Bottomonium suppression at RHIC and LHC

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Clear evidence of suppression

High energy proton-proton collision

High energy nucleus-nucleus collision

X \, N_{\text{binary}}^? \\
\text{e.g. } A=208
Clear evidence of suppression

High energy proton-proton collision

\[ p \rightarrow b \bar{b} \ (\gamma^{(1S)}) \]

High energy nucleus-nucleus collision

\[ X \ N_{binary}\ ? \]

\[ e.g. \ A=208 \]

C. Flores, QM2017
Clear evidence of suppression

High energy proton-proton collision

$p\ p$ → $b\ b^{\prime}$

$\gamma^{(1S)}$

High energy nucleus-nucleus collision

$\sqrt{s} = 5.02\ TeV$

CMS Preliminary

Events/(GeV/c^2)

$J/\psi$

$\psi(2S)$

$\gamma(1,2,3S)$

$Z$

$p_{\mu}^\prime > 4\ GeV/c$

C. Flores, QM2017

B. Kroupa
Pieces of the suppression puzzle

Other effects

Effective partonic luminosity modification in nuclei via nuclear modified PDFs due to saturation of the parton kinematics phase space, multiple scattering of partons in the nucleus before and after the hard scattering, the absorption or break-up of quarkonium states, and the interaction of quarkonium states with other particles produced in the collision (denoted as comovers).

[arXiv:1506.03981]

Thermal suppression

The hot QGP provides a violent medium where gluonic dampening causes the heavy quarkonium state to melt. Quarkonia are sensitive to the full spatiotemporal evolution of the QGP. Need to compute dynamical processes including non-equilibrium correction.

Regeneration

If the population of open- and closed-charm states is high, then it is possible for quarkonia to be regenerated through recombination of liberated heavy quarks (swapping dance partners). There can also be local recombination of an individual bound state due to medium interactions (square dancing).
Suppression as a thermometer

Solve the 3d Schrödinger EQ with (two) complex-valued potentials

Obtain real and imaginary parts of the binding energies for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b(1P)$, $\chi_b(2P)$, and $\chi_b(3P)$ as function of energy density and anisotropy. Yager-Elorriaga and MS, 0901.1998; Margotta, MS, et al, 1101.4651

Fold together with the non-EQ spatiotemporal evolution to obtain the survival probability.
Heavy quark potential (Rothkopf)

shifted IQCD $N_f=2+1$ asqtad data & Gauss–law fit
Bottomonium results – 200 GeV Au-Au

- QGP thermometer is continuous!

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**Strickland-Bazow bottomonia**

- $Y(1S)\ |y|<0.5\ \sqrt{s}_{NN}=0.2\ \text{TeV}\ 0<pt<20\ \text{GeV}$

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**Rothkopf bottomonia**

- $Y(1S)\ 4\pi\eta/s=2\ |y|<0.5\ \sqrt{s}_{NN}=0.2\ \text{TeV}\ 0<pt<20\ \text{GeV}$

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B. Krouppa

arXiv:1710.02319
Bottomonium results – 200 GeV Au-Au

\[ \Upsilon(1S) \]
\[ 4\pi\eta/s = 2 \text{ (lattice–vetted)} \]
\[ |y| < 0.5 \]
\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]
\[ 0 < p_T < 20 \text{ GeV} \]

STAR Data

\[ R_{AA} \]
\[ N_{\text{part}} \]
Reality check: regeneration (theorizing)

- Larger collision energies and lighter (charm) quark mass
Reality check: regeneraZon (theorizing)

- Larger collision energies and lighter (charm) quark mass
Reality check: regeneration (theorizing)

- Larger collision energies and lighter (charm) quark mass

$M_{\text{kitter}} < M_{\text{pupper}}$

Mike Strickland’s new kitten

Source: Google

Both have a finite mass $\rightarrow$ Regeneration possible!
Reality check: regeneration (experimental data)

- No significant centrality dependence for ALICE $N_{\text{part}} > 70$
- Stronger $J/\psi$ suppression at RHIC at mid and forward rapidity!
- Evidence of regeneration of charmonia states?
Reality check: regeneration (other models)

Models

**TM1**: Zhao-Rapp NPA 859 (2011) 114

**TM2**: Zhou et al., PRC 89 (2014) 054911

### Figures

1. **Figure 1**: Graph showing $R_{AA}$ as a function of $p_T$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au at $\sqrt{s_{NN}} = 0.2$ TeV. The graph includes data from ALICE and PHENIX, with error bars indicating statistical uncertainties.

2. **Figure 2**: Graph comparing $R_{AA}$ for $J/\psi \rightarrow \mu^+\mu^-$ at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 0.2$ TeV, showing the trend and comparison with theoretical predictions.

### Text

- **Models**
  - **TM1**: Zhao-Rapp NPA 859 (2011) 114
  - **TM2**: Zhou et al., PRC 89 (2014) 054911

- **Graph 1**: Inclusive $J/\psi \rightarrow \mu^+\mu^-$, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au $\sqrt{s_{NN}} = 0.2$ TeV

  - ALICE, $2.5 < y < 4$, 0-20% global syst. = ± 8%
  - PHENIX, $1.2 < |y| < 2.2$, 0-20% global syst. = ± 10%

- **Graph 2**: Comparison of $R_{AA}$ for $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow \rho^+\rho^-$, showing the impact of different models.

### References

- B. Krouppa
Reality check: regeneration (for our model)

- Based on the rate equation

\[
\frac{dn(\tau, x)}{d\tau} = -\Gamma(T(\tau, x)) \left[ n(\tau, x) - n_{eq}(T(\tau, x)) \right]
\]
Reality check: regeneration (for our model)

- Based on the rate equation

\[
\frac{dn(\tau, x)}{d\tau} = -\Gamma(T(\tau, x)) \left[ n(\tau, x) - n_{eq}(T(\tau, x)) \right]
\]
Reality check: a regeneration component

- Based on the rate equation
  \[ \frac{dn(\tau, x)}{d\tau} = -\Gamma(T(\tau, x)) [n(\tau, x) - n_{eq}(T(\tau, x))] \]

- Factor of $\gamma^2$ in $n_{eq}(T(\tau, x))$

\[ n_{eq}(T, \gamma_q) = 3\gamma^2_q(T) \int \frac{d^3q}{(2\pi)^3} f(m; T) \]

- Fugacity factor driving statistical regeneration
- Calculated for bottomonia (left)
Reality check: a regeneration component

- Based on the rate equation \( \frac{dn(\tau, x)}{d\tau} = -\Gamma(T(\tau, x)) [n(\tau, x) - n_{eq}(T(\tau, x))] \)

- Factor of \( \gamma^2 \) in \( n_{eq}(T(\tau, x)) \)

\[
N_{q\bar{q}} = \frac{1}{2} N_{op} \frac{I_1(N_{op})}{I_0(N_{op})} + N_{hid}
\]

\[
N_{op} = \gamma_q V_{coll} d_b \int \frac{d^3p}{(2\pi)^3} f^q(p; T)
\]

\[
N_{hid} = \gamma_q^2 V_{coll} \sum_{\text{states}} d_{\text{states}} \int \frac{d^3p}{(2\pi)^3} f_{\text{states}}(p; T)
\]
Bottomonium results – 5.02 TeV Pb-Pb

Strickland-Bazow bottomonia

Preliminary Result

Rothkopf bottomonia

Y(1S) 4πη/s = 1
|y|< 2.4
\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]
0 < p_T < 30 GeV

B. Krouppa
Bottomonium results – 5.02 TeV Pb-Pb

Strickland-Bazow bottomonia

Preliminary Result

$\sqrt{s_{NN}} = 5.02$ TeV
$0 < p_T < 30$ GeV

Rothkopf bottomonia

Preliminary Result

$\sqrt{s_{NN}} = 5.02$ TeV
$0 < p_T < 30$ GeV

CMS Data
Bottomonium results – 5.02 TeV Pb-Pb

- Small amount of regeneration seen in the mid-rapidity window
- Charmonium expt. data showed regeneration for mid AND forward rapidity
- Indicates less significance for bottomonium regeneration
Bottomonium results – 5.02 TeV Pb-Pb

- Regeneration component occurs mostly for low-\textit{pt} bottomonia
- Regeneration effect is small for relatively massive bottomonia (only mid-rapidity)
- Charmonium state data just finished running

\begin{align*}
\sqrt{s_{\mathrm{NN}}} = 5.02 \, \text{TeV} \\
0 - 100\%\,\text{centrality} \\
|y| < 2.4
\end{align*}

\begin{align*}
4\pi\eta/s = 1 \\
4\pi\eta/s = 2 \\
4\pi\eta/s = 3
\end{align*}

B. Krouppa
Thank you

Comparison
Between Strickland-Bazow and Rothkopf potentials.

Charmonia
Still reviewing the charmonia calculation; coming soon.

Thermal suppression
Explains the bulk of bottomonium suppression data.

Regeneration
Inclusion of a local regeneration model.
Extra Slides
Extra – CNM effect for bottomonium

• Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt
• Effect seems to be quite small (max ~10%)
Extra - anisotropic hydrodynamics basics

Viscous Hydrodynamics Expansion

\[ f(\tau, x, p) = f_{\text{eq}}(p, T(\tau, x)) + \delta f \]

Isotropic in momentum space

Anisotropic Hydrodynamics (aHydro) Expansion

\[ f(\tau, x, p) = f_{\text{aniso}}(p, \Lambda(\tau, x), \xi(\tau, x)) + \delta \tilde{f} \]

Non-equilibrium corrections from e.g. shear stress

Treat this term perturbatively \( \rightarrow \) “NLO aHydro”

“Romatschke-Strickland” form in LRF

\[ f^{\text{LRF}}_{\text{aniso}} = f_{\text{iso}} \left( \frac{\sqrt{p^2 + \xi(x, \tau)p^2_z}}{\Lambda(x, \tau)} \right) \]

\[ \xi = \frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} - 1 \]

-1 < \xi < 0 \hspace{1cm} \xi = 0 \hspace{1cm} \xi > 0

pulate \hspace{1cm} oblate

B. Krouppa


\[
\sqrt{s_{NN}} = 2.76 \text{ TeV} \\
|y| < 2.4 \\
0 < p_T < 40 \text{ GeV}
\]

\[
\mu \eta \approx 2.76 \text{ TeV} \\
-4 \pi \eta / s = 1 \\
-4 \pi \eta / s = 2 \\
-4 \pi \eta / s = 3 \\
\bullet \ Y(1S) \ CMS \\
\bigcirc \ Y(2S) \ CMS
\]

\[
\sqrt{s_{NN}} = 5.02 \text{ TeV} \\
|y| < 2.4 \\
0 < p_T < 30 \text{ GeV}
\]

\[
\mu \eta \approx 5.02 \text{ TeV} \\
-4 \pi \eta / s = 1 \\
-4 \pi \eta / s = 2 \\
-4 \pi \eta / s = 3 \\
\bullet \ Y(1S) \ CMS \\
\bigcirc \ Y(2S) \ CMS
\]
Extra – QM2017 results – ALICE $N_{\text{part}}$

$\sqrt{s_{\text{NN}}} = 5.02$ TeV

$2.5 < y < 4.0$

$0 < p_T < 15$ GeV

$\Upsilon(1S)$ ALICE

Strickland-Bazow Potential
Extra – QM2017 results – Combined $|y|$
Extra – QM2017 results – $p_T$

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ 2.5 < y < 4.0 \]
\[ 0-100\% \]

$\Upsilon^{(1S)}$ ALICE

$\Upsilon^{(2S)}$

$\Upsilon^{(3S)}$

\[ \frac{\pi\eta}{\pi\eta} = \frac{\pi\eta}{\pi\eta} = \frac{\pi\eta}{\pi\eta} \]

Strickland-Bazow Potential