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Effective theories of open heavy flavor and quarkonium production in heavy ion collisions

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Introduction

- Heavy flavor, both open and quarkonia, is an important probe of all forms of nuclear matter QGP, strong gluon fields, etc

C. Bauer et al. (2001)

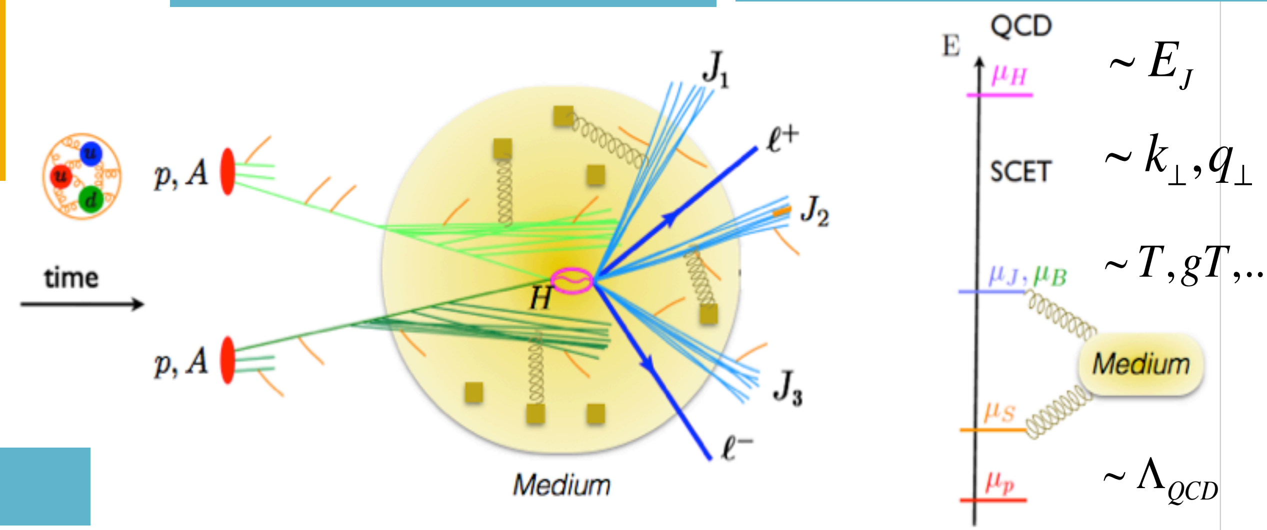
D. Pirjol et al. (2004)

- On the example of SCET: Factorization, with modified J, B, S

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

A. Idilbi et al. (2008)

G. Ovanesyan et al. (2011)



- What is missing in the SCET Lagrangian is the interaction between the jet and the medium. Background field approach

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

Heavy quarks in the vacuum and the medium

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

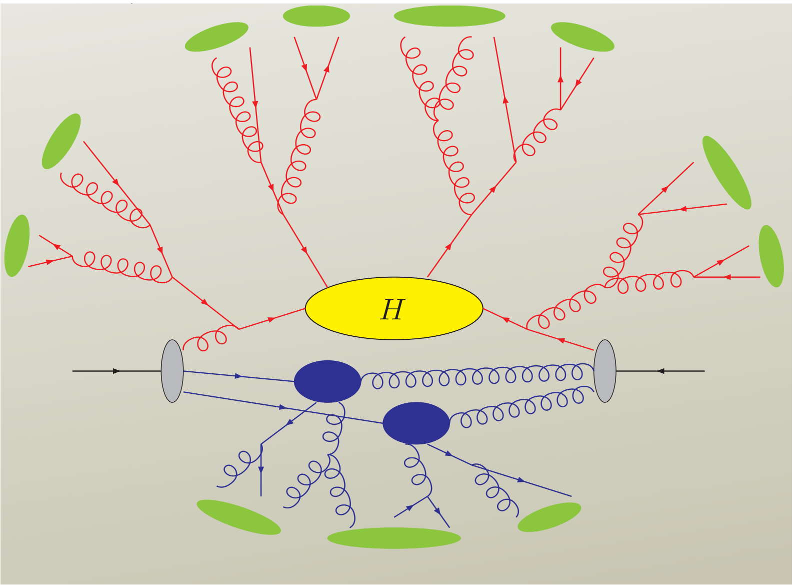
$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^\mu = \partial^\mu + gA^\mu \qquad A^\mu = A^\mu_c + A^\mu_s + A^\mu_G$$

A. Leibovich et al. (2003)

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

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

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



G. Altarelli et al. (1977)

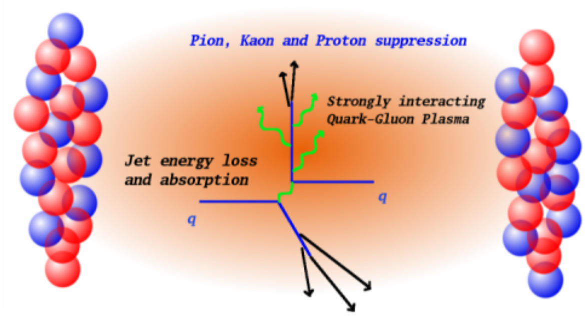
$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2}\frac{1}{k_\perp^2 + m^2}\left[x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_\perp^2+m^2}\right]$$

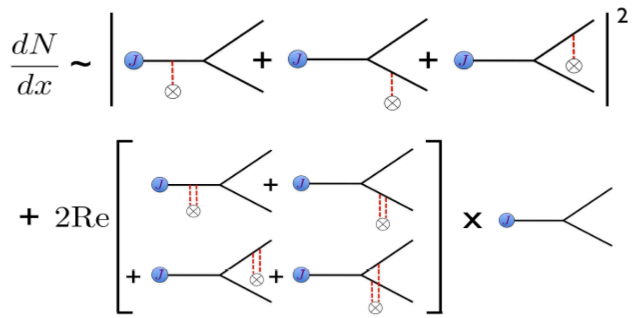
$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2}\frac{1}{k_\perp^2 + x^2 m^2}\left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2+x^2m^2}\right]$$

F. Ringer et al . (2016)

- You see the dead cone effects
- You also see that it depends on the process – it not simply x^2m^2 everywhere: x^2m^2, $(1\text{-}x)^2m^2$, m^2

Main results: in-medium splitting & parton energy loss





- Organizing principle – build powers of the scattering cross section in the medium

Representative example

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

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

F. Ringer et al . (2016)

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

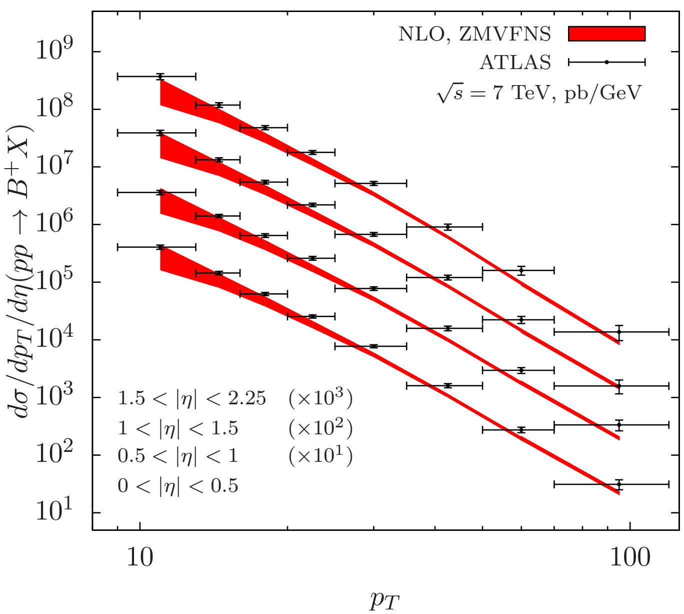
$$
\mathbf{A}_\perp=\mathbf{k}_\perp,\ \mathbf{B}_\perp=\mathbf{k}_\perp+x\mathbf{q}_\perp,\ \mathbf{C}_\perp=\mathbf{k}_\perp-(1-x)\mathbf{q}_\perp,\ \mathbf{D}_\perp=\mathbf{k}_\perp-\mathbf{q}_\perp \qquad \Omega_1-\Omega_2=\frac{\mathbf{B}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \Omega_1-\Omega_3=\frac{\mathbf{C}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \Omega_4=\frac{\mathbf{A}_\perp^2+\nu^2}{p_0^+x(1-x)},
$$

Baseline ZMVFS open heavy flavor at NLO

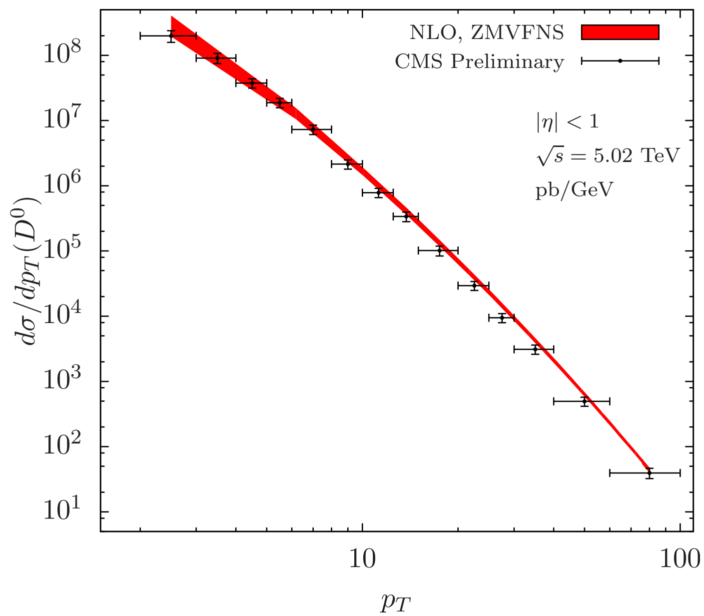
- Typically assumed that only c to D, b to B fragment perturbatively
- Perform an NLO calculation

$$\frac{d\sigma^H_{pp}}{dp_T d\eta} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu) \times \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}^c_{ab}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz} D_c^H(z_c,\mu),$$

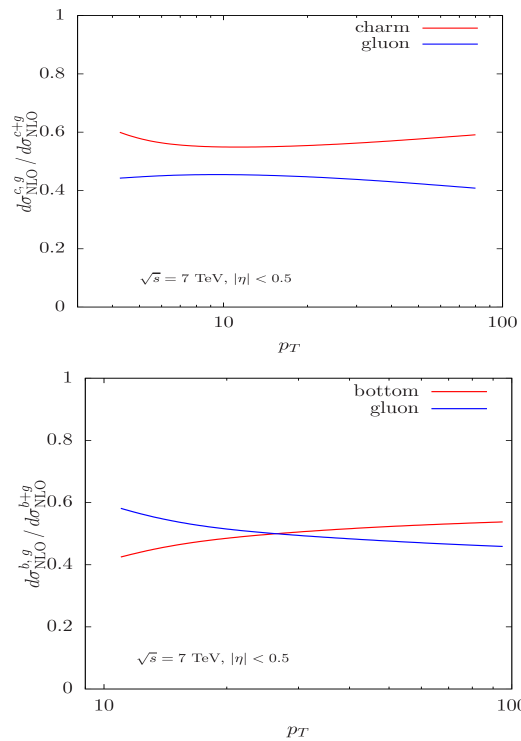
B. Jager et al . (2002)



Kneesch et al . (2008)



Kniehl et al . (2008)



When $p_T > m_c, m_b$ **Factorization, non-perturbative physics is long distance**

Cross section calculation in the QCD medium

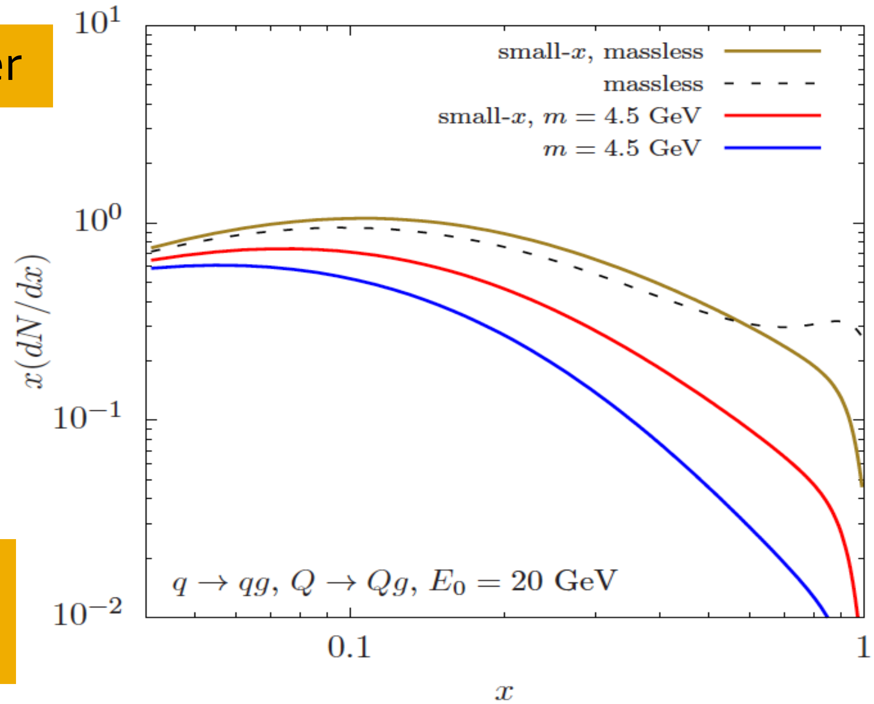
Medium contribution implemented at fixed order

$$d\sigma^{H}_{\text{PbPb}} = d\sigma^{H,\text{NLO}}_{pp} + d\sigma^{H,\text{med}}_{\text{PbPb}}$$

$$\sum_j \hat{\sigma}^{(0)}_i \otimes \mathcal{P}^{\text{med}}_{i\to jk} \otimes D^H_j \equiv \hat{\sigma}^{(0)}_i \otimes D^{H,\text{med}}_i$$

$$\mathcal{P}_{i\to jk}(z,\mu) = \int_{Q_0}^{\mu} dk_\perp \left(\frac{dN}{dz dk_\perp}\right)$$

First step in the DGLAP evolution equations.
Virtual corrections form sum rules



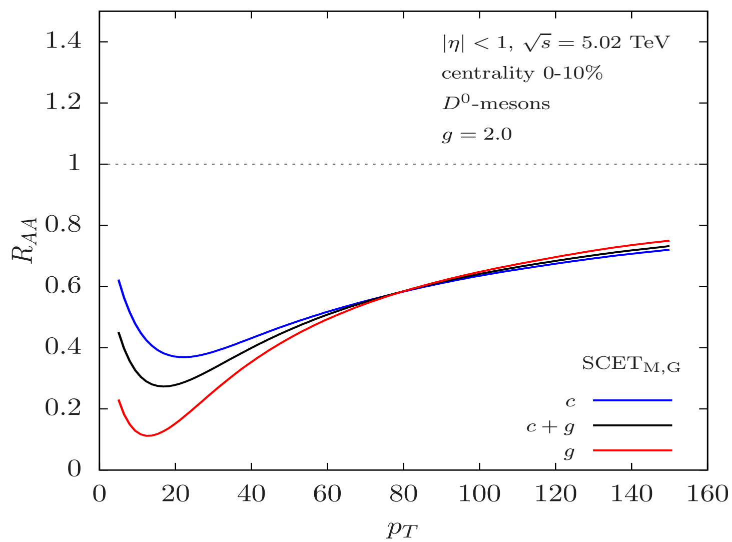
For numerical implementation one can rewrite these expression in the + prescription and finds that the correction is negative

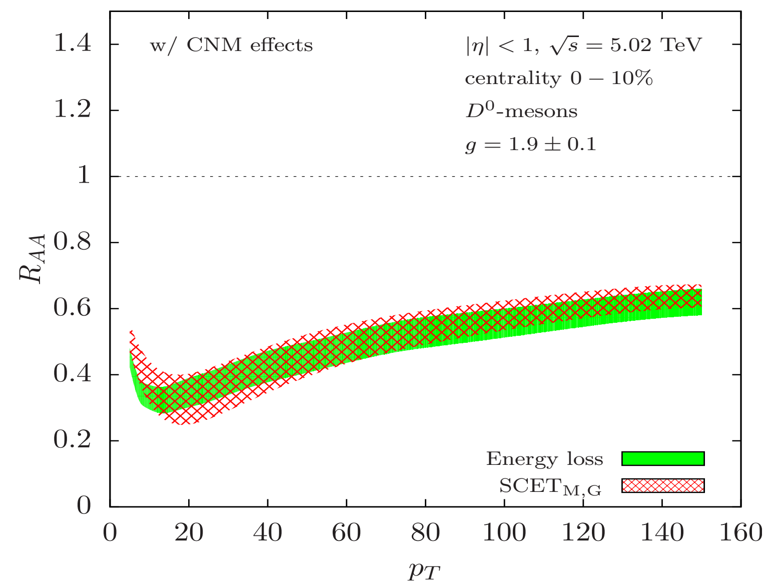
$$D^{H,\text{med}}_q(z,\mu) = \int_z^1 \frac{dz'}{z'} D^H_q\left(\frac{z}{z'},\mu\right)\mathcal{P}^{\text{med}}_{q\to qg}(z',\mu) - D^H_q(z,\mu)\int_0^1 dz' \mathcal{P}^{\text{med}}_{q\to qg}(z',\mu)$$
$$+ \int_z^1 \frac{dz'}{z'} D^H_g\left(\frac{z}{z'},\mu\right)\mathcal{P}^{\text{med}}_{q\to gq}(z',\mu),$$

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

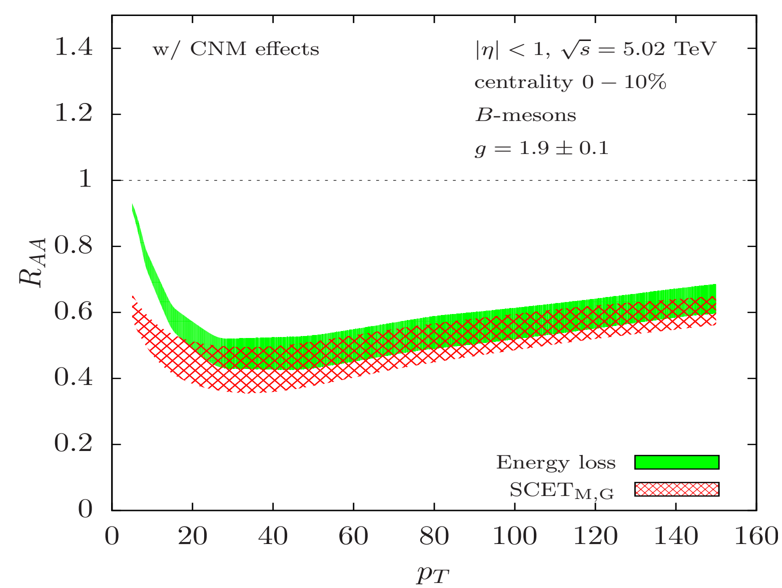
Combined uncertainty – theoretical model + jet-medium coupling

Jet quenching enhancement at intermediate p_T. Consequence of gluon contribution to open heavy flavor

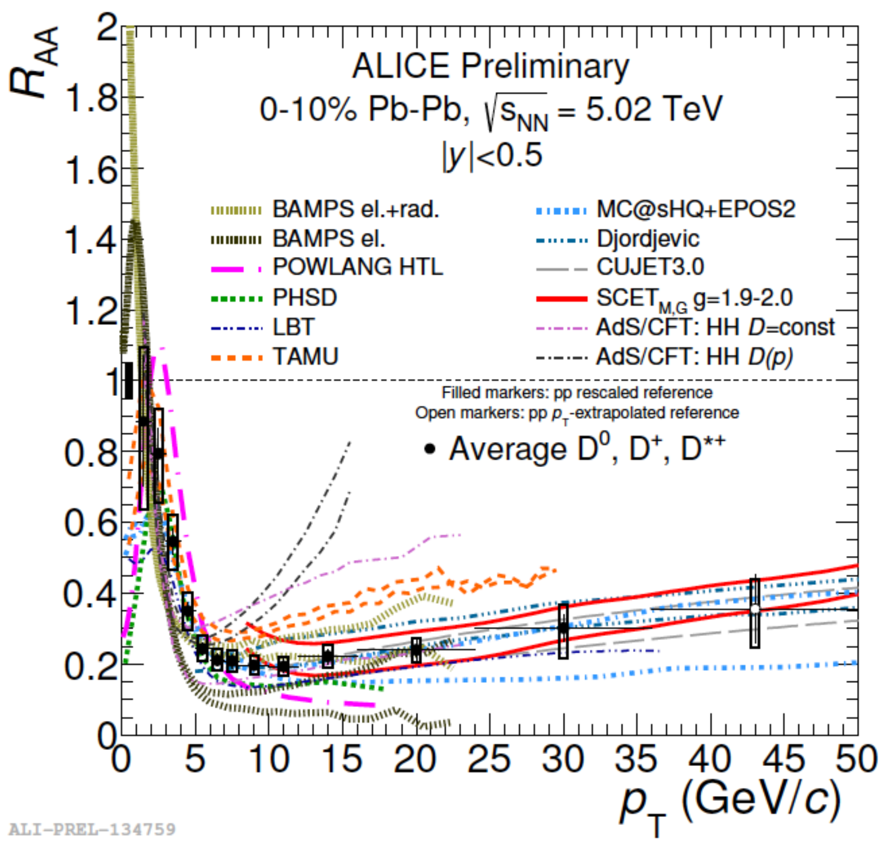


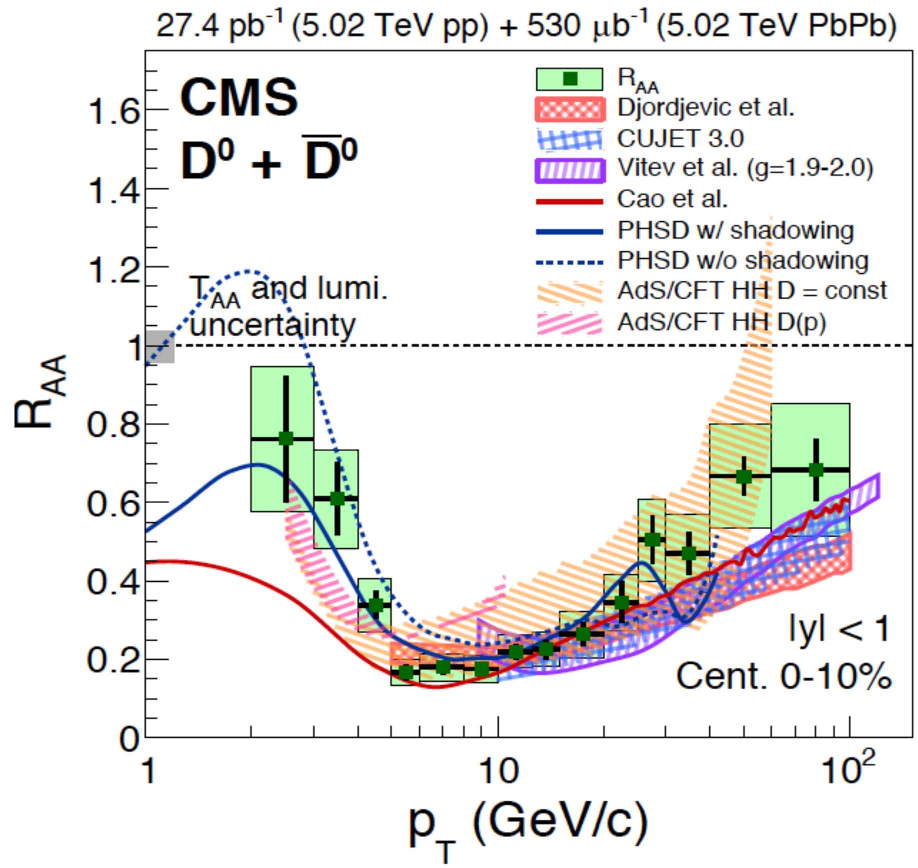


- The pure scale uncertainty largely cancels in the ratio
- At high p_T there is at least 20% combined uncertainty. Did not increase much since gluon fragmentation in H is softer and offsets the difference between quark-gluon energy loss.
- At low P_T the uncertainties can grow to 30% D and 50+% B.



Comparison to experimental data



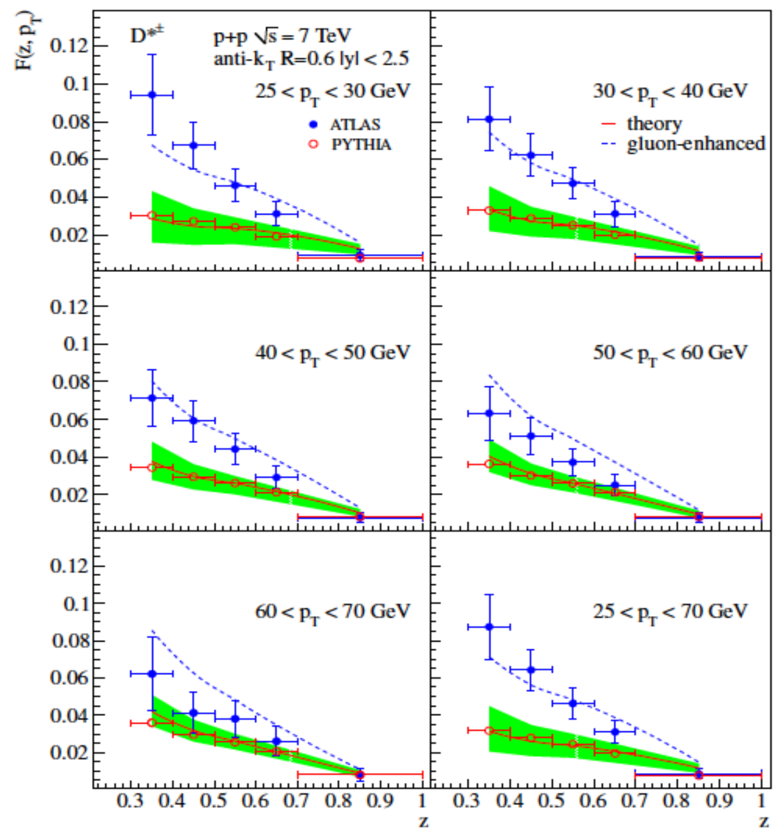


- For D mesons the theoretical framework validated well at high p_T. Below 10 GeV room for some additional effects: collisional energy loss, dissociation. Similar for B, perhaps to slightly larger extent
- There is also a possibility for an even larger gluon contribution

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	$\mathcal{N}_i$	#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]	$25 \leq \frac{p_T^{jet}}{\mathrm{GeV}} \leq 30$	(jet $D^{*\pm}$)	1	5	5.5
	$30 \leq \frac{p_T^{jet}}{\mathrm{GeV}} \leq 40$	(jet $D^{*\pm}$)	1	5	4.1
	$40 \leq \frac{p_T^{jet}}{\mathrm{GeV}} \leq 50$	(jet $D^{*\pm}$)	1	5	2.4
	$50 \leq \frac{p_T^{jet}}{\mathrm{GeV}} \leq 60$	(jet $D^{*\pm}$)	1	5	0.9
	$60 \leq \frac{p_T^{jet}}{\mathrm{GeV}} \leq 70$	(jet $D^{*\pm}$)	1	5	1.6
TOTAL:				96	102.9

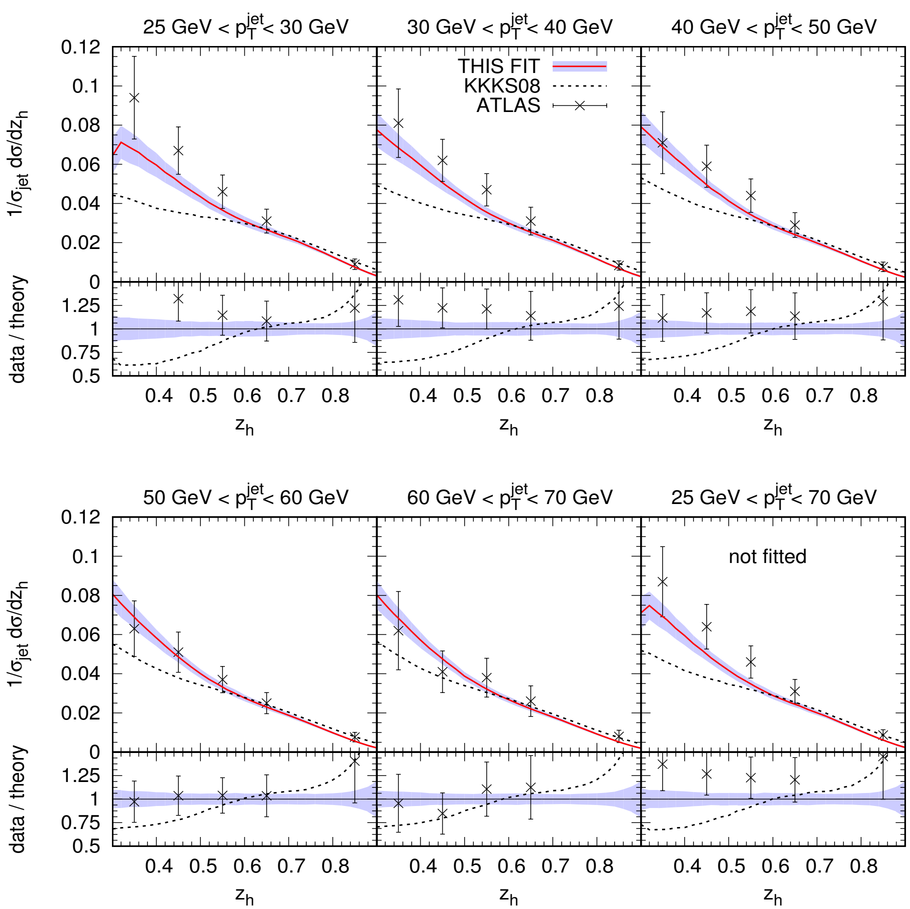


Y. Chien. *et al.* (2016)

Motivation to do global analysis including semi-inclusive annihilation, inclusive hadron production and <u>hadrons in jets</u>

D. Anderle *et al.* (2017)

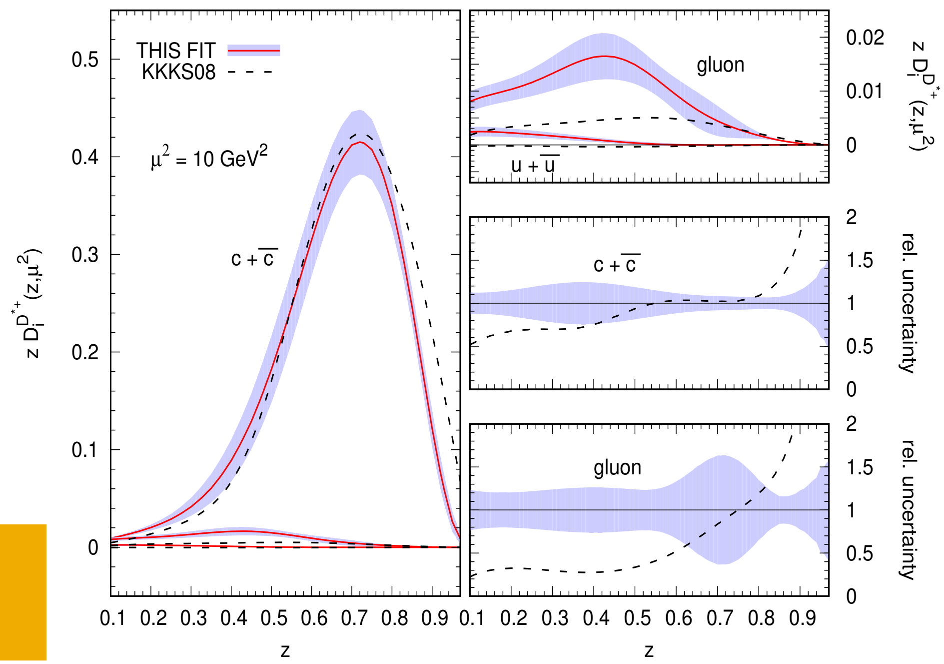
Final results for D* FFs



D. Anderle *et al.* (2017)

- Fit to NLO in Melin space

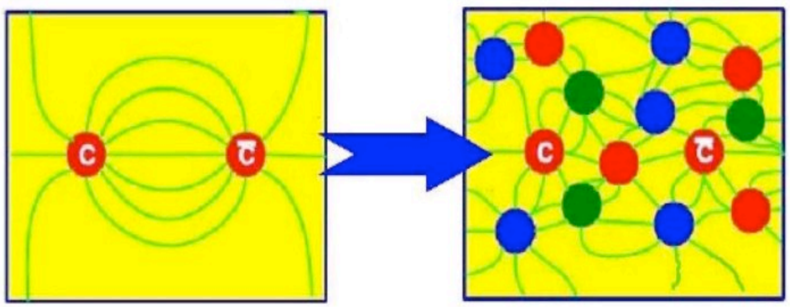
$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T^{\text{jet}}\,d\eta^{\text{jet}}\,dz_h} = \frac{2p_T^{\text{jet}}}{S}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)$$
$$\times\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)\int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{v\,dv\,dw}$$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



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

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

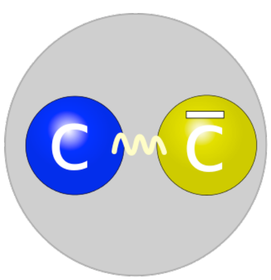


$$\psi(\mathbf{r}) \;=\; Y_l^m(\hat{r})R_{nl}(r)$$

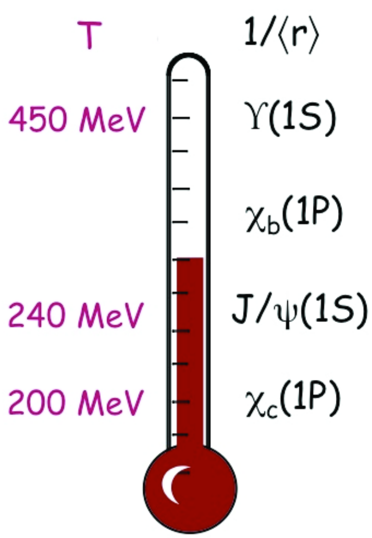
$$\left[-\frac{1}{2\mu_{\rm red}}\frac{\partial^2}{\partial r^2}+\frac{l(l+1)}{2\mu_{\rm red}r^2}+V(r)\right]rR_{nl}(r)=(E_{nl}-2m_Q)rR_{nl}(r)$$

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	$\chi_b(3P)$

Quarkonium production at intermediate and high p_T

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

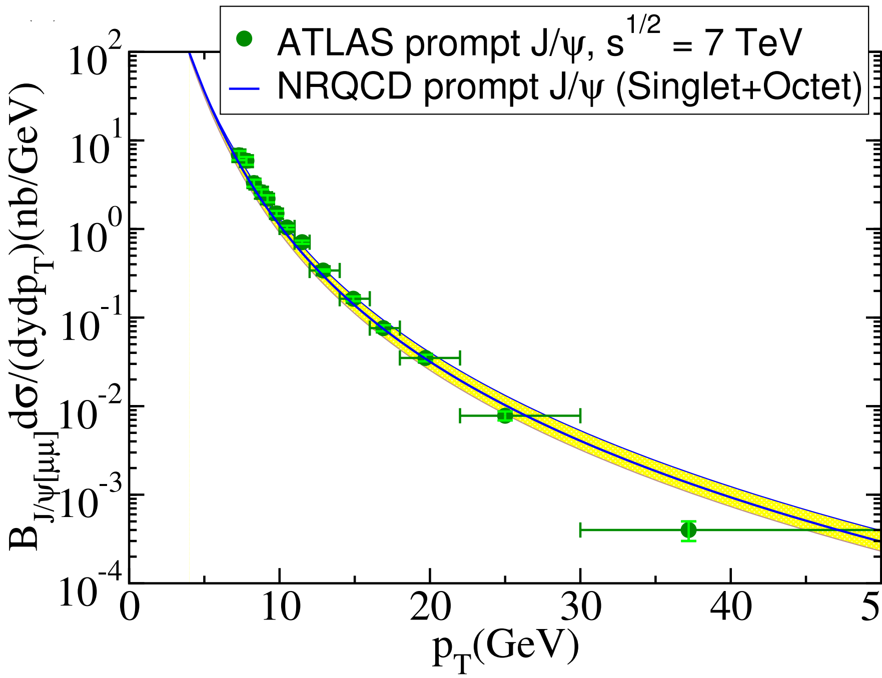
J. Bodwin *et al.* (1995)

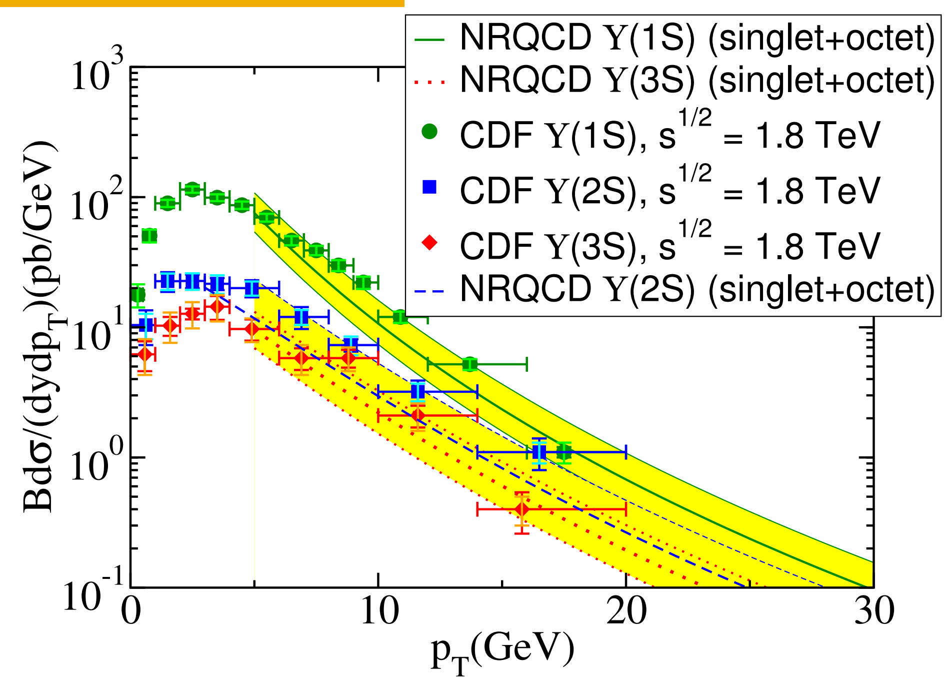
Example for J/ψ

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

- LO fit, improved χ_c and ψ(2s) softer at high p_T

R. Sharma *et al.* (2011)





Model of the medium

- Proto-quarkonia distributed according to the binary collisions density
- QGP modelled by relativistic fluid dynamics

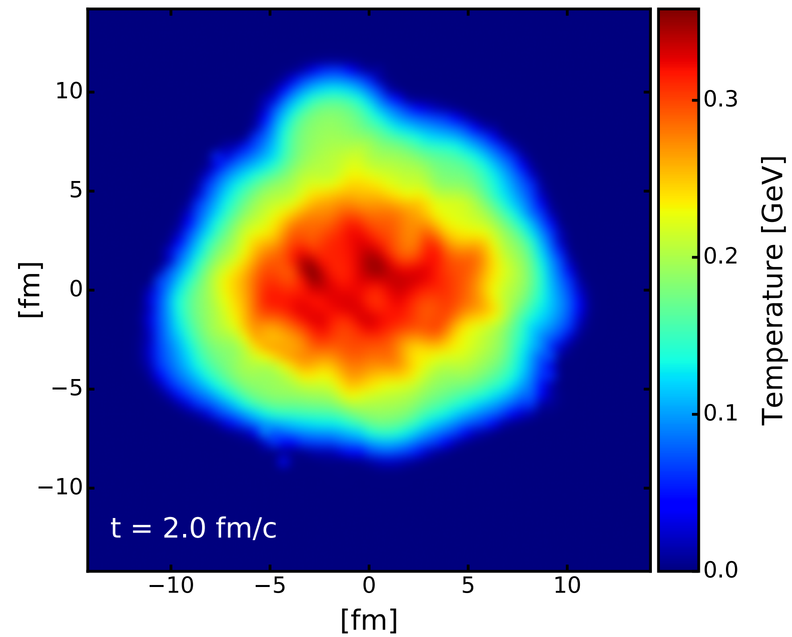
Compare to solutions at T = 190 MeV

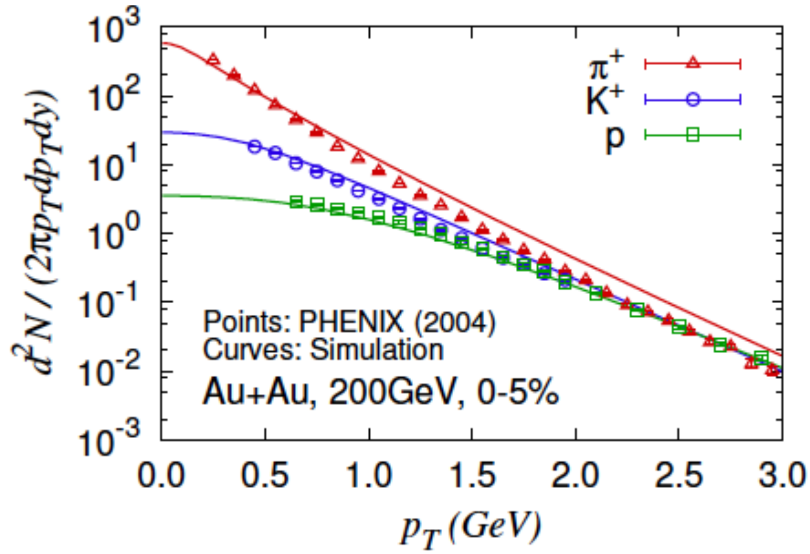
l	n	E_{nl} (GeV)	$\sqrt{\langle r^2 \rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.366	2.24	0.27	J/ψ
0	2	-	-	-	$\psi(2S)$
1	1	0.003	8.15	0.04	χ_c
0	1	0.782	1.23	0.98	$\Upsilon(1S)$
0	2	0.244	2.72	0.20	$\Upsilon(2S)$
0	3	-	-	-	$\Upsilon(3S)$
1	1	0.371	2.09	0.57	$\chi_b(1P)$
1	2	0.040	4.56	0.12	$\chi_b(2P)$
1	3	-	-	-	$\chi_b(3P)$

iEBE-VISHNU simulator (1+2D)

C. Shen *et al.* (2014)

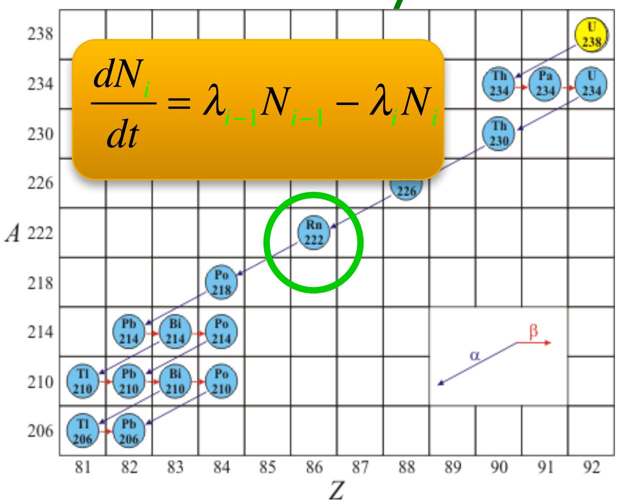
- Viscous second order Israel Stewart event-by-event hydrodynamics





Time evolution of quarkonium states

Very rough analogy with a radioactive decay chain



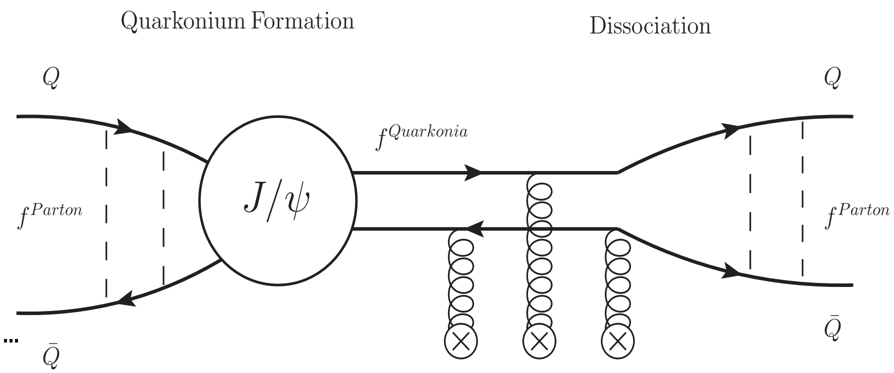
$$\frac{dN_i}{dt} = \lambda_{i-1} N_{i-1} - \lambda_i N_i$$

- Competition between the energetic, heavy quark pairs ("partons") binding into quarkonia vs. dissociating into free quarks

$$f^{Parton} = \sum_{g,\bar{Q}Q} g, \bar{Q}Q(\text{spin,color})$$

$$f^{Quarkonia} = \sum_{States} J/\psi, \psi(2s), \chi_c$$

$$\ldots \Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_b(1S)\chi_b(2S) \ldots$$



- Dynamics reduces to a kinetic approximation

$$\partial_t f^{Parton}(E,t) = -\frac{1}{\langle \tau_{\text{form}}(E,t) \rangle} f^{Parton}(E,t) + \frac{1}{\langle \tau_{\text{diss}}(E,t) \rangle} f^{Quarkonia}(E,t)$$

$$\partial_t f^{Quarkonia}(E,t) = +\frac{1}{\langle \tau_{\text{form}}(E,t) \rangle} f^{Parton}(E,t) - \frac{1}{\langle \tau_{\text{diss}}(E,t) \rangle} f^{Quarkonia}(E,t)$$

Initial conditions: perturbatively produced, QQ-bar states

$$f^{Parton}(E, t=0) = \frac{dN^{Parton}}{dp_T}$$

$$f^{Quarkonia}(E, t=0) = 0$$

This is the effect of the medium

Well-understood asymptotic limits

Effects of the medium

- Formation time – a bit of a misnomer. Typical time for the onset of interactions – take it to be O(1 fm)

- Dissociation time – incudes thermal wavefunction effect and collisional broadening

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

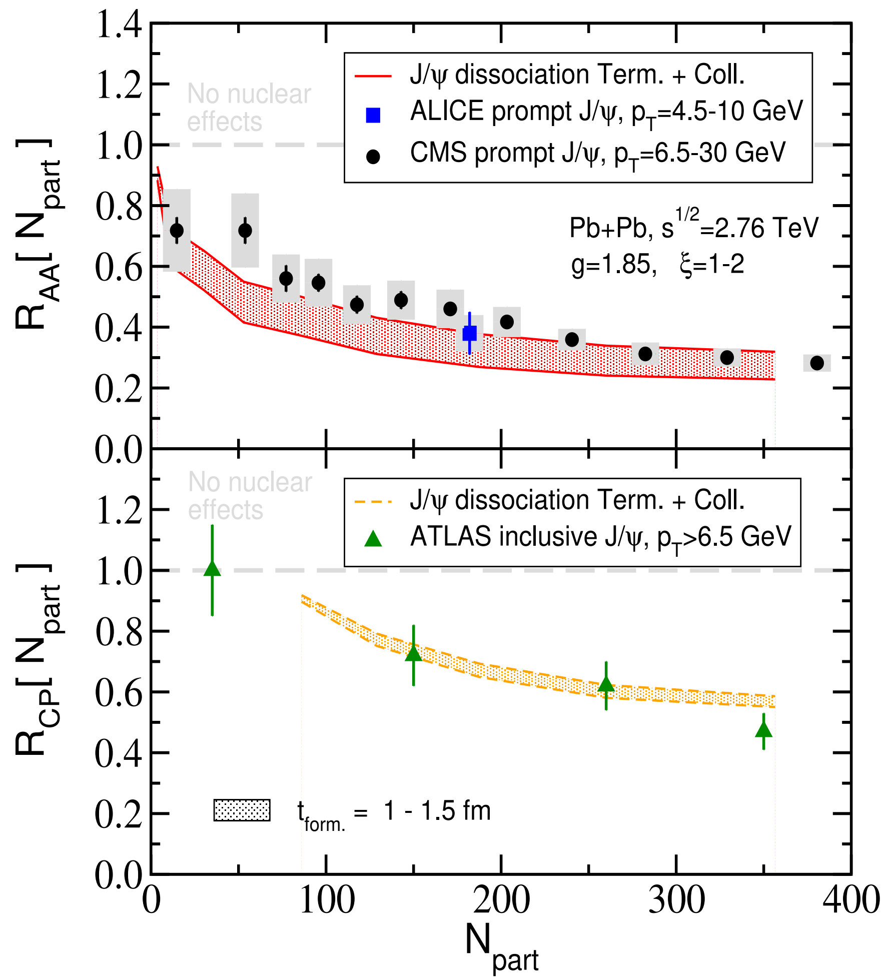
$$= \left|\frac{1}{2(2\pi)^3}\int dx\ \mathrm{Norm}_f\mathrm{Norm}_i\,\pi\, e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$

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

Dissociation time

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

Perform full feed down



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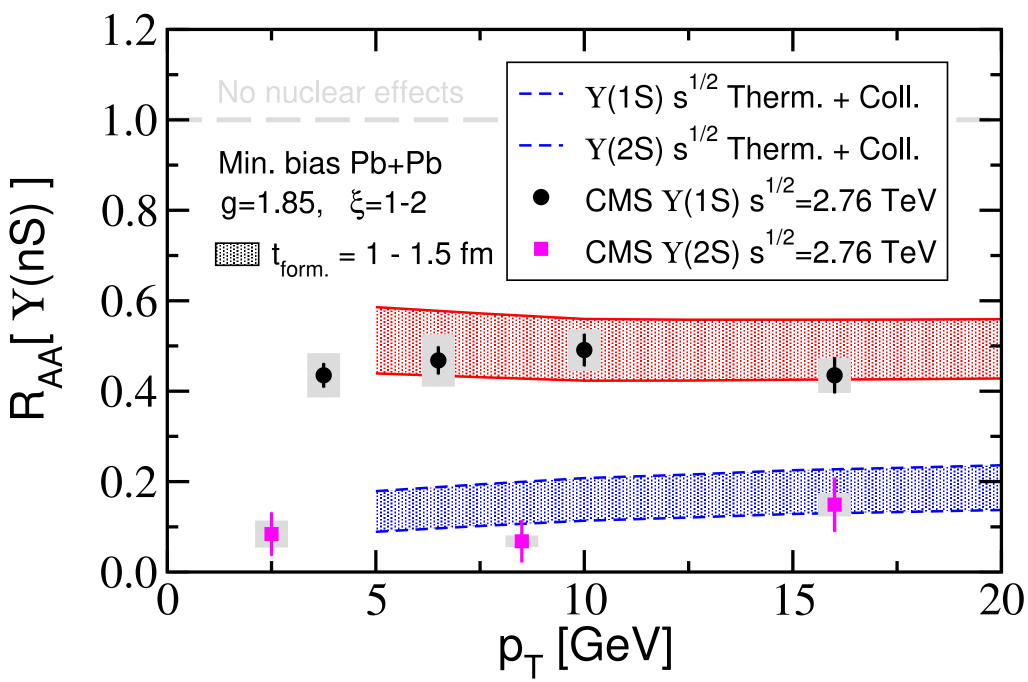
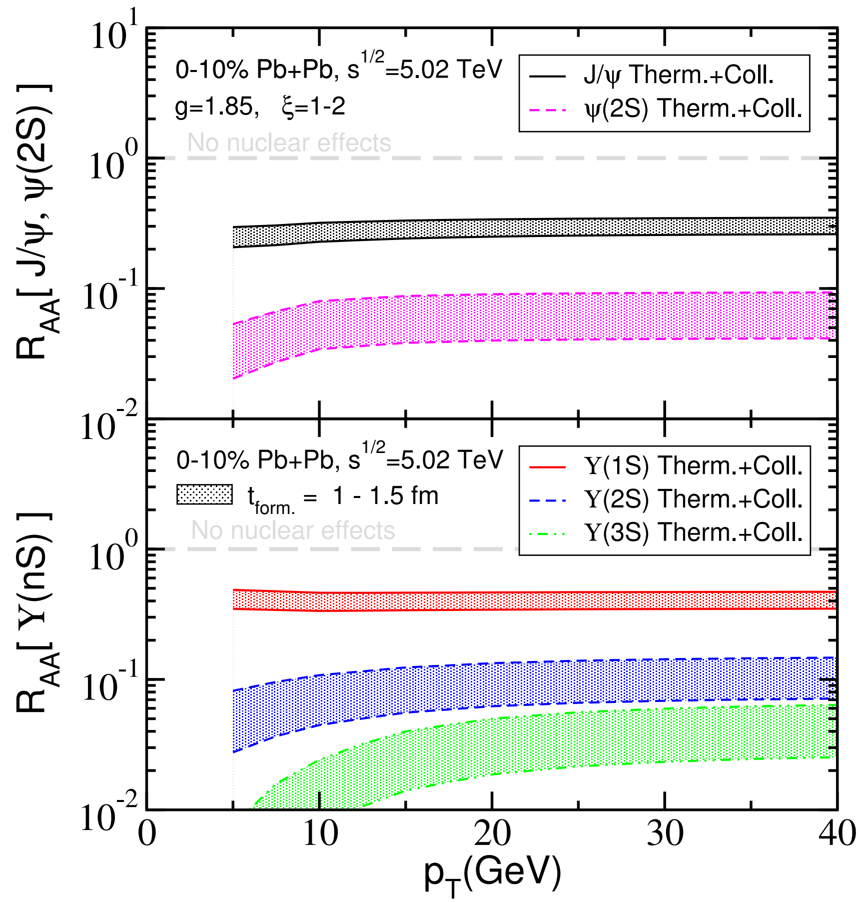
Phenomenological results

- We have centrality and p_T dependence at 2.76 TeV and 5.02 TeV around midrapidity
- Both ground and excited quarkonium states with consistent feed down

Approximately flat p_T dependence





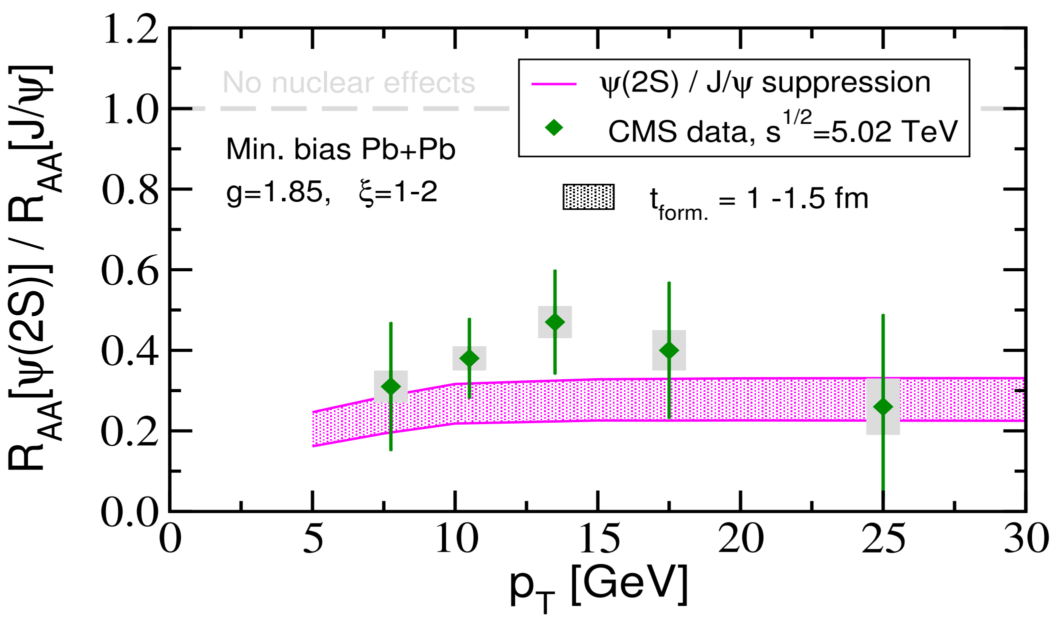
- Good separation the suppression of the ground and excited

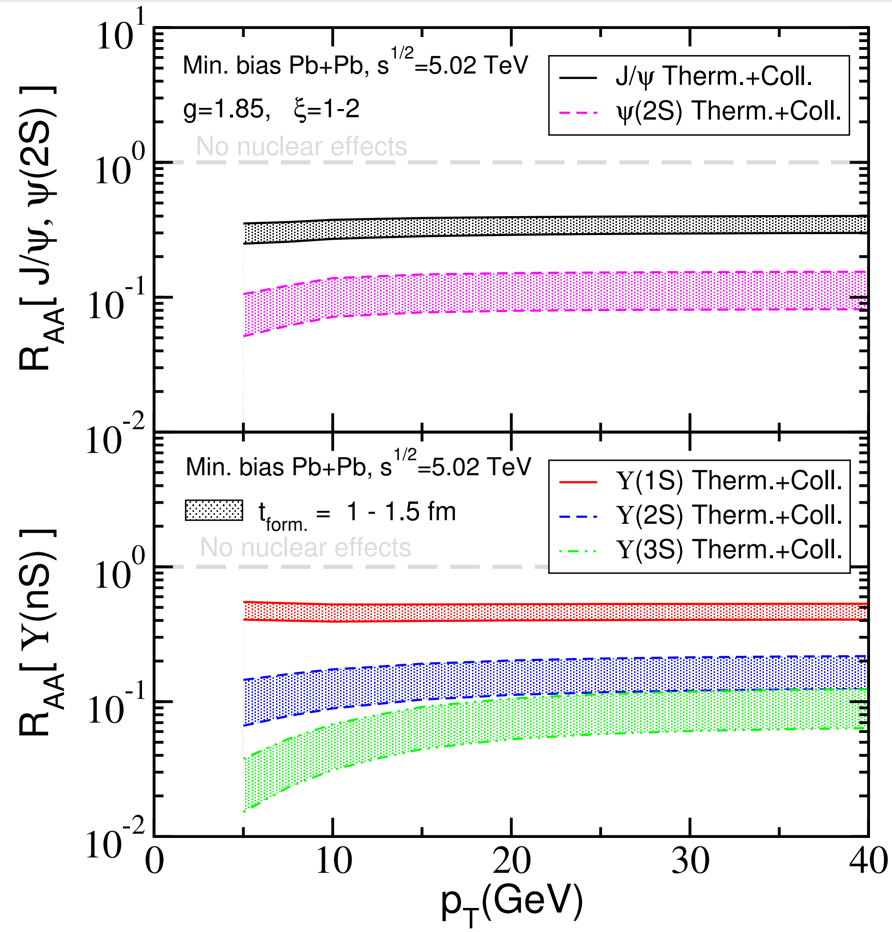
Min bias and excited to ground state ratios

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

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

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





S. Aronson *et al.* (2017)

Results for various centralities, p_T ranges, available upon request. We will proceed with calculations at forward rapidities, lower CM

Conclusions

- New theoretical developments that address the physics heavy flavor in heavy ion collisions emerge in the EFT framework
- Developed an effective theory of heavy quark propagation in QCD matter. Obtained heavy quark splitting functions
- Phenomenological application to open heavy flavor at NLO. Implemented q, g fragmentation functions to B,D. Large g contribution~50%. Below 10 GeV room for additional effects
- Performed global analysis of D*, including hadron-in-jet production. Found additional enhancement of g fragmentation contribution
- Quarkonia at high p_T provide complementary probes of the medium (focused on QGP). More sensitive to the temperature. Described their evolution by kinetic rate equations
- NRQCD baseline and feed down for all J/ψ and Y states performed. Approximately constant p_T dependence of the suppression. Found slight tension between the ground and excited states
- In the future address forward rapidities, lower CM energies