Suppression of high-p_T quarkonia in the QGP

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January 31, 2018

Separation of scales

- NRQCD is a concrete framework to calculate the production of high-p_T quarkonia *[Bodwin, Braaten, LePage (1995)]*
- It relies on the hierarchy between the large energy scale, m_Q — the mass of the heavy quark — and the inverse of the separation between $Q\bar{Q}$: $1/a \sim q$. $q \ll m_Q$
- A further simplification occurs if there is a second hierarchy between the binding energy and q: $E_b \ll q$
- Then the quarkonium states can be described by a non-relativistic potential in their rest frame: pNRQCD *[Brambilla et. al. 2004]*

Separation of scales

- Can obtain rough estimates by assuming that the states are so small in size that the Coulombic part of the Cornell potential dominates
- $v \sim \alpha(m_Q v)$ is the relative velocity of Q and $\bar{Q}$
- Inverse size $q \sim m_Q v$
- $E_b \sim m_Q v^2$
- Finally, the non-perturbative scale Λ_{QCD}
- If v is small, $m_Q \gg q \gg E_b \gg \Lambda_{QCD}$

Separation of scales

- For the lowest bound states one obtains by solving the Schrödinger equation
- Bottomonia:
  - $m_b \sim 4.5\text{GeV}$
  - $q \sim 1\text{GeV}$
  - $E_b \sim 0.5\text{GeV}$
- Charmonia:
  - $m_c \sim 1.34\text{GeV}$
  - $m_c v \sim 0.6\text{GeV}$
  - $m_c v^2 \sim 0.5\text{GeV}$
- Both the intermediate distance and the short range part of the potential are relevant

Separation of scales

- In NRQCD, the cross-section for production in *pp* collisions can be written in a factorized form. For example, in the intermediate p_T range

$$d\sigma(\Upsilon) = \sum_{[b\bar{b}]} d\sigma([b\bar{b}])|\mathcal{M}[b\bar{b}] \to \Upsilon|^2$$

- The short distance part $[b\bar{b}]$ can have color-octet and singlet quantum numbers and appropriate spin quantum numbers
- The long distance matrix elements (LDMEs) $\mathcal{M}$ are fitted to match $d\sigma/dp_T$
- If $\alpha_S(m_Q)$ is perturbative, the short distance cross-sections can be computed perturbatively *[Cho, Leibovich (1995)]*
- This picture also suggests a time scale separation of formation: $\tau_f(\Upsilon) \sim 1/E_b$ and $\tau_f([b\bar{b}]) \sim 1/(2m_b)$ in *pp* collisions

Modified picture in the QGP

- $\tau_f([b\bar{b}])$ is smaller than the medium time scale $\sim 1/T$ and hence $d\sigma[Q\bar{Q}]$ is not modified ($T \sim 400$MeV for 5.5TeV at 0.6fm)
- The formation of quarkonia from the $Q\bar{Q}$ is modified due to the screening of the interaction between $Q\bar{Q}$ and due to dissociation processes
- Assume that a suitably modified thermal pNRQCD describes the $Q\bar{Q}$ interaction *[See Ralf Rapp's talk]*

Modified picture in the QGP

- The $Q\bar{Q}$ potential has a real part and an imaginary part (associated with dissociation)
- The real potential as a function of r can be captured well by lattice QCD by measuring correlators separated by a distance *eg. [A. Bazavov and P. Petreczky (2013)]*
- The imaginary part is not yet well constrained by lattice data
- It has been evaluated assuming that the interaction between $Q\bar{Q}$ is Coulombic *[Laine et. al. (2007), Brambilla, Ghiglieri, Vairo, Petreczky (2008)]* but this is not a good assumption
- Other approaches use the in-medium $T-$matrix to calculate both the real and imaginary parts *[Rapp et. al]*
- Furthermore, most calculations valid for $Q\bar{Q}$ at rest in the medium

Model description

- We use the real part of the potential at finite T obtained by the lattice calculations
- The instantaneous T dependent eigenstates can be found by solving the Schrödinger equation
- Use the light cone formalism to boost the wavefunctions to finite p_T

Model description

- $$|\vec{P}^+\rangle = \int \frac{d^2\mathbf{k}}{(2\pi)^3} \frac{dx}{2\sqrt{x(1-x)}} \frac{\delta_{c_1 c_2}}{\sqrt{3}} \psi(x,\mathbf{k}) \times a_Q^{\dagger\, c_1}(x\vec{P}^+ + \mathbf{k}) b_{\bar{Q}}^{\dagger\, c_2}((1-x)\vec{P}^+ - \mathbf{k})|0\rangle \,,$$

  where $\mathbf{k}$ corresponds to the momentum transverse to p_T and P^+ is the light cone momentum of the state parallel to p_T
- $$\psi(x,\mathbf{k}) = \mathrm{Norm} \times \exp\left(-\frac{\mathbf{k}^2 + m_Q^2}{2\Lambda^2(T)x(1-x)}\right)$$
- Λ is related to the width of the wavefunctions in momentum space *[Adil, Vitev (2007)]*

Dissociation

- To calculate the dissociation rate, we use a formalism used to describe the transverse momentum broadening of high p_T particles *[BDMPS, GLV, ...]*
- The Q and $\bar{Q}$ get kicks to the relative transverse momentum $\mathbf{k}$ thus modifying the light cone wavefunction as the $Q\bar{Q}$ propagates in the medium: $\mathbf{k}^2 \to \mathbf{k}^2 + \Delta\mathbf{k}^2$
- The distribution of the transverse kicks is

$$\frac{dP(\Delta k^2)}{d\Delta k^2} \propto e^{-\Delta k^2/(\chi \mu_D^2 \xi)}$$

where $\chi \mu_D^2 \xi$ is the analog of $\hat{q}L$

Dissociation

- $P_{\mathrm{surv}}(t) = |\langle \Psi_T(t) | \Psi_T(0) \rangle|^2$
- Overlap with the ground state reduces due to momentum broadening

$$\tau_{\mathrm{diss}} = -\frac{1}{P_{\mathrm{surv}}(t)} \frac{dP_{\mathrm{surv}}(t)}{dt}$$

Formation

- We start with the initial state with the vacuum form assuming the initial formation is not strongly modified
- The formation dynamics can not be handled rigorously: We assume that formation happens on a time scale τ_{form} which we vary from $1 - 1.5$fm
- This is the biggest systematic uncertainty in our calculation

Rate equations

- We have all the ingredients to find the p_T differential yields
- Rate equations

$$\frac{d}{dt}\left(\frac{d\sigma^{\text{meson}}(t;p_T)}{dp_T}\right) = \frac{1}{t_{\text{form.}}}\frac{d\sigma^{Q\bar{Q}}(t;p_T)}{dp_T} - \frac{1}{t_{\text{diss.}}}\frac{d\sigma^{\text{meson}}(t;p_T)}{dp_T}$$

- $$\frac{d}{dt}\left(\frac{d\sigma^{Q\bar{Q}}(t;p_T)}{dp_T}\right) = -\frac{1}{t_{\text{form.}}}\frac{d\sigma^{Q\bar{Q}}(p_T)}{dp_T}$$

- $$\frac{d}{dt}\left(\frac{d\sigma^{\text{diss.}}(t;p_T)}{dp_T}\right) = \frac{1}{t_{\text{diss.}}}\frac{d\sigma^{\text{meson}}(t;p_T)}{dp_T}$$

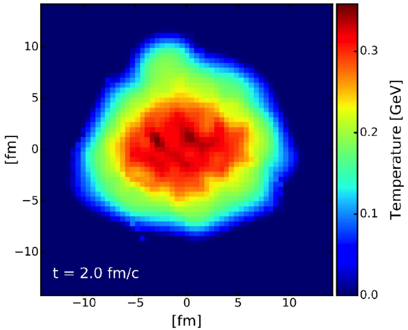
Rate equations

- Start with $\sigma^{\mathrm{meson}}(t = 0; p_T) = 0$
- $\sigma^{Q\bar{Q}}(t = 0; p_T) = \sigma^{\mathrm{meson}}(p_T)_{pp}$
- τ_{diss} can not be small than the mean free path so we put a lower limit on it

Similar to approaches treating quarkonium as an open system

- While treating quarkonium as an open system
- $Q\bar{Q}$ is propagates in a stochastic potential *[Kajimoto, Akamatsu, Asakawa, Rothkopf (2017)]*

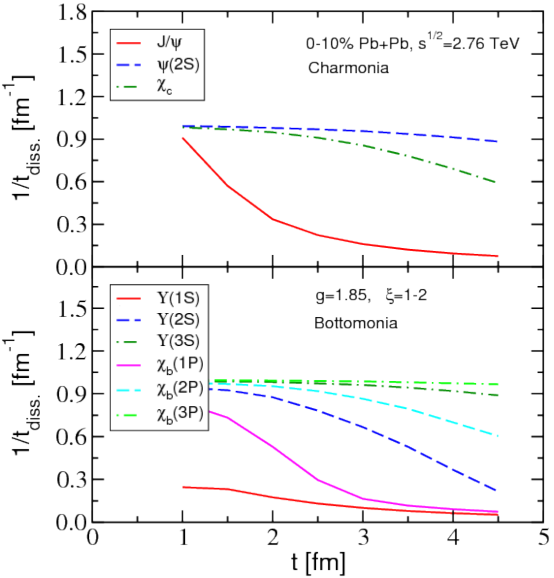
Medium



- Use the public $2+1$ hydro code iEBE-VISHNU *[Shen et. al. (2016)]*
- An example shown above for the T distribution a central event at 2.76TeV

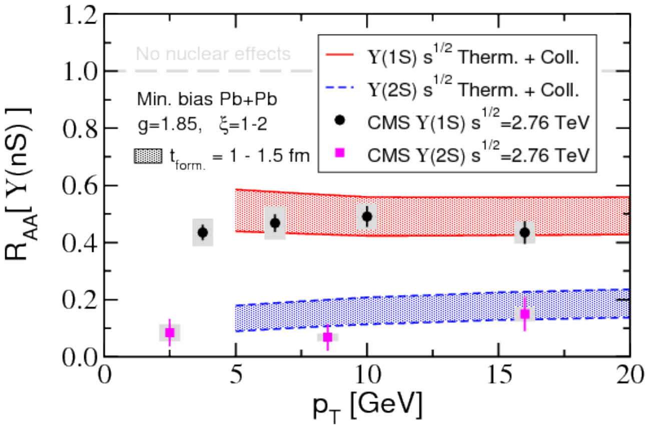
Results

τ's



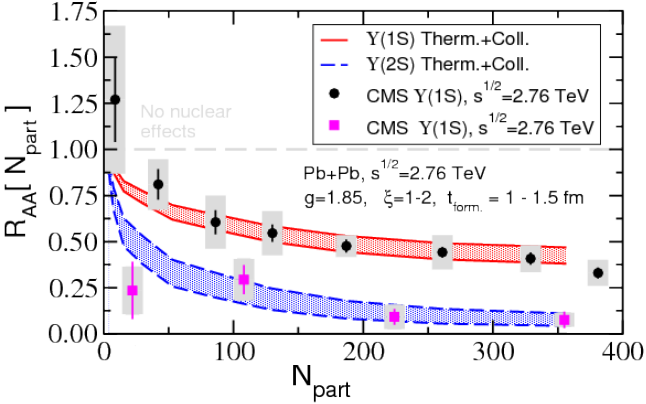
[Aaronson, Borras, Odegard, Sharma, Vitev (2017)]

$R_{AA}(\Upsilon)$



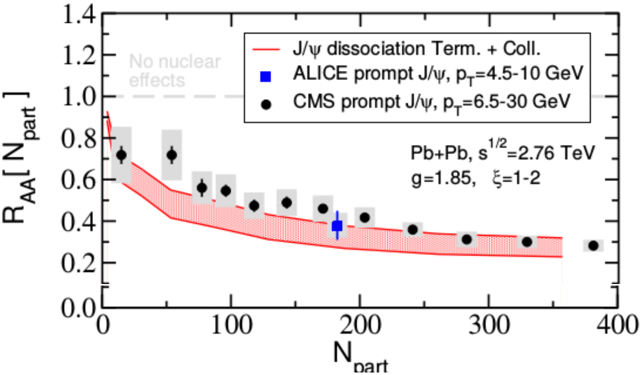
No nuclear effects
Min. bias Pb+Pb
g=1.85, ξ=1-2
t_form. = 1 - 1.5 fm
Υ(1S) s^1/2 Therm. + Coll.
Υ(2S) s^1/2 Therm. + Coll.
CMS Υ(1S) s^1/2=2.76 TeV
CMS Υ(2S) s^1/2=2.76 TeV
R_AA[Υ(nS)]
p_T [GeV]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20

$R_{AA}(\Upsilon)$



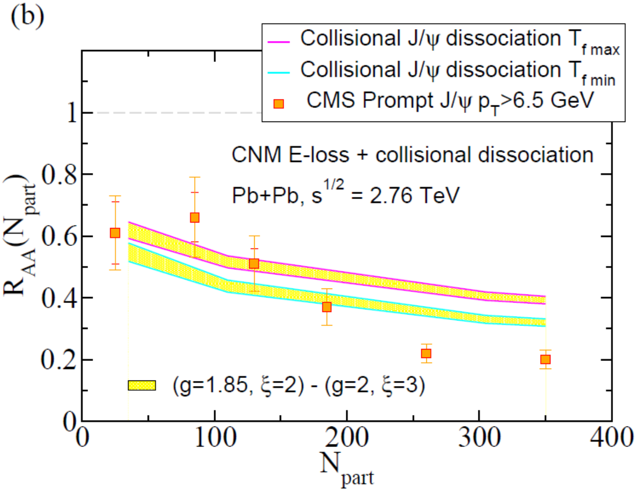
Υ(1S) Therm.+Coll.
Υ(2S) Therm.+Coll.
CMS Υ(1S), s^1/2=2.76 TeV
CMS Υ(1S), s^1/2=2.76 TeV
No nuclear effects
Pb+Pb, s^1/2=2.76 TeV
g=1.85, ξ=1-2, t_form. = 1 - 1.5 fm
R_AA[N_part]
N_part
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
100
200
300
400

$R_{AA}(J/\psi)$



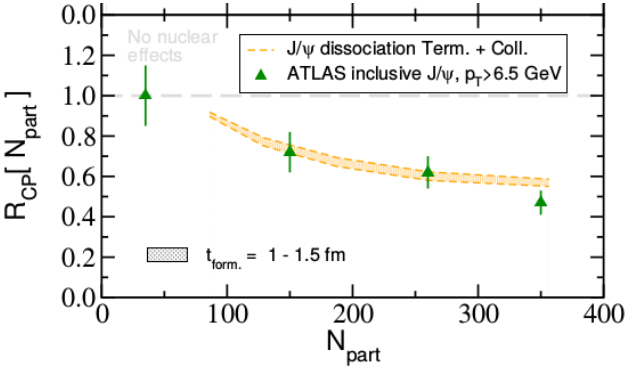
[Aaronson, Borras, Odegard, Sharma, Vitev (2017)] Both screening and dissociation

J/ψ without screening



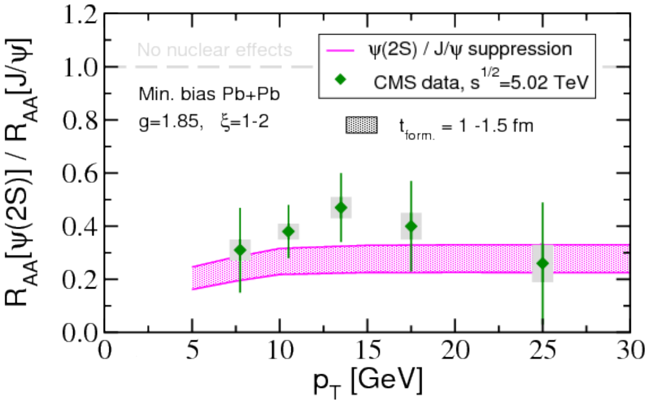
[Sharma, Vitev (2013)] Suppression not enough without screening

$R_{CP}(J/\psi)$



No nuclear effects
J/ψ dissociation Term. + Coll.
ATLAS inclusive J/ψ, p_T>6.5 GeV
t_form. = 1 - 1.5 fm
R_CP[N_part]
N_part
0.0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400

$R_{AA}(\psi(2S))/R_{AA}(J/\psi)$



Conclusions

- Screening is an important effect even for high p_T quarkonia
- Main uncertainty in our calculation due to τ_f
- In future look at high p_T data at finite y
- Predictions for 5.02TeV run also given in *[Aaronson, Borras, Odegard, Sharma, Vitev (2017): arXiv:1709.02372]*.

Centrality v/s N_{part}

centrality	N_{part}
$0 - 20\%$	307
$20 - 40\%$	130
$40 - 80\%$	35
$0 - 100\%$ (Min. Bias)	110

Medium parameters

for LHC 0-20%	PbPb	dNdy(g) = 2260 (b=4.5)
for RHIC 0-20%	AuAu	dNdy(g) = 925 (b=4.3)
for RHIC 0-20%	CuCu	dNdy(g) = 235 (b=3.5)

Additional scales at finite T

- In the medium, additional energy scales, T, m_D
- Central $T \sim 250$MeV at RHIC at 0.6fm
- $T \sim 310$MeV at LHC 2.76TeV
- $T \sim 370$MeV at LHC 5.5TeV
- Additional time scales: dissociation and screening time scales