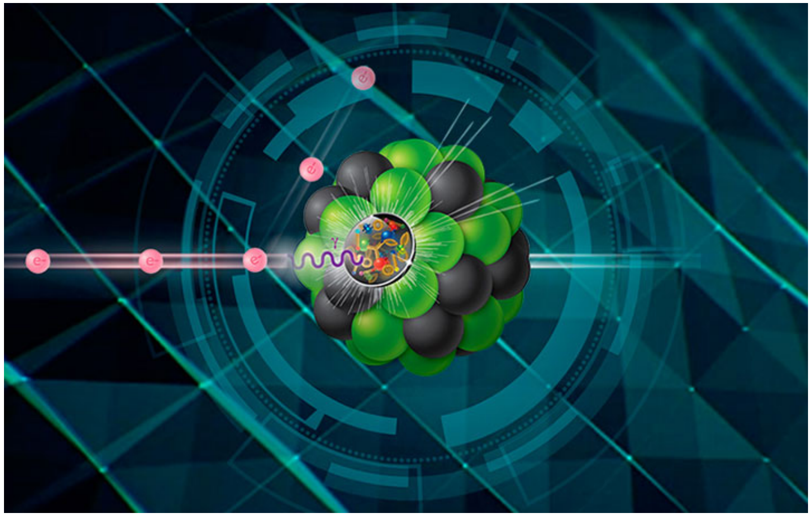
Outline of the talk





What can be done at somewhat smaller CM energies and higher luminosity?

- Quarkonium production and propagation in matter
- Meson production, HERMES constraints
- Heavy flavor jets in e+A at the EIC

Work of (or with) M. Durham, H. Li, X. Li, Z. Liu, Y. Makris, P. Wong

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

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

TMD Collaboration

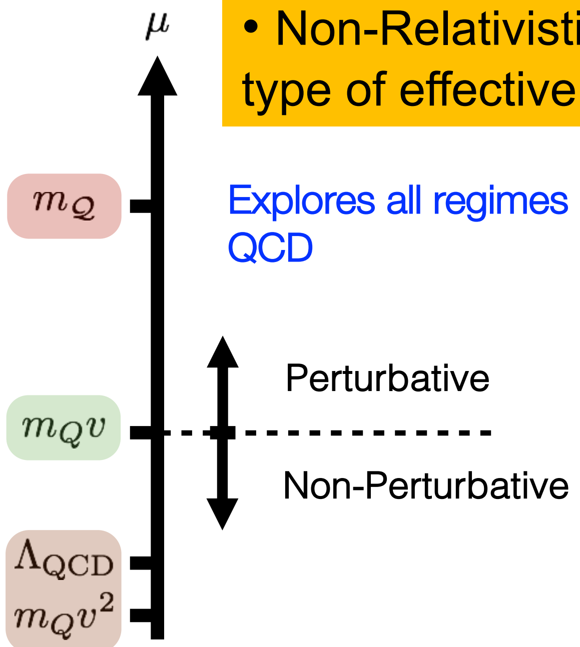
LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Production of quarkonia at intermediate and high p_T

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

Bodwin *et al.* (1995)

Cho *et al.* (1996)



Explores all regimes of QCD

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

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

Ultra-soft

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

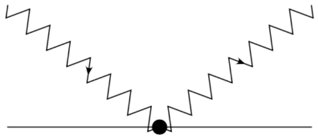
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

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

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: $K_Q \sim m_Q v^2$

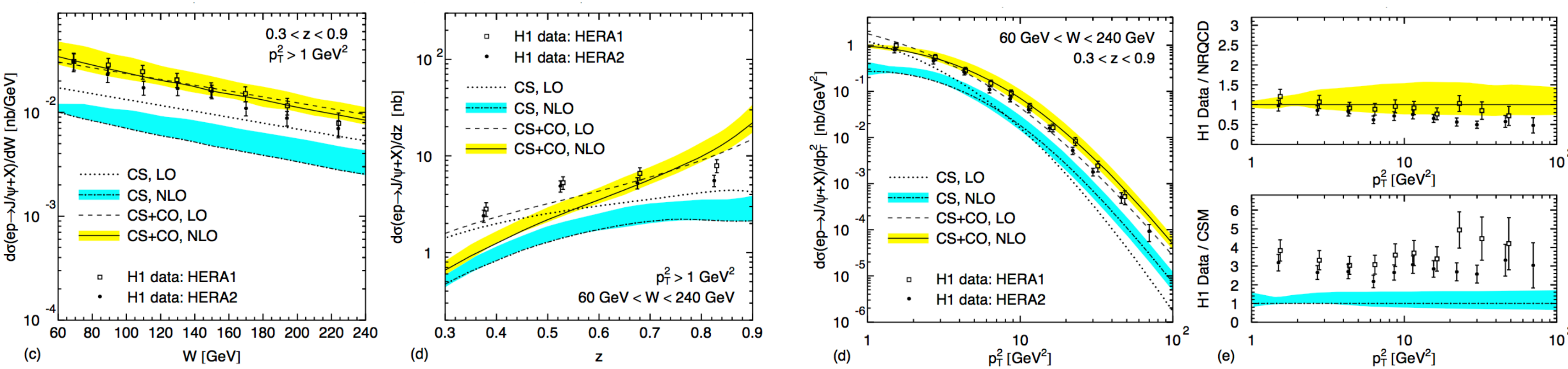
- NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

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

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, especially IR2. Production at low p_T can probe gluon TMDs and universal Shape functions

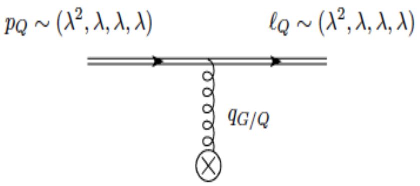
$$\frac{d\sigma}{d^2\mathbf{q}} = \sigma_0([n])\, H(2m_Q, \mu; [n]) \int d^2\mathbf{k}\, \mathbf{F_{g/P}}(\mathbf{x}, \mathbf{k})\, \mathbf{Sh}(\mathbf{q} - \mathbf{k}; [\mathbf{n}])$$

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

		0 1 2 3	+ − ⊥
(1)	$q_G \sim$	$(\lambda^2, \lambda^1, \lambda^1, \lambda^2)$	$\sim (\lambda^2, \lambda^2, \boldsymbol{\lambda}_\perp)_n$
(2)	$q_C \sim$	$(\lambda^2, \lambda^1, \lambda^1, \lambda^1)$	$\sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_\perp)_n$

- 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

Z. Citron *et al.* (2018)

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

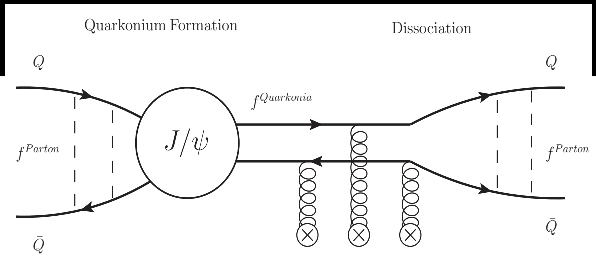
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_G) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\big[(\boldsymbol{\mathcal{P}}_\perp\times\mathbf{n})A^{\mathbf{n}}_G\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}}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

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

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

Phenomenology with $NRQCD_G$

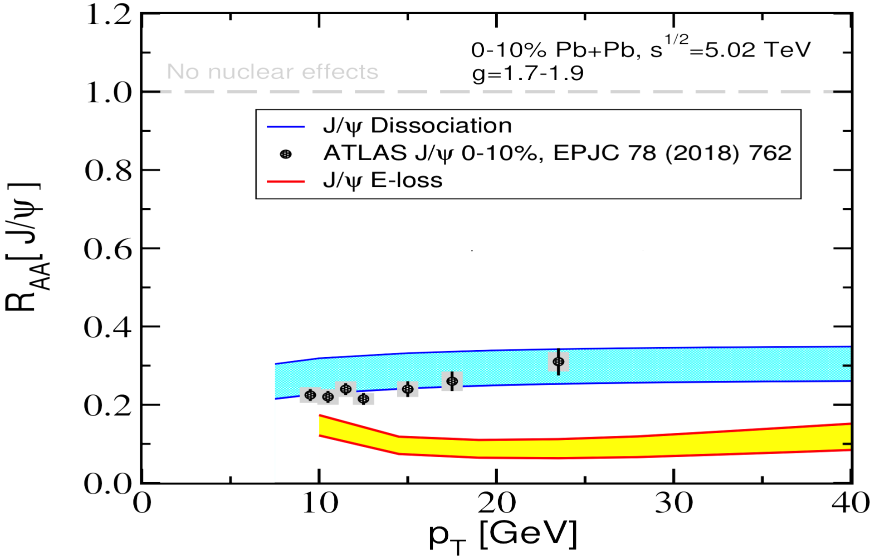
At the moment data exists in heavy ion collisions (as far as nucleus A is involved)

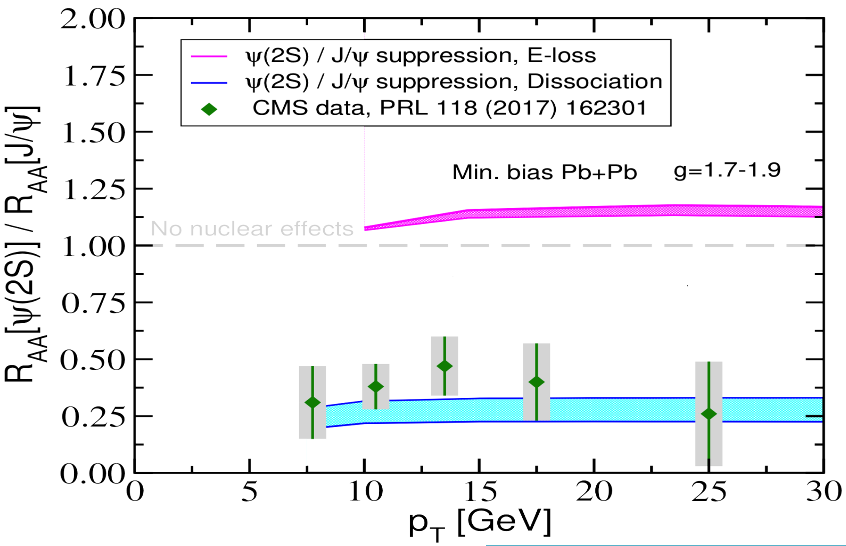


- Much better description of the J/\psi suppression

- Correct hierarchy of excited and ground state suppression

E. Chapon et al. (2021)



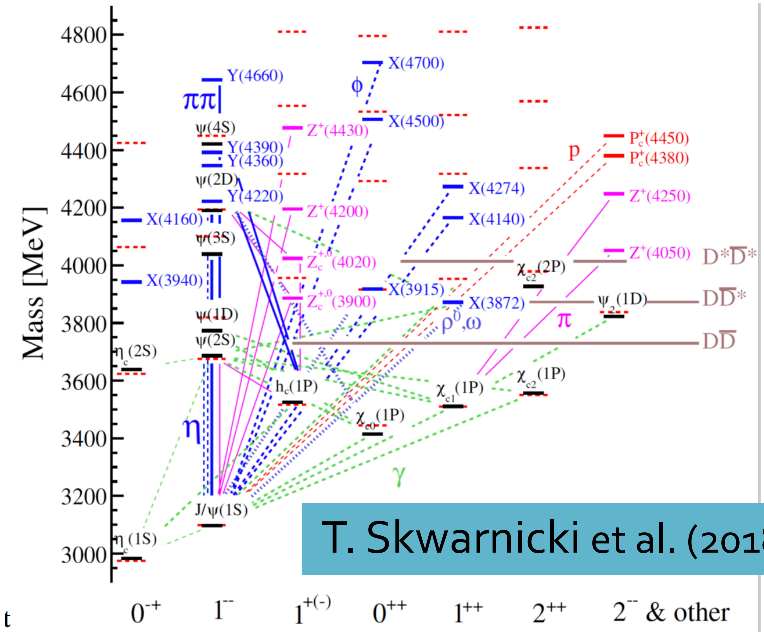


Work to extend this to e+A is under way. Cold nuclear matter vs QGP, lower transverse momenta

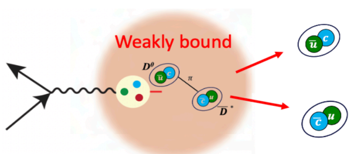
- Open quantum systems

Y. Akamatsu et al. (2011)

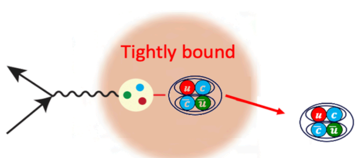
Exotics states in e+A



T. Skwarnicki et al. (2018)



Weakly bound hadronic molecule has large radius, samples large volume of nucleus



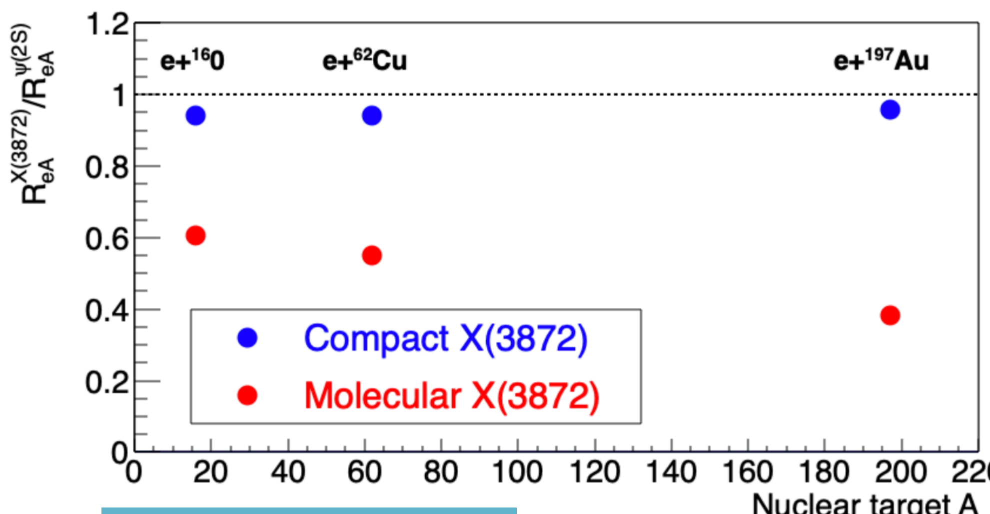
Tightly bound compact tetraquark has small radius, could more easily escape nucleus unscathed

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

- Questions remain about their nature – tightly-bound quark states, molecules of hadrons, or hybrids

Use the nucleus as a filter and compare to a known state

$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Big/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$



M.Durham (2020)

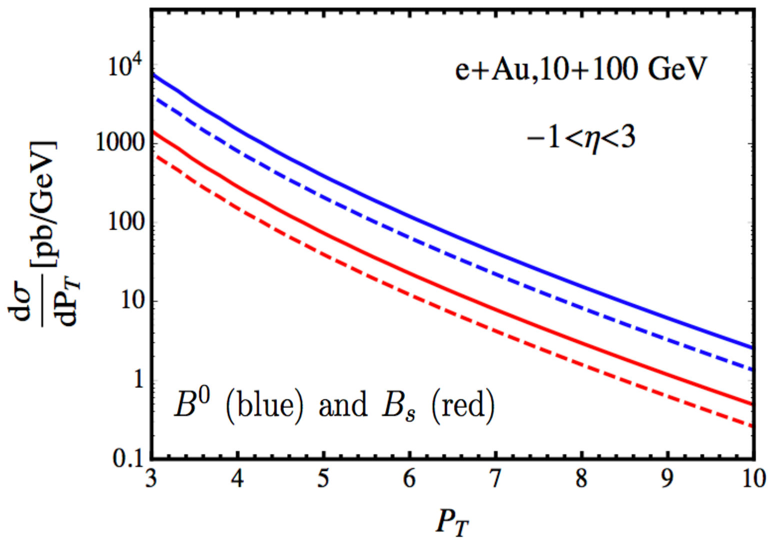
Heavy meson production in e+p, NLO corrections

Factorization formula

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

		5 GeV×40 GeV		10 GeV×100 GeV		18 GeV×275 GeV	
p_T^h [GeV]		[2 ,3]	[5 ,6]	[2 ,3]	[5 ,6]	[2 ,3]	[5 ,6]
π^+	LO	5.3×10^6	24260	1.4×10^7	3.0×10^5	2.9×10^7	9.6×10^5
	NLO	1.1×10^7	69473	2.8×10^7	6.1×10^5	5.6×10^7	1.9×10^6
D^0	LO	1.4×10^6	3242	8.6×10^6	89952	3.1×10^7	6.6×10^5
	NLO	3.7×10^6	8536	2.1×10^7	2.1×10^5	7.2×10^7	1.5×10^6
B^0	LO	3.7×10^5	1171	2.4×10^6	28413	9.0×10^6	2.0×10^5
	NLO	1.1×10^6	3333	6.2×10^6	72329	2.1×10^7	4.7×10^5

Example of light, charm, and bottom hadron multiplicities at the EIC in selected p_T bins to lowest and next-to-leading order. We have integrated over the hadron pseudo-rapidity is the interval $-2 < \eta < 4$ and used a typical one year integrated luminosity of 10 fb^{-1} in e+p collisions



The WW contribution not included
In the figure

The resolved photon contribution (with WW photons) gives a large contribution - 40-50% of the NLO correction

Generally production is at more forward rapidities. Most pronounced for pions. Differences are attributed to parton distributions

Heavy quarks in the vacuum and the medium

- SCET$_{M,G}$ – for massive quarks with Glauber gluon interactions
- You see the dead cone effects. You also see that it depends on the process – it not simply x^2m^2 everywhere: x^2m^2, $(1-x)^2m^2$, m^2

Dokshitzer et al. (2001)

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \quad iD^\mu = \partial^\mu + gA^\mu \quad A^\mu = A^\mu_c + A^\mu_s + A^\mu_G$$

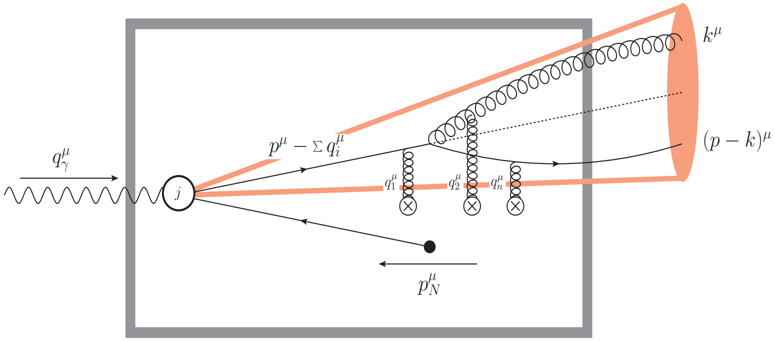
Result: SCET$_{M,G}$ =SCET$_M$ $\times$ SCET$_G$

I. Rothstein (2003)

F. Ringer et al . (2016)

There is a an easier/ more elegant way to derive the in-medium splitting functions base on the LCWF approach

M. Sievert et al, (2019)

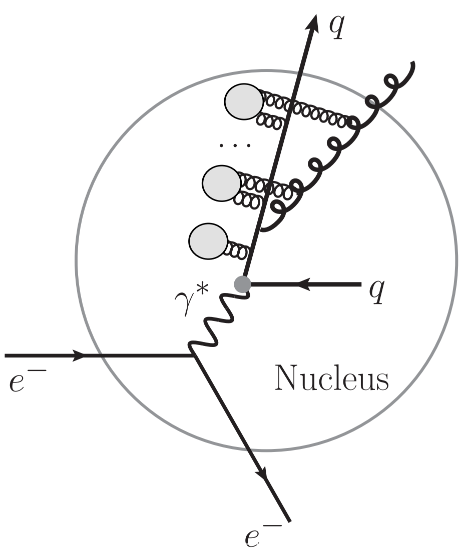


$$\left(\frac{dN^{\rm med}}{dxd^2k_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2q_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{B_\perp}{B_\perp^2+\nu^2} \right.\right.$$
$$\times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

In-medium splitting function derivation, evaluation, and implementation is the most challenging part of calculations involving nuclei

Have to take cues from the modification of light hadrons

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



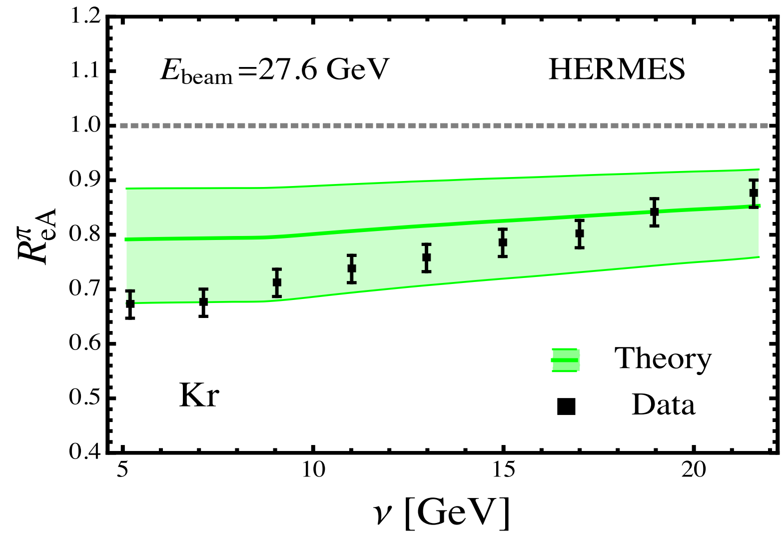
$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

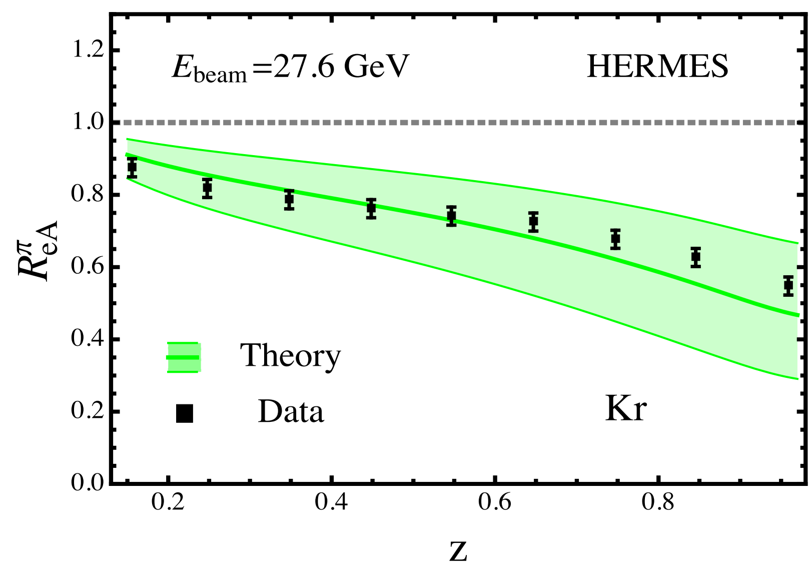
In-medium evolution of fragmentation functions

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

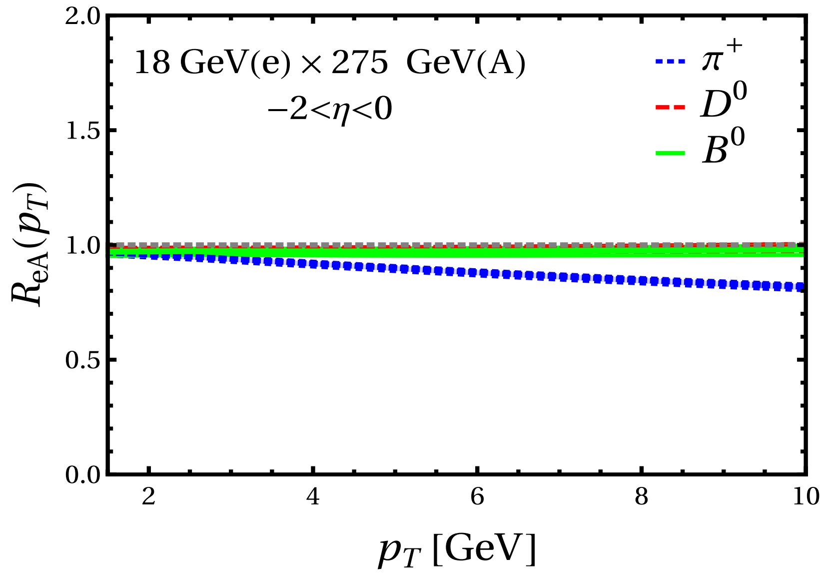
- We constrain a range of transport properties to explore from HERMES

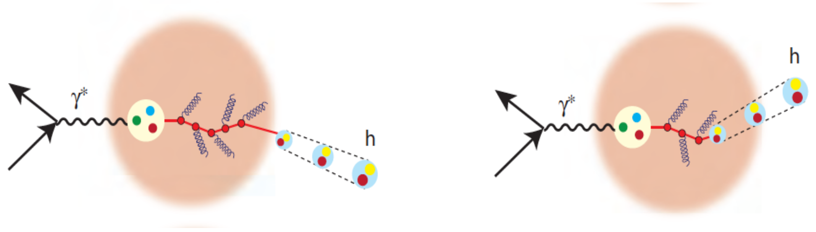
Transport properties: $2\frac{\mu^2}{\lambda g} = 0.12\frac{GeV^2}{fm}$ $(vary \times 2,/2)$





Light flavor suppression at the Electron Ion Collider

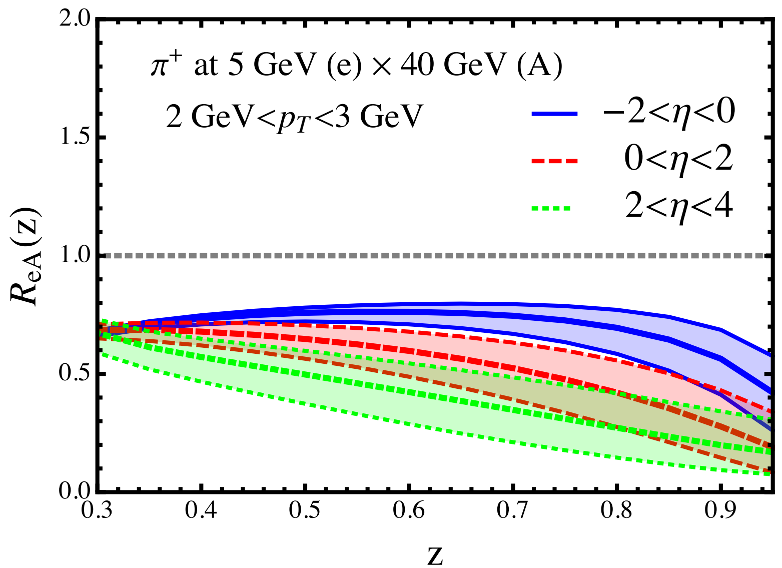




Light pions show the largest nuclear suppression at the EIC. However to differentiate models of hadronization heavy flavor mesons are necessary

- This is the figure that illustrates the usefulness of smaller CM energies and forward rapidities.

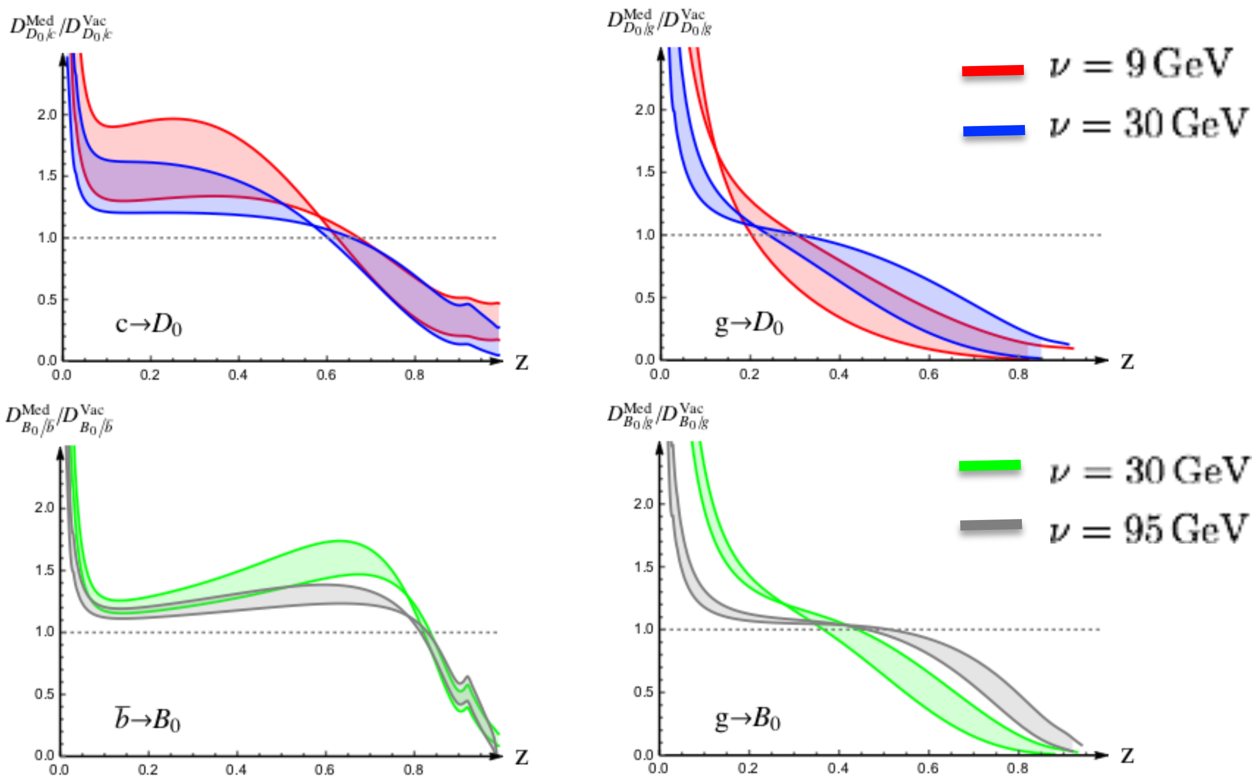
This is to study in-medium evolution / energy loss. Effects depend on the energy of the parton in nuclear rest frame. Minimize the rapidity gap between the nucleus and the parton



H. Li et al . (2020)

In-medium evolution of HF fragmentation functions

- The modification of heavy flavor channels is very different than for light channels



Ratio of in-medium evolution to vacuum-evolved FFs

- Very characteristic enhancement at small and moderate values of z. Transition from. Suppression to enhancement is much steeper for B mesons
- Gluon fragmentation pattern different

However gluons give minimal contribution

Modification of heavy mesons vs p_T - rapidity, CM dependence

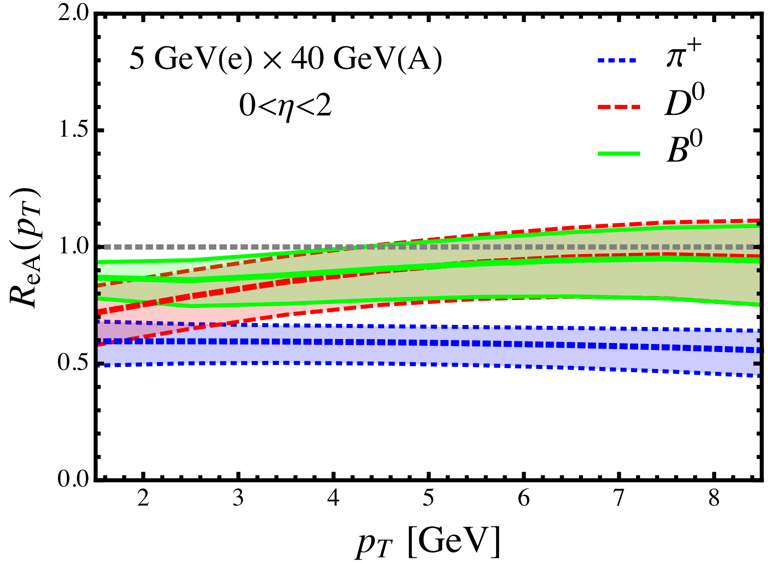
Normalization is important. Aimed at minimizing the initial-state PDF effects

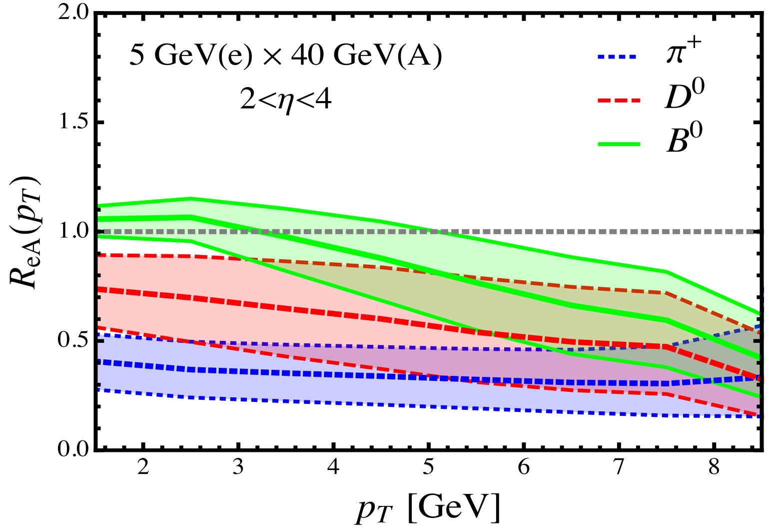
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+p}}$$

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

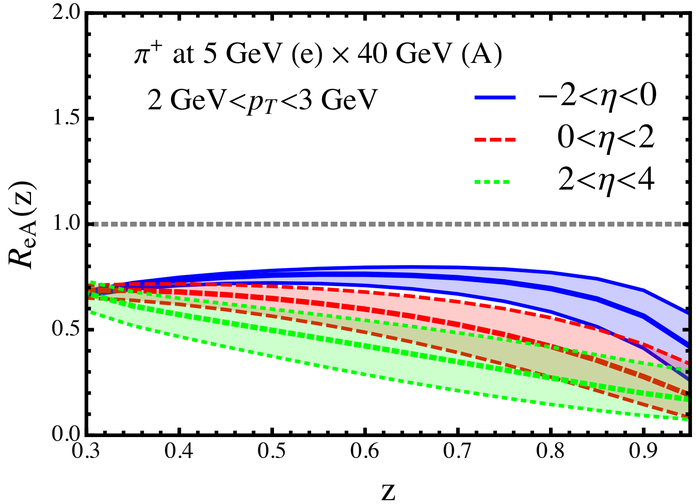
- Observe suppression – large effects. Suppression can be as large as a factor of 2 to 3
- Forward rapidities show the largest effects. Higher CM energy, backward y – small effects
- However, in many kinematic ranges the modification of D, B mesons (or lack there off) is ~1

H. Li et al . (2020)



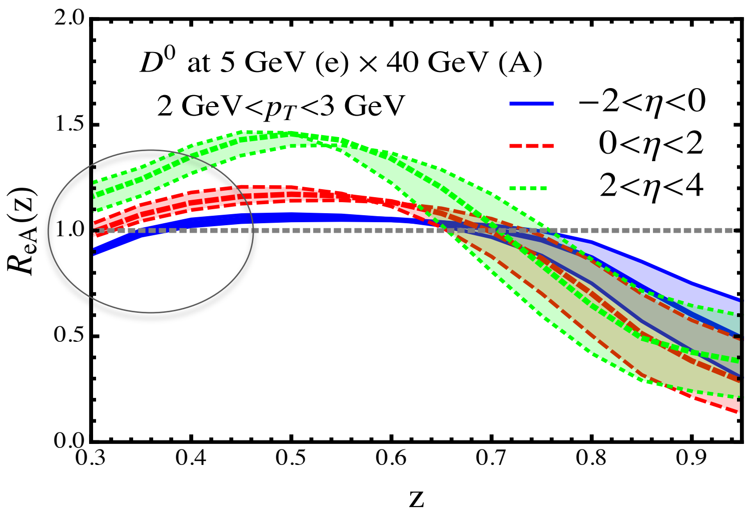


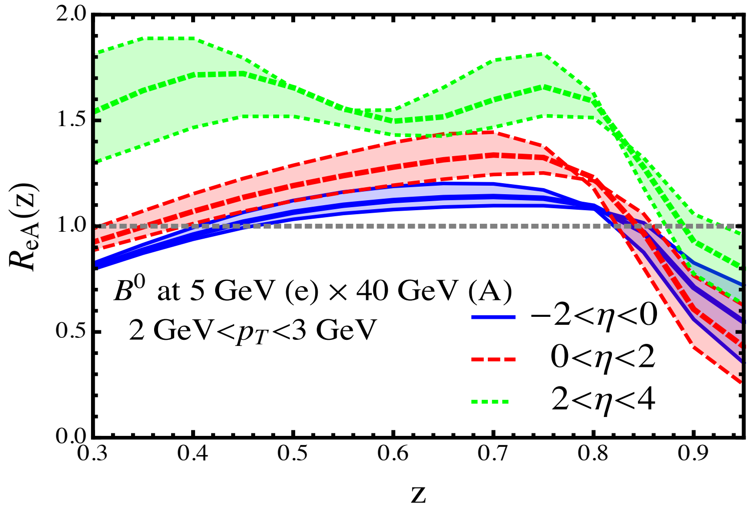
A better observable



- 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





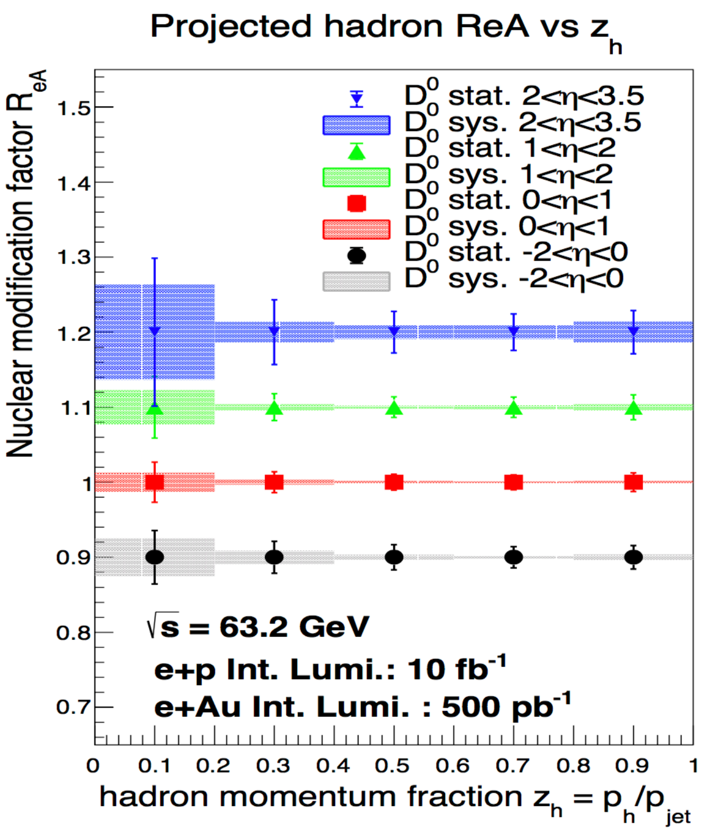
H. Li et al . (2020)

As I will show this modification can be measured with a forward silicon tracker

Can this be measured?

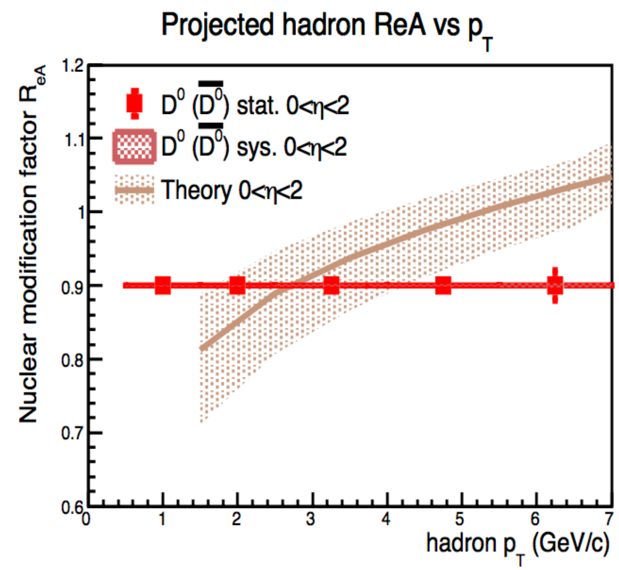
Yes it can. Quite accurately on top of that

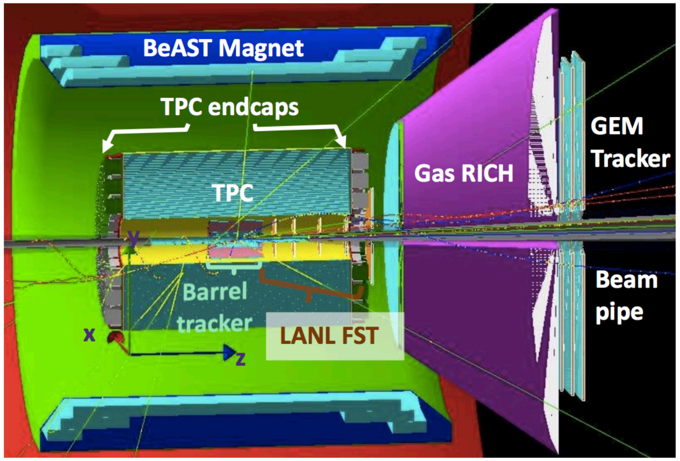
Differentially vs rapidity and momentum fraction



- Can constrain the transport properties to about 30%

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



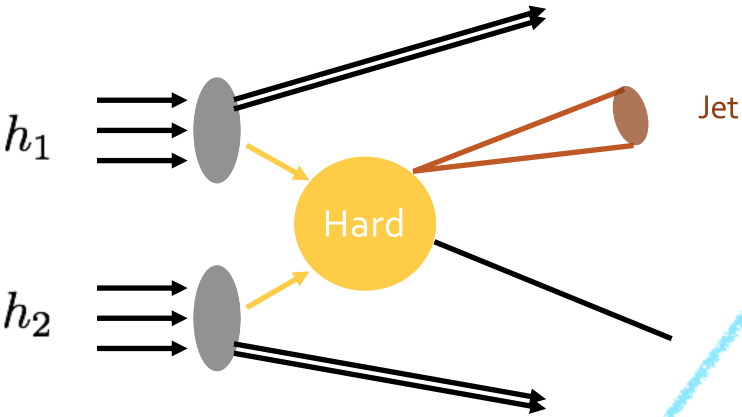


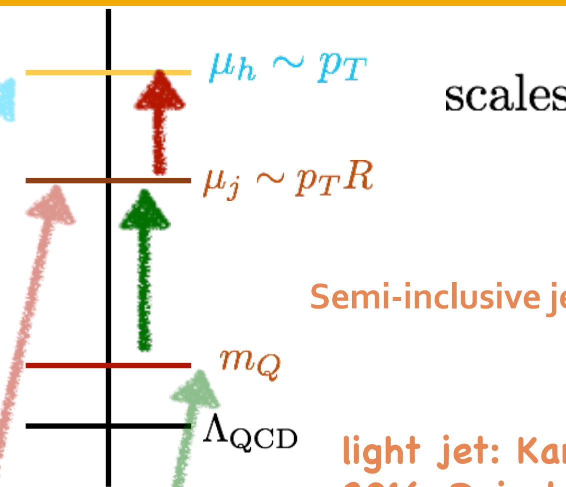
X. Li et al . (2021)

R. Abhdul Khalek et al . (2021)

Inclusive heavy jet production

- Jet production is one of the cornerstone processes of QCD. Light jets have been studied for a long time. Recent advances based in SCET





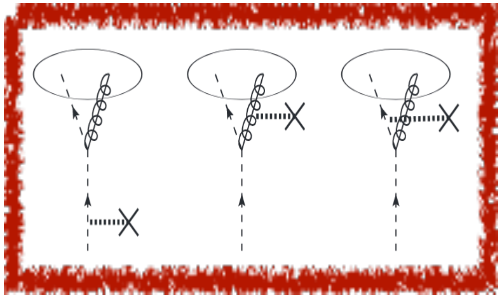
Semi-inclusive jet function

$$h_1 + h_2 \to \text{Jet} + X$$

light jet: Kang et al 2016, Dai et al 2016
heavy flavor jet: Dai e
al 2018

$$\frac{d\sigma_{pp\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\rm min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\rm min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)$$

$$\times \int_{z_{\rm min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s}, p_T/z_c,\hat{\eta},\mu)}{dvdz} J_{J/c}(z_c, w_J\tan(R'/2), m_Q,\mu)$$



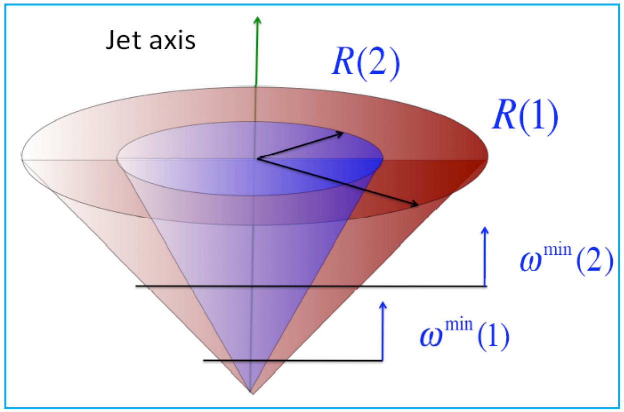
Hard scattering kernel

Aversa et al 1989, Jager et al 2002

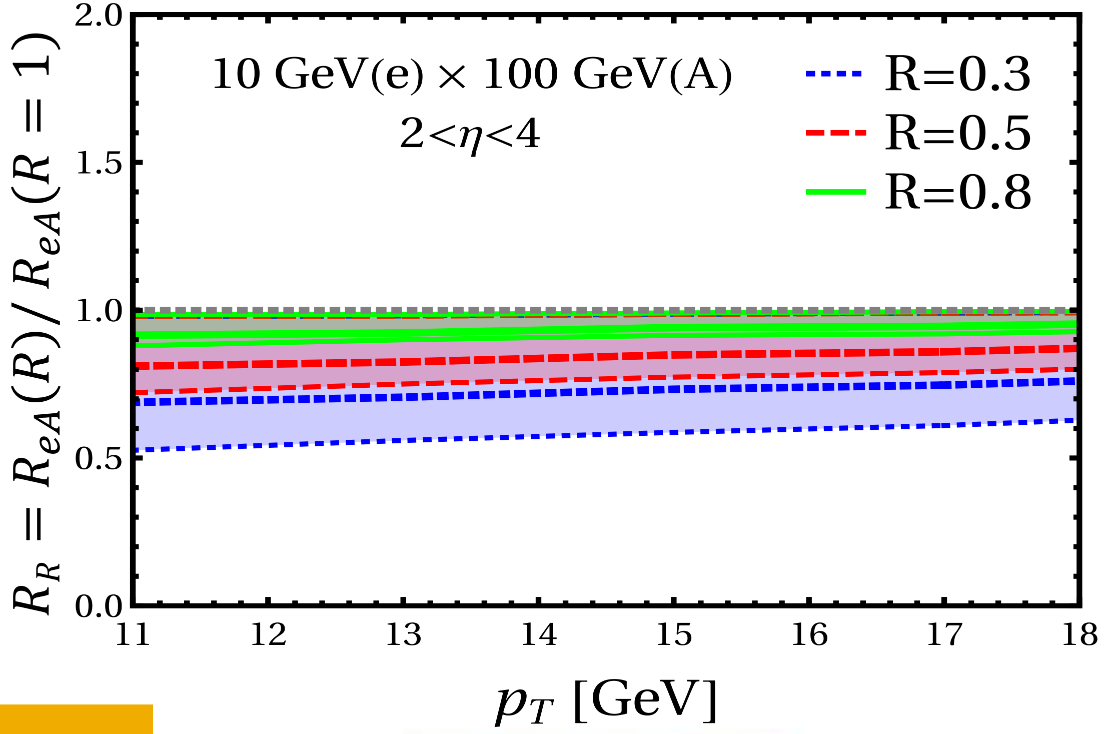
Heavy flavor jets at the EIC

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

- The physics of reconstructed jet modification



To eliminate initial-state effects we take a double ratio



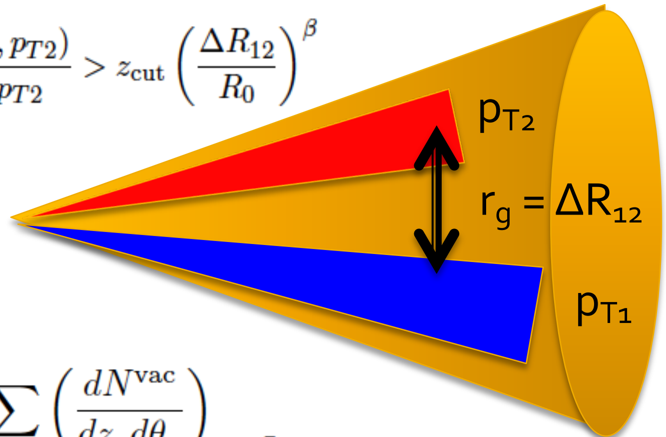
PRELIMINARY

- Relative jet modification nearly a factor of 2 for small radius jets
- Comparable to light jets

Z. Liu et al. (2021)

Inverting the mas hierarchy of jet quenching effects

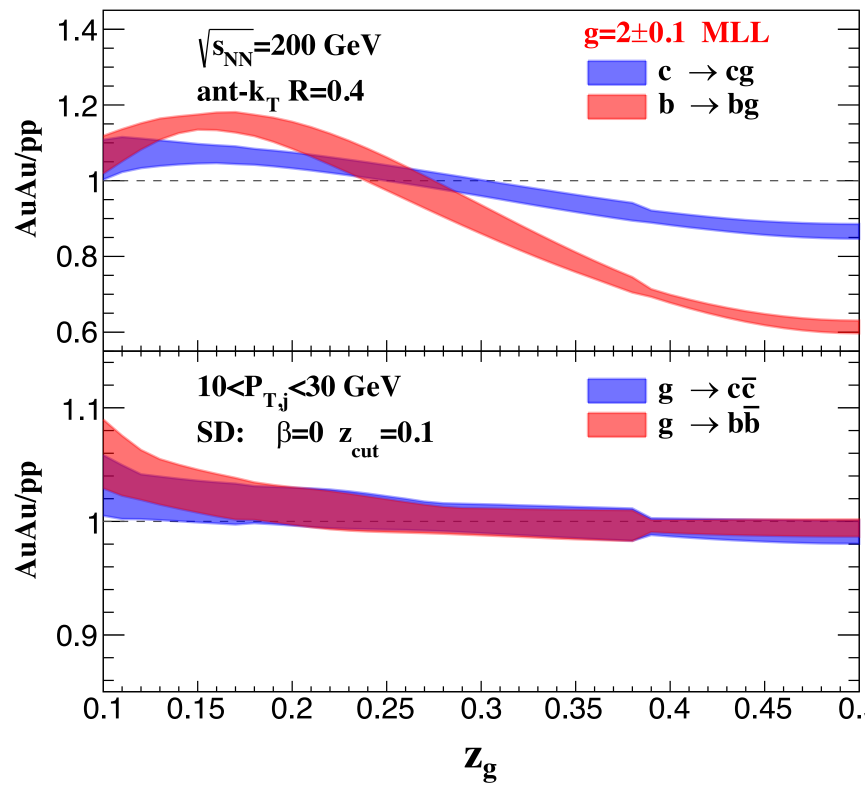
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



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

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

At lower 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



Due to the smaller CM energies / p_T at the EIC we expect similar non-trivial effects in jet substructure modification for heavy flavor

H. Li et al . (2017)

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/
- 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
- 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 are underway in e+A collisions. 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 exhibits unique features that could be studied at the EIC (TBD)
- Lower CM energies/higher luminosity maximize nuclear effects