Suppression of high-$p_T$ quarkonia in the QGP

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Separation of scales

- NRQCD is a concrete framework to calculate the production of high-$p_T$ quarkonia \cite{Bodwin1995}
- 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 \cite{Brambilla2004}
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.
- $v \sim \alpha(m_Qv)$ is the relative velocity of $Q$ and $\bar{Q}$.
- Inverse size $q \sim m_Qv$.
- $E_b \sim m_Qv^2$.
- Finally, the non-perturbative scale $\Lambda_{QCD}$.
- 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:
  - $m_c \sim 1.34\text{GeV}$
  - $m_c \nu \sim 0.6\text{GeV}$
  - $m_c \nu^2 \sim 0.5\text{GeV}$

- 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

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

- 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 (\( T \sim 400\text{MeV} \) 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 \([\text{See Ralf Rapp’s talk}]\)
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

\[ |\vec{P}^+\rangle = \int \frac{d^2k}{(2\pi)^3} \frac{dx}{2\sqrt{x(1-x)}} \frac{\delta_{c_1c_2}}{\sqrt{3}} \psi(x, k) \times a_Q^{\dagger} c_1 (x\vec{P}^+ + k) b_Q^{\dagger} c_2 ((1-x)\vec{P}^+ - k) |0\rangle , \]

where \( k \) corresponds to the momentum transverse to \( p_T \) and \( P^+ \) is the light cone momentum of the state parallel to \( p_T \)

\[ \psi(x, k) = \text{Norm} \times \exp \left( -\frac{k^2 + m_Q^2}{2\Lambda^2(T) x(1-x)} \right) \]

\( \Lambda \) 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 $k$ thus modifying the light cone wavefunction as the $Q\bar{Q}$ propagates in the medium: $k^2 \rightarrow k^2 + \Delta k^2$
- 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

\[ P_{\text{surv}}(t) = |\langle \Psi_T(t) | \Psi_T(0) \rangle|^2 \]

- Overlap with the ground state reduces due to momentum broadening

\[ \tau_{\text{diss}} = -\frac{1}{P_{\text{surv}}(t)} \frac{dP_{\text{surv}}(t)}{dt} \]
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 $\tau_{\text{form}}$ which we vary from $1 - 1.5\text{fm}$.
- 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 $\sigma_{\text{meson}}(t = 0; p_T) = 0$
- $\sigma_{Q\bar{Q}}(t = 0; p_T) = \sigma_{\text{meson}}(p_T)_{pp}$
- $\tau_{\text{diss}}$ cannot be smaller 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)]
- 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
$\tau'$

![Graph showing $1/t_{\text{diss.}}$ as a function of $t$ for different resonances.](image)

[Aaronson, Borras, Odegard, Sharma, Vitev (2017)]
$R_{AA}(\Upsilon)$

![Graph showing $R_{AA}[Y(nS)]$ vs. $p_T$]
$R_{AA}(\Upsilon)$

![Graph showing $R_{AA}[N_{\text{part}}]$ vs. $N_{\text{part}}$ for different conditions.]

- **Red line** with squares: $Y(1S)$ Therm.+Coll.
- **Blue dashed line** with circles: $Y(2S)$ Therm.+Coll.
- **Black circles with error bars**: CMS $Y(1S)$, $s^{1/2} = 2.76$ TeV
- **Pink hexagons**: CMS $Y(1S)$, $s^{1/2} = 2.76$ TeV

- **Legend**:
  - Pb+Pb, $s^{1/2} = 2.76$ TeV
  - $g = 1.85$, $\zeta = 1.2$, $t_{\text{form.}} = 1 - 1.5$ fm

- **Note**: No nuclear effects
Both screening and dissociation

[Aaronson, Borras, Odegard, Sharma, Vitev (2017)]
$J/\psi$ without screening

[Sharma, Vitev (2013)] Suppression not enough without screening
$R_{CP}(J/\psi)$
$R_{AA}(\psi(2S))/R_{AA}(J/\psi)$
Conclusions

- Screening is an important effect even for high $p_T$ quarkonia
- Main uncertainty in our calculation due to $\tau_f$
- 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].
<table>
<thead>
<tr>
<th>Centrality</th>
<th>$N_{part}$</th>
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<tbody>
<tr>
<td>0 – 20%</td>
<td>307</td>
</tr>
<tr>
<td>20 – 40%</td>
<td>130</td>
</tr>
<tr>
<td>40 – 80%</td>
<td>35</td>
</tr>
<tr>
<td>0 – 100% (Min. Bias)</td>
<td>110</td>
</tr>
</tbody>
</table>
Medium parameters

for LHC 0-20% PbPb  \( dN/dy(g) = 2260 \ (b=4.5) \)
for RHIC 0-20% AuAu  \( dN/dy(g) = 925 \ (b=4.3) \)
for RHIC 0-20% CuCu  \( dN/dy(g) = 235 \ (b=3.5) \)
Additional scales at finite $T$

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