Quarkonium measurements with the STAR experiment

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Heavy quarkonia in QGP

- Dissociation: quarkonia dissociate in QGP due to color-screening
  → Proposed as a direct proof of QGP formation
  T. Matsui and H. Satz, PLB 178 (1986) 416

- Sequential melting: different quarkonia dissociate at different temperatures
  → QGP thermometer

- Other effects add additional complications
  - Cold nuclear matter (CNM) effects
  → Measurements in p+A
  - Regeneration → Elliptic flow ($v_2$) measurements
  - Co-mover absorption
  → $\Upsilon$ is a cleaner probe
  - Feed down

A. Mocsy, EPJ C61 (2009) 705
The **Solenoid Tracker At RHIC**

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

- **TPC**: Measure momentum and energy loss
- **TOF**: Measure time-of-flight
- **BEMC**: Trigger on and identify high $p_T$ electrons
- **MTD**: Identify and trigger on muons
  - $|\eta| < 0.5$, $\phi \sim 45\%$
  - Less bremsstrahlung compared to electrons
p+p: inclusive J/ψ and ψ(2S)/J/ψ ratio

- Inclusive J/ψ cross-section measured in 0 < p_T < 14 GeV/c
  - CGC+NRQCD and NLO NRQCD (prompt) agree with data
  - Improved CEM model (direct) is below data in 3.5 < p_T < 12 GeV/c
- Measured ψ(2S)/J/ψ ratio in p+p 200 GeV is consistent with world-wide data
Inclusive $J/\psi$ $R_{pAu}$

- First $J/\psi$ $R_{pAu}$ measurement at RHIC
- $R_{pAu}$ is less than unity at low $p_T$, and consistent with unity within uncertainties at high $p_T$

$$R_{pAu} = \frac{\sigma_{pp}^{inel} d^2N_{pAu}/dydp_T}{\langle N_{coll} \rangle d^2\sigma_{pp}/dydp_T}$$

Global Uncertainty
- $p+p$ Luminosity
- $N_{coll}$
- Trigger efficiency
- Tracking efficiency
Inclusive $J/\psi$ $R_{pAu}$ vs. $R_{dAu}$ vs. model

• $R_{pAu}$ vs. $R_{dAu}$: Consistent within uncertainties, but there seems to be a tension at $3.5 < p_T < 5$ GeV/c ($1.4\sigma$)

• Data vs. model: Data favor the model calculation with additional nuclear absorption effect on top of the nuclear PDF effect
First mid-rapidity $\psi(2S)$ to $J/\psi$ double ratio measurement in p+Au to p+p collisions at RHIC, $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pAu} / [\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp} = 1.37 \pm 0.42\text{(stat.)} \pm 0.19\text{(syst.)}$
$J/\psi$ $v_2$ results at STAR

- First measurement of $J/\psi$ $v_2$ in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV - U+U result is consistent with Au+Au result within uncertainties
- $J/\psi$ $v_2$ is consistent with zero within uncertainties above 2 GeV/c -> Disfavor the scenario that the regeneration is the dominant contribution in this kinematic range
\( J/\psi \) suppression: \( R_{AA} \) vs. centrality

- Strong suppression of \( J/\psi \) above 5 GeV/c in central collisions 
  \( \rightarrow \) Dissociation in effect
Y results in p+p and p+Au collisions

- **p+p**: $\sigma = 81 \pm 5\text{(stat.)} \pm 8\text{(syst.)} \text{ pb}$
  - Baseline for A+A collisions with improved precision
  - Consistent with the Color Evaporation Model (CEM) prediction

- **p+Au**: $R_{pAu} = 0.82 \pm 0.10\text{(stat.)} \mp 0.07 \pm 0.08\text{(syst.)} \pm 0.10\text{(global)}$
  - Quantify CNM effects

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Xinjie Huang, SQM2017, Utrecht
$R_{AA}$ vs. $N_{part}$ at RHIC

- Di-muon result from 2014 data and di-electron result from 2011 data are combined
- Indication of more suppression with increasing centrality
- $\Upsilon(2S+3S)$ is more suppressed than $\Upsilon(1S)$ in central collision → Sequential melting
• $\Upsilon(1S)$: Consistent with CMS result.
• $\Upsilon(2S+3S)$: Indication of less suppression at RHIC than at LHC

CMS Collaboration, arXiv:1611.01510

CMS: PLB 770 (2017) 357
$R_{AA}$ vs. $p_T$ at RHIC

- $\Upsilon(1S)$: No obvious dependence on $p_T$; consistent with CMS result.
- $\Upsilon(2S+3S)$: Indication of less suppression at RHIC at high $p_T$
Compare with models

- **SBS (Strongly Binding Scenario):** Fast dissociation—potential based on internal energy
- **WBS (Weakly Binding Scenario):** Slow dissociation—potential based on free energy
- **Strickland, Bazov:** No CNM; no regeneration
- **Liu, Chen, Xu, Zhuang:** Dissociation only for excited states; suppression of ground state due to feed-down; SBS
- **Emerick, Zhao, Rapp:** Includes CNM; SBS case

→ Data seem to favor the SBS models
Summary and Outlook

• **p+p**
  - Models describe the quarkonium production cross-section reasonably well
  - Baseline with improved precision for Υ

• **p+Au**
  - J/ψ \( R_{pAu} \) measurement → Additional suppression mechanisms seem to be favored by data, but nPDF effects only cannot be fully ruled out yet
  - Quantify CNM effects for Υ,
    \[
    R_{pAu} = 0.82 \pm 0.10(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.10(\text{global})
    \]

• **A+A**
  - J/ψ \( v_2 \) in U+U collisions: Consistent with zero above 2 GeV/c within uncertainties as for Au+Au collisions → Small regeneration contribution
  - Strong high-\( p_T \) J/ψ suppression in central Au+Au collisions
    → Dissociation in effect
  - Υ(2S+3S) is more suppressed than Υ(1S) in central Au+Au collisions at RHIC
    → Sequential melting
  - RHIC vs. LHC
    Υ(1S): Consistent results
    Υ(2S+3S): Hint of less suppression at RHIC than at LHC

• **Outlook:** Analyses from 2x Au+Au data are underway
Back up
$\nu_2$ measurement in U+U collisions

- Event plane method:
  fit $J/\psi$ yield as the function of the relative angle between $J/\psi$ ($\phi$) and the event plane ($\Psi$) by the function
  \[ N \cdot (1 + 2 \cdot \nu_{2,obs} \cdot \cos(2 \cdot (\phi - \Psi))) \]

- Invariant mass method:
  fit $\nu_2$ vs. $m$ by
  \[ \frac{\nu_{2, J/\psi} \cdot \text{Sig}(m) + (a_0 + a_1 \cdot m) \cdot Bg(m)}{(\text{Sig}(m) + Bg(m))} \]
  Where $\text{Sig}(m)/Bg(m)$ is the unlike-sign/like-sign yield
**Y signal in Au+Au collisions**

\[ Y \rightarrow e^+e^-, \text{ 2011 data} \]

\[ Y \rightarrow \mu^+\mu^-, \text{ 2014 data} \]

- Background sources:
  - Combinatorial background (estimated with \( N_{l^+l^+} + N_{l^-l^-} \))
  - \( b\bar{b} \) and Drell-Yan contributions
$\gamma$ nuclear modification factor in Au+Au collisions

$$R_{AA} = \frac{\sigma_{pp}^{inel} d^2 N_{AA}/dydp_T}{\langle N_{coll} \rangle d^2 \sigma_{pp}/dydp_T}$$

- ⭐ are combinations of ⭐ results
- Di-muon and di-electron results consistent with each other → Results combined for higher statistical precision