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Quarkonium tomography of heavy ion collisions at the LHC

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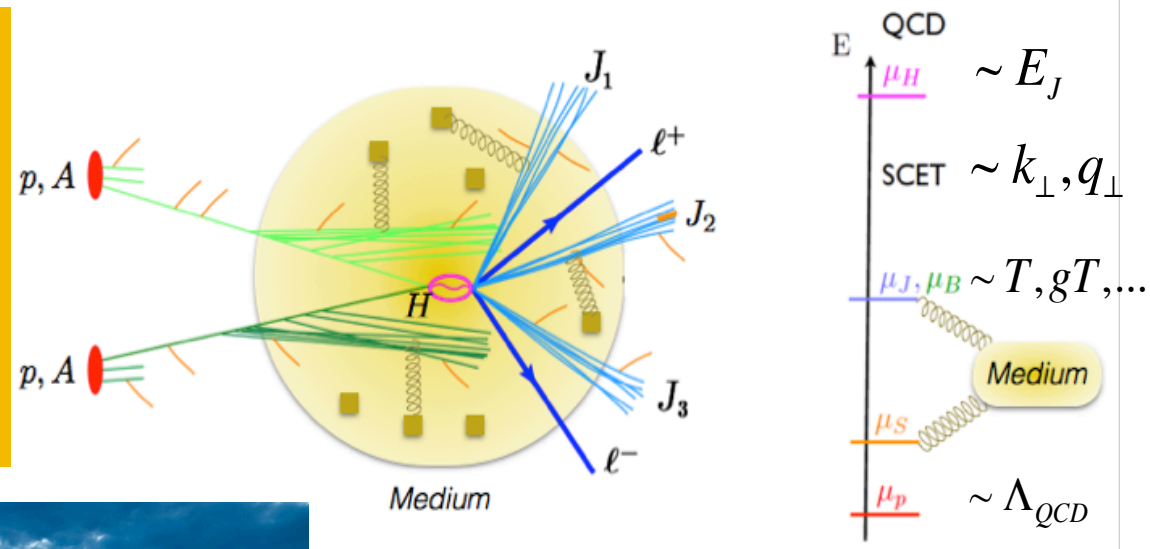
In collaboration with E. Boras, H. Li, B. Odegard, R. Sharma

Introduction

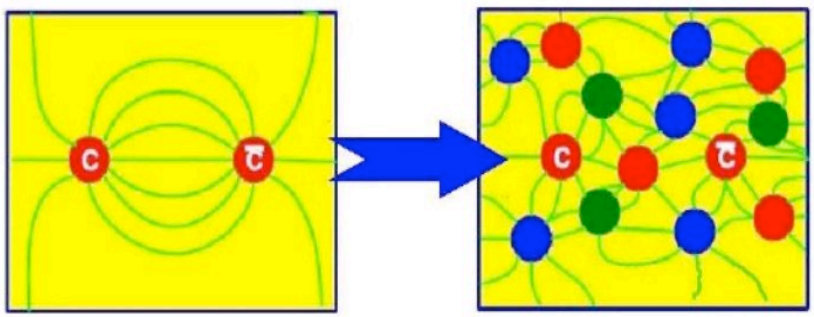
- Heavy flavor, both open and quarkonia, is an important probe of all forms of nuclear matter QGP, strong gluon fields, etc



- NRQD and quarkonium production in p+p
- Quarkonia in the medium – thermal and collisional dissociation
- Different systems and rapidities
- Heavy flavor in jets

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

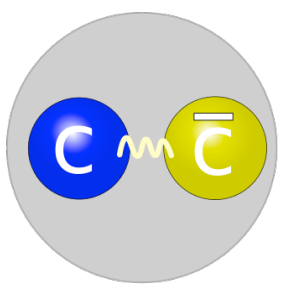


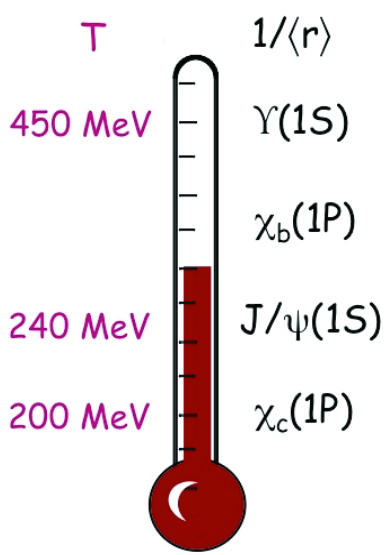
$$\psi(\mathbf{r}) = Y_l^m(\hat{r})R_{nl}(r)$$

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

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

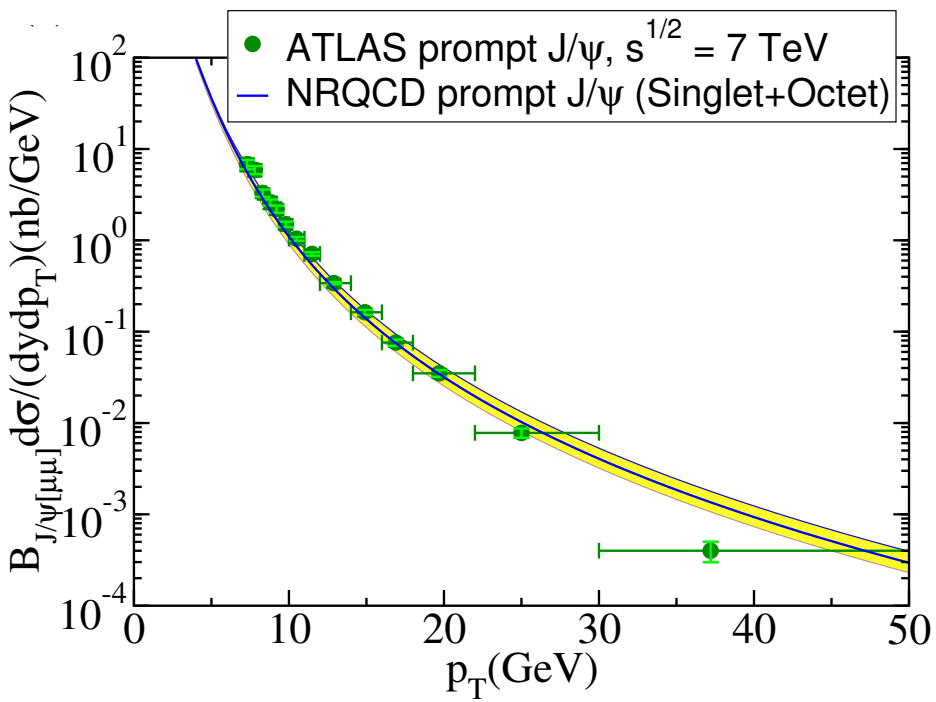
J. Bodwin *et al.* (1995)

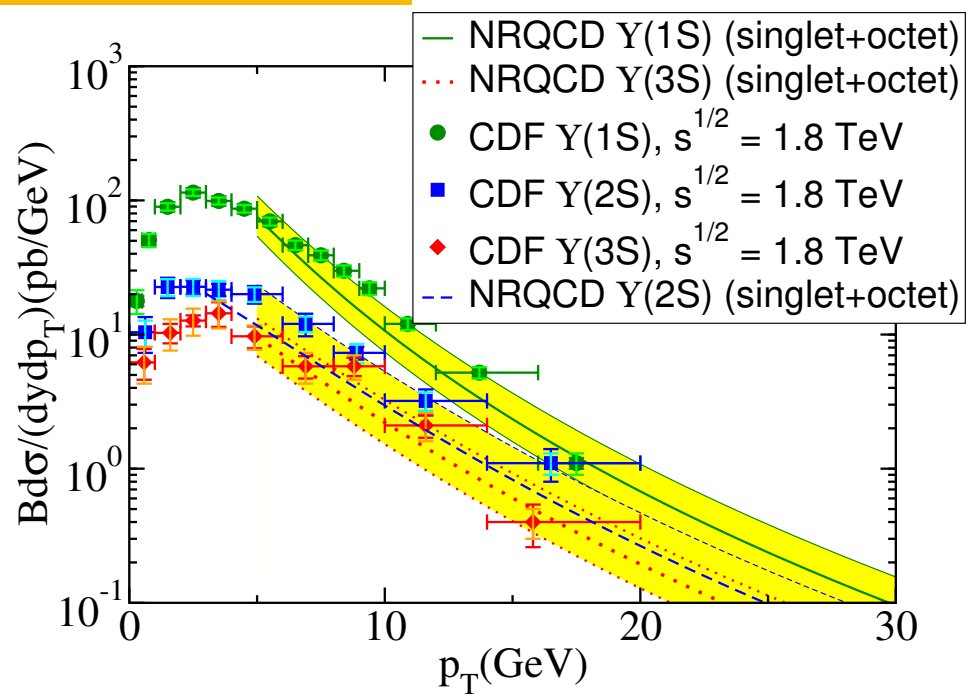
Example for J/ψ

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

- 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

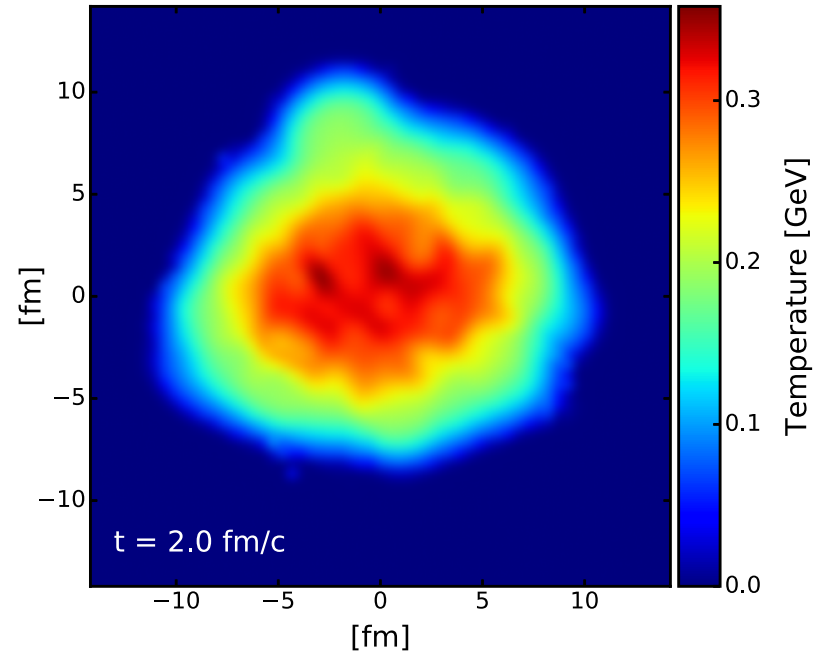
Compare to solutions at T = 190 MeV

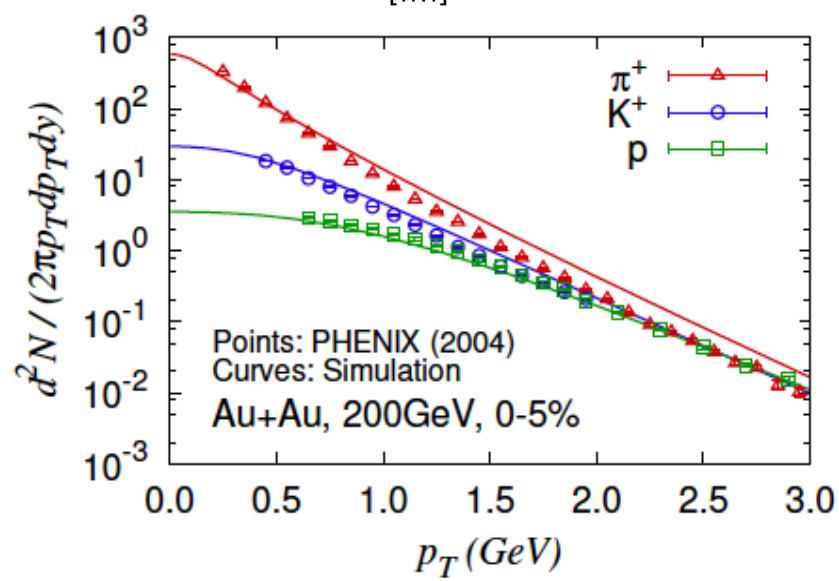
l	n	E_{nl} (GeV)	$\sqrt{\langle r^2 \rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.366	2.24	0.27	J/ψ
0	2	-	-	-	$\psi(2S)$
1	1	0.003	8.15	0.04	χ_c
0	1	0.782	1.23	0.98	$\Upsilon(1S)$
0	2	0.244	2.72	0.20	$\Upsilon(2S)$
0	3	-	-	-	$\Upsilon(3S)$
1	1	0.371	2.09	0.57	$\chi_b(1P)$
1	2	0.040	4.56	0.12	$\chi_b(2P)$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

iEBE-VISHNU simulator (1+2D)

C. Shen *et al.* (2014)

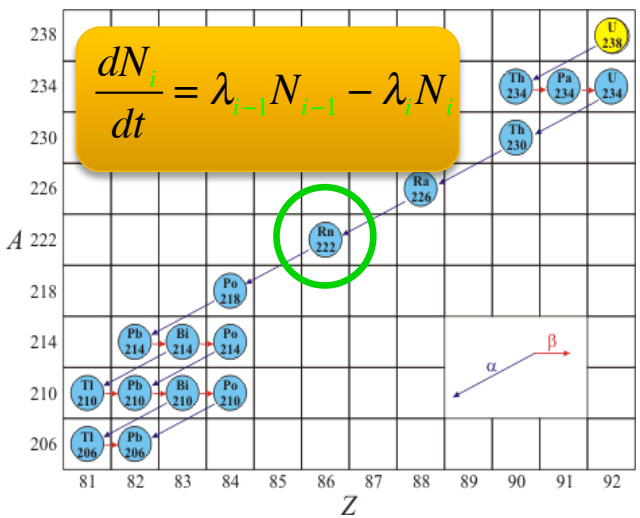
- Viscous second order Israel Stewart event-by-event hydrodynamics





Time evolution of quarkonium states

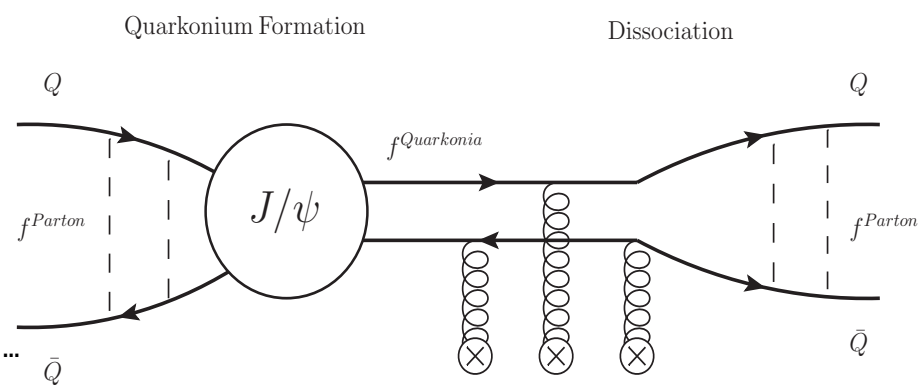
Very rough analogy with a radioactive decay chain



- 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

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

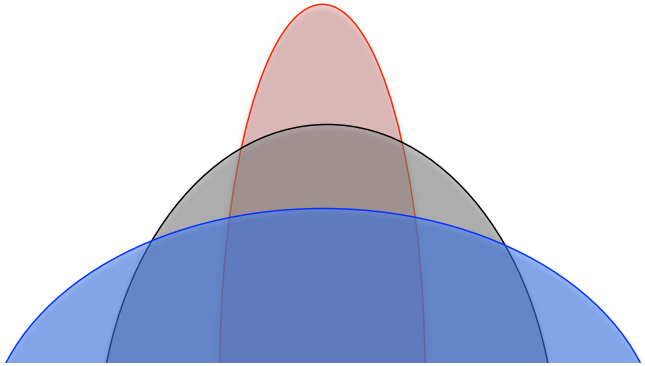
$$= \left|\frac{1}{2(2\pi)^3}\int dx\,\mathrm{Norm}_f\mathrm{Norm}_i\,\pi\,e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}\,e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$

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

Dissociation time

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

S. Aronson *et al.* (2017)

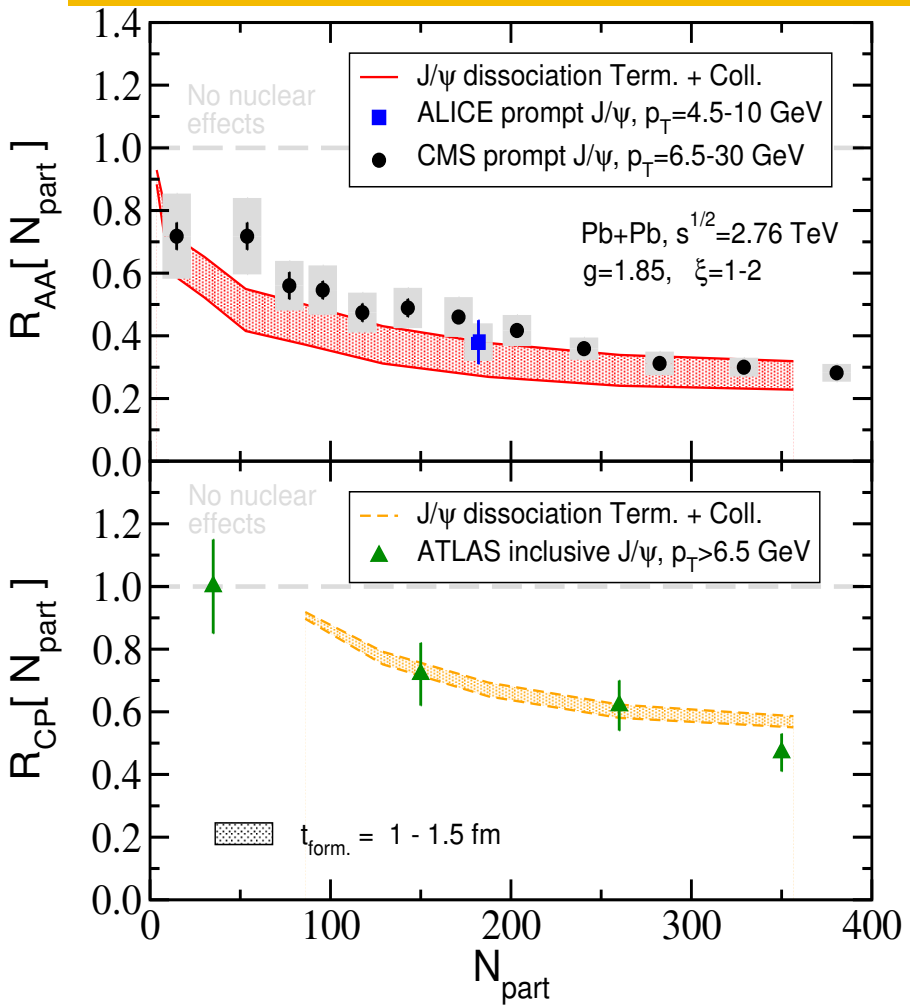


- **Initial wavefunction ~ vacuum**
- **Collisional broadening**
- **Thermal narrowing**

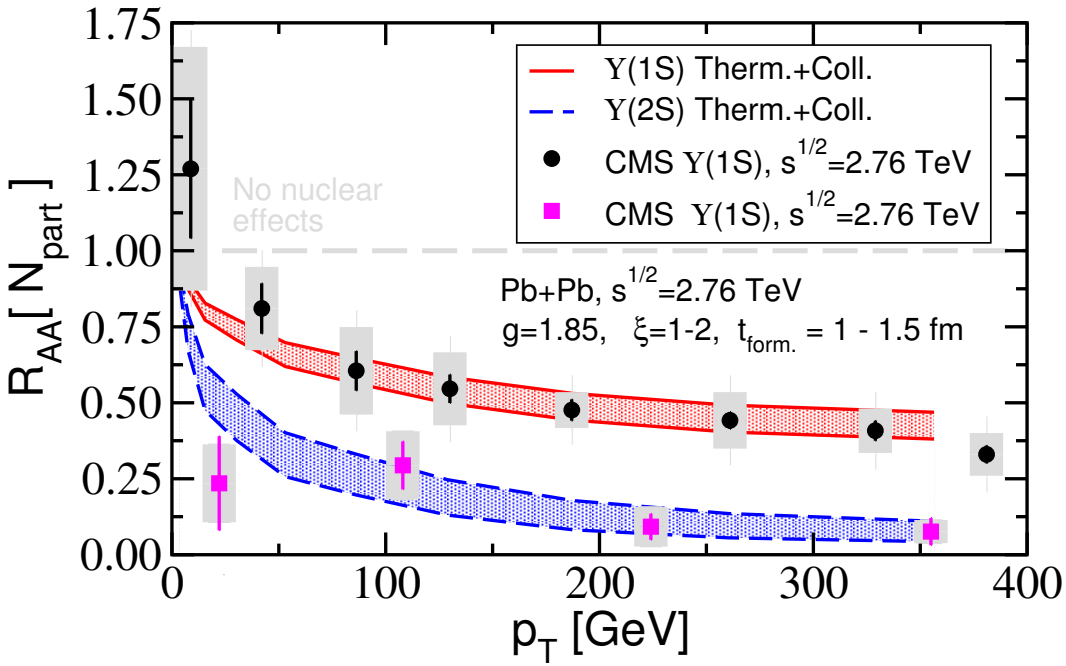
Momentum space picture

Phenomenology – centrality results

- The model predicts slow change of R_{AA} for mid-peripheral to central collisions. Applicable at moderate high p_T under the fragmentation region



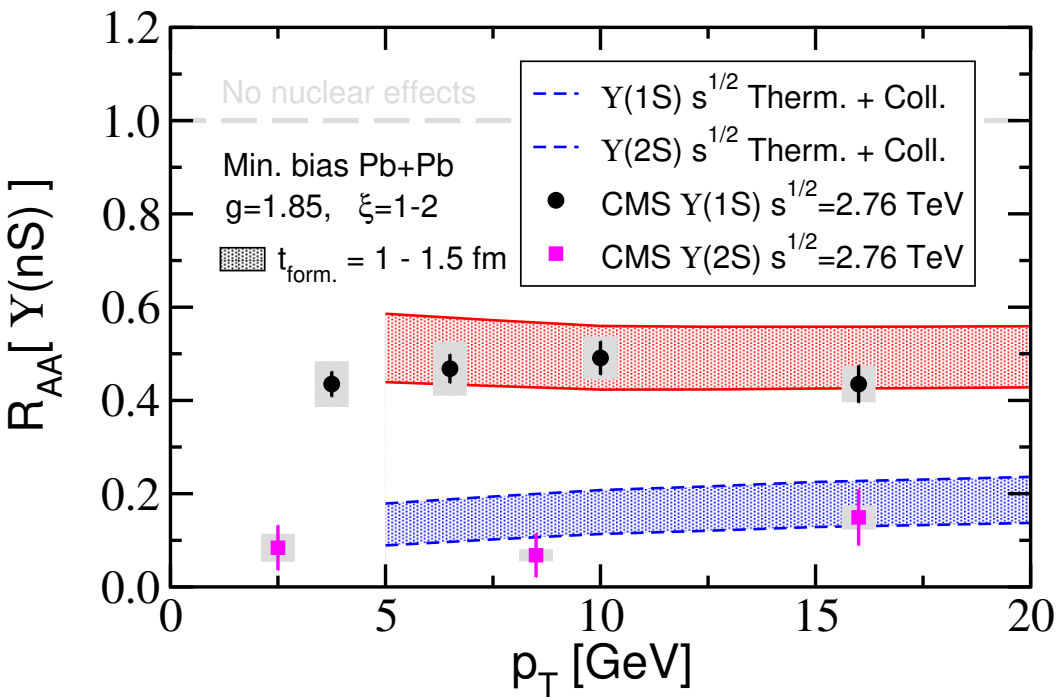
- For Upsilons p_T integrated results available. Mean p_T~ 5 GeV (for 3S even 7 GeV)

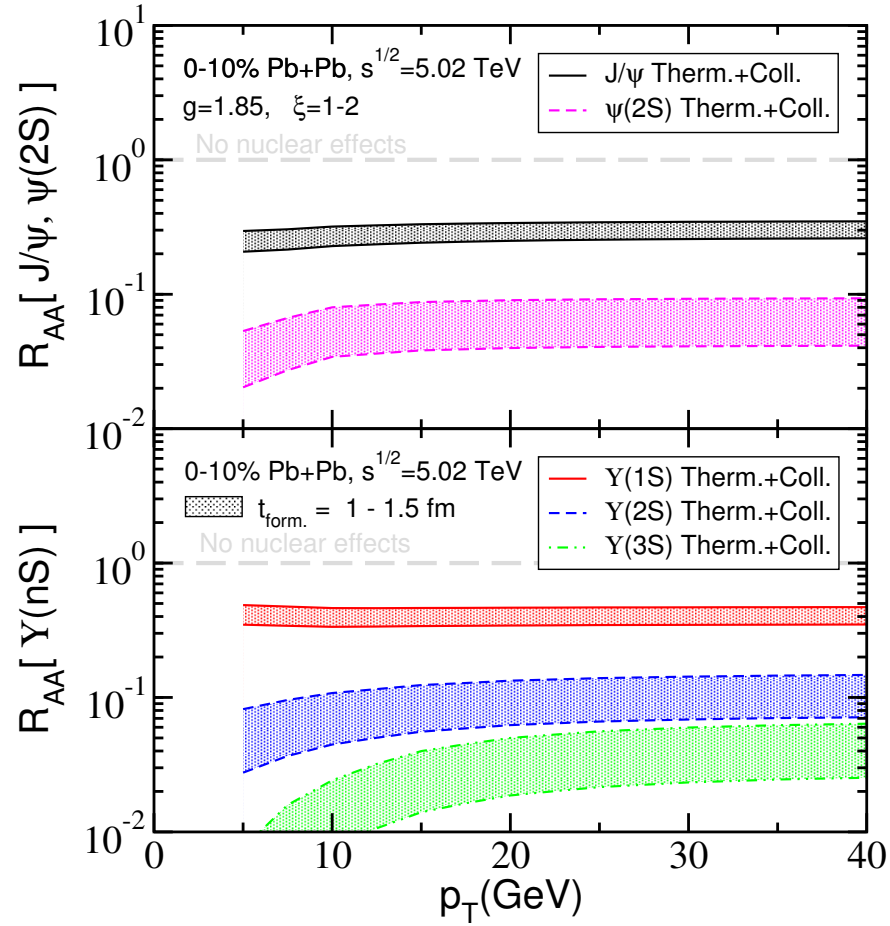


Phenomenological results – transverse momentum

- Both ground and excited quarkonium states with consistent feed down – which is p_T dependent!
- We have centrality and p_T predictions for 5.02 TeV around midrapidity

Approximately flat p_T dependence





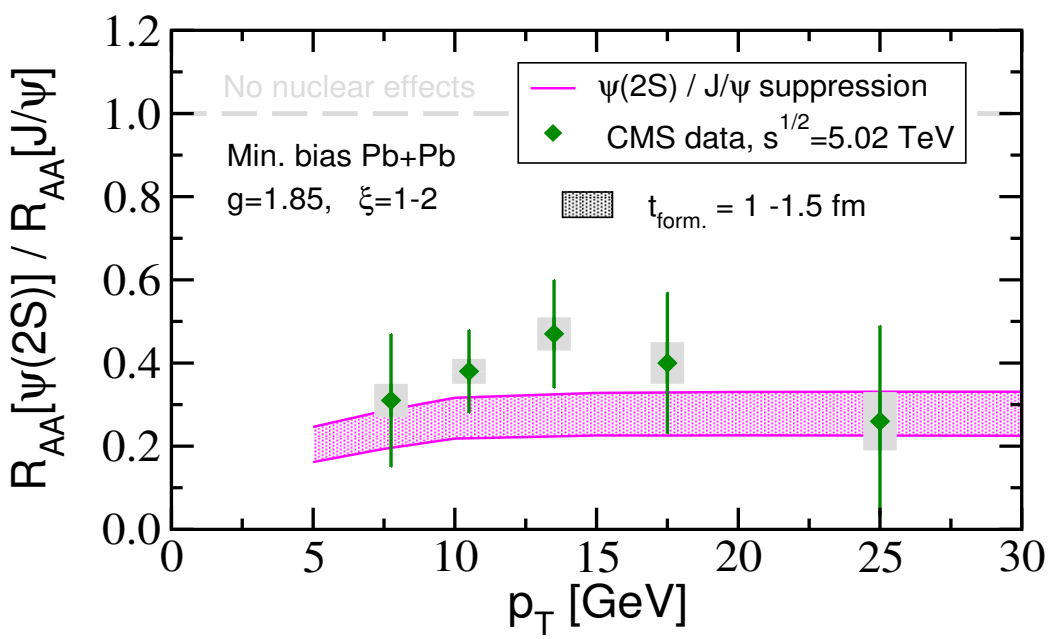
- Good separation the suppression of the ground and excited

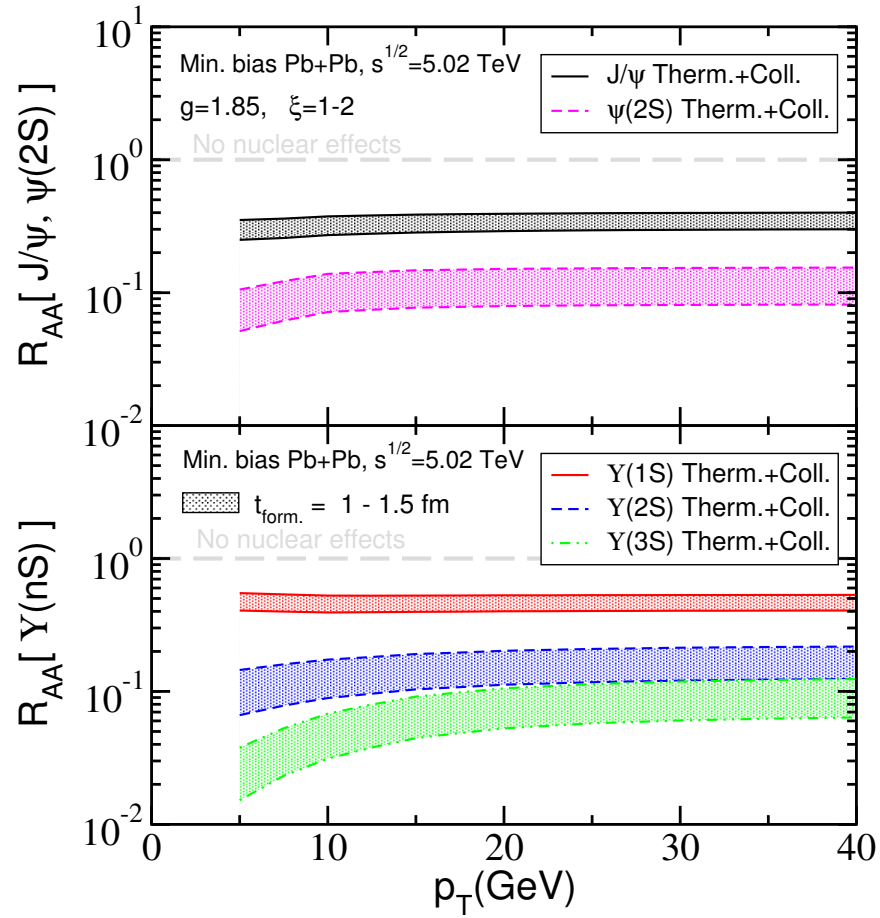
Phenomenology – exited states

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

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

- Suppression of excited states is very important to clarify the mechanism of quarkonium production and suppression





S. Aronson *et al.* (2017)

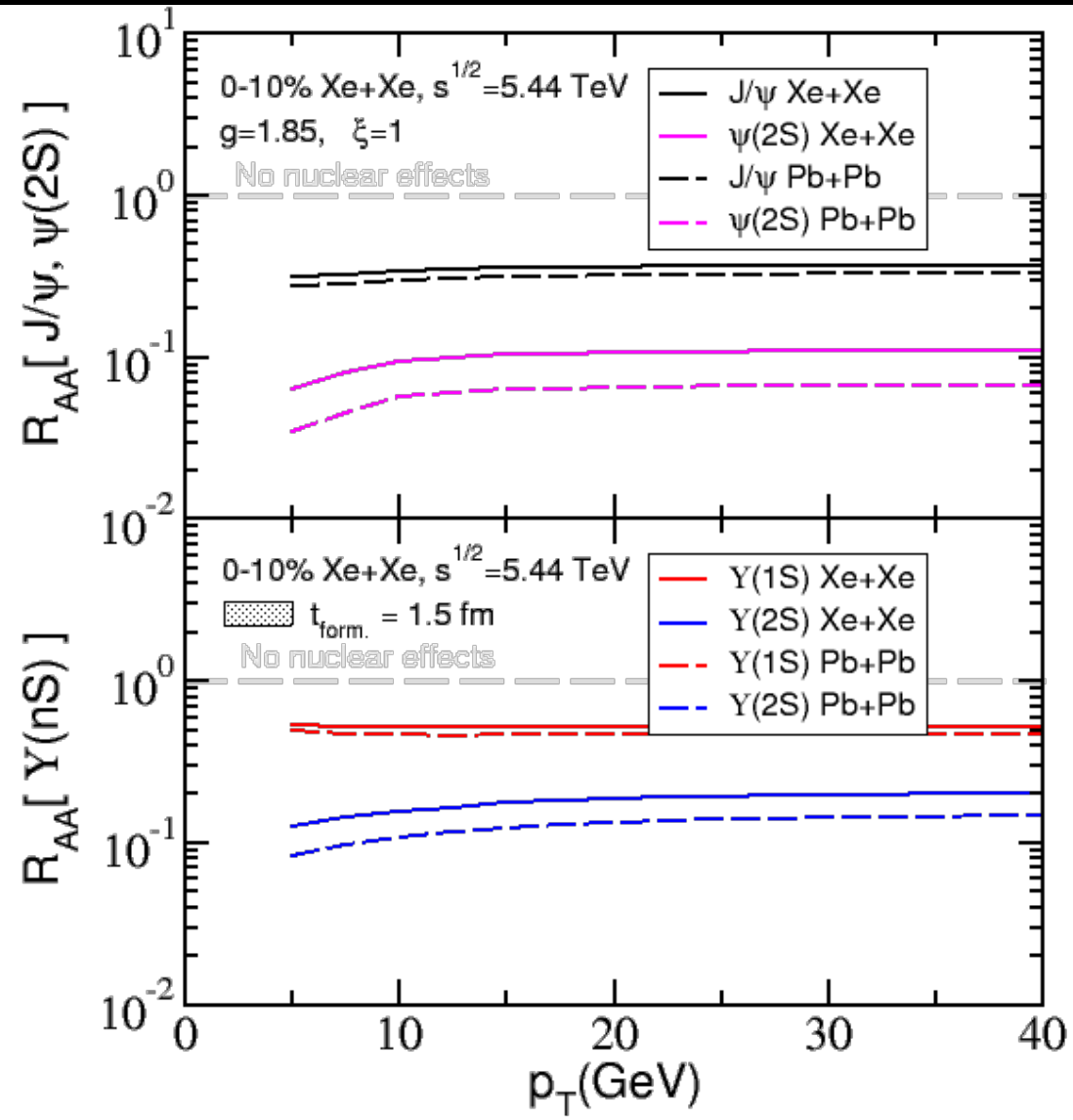
If at very high p_T fragmentation dominates and there is energy loss – suppression of ground and excited states will be the same. We have not seen that yet

Other systems (Xe+Xe) and forward rapidities

- Xenon collisions provide a smaller system but results are similar to lead at smaller centralities. E.g. 0-10% Xe+Xe ~ 10-30% Pb+Pb
- At the same centrality the differences are subtle. 10% for the ground states, 30% for the first excited states

- At forward raidities the slightly smaller densities are offset by cold nuclear matter effects. Very slightly larger suppression overall

Results are preliminary



R. Sharma *et al.* in preparation (2018)

Heavy quarks and quark pairs in the vacuum and the medium

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

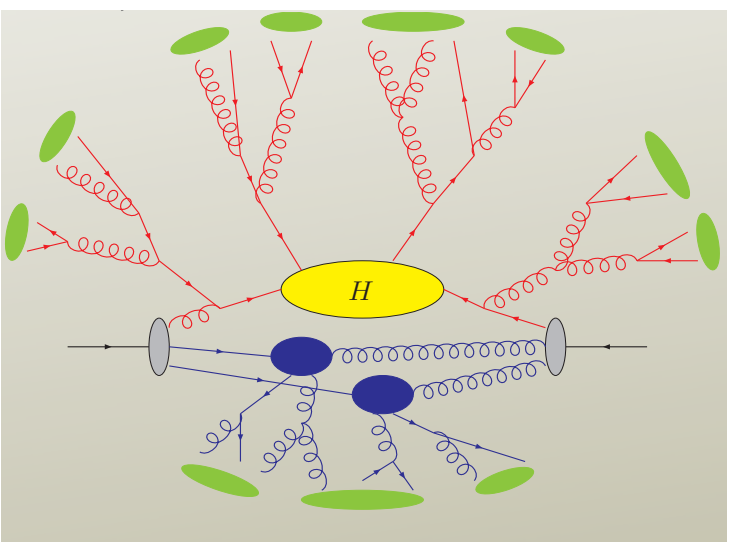
$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^\mu = \partial^\mu + gA^\mu \qquad A^\mu = A^\mu_c + A^\mu_s + A^\mu_G$$

A. Leibovich et al. (2003)

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

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

Quarkonia produced by gluon splitting for example, together with quark fragmentation. The key is to understand the mass dependence in parton showers



G. Altarelli et al. (1977)

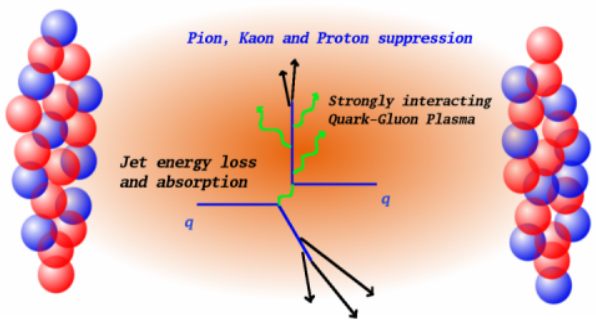
$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2}\frac{1}{\boldsymbol{k}_\perp^2 + m^2}\left[x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{\boldsymbol{k}_\perp^2 + m^2}\right]$$

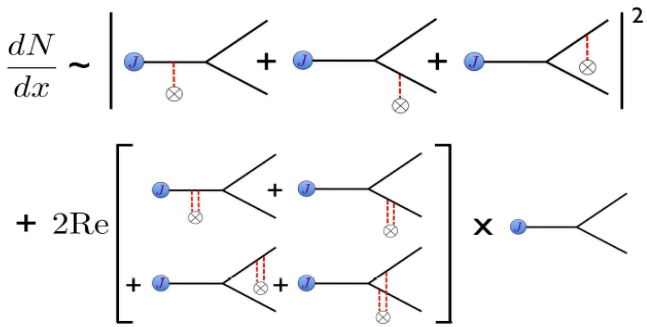
$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2}\frac{1}{\boldsymbol{k}_\perp^2 + x^2m^2}\left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{\boldsymbol{k}_\perp^2 + x^2m^2}\right]$$

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, $(1-x)^2m^2$, m^2

Main results: in-medium splitting & parton energy loss





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

Representative example

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

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

F. Ringer et al . (2016)

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

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

How to pin down the mass dependence

See poster by Haitao Li

- Look at jet substructure. The first observable is the jet splitting function

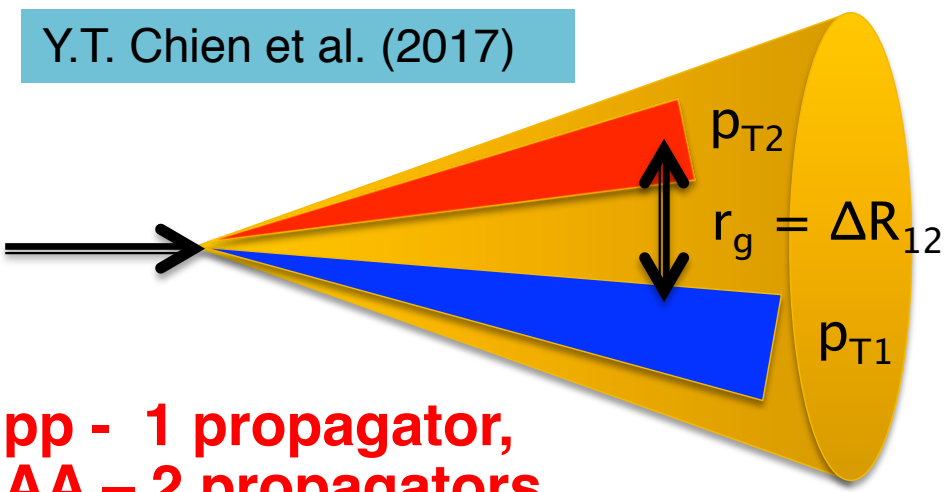
- Allows to write down factorization theorems, no non-global logs elimination
- Directly related to the splitting functions / parton showers
- Eliminates background, medium, etc

A. Larkoski et al . (2014)

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

- Groomed subjet distribution using "soft drop"

Y.T. Chien et al. (2017)



- Look for a regime where: x^2m^2, $(1-x)^2m^2$, $m^2 <= k_T^2$ If we translate k_T into angle, relate it to the jet splitting kinematics for $z_g \sim 1/2$

pp - 1 propagator,
AA – 2 propagators

Q to Qg

$$\left(\frac{1}{k_\perp^{\,2}+x^2m^2}\right)\times\left(\frac{1}{k_\perp^{\,2}+x^2m^2}\right)c \sim \frac{1}{x^4m^4}c$$

g to QQbar

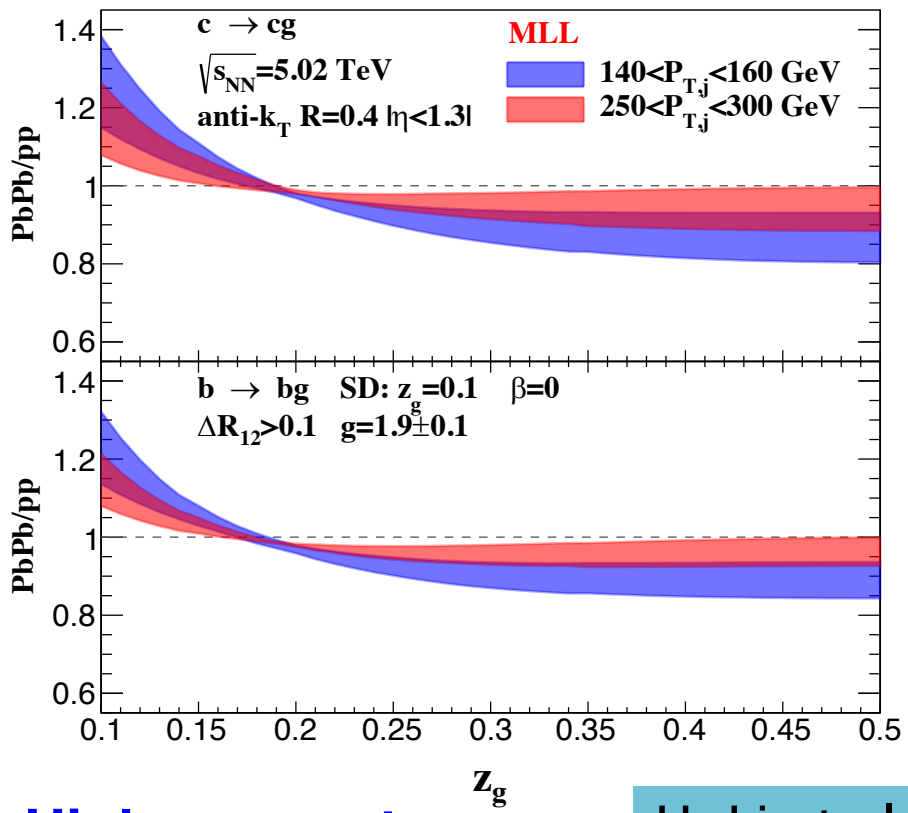
$$\left(\frac{1}{k_\perp^{\,2}+m^2}\right)\times\left(\frac{1}{k_\perp^{\,2}+m^2}\right)c \sim \frac{1}{m^4}c$$

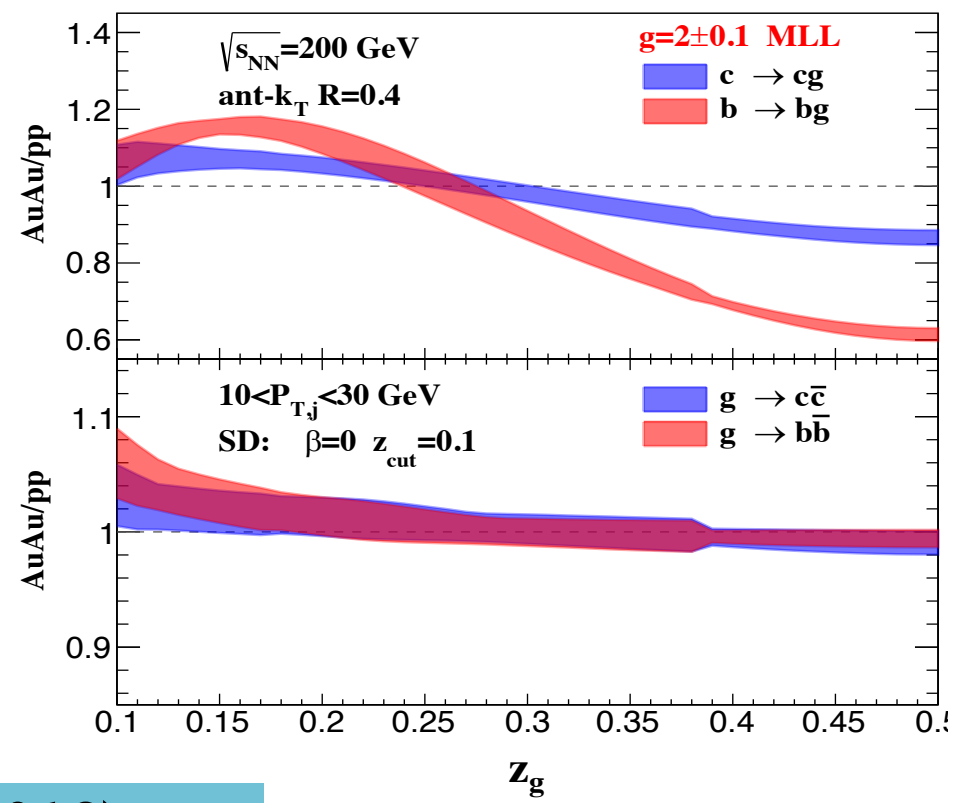
light partons

$\sim 1/x^2$

Inverting the mas hierarchy of jet quenching effects

- At RHIC jet energies, and at lower jet energies at the LHC there is a unique reversal of the mass hierarchy effects on b > c >= u,d.
- Can help place constraints on the parton mass dependence of in-medium showers – not ony open heavy flavor but also J





High momentum

H. Li et al. (2018)

"Low" momentum

Conclusions

- Quarkonia at high p_T provide complementary probes of the medium. More sensitive to the temperature (than transport coefficients). Described their evolution by kinetic rate equations
- NRQCD baseline and feed down for all J/ψ and Υ states performed. Approximately constant p_T dependence of the suppression. Found slight tension between the ground and excited states' description
- Centrality dependence rather flat, hence the suppression in Xe+Xe is quite similar at the same centrality to the one in Pb+Pb
- Excited states' suppression provide constraints on the picture of parton fragmentation in quarkonia and energy loss. Developed an effective theory of heavy quark propagation in QCD matter. Obtained heavy quark splitting functions, relevan to open heavy flavor and quarkonia at high p_T
- The most important mass dependence ("dead cone" effect) in parton showers can be studies with b-jets substructure. The region of interest can be identified with a unique reversal of the mass hierarchy of jet quenching effects