Recent results on quarkonia from STAR experiment

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Quarkonium physics at STAR

Production in p+p
- Production mechanism
- Reference for hot/cold nuclear matter effects

Production in p/d/He+A
- Cold nuclear matter effect
  - nPDFs, Nuclear absorption, Co-mover interactions etc.

Production in A+A
- Probing QGP and its properties
- Coherent photoproduction process in HIC
The Solenoid Tracker At RHIC (STAR)

- TPC - momentum and energy loss
- BEMC - trigger on and identify electrons
- TOF - 1/β and charged particle multiplicity
- MTD - trigger on and identify muons

Reactions:
- $J/\psi \rightarrow e^+e^-$
- $J/\psi \rightarrow \mu^+\mu^-$
- $\Upsilon (ns) \rightarrow e^+e^-$
- $\Upsilon (ns) \rightarrow \mu^+\mu^-$
Quarkonia at STAR

$p + p @ \sqrt{s} = 500 GeV$

$$J/\psi \rightarrow e^+e^-$$

$$\Upsilon \rightarrow e^-e^+$$

$$N^{e^+e^-} = 350 \pm 89$$

$$N^{e^-e^+} = 9581 \pm 207$$

$$p+p @ 500 GeV$$

$$4 < p_T < 12 GeV/c$$

$$|y| < 1$$

$$4 < p_T < 20 GeV/c$$

$$|y| < 1$$

$$N^{e^+e^-} = 350 \pm 89$$

$$N^{e^-e^+} = 9581 \pm 207$$

$$Au + Au @ 200 GeV, 0-80\%$$

$$J/\psi \rightarrow \mu^+\mu^-; L \sim 14.2 nb^{-1}$$

$$|y| < 0.5, p_T > 5 GeV/c$$

$$N_{\mu\mu} = 1091 \pm 65$$

$$S/B = 1:2.1$$

$$Au + Au @ 200 GeV, 14.2 nb^{-1} (2014) and 12.8 nb^{-1} (2016)$$

$$0 - 60\%, 0 < p_T < 10 (GeV/c)$$

$$|y| < 1$$

$$\Upsilon(1S) = 544 \pm 34$$

$$\Upsilon(2S) = 105 \pm 27$$

$$\Upsilon(3S) = 51 \pm 25$$

$$\Upsilon \rightarrow e^+e^-$$

$$\Upsilon \rightarrow \mu^+\mu^-$$
p+p collisions
Quarkonia production

- Heavy quarkonium: an ideal laboratory for testing the interplay between **perturbative** and **nonperturbative** QCD

  Bound state of $Q\bar{Q}$ pair under strong interaction
  The simplest system in QCD: two-body problem

  - Charmonium: $m \approx 1.3$ GeV, $v^2 \approx 0.3$
  - Bottomonium: $m \approx 4.5$ GeV, $v^2 \approx 0.1$

![Diagram of quarkonium production and evolution](image)

- Production of the $Q\bar{Q}$ pair (large momentum transfer)
  - **pQCD process**

- Evolution of the $Q\bar{Q}$ pair into quarkonium
  - **Non-pQCD process**

$v$ and $\Delta r$ are related by:

- $\Delta r \sim \frac{1}{2m}$
- $\frac{1}{m v}$
- $\frac{1}{m v^2}$
Inclusive J/ψ cross section

- Precision measurement within large dynamic range ($p_T = 0$-20 GeV/c)
- Measurements consistent with CGC+NRQCD & NLO NRQCD as well as ICEM calculations, within the polarization envelope

First $\psi(2S)$ to J/ψ ratio vs. $p_T$ from STAR
- Results are consistent with ICEM prediction
**Y** differential cross section

- **CEM predictions describe the inclusive \( \Upsilon(1S) \) production**
- **CGC+NRQCD calculation of direct \( \Upsilon(1S) \) overestimates the inclusive \( \Upsilon(1S) \) measurement**
J/ψ polarization

\[
\frac{d^2N}{d\cos\theta d\phi} \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi
\]

- \( \lambda_\theta \), \( \lambda_\phi \) and \( \lambda_{\theta\phi} \) are consistent with 0 in both HX and CS frames

- NRQCD calculations with two different sets of LDMEs and CGC+NRQCD calculation are all consistent with data within uncertainties

NRQCD1: Hong-fei Zhang et al., PRL 114 (2015) 092006
NRQCD2: Bin Gong et al., PRL 110 (2013) 042002
CGC+NRQCD: Yan-Qing Ma et al., JHEP 12 (2018) 057

Accepted by PRD (arxiv:2007.04732)
Quarkonium production vs $N_{ch}$

- Similar increasing trends of $J/\psi$ and $\Upsilon$ yields vs. mid-rapidity activity
- Interplay between hard and soft process
- PYTHIA8 and String Percolation models reproduce the trend in data for both $J/\psi$ and $\Upsilon$
- CGC/Saturation model describes $\Upsilon$ data within large uncertainties

STAR, PLB 786 (2018) 87-93

E. Ferreiro, et al., PRC 86 (2012) 034903

2020/10/22 Qian Yang @2020 RHIC/AGS Annual Users Meeting, Oct. 22th - 23th 2020, Online
Charged jet to $J/\psi$ fragmentation function:

- No significant $z$ dependence observed within uncertainties
- Different trends and probabilities of producing a $J/\psi$ in charged jet for the measured kinematics range between data and Pythia8
p+A collisions
\( J/\psi \, R_{pAu} \)

- \( R_{pAu} \) consistent with unity at high \( p_T \), suggesting no modifications due to the CNM effects
  - And in agreement with models with nPDF effects
- Consistent with PHENIX \( R_{dAu} \), indicating similar cold nuclear matter effects in \( p+Au \) and \( d+Au \) collisions

PHENIX, PRC 87 (2013) 034904
EPS09+NLO, Ma & Vogt, Private Common
• Improved precision over previous d+Au results (~50% smaller statistical uncertainty)
• Indication of more suppression than that from models with nPDF effects and energy loss in cold nuclear matter
A+A collisions
J/ψ suppression

**Low-p\(_T\):** more suppression at RHIC than at LHC in central collisions → smaller charm production cross-section at RHIC and thus smaller regeneration

**High-p\(_T\):** J/ψ is strongly suppressed at both RHIC and LHC in (semi-)central collisions → Color Screening
$\Upsilon(1S)$ suppression

$\Upsilon(1S)$ $R_{AA}$:

- Stronger suppression towards central collisions
- Both Rothkopf’s and Rapp’s models describe data

**Rothkopf’s model**: use a lattice-vetted heavy-quark potential

**Rapp’s model**: use in-medium binding energies predicted by thermodynamic
T-matrix calculations using internal-energy potentials, from lattice QCD

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CMS: PLB 770 (2017) 357
Rothkopf: B. Krouppa et al., PRD 97 (2018) 016017
Rapp: X. Du et al., PRC 96 (2017) 054901

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\( \Upsilon(2S+3S) \) suppression

\( \Upsilon(2S+3S) \):
- Stronger suppression in more central collisions
- More suppressed than \( \Upsilon(1S) \) in 0-10\% central collisions — sequential suppression
Very low $p_T$ $J/\psi$ in HIC

- Significant excess of $J/\psi$ observed in 200 GeV Au+Au collisions and 193 GeV U+U collisions at very low-$p_T$.

- Indication of coherent photoproduction process
  - four scenarios can describe the data points in 60-80% centrality
  - favor the nucleus + spectator or spectator + nucleus scenarios in semicentral collisions.
Summary

**p+p results:**
- Quarkonium production study with improving precision
- Quarkonia associated with hadrons are informative observables for quarkonium production mechanism studies

**p+Au results:**
- The CNM effect are negligible for high-\(p_T\) J/\(\psi\) (\(p_T > 4\) GeV/c), but not for low-\(p_T\) \(\Upsilon\)

**Au+Au results:**
- Strong suppression for J/\(\psi\) with \(p_T > 0.15\) GeV/c in 200 GeV Au+Au collisions
- Strong suppression of different \(\Upsilon\) states and a sequential suppression picture is observed
- Significant excess of very low-\(p_T\) J/\(\psi\) in HIC, which likely originates from coherent photon production. Further studies are needed to understand the impact of hadronic interactions to the yields