Quarkonia : Overview of LHC and prospectives towards RHIC

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- 2023 RHIC/AGS Annual Users’s Meeting -
Quarkonia in heavy ion collisions

- What are the suppression/recombination mechanisms of quarkonia in QGP?

- What is the dominant process in the ‘measured’ quarkonium states?

- When are quarkonium states produced in the medium?
  - Are they created at early stages?
  - Bonus: is $q\bar{q}$ pair created early?

- Is the melting picture of Debye screening still valid?

- Does quarkonium production have connections to UE? (Even in pp?)
Motivation

**Quarkonia**: Bound states of quark and its anti-quark → Powerful tool to study thermal properties of QGP

Sequential melting by Debye screening

Quarkonia as thermometer of the QGP

T &lt; T_c

T ≈ 1.1T_c

T ≈ 2T_c

T. Matsui, H. Satz [PLB 178 (1986) 416]

S. Digal, P. Petreczky, H. Satz [PRD 64 (2001) 094015]
Not that simple anymore...
Motivation: in-medium effects

**Suppression**
- Debye screening
  - static color screening: \( \text{Re}V_s(r,T) \)
- Gluo-dissociation / Landau-damping
  - dynamical screening: \( \text{Im}V_s(r,T) \)

**Recombination (Regeneration)**
- Uncorrelated recombination (off-diagonal)
- Correlated recombination (diagonal)

Recent theories: Non-negligible even for \( Y(1S) \)!
Motivation: CNM/initial state effects

- **Initial/Final state effects of nucleus**
  - nPDF, CGC, coherent energy loss (initial/final)
  - co-mover, nuclear absorption, …

- **Feed-down contributions**
  - Various contributions from S- and P-wave states
  - Strongly depends on $p_T$ and changes versus centrality in heavy ion collisions
Motivation: Quarkonia in HIC

If the medium evolves slowly: state remains in a given eigenstate

In reality: rapid expansion $\Rightarrow$ too fast to catch the change of the potential

Quarkonia in heavy ion: not a simple picture...

- Rapid expansion...
- Corona region..
- Formation time...
- ...

$Q-Q\bar{Q}$ state = projection on various eigenstates

$$Q-Q\bar{Q} = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4$$
Overview of $J/\psi$ in AA

- Clear sign of regeneration for $J/\psi$ at low-$p_T$ in LHC energies (abundant charm cross section)
Overview of $J/\psi$ in AA

- Clear sign of **regeneration for $J/\psi$** at low-$p_T$ in LHC energies (abundant charm cross section)
- Stronger suppression at LHC than RHIC at high-$p_T$ (higher medium energy density)
Overview of $J/\psi$ in AA

- Clear sign of **regeneration for $J/\psi$** at low-$p_T$ in LHC energies (abundant charm cross section)
- Stronger suppression at LHC than RHIC at high-$p_T$ (higher medium energy density)
- $v_2(J/\psi)_{\text{LHC}} \geq v_2(J/\psi)_{\text{RHIC}}$ at low-$p_T$: To be confirmed with more precision measurements
Overview of J/ψ in AA

Theoretical calculations doing qualitatively good jobs including recombination processes

[ALICE]
Pb–Pb, 0–20%, $\sqrt{s_{NN}} = 5.02$ TeV
Inclusive J/ψ, 2.5 < y < 4

[arXiv:2303.13361]

[PRL 128 (2022) 162301]
Overview of J/ψ in AA

Theoretical calculations doing qualitatively good jobs including recombination processes
- OQS inspired microscopic approaches suggesting dynamical recombination rather than instantaneous formation at the phase boundary
Stronger suppression for $\psi(2S)$ than $J/\psi$ in all $p_T$ & centrality region

Similar trend of enhancement at low-$p_T$: qualitatively described by recombination effects
Stronger suppression for $\psi(2S)$ than $J/\psi$ in all $p_T$ & centrality region

Similar trend of enhancement at low-$p_T$ : qualitatively described by recombination effects

$\text{prompt } \psi(2S) v_2 \geq \text{prompt } J/\psi v_2$ : Dissociation propagated to $v_2$? Still huge unc.
J/ψ in jets

- Significant amount of J/ψ production in jets at high-p_T: Not supported by LO calculations
- Observed both at LHC and RHIC
- pp 8 TeV for E_{J/ψ} > 15 GeV: ~85% of J/ψ are produced within a jet

CMS
Prompt J/ψ
p_{T,J/ψ} > 6.5 GeV
30 < p_{T,jet} < 40 GeV
ln |η_{jet}| < 2

[Data (syst) -- DPS --- LO NRQCD --- SPS]

LHCb
\sqrt{s} = 13 TeV
Prompt

[STAR Data --- Pythia8 inclusive J/ψ]

02 Aug 2023
RHIC/AGS User’s Meeting 2023
**J/ψ in jets**

- GFIP and FJF improves describing the data — limitation of LO NRQCD in PYTHIA
- Suggests later J/ψ production from parton shower
- Towards heavy ion collisions: amount of suppression for high-\(p_T\) J/ψ lead by jet quenching?

![Graph showing distribution of J/ψ in jets](image)

- Bodwin et al. \(\sqrt{s} = 13\text{ TeV}\)
- LHCb

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**Proton-Proton**

- Gluon shower
- \(c\bar{c} / J/ψ\) creation

**Heavy Ion**

- Gluon shower
- \(c\bar{c} / J/ψ\) creation

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R_{AA} of J/ψ in jets

- Less suppression for isolated J/ψ: stronger suppression for more surrounding jet-activity
- Related to results of sizable v_2 at high-p_T? Increasing R_{AA} vs p_T for inclusive prompt J/ψ?

[PLB 805 (2020) 135434]
J/$\psi$ in jets: Model comparison

NRQCD + LBT based model — assume all high-$p_T$ J/$\psi$ coming from jet-fragmentation

Good agreement in cross section and $R_{AA}$ above 10 GeV/c

Disagreement with latest $v_2$ measurements at high-$p_T$: still some parts missing…

Future prospects w/ or w/o jets: $\gamma$-tagged D vs Inclusive D vs $\gamma$-tagged J/$\psi$ vs Inclusive J/$\psi$
Nonzero polarization w.r.t. the event plane in semi central collisions (~3.9 σ)
No sign of polarization in pp collisions so far up to $p_T = 60$ GeV/c
Electromagnetic field? Recombination? Spin alignment for vector meson?
Identification of all three Y states at the LHC: Sequential suppression $R_{AA}(Y(1S)) > R_{AA}(Y(2S)) > R_{AA}(Y(3S))$

Gradual decrease versus centrality: implication of subdominant effect for static color screening
Bottomonia in AA: Theory comparison

 mostly works for Y(1S)…

[Universe 60:50061]  [PLB 801 (2020) 135147]  [PRC 88 044908]
[arXiv:2208.10050]  [PLB 778 (2018) 384]  [QM2022 link]
Double ratio of $Y(2S)/Y(3S)$ to probe the sensitivity of theory calculations

Deviation among theory models start when looking at excited states
Recent theory models suggest the importance of recombination for Y in heavy ion collisions: correlated recombination being the dominant source.

- Larger effect for excited states — relative effect in some models not following the binding energy ordering e.g. recombination contribution in $R_{AA}$: $Y(2S) > Y(3S) > Y(1S)$
Sequential suppression in all $p_T$ region from 0 to 30 GeV/c

No $v_2$ observed in contrast to $J/\psi$: Different in-medium effects for charmonia and bottomonia
Bottomonia in AA : LHC

- **Y** has much smaller velocity compared to other species
  - **Low-**$p_T$ : $\nu^Y < \nu^{QGP}_{flow}$ → Cannot escape QGP
  - **Intermediate** $p_T$ : $\nu^Y \approx \nu^{QGP}_{flow}$ → Long effective travel distance (depending on axis direction) → Even possible negative $v_2$
  - **High-**$p_T$ : $\nu^Y > \nu^{QGP}_{flow}$ → Experience initial geometry from fast QGP escape

- **Y** mesons are very slow! → Even possible negative $v_2$? (Different effective path-length)
Bottomonia in AA: LHC vs RHIC

- Similar suppression for Y(1S) at 0.2 vs 5.02 TeV?
  - Different CNM effects?
  - Feed down
  - corona region
  - ...

[arXiv:2303.17026]
[PRL 130 (2023) 112301]

Graph showing data points for LHC and RHIC measurements of various bottomonia states (Y(1S), Y(2S), Y(3S)) at different values of \(N_{\text{part}}\).
Bottomonia in AA: LHC vs RHIC

Similar suppression for $Y(1S)$ at 0.2 vs 5.02 TeV?
- Different CNM effects?
- Feed down
- Corona region
- …

Theory calculations suggest stronger suppression at the LHC compared to RHIC

Still large uncertainties for firm conclusions…
Future prospects at RHIC

- Limitations on mass resolution in current RHIC measurements
- Capability of mass separation among Y states expected by sPHENIX
- Y medium response to be confirmed in the future
Sequential modification for charmonia at both LHC & RHIC in pA collisions!
Sequential modification for bottomonia at LHC in pPb collisions!
Small systems: flow

\[ J/\psi : \text{PbPb } v_2 \geq \text{pPb } v_2 > \text{pp } v_2 \approx 0 \]

\[ Y(1S) : \text{PbPb } v_2 \approx \text{pPb } v_2 \approx 0 \]
Enormous studies done in quarkonium production and medium response in both theory and experiment

Clear signature of recombination effects for charmonia at low-$p_T$ in LHC energies compared to RHIC

Sequential suppression observed for Y(1S), Y(2S), and Y(3S) in PbPb collisions

Production inside jets to be studied in more detail both in theory and experiment

Sophisticated studies needed of dynamical recombination effects for bottomonia in AA collisions

Still unclear of the feature in small systems

Many new useful measurements expected at RHIC to further study / confirm the understanding of the dynamics of quarkonia in heavy ion collisions
Back-up
Open vs Hidden charm in AA

Similar $v_2$ for STAR & CMS: expected?
: need more precision data from RHIC

Similar results although of the very different medium response mechanisms
: Efforts to disentangle ingredients both on theory & experiment

<table>
<thead>
<tr>
<th>Frag.</th>
<th>Recom.</th>
<th>Recom. Form</th>
<th>Charmed hadrons involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catania</td>
<td>Peterson</td>
<td>Phase space Wigner function $W_{\text{ps}}(p) = \prod_{i} f_i \exp \left( -\frac{p_i^2}{2m_i^2} \right)$</td>
<td>S-wave, D0, Ds, D^+, D^0, D', D'^*, several excited states of Lambda_c, Sigma_c</td>
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<tr>
<td>Duke</td>
<td>Pythia 6.4/ Peterson</td>
<td>Momentum space Wigner function $W(p) = h_0 \left( \frac{2 \sqrt{\pi}}{V} \right)^{3/2} e^{-\frac{p^2}{V}}$</td>
<td>S-wave, D'</td>
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<tr>
<td>LBT</td>
<td>Pythia 6.4/ Peterson</td>
<td>Momentum space Wigner function $W(p) = h_0 \left( \frac{2 \sqrt{\pi}}{V} \right)^{3/2} e^{-\frac{p^2}{V}}$</td>
<td>S-wave, P-wave, D, Ds, D^+, \Lambda_c, \Sigma_c, \Xi_c, \Omega_c</td>
</tr>
<tr>
<td>Nantes</td>
<td>HQET</td>
<td>Phase space Wigner function $W_{\text{ps}}(p_1, p_2) = \prod_{i=1}^{2} f_i \exp \left( -\frac{p_i^2}{2m_i^2} \right)$</td>
<td>S-wave, D0</td>
</tr>
<tr>
<td>PHSD</td>
<td>Peterson</td>
<td>Phase space Wigner function $W(p) = h_0 \left( \frac{2 \sqrt{\pi}}{V} \right)^{3/2} e^{-\frac{p^2}{V}}$</td>
<td>S-wave, P-wave, D+, D0, Ds, D^+, D^0, D'</td>
</tr>
<tr>
<td>TAMU</td>
<td>thermal density correlated HQET</td>
<td>Resonance amplitude $\frac{g_{p} f_{p} f_{\pi}^2}{1 + s_{\pi}^2 + s_{\pi}^2} \left( \frac{4\pi}{\sqrt{s_{\pi}^2 + s_{\pi}^2}} \right)$</td>
<td>D+, D0, Ds and few excited states. Charm baryons+missing baryons</td>
</tr>
<tr>
<td>Turin</td>
<td>Pythia 6.4/ String fragmentation</td>
<td>Invariant mass criterion $M_0 &lt; M_{\text{inv}} &lt; M_{\text{max}}$</td>
<td>(prompt) D+, D0, Ds, Lambda_c, Xi_c, Omega_c</td>
</tr>
<tr>
<td>Los Alamos</td>
<td>HQET</td>
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</table>
Decrease of $Y(3S)/Y(2S)$ double ratio w/ recomb. $\rightarrow$ more recomb. for $Y(2S)$!

Suppression : $Y(3S) > Y(2S) > Y(1S)$ $\longleftrightarrow$ Recombination : $Y(2S) > Y(3S) > Y(1S)$
Recombination effect

- Similar finding seen vs $p_T$: Larger recombination for $Y(2S)$ than $Y(3S)$
- Important for sophisticated treatment of recombination for excited states
Quarkonia $R_{AA}$

- $R_{AA}$ of five S-wave quarkonium states vs $p_T$
- Enhancement of $R_{AA}$ for charmonia at low-$p_T$
  - Abundant charm production
- Towards high-$p_T$
  - When (if any) start to see increase vs $p_T$?
  - Interesting to see how much coming from jet-fragmentation

**Graph**

- CMS, $|y|<2.4$, cent. 0-90%
- ALICE, 2.5<$y<$4.0, cent. 0-90%

**Data**

- PbPb 1.61 nb$^{-1}$, pp 300 pb$^{-1}$ (5.02 TeV)

**Supplementary References**

- PLB 790 (2019) 270
- EPJC 78 (2018) 509
- JHEP 02 (2020) 041
- arXiv:2210.08893
Feed down correction

\[ F_{nS}^{mS} = B(mS \rightarrow nS) \frac{\sigma_{mS}}{\sigma_{nS}} \]

Feed-down fraction to \( \Upsilon(1S) \)

Feed-down fraction to \( \Upsilon(2S) \)

Feed-down fraction to \( \Upsilon(3S) \)

[PRC 107 (2023) 054905]
[JHEP 11 (2015) 103]
[PLB 749 (2015) 14]
[EPJC 74 (2014) 3092]
Comover vs Transport

**Comover Interaction Model**

- Survival probability of quarkonium interacting with comovers
  \[
  \tau \frac{d\rho^c}{d\tau}(b, s, y) = -\sigma^{co-psi}\rho^c(b, s, y)\rho^\psi(b, s, y)
  \]
  \[
  S^c_\psi(b, s, y) = \exp\left\{-\sigma^{co-psi}\frac{\rho^c(b, s, y) \ln \left[\frac{\rho^c(b, s, y)}{\rho^{pp}(y)}\right]}{\rho^{pp}(y)}\right\}
  \]
- Depends on
  1) **quarkonium dissociation rate**
  2) **comover density**

**Transport Model**

- Thermal rate equation of quarkonium yields
  \[
  \frac{dN_\psi(\tau)}{d\tau} = -\Gamma_\psi(T(\tau))\left[N_\psi(\tau) - N^{eq}_\psi(T(\tau))\right]
  \]
  \[
  N^{eq}_\psi(T) = V_{FB}^2 \int \frac{d^3p}{(2\pi)^3} f^{eq}(E_p, T)
  \]
- **Dissociation rate** depending on T (E. density)
- **Medium evolution** matched to dN_{ch}/d\eta

- **CIM vs Transport calculation ‘actual’ treatment similar?**
- **How much of modifications in pA to be considered in AA interpretation?**
Multiplicity dependence

- Quarkonium production sensitive to DRR/SRR
- Excited-to-ground state suppression in DRR due to MPI/UE/correlation?
Multiplicity dependence

\[ \sqrt{s} = 7 \text{ TeV} \]

CMS

4.8 fb\(^{-1}\) (7 TeV)

- \( p_T^{\mu\mu} > 7 \text{ GeV}, \mid \eta^{\mu\mu} \mid < 1.2 \)

- \( \Delta R < 0.5 \)

- Y direction

- \( Y(2S) / Y(1S) \)
  - \( N_{\text{track}} = 0 \)
  - \( N_{\text{track}} = 1 \)
  - \( N_{\text{track}} = 2 \)
  - \( N_{\text{track}} > 2 \)

- \( Y(3S) / Y(1S) \)
  - \( N_{\text{track}} = 0 \)
  - \( N_{\text{track}} = 1 \)
  - \( N_{\text{track}} = 2 \)
  - \( N_{\text{track}} > 2 \)

- CMS

Sphericity \( \rightarrow 0 \)

Sphericity \( \rightarrow 1 \)

\( s_T = \frac{2 \lambda_1}{\lambda_1 + \lambda_2} \)

\[ s_T^H = \frac{1}{P_T^H} \sum_{\mu} \frac{1}{P_{\mu}} \left( p_{\mu H}^T \cdot p_{\mu H}^T \right) \]
• Quarkonium production increases in case of POI & N_{ch} at the same y
• Production behavior becomes similar after removing tracks from POI? — hint of MPI or correlation?