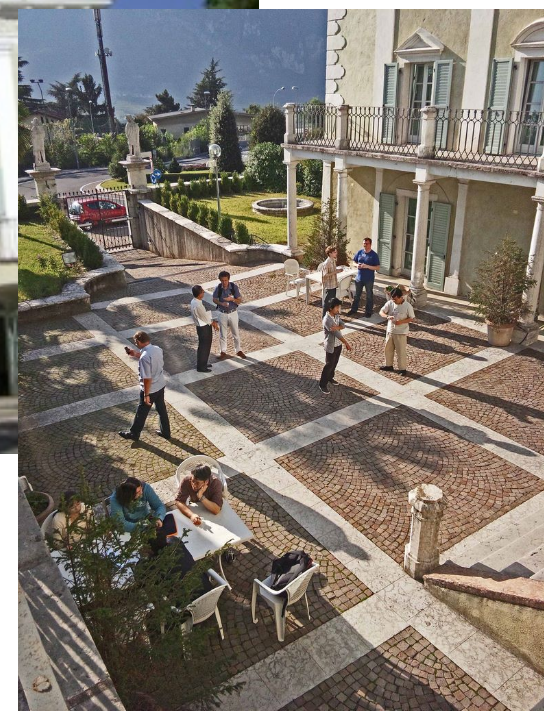
Ivan Vitev
LANL

Heavy flavors as probe of the nuclear medium

ECT Workshop "The spectroscopy program at EIC and future accelerators"*
Trento, Italy, December 19-21, 2018

Outline of the talk

- Opportunities for heavy flavor studies in DIS with nuclei
- Status of open heavy flavor theory in nuclear matter
- Status of quarkonium theory in nuclear matter
- Conclusions



Thanks to the organizers for the opportunity to discuss this type of physics

I have relied for illustration on the following experimental / theoretical reviews

A. Andronic *et al.*, Eur.Phys.J. C76 (2016) no.3, 107

R. Rapp (ed.) *et al.*, Nucl.Phys. A979 (2018) 21-86

Introduction

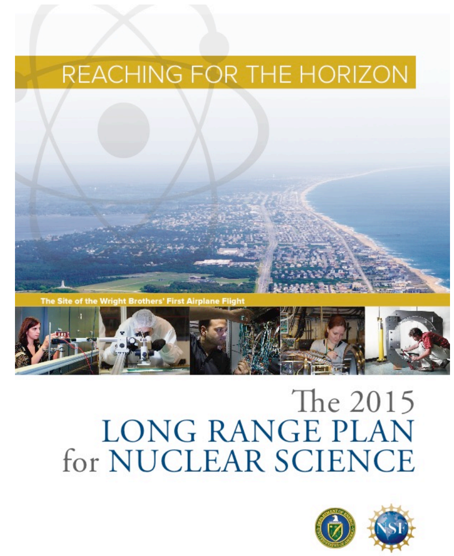
A new era of high-energy nuclear physics at the EIC

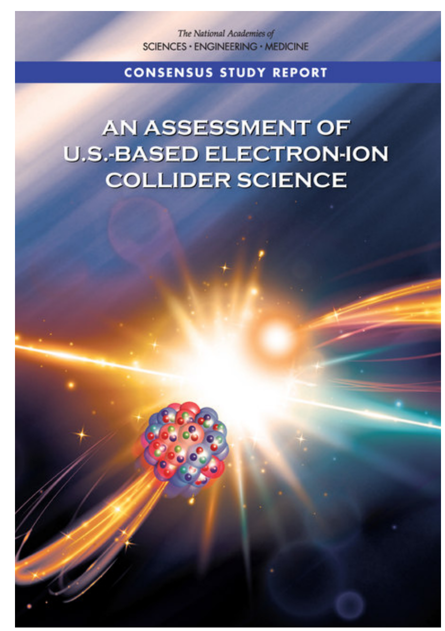
LRP recommendations

- We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB

NAS: Extensive list of findings

- EIC essential for US leadership in nuclear physics and accelerator design
- Physics at EIC has very close connections to solid state and atomic physics, high energy physics, astrophysics and computing
- …
- To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD and, furthermore, to glean the fundamental insights into QCD that an EIC can reveal.

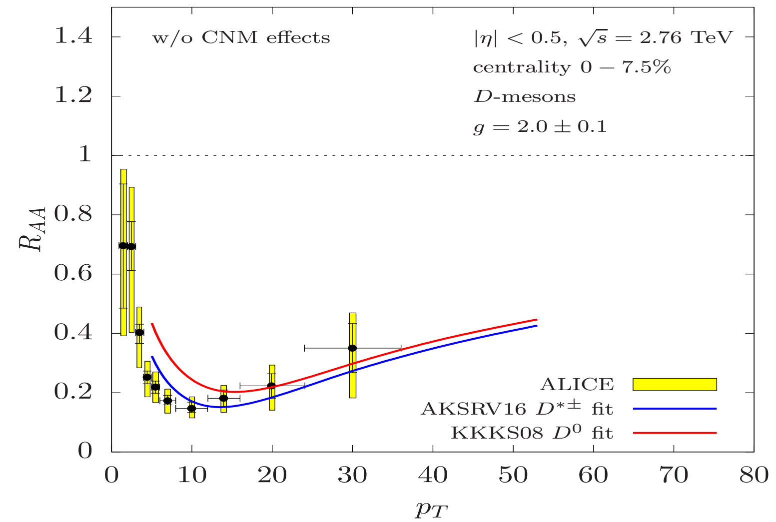




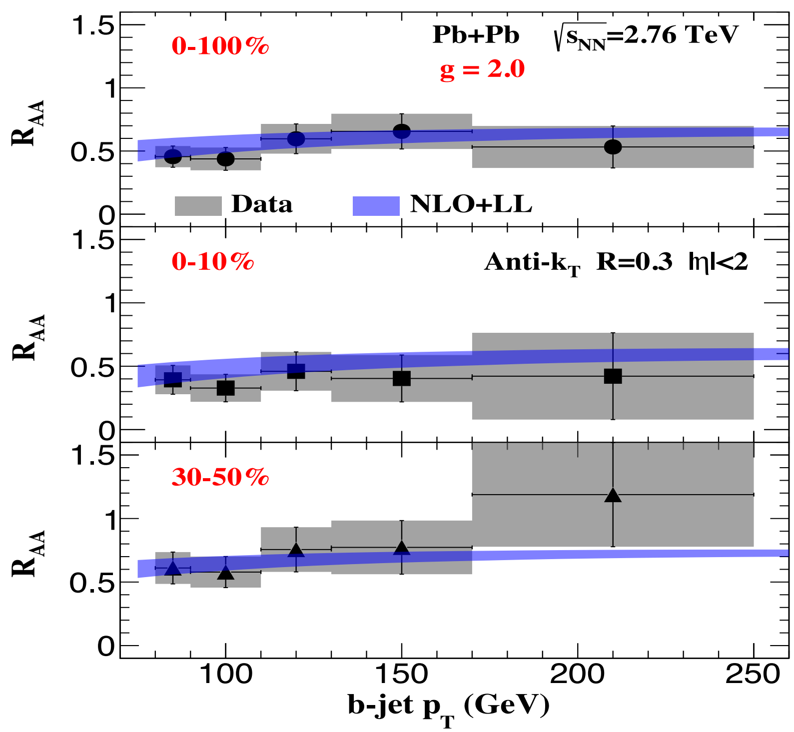
Critical gaps in the EIC program

Modification of hadron and jet observables in nuclear matter

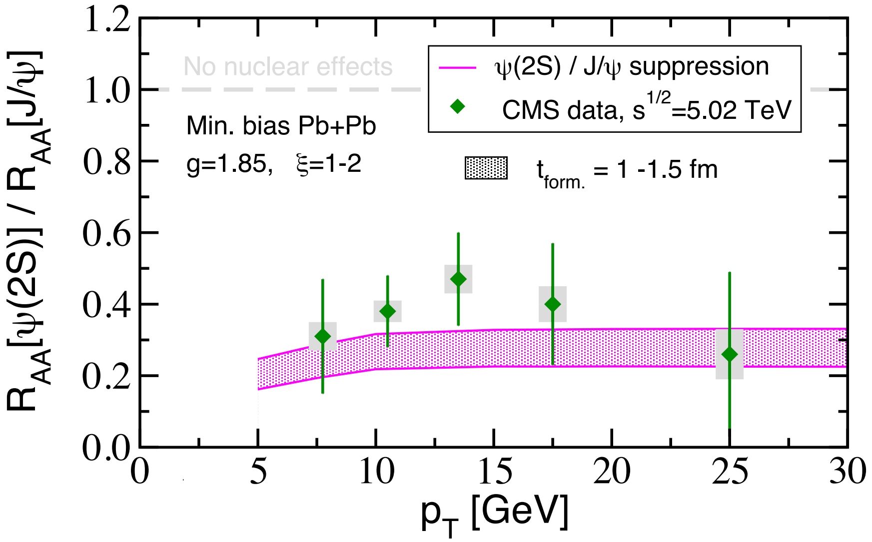
- In heavy ion collisions medium-modified parton showers are the cornerstone of high-p_T physics. These are the most significant effects and are not related to nPDFs and small-x physics



Open heavy flavor suppression and azimuthal momentum asymmetries



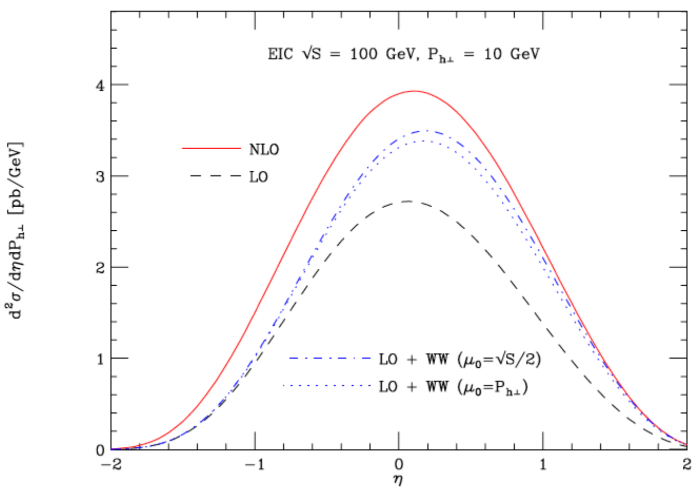
Heavy flavor jets and jet substructure



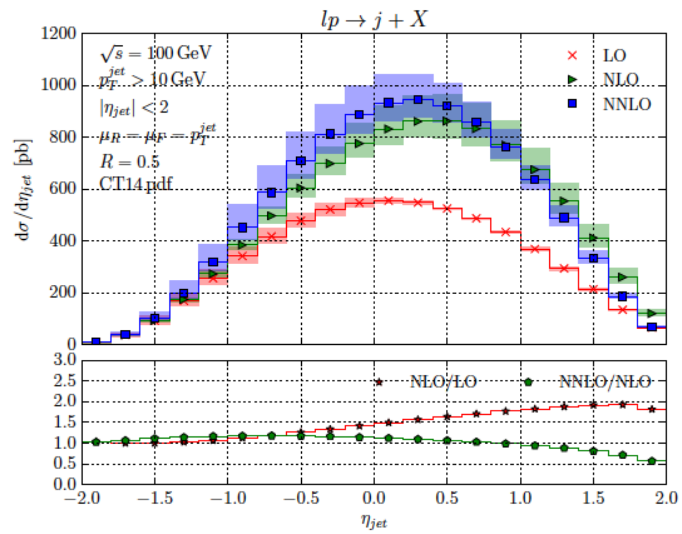
Suppression of quarkonia in nuclear matter

Hadron and jet production at the EIC – interest from HEP

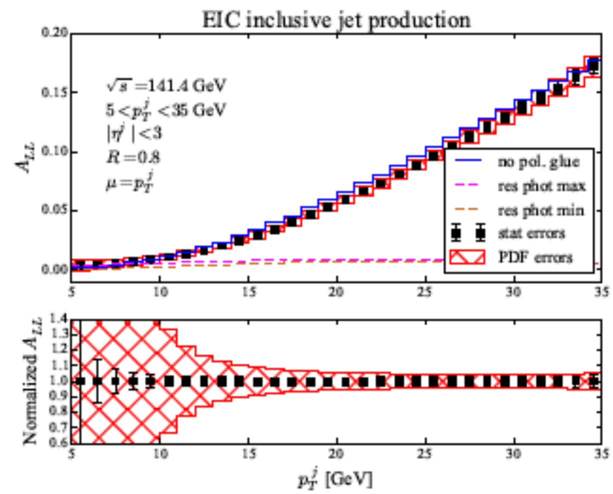
SIDIS has played a key role in pushing the boundaries of QCD, nucleon structure, the TMD approach, and QCD in reactions with nuclei



P. Hinderer et al. (2015)



G. Abelof et al. (2016)



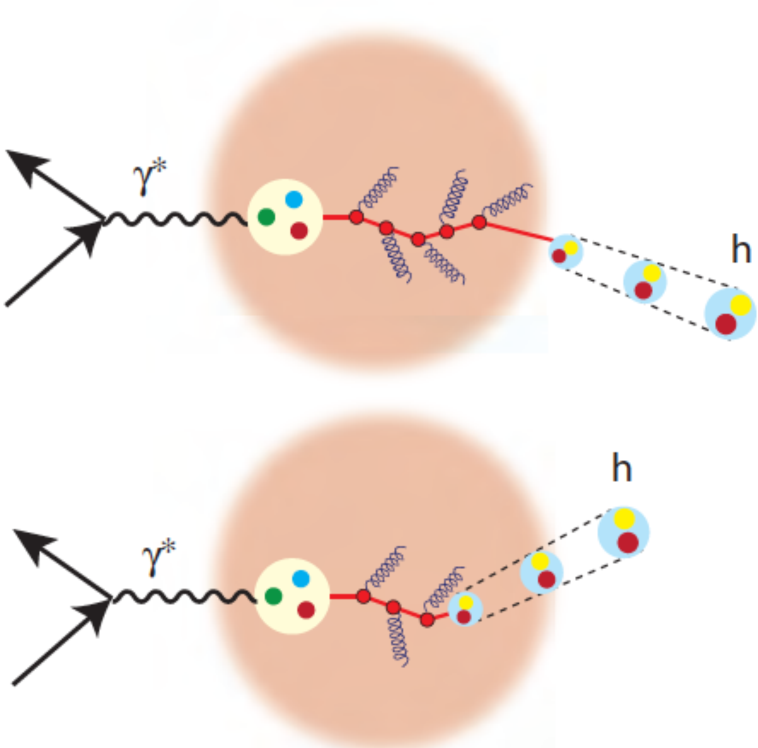
$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}}{d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}}$$

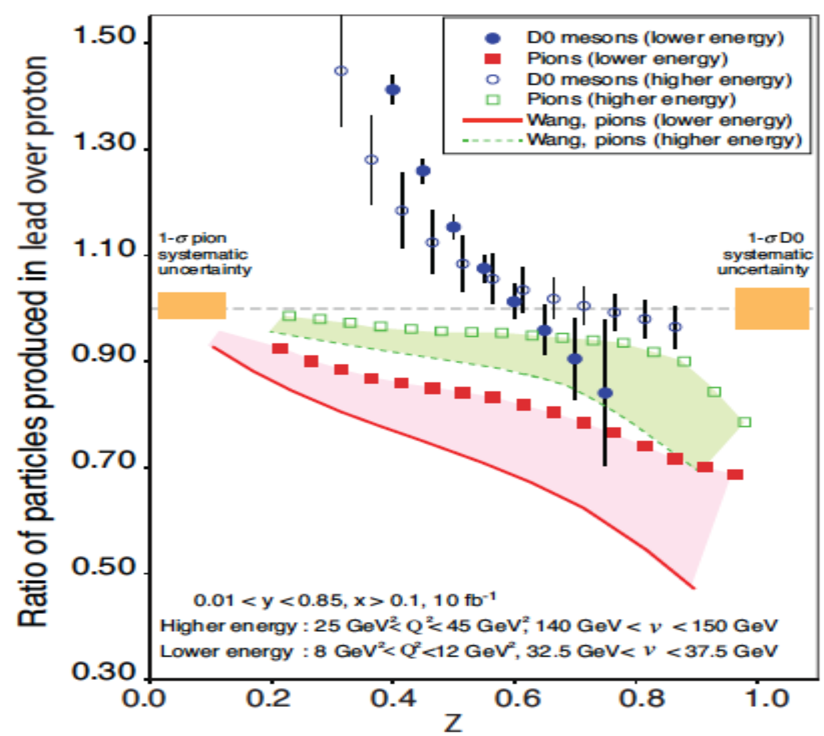
R. Boughezal et al. (2018)

- There is a renewed interest in precision calculations of hadron and jet production at the EIC – wide range of applications. At present – light hadrons and jets – but can be extended to heavy flavor, especially in the ZMVFNS

Status of calculations of particles and jets in large nuclei

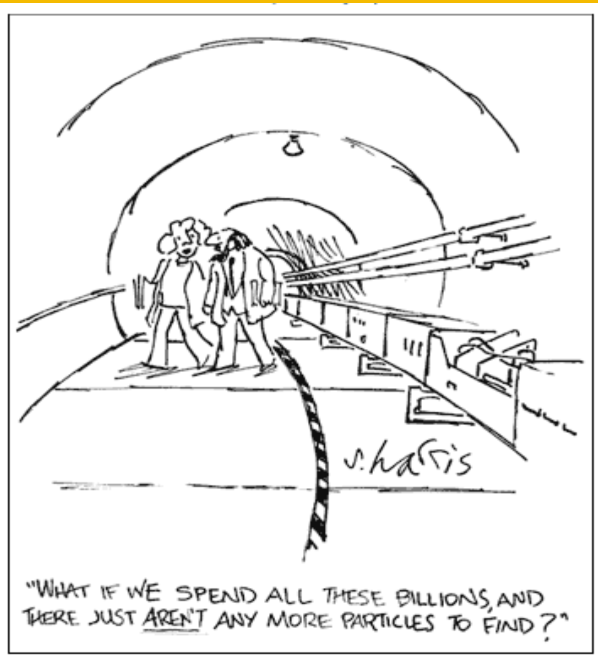
Jets and heavy flavor physics is seriously underdeveloped. Realized by EIC working group and the broader community





- The two topics mentioned are: (1) the possibility of hadronization in nuclei and (2) energy loss in nuclear matter. Circa 2000 physics which has a lot of merit but needs to be updated and extended

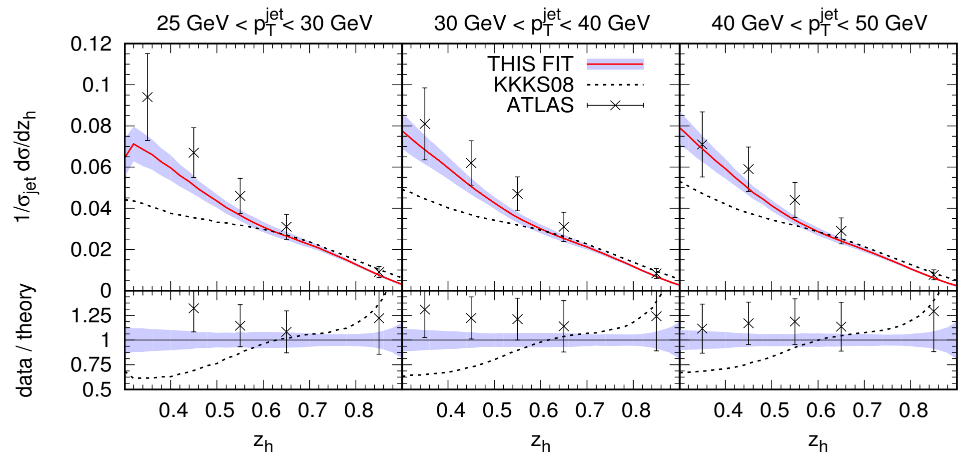
Status of in-medium modification of open heavy flavor

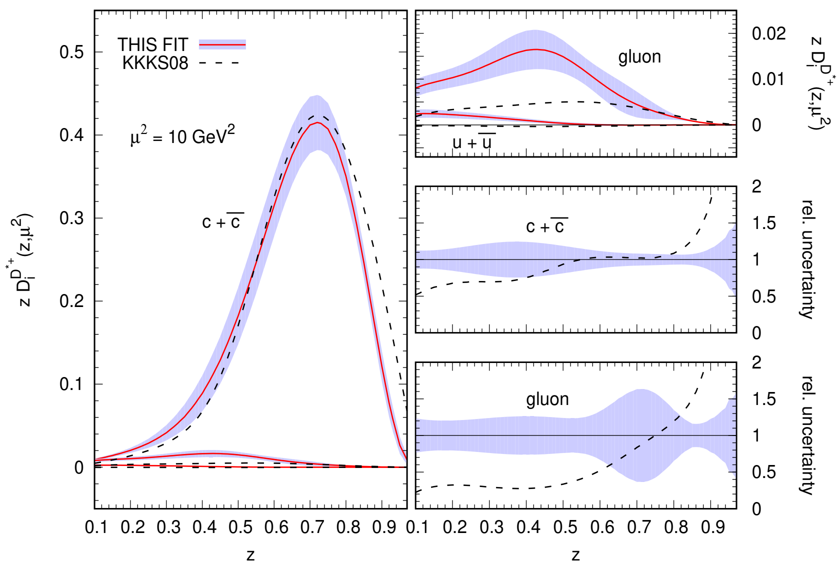


Need to better understand heavy meson production

- The gluon contribution to heavy flavor is very important for reactions with nuclei
- We also have indication that the gluon to heavy flavor contribution can be even larger (x 2)

experiment		data type	$\mathcal{N}_i$	#data in fit	χ^2
ALEPH [50]		incl.	0.991	17	31.0
OPAL [51]		incl.	1.000	9	6.5
		c tag	1.002	9	8.6
		b tag	1.002	9	5.6
ATLAS [34]		$D^{*\pm}$	1	5	13.8
ALICE [37]	$\sqrt{S} = 7$ TeV	D^{*+}	1.011	3	2.4
ALICE [38]	$\sqrt{S} = 2.76$ TeV	D^{*+}	1.000	1	0.3
CDF [39]		D^{*+}	1.017	2	1.1
LHCb [36]	$2 \leq \eta \leq 2.5$	$D^{*\pm}$	1	5	8.2
	$2.5 \leq \eta \leq 3$	$D^{*\pm}$	1	5	1.6
	$3 \leq \eta \leq 3.5$	$D^{*\pm}$	1	5	6.5
	$3.5 \leq \eta \leq 4$	$D^{*\pm}$	1	1	2.8
ATLAS [26]	$25 \leq \frac{p_T^{jet}}{GeV} \leq 30$	(jet $D^{*\pm}$)	1	5	5.5
	$30 \leq \frac{p_T^{jet}}{GeV} \leq 40$	(jet $D^{*\pm}$)	1	5	4.1
	$40 \leq \frac{p_T^{jet}}{GeV} \leq 50$	(jet $D^{*\pm}$)	1	5	2.4
	$50 \leq \frac{p_T^{jet}}{GeV} \leq 60$	(jet $D^{*\pm}$)	1	5	0.9
	$60 \leq \frac{p_T^{jet}}{GeV} \leq 70$	(jet $D^{*\pm}$)	1	5	1.6
TOTAL:				96	102.9





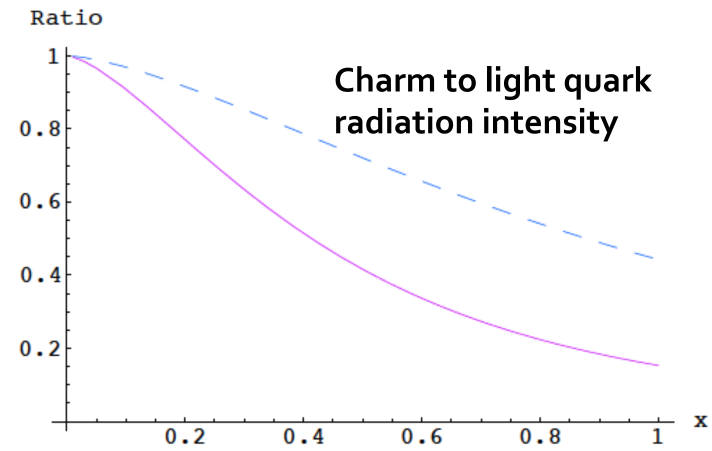
Global analysis including semi-inclusive annihilation, inclusive hadron production and hadrons in jets, no SIDIS data
Need to better understand heavy flavor production in SIDIS, jets

D. Anderle *et al.* (2017)

First studies of heavy flavor energy loss – gluon bremsstrahlung

- First studies, and a lot of studies till now, focus on parton energy loss (this is a very specific limit where energy is lost in small quanta)

Y. Dokshitzer et al. (2001)



The "dead cone" effect – argued by extrapolation from the vacuum case

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 \, dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2}, \qquad \theta_0 \equiv \frac{M}{E}$$

A more detailed look was taken in the opacity expansion approach, generalizing earlier massless derivation

M. Gyulassy et al. (2003)

$$\frac{dE_{ind}^{(1)}}{dx} = \frac{C_R \alpha_S}{\pi} \frac{L}{\lambda} E \int \frac{d\mathbf{k}^2}{\mathbf{k}^2 + m_g^2 + M^2 x^2} \int \frac{d^2\mathbf{q}_1}{\pi} \frac{\mu^2}{(\mathbf{q}_1^2 + \mu^2)^2} \times$$

$$\times \; 2 \, \frac{\mathbf{k}\cdot\mathbf{q}_1 (\mathbf{k}-\mathbf{q}_1)^2 + (m_g^2 + M^2x^2)\, \mathbf{q}_1\cdot(\mathbf{q}_1 - \mathbf{k})}{(\frac{4Ex}{L})^2 + ((\mathbf{k}-\mathbf{q}_1)^2 + M^2x^2 + m_g^2)^2} \;,$$

High twist approach

B.W. Zhang et al. (2004)

- Initial results for p_T integrated non-photonic decay electrons showed no significant suppression – they were badly misinterpreted

Collisional energy losses

- With radiative energy loss tuned to be as little as possible – models were challenged by p_T differential measurements

J. Bjorken. (1990)

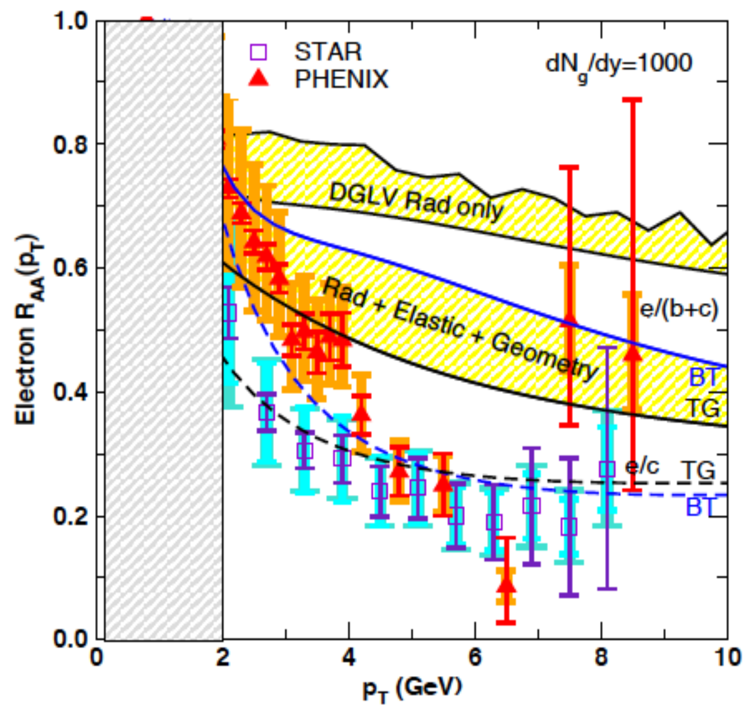
Renewed interest in collisional energy losses

$$-\Delta E_{coll}(L_p) = \frac{C_F \alpha_s m_D^2 L_p}{2}\left[\frac{1}{v} - \frac{1-v^2}{2v^2}\log\left(\frac{1+v}{1-v}\right)\right]\log\left(\frac{k_{\max}}{m_g}\right)$$

$$\text{where } k_{\max} \equiv \text{Min}\left\{\frac{ET}{M}, \sqrt{ET}\right\} \text{ and } m_g = m_D/\sqrt{3} \ .$$

Done exclusively in thermal medium. Estimates very form collisional energy losses comparable to radiative to being only 10% correction

- These calculations have not been done for cold nuclear matter. Also some trouble still remains



M. Djordjevic et al. (2005)

A. Adil et al. (2005)

X. N. Wang et al. (2006)

P.B Gossauix et al. (2007)

Transport approaches

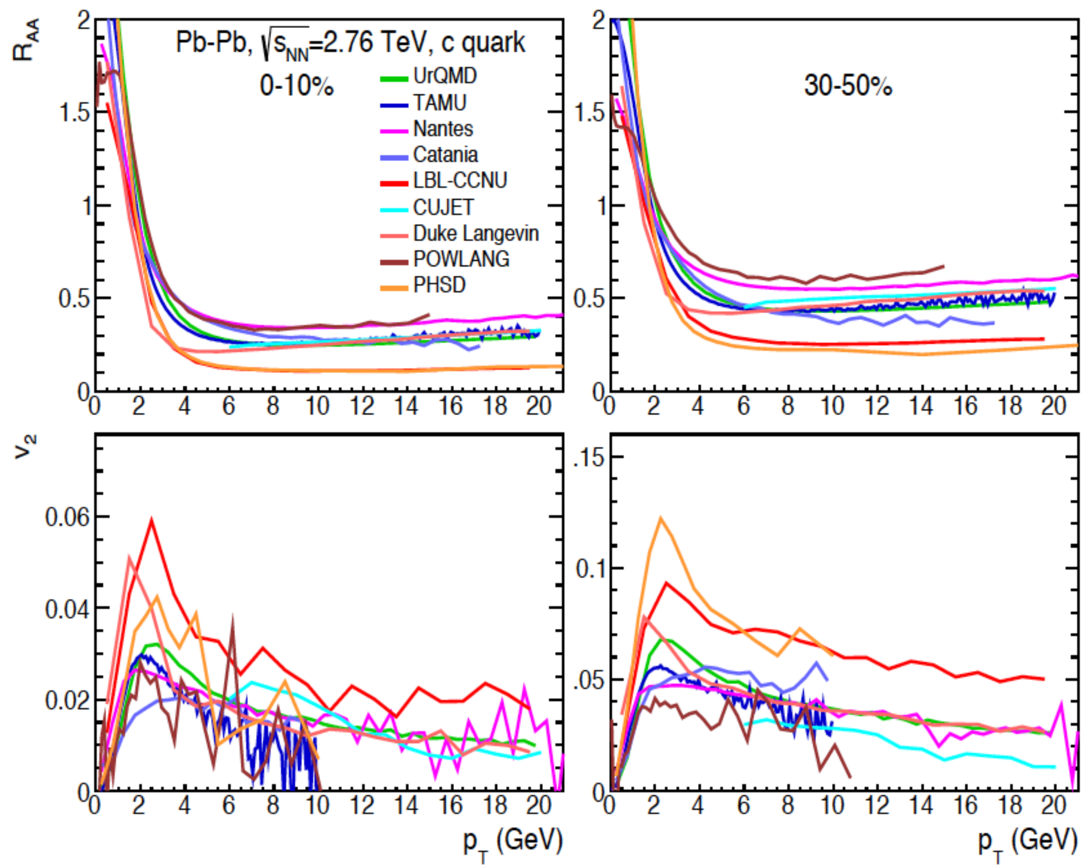
- At low transverse momenta there has been development of Langevin, Fokker-Plank and Boltzman transport approaches.

Van Hees et al. (2004)

G. Moore et al. (2005)

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

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



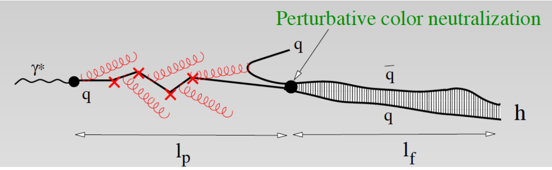
Note that to get close to the data the perturbative cross sections were multiplied by a factor of 5

R. Rapp et al. (2018)

- Often times the results are presented in terms of Diffusion coefficient, message is the same. Difficult to extend to DIS for now

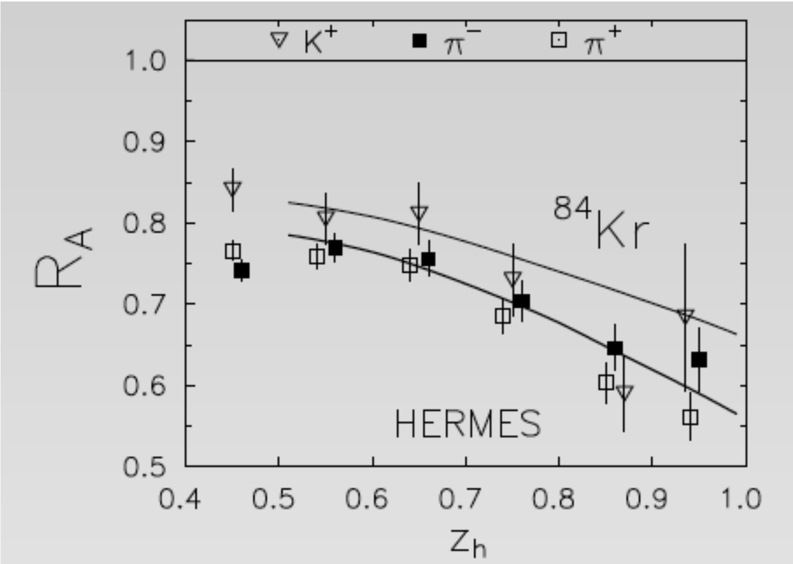
In-medium hadronization and dissociation

Takes us to phenomenological work in semi-inclusive DIS

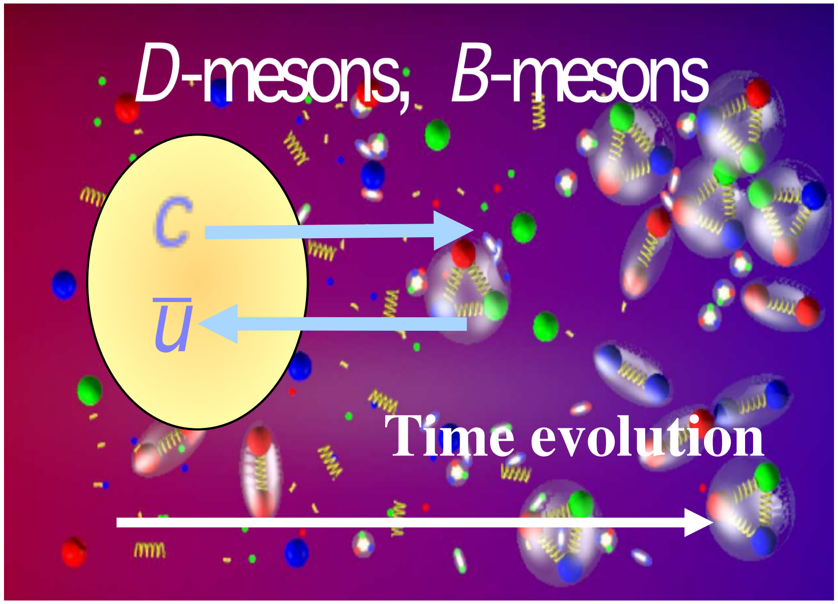


B. Kopeliovich et al. (2003)

$$R_A^h(z,\nu) = \left(\frac{N^h(z,\nu)}{N^e(\nu)}\Big|_A \right) \Big/ \left(\frac{N^h(z,\nu)}{N^e(\nu)}\Big|_D \right)$$

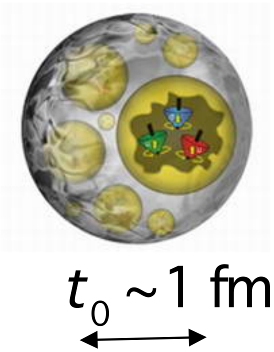


- We have arrived at a similar picture for open heavy flavor in matter



Main uncertainty comes from formation times

$$\Delta y^+ \simeq \frac{1}{\Delta p^-} = \frac{2z(1-z)p^+}{\mathbf{k}^2 + (1-z)m_h^2 - z(1-z)m_Q^2}$$



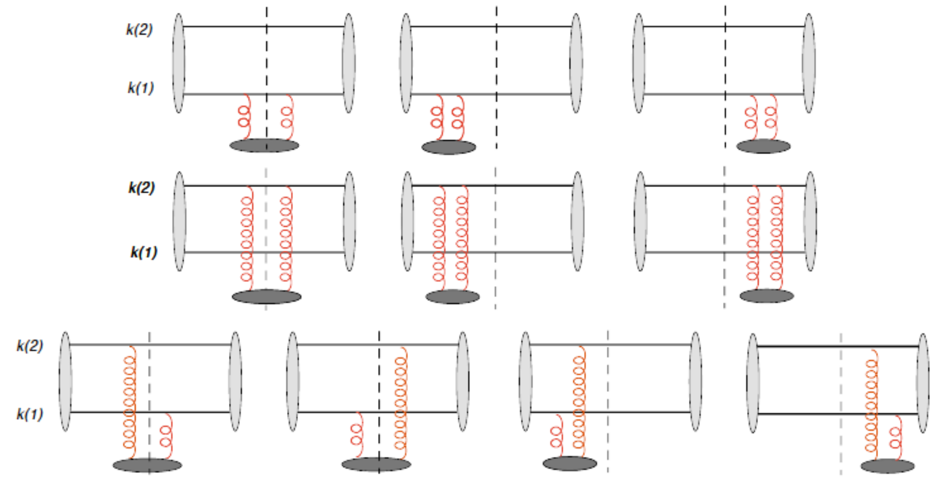
Proportional to the boost, inversely proportional to the heavy meson mass

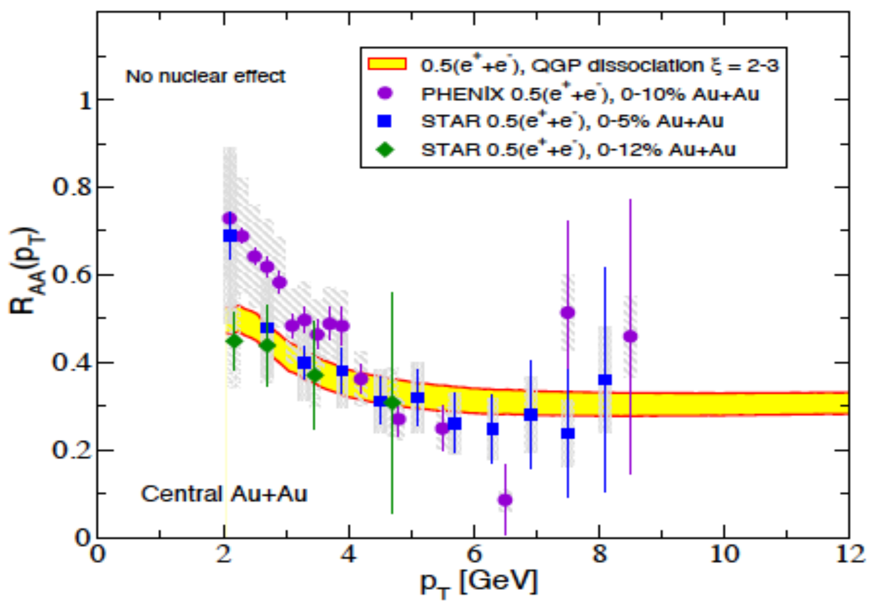
A. Adil et al. (2007)

The physics of in-medium interactions

If a hadron is formed in the medium it does not mean it does not interact

- Rich physics: Solve the Dirac eq. for heavy mesons. Construct their lightcone wavefunctions. Evaluate the dissociation probability and solve a set of coupled rate equations





$$\partial_t f^Q(p_T,t) = -\frac{1}{\langle \tau_{\rm form}(p_T,t)\rangle} f^Q(p_T,t) + \frac{1}{\langle \tau_{\rm diss}(p_T/\bar{x},t)\rangle}\int_0^1 dx\, \frac{1}{x^2}\phi_{Q/H}(x) f^H(p_T/x,t)$$

$$\partial_t f^H(p_T,t) = -\frac{1}{\langle \tau_{\rm diss}(p_T,t)\rangle} f^H(p_T,t) + \frac{1}{\langle \tau_{\rm form}(p_T/\bar{z},t)\rangle}\int_0^1 dz\, \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T/z,t)$$

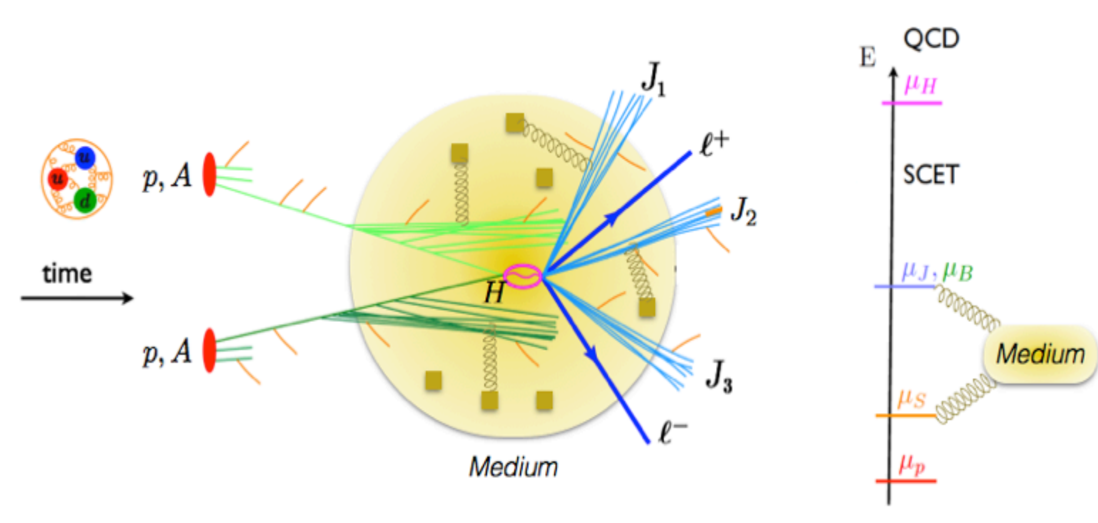
R. Sharma et al. (2009)

Can be matched to energy loss at high p_T

Easy to generalize to DIS

In-medium parton shower

- Traditional energy loss approach, phenomenologically successful but cannot be systematically improved, higher orders and resummation
- We demonstrate how HEP parton shower technology can be applied to reactions with nuclei NLO, NLL



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

We have derived all splitting functions

For heavy flavor

F. Ringer et al . (2016)

M. Sievert et al. (2018)

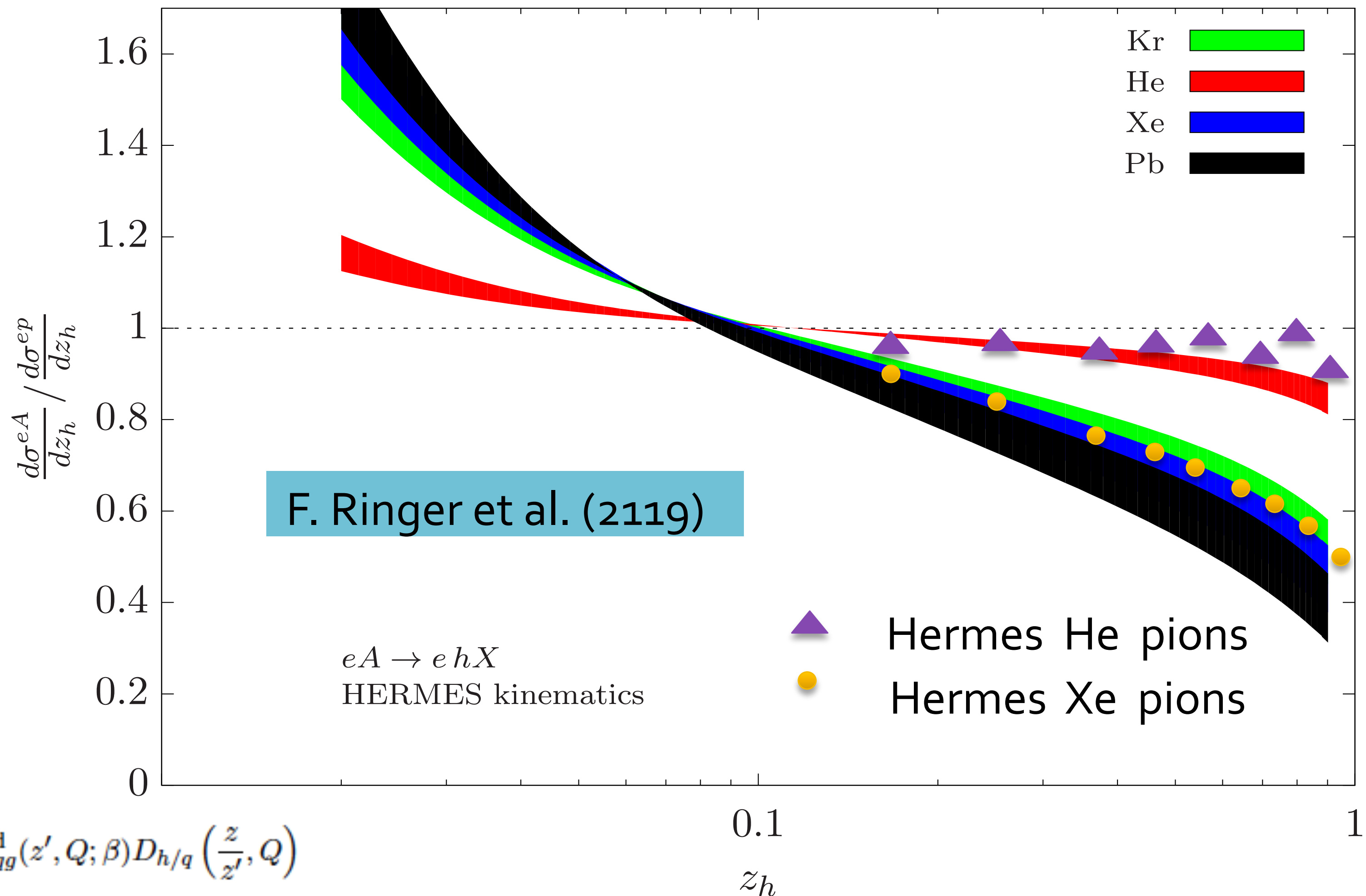
- Implemented in DGLAP evolution equations

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

Full QCD evolution and validation against Hermes data

- Description of light pions. On the upper edge of the theory uncertainty bands
- For heavy particle one has to be careful when E~m

NLO calculation



$$\frac{dD_{h/q}(z,Q)}{d\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{dz'}{z'}\left[P^{\rm med}_{q\to qg}(z',Q;\beta)D_{h/q}\left(\frac{z}{z'},Q\right) + P^{\rm med}_{q\to gq}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right)\right],$$

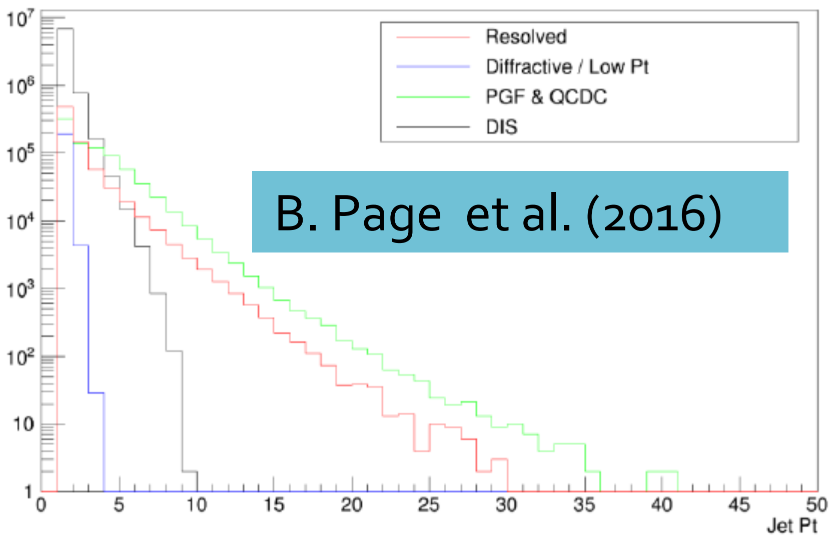
$$\frac{dD_{h/g}(z,Q)}{d\ln Q} = \frac{\alpha_s(Q)}{\pi}\int_z^1 \frac{dz'}{z'}\left[P^{\rm med}_{g\to gg}(z',Q;\beta)D_{h/g}\left(\frac{z}{z'},Q\right) + P^{\rm med}_{g\to q\bar{q}}(z',Q;\beta)\sum_q D_{h/q}\left(\frac{z}{z'},Q\right)\right].$$

$$E_h\frac{d^3\sigma^{\ell N\to hX}}{d^3P_h} = \frac{1}{S}\sum_{i,f}\int_0^1\frac{dx}{x}\int_0^1\frac{dz}{z^2}\, f^{i/N}(x,\mu)\times D^{h/f}(z,\mu)\,\hat{\sigma}^{i\to f}(s,t,u,\mu)$$

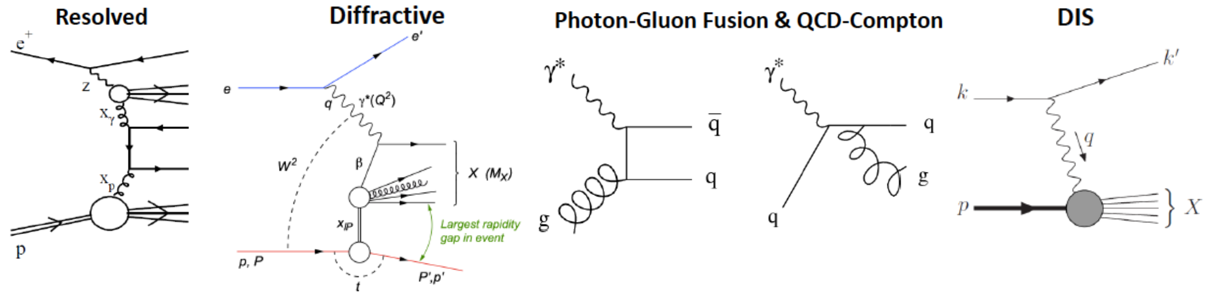
Energy loss is a special limiting case of DGLAP evolution

Jet production in SIDIS

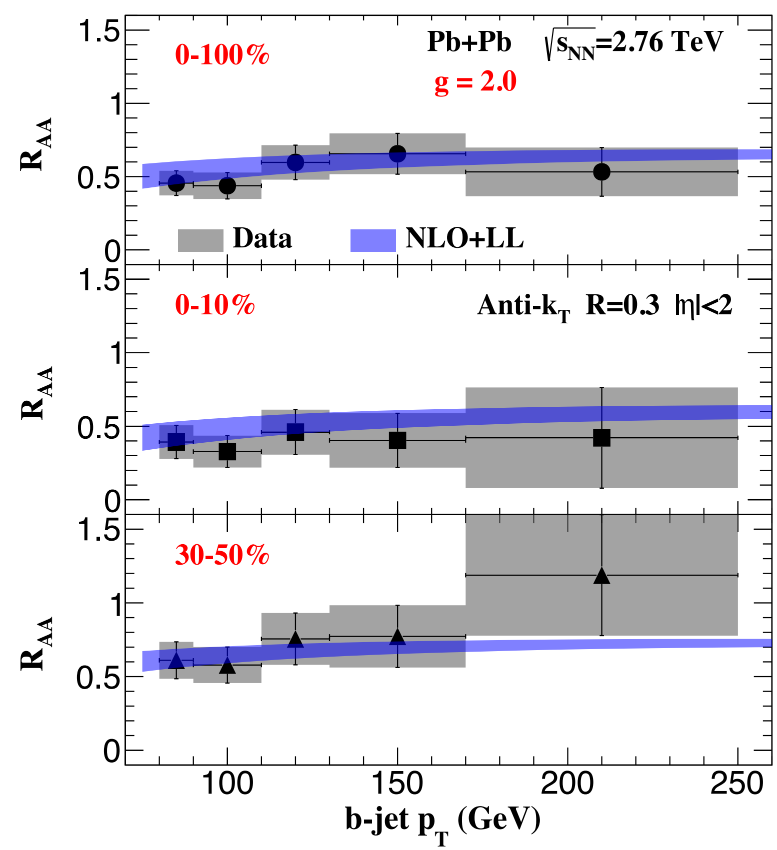
Inclusive Jet p_T: Q^2 = 10-100 GeV^2



B. Page et al. (2016)



Note – the simulations were done with light jets



H. Li et al. (2018)

- Modern SCET techniques to calculate heavy jet modification. Applicable to EIC

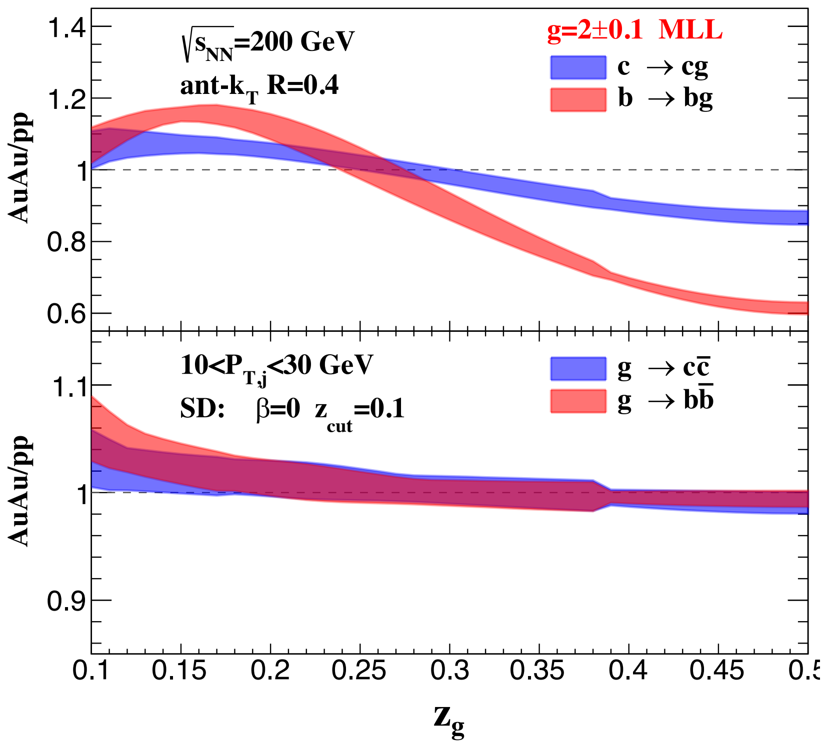
$$J^{\rm med}_{J_Q/i} = J^{{\rm med},(0)}_{J_Q/i} + \frac{\alpha_s}{2\pi} J^{{\rm med},(1)}_{J_Q/i}$$

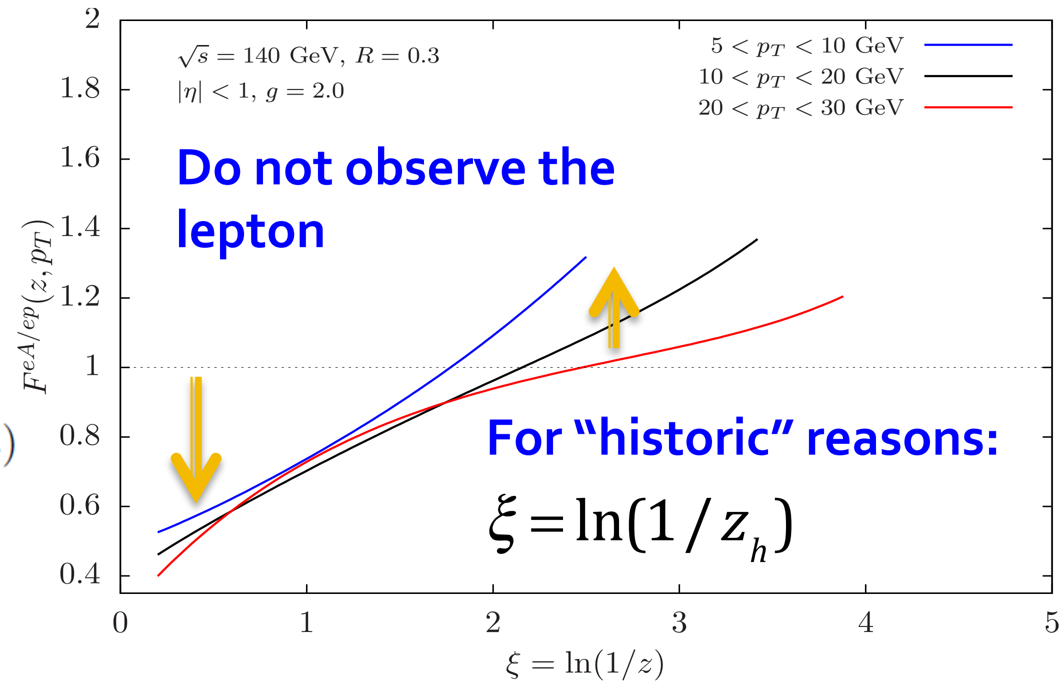
$$J^{{\rm med},(1)}_{J_s/g}(z, p_T R, m, \mu) = \int_{z(1-z)p_T R}^{\mu} dq_\perp \left(P^{\rm med}_{Qg}(z, m, q_\perp) + P^{\rm med}_{\bar{Q}g}(z, m, q_\perp) \right) + \delta(1-z) \int_0^1 dx \int_0^{x(1-x)p_T R} dq_\perp P^{\rm med}_{Qg}(x, m, q_\perp) \,,$$

Jet substructure – hadron distributions and splitting functions

- Semi-inclusive fragmenting jet functions

$$\frac{d\sigma^{pp\to(\text{jet }h)X}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H^c_{ab}(\eta, p_T/z, x_a, x_b, \mu) \otimes \mathcal{G}^h_c(z, z_h, \omega_J R, \mu)$$





Very preliminary EIC results

- Jet fragmentation functions – unique reversal of the mass hierarchy of jet quenching effects

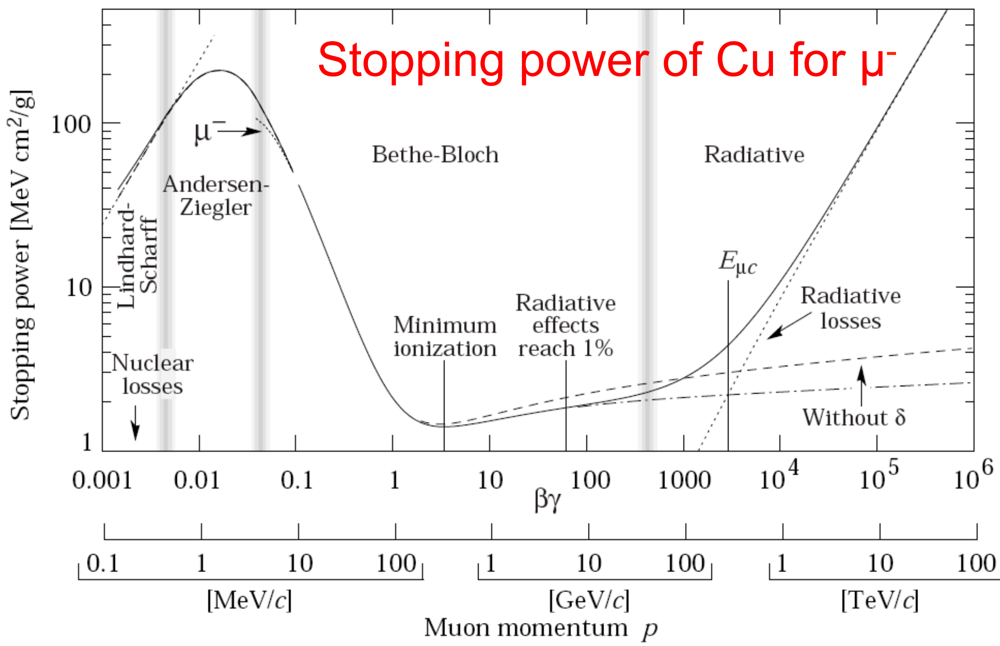
P. Ilten et al. (2017)

H. Li et al. (2018)

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

Opportunities with open heavy flavor at EIC

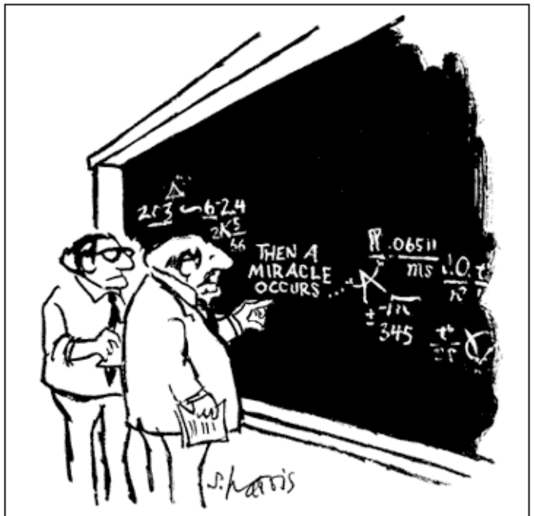
- Theory of nuclear modification as a function of momentum transfer ν, virtuality Q - constrained kinematics & B- and D-mesons (mass) to vary formation times
- Stopping power of matter for charged particles is a fundamental probe of its properties. In QED X_0(min) ~ mm, in nuclei 10 orders of magnitude smaller! Transport properties of CNM
- Determination of the production mechanisms for open heavy flavor in SIDIS. Global analysis
- A whole class of new observables to be added – jets and jet substructure



PDG (2008)

- Test unique predictions of QCD
- Determine the cross sections for heavy jet suppression
- Pinpoint the heavy quark mass effect in parton showers

Status of in-medium modifications of quarkonia



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

Quarkonium production from low to high p_T

- Use NRQCD, expansion in the small velocity between the heavy quarks

J. Bodwin *et al.* (1995)

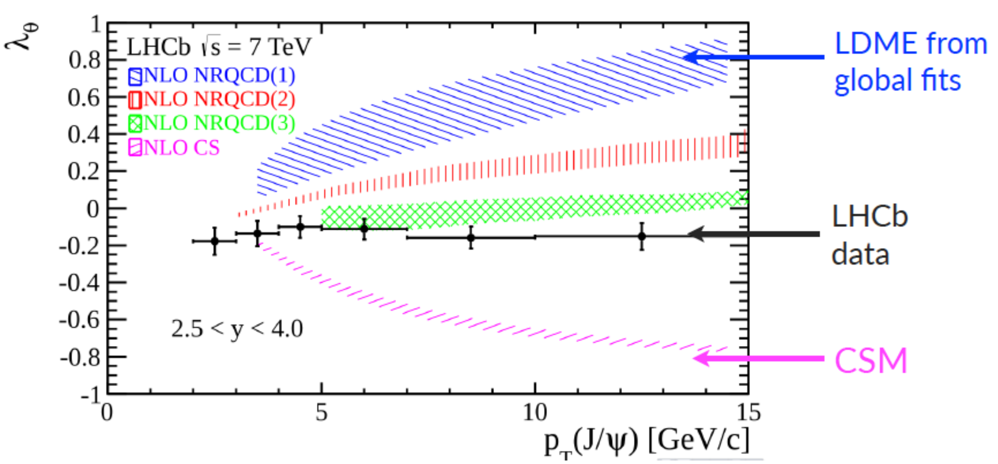
M. Luke *et al.* (1999)

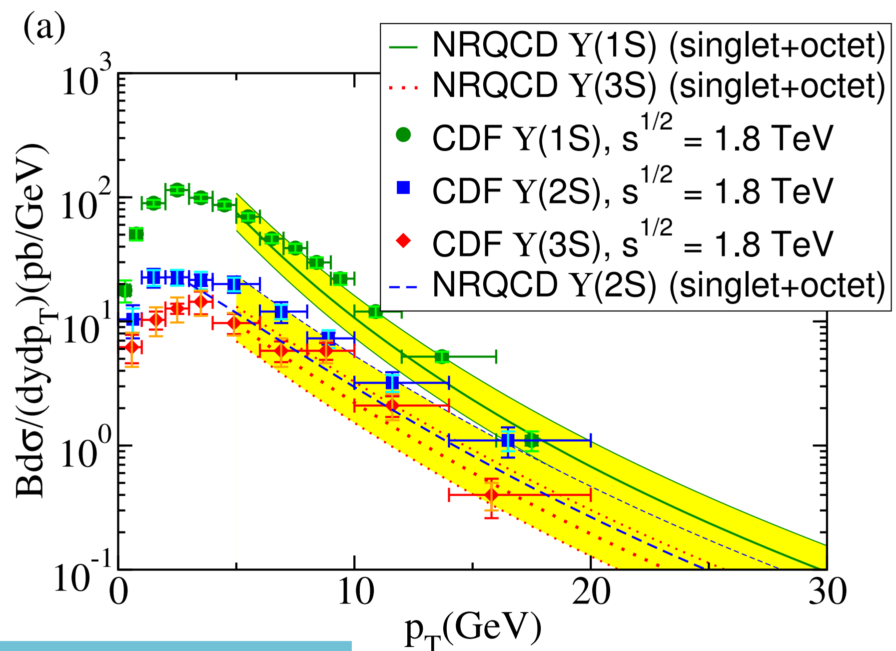
N. Brambilla *et al.* (2005)

R. Sharma *et al.* (2011)

$$d\sigma(J/\psi) = d\sigma(Q\bar{Q}([^3S_1]_1))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle\mathcal{O}(Q\bar{Q}([^1S_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3S_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3P_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_2]_8) \to J/\psi)\rangle + \cdots$$

- Improvements, pNRQCD, vNRQCD
- Polarization puzzle



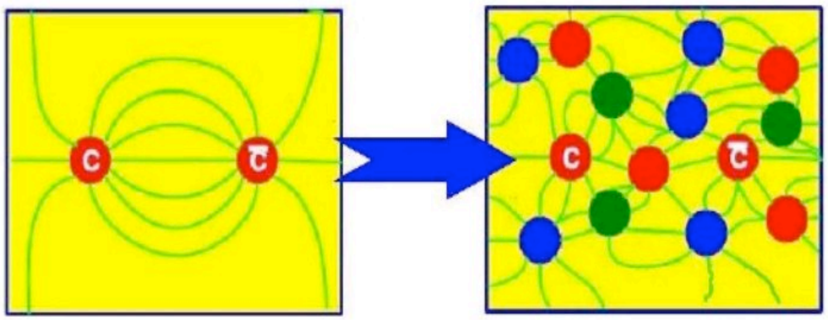


- Fragmentation at high p_T

M. Baumgart *et al.* (2014)

Quarkonium properties and the QGP

- Quarkonia (e.g. J/ψ,ϒ), bound states of the heaviest elementary particles, long considered standard candle to characterize QGP properties. Most sensitive to the space-time temperature profile

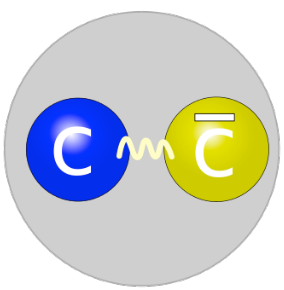


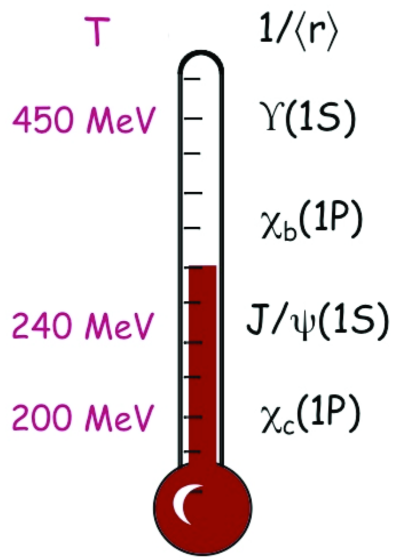
$$\psi(\mathbf{r}) = Y_l^m(\hat{r}) R_{nl}(r)$$

$$\left[-\frac{1}{2\mu_{\rm red}}\frac{\partial^2}{\partial r^2} + \frac{l(l+1)}{2\mu_{\rm red} r^2} + V(r)\right] rR_{nl}(r) = (E_{nl} - 2m_Q) rR_{nl}(r)$$

Mocsy *et al.* (2007)

Bazavov *et al.* (2013)

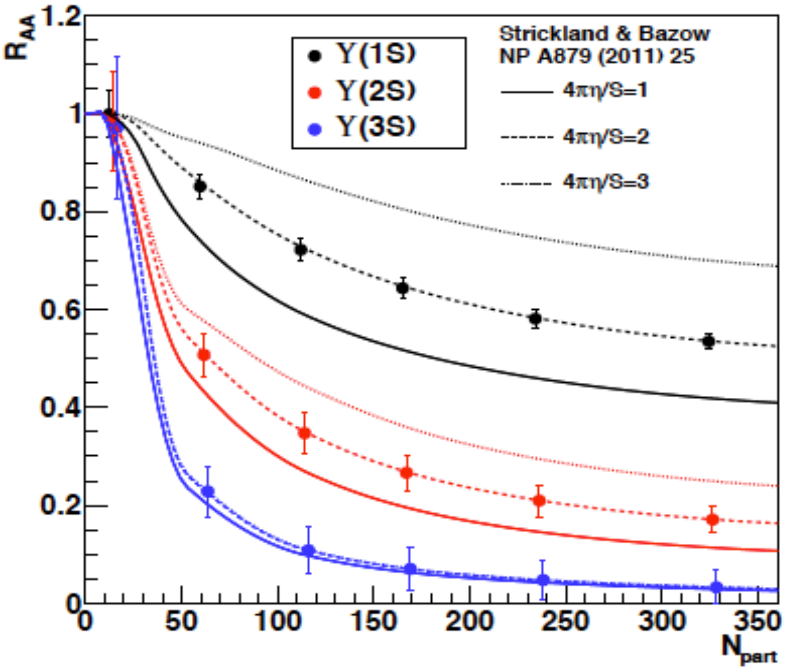




Matsui *et al.* (1986)

l	n	E_{nl} (GeV)	$\sqrt{\langle r^2 \rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.700	2.24	0.30	J/ψ
0	2	0.086	5.39	0.05	$\psi(2S)$
1	1	0.268	3.50	0.20	χ_c
0	1	1.122	1.23	0.99	$\Upsilon(1S)$
0	2	0.578	2.60	0.22	$\Upsilon(2S)$
0	3	0.214	3.89	0.10	$\Upsilon(3S)$
1	1	0.710	2.07	0.58	$\chi_b(1P)$
1	2	0.325	3.31	0.23	$\chi_b(2P)$
1	3	0.051	5.57	0.08	$\chi_b(3P)$

Evolution of quarkonium dissociation models



M. Strickland *et al.* (2011)

$$\Im[V_{\rm pert}] = -\alpha p_{\rm hard}\left\{\phi(\hat{r}) - \xi\left[\psi_1(\hat{r},\theta) + \psi_2(\hat{r},\theta)\right]\right\}$$

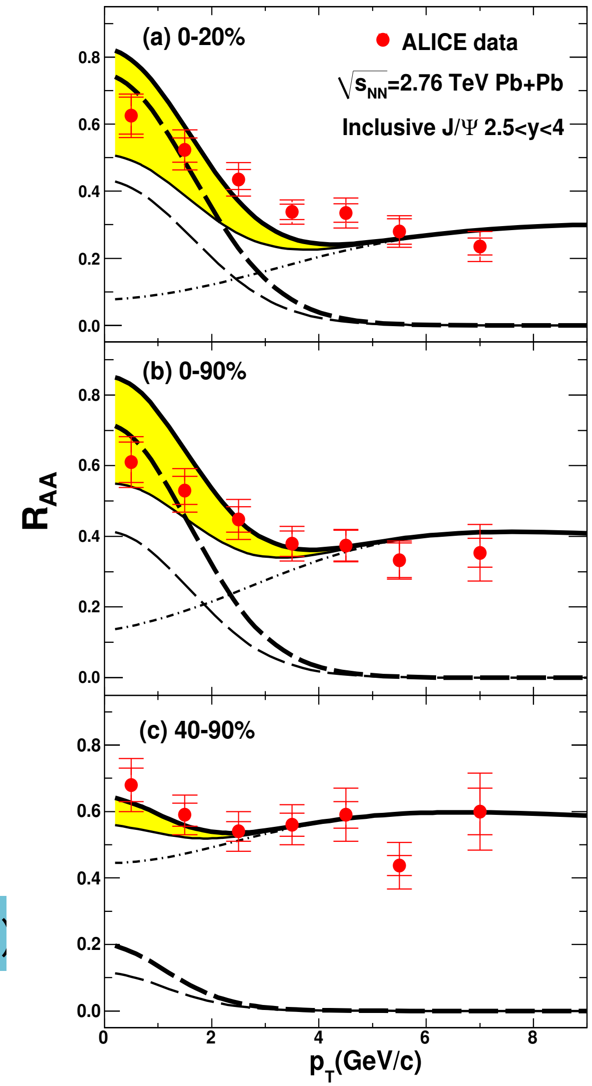
- Recombination effects – limited to low p_T

- Quarkonium dissociation related to the imaginary part of the potential – singlet to octet transition. LQCD results with very large uncertainties.

P. Braun-Munzinger *et al.* (2000)

R. Thews *et al.* (2000)

L. Grandchamp *et al.* (2001)



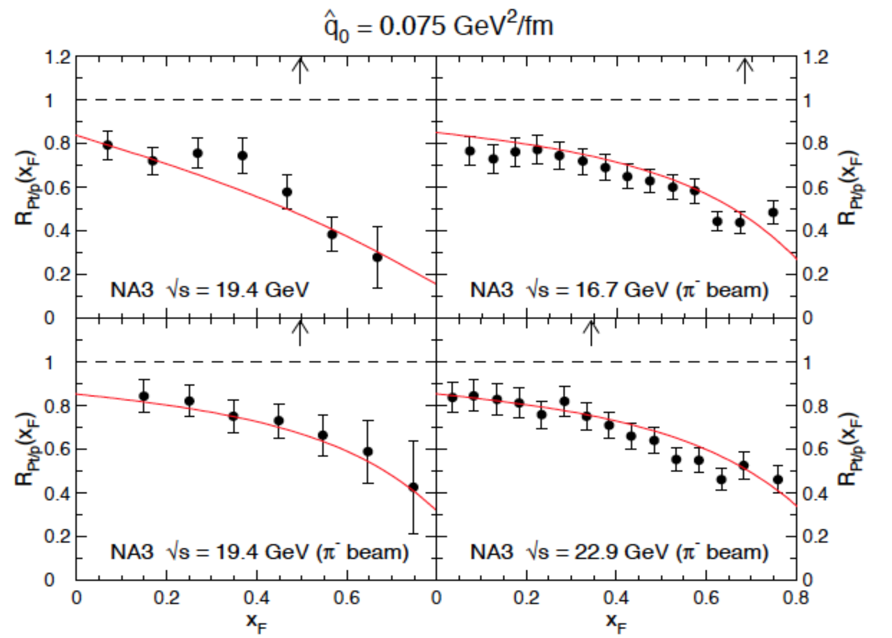
K. Zhou *et al.* (2013)

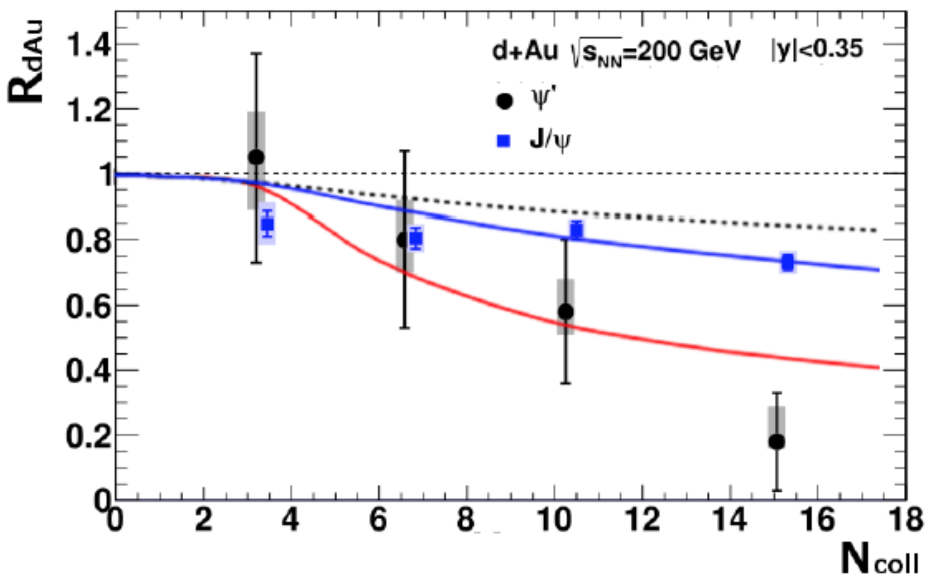
Energy loss for quarkonia in nuclei and co-mover dissociation

- 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)

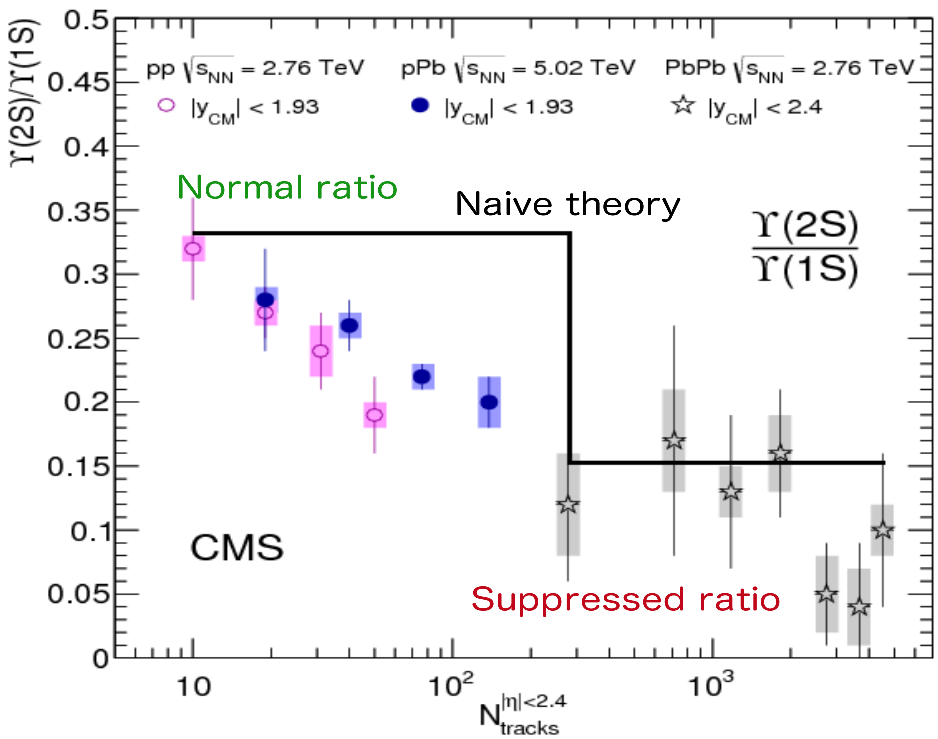
$$\tau \frac{\mathrm{d}\rho^\psi}{\mathrm{d}\tau}(b,s,y) = -\sigma^{co-\psi}\, \rho^{co}(b,s,y)\, \rho^\psi(b,s,y)$$

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

Quarkonia as probes of the QGP

- Suppression puzzle - similar dissociation behavior observed in small system, p+A and even in p+p (where QGP is not expected) , as a function of the number of hadrons.

Excited Upsilon suppression



Chatrachyan *et al.* (2014)

- Suggests that an effective field theory framework may be the way to go. Capture the interactions without explicitly specifying their nature

Lowest order

$$\mathcal{L}_0 = \mathcal{L}_{\text{light}} + \psi^\dagger \left(i\partial_0 - gA_0 + \frac{\nabla^2}{2M} \right) \psi$$

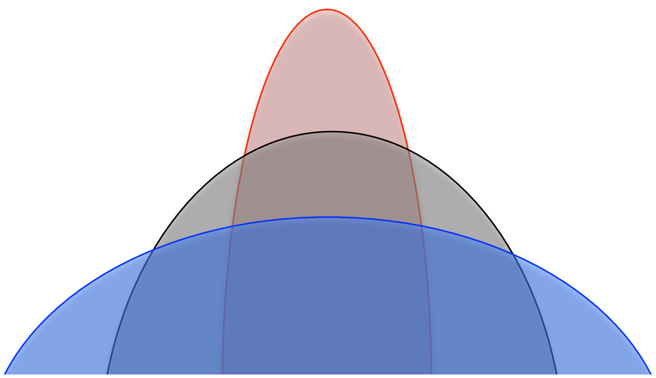
First correction

$$\mathcal{L}_1 = -\frac{1}{M}\psi^\dagger (ig\mathbf{A}\cdot\nabla)\psi + \frac{c_4}{2M}\psi^\dagger (\nabla \times g\mathbf{A})\cdot\boldsymbol{\sigma}\psi$$

Toward an EFT for quarkonia in matter

- Dissociation time – incudes thermal wavefunction effects and collisional broadening (can be generally applicable to different media)

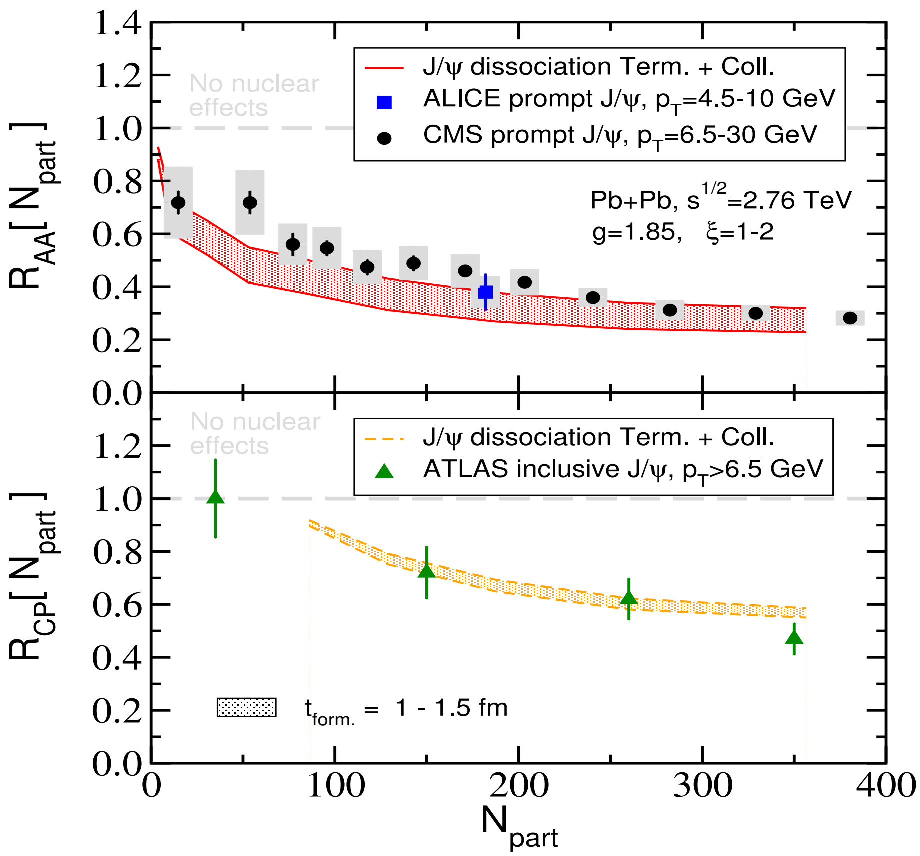
S. Aronson *et al.* (2017)



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

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

Momentum space picture



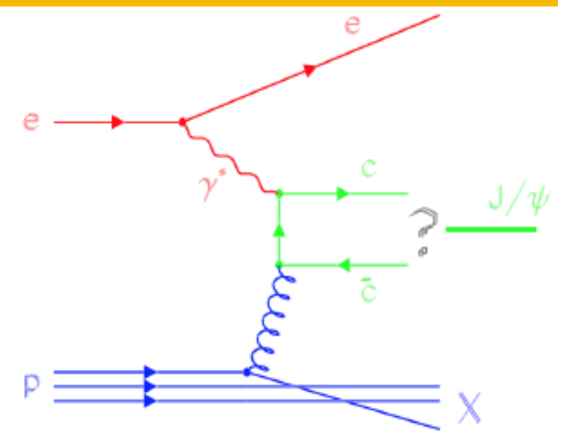
Energy loss picture not yet supported at these p_Ts

Opportunities with quarkonia at the EIC

- Historically J/ψ used to determine gluon densities at HERA. Suitable for studies of shadowing and gluon saturation physics at the the EIC

- Variety of presumed production mechanisms:
  - Diffractive/elastic
  - Gluon-gluon-fusion, photon-gluon-fusion
  - Gluon fragmentation
  - "Resolved photon"-gluon/quark-fusion
  - + decays

A. Mayer (2002)



- Using J/ψ to study the saturation limit and determine the proximity to black body limit in DIS

T. Rogers (2003)

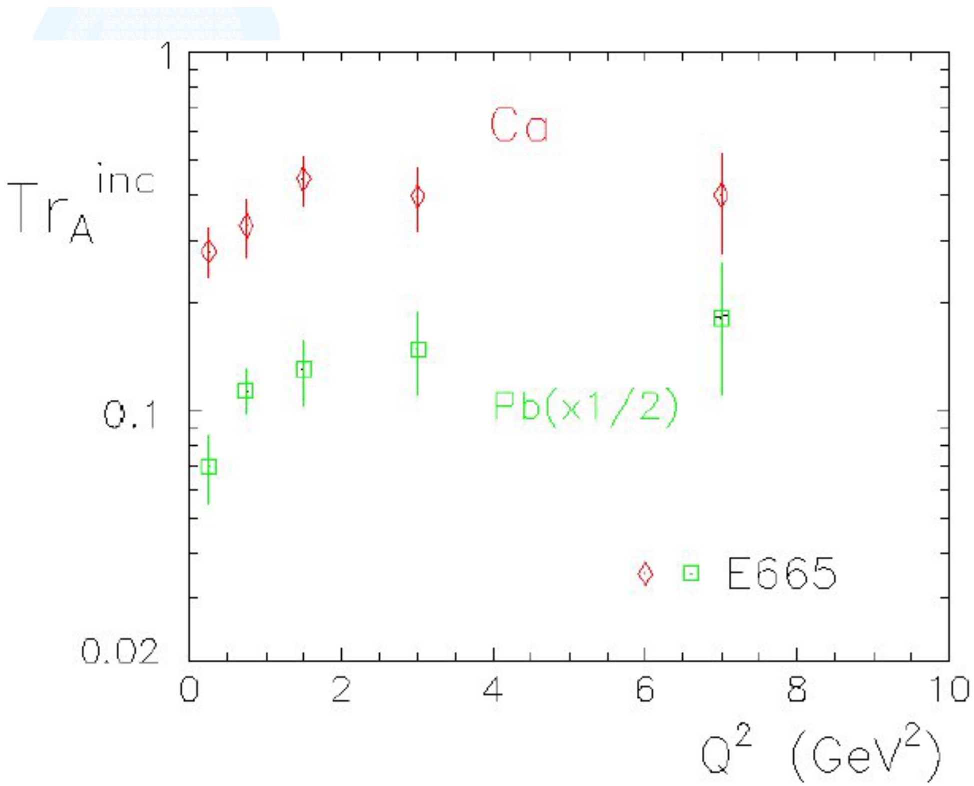
- It could be interesting to add a program that focuses on the ground and excited charmonim and bottomonium states and their dissociation in nuclear matter to the EIC program.

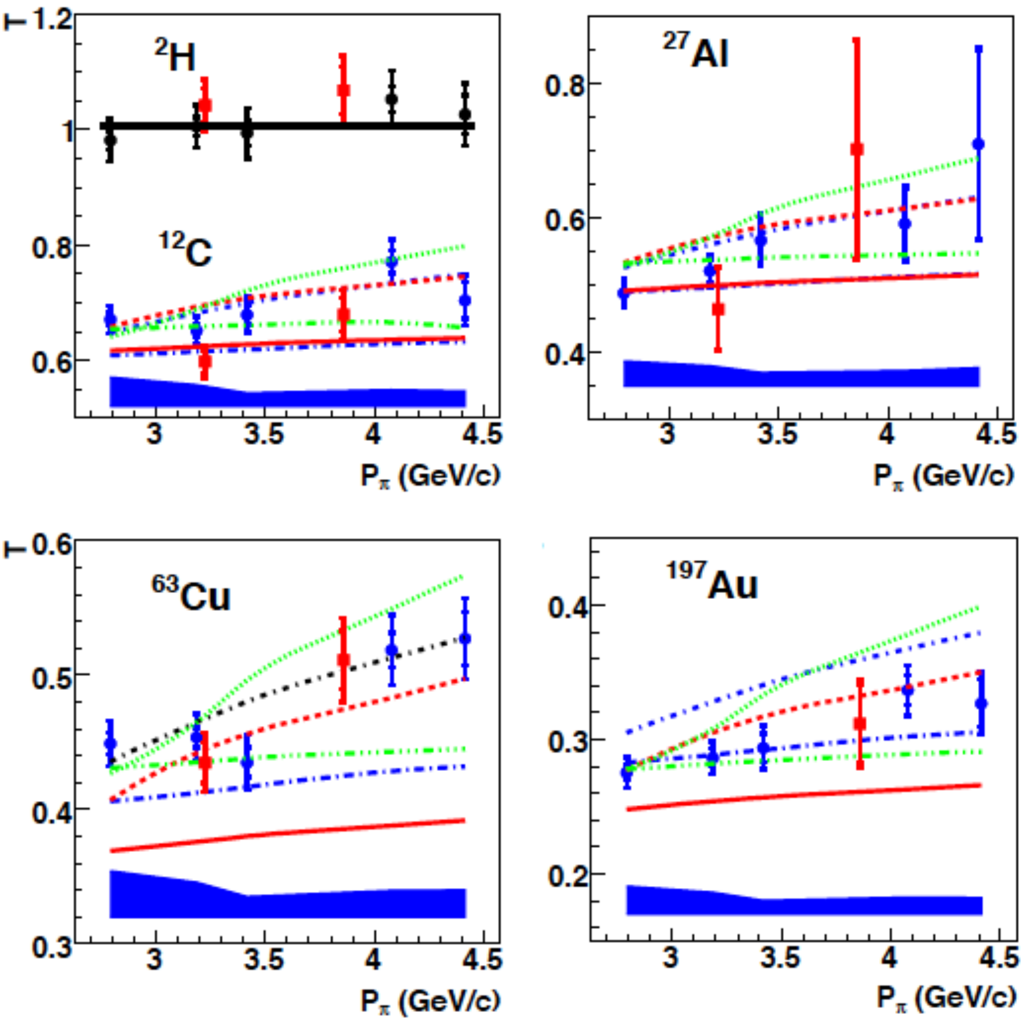
Conclusions

- There are tremendous opportunities for heavy flavor physics, both open heavy flavor and quarkonia , in ep and eA collisions that are not fully explored at the EIC
- On the experimental side one can leverage the more precise kinematic constraints in DIS (relative to pp) and select different species (D-mesons, B-mesons) and quarkonium families (J/ψ and Υ) to compare and contrast different production pictures and nuclear modification paradigms. A multi-year physics program
- On the formal side we now have to relate heavy flavor to full in-medium parton showers. Construct novel EFTs without loss of generality that describe heavy flavor in a variety of nuclear media.
- Putting theory and experiment together we can determine the transport properties of large nuclei and radiation lengths in nuclear matter, in addition to the more traditional use of heavy flavor to determine gluon densities
- Need numerical tools (implementation) for jet and heavy flavor simulations in reactions with nuclei at the EIC to check which channels are feasible

Transparency or lack thereof

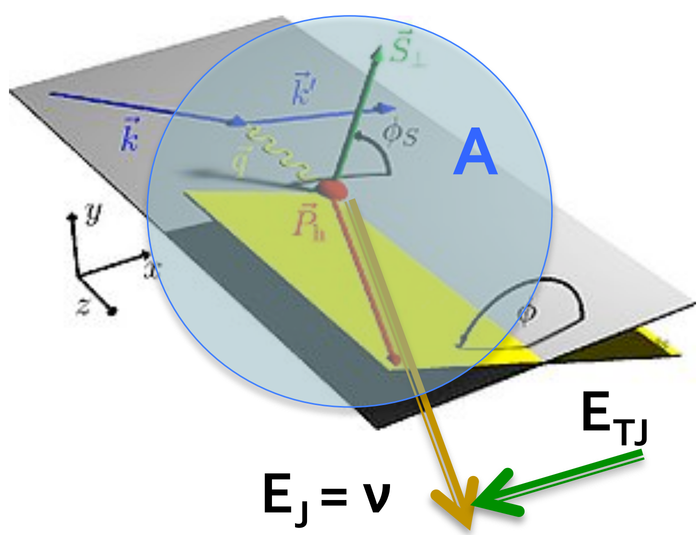
We haven't see transparency but we have seen suppression



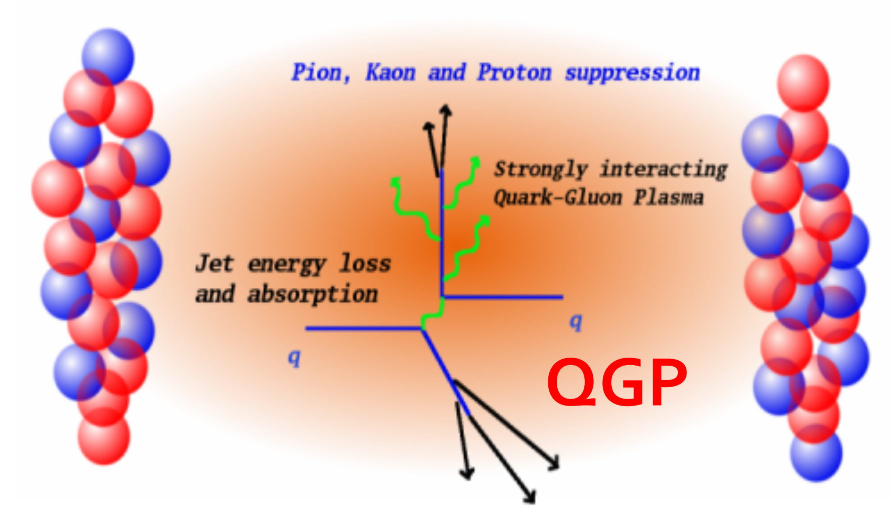


Comparison of EIC to RHIC and LHC jet production

- Medium-induced parton shower modification is evaluated in the rest frame of the medium



ν in the range (5 GeV – 200 GeV)



p_T / E_T in the range (5 GeV – 200 GeV)

- EIC will cover jet energy ranges where the bulk of the jet quenching phenomena are at RHIC and LHC