Quarkonium measurements with the STAR experiment

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- Introduction
- STAR experiment
- Charmonium
- Bottomonium
- Summary
Why quarkonium?

- **Color-screening**: quark-antiquark potential is color-screened by the surrounding partons -> *dissociation*
  
  - J/ψ suppression was proposed as a direct proof of QGP formation [T. Matsui and H. Satz, PLB 178 (1986) 416]

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

  Illustration: A. Rothkopf

A. Mocsy, EPJ C61 (2009) 705
However, different effects in play...

- **Hot medium effects:**
  - Dissociation
  - Regeneration
  - Medium induced energy loss
  - Formation time

- **Feed-down contributions**

- **Cold nuclear matter effects (CNM)**
Cold nuclear matter effects

- **nPDF**: modification of parton distribution functions in nucleus

- **Nuclear absorption**

- **Interaction with co-movers**

- **Energy loss**

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Ferreiro et al., PRC 81 (2010) 064911

Gavin et al., PRL 78 (1997) 1006

Capella and Ferreiro, EPJC 42 (2005) 419
STAR detector

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

- **TPC**: tracking and PID (dE/dx)
- **TOF**: PID ($1/\beta$)
- **BEMC**: trigger on and identify high-$p_T$ electrons
- **MTD** ($|\eta| < 0.5$, 45% azimuthal coverage): trigger on and identify muons
  - Less bremsstrahlung: help separate $\Upsilon(2S+3S)$ from $\Upsilon(1S)$
Charmonium

- **Advantage:** large cross section at RHIC energy
- **Disadvantage:** interplay of several effects
Inclusive $J/\psi$ cross section in pp@200 GeV

- Inclusive $J/\psi$ cross section is measured in $0 < p_T < 14$ GeV/c
- CGC+NRQCD & NLO NRQCD (prompt $J/\psi$) model calculations can describe data in the full $p_T$ range
- Improved CEM model (direct $J/\psi$) describes data well at low $p_T$
  - Data are above ICEM calculation at $3.5 < p_T < 12$ GeV/c
- $\sim$10-25% feed-down contribution from bottom hadrons in $4 < p_T < 14$ GeV/c.

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CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029
First $J/\psi$ $R_{pAu}$ measurement at RHIC

- $R_{pAu}$ is consistent with unity at high $p_T$ and is less than unity at low $p_T$

- $R_{pAu}$ is consistent with $R_{dAu}$ within uncertainty
  - There seems to be tension at $3 < p_T < 5$ GeV/c with $1.4\sigma$ significance

- Suggests similar CNM effects in these collision systems
$J/\psi \ R_{pAu}$ at 200 GeV

- Model calculations with only shadowing effect can touch the upper limit of data within uncertainties
- Additional nuclear absorption is favored by data

Ferrerio et al., Few Body Syst. 53 (2012) 27

EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao,
Comp. Phys. Comm. 198 (2016) 238

6/13/18
Shuai Yang, RHIC & AGS Annual Users' Meeting
Central collisions: significant suppression in both $p_T > 0$ and $p_T > 5$ GeV/c -> interplay of different effects

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 cold nuclear matter effects
Centrality dependence: RHIC vs. LHC

STAR preliminary

\[ p_T > 0 \text{ GeV/c} \]

\[ p_T, J/\psi > 0 \text{ GeV/c} \]

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

- STAR data are consistent with PHENIX
- \( p_T > 0 \text{ GeV/c} \): less suppressed at LHC in central events -> larger regeneration contribution due to larger charm cross-section at LHC
Centrality dependence: RHIC vs. LHC

**STAR data are consistent with PHENIX**

- $p_T > 0$ GeV/c: less suppressed at LHC in central events -> larger regeneration contribution due to higher charm cross-section
- $p_T > 5$ GeV/c: more suppressed at LHC in all centralities -> higher dissociation rate due to higher temperature

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**RHIC vs. LHC**

- $p_T > 0$ GeV/c: RHIC data are less suppressed compared to LHC.
- $p_T > 5$ GeV/c: RHIC data are more suppressed compared to LHC.

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**STAR Preliminary Results**

- $p_T > 0$ GeV/c: STAR data are consistent with PHENIX.
- $p_T > 5$ GeV/c: RHIC data are more suppressed compared to LHC.

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**RHIC Experiments**

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

- **PHENIX**
  - Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $J/\psi \rightarrow e^+e^-$, $|y| < 0.5$, $p_T > 5$ GeV/c
  - Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $J/\psi \rightarrow e^+e^-$, $|y| < 2.4$, $p_T > 6.5$ GeV/c

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**LHC Experiments**

- **ALICE**
  - Pb+Pb, $p_T > 0$ GeV/c
  - Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $J/\psi \rightarrow e^+e^-$, $|y| < 0.8$

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**References**

- ALICE, PLB 734 (2014) 314
- PHENIX, PRL 98 (2007) 232301
- PHENIX, PRL 98 (2007) 232301
- CMS, JHEP 05 (2012) 063
- CMS, JHEP 05 (2012) 063
- STAR data are consistent with PHENIX.
Comparison to models

$p_T > 0 \text{ GeV/c}$: both models can describe centrality dependence at RHIC, but tend to overestimate suppression at LHC

$p_T > 5 \text{ GeV/c}$: there is tension among models and data

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

- **Advantage:** a cleaner probe at RHIC
- **Disadvantage:** small production cross section
\( \Upsilon \) results in pp and pAu collisions

- **p+p@200 GeV**: \( \sigma = 81 \pm 5 \text{(stat.)} \pm 8 \text{(syst.)} \) pb
  - Baseline for p+A/A+A collisions with improved precision
  - Consistent with the Color Evaporation Model (CEM) prediction
- **p+Au@200 GeV**: \( R_{pAu} = 0.82 \pm 0.10 \text{(stat.)} \pm 0.10 \text{(global)} \)
  - Indicates CNM effects
  - Additional suppression mechanism seems needed beyond nPDF effects

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\( \Upsilon(1S+2S+3S) \) STAR Preliminary

\[ B \cdot d\sigma / dy \big|_{y=0} \]

\( NLO \text{ CEM, MRST HO, } m=4.75 \text{ GeV}/c^2, m/\mu=1 \)

\( s (\text{GeV}) \)

\[ \Ypsilon(s) = 200 \text{ GeV}, \quad \STAR \]  
\[ \Ypsilon(s) = 500 \text{ GeV}, \quad \STAR \]  
\[ \Ypsilon(s) = 200 \text{ GeV Published, } |y| < 0.5 \]

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STAR Preliminary

\[ R_{pAu} \text{ (p+p@200 GeV)} \]

\[ |y| < 0.5 \]

\[ \STAR, \ PLB \, 735 \, (2014) \, 127 \]

\[ \text{PHENIX, PRC} \, 87 \, (2013) \, 044909 \]

\[ R. \ Vogt \, \text{et al.,} \ \text{PoS ConfinementX} \, 203 \, (2012) \]

\[ F. \ Arleo \, \text{and} \, S. \ Peigne, \ \text{JHEP} \, 1303 \, (2013) \, 122 \]

\[ K. \ J. \ Eskola \, \text{et al.,} \ \text{JHEP} \, 0904 \, (2009) \, 065 \]
Results from di-muon and di-electron channels are consistent within uncertainty
- Statistics hungry -> combine results from two decay channels

<table>
<thead>
<tr>
<th>Datasets</th>
<th>2014</th>
<th>2014+2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>14.2 nb⁻¹</td>
<td>27 nb⁻¹</td>
</tr>
<tr>
<td>( \Upsilon(1S) )</td>
<td>149±18</td>
<td>266±26</td>
</tr>
</tbody>
</table>


\( \Upsilon(1S) \ R_{AA} \ vs. \ centrality \ at \ RHIC \)

- **Indication of more suppression towards central collisions**
- **Is direct \( \Upsilon(1S) \) suppressed?**
  - \( \Upsilon(1S) \ R_{AA} \) in 0-10% central collisions: \( 0.50 \pm 0.06 \text{(stat.)} \pm 0.05 \text{(syst.)} \pm 0.06 \text{ (global)} \)
  - \( \sim30\% \) \( \Upsilon(1S) \) from feed down contribution of excited states
  - \( R_{pAu}(1S+2S+3S) = 0.82 \pm 0.10 \text{(stat.)}^{+0.08}_{-0.07} \text{ (syst.)} \pm 0.10 \text{ (global)} \)
  - Unlikely to happen at top RHIC energy

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More suppression in 0-30% central collisions than 30-60%
More suppression compared to $\Upsilon(1S)$ in 0-10% centrality -> consistent with “sequential melting” expectation
$\Upsilon(1S)$ and $\Upsilon(2S+3S) R_{AA}$ vs. $p_T$ at RHIC

- No clear $p_T$ dependence

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\( \Upsilon(1S) R_{AA} : \) RHIC vs. LHC

- \( \Upsilon(1S) \) suppression: similar at RHIC and LHC energies!
  - CNM + suppression of excited states?

\[ \text{CMS, PLB 770 (2017) 357} \]
\( \Upsilon(2S+3S) R_{AA}^{RHIC} : RHIC \text{ vs. LHC} \)

\[ \begin{align*}
R_{AA}^{RHIC} & \text{ are consistent with } R_{AA}^{LHC} \text{ within uncertainty, but systematically higher} \\
\text{• Indication of less suppression at RHIC than at LHC?}
\end{align*} \]

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STAR Preliminary

\[ \begin{align*}
\text{CMS, PLB 770 (2017) 357}
\end{align*} \]
What do models say at RHIC? - $\Upsilon(1S)$

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

X. Du, M. He, and R. Rapp, PRC 96, 054901 (2017)
What do models say at RHIC? - $\Upsilon(2S+3S)$

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

Can models consistently describe the data at RHIC and at LHC? - $\Upsilon(1S)$

Both models show good description of $\Upsilon(1S)$ suppression from RHIC to LHC energies.

Can models consistently describe the data at RHIC and at LHC? - $\Upsilon(2S+3S)$ or $\Upsilon(2S)$

Both models consistently describe RHIC and LHC excited $\Upsilon$ states suppression in semi-central and central collisions.

Summary

- **p+p collisions at $\sqrt{s} = 200$ GeV**
  - Inclusive $J/\psi$ cross section can be described by CGC+NRQCD and NLO NRQCD
  - NLO CEM model describes the total $\Upsilon$ cross section -> more precise baseline

- **p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV**
  - $J/\psi$ $R_{pAu} \approx R_{dAu}$: suggests similar CNM effects between p+Au and d+Au collisions
  - $\Upsilon(1S+2S+3S) R_{pAu}$: indication of $\Upsilon$ suppression due to CNM effects

- **Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV**
  - Clear $J/\psi$ suppression at $p_T > 5$ GeV/c in central collisions -> dissociation
  - $J/\psi$ $R_{AA}$ can be qualitatively described by transport models including dissociation and regeneration
  - $\Upsilon(1S)$:
    - Indication of more suppression towards central collisions
    - Similar suppression as at LHC
    - Both Rothkopf and Rapp models consistently describe the data from RHIC to LHC energies
  - $\Upsilon(2S+3S)$:
    - Stronger suppression in central collisions
    - More suppressed than $\Upsilon(1S)$ in 0-10% centrality -> sequential melting
    - Indication of less suppression at RHIC than at LHC
    - Both Rothkopf and Rapp models describe RHIC and LHC data in semi-central and central collisions