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Effective theory of heavy flavor production in heavy ion collision

INSTITUTE for NUCLEAR THEORY

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Los Alamos NATIONAL LABORATORY EST. 1943

Outline of the talk

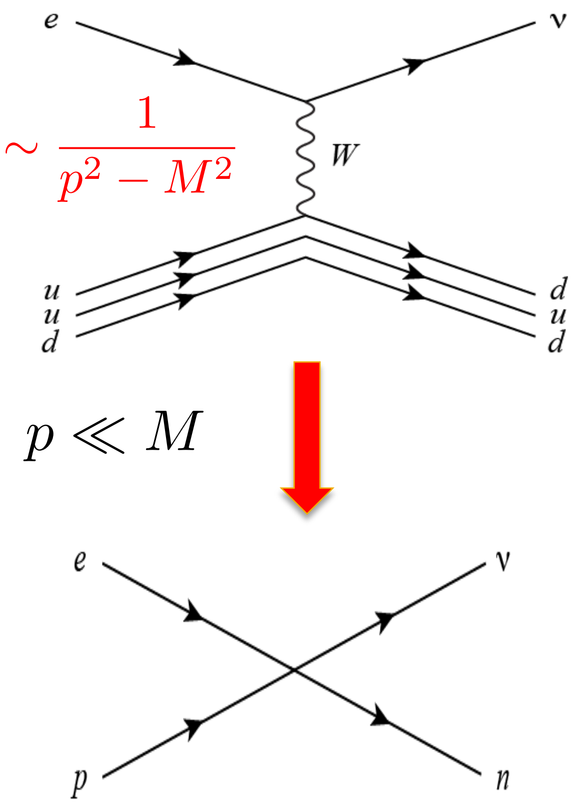
- A brief introduction to effective field theories (EFTs)
- An effective theory for open heavy flavor $SCET_{M,G}$ phenomenological applications
- An effective theory of qaurkonia in matter – $NRQCD_G$ Connection to quarkonium dissociation in matter and existing phenomenology
- Conclusions

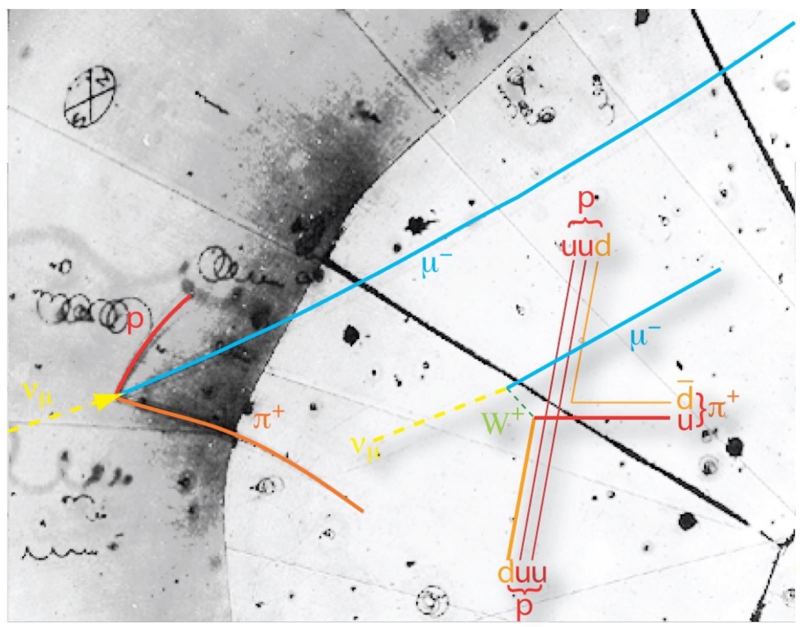
Thanks for the invitation!

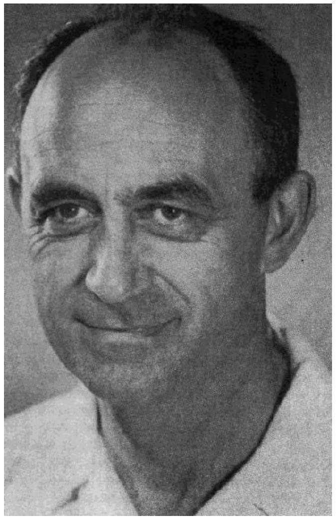
Introduction

The Fermi interaction

- The first, probably best known, effective theory is the Fermi interaction



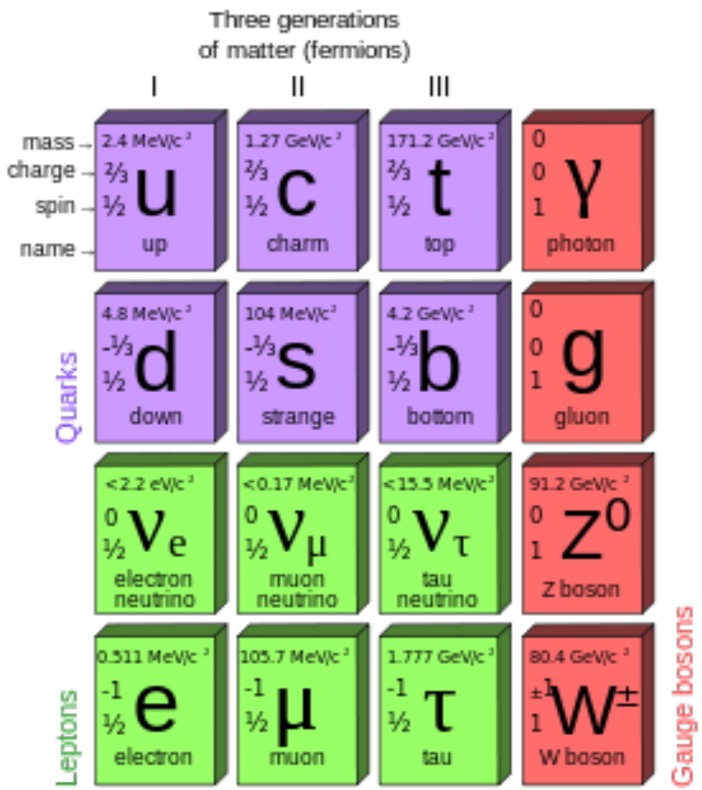




E. Fermi
(Nobel Prize)

- First direct observation of the neutrino, Nov. 1970

Effective field theories

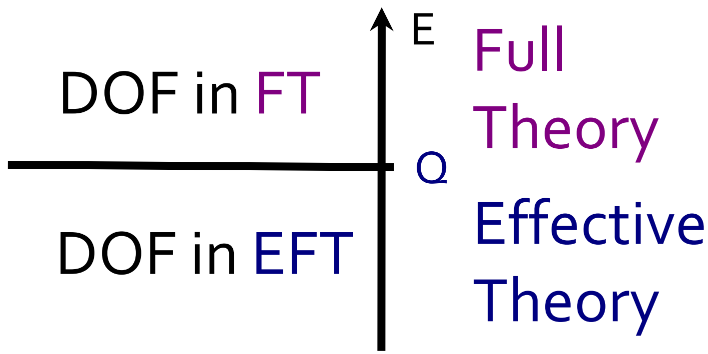


- Powerful framework based on exploiting symmetries and controlled expansions for problems with a natural separation of energy/momentum or distance scales.

- Particularly well suited to QCD and nuclear physics

- Effective theories are ubiquitous. The Standard Model is likely a low energy EFT of a theory at a much higher scale

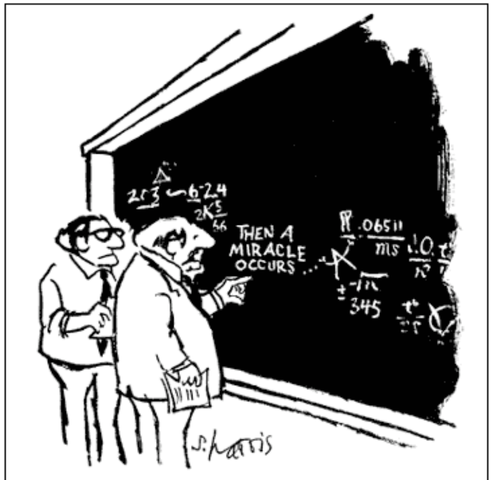
Examples of effective field theories [EFTs]



- Focus on the significant degrees of freedom [DOF]. Manifest power counting

	Q	power counting	DOF in FT	DOF in EFT
Chiral Perturbation Theory (ChPT)	Λ_{QCD}	p/Λ_{QCD}	q, g	K,π
Heavy Quark Effective Theory (HQET)	m_b	Λ_{QCD}/m_b	ψ,A	h_v, A_s
Soft Collinear Effective Theory (SCET)	Q	$p_\perp/Q$	ψ,A	ξ_n, A_n, A_s
Non-Relativistic QCD (NRQCD)	m_Q	p/m_Q	ψ,A	ψ_Q, A_s, A_{us}

Open heavy flavor



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

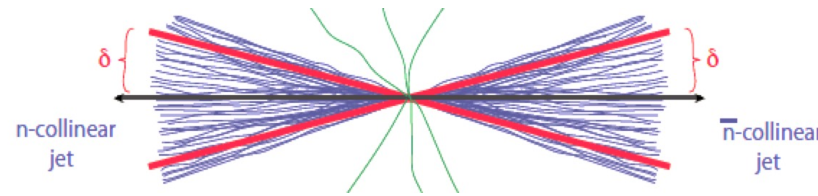
EFT for jets – SCET

- Modes in SCET

C. Bauer et al. (2001)

M. Beneke et al. (2002)

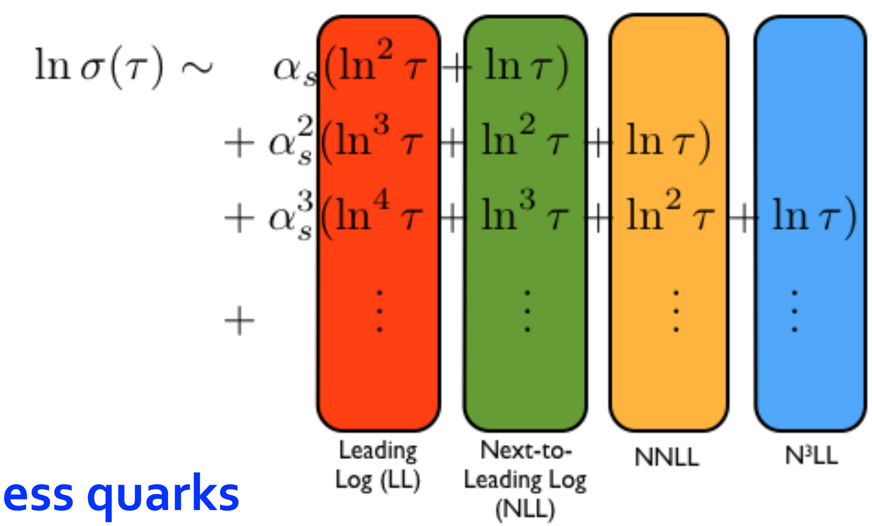
Collinear quarks, antiquarks	$\xi_n,\ \bar{\xi}_n$
Collinear gluons, soft gluons	$A_n,\ A_s$



- Different SCET formulations exist

modes	$p^\mu = (+, -, \perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

- Allows to easily write factorization theorems
- Facilitates the resummation of large logarithms through RG evolution equations



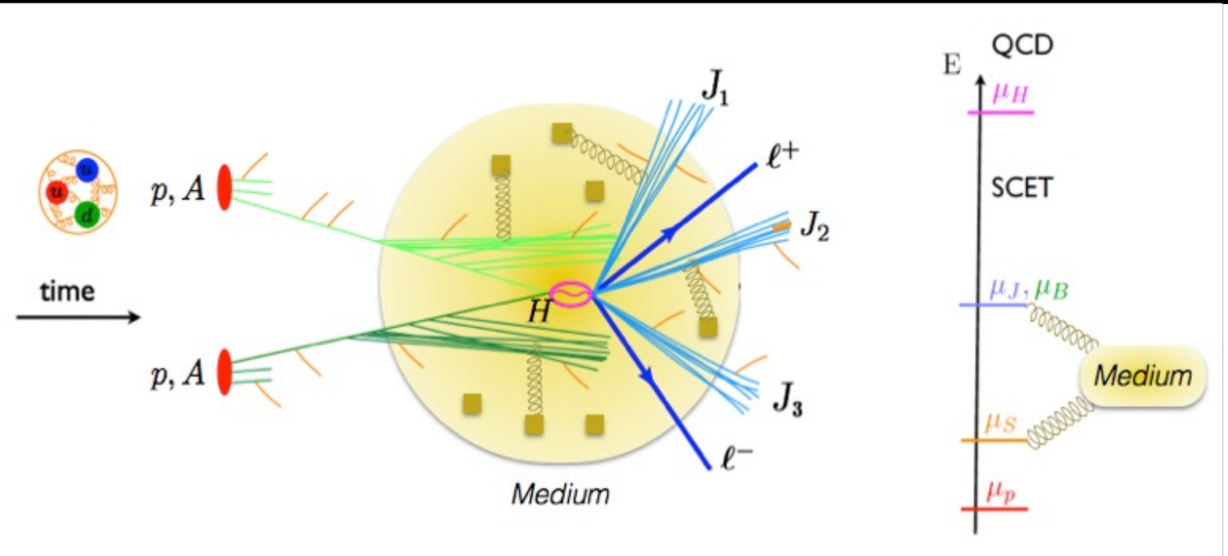
Original formulation of SCET with massless quarks

Example of successful EFT in matter

RHIC (though not the first HI machine) has played a very important role in truly developing a new field – interaction of hard probes in matter

Energy loss approach

- 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)



EFT approach

- Idilbi et al. (2008)

- Factorization, with modified J (jet), B (beam), S (soft) functions

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

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

- Accomplished for light partons. I will discuss how to do it for heavy quarks

Heavy quarks in the vacuum

$\text{SCET}_{M,G}$ – for massive quarks with Glauber gluon interactions

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

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

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

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

The process is not written Q to gQ

Z. Kang et al . (2016)

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

- 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, $(1\text{-}x)^2m^2$, m^2

Heavy quarks splitting functions in the medium

Kinematic variables

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

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

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

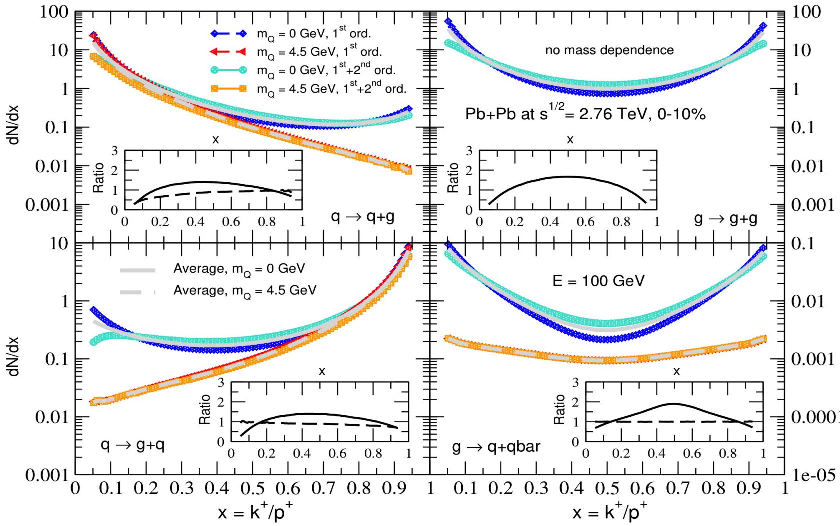
New physics – many-body quantum coherence effects

Z. Kang et al . (2016)

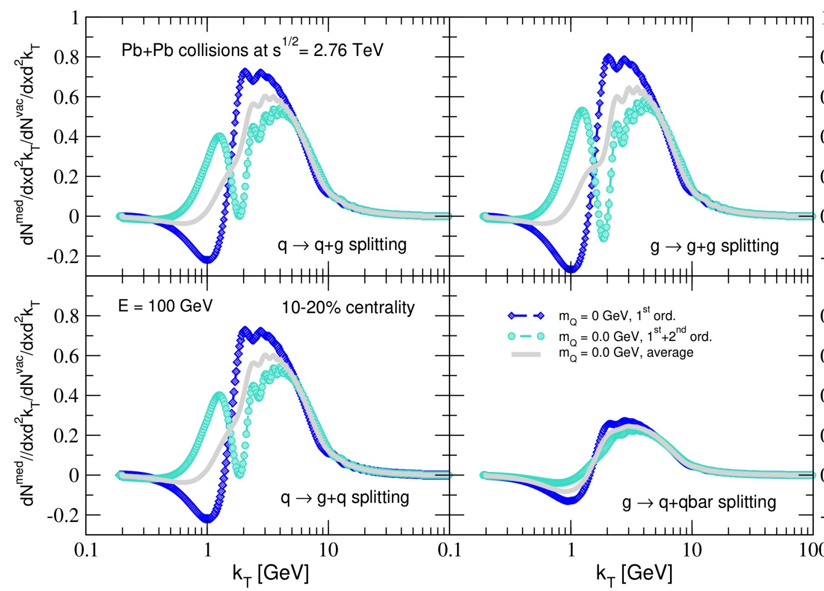
$$\begin{aligned} \left(\frac{dN^{\rm med}}{dx d^2k_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2 q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2 q_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{B_\perp}{B_\perp^2+\nu^2}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

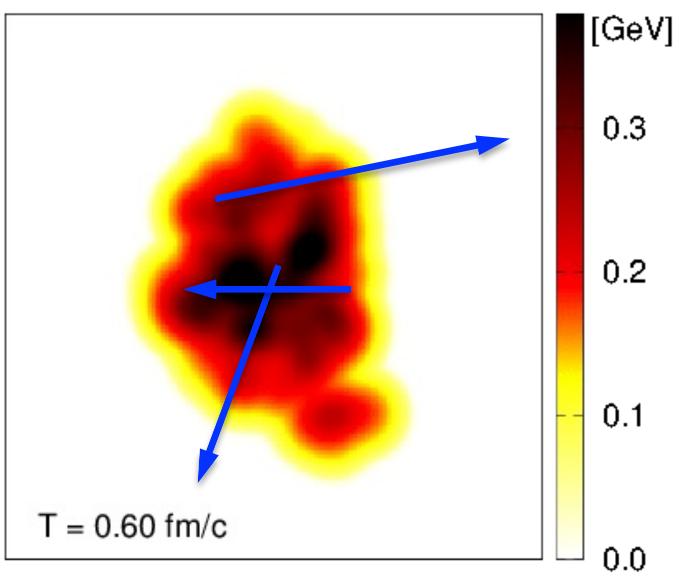
- Full massive in-medium splitting functions now available
- Can be evaluated numerically

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

- Heavy flavor still posed many unresolved questions
- High-P_T stable, low p_T 30-50% more suppression
- Does not fully eliminate the need for collisional interactions / energy loss or dissociation

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

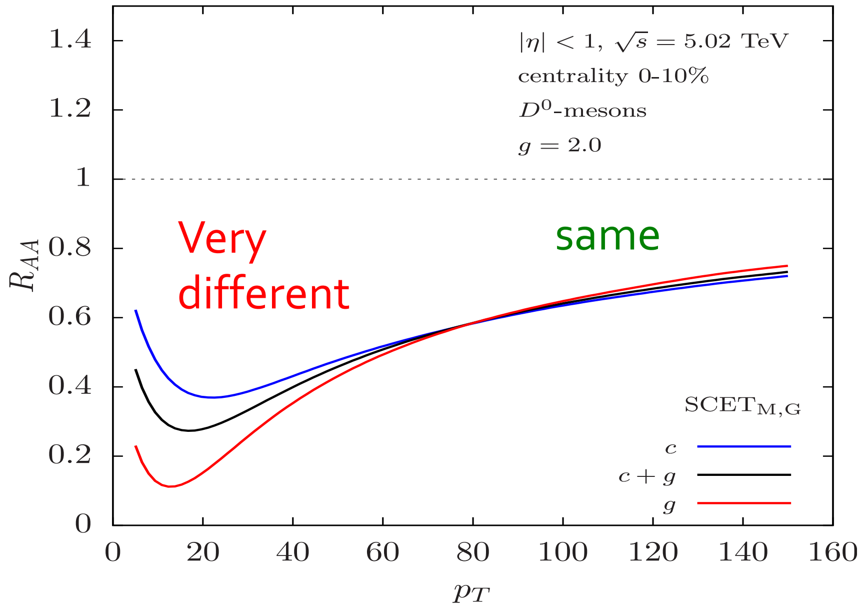
$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}_{i\to jk}^{\rm med} \otimes D_j^H \equiv \hat{\sigma}_i^{(0)} \otimes D_i^{H,{\rm med}}$$

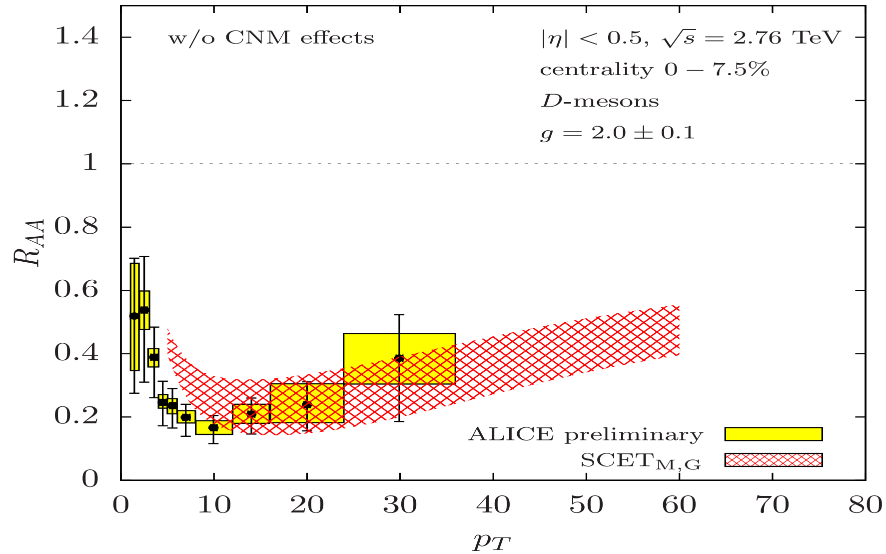
$$D_q^{H,{\rm med}}(z,\mu) = \int_z^1 \frac{dz'}{z'} D_q^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{q\to qg}^{\rm med}(z',\mu) - D_q^H(z,\mu)\int_0^1 dz' \mathcal{P}_{q\to qg}^{\rm med}(z',\mu) + \int_z^1 \frac{dz'}{z'} D_g^H\left(\frac{z}{z'},\mu\right) \mathcal{P}_{q\to gq}^{\rm med}(z',\mu),$$

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

Importance of gluon fragmentation into HF

Kneesch et al . (2008) | Kniehl et al . (2008)

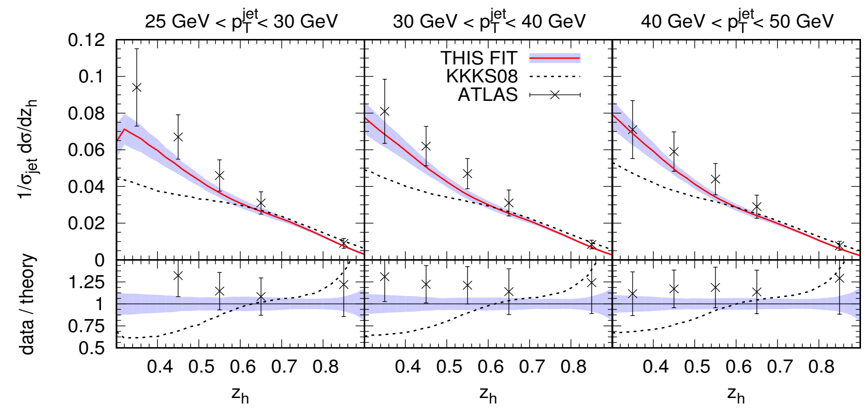


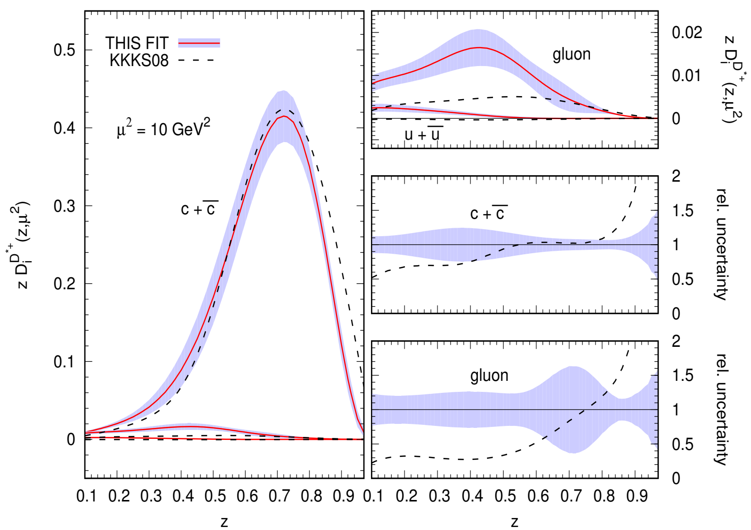


Further constraints on the gluon fragmentation in heavy mesons

- Clearly 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	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]	$25 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 30$	(jet $D^{*\pm}$)	1	5	5.5
	$30 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 40$	(jet $D^{*\pm}$)	1	5	4.1
	$40 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 50$	(jet $D^{*\pm}$)	1	5	2.4
	$50 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 60$	(jet $D^{*\pm}$)	1	5	0.9
	$60 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 70$	(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

D. Anderle *et al.* (2017)

A different set of fragmentation functions

Large systems and applications of in-medium evolution

W. Ke et al. (2022)

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

Heavy flavor specific treatment

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

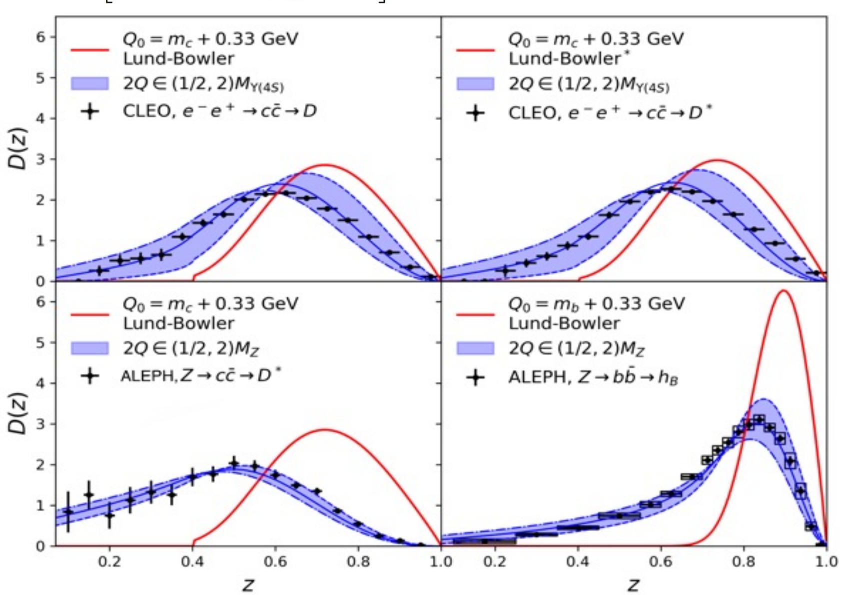
$$d_{HH}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi}C_F c_{HH}(r),$$

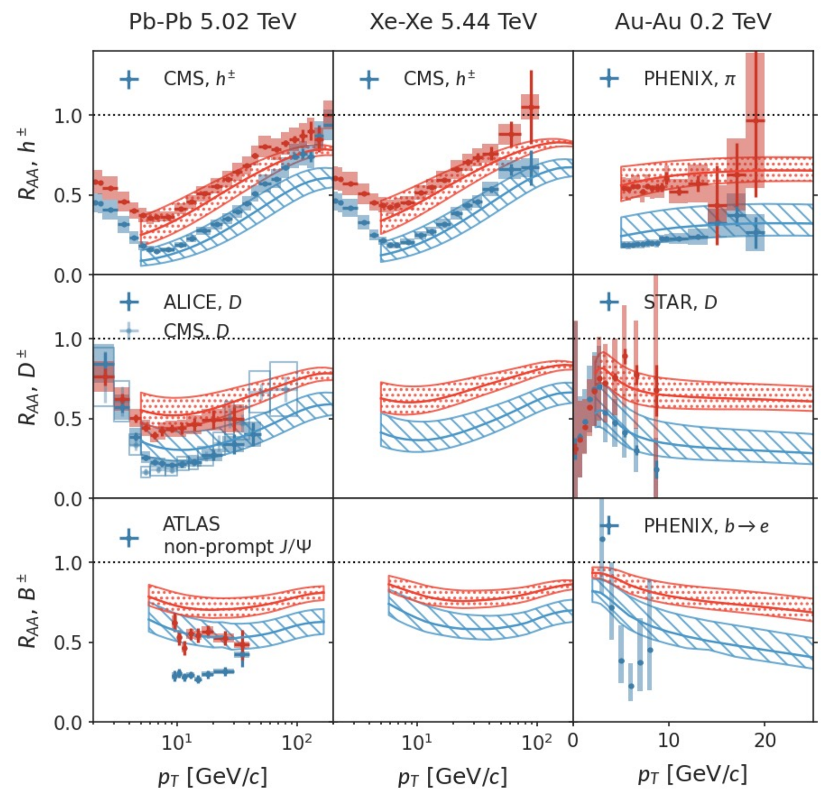
$$d_{gg}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi}\left[\frac{11}{6}N_c - N_f T_F\frac{2}{3} + \sum_{H=c,b} T_F c_{gH}(r)\right]$$

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

$$F(x) = -x^4 + \frac{4}{3}x^3 - x^2, \qquad r = M/Q.$$

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



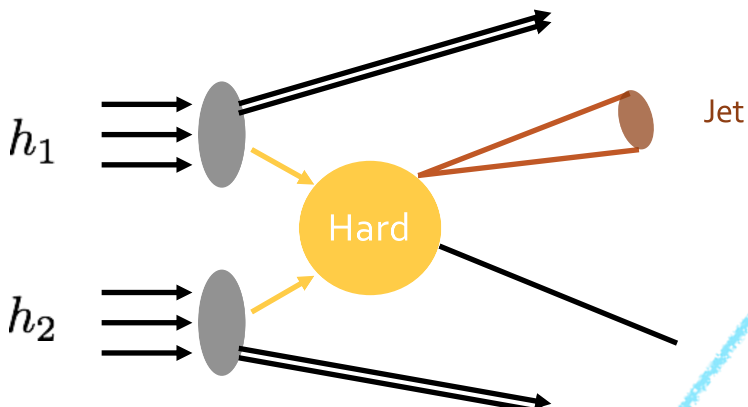


Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions

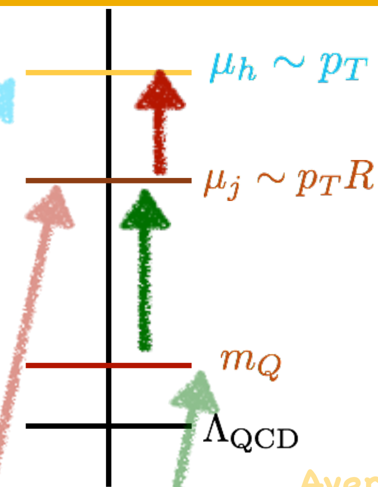
There is tension with the B meson production (or non-prompt J/psi). Combination with the May be dissociation?

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
....

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

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

Hard scattering kernel

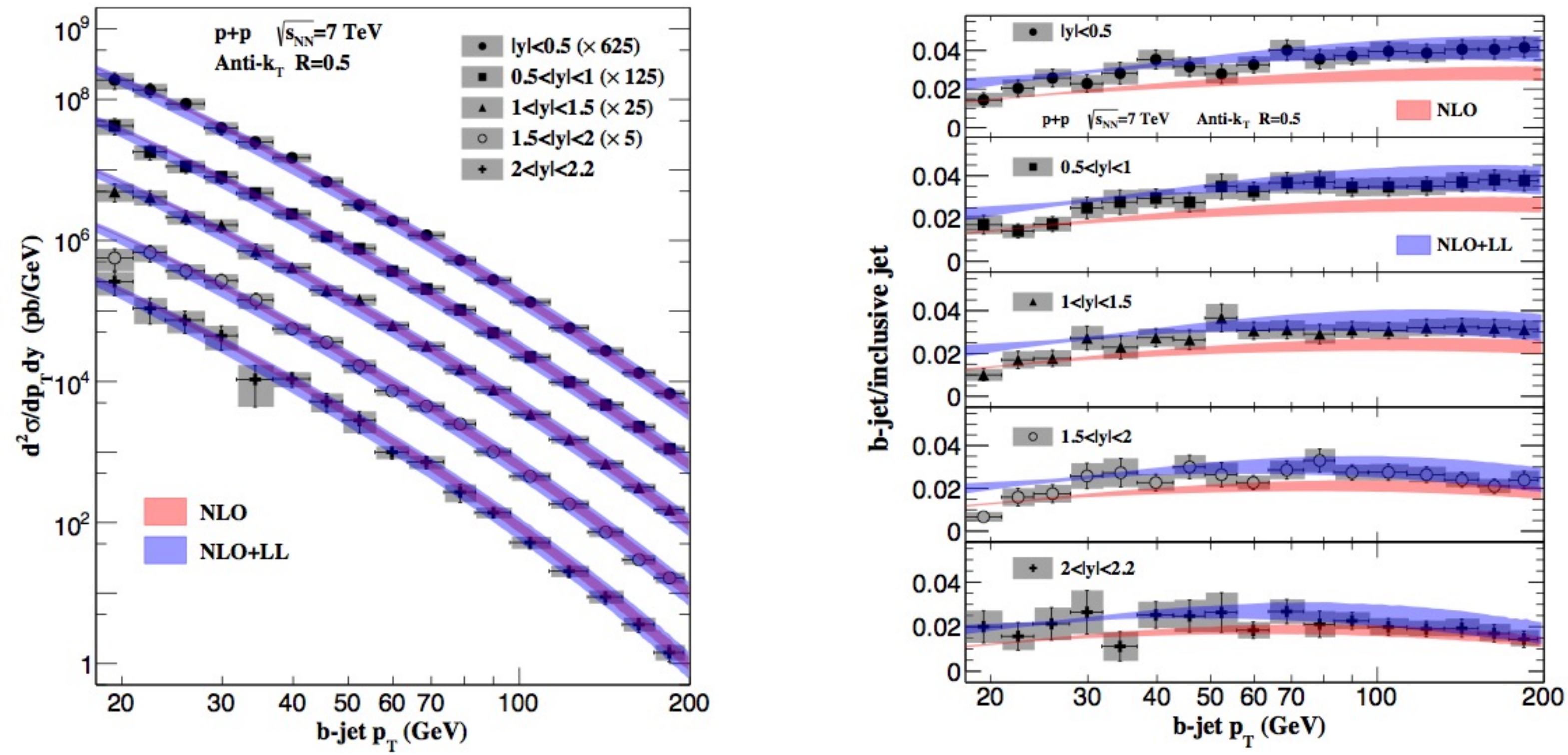
Aversa et al 1989, Jager et al 2002

Semi-inclusive jet function

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

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

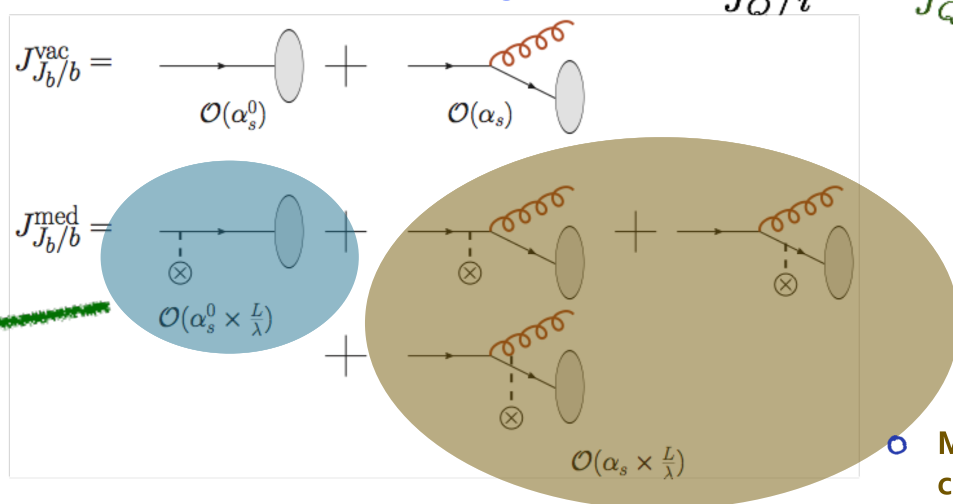
Encodes the effects when the jet evolving in the QCD medium

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

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

Vacuum jet function:

Medium corrections:

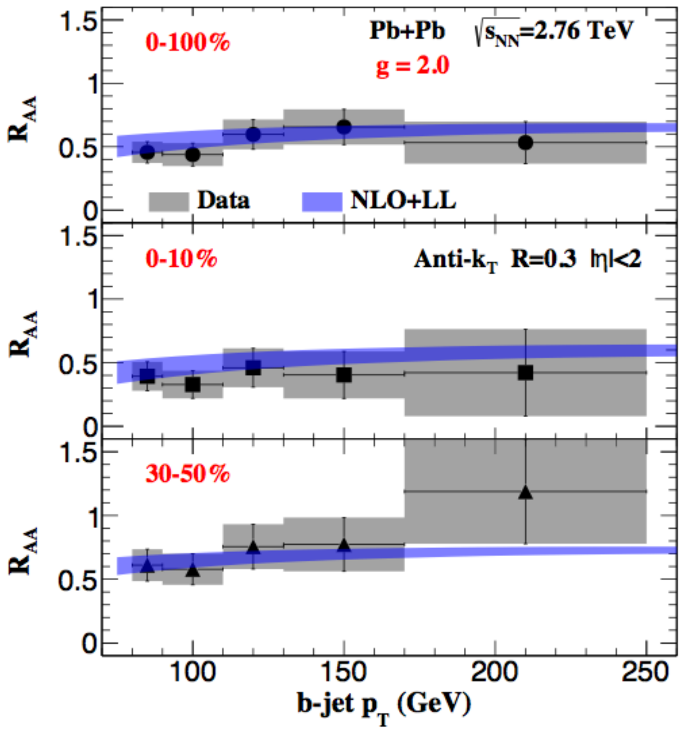


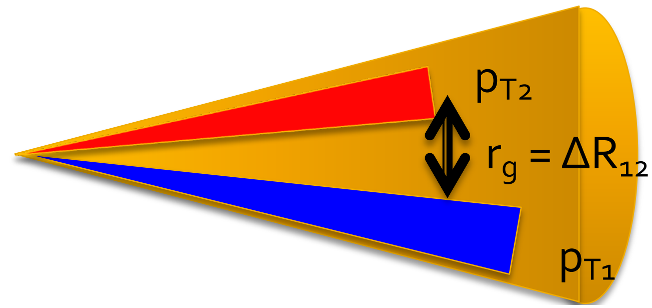
- Medium induced corrections to the LO jet function

- Medium induced corrections to the NLO jet function

B-jet production in A+A collisions

H. Li et al. (2019)

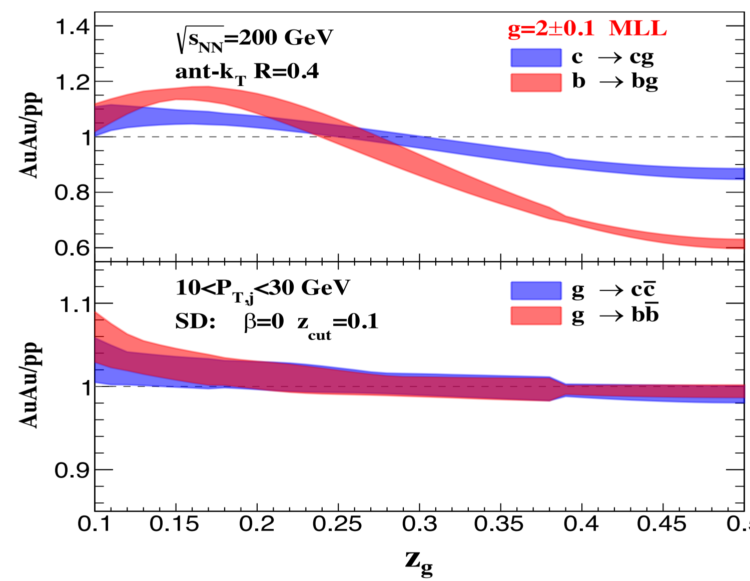




Soft dropped momentum sharing distribution

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

HF jet substructure shows some unique features



- 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 jets at EIC

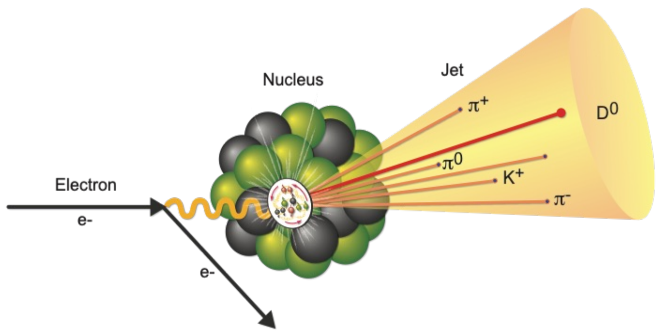
Z. Liu et al. (2021)

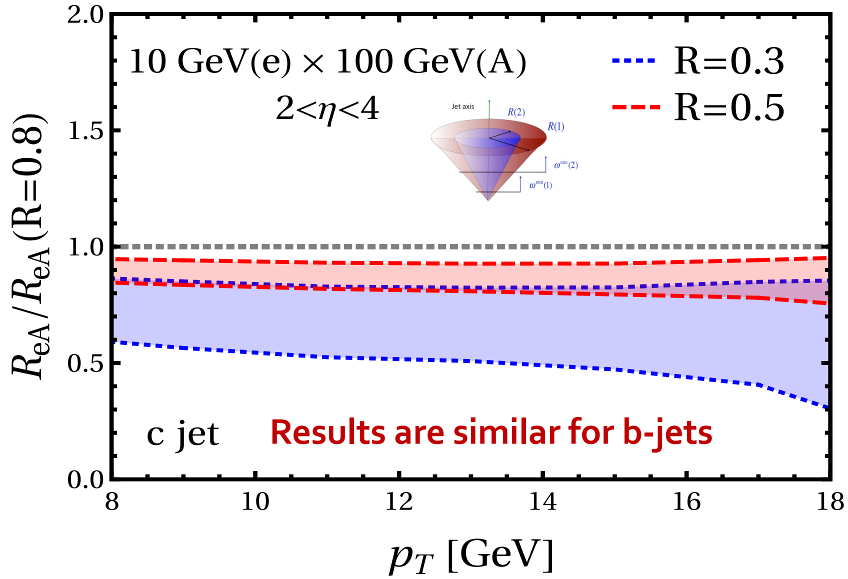
A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

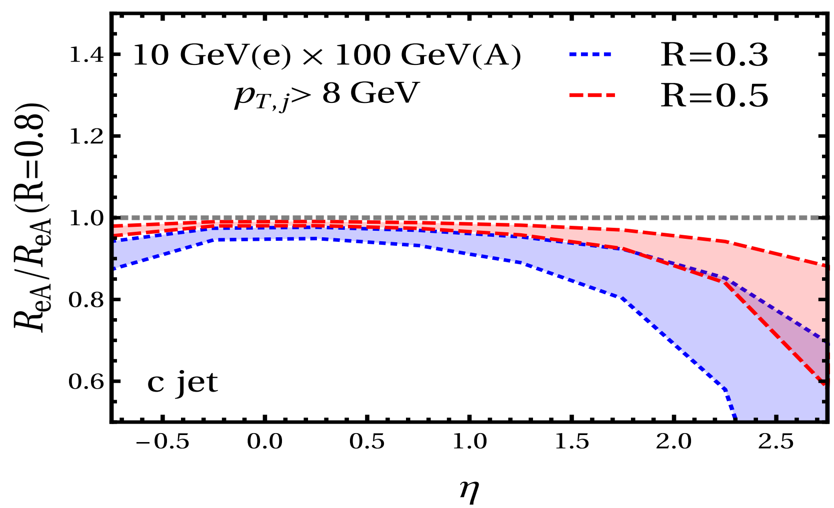
Leveraging the vacuum and in-medium shower differences. Define the ratio of modifications for 2 radii (it is a double ratio)

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

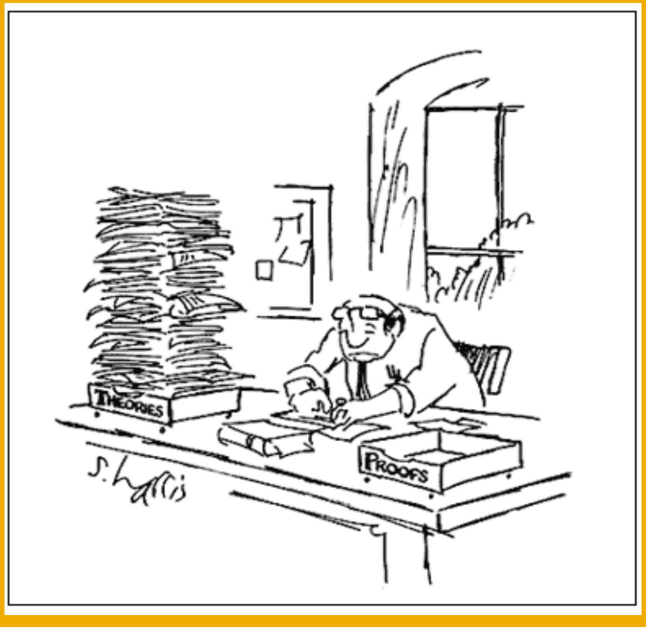
- Effectively eliminates initial-state effects
- Final-state interactions can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)



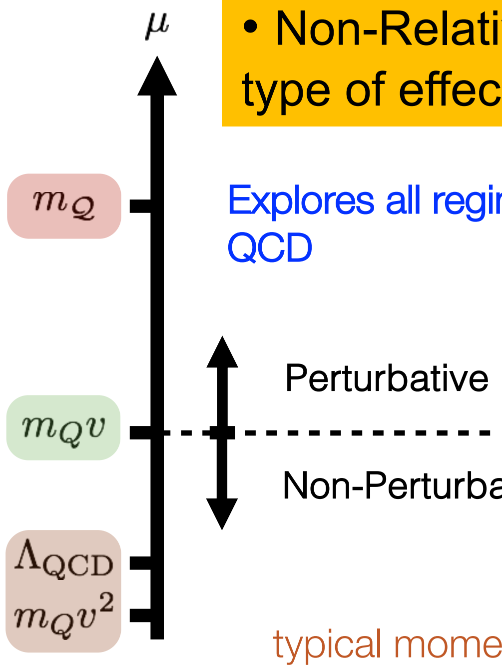




Quarkonia



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

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

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

Ultra-soft

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

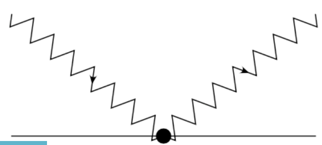
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

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

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO



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

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

pNRQCD — N. Brambilla *et al.* (2000)

vNRQCD — M. Luke *et al.* (2000)

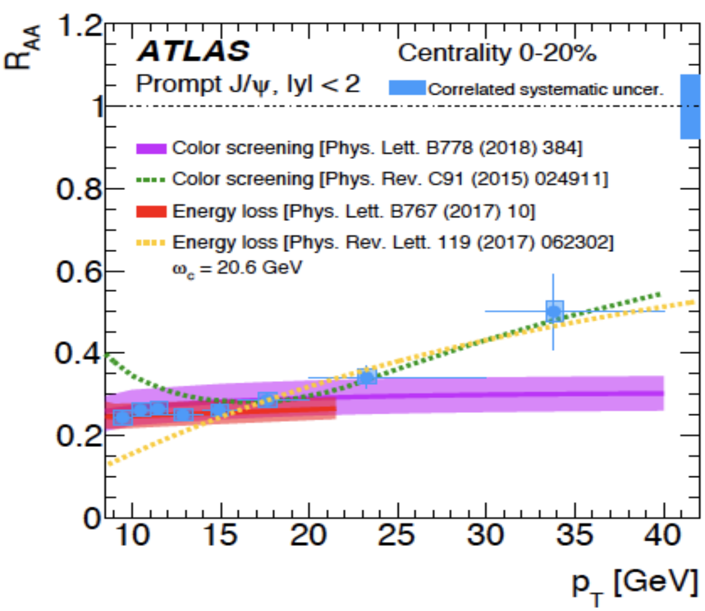
• NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

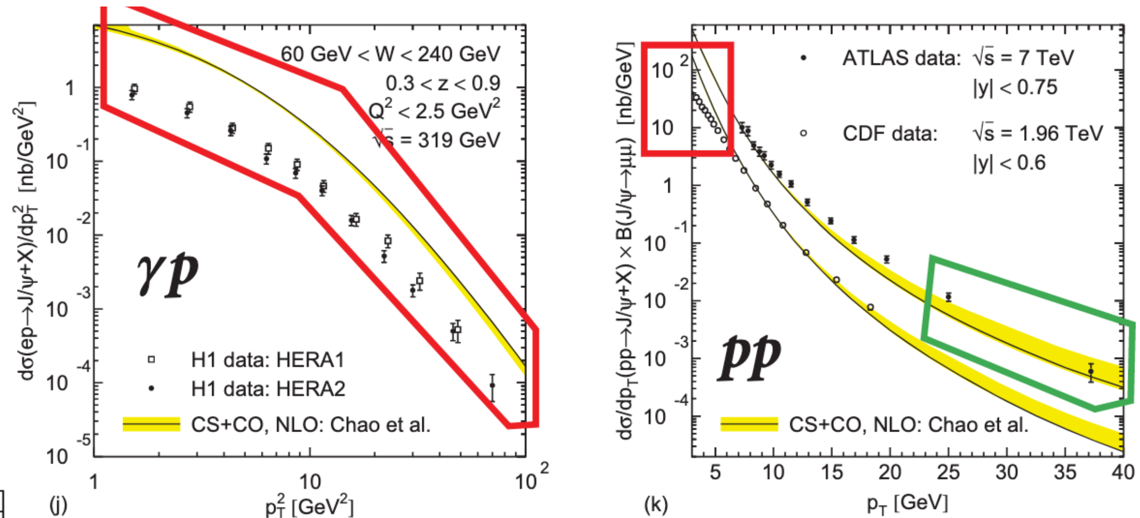
$$d\sigma(a+b\to\mathcal{Q}+X) = \sum_n d\sigma(a+b\to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

Open questions

- Universality of LDMEs – strong tensions remain if one attempts global description

Aabud et al. (2018)





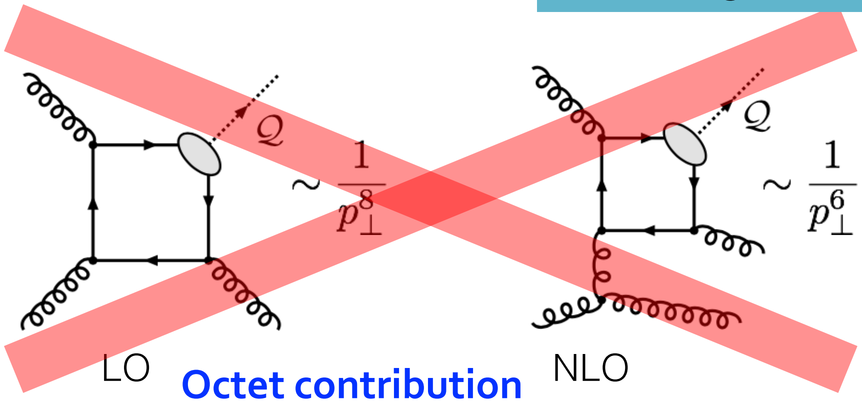
- Suppression puzzle - similar dissociation behavior observed in small system, p+A and even in p+p (where QGP is not expected)
- Various models of quarkonium suppression proposed

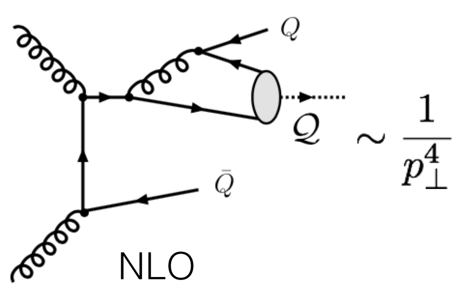
I got interested in the energy loss claims and decided to test them (and also look at more than one state)

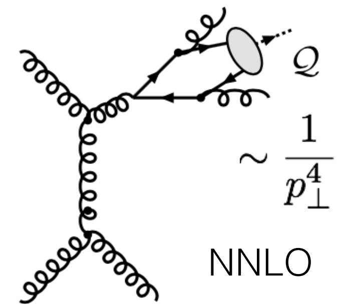
Leading power factorization

Singlet contribution

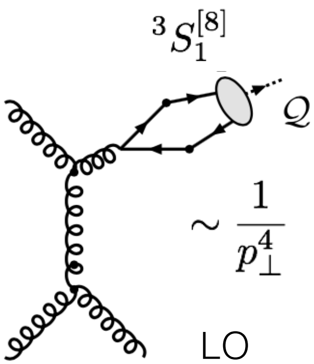
S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)

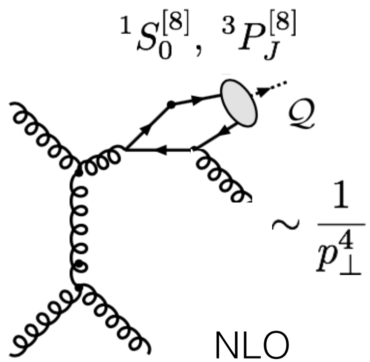




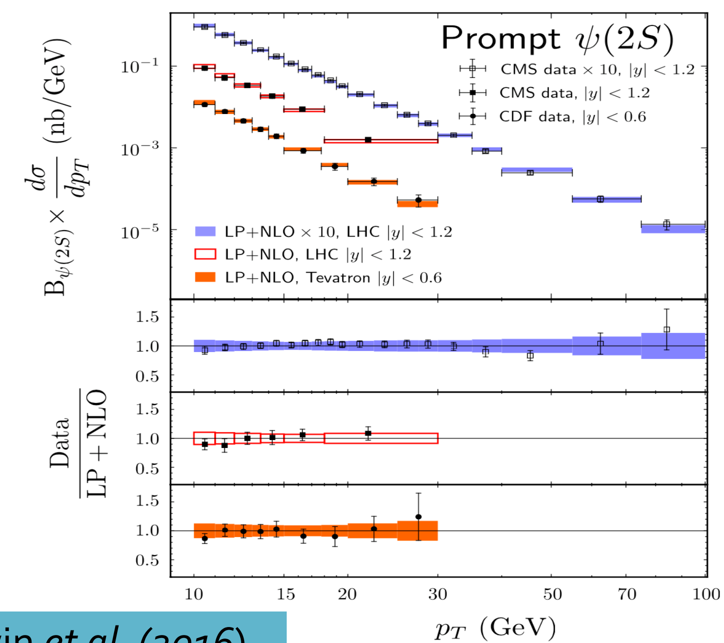


Octet contribution



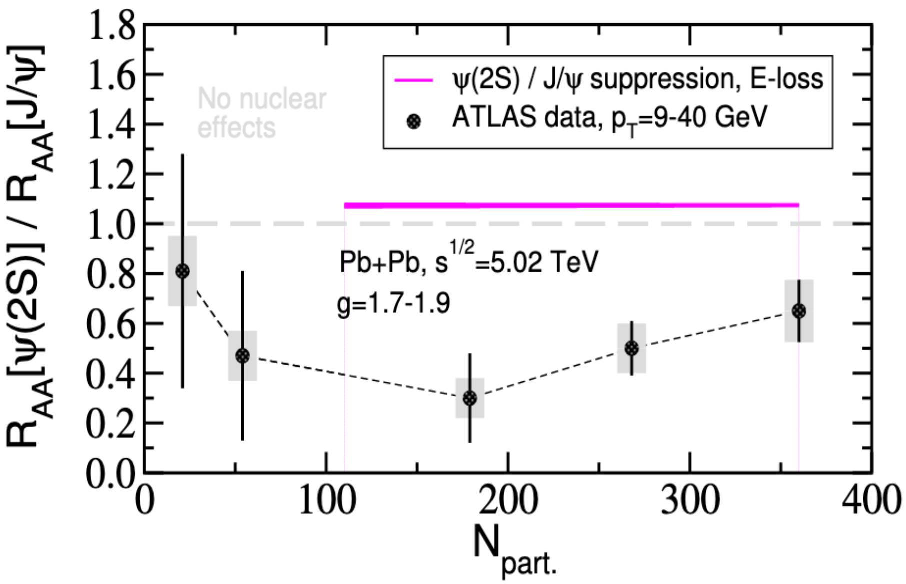


Only a subset of contributions survive, now interpretable as parton fragmentation in quarkonia



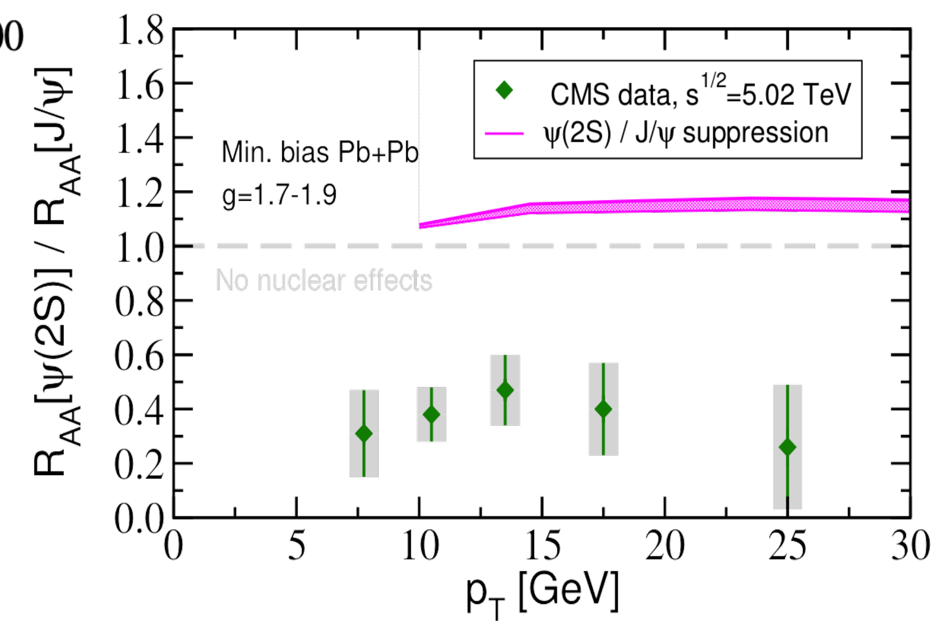
G. Bodwin *et al.* (2016)

Double suppression ratio ψ(2S) / J/ψ



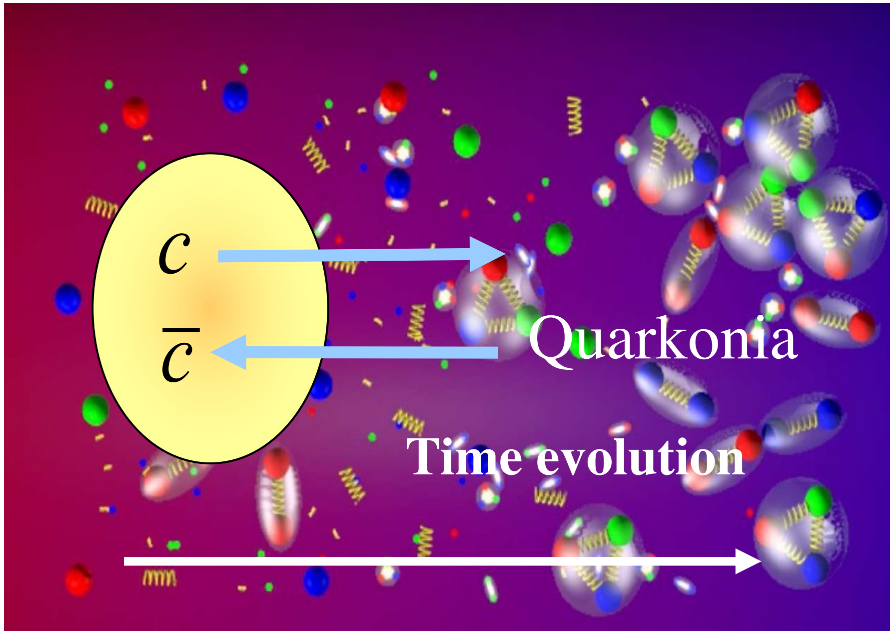
- In the double suppression ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ the discrepancy is not simply in magnitude. There is a discrepancy in the sign of prediction

Y. Makris et al. (2019)



The energy loss picture of quarkonium suppression in the p_T range measured by ATLAS and CMS (up to 40 GeV) is strongly disfavored

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)

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_p \left|p^\mu A_p^\nu - p^\nu A_p^\mu\right|^2 + \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \left\{ iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m} \right\} \psi_{\mathbf{p}}$$

$$-4\pi\alpha_s \sum_{q,q',\mathbf{p},\mathbf{p}'} \left\{ \frac{1}{q^0}\psi^\dagger_{\mathbf{p}'} \left[A^0_{q'}, A^0_q\right] \psi_{\mathbf{p}} \right.$$

$$\left. + \frac{g^{\nu 0}(q'-p+p')^\mu - g^{\mu 0}(q-p+p')^\nu + g^{\mu\nu}(q-q')^0}{(\mathbf{p}'-\mathbf{p})^2} \psi^\dagger_{\mathbf{p}'} \left[A^\nu_{q'}, A^\mu_q\right] \psi_{\mathbf{p}} \right\}$$

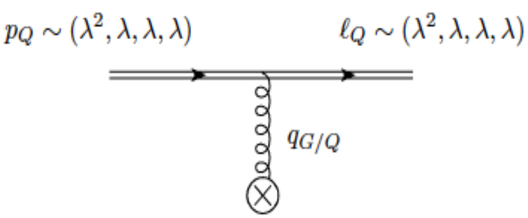
$$+\psi \leftrightarrow \chi,\ T \leftrightarrow \bar{T}$$

$$+\sum_{\mathbf{p},\mathbf{q}} \frac{4\pi\alpha_s}{(\mathbf{p}-\mathbf{q})^2} \psi^\dagger_{\mathbf{q}} T^A \psi_{\mathbf{p}} \chi^\dagger_{-\mathbf{q}} \bar{T}^A \chi_{-\mathbf{p}} + \ldots$$

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

		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)	$q_C \sim$	$(\lambda^2, \lambda^1, \lambda^1, \lambda^1)$	$\sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_\perp)_n$

- 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)

$$\psi(x) \to \sum_{\mathbf{p}} \psi_{\mathbf{p}}(x) \,,$$

$$iD_\mu \to \mathcal{P}_\mu + i\partial_\mu - g(A^\mu_U + A^\mu_{G/C})$$

$$iD_t = \underbrace{i\partial_t - gA^0_U - gA^0_G}_{\sim \lambda^2} \,,$$

$$i\mathbf{D} = \underbrace{\boldsymbol{\mathcal{P}}}_{\sim \lambda} - (\underbrace{i\boldsymbol{\partial} + g\mathbf{A}_U + g\mathbf{n}A^{\mathbf{n}}_G}_{\sim \lambda^2}) + \mathcal{O}(\lambda^3) \,,$$

$$\mathbf{E} = \partial_t(\mathbf{A}_U + \mathbf{A}_G) + (\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}})(A^0_U + A^0_G) + gT^c f^{cba}(A^0_U + A^0_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a$$
$$= \underbrace{i\boldsymbol{\mathcal{P}}_\perp A^0_G}_{\sim \lambda^3} + \mathcal{O}(\lambda^4) \,,$$

$$\mathbf{B} = -(\boldsymbol{\partial} + i\boldsymbol{\mathcal{P}}) \times (\mathbf{A}_U + \mathbf{A}_G) + \frac{g}{2}T^c f^{cba}(\mathbf{A}_U + \mathbf{A}_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a$$
$$= -\underbrace{(i\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})\, A^{\mathbf{n}}_G}_{\sim \lambda^3} + \mathcal{O}(\lambda^4) \,.$$

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

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

Sub-leading medium corrections

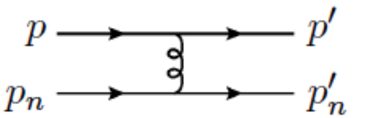
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_G) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\Big[(\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})A^{\mathbf{n}}_G\Big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}}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

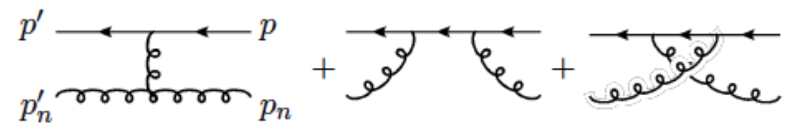
$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = 0 \quad (static)$$

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

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

$$A_G^{\mu,a} = \frac{n^\mu}{\mathbf{q}_T^2}\sum_\ell \bar{\xi}_{n,\ell-\mathbf{q}_T}\frac{\bar{\not n}}{2}(gT^a)\xi_{n,\ell}$$

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

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

Coulomb field for soft source

Y. Makris et al. (2019)

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

- 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

$$P_{f\leftarrow i}(\chi\mu_D^2\xi,T) = \left|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\right|^2$$

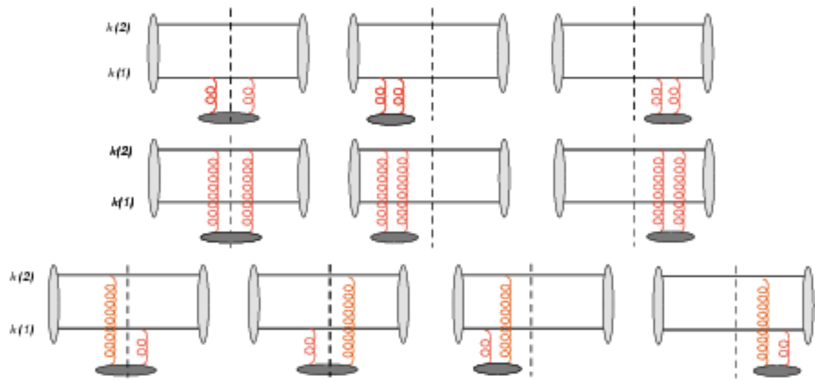
$$= \left|\frac{1}{2(2\pi)^3}\int dx\;\mathrm{Norm}_f\mathrm{Norm}_i\,\pi\,e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$

$$\left.\times\frac{2[x(1-x)\Lambda(T)^2][\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2]+[\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}\right|^2.$$

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

$$\psi(2S):\quad \mathrm{Br}\left[\psi(2S)\to J/\psi+X\right]=61.4\pm0.6\%$$

$$\chi_{c1}:\quad \mathrm{Br}\left[\chi_{c1}\to J/\psi+\gamma\right]=34.3\pm1.0\%$$

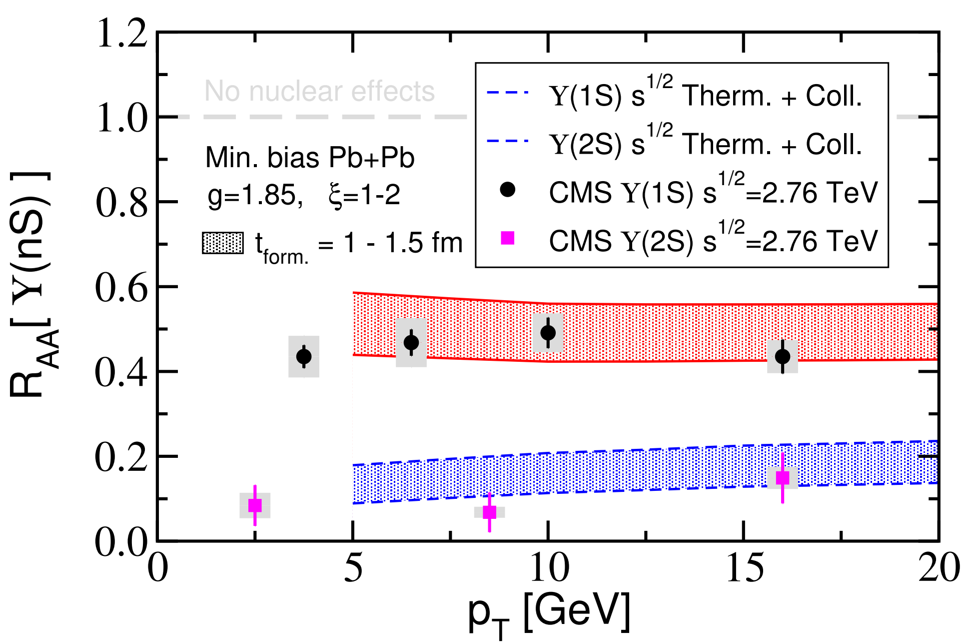
$$\chi_{c2}:\quad \mathrm{Br}\left[\chi_{c2}\to J/\psi+\gamma\right]=19.0\pm0.5\%$$

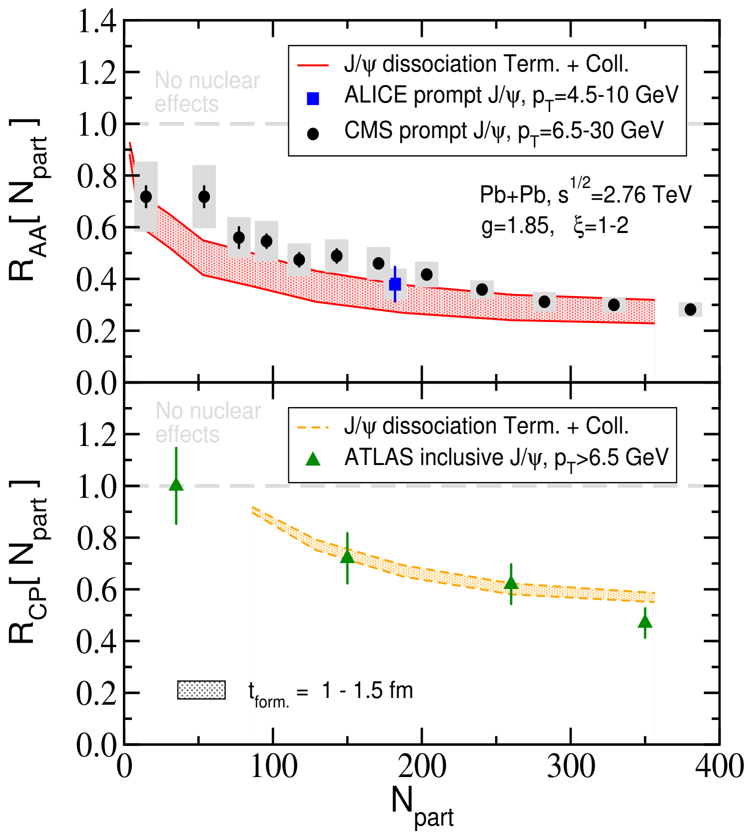
S. Aronson *et al.* (2017)

Centrality and p_T dependence

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

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



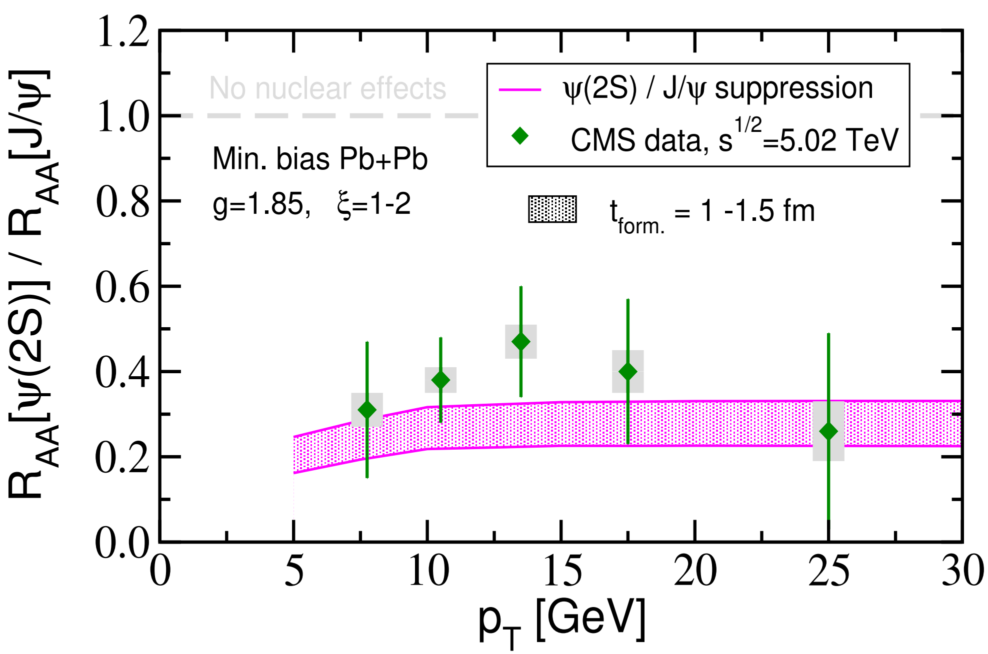


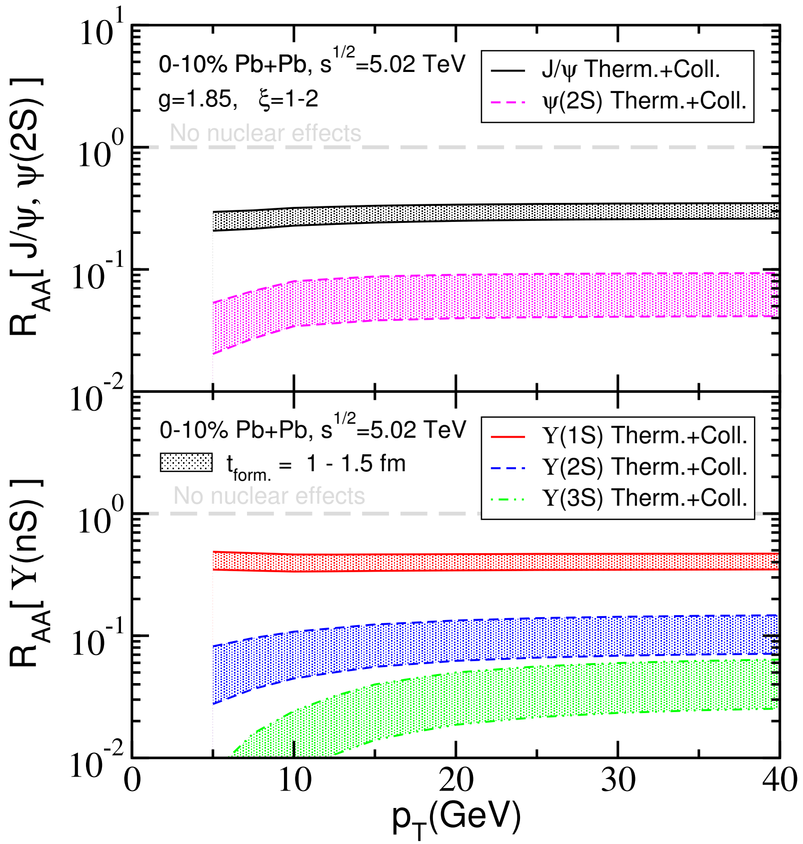
S. Aronson *et al.* (2017)

Uncertainties are related to the onset of the interactions

Min bias and excited to ground state ratios

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





S. Aronson *et al.* (2017)

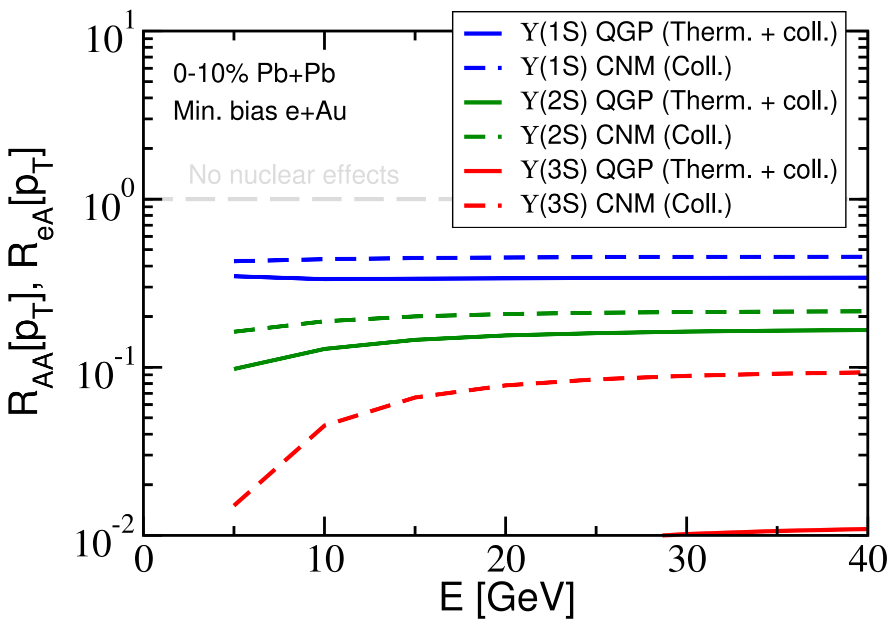
We wee differences in suppression of Upsilon(2S) and Upsilon(3S). Latest measurements don't seem to see that (quite puzzling)

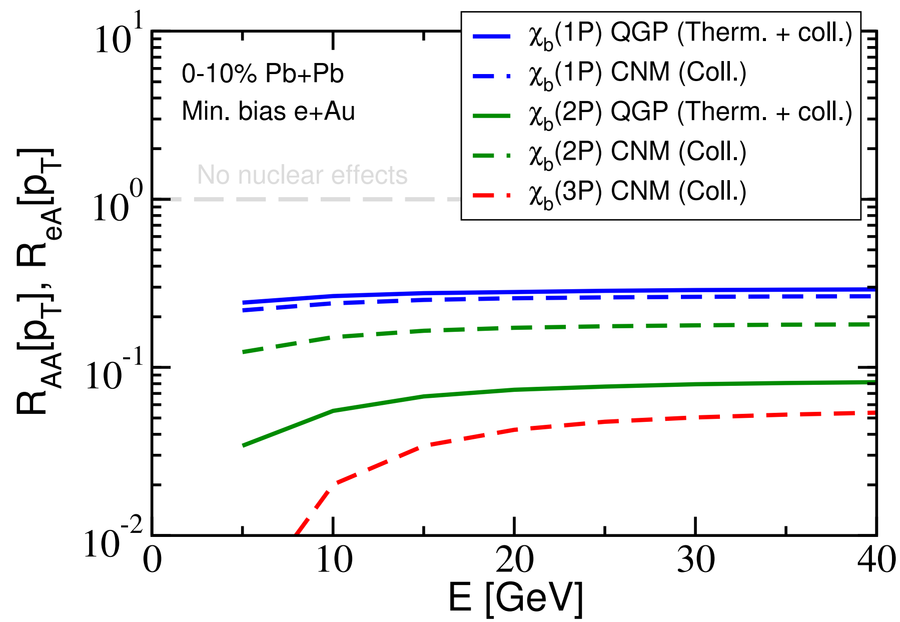
- Good separation the suppression of the ground and excited

Comparison results for bottomonia

- 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

- Effective theories of QCD have enabled important conceptual and technical breakthroughs in our understanding of strong interactions and very significant improvement in the accuracy of the theoretical predictions

- Theories have been generalized to nuclear matter. They are general and applicable to both hot (QGP) and cold (large nucleus) nuclear matter.

- We constructed and EFT for heavy quark propagation in matter – $SCET_{M,G}$ Introduced higher order and resumed calculations. Found significant dependence of heavy meson quenching on fragmentation functions. Generalized the semi-inclusive jet function techniques to HF. HF jet substructure shows interesting features (vs light)

- We have also constructed an effective theory of quarkonia in matter - $NRQCD_{G.}$ Derived the Feynman rules (3 different ways) to leading and subleading power for different sources of interactions in the medium. We showed the connection to existing quarkonium dissociation phenomenology. Promising results for the EIC

- More EFTs for nuclear physics on the way (for example for lepton nucleus scattering, neutrino physics)