J/ψ production in heavy-ion collisions and related items

Roberta Arnaldi
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Outlook:

charmonium production in pA and AA collisions from

SPS → RHIC → LHC
Quarkonium in a hot medium

Sequential melting
Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature

Quarkonium is a thermometer of the initial QGP temperature

Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature
(Re)combination

Increasing the collision energy the cc pair multiplicity increases

<table>
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<tr>
<th>Central AA collisions</th>
<th>SPS 20 GeV</th>
<th>RHIC 200 GeV</th>
<th>LHC 2.76 TeV</th>
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<tbody>
<tr>
<td>$N_{ccbar}$/event</td>
<td>~0.2</td>
<td>~10</td>
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enhanced quarkonia production via (re)combination at hadronization or during QGP stage

Cold Matter Effects

Cold Matter Effects (CNM)
on top of mechanisms related to hot matter, other effects have to be taken into account to interpret quarkonium A-A results:

- nuclear parton shadowing
- energy loss
- $c\bar{c}$ in medium break-up

investigated through p-A collisions

Nuclear modification factor
Medium effects are quantified comparing the quarkonium yield in AA with the pp one, scaled by a geometrical factor (from Glauber model)

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \sigma_{pp}^{J/\psi}}$$

- $R_{AA} = 1 \rightarrow$ no medium effects
- $R_{AA} \neq 1 \rightarrow$ hot/cold matter effects
Quarkonium studies in Heavy-Ion collisions

A-A
- Quarkonium as a probe of the hot medium created in the collision (QGP)
- Suppression vs (re)combination

p-A
- Investigation of cold nuclear matter effects (shadowing, energy loss...)
- Crucial tool to disentangle genuine QGP effect is AA collisions

p-p
- Reference process to understand behaviour in pA, AA collisions
- Useful to investigate production mechanisms (NRQCD, CEM models...)
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*pp collision program has also been scheduled at RHIC and LHC*
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- Fixed target experiments
- Collider experiments

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For all experiments, the AA program is followed by the pA one.

Quarkonium in Heavy-Ion collisions

pp collision program has also been scheduled at RHIC and LHC.
Quarkonium resonances

Focus on $J/\psi$

CMS Preliminary
$\sqrt{s_{NN}} = 2.76$ TeV

$\rho, \omega, \phi$

$\psi(2S)$

$\Upsilon(1,2,3S)$

$E_{\text{vis}} > 4$ GeV/c

$\mu\mu$ (GeV/c$^2$)
**SPS (NA38, NA50, NA60)**
\[ \sqrt{s_{NN}} = 17 \text{ GeV} \]

First evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb

\( \sim 30\% \) suppression compatible with \( \psi(2S) \) and \( \chi_c \) decays

**RHIC (PHENIX, STAR)**
\[ \sqrt{s_{NN}} = 39, 62.4, 200 \text{ GeV} \]

Suppression, strongly rapidity dependent, in Au-Au at \( \sqrt{s} = 200 \) GeV

Stronger suppression at forward \( y \) (not expected if suppression increases with energy density, larger at mid-\( y \))

In-In 158 GeV (NA60)
Pb-Pb 158 GeV (NA50)
Puzzles from SPS and RHIC
- **RHIC**: stronger suppression at forward rapidities
- **SPS vs. RHIC**: similar $R_{AA}$ pattern versus centrality

Hint for (re)combination at RHIC?
No final theoretical explanation

Decisive inputs expected from LHC results, having access to:
- higher energies → stronger suppression?
- more charm → larger (re)combination?
- more bottom → $\gamma$ can be investigated
Quarkonium at LHC

**ALICE**
- $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$
- $\gamma \rightarrow \mu^+\mu^-$
- $J/\psi \rightarrow e^+e^-$

**ATLAS**
- $J/\psi \rightarrow \mu^+\mu^-$

**CMS**
- $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$
- $\gamma \rightarrow \mu^+\mu^-$

**LHCb**
- $J/\psi$, $\gamma \rightarrow \mu^+\mu^-$
- (no heavy ion physics program)

Kinematic coverage of quarkonium measurements:

Complementary quarkonium results from LHC experiments!
J/ψ in AA collisions at LHC
Centrality dependence of the $J/\psi$ inclusive $R_{AA}$ studied by ALICE in both central and forward rapidities down to zero $p_T$

$\Rightarrow$ ALICE results:
- clear $J/\psi$ suppression with almost no centrality dependence for $N_{\text{part}} > 100$

$\Rightarrow$ Comparison with PHENIX:
- ALICE results show weaker centrality dependence and smaller suppression for central events
- behaviour expected in a (re)combination scenario
Comparison to theory calculations:

- Models including a large fraction (> 50% in central collisions) of J/ψ produced from (re)combination or models with all J/ψ produced at hadronization provide a reasonable description of ALICE results.

- Still rather large theory uncertainties: models will benefit from a precise measurement of $\sigma_{cc}$ and from cold nuclear matter evaluation.
J/ψ production via (re)combination should be more important at low transverse momentum ($p_T$ region accessible by ALICE)

Different suppression for low and high $p_T$ J/ψ

→ Smaller $R_{AA}$ for high $p_T$ J/ψ

Striking difference, at low $p_T$, between PHENIX and ALICE patterns
**Low $p_T$ J/$\psi$: ALICE & PHENIX**

J/$\psi$ production via (re)combination should be more important at low transverse momentum ($p_T$ region accessible by ALICE)

Different suppression for low and high $p_T$ J/$\psi$

- Smaller $R_{AA}$ for high $p_T$ J/$\psi$
- Models: $\sim$50% of low-$p_T$ J/$\psi$ are produced via (re)combination, while at high $p_T$ the contribution is negligible
At LHC high $p_T$ J/$\psi$ have been investigated by CMS

Limits in the CMS low-$p_T$ J/$\psi$ acceptance since muons need to overcome the magnetic field and energy loss in the absorber:

- mid-$y$: $p_T > 6.5$ GeV/c
- forward $y$: $p_T > 3$ GeV/c

Opposite behavior when compared to ALICE low-$p_T$ results

Suppression is stronger at LHC energy (by a factor $\sim 3$ compared to RHIC for central events)
At LHC high $p_T$ J/$\psi$ have been investigated by CMS.

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Negligible (re)generation effects expected at high $p_T$. 

CMS-PAS HIN-12-2014
The contribution of J/$\psi$ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

ALICE: qualitative agreement with transport models including regeneration

STAR, PRL 052301(2013)

CMS: path-length dependence of energy loss?

D.Moon, HP2013

Hint for J/$\psi$ flow at LHC, contrary to $v_2 \sim 0$ observed at RHIC!
J/ψ in pA collisions at LHC
J/ψ in p-Pb collisions

→ J/ψ production in modified also in pA because of CNM effects:
  \( R_{pA} \) decreases towards forward \( y \)

Theoretical predictions: reasonable agreement with
- shadowing calculations and models including coherent parton energy loss
- CGC description seems not to be favoured
**p-Pb: role of CNM effects on J/ψ**

- **R_{pA} p_T** dependence in 3 y ranges:
  - Backward-y: negligible \( p_T \) dependence, \( R_{pA} \) compatible with unity
  - Mid-y: small \( p_T \) dependence, \( R_{pA} \sim 1 \) for \( p_T > 3 \text{GeV/c} \)
  - Forward-y: \( R_{pA} \) increases with \( p_T \)

- Comparison with theoretical models:
  - Fair agreements with models based on shadowing + energy loss (except at forward-y and low \( p_T \))
**J/ψ versus event activity**

\[ Q_{pA} = \frac{Y_{J/\psi}^{pA}}{\langle T_{pA} \rangle \sigma_{pp}^{J/\psi}} \]

\( Q_{pA} \) is a nuclear modification factor with a possible influence due to potential bias in the event activity estimator, not related to nuclear effects.

- At forward-\( y \), strong \( J/\psi \) \( Q_{pA} \) decrease from low to high event activity
- At backward-\( y \), \( Q_{pA} \) consistent with unity, with a feeble event activity dependence
Once CNM effects are measured in pA, what can we learn on J/ψ production in PbPb?

Hypothesis:
- 2→1 kinematics for J/ψ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM obtained as \( R_{pA} \times R_{Ap} (R_{pA}^2) \), similar x-coverage as PbPb

Sizeable \( p_T \) dependent suppression still visible → CNM effects not enough to explain AA data at high \( p_T \)

we get rid of CNM effects, by doing the ratio \( \frac{AA}{pA} \)
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we get rid of CNM effects, by doing the ratio $\frac{AA}{pA}$
\( \psi(2S) \) vs J/\( \psi \) in p-A collisions

Being a more weakly bound state than the J/\( \psi \), the \( \psi(2S) \) is an interesting probe to investigate charmonium behaviour in the medium.

A strong decrease of the \( \psi(2S) \) production in p-Pb, relative to J/\( \psi \), is observed with respect to the pp measurement (2.5\( < y_{\text{CMS}} < 4 \), \( \sqrt{s} = 7 \text{ TeV} \)).

Similar effect seen by PHENIX in d-Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

same initial state CNM effects (shadowing & coherent energy loss) for J/\( \psi \) and \( \psi(2S) \)

theoretical predictions in disagreement with \( \psi(2S) \) result

\( R_{pPb} \) vs \( y_{\text{CMS}} \)

- ALICE, p-Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), inclusive J/\( \psi \), \( \psi(2S) \rightarrow \mu^+\mu^- \)
- J/\( \psi \)
- \( \psi(2S) \)

JHEP 12(2014)073
Can the stronger $\psi(2S)$ suppression be due to break-up of the fully formed resonance in CNM?

Possible if:
formation ($\tau_f < \tau_c$)
forward-$y$: $\tau_f \sim 10^{-4}$ fm/c
backward-$y$: $\tau_c \sim 10^{-1}$ fm/c
while $\tau_f \sim 0.05-0.15$ fm/c

Forward-$y$: break-up effects excluded
Backward-$y$: $\tau_f \sim \tau_c$, hence break-up in CNM hardly explains the strong J/$\psi$ and $\psi(2S)$ difference

Final state effects related to the (hadronic) medium created in the p-Pb collisions?
Final state effects related to the (hadronic) medium created in the p-Pb collisions?

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

E. Ferreiro arXiv:1411.0549
**J/ψ in heavy ion collisions: where are we?**

- Large wealth of results at LHC complementing SPS and RHIC measurements!

- Two main mechanisms at play in AA collisions
  1. Suppression in a deconfined medium
  2. (charmonium) re-combination at high $\sqrt{s}$ and low $p_T$

Qualitatively explanation of the main features of the results

- In p-A collisions:
  - interplay of shadowing and coherent energy loss can satisfactorily describe the J/ψ results
  - loosely bound $\psi(2S)$ is likely influenced by the hadronic final state

- Results from LHC Run2 eagerly awaited!
  - Energy increase ($\sqrt{s}_{NN}=5$TeV) will allow for confirmation of the (re) combination role at low $p_T$
  - Statistics increase will allow to sharpen Run-I results
Two main mechanisms at play in AA collisions:

1. Suppression in a deconfined medium

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SPS RHIC dA AA LHC pA

J/$\psi$ in heavy ion collisions: where are we?

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Backup slides
**p-Pb: role of CNM effects on J/ψ**

ATLAS and LHCb measure the forward to backward cross section ratio, $R_{FB}$, for:

- Prompt J/ψ
- Non prompt J/ψ from B decay

Similar shadowing/saturation expected for quarkonia and b quarks

ATLAS/LHCb results indicate a strong kinematic dependence of CNM for both charmonium and b quark production.
LOW ENERGY RESULTS: $\psi(2S)$ FROM SPS & RHIC

SPS (NA50) pA, AA @ $\sqrt{s_{NN}} = 17$ GeV

RHIC (PHENIX) d-Au @ $\sqrt{s_{NN}} = 200$ GeV

$\psi(2S)$ is more suppressed than $J/\psi$ already in pA collisions and the suppression increases in Pb-Pb

unexpected $\psi(2S)$ suppression, stronger than the $J/\psi$ one in d-Au
Being a more weakly bound state than the J/ψ, the ψ(2S) is another interesting probe to investigate charmonium behaviour in the medium.

The ψ(2S) yield is compared to the J/ψ one in Pb-Pb and in pp.

**Improved agreement between ALICE and CMS data** (new pp CMS reference)

**Large statistics and systematic uncertainties prevent a firm conclusion on the ψ(2S) trend vs centrality**

**ALICE: reference pp@\(\sqrt{s}=7\text{TeV}\)**

- Low \(p_T\) (0<\(p_T<3\text{GeV/c}\)) \(\rightarrow\) ψ(2S) more suppressed than J/ψ

**CMS: reference pp@\(\sqrt{s}=2.76\text{TeV}\)**

- \(p_T>3\text{ GeV/c} \& 1.6<|y|<2.4\) \(\rightarrow\) ψ(2S) less suppressed than J/ψ
- \(p_T>6.5\text{ GeV/c} \& |y|<1.6\) \(\rightarrow\) ψ(2S) more suppressed than J/ψ
Quarkonium production and decay

**J/ψ production**

Quarkonium production can proceed:
- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)

For J/ψ (LHC energies) the contributing mechanisms are:

- **Prompt**
  - Direct production
  - Feed-down from higher charmonium states:
    - ~8% from ψ(2S), ~25% from χ_c
- **Displaced**
  - B decay
    - contribution is p_T dependent
    - ~10% at p_T~1.5GeV/c

**J/ψ decay**

J/ψ can be studied through its decays:

\[ J/ψ \rightarrow \mu^+\mu^- \quad J/ψ \rightarrow e^+e^- \quad (~6\% \text{ branching ratio}) \]
Open charm should be a very good reference to study J/ψ suppression (a’ la Satz)

Interesting comparison between ALICE and CMS J/ψ compared to D

Caveat: complicate to compare J/ψ and D R_{AA} at LHC because of restricted kinematic regions. Low p_T D not accessible for the moment

Different trend observed at low p_T at RHIC. At high p_T trend is similar to the LHC one
The high $p_T$ region can be investigated by CMS!

Good agreement with ALICE (at high $p_T$) in spite of the different rapidity range.
Comparison $\Upsilon$ and J/$\psi$

- Similar $R_{AA}$ for low $p_T$ inclusive J/$\psi$ and $\Upsilon$(1S)
- Sequential suppression observed for prompt J/$\psi$ and $\Upsilon$(nS) at high $p_T$
- Interplay of the competing mechanisms for J/$\psi$ and $\Upsilon$ can be different and dependent on kinematics!
Theory still meets difficulties in describing simultaneously the $R_{AA}$ centrality and rapidity dependence (suppression slightly overestimated at forward-$y$, while better reproduced at mid-$y$).

Stronger suppression at forward rapidity (ALICE) than at mid-rapidity (CMS)
A strong decrease of the $\psi(2S)$ production in p-Pb, relative to $J/\psi$, is observed with respect to the pp measurement ($2.5<y_{\text{cms}}<4$, $\sqrt{s}=7\text{TeV}$).

Double ratio allows a direct comparison of the $J/\psi$ and $\psi(2S)$ production yields between experiments.

Similar effect seen by PHENIX in d-Au collisions, at mid-$y$, at $\sqrt{s_{\text{NN}}}=200\text{ GeV}$.

$[\psi(2S)/J/\psi]_{pp}$ variation between ($\sqrt{s}=7\text{TeV}$, $2.5<y<4$) and ($\sqrt{s}=5.02\text{TeV}$, $2.03<y<3.53$ or $-4.46<y<-2.96$) based on CDF and LHCb data (~8% included in the systematic uncertainty)
Main features of bottomonium production wrt charmonia:

- no B hadron feed-down
- gluon shadowing effect are smaller
- (re)combination expected to be smaller
- theoretical predictions more robust due to the higher mass of b quark

with a drawback...smaller production cross-section

Clear suppression of $\Upsilon$ states in PbPb with respect to pp collisions
Clear suppression of $\Upsilon(2S)$

$\Upsilon(1S)$ suppression compatible with suppression of excited states (50% feed-down)

Sequential suppression of the three $\Upsilon$ states according to their binding energy:

$$R_{AA} \Upsilon(3S) < R_{AA} \Upsilon(2S) < R_{AA} \Upsilon(1S)$$

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08 \text{ (stat)} \pm 0.07 \text{ (syst)}$$

$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04 \text{ (stat)} \pm 0.02 \text{ (syst)}$$

$$R_{AA}(\Upsilon(3S)) < 0.1 \text{ (at 95\% C.L)}$$

Suppression at LHC is stronger than at RHIC
$\Upsilon(1S)$ measured at mid-$y$ by CMS and at forward-$y$ by both ALICE and LHCb

→ Compatible $R_{pA}$ results within uncertainties (but LHCb systematically higher)

Hint for stronger suppression at forward-$y$ (similarly to $J/\psi$)

Theoretical calculations based on initial state effects seem not to describe simultaneously forward and backward $y$

ALICE: arXiv:1410.2234, accepted by PLB
LHCb: JHEP 07(2014)094
\[ \frac{\gamma(nS)/\gamma(1S)}{\gamma(1S)/\gamma(1S)} \text{ PRODUCTION IN p-Pb} \]

**Initial state effects similar for the three \( \gamma \) states**

- **p-Pb vs pp @mid-y:**
  - different/stronger final states effects in p-Pb affecting the excited states
- **p-Pb vs PbPb @mid-y:**
  - even stronger suppression of excited states in PbPb

**ALICE (and LHCb) observes:**

\[ \frac{\gamma(2S)/\gamma(1S)}{\gamma(1S)/\gamma(1S)} \text{ (ALICE)} \]

\begin{align*}
  \text{2.03} & < y < 3.53: \quad 0.27 \pm 0.08 \pm 0.04 \\
  -4.46 & < y < -2.96: \quad 0.26 \pm 0.09 \pm 0.04
\end{align*}

Compatible with pp results 0.26\pm0.08 (ALICE, pp@7TeV)

**CMS analyses the double ratio**

\[ \frac{\gamma(2S)/\gamma(1S)}{\gamma(1S)/\gamma(1S)}_{pp} \text{ and finds} \]

\[ 0.83 \pm 0.05 \pm 0.05 \]