Understanding the $J/\psi$ and $\Upsilon$ suppression (and enhancement) at LHC and RHIC

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Potential between q-anti-q pair grows linearly at large distances

\[ V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr \]

**Screening** of long range confining potential at high enough temperature or density.
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What happens when the range of the binding force becomes smaller than the radius of the state?

different states “melting” at different temperatures due to different binding energies.

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Matsui and Satz:

**J/ψ** destruction in a QGP by Debye screening

**J/Ψ** suppression = QGP signature

E. G. Ferreiro USC

Understanding the J/ψ and Υ suppression @ LHC & RHIC

EPS, 23 July 2015
But the story is not so simple.... Open questions
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- Do we understand charmonium production in elementary \( p+p \) collisions?

- Do experimental observations fit in a coherent picture?
Three main topics

Sequential suppression
Charmonium $\rightarrow J/\psi, \psi_c, \psi(2S)$
Bottomonium $\Upsilon \rightarrow (1S), \Upsilon(2S), \Upsilon(3S), \chi_b$
Relying on theory for connection with temperature

Two competing mechanisms
Color screening $\rightarrow$ suppression
(Re)-combination $\rightarrow$ enhancement

Cold nuclear matter effects
Shadowing, absorption, comovers
Description/understanding of underlying mechanisms difficult
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Color screening $\rightarrow$ suppression
(Re)-combination $\rightarrow$ enhancement
feed down?

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Shadowing, absorption, comovers
Description/understanding of underlying mechanisms difficult
High density, collectivity
**Quarkonium and the QGP - “sequential suppression”**

H. Satz, arXiv:1310.1209

LQCD results (still debated) ...→

\[ T < T_c \]
\[ T \approx 1.2 T_c \]
\[ T \approx 3 T_c \]

\[ \psi \chi \psi \]
\[ \chi_b \psi \]
\[ Y \chi_b \psi \]

J/ψ Survival Probability

\[ \varepsilon(2S) \varepsilon(1P) \]
\[ \varepsilon(1S) \]

Energy Density

quarkonium as thermometer?

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\[ J/\psi \text{ Survival Probability} \]

Energy Density

Phenomenon.

Quarkonium as thermometer?

In particular \( J/\psi \)...

LQCD results (still debated) ..

- By determine heavy quark potential $V(r,T)$ in finite $T$ QCD and solving Schrödinger eq:

Dissociation temperatures $T_{\text{diss}}/T_c$

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Energy densities:

- $0.5-1.5$ GeV/fm$^3 = 1.0$ $T_c$
- $10$ GeV/fm$^3 = 1.5$ $T_c$
- $30$ GeV/fm$^3 = 2.0$ $T_c$
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- quarkonium as thermometer?
- In particular $J/\psi$...

H. Satz, arXiv:1310.1209
Present situation: Bottomonia in AA at RHIC and LHC

- Centrality integrated:
  - $\Upsilon(1S)$: $0.56 \pm 0.08 \pm 0.07$
  - $\Upsilon(2S)$: $0.12 \pm 0.04 \pm 0.02$
  - $\Upsilon(3S)$: $<0.10$ at 95% CL

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Present situation: Bottomonia in AA at RHIC and LHC

- **Centrality integrated:**
  
  \[
  R_{AA}(Y(3S)) = 0.425 \pm 0.029 \pm 0.070,
  
  R_{AA}(Y(2S)) = 0.116 \pm 0.028 \pm 0.022,
  
  R_{AA}(Y(3S)) < 0.14 \text{ at } 95\% \text{ CL},
  \]

- **Ordered suppression with binding E**
  
  \[\Rightarrow \text{Sequential melting}\]

- **The situation seems clear for } Y \text{ less effects than on } J/\psi\]
Transport models
(Rapp et al., Emerirck et al)
with small or none
regeneration/CNM
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Dynamical aHYDRO
(Strickland)
model without regeneration/CNM effects

\( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) in PbPb @ LHC
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**Transport models**
(Rapp et al., Emerirck et al) with small or none regeneration/CNM effects

**Dynamical aHYDRO**
(Strickland) model without regeneration/CNM effects

**Reasonable description of data**

Precise measurement of feed-down needed
(\( \Upsilon(1S) \) from feed-down between 30%-50%)
Clear suppression of $\Upsilon(2S)$

$\Upsilon(1S)$ suppression consistent with excited state suppression ($\approx 50\%$ feed down)
γ(1S), γ(2S), γ(3S) in PbPb @ LHC

Clear suppression of γ(2S)

γ(1S) suppression consistent with excited state suppression (≈ 50% feed down)

Updated CMS results: Improved pp reference & PbPb data sample

γ(1S) RAA decreases with centrality down to 0.3
Ground state suppressed?

Precise measurement of feed-down needed (γ(1S) from feed-down between 30%-50%)
• **Suppression**, but not clear pattern/picture

• **Interplay** of **hot** and **cold** medium effects:
  - shadowing, nuclear absorption, energy loss, comovers, colour screening, regeneration

• **Quarkonium in p+p** still not fully controlled theoretically
  - CSM, COM, polarization..
Quarkonium production is suppressed in nuclear collisions ...but for a variety of reasons

- dissociation by screening ("melting") and/or collisions in hot QGP

QGP effects
A+A collisions
Quarkonium production is suppressed in nuclear collisions...but for a variety of reasons:

- dissociation by screening (“melting”) and/or collisions in hot QGP (QGP effects A+A collisions)
- shadowing, saturation, intrinsic charm (CNM effects p+A and A+A collisions)
- nuclear absorption
- energy loss
- comovers
Quarkonium production is suppressed in nuclear collisions ... but for a variety of reasons

- dissociation by screening ("melting") and/or collisions in hot QGP
- shadowing,
- saturation
- intrinsic charm
- nuclear absorption
- energy loss
- comovers

Quarkonium suppression in p+A collisions: CNM effects

E. G. Ferreiro USC
Understanding the J/ψ and Ψ suppression @ LHC & RHIC
EPS, 23 July 2015
Initial shadowing effects are important: $J/\psi$ production in PbPb @ LHC

- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

**Shadowing effects increases with energy ($1/x$) and decrease with $Q^2$ ($m_T^2$)**

Production mechanism affects CNM effects intimately:
- Shadowing depends on momentum fraction $x$ of the target (and projectile in AA) which is influenced by how the state was produced: $2 \rightarrow 1$ or $2 \rightarrow 2$ process
- Production can also affect other CNM effects, since singlet and octet states can be absorbed differently
good agreement with EPS09 LO and nDSg shadowing
also consistent w/ energy loss models w/wo EPS09NLO shadowing
EPS09 NLO and CGC calculation disfavored

Cross check: $J/\psi$ production in pPb @ LHC

E.G.F, F. Fleuret, J.P. Lansberg, A.Rakotozafindrabe

E.G. Ferreiro USC
Understanding the $J/\psi$ and $Y$ suppression @ LHC & RHIC
EPS, 23 July 2015
CNM effects from p-Pb to Pb-Pb

Once CNM effects are measured in pA, what can we learn on J/ψ production in PbPb?

Sizeable $p_T$ dependent suppression still visible

→ CNM effects not enough to explain AA data at high $p_T$

From enhancement to suppression increasing $p_T$

→ hint for recombination
Theoretical models on recombination

**Statistical hadronization model**


all charm quarks are produced in primary hard collisions \( t_{cc} \sim 1/2m_c \approx 0.1 \text{ fm/c} \)

thermalized in QGP (thermal, but not chemical equilibrium)
charmed hadrons are formed at chemical freeze-out together with all hadrons ("generation")

no J/\( \psi \) survival in QGP (full screening)

if supported by data, J/\( \psi \) loses status as "thermometer" of QGP

**Transport models**  Ralf Rapp et al

implement screening picture with space-time evolution of the fireball (hydro-like)
continuous destruction and "(re)generation" ("recombination")

Thews et al., PRC 63 (2001) 054905 ...


**Comover model**


Similar to transport model

Hadronic and partonic comovers contribute
to suppression and recombination

No thermalization

Similar gain and loss differential eqs.

\[
\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c N_{\bar{c}} [V(\tau)]^{-1} - \lambda_D N_{J/\psi} \rho_g
\]
Inclusive J/ψ R_{PbPb} versus Event Centrality @ LHC

Comparison to theory calculations

Statistical hadronization, transport and comover models with recombination component can describe the trend in data.
Inclusive $J/\psi R_{\text{PbPb}}$ versus Event Centrality @ LHC

Comparisons with models

CIM: Comover Interaction Model
PLB 731,57 (2014)
Shadowing, interaction with co-moving dense partonic medium, recombination effects.

TM1: Transport Model from Zhao
Shadowing, transport approach accounting for both suppression and regeneration mechanisms, beauty-meson decays.
Mainly differ in the rate equation.

TM2: Transport Model from Zhou

To match our $J/\psi R_{\text{AA}}$ results, all models need to include a sizable $J/\psi$ production from regeneration

Within the large uncertainties on the shadowing and the charm cross section, all models reproduce reasonably well our measurement for $\langle N_{\text{part}} \rangle > 70$

Lardeux, HP2015
A strong decrease of the $\psi(2S)$ production, relative to $J/\psi$, is observed in p+Pb at LHC and d+Au at RHIC.

Same initial CNM effects (shadowing –similar $m_T$-, energy loss, nuclear absorption - charmonium formation time $t_f = \gamma \tau > R_A$) for both $J/\psi$ and $\psi(2S)$.

$\Rightarrow$ theoretical predictions in disagreement with $\psi(2S)$ results.

Final state effects related to the medium created in the p-Pb collisions?:

co-moving medium
Charmonium interaction with comoving particles:

- Comovers dissociation affects more strongly the loosely bound $\psi(2S)$ than the $J/\psi$
- Comovers density larger at backward rapidity

![Graph showing $R_{dAu}$ vs $N_{coll}$](image1)

![Graph showing $R_{pPb}$ vs $y_{cms}$](image2)

E. Ferreiro arXiv:1411.0549

$\psi(2S)$ and $J/\psi$ in pPb @ LHC: comover scenario

E. G. Ferreiro USC

Understanding the $J/\psi$ and $\Upsilon$ suppression @ LHC & RHIC

EPS, 23 July 2015
What have we learnt from quarkonia production @ LHC?

\( \Upsilon(nS) \): Sequential suppression of the three states in order of their binding energy
- \( \Upsilon(2S) \) and \( (3S) \) are strongly suppressed at LHC, \( \Upsilon(1S) \) suppression consistent with higher mass excited states suppression?
- Small room for recombination, some shadowing effects

\( J/\psi \) production seems at least qualitatively understood
- Initial cold nuclear matter effects can be described with shadowing/energy loss
- Production in HI collisions is described by a combination of
  - suppression (either color screening, or in-medium dissociation)
  - recombination (either in-medium or at phase boundary)

Challenge will be to discriminate between these possible scenarios

What is the state of the art for \( \psi(2S) \)?
- Initial cold nuclear matter effects (shadowing/energy loss) are considered to be the same for than for the \( J/\psi \)
- In-medium effects depending on density (comovers) are able to distinguish between \( J/\psi \) and \( \psi(2S) \)