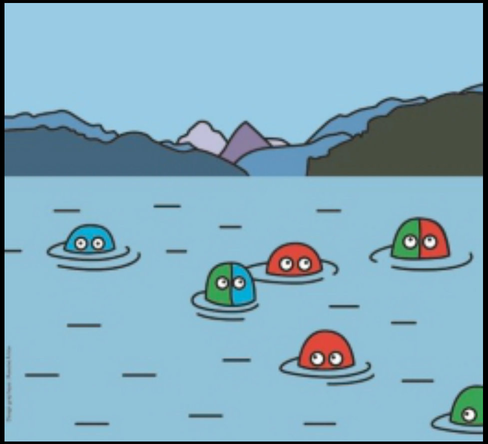
Ivan Vitev

Heavy flavor production in heavy ion and electron-nucleus collisions



FH2022 Programme "Heavy Flavours from small to large systems "
Institut Pascal, Orsay, France
October 3-21, 2022

Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline of the talk

- The physics of HF hadronization and current status
- Open heavy flavor and production in elementary collisions
- Heavy flavor in nuclei – Glauber gluons, energy loss and in-medium showers. Phenomenology
- Quarkonium EFTs - in the vacuum and in nuclear matter. Phenomenology
- Conclusions and future directions

Bottom line up front: Heavy Flavor is an underexplored area at the intersections of hadronic, heavy ion, and EIC science. It provides tremendous theory advancement opportunities.

Open HF at the EIC: https://indico.bnl.gov/event/9273/
Quarkonia at the EIC: https://indico.bnl.gov/event/12899/

Acknowledgment of support

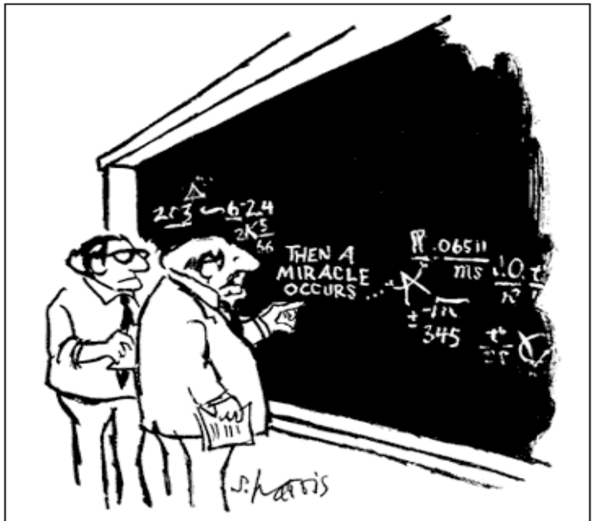
and Horizons 2020

U.S. DEPARTMENT OF ENERGY Office of Science

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Heavy flavor in elementary collisions and hadronization



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

Hadronization

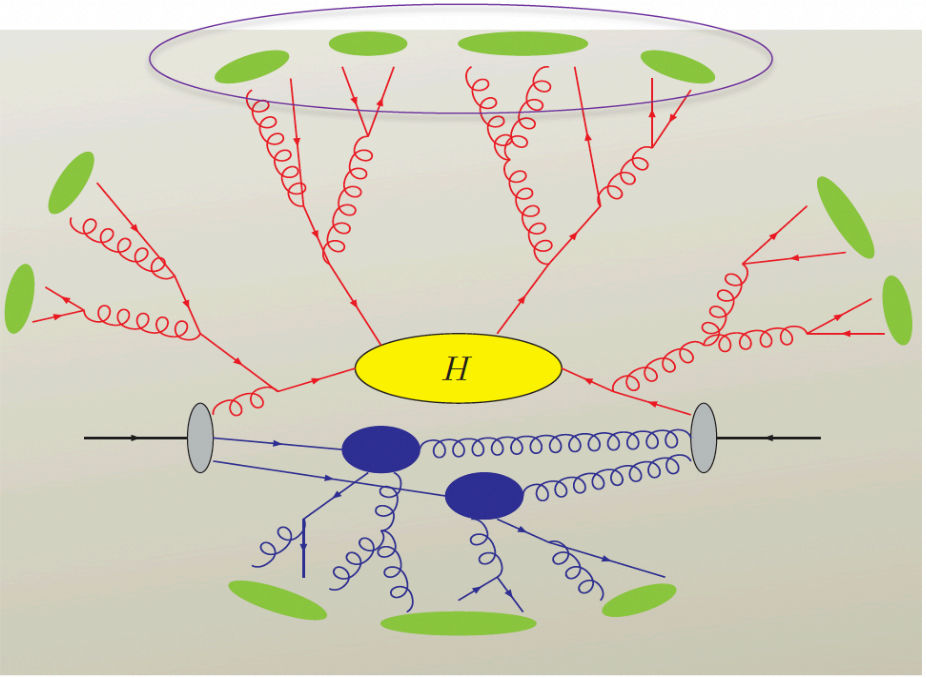
B. Webber (1999)

Change the order a little bit and discuss this first

T. Sjostrand (2015)

- Hadronization is the inherently non-perturbative process where energy is converted to matter and the fundamentally unobservable in isolation degrees of freedom of QCD (quarks and gluons) form the elementary particles that we can measure

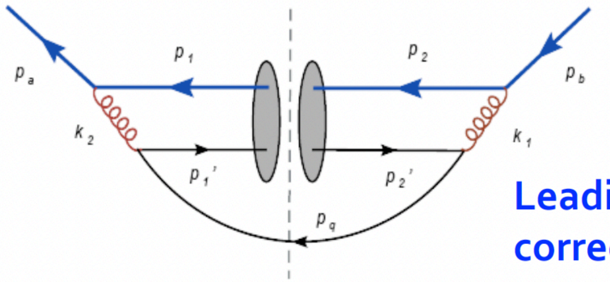
Note, fragmentation is not the same as hadronization. Fragmentation (and there are different varieties) is a model of hadronization



- Hadronization is a long-distance, late-stage phenomenon. We have no first principles understanding yet of the timescales involved

Heavy quark fragmentation in HQET

Heavy quarks introduce a mass scale that allows the fragmentation function shape to be computed perturbatively.

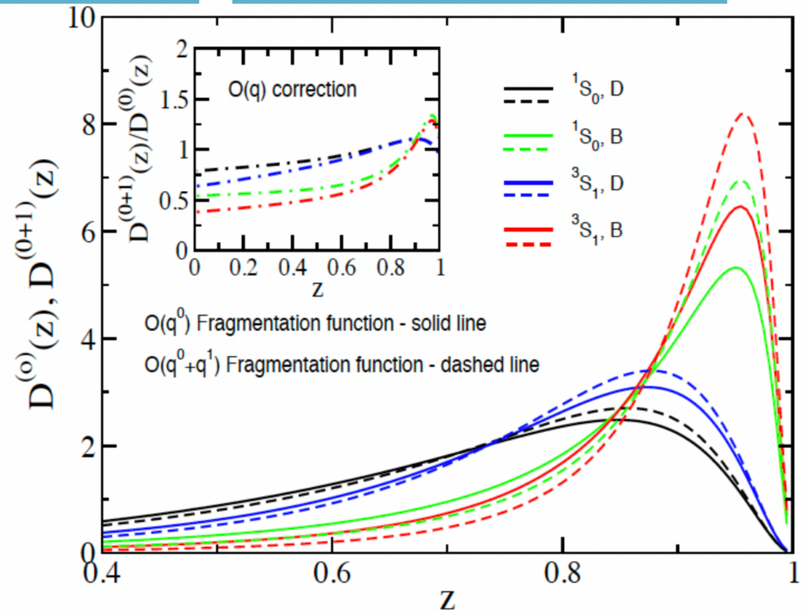


Chang et al. (1992)

Braaten et al. (1995)

Leading result and first correction from transverse motion

$$T_P^{(1)}(z) = \frac{(z-1)^2 z^2}{6M^3(1-r)r^3((r-1)z+1)^8}\left[\frac{p_Q^+}{q_{1P}^+}\frac{\mathbf{q}_{1T}^2}{M^2}+\frac{p_Q^+}{q_{2P}^+}\frac{\mathbf{q}_{2T}^2}{M^2}\right]\Big\{3(r-1)^4 r z^6+(r-1)^3(2r+5)z^5+3(r-1)^3(4r-7)z^4 -(r-1)(r(r(8r-63)+88)-36)z^3+[r((81-28r)r-90)+32]z^2+((25-8r)r-15)z+3\Big\},$$



R. Sharma et al. (2009)

- Still depends on non-perturbative parameters $r = m_q/M_Q$, the square of the wavefunction in the origin. Fitted to data

Light and heavy flavor fragmentation and evolution

Another heavy flavor FF parametrization - Lund-Bowers

$$D(z) = z^{-1-bM_\perp^2}(1-z)^a e^{-\frac{bM_\perp^2}{z}}$$

M. Bowers (1981)

$$\frac{\partial D^0_{h/i}(z,Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x}\left[P'_{ji}(x\to 1-x, Q^2) + d_{ji}(Q^2)\delta(1-x)\right] D_{h/j}\left(\frac{z}{x}, Q^2\right)$$

Heavy flavor specific

$$r = M/Q$$

$$d_{qq}(Q^2) = \frac{\alpha_s(Q^2)}{2\pi} C_F \frac{3}{2},$$

$$d_{HH}(Q^2, r) = \frac{\alpha_s(Q^2)}{2\pi} C_F c_{HH}(r),$$

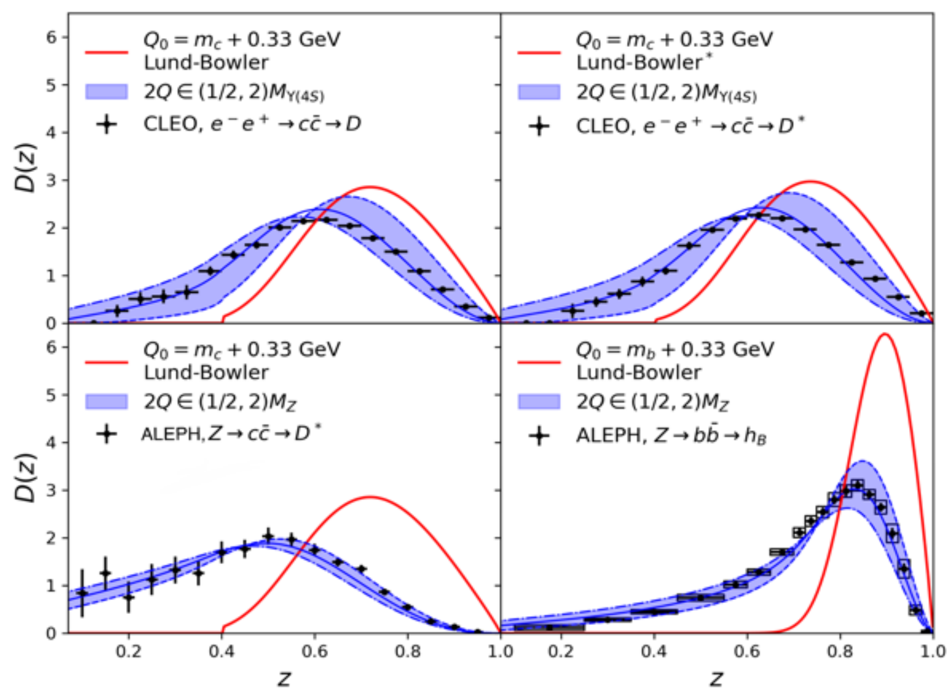
$$d_{gg}(Q^2, r) = \frac{\alpha_s(Q^2)}{2\pi}\left[\frac{11}{6}N_c - N_f T_F \frac{2}{3} + \sum_{H=c,b} T_F c_{gH}(r)\right]$$

$$c_{gH}(r) = F\left(\frac{1+\sqrt{1-4r^2}}{2}\right) - F\left(\frac{1-\sqrt{1-4r^2}}{2}\right) - 2r^2\sqrt{1-4r^2},$$

$$F(x) = -x^4 + \frac{4}{3}x^3 - x^2,$$

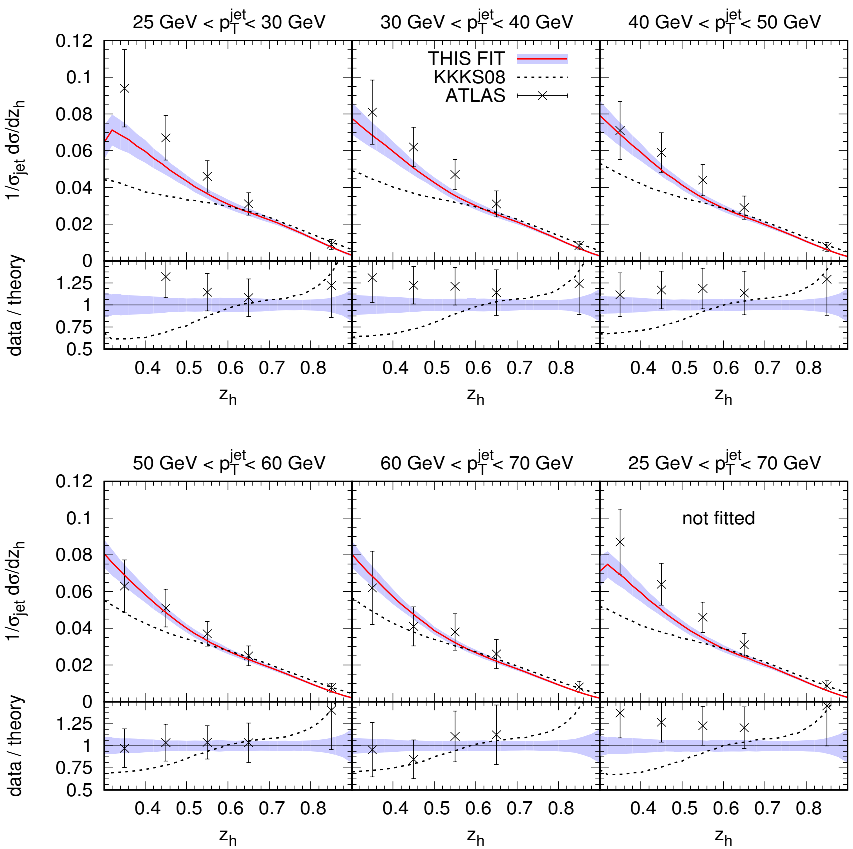
$$c_{HH}(r) = \frac{1}{1+r^2} + \frac{2r^2+1}{2(1+r^2)^2} + \frac{2r^2}{1+r^2} - 2\ln\frac{1}{1+r^2}.$$

Evolution generates gluon fragmentation component to HF



Evolution softens HQ fragmentation functions

Constraints on fragmentation from heavy mesons in jets



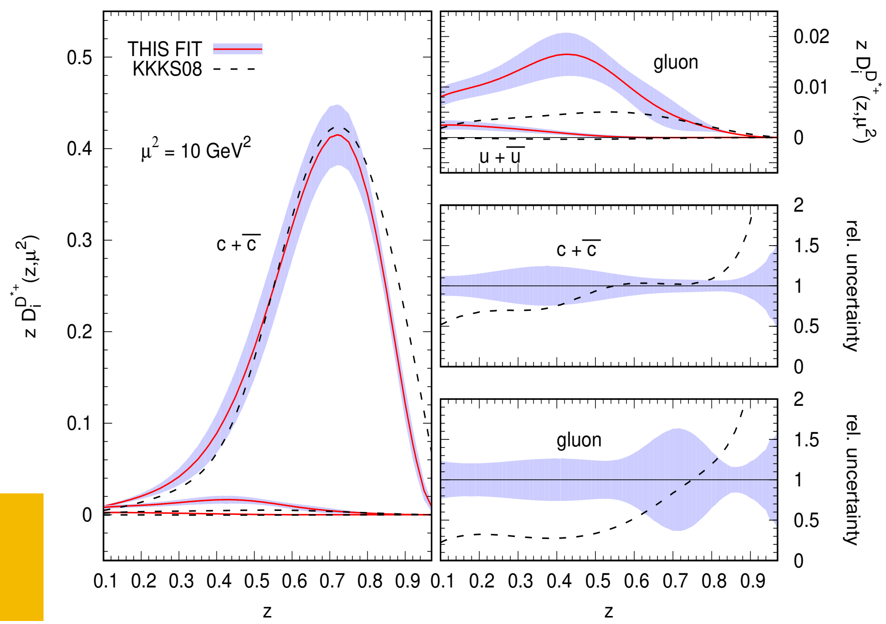
D. Anderle *et al.* (2017)

Significant enhancement of the gluon fragmentation component at small and intermediate z

Using a new formalism of semi-inclusive fragmenting jet functions

$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T^{\text{jet}}\,d\eta^{\text{jet}}\,dz_h} = \frac{2p_T^{\text{jet}}}{S}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)$$
$$\times\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)\int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}^c_{ab}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{v\,dv\,dw}$$
$$\times\,\mathcal{G}_c^h(z_c,z_h,\mu,R)\,,$$

Z. Kang *et al.* (2016)

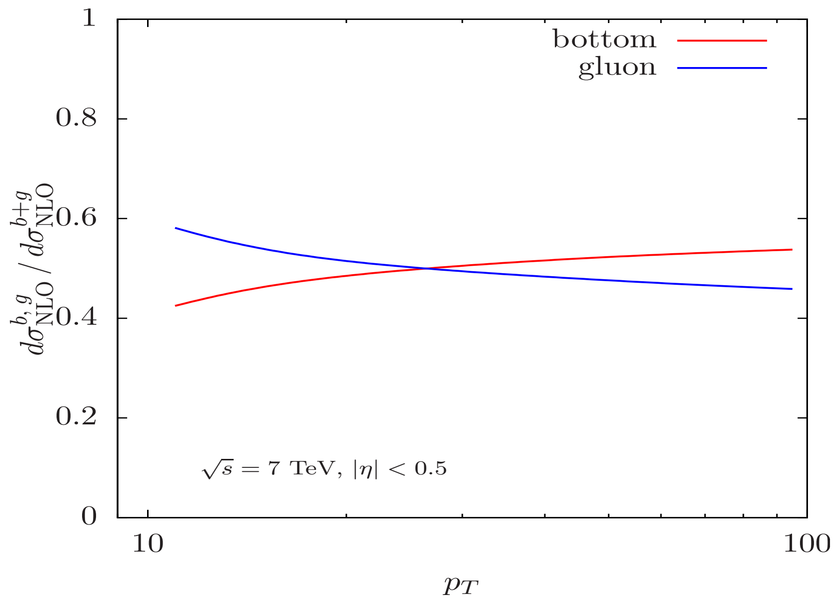


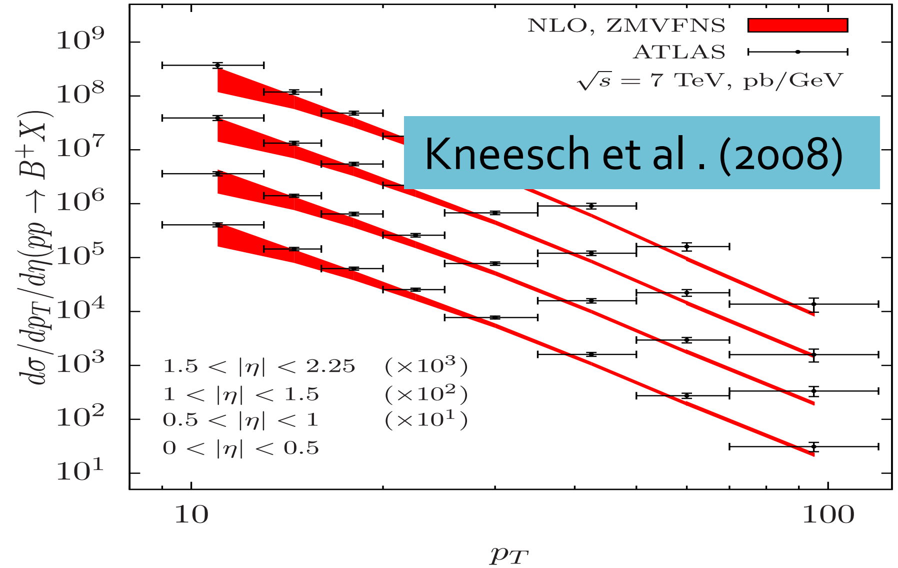
ZMVFS open heavy flavor at NLO

- Perform and NLO calculation
- A very large contribution of gluon FF to heavy flavor

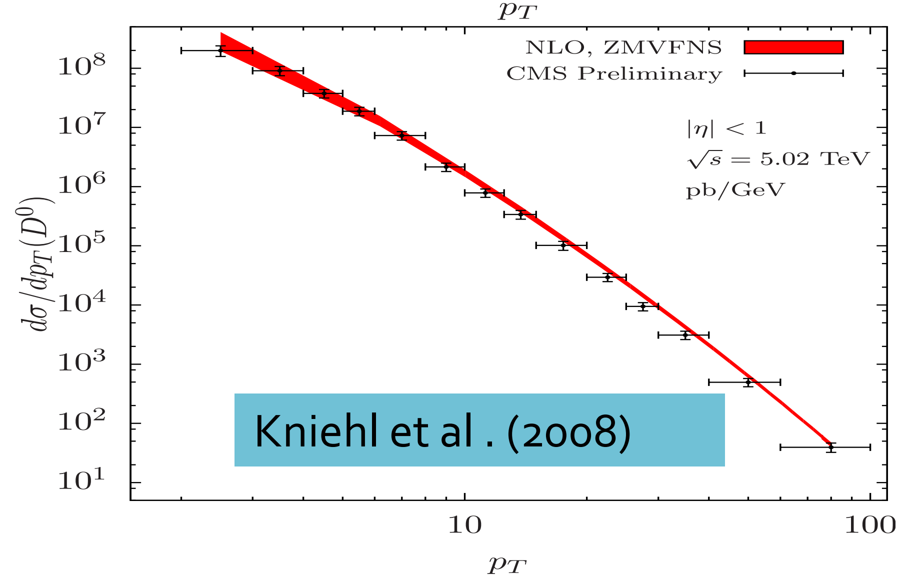
When $p_T > m_c, m_b$

Z. Kang et al . (2016)





Kneesch et al . (2008)

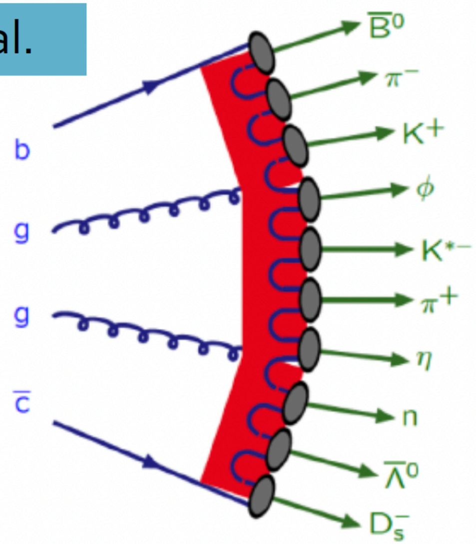


Kniehl et al . (2008)

Hadronization in Monte Carlo models

String fragmentation

PYTHIA et al.

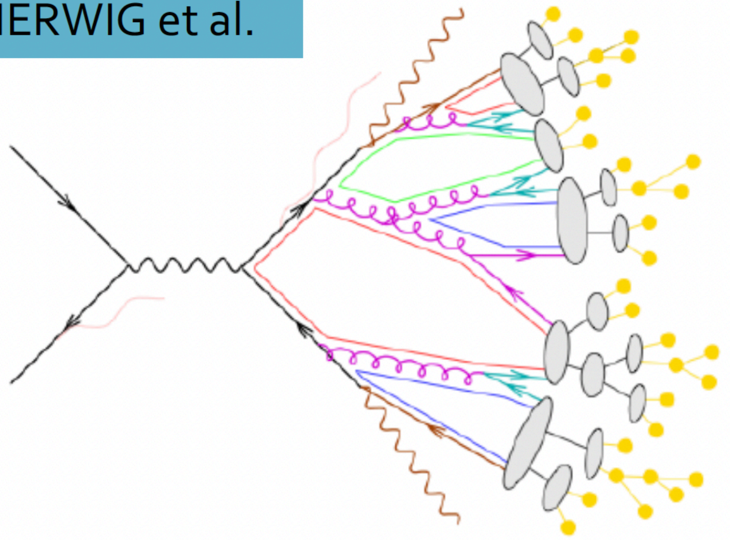


$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

- This picture allows to derive the form of fragmentation functions (not as general) but comes from a model

Cluster hadronization

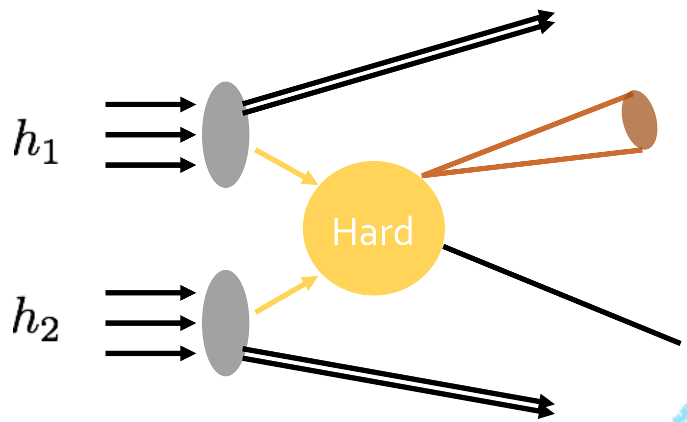
HERWIG et al.



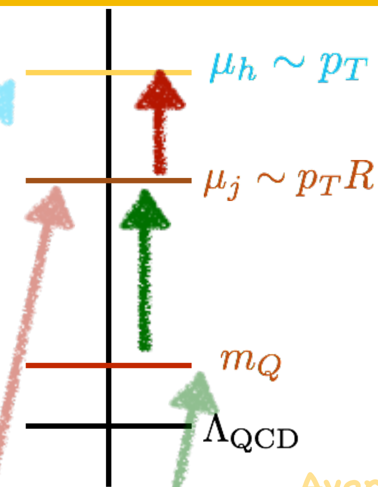
program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

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 for heavy jets (e.g. b) based in SCET



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



Scales in the EFT

Aversa et al 1990
Jager et al 2004
Mukherjee et al 2012
Kaufmann et al 2016
….

$$\frac{d\sigma_{pp\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1} \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^{1} \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_{\min}}^{1} \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s}, p_T/z_c,\hat{\eta},\mu)}{dvdz} J_{J/c}(z_c, w_J\tan(R'/2), m_Q,\mu)$$

Semi-inclusive jet function

Hard scattering kernel

Aversa et al 1989, Jager et al 2002

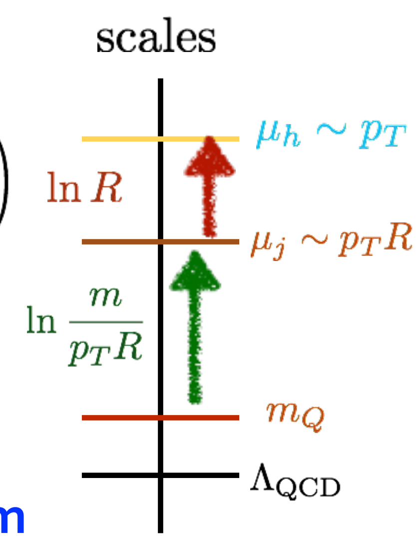
light jet: Kang et al 2016, Dai et al 2016
heavy flavor jet: Dai et al 2018

Evolution between scales

- Recent advances are based in SCET – precision theory for small radius jets and heavy flavor jets based on semi-inclusive jet functions

The SiJFs Evolve according to DGLAP-like equations

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



Resums ln $\mu/p_T R$

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

Resums ln $p_T R/m$

The integrated perturbative kernel at the jet typical scale

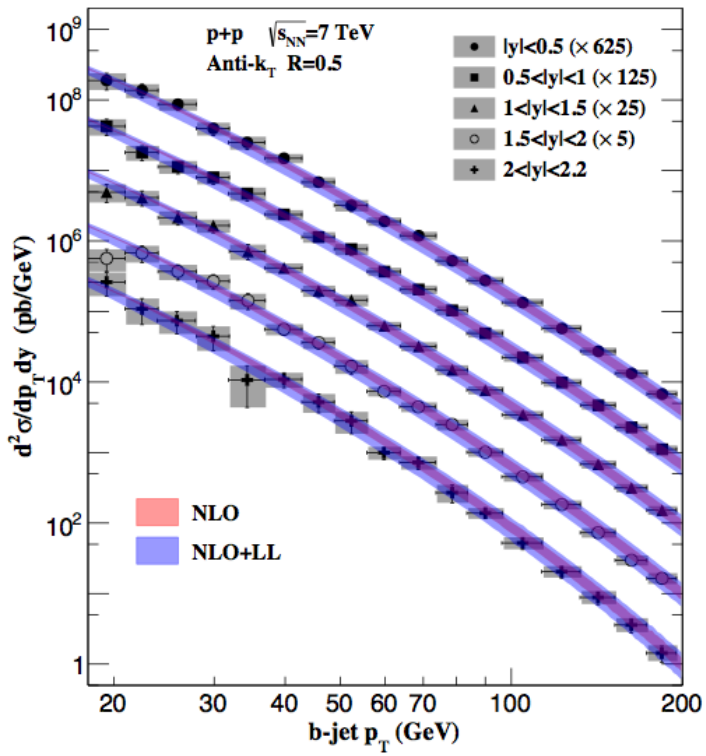
The integrated parton fragmentation function from parton *l* to parton *Q*

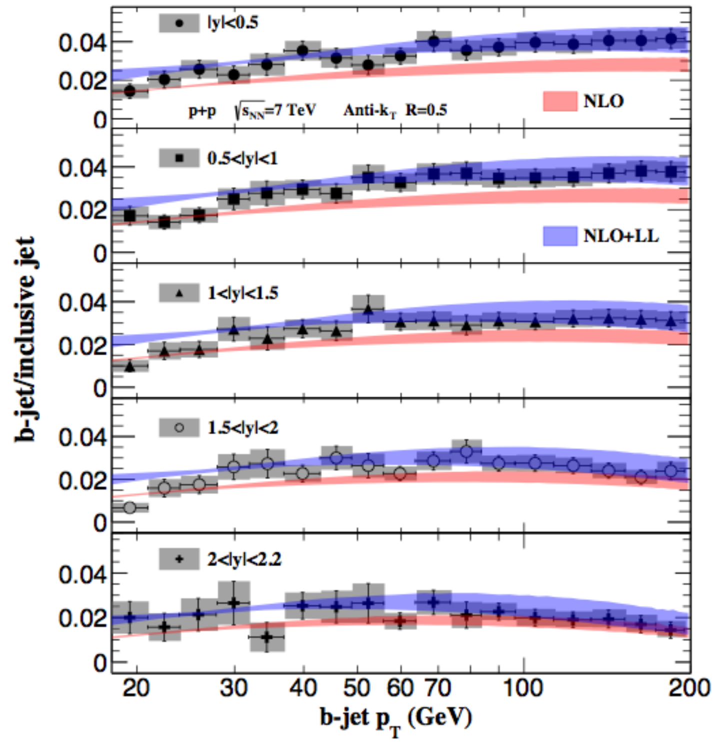
C. Bauer et al. (2013)

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

B-jet production in pp collisions

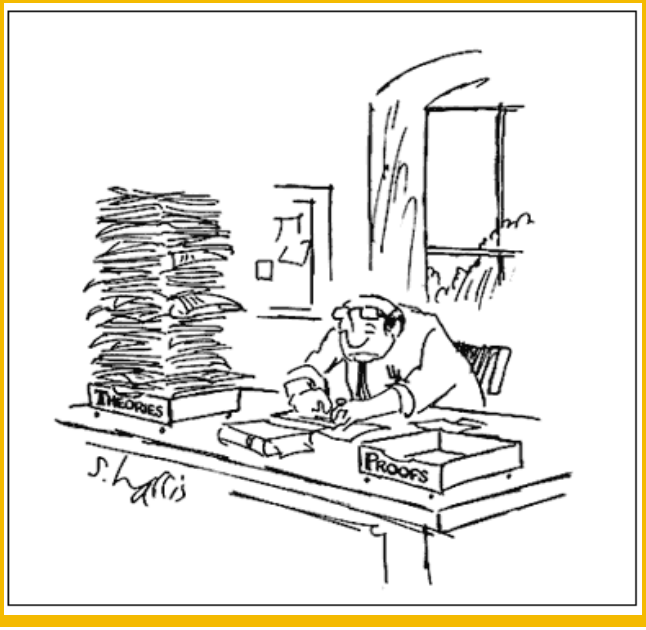
H. Li et al. (2019)





- Data are consistent with the theoretical predictions
- For the ratio b-jets to inclusive jets the difference between NLO+LL and NLO can be traced also to the differences in the inclusive jet cross section

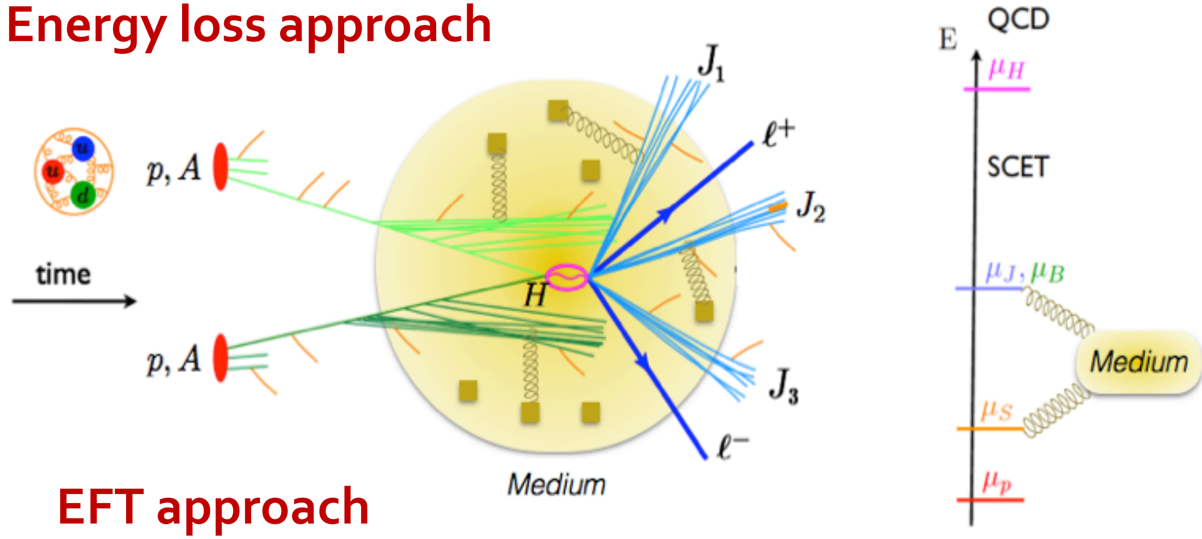
Heavy flavor in nuclei – energy loss and in-medium showers



Example of successful EFT in matter

- M. Gyulassy et al. (1993)
- B. Zakharov (1995)
- R. Baier et al. (1997)
- M. Gyulassy et al. (2000)
- X. Guo et al. (2001)
- P. Arnold et al. (2003)
- M. Djordjevic et al. (2003)

Energy loss approach



EFT approach

$$\mathcal{L}_G(\xi_n, A_n, A_G) = g \sum_{\tilde{p},\tilde{p}'} e^{-i(\tilde{p}-\tilde{p}')\cdot x} \left(\bar{\xi}_{n,p'} T^a \frac{\bar{\not{n}}}{2} \xi_{n,p} - i f^{abc} A^{\lambda c}_{n,p'} A^{\nu,b}_{n,p} g^{\perp}_{\nu\lambda} \bar{n} \cdot p \right) n \cdot A^a_G$$

- Idilbi et al. (2008)
- Ovanesyan et al. (2011)
- Z. Kang et al. (2016)

- Factorization, with modified J (jet), B (beam), S (soft) functions
- Accomplished for light partons. I will discuss how to do it for heavy quarks

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

Heavy quarks in the vacuum

$SCET_{M,G}$ – for massive quarks with Glauber gluon interactions

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^\mu = \partial^\mu + gA^\mu \qquad A^\mu = A_c^\mu + A_s^\mu + A_G^\mu$$

Feynman rules depend on the scaling of m. The key choice is $m/p^+ \sim \lambda$

I. Rothstein (2003)

A. Leibovich et al. (2003)

With the field scaling in the covariant gauge for the Glauber field there is no room for interplay with mass in the LO Lagrangian

$$\left(\frac{dN}{dx d^2k_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2m^2} \left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2 + x^2m^2}\right]$$

$$\left(\frac{dN}{dx d^2k_\perp}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_\perp^2 + m^2} \left[x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_\perp^2 + m^2}\right]$$

The process is not written Q to gQ

Z. Kang et al . (2016)

Result: $SCET_{M,G} = SCET_M \times SCET_G$

- You see the dead cone effects

  Dokshitzer et al. (2001)

- 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

Heavy quarks splitting functions in the medium

Kinematic variables

$$A_\perp = k_\perp,\ B_\perp = k_\perp + x q_\perp,\ C_\perp = k_\perp - (1-x) q_\perp,\ D_\perp = k_\perp - q_\perp$$

$$\Omega_1 - \Omega_2 = \frac{B_\perp^2 + \nu^2}{p_0^+ x(1-x)},\ \Omega_1 - \Omega_3 = \frac{C_\perp^2 + \nu^2}{p_0^+ x(1-x)},\ \Omega_4 = \frac{A_\perp^2 + \nu^2}{p_0^+ x(1-x)},$$

$$\begin{aligned} \nu &= m && (g \to Q\bar{Q}), \\ \nu &= x\, m && (Q \to Qg), \\ \nu &= (1-x)\, m && (Q \to gQ), \end{aligned}$$

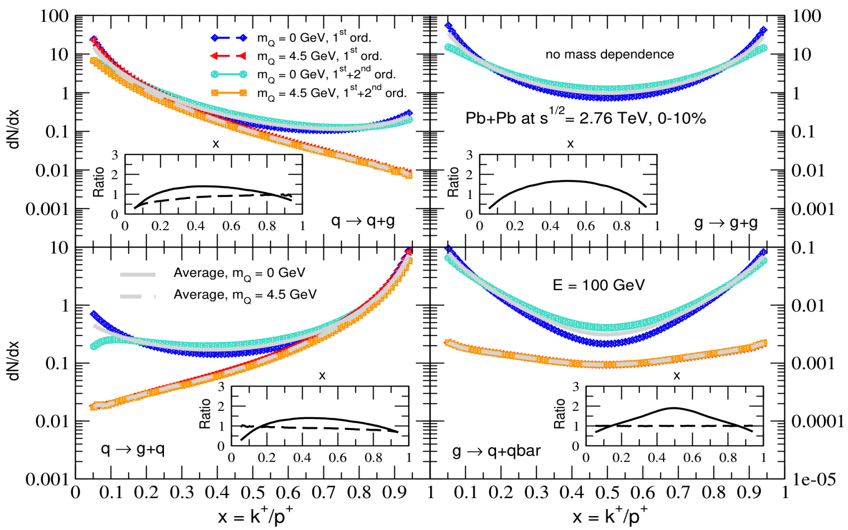
New physics – many-body quantum coherence effects

Z. Kang et al . (2016)

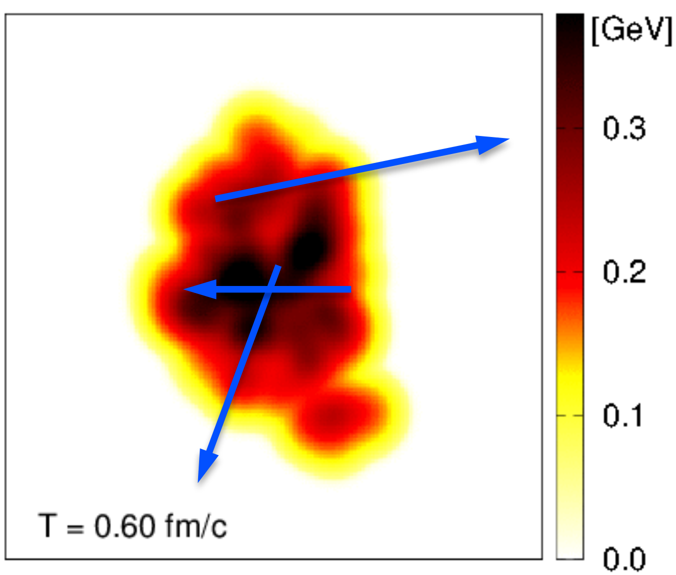
$$\begin{aligned}
\left(\frac{dN^{\rm med}}{dx d^2k_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2 q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2 q_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{B_\perp}{B_\perp^2+\nu^2}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

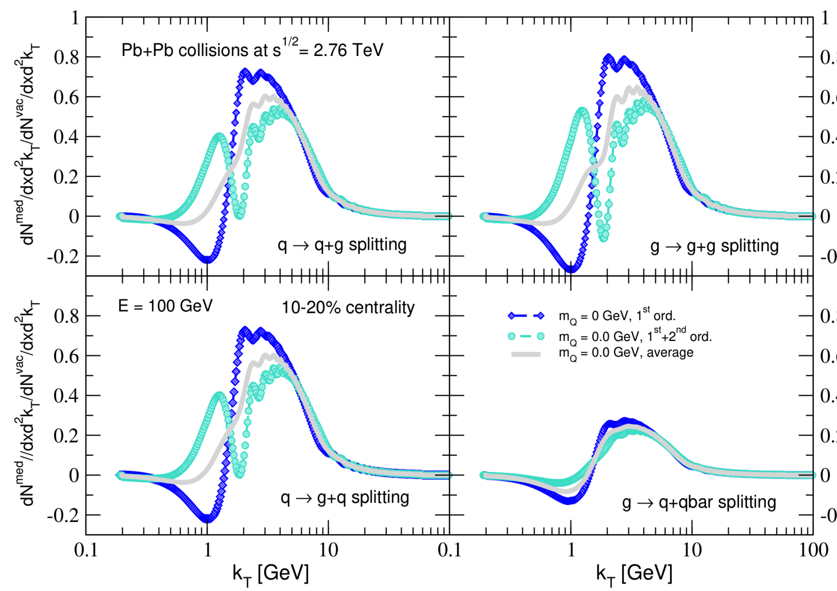
- Full massive in-medium splitting functions now available
- Can be evaluated numerically

Differential branching spectra



In-medium parton showers are softer and broader than the ones in the vacuum. There is even more soft gluon emission – medium induced scaling violations, enhancement of soft branching





C. Shen et al . (2014)

B. Yoon et al . (2019)

Implications for A+A Collisions

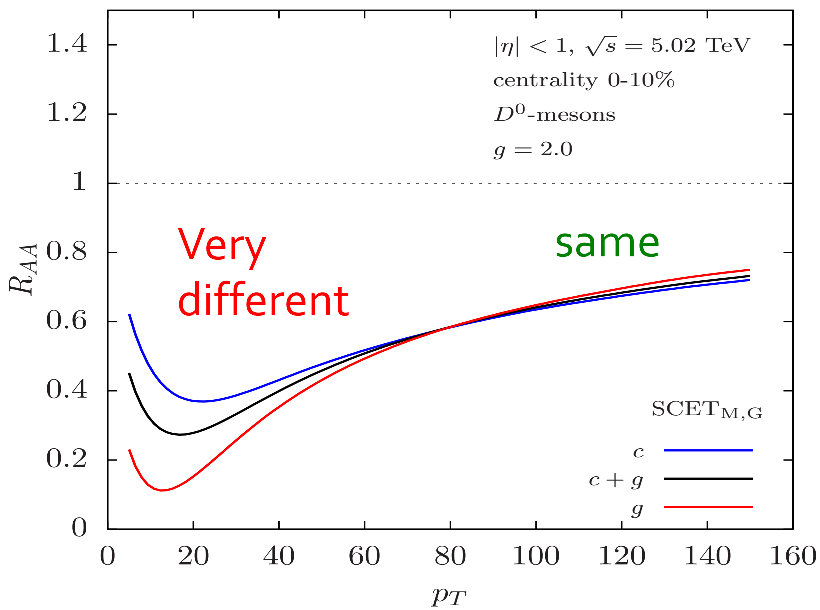
Full in-medium parton showers require different techniques – higher order and resumed calculations

- High-P_T stable, low p_T 30-50% more suppression
- Does not fully eliminate the need for collisional interactions / energy loss or dissociation

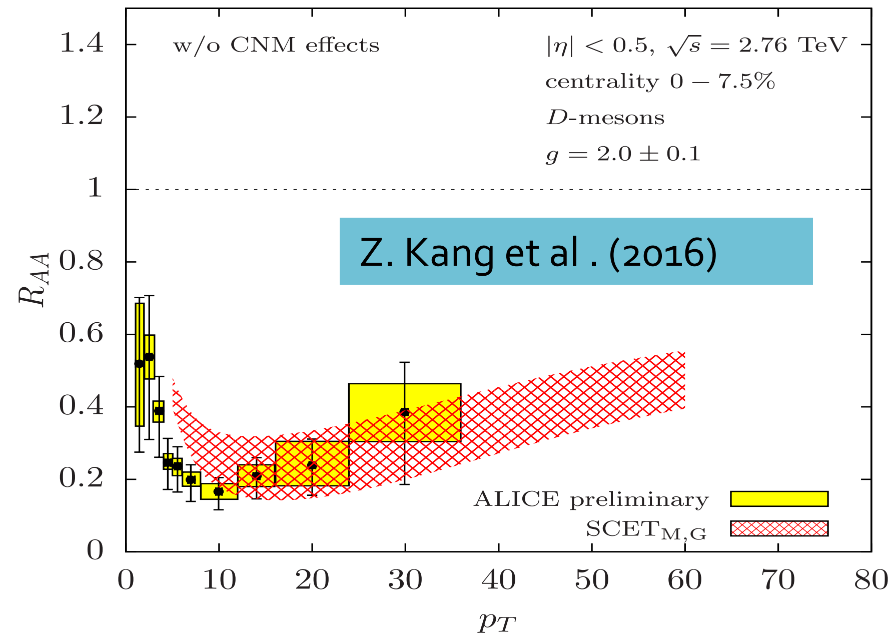
$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}^{\rm med}_{i\to jk} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,\rm med}$$

$$D_q^{H,\rm med}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_q^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\rm med}_{q\to qg}(z',\mu) - D_q^H(z,\mu)\int_0^1 dz' \mathcal{P}^{\rm med}_{q\to qg}(z',\mu)$$
$$+ \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\rm med}_{q\to gq}(z',\mu),$$

$$D_g^{H,\rm med}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\rm med}_{g\to gg}(z',\mu) - \frac{D_g^H(z,\mu)}{2}\int_0^1 dz' \Big[\mathcal{P}^{\rm med}_{g\to gg}(z',\mu)$$
$$+2N_f \mathcal{P}^{\rm med}_{g\to q\bar{q}}(z',\mu)\Big] + \int_z^1 \frac{dz'}{z'} \sum_{i=q,\bar{q}} D_i^H\left(\frac{z}{z'},\mu\right) \mathcal{P}^{\rm med}_{g\to q\bar{q}}(z',\mu).$$



Importance of gluon fragmentation into HF

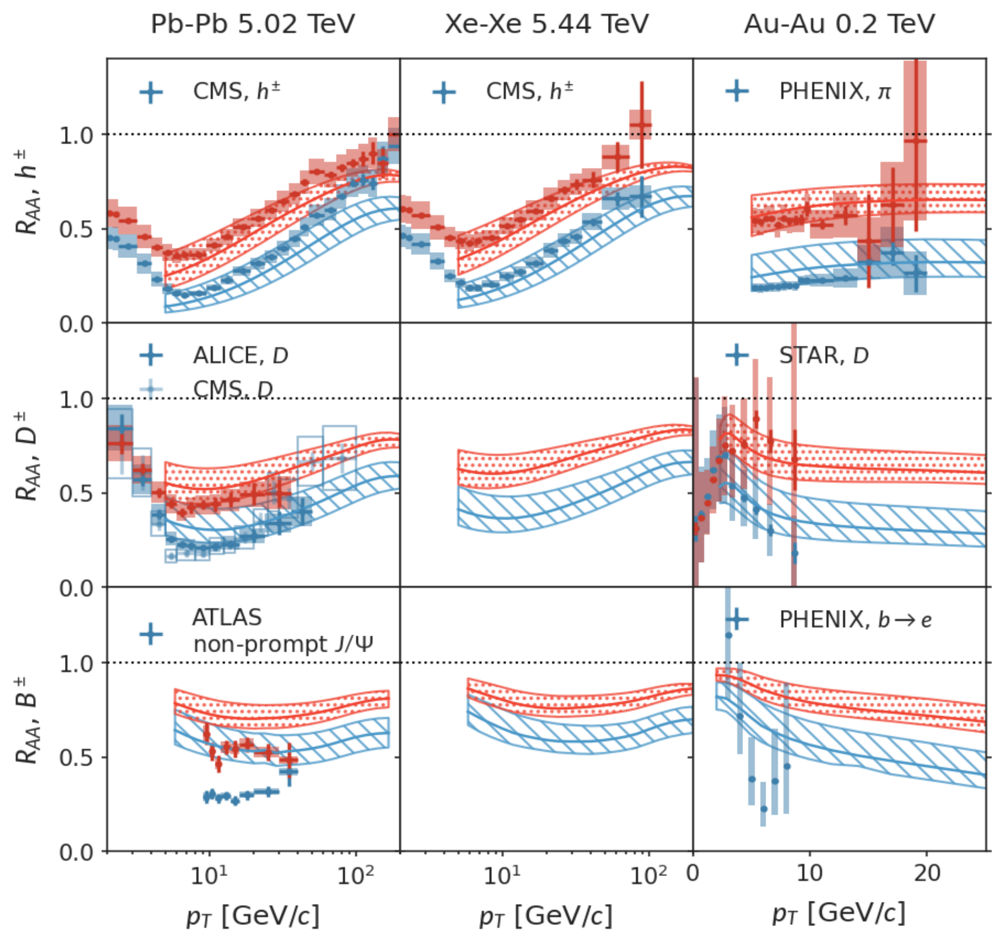


A different set of fragmentation functions

$$\frac{\partial D^0_{h/i}(z,Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x} \left[P'_{ji}(x \to 1-x, Q^2) + d_{ji}(Q^2)\delta(1-x)\right] D_{h/j}\left(\frac{z}{x}, Q^2\right)$$

W. Ke et al. (2022)

Large systems and applications of in-medium evolution



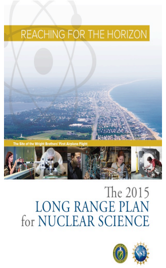
Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions

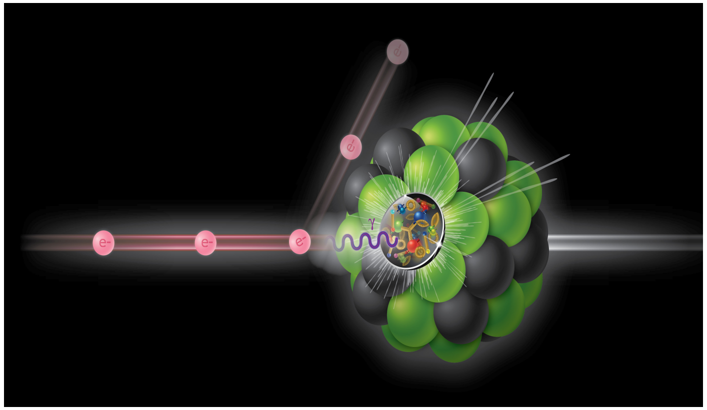
There is tension with the B meson production (or non-prompt J/psi). Combination with the May be dissociation?

One slide on the EIC

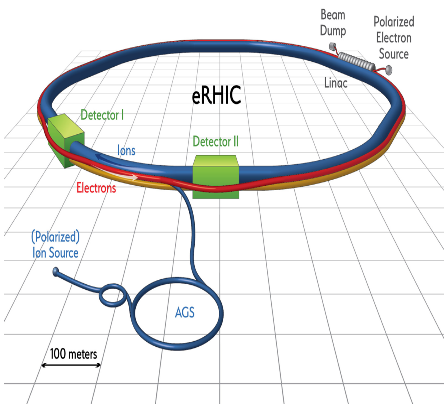
Long Range Plan recommendations

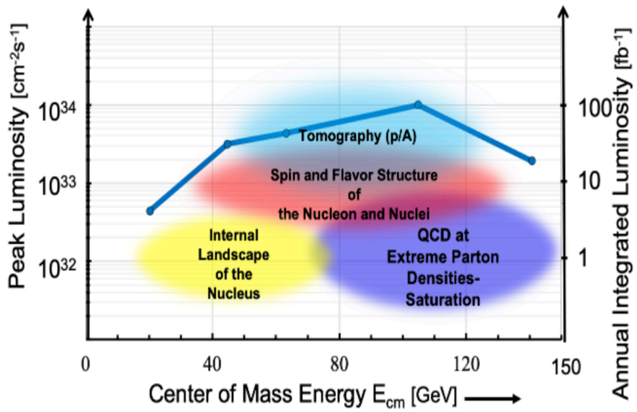
- We recommend a high-energy high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of Facility for Rare Isotope Beams (FRIB)

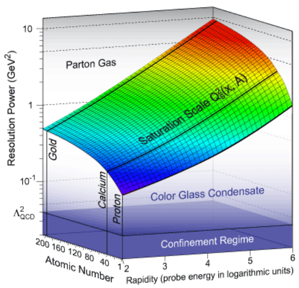


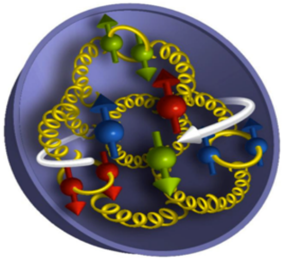


EIC Science









CD-0 and site selection announced Jan. 2020

CD-1 approval in Jul. 2021

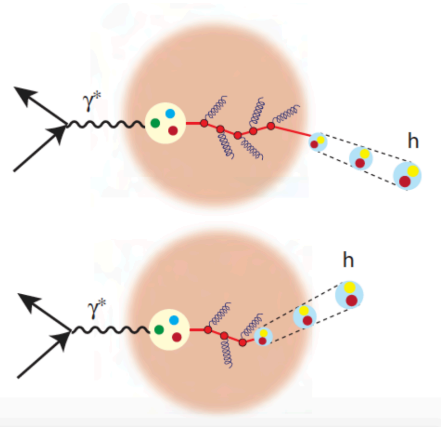
CD-2 expected in Jan. 2024

- The non-linear physics of strong color fields – gluon saturation
- The internal landscape of nucleons and the origin of mass

… CD-4 expected in Jul. 2031

The space-time picture of hadronization

- The space-time picture of hadronization is unknown, but critical for e+A
- Competing physics explanations of HERMES hadron suppression data based on energy loss and absorption

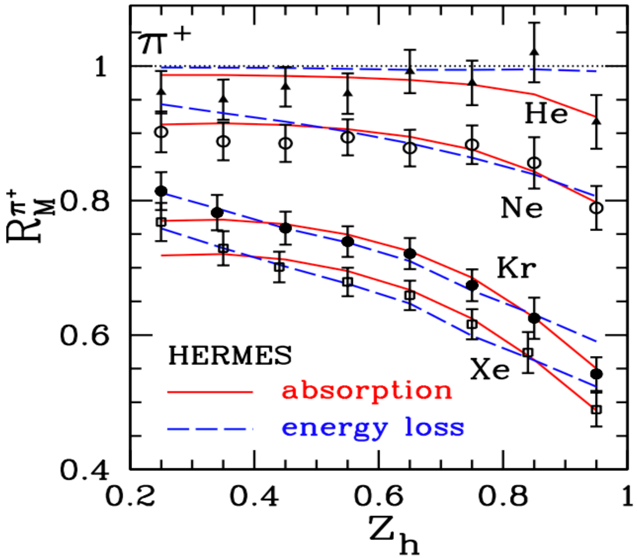


X. Wang et al. (2002)

B. Kopeliovich et al. (2003)

Light hadron measurements cannot differentiate between competing mechanisms

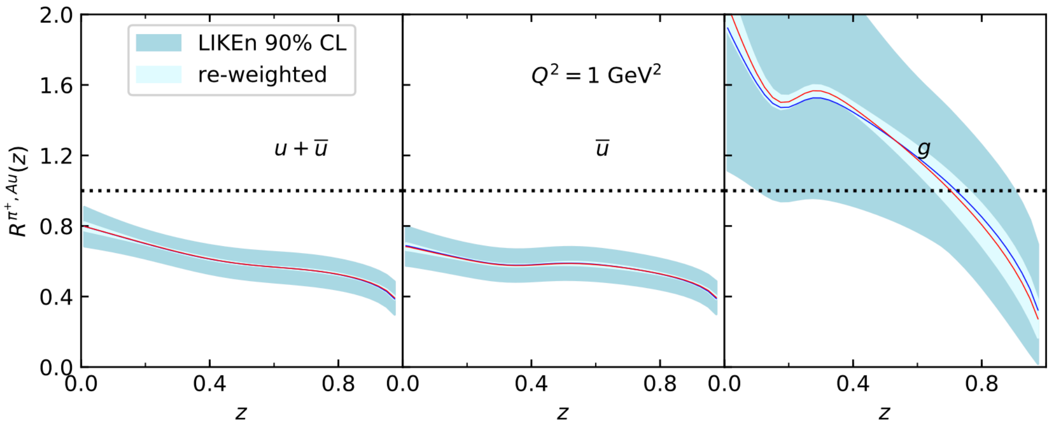
A. Accardi et al. (2009)



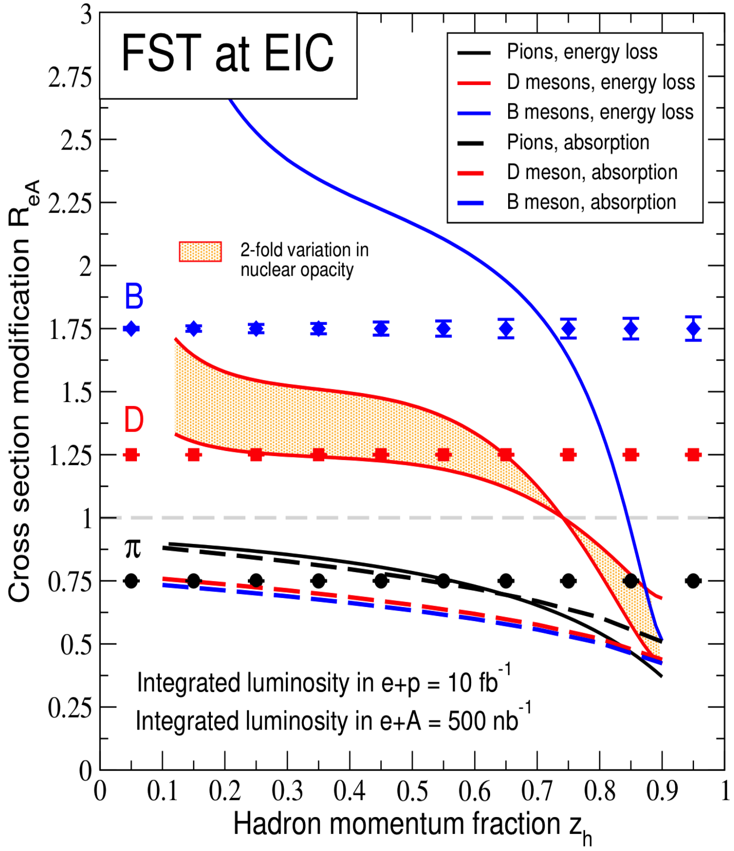
Ideas to parametrize nFFs assuming universality.
Effect of 10 fb-1 EIC data

R . Sassot et al. (2009)

P . Zurita et al. (2021)



Heavy meson tomography

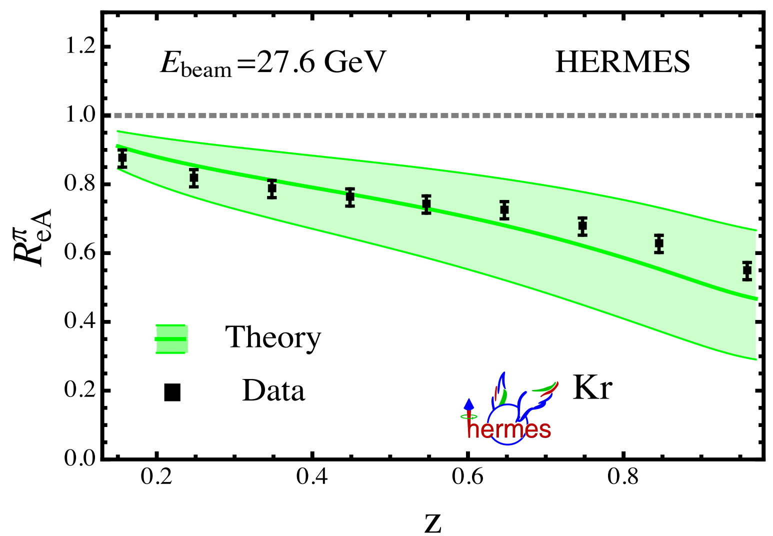


Heavy flavor can be produced at the EIC. It will differentiate between energy loss and absorption models. Allows to develop e+A theory further.

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

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

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

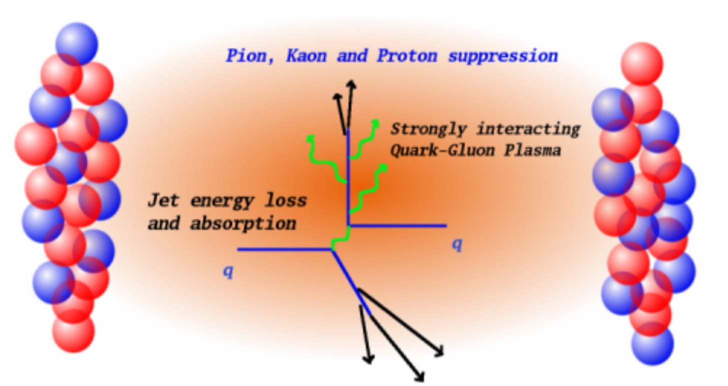


Help constrain the transport properties of nuclear matter:

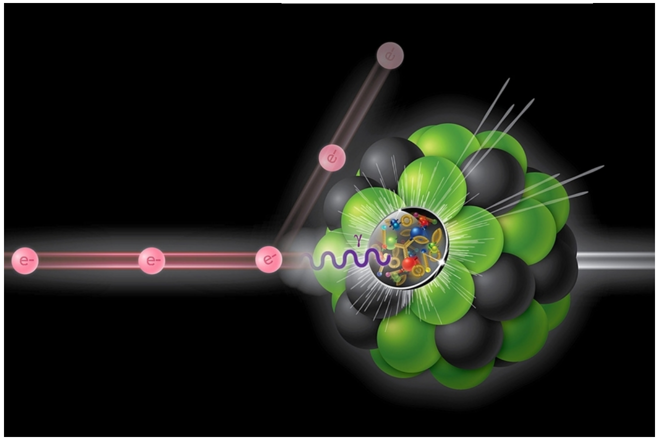
H. Li et al. (2020)

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

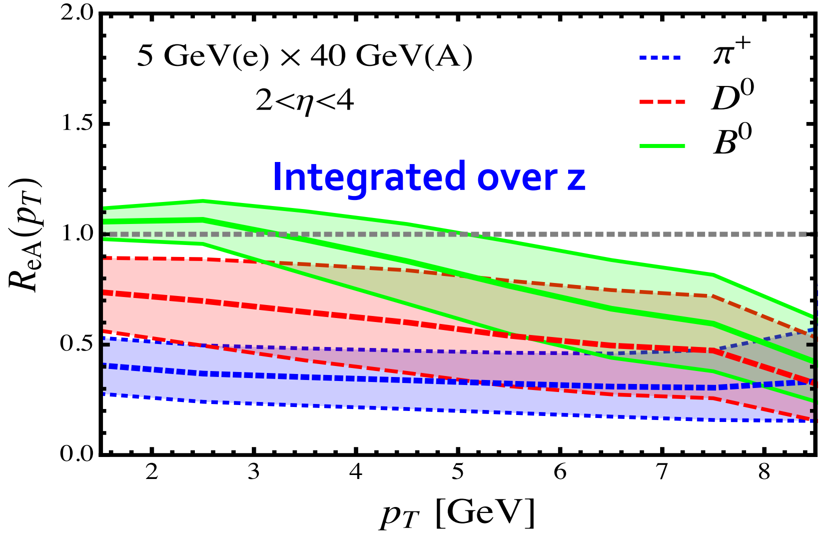


- Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)
- Largest effects at midrapidity
- Higher C.M. energies correspond to larger plasma densities



- 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)

Light and heavy flavor suppression at the EIC

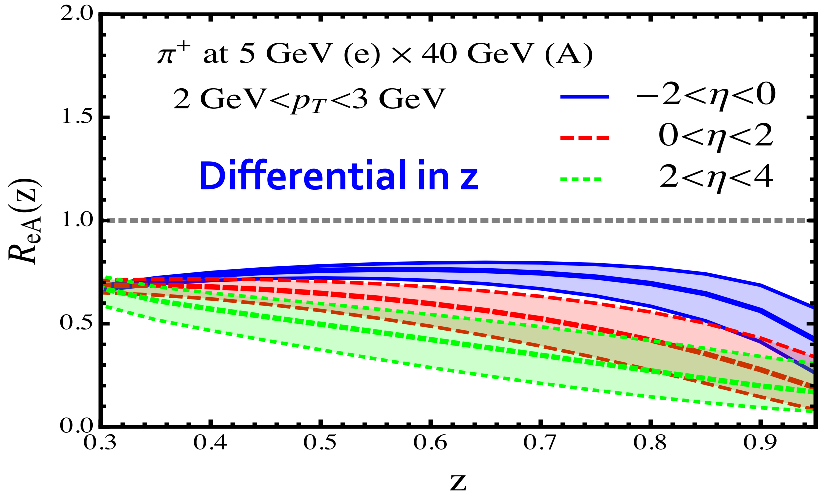


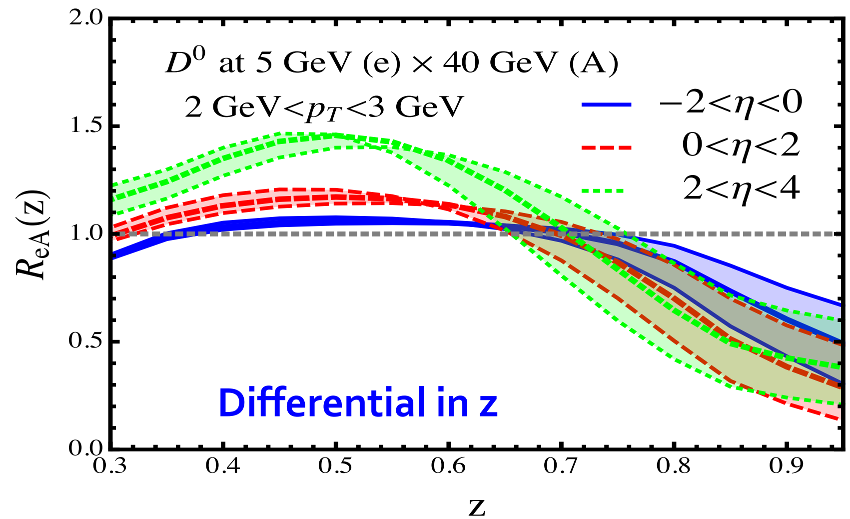
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+p}}$$

Effects are the largest at forward rapidities (p/A going)

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

Z. Liu et al . (2020)





EIC theory will provide clear new insights into hadronization from light+heavy flavor

Corrections in A+A collisions

Let us now focus on the jet function and final-state modification in the QGP

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

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

CNM effects

The short-distance hard part remains the same

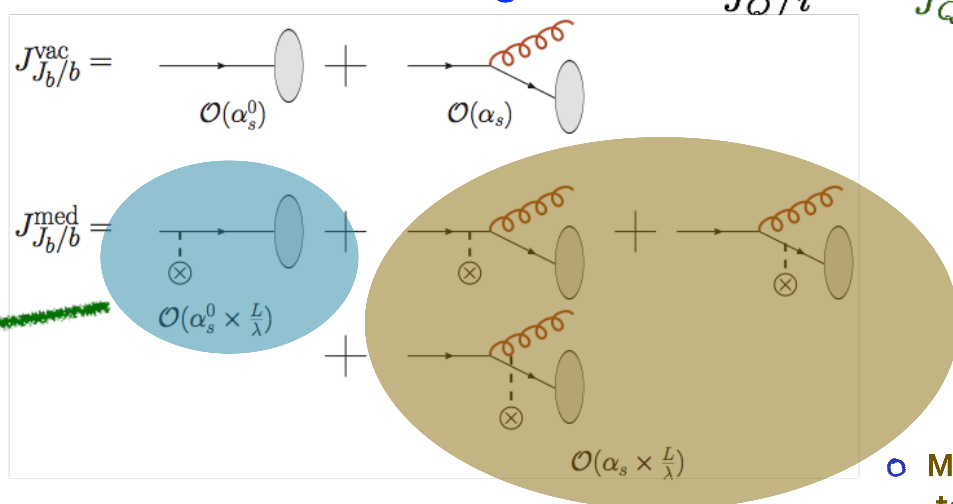
Encodes the effects when the jet evolving in the QCD medium

The jet function receives medium contributions from collisional energy loss and in-medium branching processes

$$J^{\text{med}}_{J_Q/i} = J^{\text{med},(0)}_{J_Q/i} + J^{\text{med},(1)}_{J_Q/i}$$

Vacuum jet function:

Medium corrections:



- Medium induced corrections to the LO jet function

- Medium induced corrections to the NLO jet function

Heavy flavor jets in matter

The semi-inclusive jet function theory can be generalized to heavy jet production in matter. Medium corrections to the NLO jet function are written in terms of integrals over splitting functions.

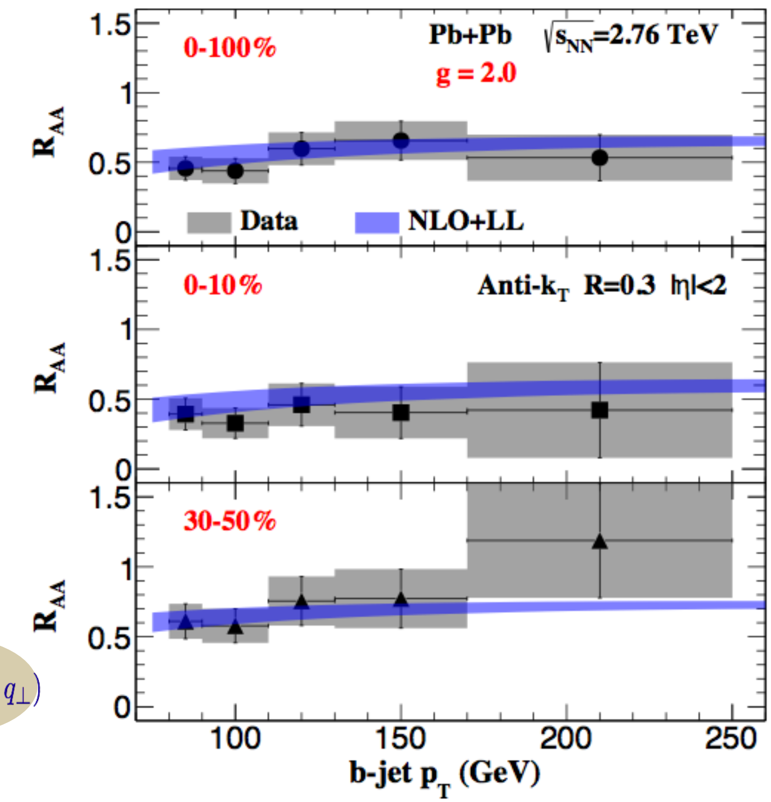
H. Li et al. (2018)

Z. Liu et al. (2021)

After summing over all diagrams

$$J^{\mathrm{med},(1)}_{J_Q/Q}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{QQ}(z, m, q_\perp)\right]_+$$

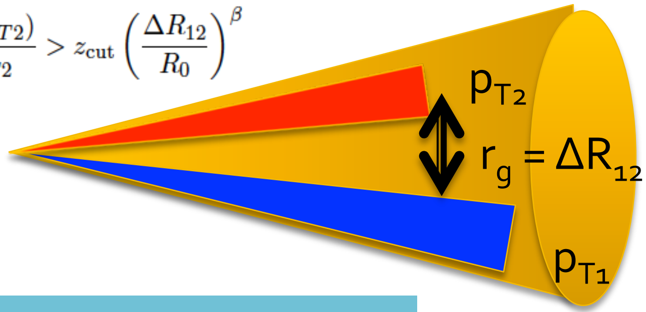
$$J^{\mathrm{med},(1)}_{J_s/g}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp)$$



- Slightly less dependence on the centrality when compared to the well-known light jet modification
- Theoretical results agree well with the data for both the inclusive cross sections and the nuclear modification factors

Heavy flavor jet substructure in A+A and DIS

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



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

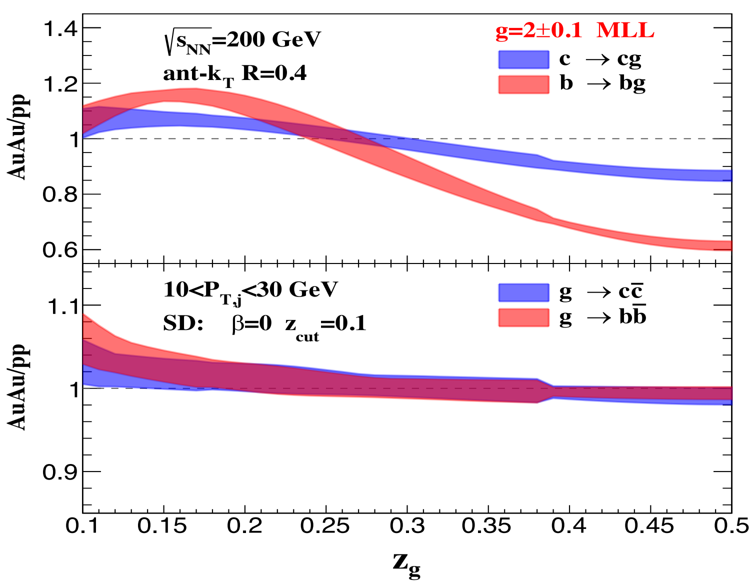
A. Larkoski et al. (2014)

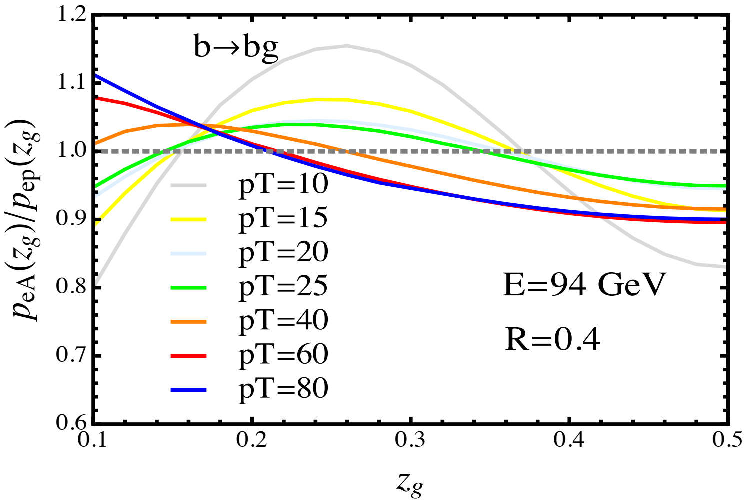
H. Li et al. (2018)

Z. Liu et al. (2021)

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

Provides access to the splitting functions





Heavy flavor jets at EIC

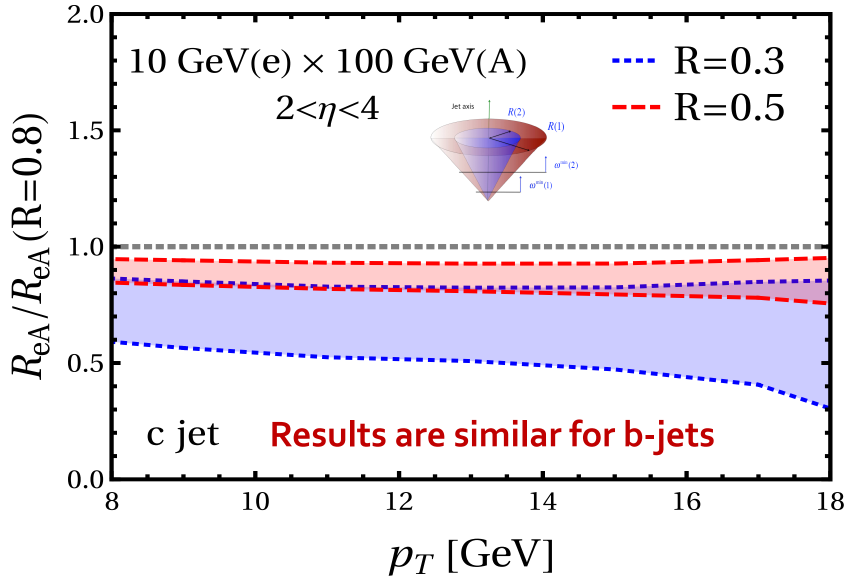
Z. Liu et al. (2021)

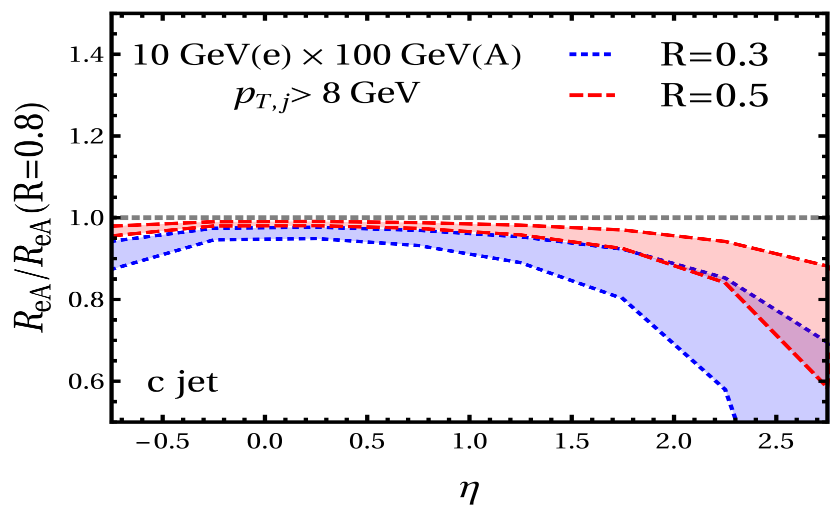
A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

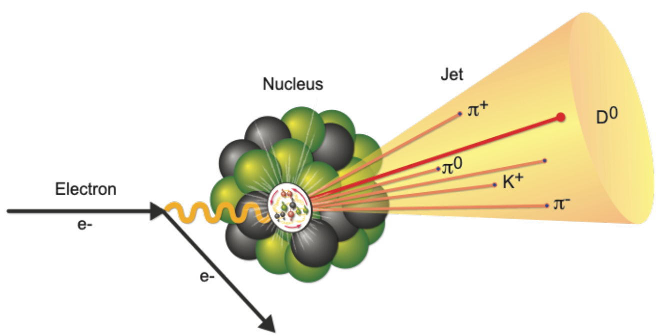
Leveraging the vacuum and in-medium shower differences. Define the ratio of modifications for 2 radii (it is a double ratio)

$$RR = R_{eA}(R) / R_{eA}(R=0.8)$$

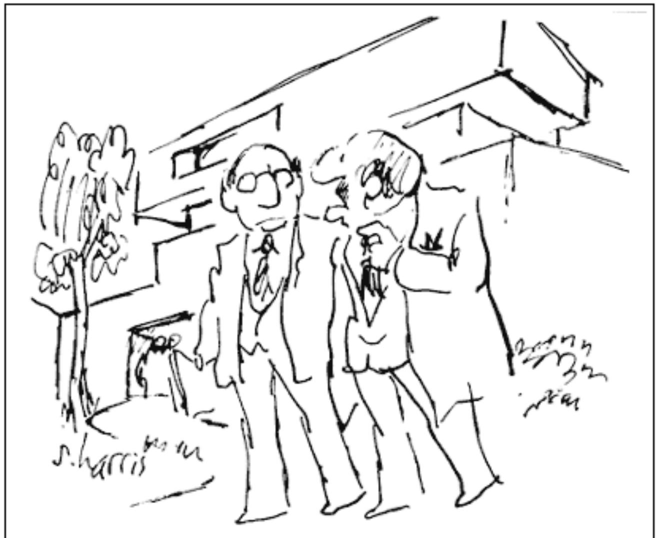
- Effectively eliminates initial-state effects
- Final-state interactions can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)







Quarkonia



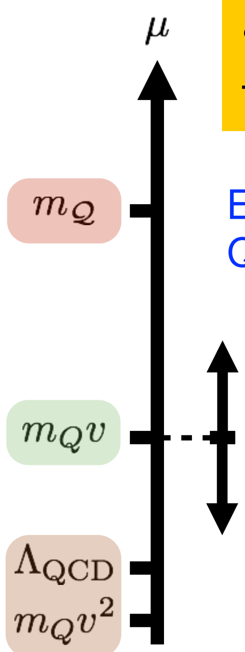
"I'm firmly convinced that behind every great man is a great computer."

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

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

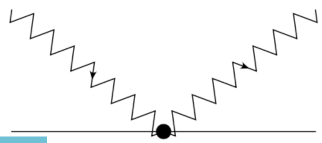
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

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

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: $K_Q \sim m_Q v^2$

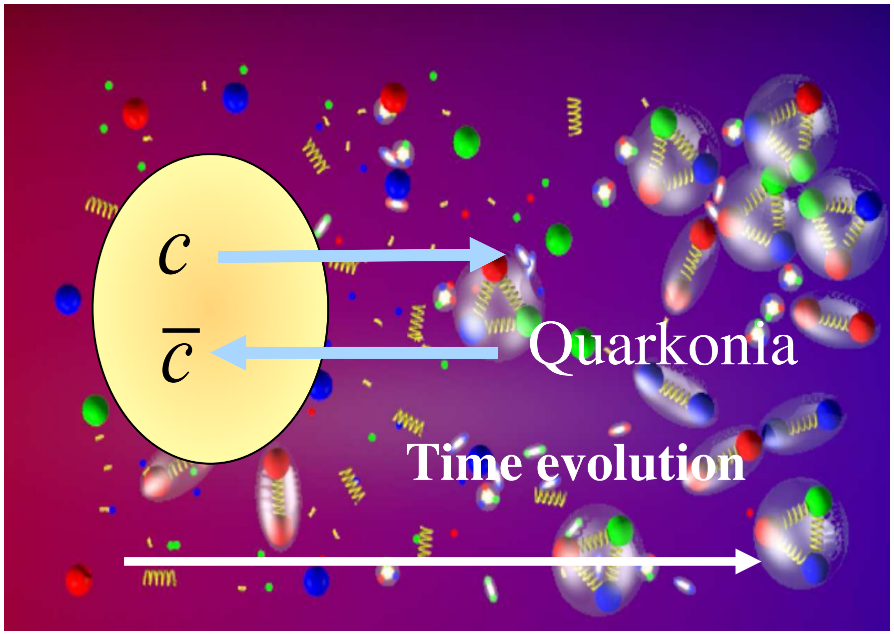
pNRQCD N. Brambilla *et al.* (2000)

vNRQCD M. Luke *et al.* (2000)

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

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

NRQCD in a background medium



- Take a closer look at the NRQCD Lagrangian below

Scales in the problem

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

$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$ ultrasoft ~ λ²

- Ultrasoft gluons included in covariant derivatives

- Soft gluons are included explicitly

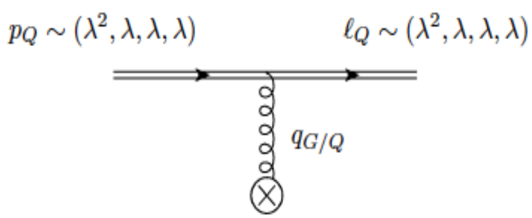
  - Double soft gluon emission
  - Heavy quark-antiquark potential
  - (can also be interaction with soft particles)

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_p \left|p^\mu A_p^\nu - p^\nu A_p^\mu\right|^2 + \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \left\{ iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m} \right\} \psi_{\mathbf{p}} \\
& -4\pi\alpha_s \sum_{q,q'\mathbf{p},\mathbf{p}'} \left\{ \frac{1}{q^0}\psi_{\mathbf{p}'}^\dagger \left[A_{q'}^0, A_q^0\right]\psi_{\mathbf{p}} \right. \\
& \left. + \frac{g^{\nu 0}(q'-p+p')^\mu - g^{\mu 0}(q-p+p')^\nu + g^{\mu\nu}(q-q')^0}{(\mathbf{p}'-\mathbf{p})^2}\psi_{\mathbf{p}'}^\dagger \left[A_{q'}^\nu, A_q^\mu\right]\psi_{\mathbf{p}} \right\} \\
& + \psi \leftrightarrow \chi,\ T \leftrightarrow \bar{T} \\
& + \sum_{\mathbf{p},\mathbf{q}} \frac{4\pi\alpha_s}{(\mathbf{p}-\mathbf{q})^2}\psi_{\mathbf{q}}^\dagger T^A \psi_{\mathbf{p}} \chi_{-\mathbf{q}}^\dagger \bar{T}^A \chi_{-\mathbf{p}} + \ldots
\end{aligned}
$$

Allowed interactions in the medium

- At the level of the Lagrangian

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



Possible scaling for the virtual gluons interacting with the heavy quarks

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

- Energy component must always be suppressed
- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

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

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**

Example of the background field method

- Perform the label momentum representation and field substitution (u.s. -> u.s. + Glauber)

$$\psi(x) \to \sum_{\mathbf{p}} \psi_{\mathbf{p}}(x) \,,$$
$$iD_\mu \to \mathcal{P}_\mu + i\partial_\mu - g(A_U^\mu + A_{G/C}^\mu)$$

$$iD_t = \underbrace{i\partial_t - gA_U^0 - gA_G^0}_{\sim\lambda^2} \,,$$
$$i\mathbf{D} = \underbrace{\boldsymbol{\mathcal{P}}}_{\sim\lambda} - (\underbrace{i\boldsymbol{\partial} + g\mathbf{A}_U + g\mathbf{n}A_G^{\mathbf{n}}}_{\sim\lambda^2}) + \mathcal{O}(\lambda^3) \,,$$
$$\begin{aligned}\mathbf{E} &= \partial_t(\mathbf{A}_U + \mathbf{A}_G) + (\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}})(A_U^0 + A_G^0) + gT^c f^{cba}(A_U^0 + A_G^0)^b(\mathbf{A}_U + \mathbf{A}_G)^a \\ &= \underbrace{i\boldsymbol{\mathcal{P}}_\perp A_G^0}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) \,,\end{aligned}$$
$$\begin{aligned}\mathbf{B} &= -(\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}}) \times (\mathbf{A}_U + \mathbf{A}_G) + \frac{g}{2}T^c f^{cba}(\mathbf{A}_U + \mathbf{A}_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a \\ &= -\underbrace{(i\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})\, A_G^{\mathbf{n}}}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) \,.\end{aligned}$$

Example for a collinear source (note results depend on the type of source)

Substitute, expand and collect terms up to order λ^3

- Results: depend on the type of the source of scattering in the medium

Leading medium corrections

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

Sub-leading medium corrections

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

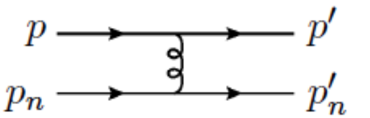
$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = 0 \;\; (static)$$

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

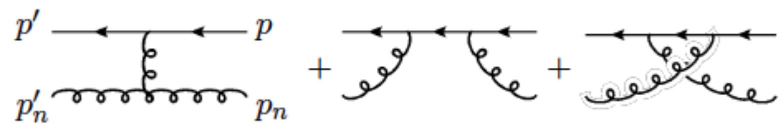
The QCD forward scattering diagram expansion

- Looking at t-channel scattering we can also extract the form of the Glauber/ Coulomb fields in terms of QCD ingredients (and recover Lagrangian)

$t_{coll.} =$



$t_{g-coll.} =$



$$= t^{(0)}_{g-coll.} + t^{(1)}_{g-coll.} + \mathcal{O}(\lambda^2)\,.$$

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \bar{\xi}_{n,\ell-\mathbf{q}_T} \frac{\bar{n}\!\!\!/}{2} (gT^a) \xi_{n,\ell}$$

Coulomb field for soft source

$$A_C^{\mu,a} \equiv \frac{1}{\mathbf{q}^2} \sum_\ell \bar{\phi}_{\ell-\mathbf{q}} \gamma^\mu (gT^A) \phi_\ell$$

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{i}{2} g f^{abc} \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \left[\bar{n} \cdot \mathcal{P} \left(\mathbf{B}^{b(0)}_{n\perp,\ell-\mathbf{q}_T} \cdot \mathbf{B}^{c(0)}_{n\perp,\ell} \right) \right]$$

Coulomb field for soft source

Y. Makris et al. (2019)

$$A_C^{\mu,a} = f^{abc} \frac{ig}{2\,\mathbf{q}^2} \sum_\ell \left\{ \left[\mathcal{P}^\mu \left(\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \mathbf{B}^{c(0)}_{s,\ell} \right) \right] - 2 (\mathbf{B}^{c(0)}_{s,\ell} \cdot \left[\boldsymbol{\mathcal{P}} \right) B^{\mu,b(0)}_{s,\ell-\mathbf{q}} \right] - 2 (\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \left[\boldsymbol{\mathcal{P}} \right) B^{\mu,c(0)}_{s,\ell} \right] \right\}$$

- Note that for the gluon the last 2 diagrams are necessary for gauge invariance but the first diagram the leading forward scattering contribution
- In the medium the momentum exchange can get dressed ~ Debye screening

Effects of the medium

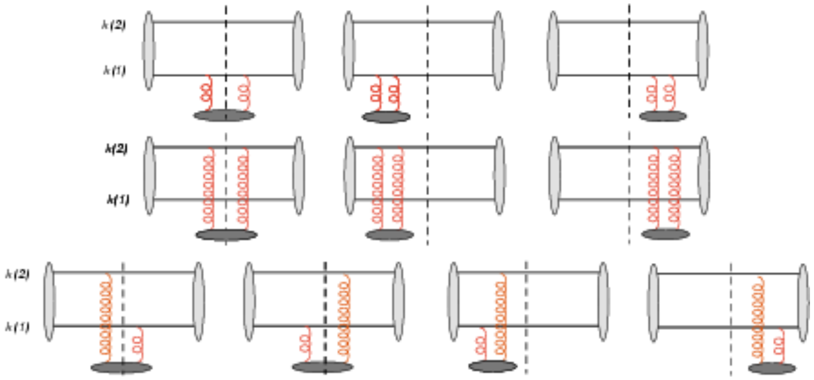
- Typical time for the onset of interactions – take it to be O(1 fm)

- Dissociation time – incudes thermal wavefunction effect and collisional broadening

$$P_{f\leftarrow i}(\chi\mu_D^2\xi,T) = \left|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\right|^2$$
$$= \left|\frac{1}{2(2\pi)^3}\int dx\ \mathrm{Norm}_f\mathrm{Norm}_i\,\pi\,e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$
$$\left.\times\ \frac{2[x(1-x)\Lambda(T)^2][\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2]+[\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}\right|^2 .$$

Dissociation time $\frac{1}{t_{\mathrm{diss.}}} = -\frac{1}{P_{f\leftarrow i}(\chi\mu_D^2\xi,T)}\frac{dP_{f\leftarrow i}(\chi\mu_D^2\xi,T)}{dt}$

Incorporated in rate equations



Adil *et al.* (2006)

Sharma *et al.* (2012)

Following feeddown contributions taken, others small

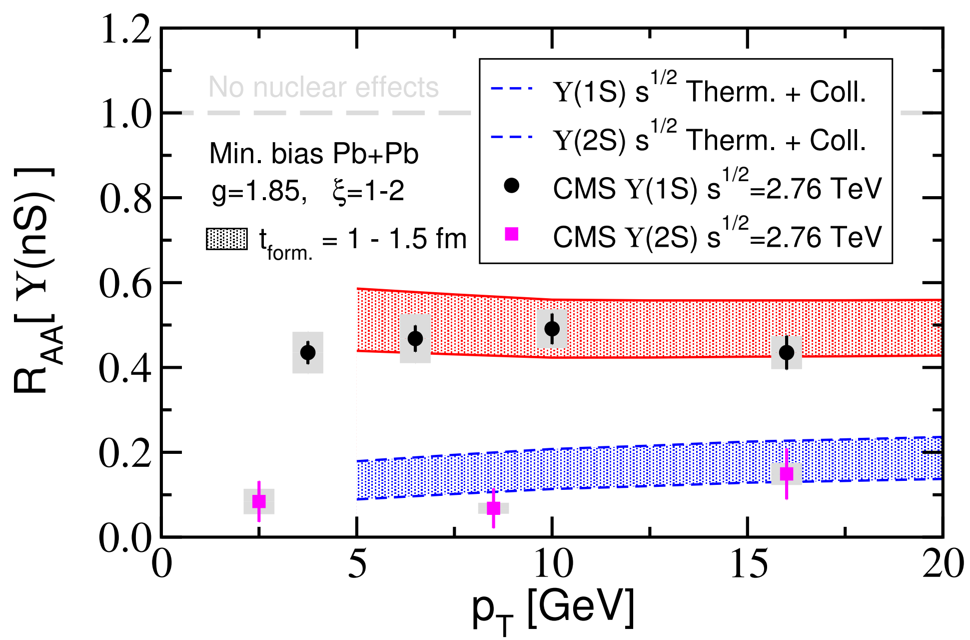
$$\psi(2S):\quad \mathrm{Br}\Big[\psi(2S)\to J/\psi+X\Big]=61.4\pm0.6\%$$
$$\chi_{c1}:\quad \mathrm{Br}\Big[\chi_{c1}\to J/\psi+\gamma\Big]=34.3\pm1.0\%$$
$$\chi_{c2}:\quad \mathrm{Br}\Big[\chi_{c2}\to J/\psi+\gamma\Big]=19.0\pm0.5\%$$

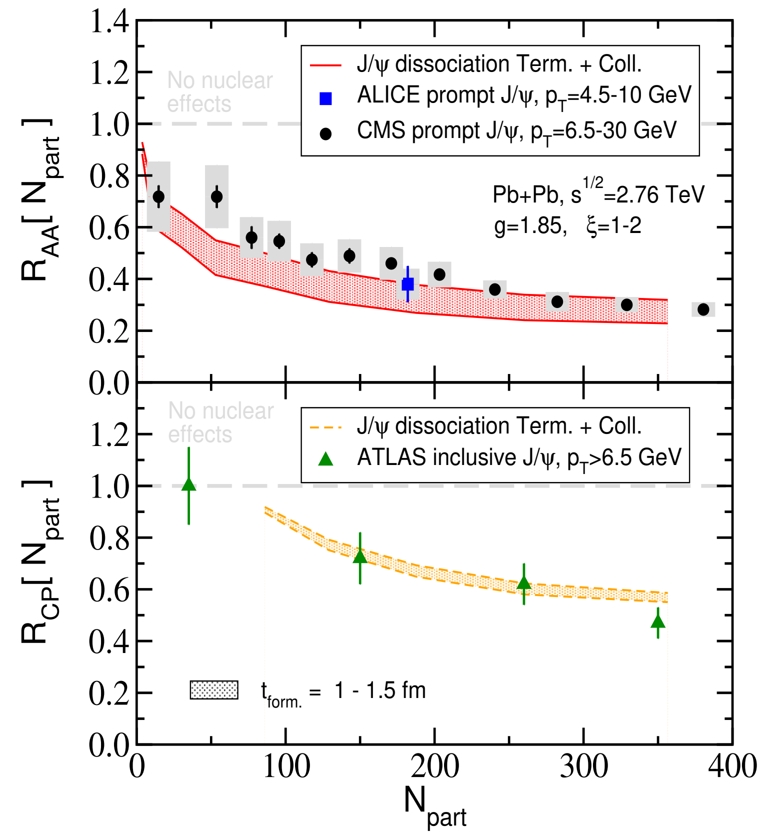
S. Aronson *et al.* (2017)

Centrality and p_T dependence

- In calculating the min bias results we found that the result is dominated by the first few centrality bins

$$R_{AA}^{\text{min. bias}}(p_T) = \frac{\sum_i R_{AA}(\langle b_i \rangle) W_i}{\sum_i W_i} \qquad W_i = \int_{b_i\ \min}^{b_i\ \max} N_{\text{coll.}}(b)\, \pi\, b\, db$$





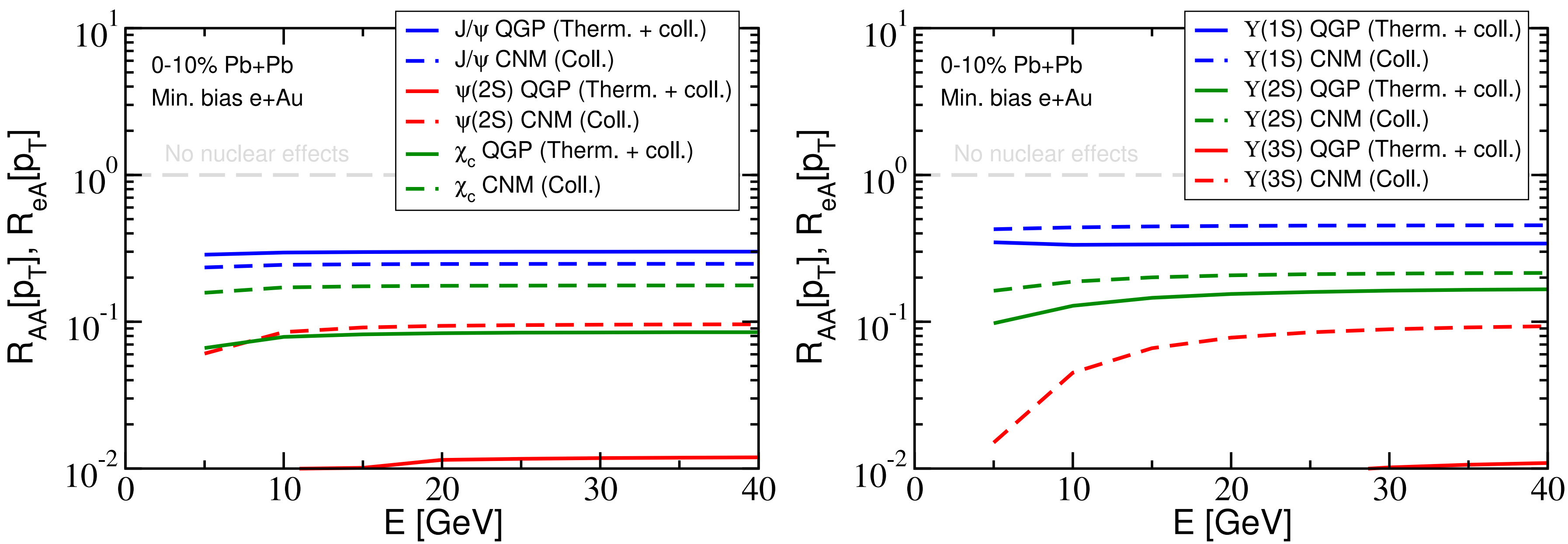
S. Aronson *et al.* (2017)

Uncertainties are related to the onset of the interactions

Some basic study for EIC

- Dissociation from collisional interactions in cold nuclear matter is large. For the very weakly bound states the QGP suppression is larger but the CNM one is still a factor of 5 -10. For the tightly bound states suppression is comparable – sometimes slightly smaller, sometimes slightly larger.

I. Olivant et al. (2021)



For full EIC predictions we need to explore feed down corrections, combine with prompt state cross sections, and explore the effect of the interaction onset.

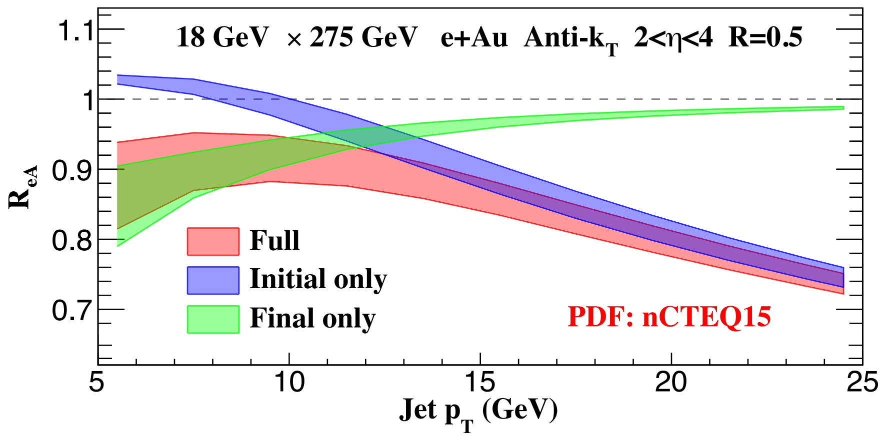
Conclusions

- Flavor production, charm & beauty, has motivated important developments in QCD. Still, many open theoretical questions remain – form the flavor number schemes, to the relevant EFTs in multi-scale problems, to the non-perturbative hadronization into charm and beauty mesons. These must be resolved to fully utilize the EIC capabilities and we view this as an opportunity
- There are tremendous intellectual communalities in heavy flavor theory applied to hadronic, heavy ion, and DIS reactions. It is a natural point of convergence for the broad QCD community in the US and beyond. Now is an opportune time for a focused theory effort and investment to answer the most pressing HF puzzles and lay the groundwork for the EIC
- At the EIC, heavy flavor will provide unique probes of hadronization, energy loss and the transport properties of cold nuclear matter, the TMD stricture of nucleons/nuclei, small-x saturation physics, parton distributions
- Heavy flavor theory, both open and quarkonia, is a key component of the the EIC theory initiative that we propose. We emphasize the need for analytic advancements and precision phenomenology

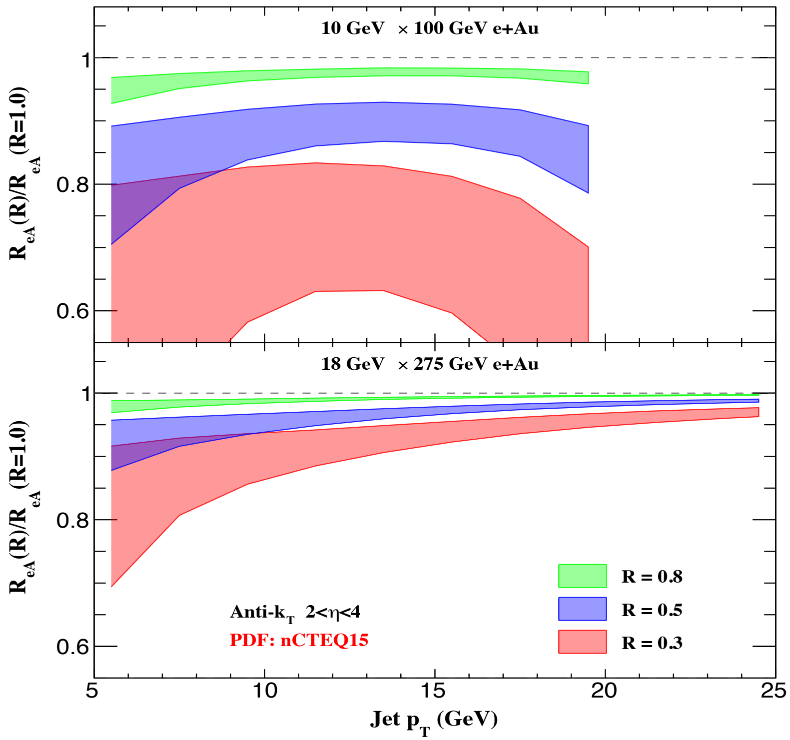
Jet results at the EIC

H. Li et al. (2020)

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



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



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

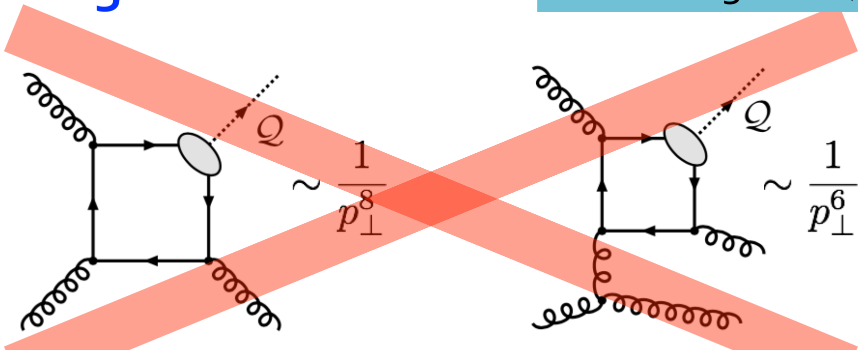
How to separate them? Define the ratio of modifications for 2 radii (it is a double ratio)

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

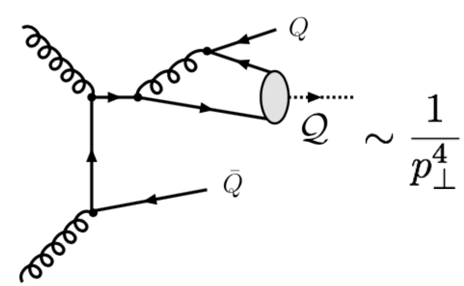
Opportunities in e+p at the EIC

Singlet contribution

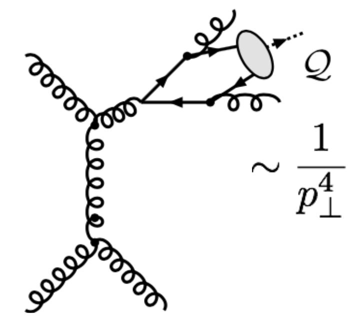
S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)



LO NLO

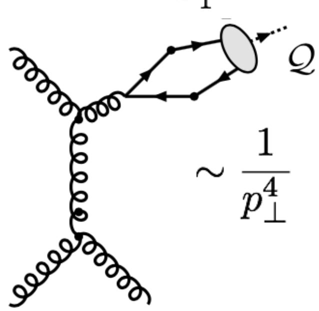


NLO



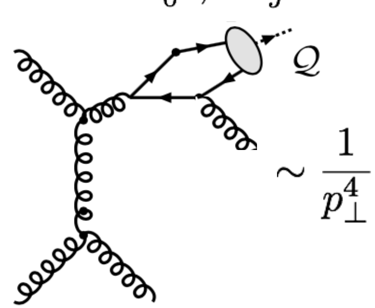
NNLO

$^3S_1^{[8]}$



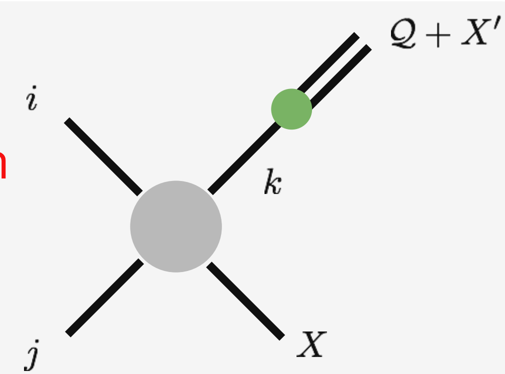
LO

$^1S_0^{[8]}, \ ^3P_J^{[8]}$



NLO

(single) Parton fragmentation process



Octet contribution

Only a subset of contributions survive, now interpretable as parton fragmentation in quarkonia

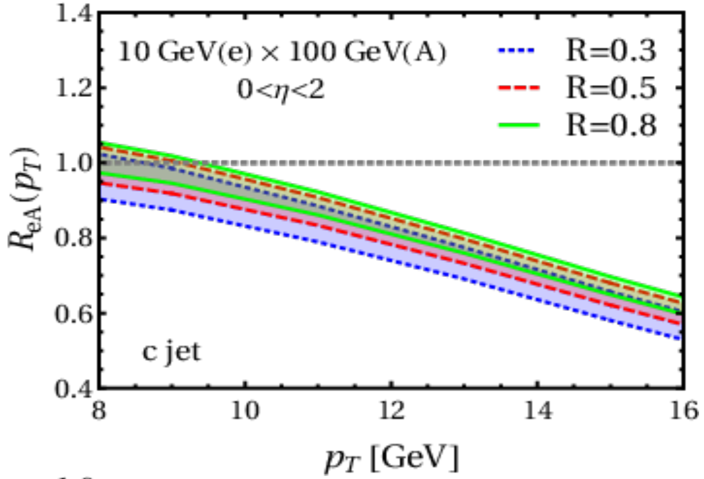
Heavy flavor jets in matter

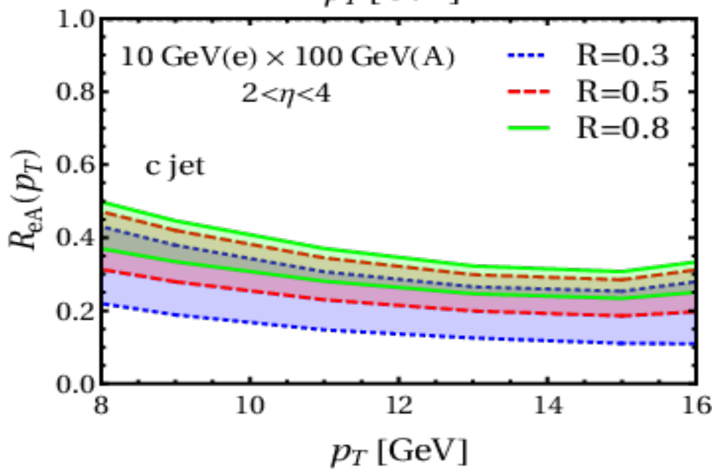
The semi-inclusive jet function theory can be generalized to heavy jet production in matter. Medium corrections to the NLO jet function are written in terms of integrals over splitting functions.

H. Li et al. (2018)

Z. Liu et al. (2021)

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





After summing over all diagrams

$$J^{\mathrm{med},(1)}_{J_Q/Q}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{QQ}(z, m, q_\perp)\right]_+$$

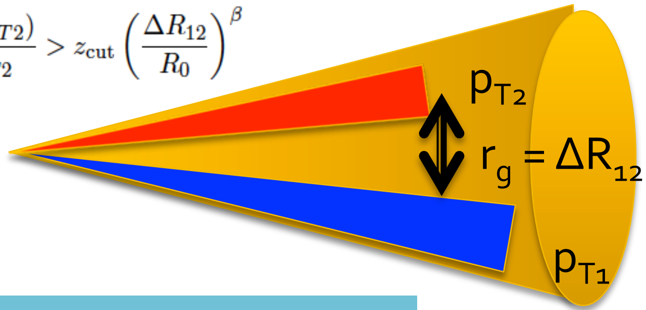
$$J^{\mathrm{med},(1)}_{J_s/g}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{Qg}(z, m, q_\perp)$$

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**

Heavy flavor jet substructure in DIS

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



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

A. Larkoski et al. (2014)

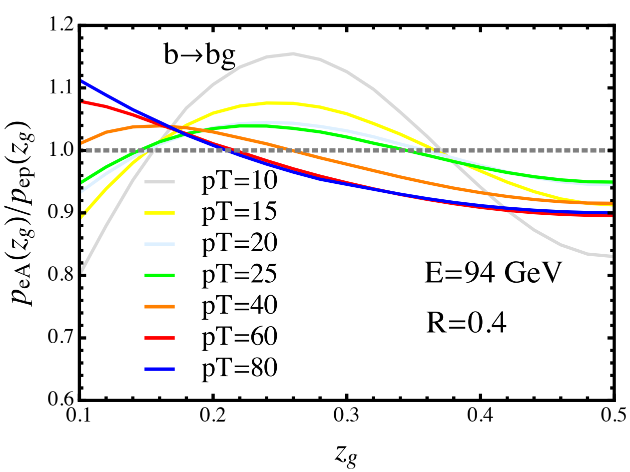
$$\frac{dN_j^{\rm vac,MLL}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\rm vac}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\rm cut}}^{1/2} dz \sum_i \left(\frac{dN^{\rm vac}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\rm Sudakov\ \ Factor}$$

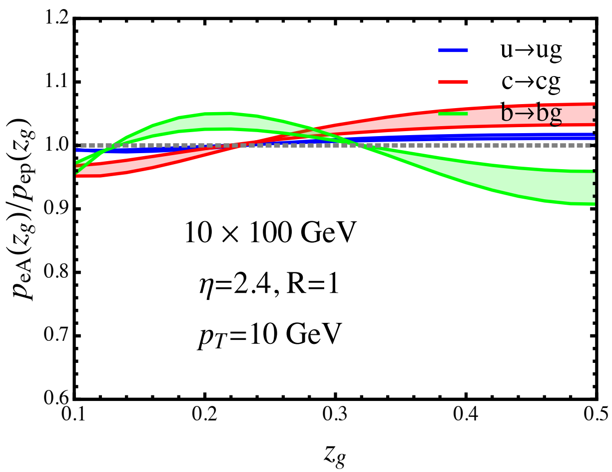
Provides access to the splitting functions

Illustrative study: DIS will cover a very different kinematic regime than HIC

Z. Liu et al. (2021)

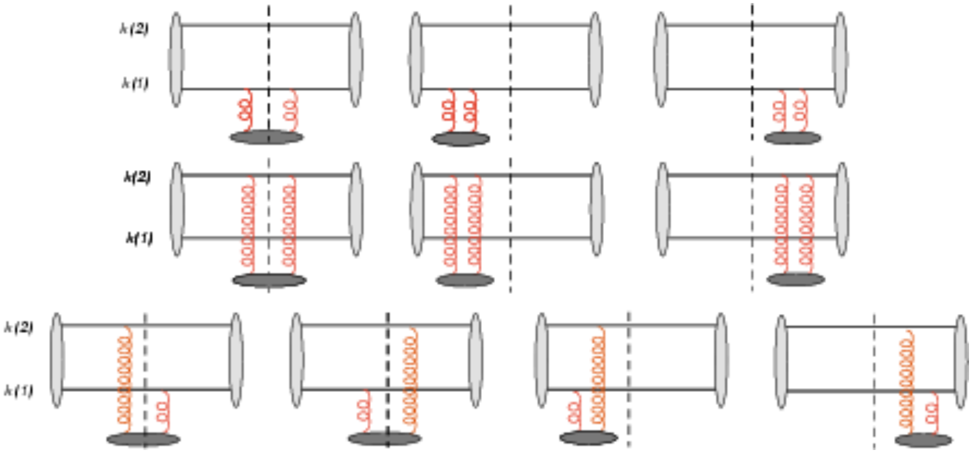
Realistic example





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

Collisional interactions of heavy meson states in matter



Adil *et al.* (2006)

- Momentum transfers q follow Glauber gluons scaling

$$|\psi_f(\mathbf{K},\Delta\mathbf{k})|^2 = \sum_{n=0}^{\infty}\frac{2^n\chi^n}{n!}\int\prod_{i=1}^{n} d^2\mathbf{q}_i\,\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2\mathbf{q}_i} \times\left[\left(e^{-\mathbf{q}_n\cdot\vec{\nabla}_{\mathbf{K}}}-\hat{\mathbf{1}}\right)\cosh\left(-\mathbf{q}_n\cdot\vec{\nabla}_{\Delta\mathbf{k}}\right) + \left(e^{-\mathbf{q}_n\cdot\vec{\nabla}_{\Delta\mathbf{k}}}-\hat{1}\right)\right]|\psi_0(\mathbf{K},\Delta\mathbf{k})|^2 \,.$$

- Resum in impact parameter space, make Gaussian approximation

$$|\psi_f(\mathbf{K},\Delta\mathbf{k})|^2 = \left[\frac{e^{-\frac{\mathbf{K}^2}{4\chi\mu^2\xi}}}{4\pi\chi\mu^2\xi}\right]\left[\mathrm{Norm}^2\,\frac{x(1-x)\Lambda^2}{\chi\mu^2\xi+x(1-x)\Lambda^2} \times e^{-\frac{\Delta\mathbf{k}^2}{4(\chi\mu^2\xi+x(1-x)\Lambda^2)}}\, e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}}\right] .$$

- Heavy meson acoplanarity
- Distortion of the light cone wave function (meson decay)

- Reduced transition probability

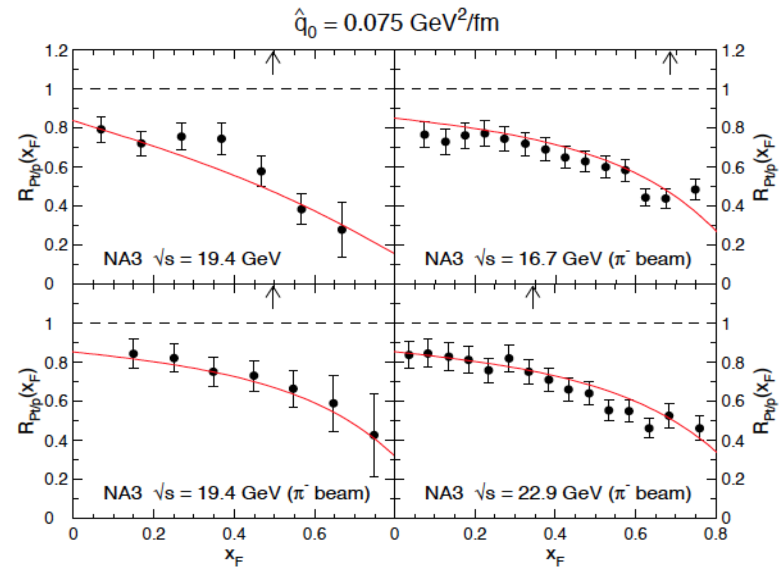
$$P_{\mathrm{surv.}}\left(\frac{\mu^2}{\lambda}L\xi\right) = \left|\int dx\,d^2\Delta k_\perp\, \psi^*_f(x,\Delta k_\perp)\psi_i(x,\Delta k_\perp)\right|^2$$

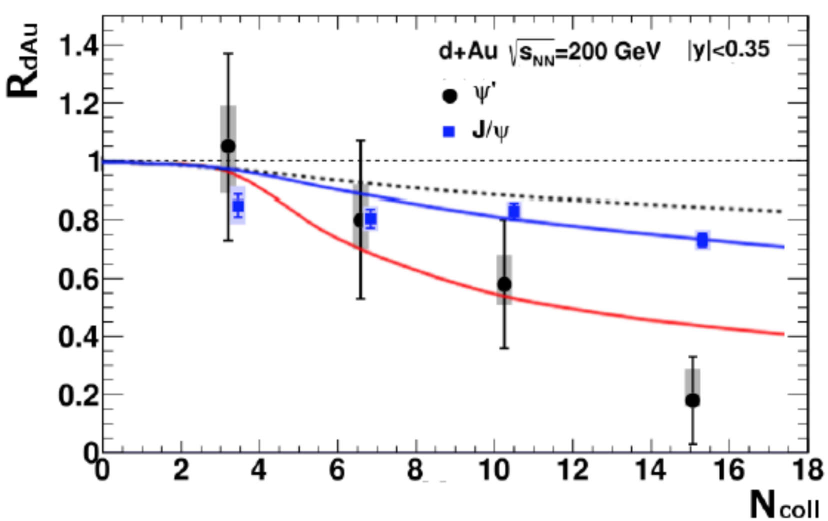
Energy loss for quarkonia in nuclei and co-mover dissociation

- Another radiative energy loss approach – Radiation off of a heavy quark. The Bertsch-Gunion spectrum is integrated from M to the cumulative broadening scale. It is suppressed by M_T at high p_T.

F. Arleo *et al.* (2012)

$$\Delta E \equiv \int_0^E \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \underset{M \gg \ell_\perp}{\simeq} N_c\, \alpha_s \frac{\ell_\perp - \Lambda}{M} E$$





- Co-mover dissociation model– phenomenological cross section to break up quarkonia in a co-moving hadron gas.

E. Ferreiro (2014)

$$\tau \frac{\mathrm{d}\rho^{\psi}}{\mathrm{d}\tau}\,(b,s,y) \;=\; -\sigma^{co-\psi}\, \rho^{co}(b,s,y)\, \rho^{\psi}(b,s,y)$$

$$S^{co}_{\psi}(b,s,y) \;=\; \exp\left\{-\sigma^{co-\psi}\, \rho^{co}(b,s,y)\, \ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

Determination of the LDMEs

- Perform LO NRQCD fit. Color singlet matrix elements can the related to the square of the wavefunction at the origin and its derivatives

$$\langle \mathcal{O}(c\bar{c}([^3S_1]_1) \to J/\psi)\rangle = 3\langle \mathcal{O}(c\bar{c}([^1S_0]_1) \to J/\psi)\rangle = 3N_c\frac{|R_{n=1}(0)|^2}{2\pi} = 1.2\ \mathrm{GeV}^3\ ,$$

$$\langle \mathcal{O}(c\bar{c}([^3S_1]_1) \to \psi(2S))\rangle = 3\langle \mathcal{O}(c\bar{c}([^1S_0]_1) \to \psi(2S))\rangle = 3N_c\frac{|R_{n=2}(0)|^2}{2\pi} = 0.76\ \mathrm{GeV}^3\ ,$$

$$\frac{1}{5}\langle \mathcal{O}(c\bar{c}([^3P_2]_1) \to \chi_{c2}(1P))\rangle = \frac{1}{3}\langle \mathcal{O}(c\bar{c}([^3P_1]_1) \to \chi_{c1}(1P))\rangle = \langle \mathcal{O}(c\bar{c}([^3P_0]_1) \to \chi_{c0}(1P))\rangle = 3N_c\frac{|R'_{n=1}(0)|^2}{2\pi} = 0.054 m^2_{\mathrm{charm}}\ \mathrm{GeV}^3\ ,$$

- Octet elements determined by fit to data

$$\begin{aligned}
\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to J/\psi)\rangle &= (0.0013 \pm 0.0013)\ \mathrm{GeV}^3\ ,\\
\langle \mathcal{O}(c\bar{c}([^1S_0]_8) \to J/\psi)\rangle &= (0.018 \pm 0.0087)\ \mathrm{GeV}^3\ ,\\
&= \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle/(m^2_{\mathrm{charm}})\ ,\\
\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to \psi(2S))\rangle &= (0.0033 \pm 0.00021)\ \mathrm{GeV}^3\ ,\\
\langle \mathcal{O}(c\bar{c}([^1S_0]_8) \to \psi(2S))\rangle &= (0.0080 \pm 0.00067)\ \mathrm{GeV}^3\ ,\\
&= \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle/(m^2_{\mathrm{charm}})\ ,\\
\langle \mathcal{O}(c\bar{c}([^3P_1]_8) \to J/\psi)\rangle &= 3 \times \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle\ ,\\
\langle \mathcal{O}(c\bar{c}([^3P_2]_8) \to J/\psi)\rangle &= 5 \times \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle\ ,\\
\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to \chi_{c0}(1P))\rangle &= (0.00187 \pm 0.00025)\ \mathrm{GeV}^3\ ,
\end{aligned}$$

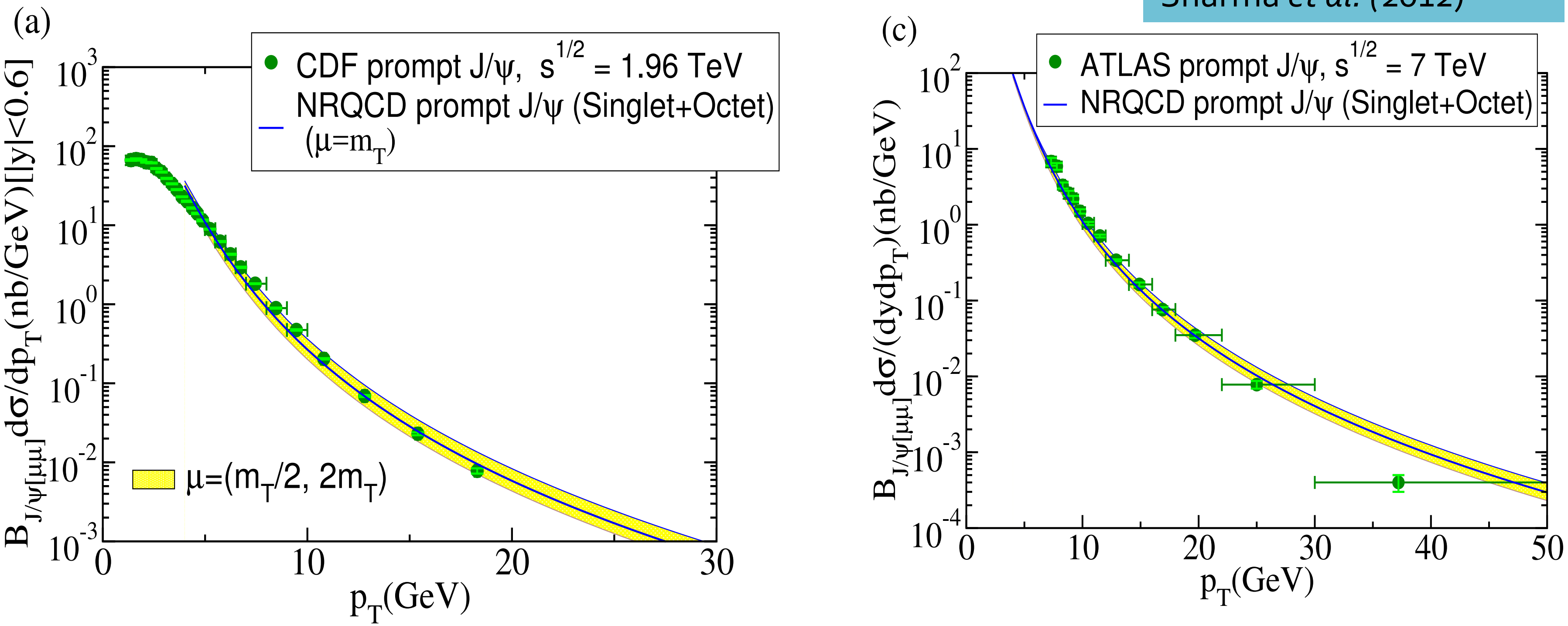
- Approximate scaling with velocity and mass
- Note that excited states such as χ have different expansion and different LDMEs

Sharma *et al.* (2012)

Example of charmonium production

- Limit of applicability p_T > 3-5 GeV. Same is true for other fixed order calculations, e.g. NLO

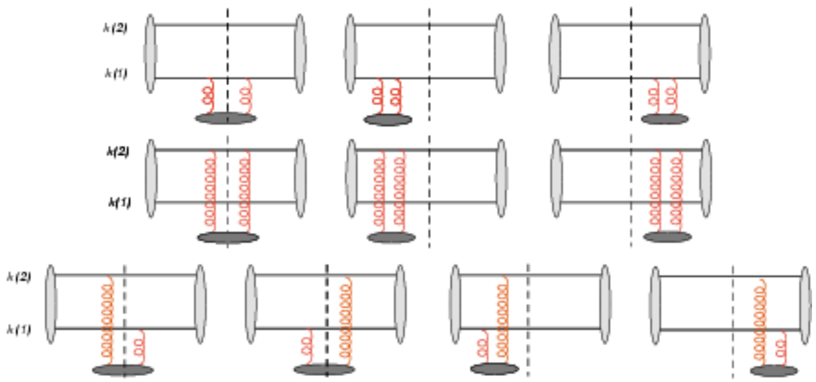
Sharma *et al.* (2012)



- Note, NLO fits exist mostly quarkonia by several groups, also include photoproduction. Tensions still remain with quarkonium polarization

Butenchoen *et al.* (2012)

Collisional interactions of heavy meson states in matter



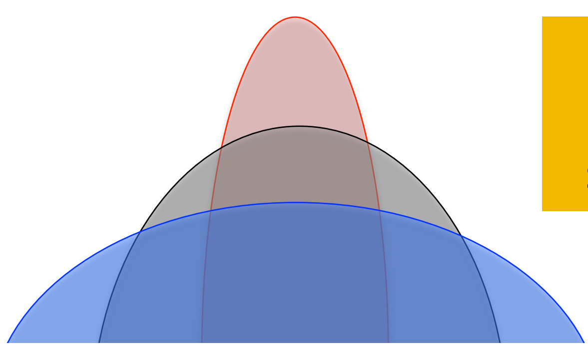
Adil *et al.* (2006) Sharma *et al.* (2012)

Heavy meson acoplanarity & distortion of the light cone wave function (meson decay)

- Resum in impact parameter space, make Gaussian approximation

$$|\psi_f(\mathbf{K},\Delta\mathbf{k})|^2 = \left[\frac{e^{-\frac{\mathbf{K}^2}{4\chi\mu^2\xi}}}{4\pi\chi\mu^2\xi}\right]\left[\mathrm{Norm}^2\,\frac{x(1-x)\Lambda^2}{\chi\mu^2\xi+x(1-x)\Lambda^2}\right.$$
$$\left.\times\, e^{-\frac{\Delta\mathbf{k}^2}{4(\chi\mu^2\xi+x(1-x)\Lambda^2)}}\, e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}}\right].$$

$$P_{\mathrm{surv.}}\left(\frac{\mu^2}{\lambda}L\xi\right)=\left|\int dx d^2\Delta k_\perp\, \psi^*_f(x,\Delta k_\perp)\psi_i(x,\Delta k_\perp)\right|^2$$



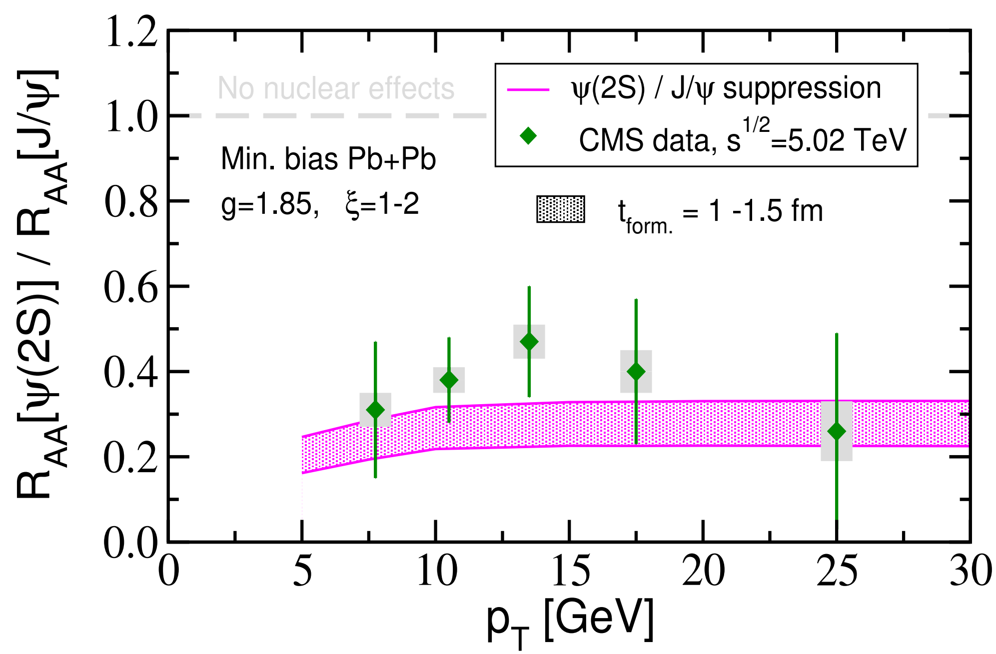
S. Aronson *et al.* (2017)

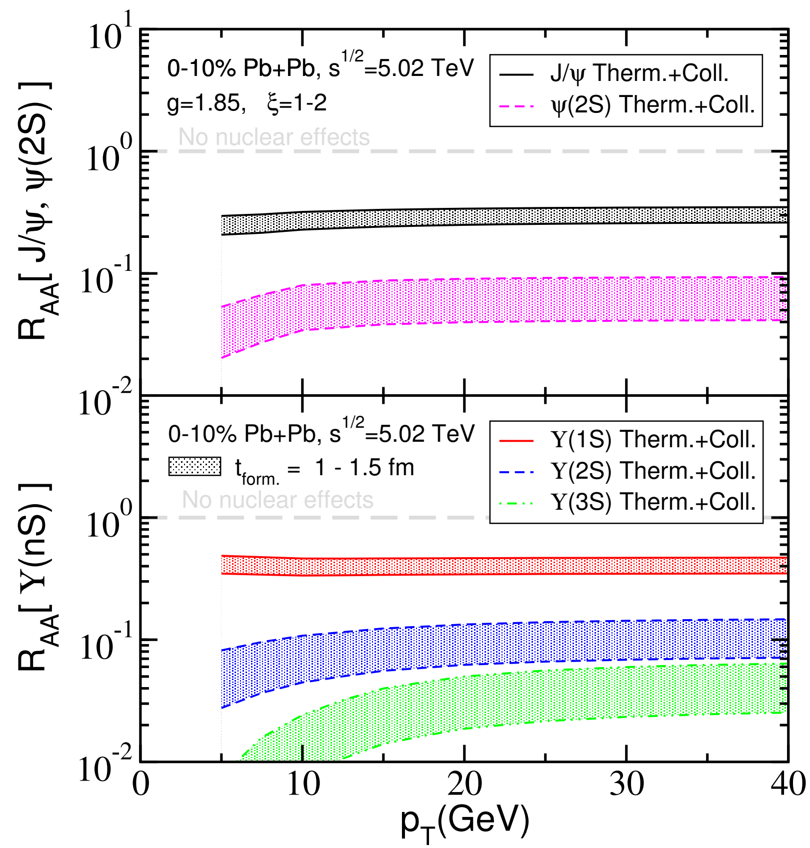
Momentum space picture – may be counter intuitive (note that broadening in configuration space is narrowing in momentum space)

- **Initial wavefunction ~ vacuum**
- **Collisional broadening**
- **Thermal narrowing**

Min bias and excited to ground state ratios

- Good description of the relative suppression of excited to ground states





S. Aronson *et al.* (2017)

We wee differences in suppression of Upsilon(2S) and Upsilon(3S). Latest measurements don't seem to see that (quite puzzling)

- Good separation the suppression of the ground and excited