Quarkonium production in nuclear collisions

Rongrong Ma (BNL)
Why Quarkonium?
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- **Early creation:** experience entire evolution of quark-gluon plasma
Why Quarkonium?

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- **Proposed signature of deconfinement:** quark-antiquark potential color-screened by surrounding partons → *dissociation*
  
  - J/ψ suppression was proposed as a direct proof of QGP formation

\[
r_{q\bar{q}} \sim 1 / E_{\text{binding}} > r_D \sim 1 / T
\]

T. Matsui and H. Satz
PLB 178 (1986) 416
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- **Proposed signature of deconfinement**: quark-antiquark potential color-screened by surrounding partons → *dissociation*
  - *J/ψ* suppression was proposed as a direct proof of QGP formation

\[ r_{q\bar{q}} \sim \frac{1}{E_{\text{binding}}} > r_D \sim \frac{1}{T} \]

- “Thermometer”: different states dissociate at different temperatures → *sequential suppression*

<table>
<thead>
<tr>
<th></th>
<th><em>J/ψ</em></th>
<th><em>ψ</em>(2S)</th>
<th><em>Y</em>(1S)</th>
<th><em>Y</em>(2S)</th>
<th><em>Y</em>(3S)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E_b</em> (MeV)</td>
<td>~ 640</td>
<td>~ 60</td>
<td>~ 1100</td>
<td>~ 500</td>
<td>~ 200</td>
</tr>
</tbody>
</table>

T. Matsui and H. Satz
PLB 178 (1986) 416

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Other effects

- **(Re)generation**
  - *Deconfinement is a prerequisite*
  - Depend on species, energy, $p_T$, etc
- Medium-induced energy loss
  - Color-octet states; parton fragmentation
- Formation time
- **Feed-down contributions**
The Complications

Other effects

• (Re)generation
  – *Deconfinement is a prerequisite*
  – Depend on species, energy, $p_T$, etc
• Medium-induced energy loss
  – Color-octet states; parton fragmentation
• Formation time
• Feed-down contributions

Cold nuclear matter effects (CNM)

• nPDF: shadowing/anti-shadowing
• Coherent energy loss
• Nuclear absorption
• Interact with co-movers

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K. Eskola, et. al, EPJC 77 (2017) 163

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**Experimental Quarkonium Talks at QM2018**

- Quarkonium measurements in nucleus-nucleus collisions with ALICE – **P. Dillenseger** *(Mon. 16:30)*
- Quarkonium production in p-A collisions with ALICE – **B. Paul** *(Wed. 16:50)*
- Probing QCD deconfinement with sequential quarkonium suppression of three $\Upsilon(nS)$ states with the CMS detector – **S. Tuli** *(Tue. 11:30)*
- Beyond nPDF effects: prompt $J/\psi$ and $\psi(2S)$ production in pPb collisions with CMS – **G. Oh** *(Wed. 17:10)*
- Quarkonia production in large and small systems measured by ATLAS – **J. Lopez** *(Mon. 16:50)*
- Heavy Flavor production measurements in proton-lead and fixed target collisions at LHCb – **S. Chen** *(Tue. 12:50)*
- Upsilon Measurements in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR Experiment – **P. Wang** *(Tue. 11:10)*
- Recent Quarkonia Studies from the PHENIX Experiment – **J. Durham** *(Mon. 18:10)*
pp Collisions

pA/dA Collisions

AA Collisions
Quarkonium Production in pp

\(\Upsilon(1S)\) in \(p+p @ 7\,\text{TeV}\)

- CGC: addition of Sudakov summation can describe the \(\Upsilon(1S)\) production at low \(p_T\)
Quarkonium Production in pp

\( \Upsilon(1S) \) in p+p @ 7 TeV

- CGC: addition of Sudakov summation can describe the \( \Upsilon(1S) \) production at low \( p_T \)
- \( J/\psi \) production is accompanied by other hadrons
  - PYTHIA disagrees with data

\( J/\psi \) FF in p+p @ 5.02 TeV

Wed. 17:10 G. Oh

Wed. 17:30
K. Watanabe
pp Collisions

pA/dA Collisions

AA Collisions
Large-y $J/\psi$ in small system at RHIC

- $p/^{3}\text{He}$-going: about 10-20% suppression with Au nuclei. Consistent with shadowing expectation
- Au/Al-going: indication of suppression in $p+Au$ collisions?
J/ψ Production in pPb

- Low $p_T$: significant suppression; High $p_T$: much smaller CNM effects
- While consistent with nPDF effects, data provide constraints on gluon distribution at low-x.

ALICE-PUBLIC-2018-007
LHCb: PLB 774 (2017) 159
$J/\psi Q_{pPb}$ in Centrality Bins: data vs. model

- Models include nPDF or energy loss effects are not able to reproduce the $J/\psi$ modification, especially for central pPb collisions.

- Need to go back to the drawing board
**J/ψ Anisotropy in pPb**

- Significant J/ψ $v_2$ observed in $2 < p_T < 7$ GeV/c in high-multiplicity pPb collisions

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**References**

- CMS: HIN-18-010
- ALICE: PLB 780 (2018) 7
J/ψ Anisotropy in pPb

- Significant J/ψ v₂ observed in 2 < p_T < 7 GeV/c in high-multiplicity pPb collisions
- Same situation as other hard probes: large v₂ but no significant suppression
  - Is it flow or initial state effect or something else?

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\( \Upsilon(1S) \) Suppressed in \( pPb \)

- \( \Upsilon(1S) \): 30-40\% suppression at low \( p_T \)
- Need to be taken into account when interpreting results in PbPb collisions
\( \Upsilon(2S+3S) \) are More Suppressed

- Additional 25-35\% suppression for excited states
- Final-state effects affect the ground and excited states differently
**p+A Summary**

**pA collisions**

- Significant suppression at low $p_T$ for quarkonium
  - Need to be taken into account when interpreting measurement in AA collisions
  - Models (nPDF, energy loss) having difficulties to reproduce more differential measurements
- Excited quarkonium states more suppressed due probably to final-state effects
  - Needed for determine CNM effects for direct $\Upsilon(1S)$
- Non-zero $J/\psi \, v_2$ observed in intermediate $p_T$ region at the LHC energy
  - Collective motion for $J/\psi$. What is the origin?
pp Collisions
pA/dA Collisions
AA Collisions
Low-$p_T$ $J/\psi$ in $Xe+Xe$

- Similar level of suppression seen in $Xe+Xe$ and $Pb+Pb$
- Transport model consistent with data: interplay between dissociation and regeneration
High-$p_T$ J/$\psi$: RHIC vs. LHC

- Unlike low $p_T$, $R_{AA}$ decreases towards central collisions
  - CNM & regeneration effects small
- $R_{AA}^{RHIC} \gtrsim R_{AA}^{LHC/2.76\text{TeV}} \gtrsim R_{AA}^{LHC/5.02\text{TeV}}$

Dissociation In Effect

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CMS: JHEP 05 (2012) 063
CMS: arXiv:1712.08959

23
An increasing trend is seen in $J/\psi$ $R_{AA}$ vs. $p_T$

$J/\psi$ $R_{AA}$ follows charged-hadron $R_{AA}$ above 12 GeV/c.
Data are consistent with both color-screening and energy loss scenarios.

Data at higher $p_T$ with better precision are crucial to distinguish between models.
**LHC: J/ψ v₂ vs. pₜ**

- **J/ψ v₂** persists up to 20 GeV/c; not described by transport models
- **Due to path-length dependence of parton energy loss?**

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Mon. 16:30 P. Dillenseger

Mon. 16:50 J. Lopez

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05/18/2018  
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ATLAS-CONF-2018-013
ALICE: PRL 119 (2017) 242301
**LHC: J/ψ v₂ vs. p_T**

- J/ψ v₂ persists up to 20 GeV/c; not described by transport models
- Due to path-length dependence of parton energy loss?
- However, different suppression for ψ(2S) and J/ψ at high p_T. Hmmm …
**Sequential Suppression for Charmonium**

- $R_{AA}\psi(2S) < R_{AA}\ J/\psi$ across $p_T$ and cent. bins $\rightarrow$ sequential suppression
- **Tension in central collisions?**

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**CMS:** arXiv:1712.08959

**ATLAS:** arXiv:1805.04077

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Sequential Suppression for Bottomonium

- **Au+Au @ 200 GeV**
  - \( R_{AA}^{peri} > R_{AA}^{cent} \) : increasing hot medium effects
  - RHIC: \( R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)} \) in 0-10% central
  - LHC: \( R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)} \) in all centrality

- **Pb+Pb @ 5.02 TeV**

CMS: CMS-HIN-16-023

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

$0.2 \text{ TeV vs. } 2.76 \text{ TeV}$

- $R_{AA}^{\text{RHIC}} \sim R_{AA}^{\text{LHC/2.76TeV}}$: likely due to CNM + suppression of excited states
**Inclusive \( \Upsilon(1S) \) \( R_{AA} \): RHIC vs. LHC**

**0.2 TeV vs. 2.76 TeV vs. 5.02 TeV**

- \( R_{AA}^{RHIC} \sim R_{AA}^{LHC/2.76 TeV} \): likely due to CNM + suppression of excited states
- \( R_{AA}^{LHC/2.76 TeV} > R_{AA}^{LHC/5.02 TeV} \): onset of direct \( \Upsilon(1S) \) suppression?

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**STAR Preliminary**

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**STAR Au+Au@200 GeV, \( |y|<0.5 \)**

**CMS Pb+Pb@2.76 TeV, \( |y|<2.4 \)**

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**CMS:** CMS-HIN-16-023  
**CMS:** PLB 770 (2017) 357

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05/18/2018

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Excited $\Upsilon R_{AA}$: RHIC vs. LHC

0.2 TeV vs. 2.76 TeV

- $R_{AA}^{RHIC} \sim R_{AA}^{LHC/2.76 TeV}$: indication of less melting at RHIC peripheral?
Excited $\Upsilon R_{AA}^*$: RHIC vs. LHC

0.2 TeV vs. 2.76 TeV vs. 5.02 TeV

- $R_{AA}^{RHIC} \gtrsim R_{AA}^{LHC/2.76TeV}$: indication of less melting at RHIC peripheral?
- $R_{AA}^{LHC/2.76TeV} \sim R_{AA}^{LHC/5.02TeV}$: complete dissociation in the medium

CMS: CMS-HIN-16-023
CMS: PLB 770 (2017) 357

STAR Preliminary

CMS Pb+Pb @ 2.76 TeV, |y|<2.4

(2S): CMS Pb+Pb @ 2.76 TeV, |y|<2.4

(3S): CMS Pb+Pb @ 2.76 TeV, |y|<2.4

(2S+3S): STAR Au+Au @ 200 GeV, |y|<0.5

$\Upsilon$ (2S): CMS Pb+Pb @ 2.76 TeV, |y|<2.4

$\Upsilon$ (3S): CMS Pb+Pb @ 2.76 TeV, |y|<2.4

$N_{coll}$ uncertainty

95% C.L.
• T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

<table>
<thead>
<tr>
<th>$\Upsilon$</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
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</thead>
<tbody>
<tr>
<td>$T_{\text{disso}}$ (MeV)</td>
<td>500</td>
<td>240</td>
<td>190</td>
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| $\sqrt{s}$ (TeV) | 0.2 | 2.76 | 5.02 |
| $T_{0}^{QGP}$ (MeV) | 310 | 555 | 594 |
**ϒ Suppression: Data vs. TAMU model**

- T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

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- Good description of ϒ suppression from RHIC to LHC energies.

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X. Du, M. He, R. Rapp  PRC 96 (2017) 054901

CMS: CMS-HIN-16-023
CMS: PLB 770 (2017) 357
\( \Upsilon \text{ Suppression: Data vs. TAMU model} \)

- T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

\[
\begin{array}{|c|c|c|}
\hline
\Upsilon(1S) & \Upsilon(2S) & \Upsilon(3S) \\
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\end{array}
\]

- Good description of \( \Upsilon \) suppression from RHIC to LHC energies.
- Non-negligible regeneration, especially for \( \Upsilon(2S) \)

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**yme Suppression: Data vs. lattice-potential model**

- Complex potential (lQCD); aHydro medium; No regeneration or CNM

<table>
<thead>
<tr>
<th>( T_{\text{disso}} ) (MeV)</th>
<th>( \Upsilon(1S) )</th>
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<table>
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<tbody>
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</tbody>
</table>

- Describe RHIC data reasonably well
- Lies consistently below the experimental data at LHC. Regeneration to rescue?

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AA Summary

AA collisions

- Low $p_T$: new $J/\psi$ data in Xe+Xe compatible with Pb+Pb $\rightarrow$ regeneration
- High $p_T$: increasing suppression towards central collisions $\rightarrow$ dissociation
- Even higher $p_T$: increasing $R_{AA}$ and non-zero $v_2$ $\rightarrow$ similar to charged hadrons

- Multi-dimensional measurements of $\Upsilon$ suppression from RHIC and LHC with improved precision $\rightarrow$ sequential suppression
  - Powerful tests to model calculations
- Hint of direct $\Upsilon(1S)$ suppression at 5.02 TeV?
Discussion

• \( p+p \): production mechanism still not fully understood
  – Efforts are needed both experimentally and theoretically: \( J/\psi \) in jets; Improved Color Evaporation Model …
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  – Efforts are needed both experimentally and theoretically: $J/\psi$ in jets; Improved Color Evaporation Model …

• p+A: CNM effects on quarkonium fairly well understood
  – Need to think hard about the sizable $J/\psi v_2$
Discussion

• **p+p**: production mechanism still not fully understood
  – Efforts are needed both experimentally and theoretically: $J/\psi$ in jets; Improved Color Evaporation Model …

• **p+A**: CNM effects on quarkonium fairly well understood
  – Need to think hard about the sizable $J/\psi v_2$

• **A+A**: are we in a position to extract medium temperature?
  – Better control of feed-down contribution & further reduce uncertainties on heavy quark cross section
  – New observables, e.g. $J/\psi$ polarization, $\Upsilon v_2$, etc may shed more lights
  – Precision measurements of individual $\Upsilon$ states at both RHIC and LHC are in the planning.
Backup
And the Feed-down Contribution

$\chi_c \to J/\psi\gamma$
- LHCb, $1.2 < y < 4.0$
- ATLAS, $y < 1.2$
- CDF, $y > 1.2$

$\chi_b(1P)$ feed-down
- $10-30\%$ (vs. $p_T$)

$\chi_b(2P+3P)$
- $\sim 5\% +1-2\%$

$Y(2S+3S)$
- $8-13\% +1-2\%$

<table>
<thead>
<tr>
<th>$J/\psi$ feed-down</th>
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<tbody>
<tr>
<td>$\chi_c$</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
</tr>
<tr>
<td>B-hadron</td>
</tr>
</tbody>
</table>

$Y(1S)$ feed-down

<table>
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<tr>
<th>$Y(1S)$ from all</th>
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<tbody>
<tr>
<td>$\chi_b(1P)$</td>
</tr>
<tr>
<td>$\chi_b(2P+3P)$</td>
</tr>
<tr>
<td>$Y(2S+3S)$</td>
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</table>
**J/ψ Production vs. Event Activity**

- Strong increase of J/ψ production vs. event activity with weak $\sqrt{s}$ dependence
- CGC+ICEM model can reproduce the trend → different intermediate states have different trends

STAR: arXiv:1805.03745

Y-Q Ma, et. al, 1803.11093
J/$\psi$ Polarization

- Very different polarization predictions for different models
- Measurements of better precision are essential
**J/ψ Production in pPb at LHC**

- A slightly enhancement shows up at backward-\(y\) above 3 GeV/c while strong suppression at forward-\(y\) below 6 GeV/c
- No visible energy dependence. Saturation of CNM?
• Clear trend in different centrality bins
  – Backward-y: suppression to enhancement from peripheral to central collisions
  – Forward-y: stronger suppression at low $p_T$ in central collisions, while $Q_{pPb} \sim 1$ for high $p_T$ in all centrality bins.
**ψ(2S) Suppression in 5.02 TeV pPb**

- \( R_{pPb} \psi(2S) < R_{pPb} J/\psi \) at high-multiplicity regions (central-y, Pb-going)
- Final-state effects needed to account for the additional suppression
- Co-mover and transport models describe data qualitatively, but not quantitatively
\( \Upsilon(2S+3S) \) are More Suppressed

- Additional 25-35\% suppression for excited states; larger suppression in central collisions
- Final-state effects affect the ground and excited states differently

Mon. 16:50 J. Lopez

\[ R_{pPb}^{\Upsilon(nS)/\Upsilon(1S)} \]

\[ R_{pPb}^{\Upsilon(2S)/\Upsilon(1S)} \]

\[ R_{pPb}^{\Upsilon(3S)/\Upsilon(1S)} \]
LHCb will Contribute

- Clean separation of three \( \Upsilon \) states in pPb and PbP collisions
- Looking forward to precise measurement of CNM effects at large rapidity
A scaling of $J/\psi R_{AA}$ vs. $N_{part}$ is seen at both forward and backward rapidities.
Inclusive $\Upsilon(1S) R_{AA}:$ Forward vs. Mid

- Seems different energy dependence at forward rapidity
- But the uncertainties are relatively large
\[ \Upsilon(1S) \, R_{AA} \, vs. \, p_T: \, Data \, vs. \, Model \]

0.2 TeV

\[ \Upsilon(1S) \rightarrow \mu^+\mu^-, \, 0-60\%, \, |y|<0.5 \]

STAR Preliminary

\[ R_{AA}(0.2 \, \text{TeV}) \]

5.02 TeV

\[ \text{ALICE, Pb-Pb} \, (\sqrt{s_{NN}} = 5.02 \, \text{TeV}) \]

Inclusive \( \Upsilon(1S) \rightarrow \mu^+\mu^- \), 2.5 < \( y \) < 4, Cent. 0-90%

• No strong \( p_T \) dependence at both RHIC and LHC
• Models can well reproduce the shape

B. Krouppa, A. Rothkopf, M. Strickland
PRD 97 (2018) 016017
X. Du, M. He, R. Rapp PRC 96 (2017) 054901
ALICE: arXiv:1805.04387
\[ \Upsilon(1S) \, R_{AA} \text{ vs. Rapidity at } 5.02 \text{ TeV} \]

- Interplay between dissociation and regeneration changes vs. y
- No strong rapidity dependence at 5.02 TeV PbPb collisions

CMS: CMS-HIN-16-023
ALICE: arXiv:1805.04387