Quarkonia in heavy-ion collisions
Introduction

- Quarkonia (Q-Qbar)
- c-cbar family
  - \( \eta_c, J/\psi, \psi(2S), \chi_c \ldots \)
- b-bbar family
  - \( \Upsilon(1S) \Upsilon(2S), \Upsilon(3S) \) and \( \chi_b \)

- In heavy-ion collisions, QGP is expected to screen the confining potential of Q-Qbar.

- Leads to melting of charmonium and bottomonium states, \( J/\psi, \psi(2S), \chi_c, \Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \) and \( \chi_b \).

- The melting temperature depends on the binding energy of the quarkonia state.

<table>
<thead>
<tr>
<th>Bound state ( T_d )</th>
<th>( \chi_c )</th>
<th>( \psi' )</th>
<th>( J/\psi )</th>
<th>( \Upsilon(2S) )</th>
<th>( \chi_b )</th>
<th>( \Upsilon(1S') )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lesssim T_c \lesssim T_c )</td>
<td>( \sim 1.2T_c )</td>
<td>( \sim 1.2T_c )</td>
<td>( \sim 1.3T_c )</td>
<td>( \sim 2.0T_c )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Introduction

• At high $v_{s_{NN}}$, many c-cbar pairs created.

• At the end of the evolution of the QGP, the uncorrelated c-cbar can combine together (regeneration)

• This leads to higher quarkonia yields.

• Last class:
  – Measurements at RHIC showed that the suppression is similar to SPS
  – Suppression in forward rapidity higher than mid rapidity → puzzle not understood.
Measurements at LHC (Inclusive J/ψ)

- Include J/ψ (prompt and non-prompt) measurement in ALICE.
- Use muons at forward rapidity and electron in mid-rapidity.
- $R_{AA}$ vs centrality (forward rapidity): suppression shows no dependence on centrality for $N_{\text{part}} > 70$.
- $R_{AA}$ vs centrality (mid rapidity): suppression constant w.r.t. centrality.
- $R_{AA}$ vs $p_T$ (forward rapidity): suppression increases with increase in $p_T \rightarrow$ regeneration happens at low $p_T$.
Measurements at LHC (Inclusive J/Ψ)

Suppression at LHC much lower than at RHIC → Regeneration could be the answer.

Suppression slightly larger at forward rapidity than at mid rapidity.
Measurements at LHC (Separate prompt and non-prompt J/Ψ)

Suppression of J/Ψ could be
1. Melting of c-cabr pairs (prompt)
2. Energy loss of b quark : b → J/Ψ (non-prompt)

- Lifetime of b hadrons (≈ 500 μm/c) longer than lifetime of QGP (≈ 10 fm/c).
- This contribution should not suffer from colour screening, but instead reflect b-quark energy loss in the medium.

To understand quarkonia melting, we look at prompt J/Ψ (CMS).
Measurements at LHC (prompt $J/\Psi$)

$R_{AA}$: do not exhibit $p_T$ dependence.
**Measurements at LHC (prompt J/Ψ)**

$R_{AA}$ vs. rapidity: indication of less suppression in the most forward rapidity bin in comparison to mid rapidity.

**Figure 10**: Left: yield of inclusive J/$\psi$ (blue circles) and prompt J/$\psi$ (red squares) divided by $1/T_{AA}$ as a function of $p_T$. The results are compared to the cross sections of inclusive J/$\psi$ (black triangles) and prompt J/$\psi$ (black crosses) measured in pp. The global scale uncertainties on the PbPb data due to $1/T_{AA}$ (5.7%) and the pp integrated luminosity (6.0%) are not shown. Right: nuclear modification factor $R_{AA}$ of prompt J/$\psi$ as a function of $p_T$. A global uncertainty of 8.3%, from $1/T_{AA}$ and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average $|y|$. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

**Figure 11**: Left: yield of inclusive J/$\psi$ (blue circles) and prompt J/$\psi$ (red squares) divided by $1/T_{AA}$ as a function of rapidity. The results are compared to the cross sections of inclusive J/$\psi$ (black triangles) and prompt J/$\psi$ (black crosses) measured in pp. The inclusive J/$\psi$ points are shifted by $D_y = 0.05$ for better visibility. The global scale uncertainties on the PbPb data due to $1/T_{AA}$ (5.7%) and the pp luminosity (6.0%) are not shown. Right: nuclear modification factor $R_{AA}$ of prompt J/$\psi$ as a function of rapidity. A global uncertainty of 8.3%, from $1/T_{AA}$ and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average $|y|$. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.
Measurements at LHC (prompt J/ψ)

- $R_{AA}$ vs. $N_{\text{part}}$: Same centrality dependence as the inclusive J/ψ.
- Suppressing increases with increase in centrality
  - Different from ALICE measurement, but ALICE measurement is in forward rapidity.
Measurement of $Y$ states

$Y$ states: $Y(1S), Y(2S), Y(3S)$

$$\frac{\Gamma(2S + 3S)}{\Gamma(1S)}|_{pp} = 0.78(0.18 - 0.16)$$

$$\frac{\Gamma(2S + 3S)}{\Gamma(1S)}|_{Pb-Pb} = 0.24(0.15 - 0.14)$$

$$\frac{\Gamma(2S + 3S)}{\Gamma(1S)}|_{Pb-Pb} = 0.31(0.21 - 0.18)$$

Figure 1: Dimuon invariant-mass distributions from the pp (a) and PbPb (b) data at $\sqrt{s_{NN}} = 2.76$ TeV. The same reconstruction algorithm and analysis criteria are applied to both data sets, including a transverse momentum requirement on single muons of $p_T > 4$ GeV/c. The solid lines show the result of the fit described in the text.
Measurement of Y states

Large fraction of Y(1S) states come from decays of heavier bottomonium states.

Does this effect Y(1S) suppression??
Measurement of $\Upsilon(1S)$ states

$R_{AA}$ vs $p_T$ : Significant suppression at low $p_T$.

Disappears for $p_T > 6.5$ GeV/c.

Low $p_T$ $\Upsilon(1S)$ could come from excited states, hence suppressed.

![Graph](image.png)
Measurement of \(Y(1S)\) states

\(R_{AA}\) vs. rapidity: Large statistical error to conclude on rapidity dependence.

\(R_{AA}\) vs. \(N_{\text{part}}\): No centrality dependence within uncertainties.
Back up
Measurements at LHC (Non-prompt J/Ψ)

Figure 13: $b$ fraction of $J/\psi$ production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of $p_T$ for the rapidity bins $|y| < 2.4$ and $1.6 < |y| < 2.4$, compared to $b$ fractions measured by CDF in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and by CMS in pp collisions at $\sqrt{s} = 7$ TeV. Points are plotted at their measured average $p_T$. Statistical (systematic) uncertainties are shown as bars (boxes).

Figure 14: Left: non-prompt $J/\psi$ yield divided by $1/T_{AA}$ (orange stars) as a function of $N_{\text{part}}$ compared to the non-prompt $J/\psi$ cross section measured in pp (black cross). Right: nuclear modification factor $R_{AA}$ of non-prompt $J/\psi$ as a function of $N_{\text{part}}$. A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Statistical (systematic) uncertainties are shown as bars (boxes).