Quarkonium measurements in heavy-ion collisions at STAR

Pengfei Wang (for the STAR Collaboration)

University of Science and Technology of China
Brookhaven National Laboratory
Outline

- Introduction
- STAR experiment
- Charmonium measurements
- Bottomonium measurements
- Summary
Why Quarkonium?

- **Color-screening**: quark-antiquark potential is color-screened by the surrounding partons -> *dissociation*

- However, other effects come into play
  - Regeneration
  - Medium-induced energy loss
  - Feed-down
  - Cold Nuclear Matter (CNM) effects

- “Thermometer”: different states dissociate at different temperatures -> *sequential melting*

---

A. Mocsy, EPJ C61 (2009) 705
The Solenoidal Tracker at RHIC

Mid-rapidity coverage: $|\eta| < 1$, $0 < \phi < 2\pi$

- **TPC**
  - Tracking, PID
- **TOF**
  - Measure time of flight
- **BEMC**
  - Trigger and identification of high-$p_T$ electrons
- **MTD** ($|\eta| < 0.5$, 45% in $\phi$)
  - Dimuon trigger and muon identification
  - Less bremsstrahlung: helps separate $\Upsilon(2S+3S)$ from $\Upsilon(1S)$
Charmonium

- Large production cross-section at RHIC energy
- Interplay of several effects
Inclusive $J/\psi$ in $p+p$ collisions

- Inclusive $J/\psi$ cross-section is measured in $0 < p_T < 14$ GeV/c
- CGC+NRQCD (prompt $J/\psi$) calculations are consistent with the data within uncertainties. However, the data are close to the lower uncertainty boundary of the theoretical calculation.
- NLO NRQCD (prompt $J/\psi$) describes the data reasonably well in $4 < p_T < 14$ GeV/c.
- Improved CEM model (direct $J/\psi$) describes data well at low $p_T$, but underpredicts data in $3.5 – 10$ GeV/c. Feed-down contribution from excited charmonium states is about 40%.
- Feed-down contribution from bottom hadrons is predicted to be approximately ~10-25% in $4 < p_T < 14$ GeV/c.

Run 12, STAR, PLB 786 (2018) 87
CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029
S. Digal, P. Petreczky & H. Satz, PRD 64 (2001) 094015
J/ψ $R_{pAu}$ at 200 GeV

- $R_{pAu}$ is less than unity at low $p_T$ and is consistent with unity at high $p_T$ -> suppression at low $p_T$
- $R_{pAu}$ is consistent with $R_{dAu}$ within uncertainties -> similar CNM effects in these collision systems
  - There seems to be tension at $3.5 < p_T < 5$ GeV/c with a significance of $1.4\sigma$
J/ψ $R_{pAu}$ at 200 GeV

- Model calculations with only nPDF effects describe the data at high $p_T$, but underpredicts the suppression at low $p_T$
- Additional nuclear absorption is favored by data

EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao,
Comp. Phys. Comm. 198 (2016) 238
Ferreiro et al., Few Body Syst. 53 (2012) 27
Central collisions: significant suppression is observed for both low $p_T$ and high $p_T (> 5$ GeV/c) $J/\psi \rightarrow \mu^+\mu^-$.

Peripheral collisions: $R_{AA}$ of $J/\psi$ for $p_T > 0$ GeV/c is smaller than that for $p_T > 5$ GeV/c probably due to CNM effects.
**J/ψ R_{AA}: RHIC vs. LHC**

**p_{T} > 0 GeV/c**  
- STAR: Au+Au, √s_{NN} = 200 GeV, J/ψ → μ⁺μ⁻, |y| < 0.5
- PHENIX: Au+Au, √s_{NN} = 200 GeV, J/ψ → e⁺e⁻, |y| < 0.35
- ALICE: Pb+Pb, √s_{NN} = 2.76 TeV, J/ψ → e⁺e⁻, |y| < 0.8

**p_{T} > 5 GeV/c**  
- STAR: Au+Au, √s_{NN} = 200 GeV, J/ψ → μ⁺μ⁻, |y| < 0.5
- CMS: Pb+Pb, √s_{NN} = 2.76 TeV, |y| < 2.4, p_{T} > 6.5 GeV/c

---

- **p_{T} > 0 GeV/c:** less suppressed at the LHC in central events -> larger regeneration contribution due to higher charm cross-section
- **p_{T} > 5 GeV/c:** more suppressed at the LHC in all centralities -> higher dissociation rate due to higher temperature
**J/ψ R_{AA}: data vs. models**

**p_T > 0 GeV/c**

- STAR: Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $J/\psi \rightarrow \mu^+\mu^-$, $|y| < 0.5$
- PHENIX: Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $J/\psi \rightarrow e^+e^-$, $|y| < 0.35$
- ALICE: Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $J/\psi \rightarrow e^+e^-$, $|y| < 0.8$

**p_T > 5 GeV/c**

- STAR: Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $J/\psi \rightarrow \mu^+\mu^-$, $|y| < 0.5$
- CMS: Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $|y| < 2.4$, $p_T > 6.5$ GeV/c

---

- $p_T > 0$ GeV/c: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at the LHC
- $p_T > 5$ GeV/c: both models can qualitatively describe data

---

Tsinghua at RHIC: PLB 678 (2009) 72, Tsinghua at LHC: PRC 89 (2014) 054911
Bottomonium

- Small production cross-section at RHIC energy
- A cleaner probe at RHIC
  - Regeneration is smaller compared to $J/\psi$
  - Co-mover absorption for $\Upsilon(1S)$ is expected to be small
\[ \Upsilon \text{ cross-section in } p+p \text{ collisions} \]

\[ \Upsilon(1S+2S+3S) \]

\[ B \cdot d\sigma_{\Upsilon}/dy, (pb) \]

\[ 10^{-1} \quad 1 \quad 10 \quad 10^2 \quad 10^3 \]

\[ \sqrt{s} \text{ (GeV)}^{10^3} \]

- \text{p+p@200 GeV: } \sigma = 81 \pm 5\text{(stat.)} \pm 8\text{(syst.) pb} \]
- \text{Baseline for p+A and A+A collisions with improved precision} \]
- \text{Consistent with the Color Evaporation Model (CEM) prediction}
\( \Upsilon(1S+2S+3S) R_{pAu} \) at 200 GeV

\[ p+Au@200 \text{ GeV: } R_{pAu} = 0.82 \pm 0.10(\text{stat.}) ^{+0.08}_{-0.07} \text{ (syst.)} \pm 0.10 \text{ (global)} \]

- Indicates CNM effects
- Additional suppression mechanism beyond nPDF effects seems to be needed
**Y suppression at RHIC**

- **Improved precision of Y measurements**
  - Combining 2016 data with those taken in 2014 and 2011 (di-muon and di-electron results are combined)

  - **Y(1S):**
    - Stronger suppression towards central collisions
  - **Y(2S+3S):**
    - Stronger suppression in more central collisions
  - More suppressed than Y(1S) in 0-10% central collisions -> sequential melting
**Y suppression at RHIC**

**Y(1S):**

\[ Y(1S): \]

\[ Y(1S) R_{AA} \]

\[ p_T \text{ (GeV/c)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4 \]

- STAR Au+Au@200 GeV (0-60%)
- \( Y(1S) \rightarrow \mu^+\mu^-, |y|<0.5 \)

**STAR Preliminary**

**Y(2S+3S):**

\[ Y(2S+3S): \]

\[ Y(2S+3S) R_{AA} \]

\[ p_T \text{ (GeV/c)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4 \]

- STAR Au+Au@200 GeV (0-60%)
- \( Y(2S+3S) \rightarrow \mu^+\mu^-, |y|<0.5 \)

**STAR Preliminary**

**Y(1S) and Y(2S+3S):**

- No significant \( p_T \) dependence
$\Upsilon(1S)$ suppression: RHIC vs. LHC

$\Upsilon(1S)$ suppression is similar at RHIC and the LHC:

- Similar CNM effects ($\sim$ 20-30%)
- Suppression of excited $\Upsilon$ states

CMS, PLB 770 (2017) 357
\( \Upsilon(2S+3S) \) suppression: RHIC vs. LHC

\( \Upsilon(2S+3S) \):
- Indication of less suppression at RHIC than at the LHC in peripheral collisions

\[ \text{CMS, PLB 770 (2017) 357} \]
Young suppression: data vs. models

Both models show good agreement with data:
- Rothkopf: Complex potential (lattice QCD); No CNM or regeneration effects
- Rapp: T-dependent binding energy; Includes CNM and regeneration effects

**γ(2S+3S) suppression: data vs. models**

- Rapp model describes data
- Rothkopf model calculation is lower than data in 30-60%
Summary

- **p+p collisions**
  - Models describe the quarkonium production cross-section reasonably well (e.g. CEM, NRQCD, etc)

- **p+Au collisions**
  - $J/\psi \, R_{pA}$ favors additional nuclear absorption on top of nPDF effect
  - $\Upsilon(1S+2S+3S) \, R_{pA}$: indication of $\Upsilon$ suppression due to CNM effects

- **Au+Au collisions**
  - $J/\psi$:
    - Clear $J/\psi$ suppression at $p_T > 5$ GeV/c in central collisions $\rightarrow$ dissociation
    - $J/\psi \, R_{AA}$ can be qualitatively described by transport models including dissociation and regeneration
  - $\Upsilon(1S)$:
    - Indication of increasing suppression towards central collisions
    - Similar suppression as that at the LHC
    - Model predictions are consistent with data
  - $\Upsilon(2S+3S)$:
    - More suppressed than $\Upsilon(1S)$ in 0-10% central collisions $\rightarrow$ sequential melting