Bottomonia suppression in 2.76 TeV Pb-Pb collisions

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details:

XII Quark Confinement and the Hadron Spectrum

Thessaloniki, Greece, 29 August – 3 September,
ultimate goal of heavy-ion collision experiments at RHIC and LHC is to study properties of QGP

hydrodynamic fits to the light hadron production at LHC top energies shows large initial temperatures of the system $T_0 \sim 600$ MeV, $\eta/s \approx 1/(4\pi) - 3/(4\pi)$

light hadronic states disassociate already around $T_c$

pNRQCD models show that heavy quarkonia may survive up to $\approx 4T_c$ ($T \sim 593, 228, 172$ MeV for $\Upsilon(1s), \Upsilon(2s)$, and $\Upsilon(3s)$)

due to mass and binding energy ordering of the quarkonium spectrum, one expects that there will be an approximate sequential disassociation - different stages can be distinguished

**bottomonia probe the early stages** of the collision when the system undergoes large momentum space anisotropies, $P_L < P_T$ – viscous hydrodynamics correction to the isotropic potential is too large

the early stages of the collision has to be treated with caution – an ideal tool is **anisotropic hydrodynamics**
the potential and dynamical equations are based on the effective LRF R-S distribution function for the QGP quasi-particles

\[ f(p, x) = f_{eq} \left( \frac{\sqrt{p_T^2 + (1 + \xi(x))p_z^2}}{\Lambda(x)} \right) \]

\(-1 \leq \xi(x) < \infty\) is the spheroidal momentum-space anisotropy parameter

\(\Lambda(x)\) is the local transverse temperature
Quarkonium potential

- **anisotropic short-range potential** has the form of a Debye-screened Coulomb potential with an anisotropic screening mass \( \mu = G m_D \)
  

  \[
  V_{\text{screened}}(r; \theta, \xi, \Lambda) = -C_F \alpha_s \frac{e^{-\mu(\theta, \xi, \Lambda)r}}{r}
  \]

- heavy-quark potential \( V \) in the QGP has both \( \Re \) and \( \Im \) parts
  

  for the \( \Re \) part use internal-energy-based potential with the free energy having the anisotropic KMS form
  

  \[
  \Re[V] = -\frac{a}{r} (1 + \mu) e^{-\mu r} + \frac{2\sigma}{\mu} (1 - e^{-\mu r}) - \sigma r e^{-\mu r} - \frac{0.8\sigma}{m_b^2 r}
  \]

- the \( \Im \) part is taken from LO perturbative calculation which was performed in the small-\( \xi \) limit
  

  \[
  \Im[V] = -\alpha_s C_F \Lambda \left\{ \phi(\mu r) - \xi [\psi_1(\mu r, \theta) + \psi_2(\mu r, \theta)] \right\}
  \]
solve the 3D Schrodinger equation with $V$ to obtain the $\Re$ and $\Im$ parts of the binding energy $E_{\text{bind}}(\xi, \Lambda)$


disassociation scale defined as $\Lambda_{\text{dis}}$ at which $\Re[E_{\text{bind}}] = \Im[E_{\text{bind}}]$; $\Lambda_{\text{dis}} \uparrow$ when $\xi \uparrow$

$\Im[E_{\text{bind}}]$ is used to obtain the width of each state

$$\Gamma(\Lambda, \xi) = \begin{cases} 2\Im[E_{\text{bind}}] & \Re[E_{\text{bind}}] > 0 \\ \gamma_{\text{dis}} = 10 \text{ GeV} & \Re[E_{\text{bind}}] \leq 0 \end{cases}$$
• \( \Gamma(\Lambda, \xi) \) is a local quantity that depends on \( \tau, x_\perp, \varsigma \) through \( \Lambda \) and \( \xi \)

• previous framework employed non-boost invariant & transversally-homogeneous (1+1)D anisotropic hydrodynamics (AHYDRO)

• update: for the evolution of the QGP background we use general (3+1)D anisotropic hydrodynamics framework

see M. Strickland talk on Monday

• IC are given by smooth Glauber model with rapidity profile consistent with experimentally observed light particle multiplicity distributions
integrating the instantaneous local decay rate one obtains \( R_{AA} \)

\[
R_{AA}(p_T, y, x_\perp, b) = e^{-\zeta(p_T, y, x_\perp, b)}
\]

\[
\zeta \equiv \Theta(\tau_f - \tau_{\text{form}}) \int_{\max(\tau_{\text{form}}, \tau_0)}^{\tau_f} d\tau \Gamma(\tau, x_\perp, \zeta = y)
\]

\( \tau_{\text{form}} = \gamma \tau_{0,\text{form}}^0 = E_T \tau_{0,\text{form}}^0 / M \) where \( M \) is the mass of the state

rest-frame **formation times** \( \tau_{0,\text{form}}^0 \) are roughly proportional to the inverse vacuum binding energy


\( \tau_{0,\text{form}}^0 = 0.2, 0.4, 0.6, 0.4, 0.6 \) fm/c

for \( \Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_{b1}, \chi_{b2} \) states
Comparison with the data - prerequisites

- **spatial average**

\[ R_{AA}(p_T, y, b) = \frac{\int_{x_\perp} n(x_\perp, \varsigma) R_{AA}(p_T, y, x_\perp, b)}{\int_{x_\perp} n(x_\perp, \varsigma)} \]

- **transverse-momentum average**


\[ R_{AA}(y, x_\perp, b) \equiv \frac{\int_{p_T,\text{max}}^{p_T,\text{min}} dp_T^2 R_{AA}(p_T, y, x_\perp, b)/\left(p_T^2 + M^2\right)^2}{\int_{p_T,\text{min}}^{p_T,\text{max}} dp_T^2/\left(p_T^2 + M^2\right)^2} \]

- **rapidity average – flat distribution**

- **centrality average**: first convert \( b \rightarrow C \) using Glauber formalism

**update**: then integrate over centrality using probability function \( e^{-C/20} \)

S. Chatrchyan et al. (CMS Collaboration), J. High Energy Phys. 05 (2012) 063
"Raw" state suppression factors, $R_{AA}^I(N_{part})$

- sequential suppression of the states
- no thresholds visible as originally predicted by sequential suppression


- averaging over the full temperature distribution in the transverse plane
- the continuous decays of the states prior to their disassociation point
Feed down of excited states, inclusive $R_{AA}(N_{part})$

- **update**: use recent $p_T$-averaged feed-down fractions from ATLAS, CMS and LHCb p-p data
  
  \[ f_i^{\Upsilon(1s)} = \{0.618, 0.105, 0.02, 0.207, 0.05\} \]
  
  \[ i \in \{\Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_{b1}, \chi_{b2}\} \]
  

  \[ f_j^{\Upsilon(2s)} = \{0.5, 0.5\} \]
  
  \[ j \in \{\Upsilon(2s), \Upsilon(3s)\} \]
  

- compare to the new preliminary data from CMS
  

- $\Upsilon(1s)$ data prefer small shear viscosities in the range $1 \lesssim 4\pi\eta/s \lesssim 2$

- no tight constraint from $\Upsilon(2s)$
**Inclusive $R_{AA}(p_T)$**

- Flatness was predicted already in the original model

- Slow $R_{AA}$ increase is an effect of time dilation of the formation times

- $R_{AA}^{\gamma(2s)}$ underpredicted

- $R_{AA}^{\gamma(1s)}$ data prefer small $\eta/s$ values
use ALICE data at forward rapidities

lingering tension with the ALICE forward results

much closer to the ALICE data comparing to previous results
(due to centrality averaging procedure)
several updates to the model were made:
- QGP background evolution performed with (3 + 1)D anisotropic hydrodynamics
- mixing fractions were updated based on recent ATLAS, CMS, and LHCb data
- method for performing centrality averaging was corrected

original model with the updates reasonably describes the $N_{\text{part}}$, $y$ and $p_T$ dependence of $R_{AA}$ data for $\Upsilon(1s)$ and $\Upsilon(2s)$ states in midrapidity region $y < 2$

underprediction of the suppression at forward rapidities seen by ALICE is reduced, could be explained by cold-nuclear-matter effects (?)