From pA to AA: an experimental overview on quarkonium at LHC

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Outlook:

Selection on results on
- Charmonium: $J/\psi$ and $\psi(2S)$
- Bottomonium: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

in pPb and PbPb collisions at LHC energies
the original idea
quarkonium production suppressed via color screening in the QGP

sequential melting
differences in quarkonium binding energies lead to a sequential melting with increasing temperature

(re)combination
enhanced quarkonium production through (re)combination during QGP phase or at hadronization

<table>
<thead>
<tr>
<th>Central AA collisions</th>
<th>SPS 20 GeV</th>
<th>RHIC 200 GeV</th>
<th>LHC 2.76TeV</th>
<th>LHC 5.02TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{c\bar{c}}$/event</td>
<td>~0.2</td>
<td>~10</td>
<td>~85</td>
<td>~115</td>
</tr>
</tbody>
</table>


Cold nuclear matter effects: might affect quarkonium production on top of hot matter mechanisms

- nuclear parton shadowing/color glass condensate
- energy loss
- quarkonium in medium break-up

The assessment of the size of these effects is fundamental to interpret quarkonium A-A results.

Nuclear modification factor

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

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

- \( R_{AA} = 1 \rightarrow \) no medium effects
- \( R_{AA} \neq 1 \rightarrow \) hot/cold matter effects
<table>
<thead>
<tr>
<th>Facility</th>
<th>Experiment</th>
<th>System</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
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<tbody>
<tr>
<td>LHC</td>
<td>ALICE</td>
<td>Pb-Pb</td>
<td>2760</td>
<td>2010-2012</td>
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<td></td>
<td>ATLAS</td>
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<td>CMS</td>
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<td>5020</td>
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### Quarkonium at LHC

All LHC experiments investigate quarkonium production and their complementary results due to different kinematic coverages.

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### Quarkonium at LHC

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- pp, pA and AA systems have been studied
- top LHC energies now reached!
Quarkonium in AA collisions
Evidence of recombination for low $p_T$ $J/\psi$

Observation corroborated by the comparison of LHC results with

1) lower energy experiments

$J/\psi$ suppression vs centrality is stronger in PHENIX than in ALICE, in spite of the LHC larger energy densities

weaker suppression at low $p_T$ observed by ALICE
Evidence of recombination for low $p_T$ $J/\psi$

Observation corroborated by the comparison of LHC results with

1) lower energy experiments
2) theoretical models

models including (re)combination of $J/\psi$ in QGP or in the hadronic phase provide a reasonable description of ALICE results

still rather large theory uncertainties: models will benefit from a precise measurement of $\sigma_{cc}$ and CNM effects
Evidence of recombination for low $p_T$ $J/\psi$

Observation corroborated by the comparison of LHC results with

1) lower energy experiments
2) theoretical models
3) high $p_T$ $J/\psi$ results

suppression stronger at higher $\sqrt{s}$, as expected from QGP dissociation

opposite $J/\psi$ behavior compared to low-$p_T$ results

negligible re(combination) effects expected at high $p_T$
Pb-Pb collisions @ $\sqrt{s_{NN}}=5.02\text{TeV}$

High statistics Run-2 allows the $R_{AA}$ evaluation in narrow centrality bins.

Similar centrality dependence at the two energies, with an increasing suppression up to $N_{\text{part}} \sim 100$, followed by a plateau.

$R_{AA}$ @ 5.02TeV is $\sim 15\%$ higher than the one at 2.76TeV, even if within uncertainties.

arXiv:1606.08197
Comparison of same theory models at the two energies:

- **TM1, TM2 (Du et al, Zhou et al):** rate equation of suppression/regeneration in QGP
- **SHM (Andronic et al):** $J/\psi$ produced by stat. hadronization at phase boundary
- **CIM (Ferreiro):** suppression by the comoving partonic medium and regeneration

Data are compatible with theory models at both energies

Still large uncertainties mainly due to the choice of $\sigma_{cc}$
Theoretical and experimental uncertainties reduced in the $R_{AA}$ double ratio

Centrality dependence of the $R_{AA}$ ratio is rather flat

$R_{AA}$ increases with $p_T$, at both energies, as expected in a regeneration scenario

Hint for an increase of $R_{AA}$, at 5.02TeV, in $2<p_T<6$ GeV/c

Also $\sqrt{s_{NN}}=5.02$TeV results support a picture where a combination of $J/\psi$ suppression and (re)combination occurs in the QGP
ψ(2S) production modified in AA with a strong kinematic dependence

Fw-y, 3<p_T<30GeV/c \rightarrow R_{AA}^{J/\psi} < R_{AA}^{\psi(2S)}

later ψ(2S) regeneration, when radial flow is stronger, might explain the rise

Mid-y 6.5<p_T<30GeV/c \rightarrow R_{AA}^{J/\psi} > R_{AA}^{\psi(2S)}

stronger suppression of ψ(2S) wrt J/ψ

ALICE trend agrees with transport models and stat. hadronization approach

Run1 data not precise enough to conclude on ψ(2S) behavior
Run2 results eagerly awaited!
Main features of bottomonium production wrt charmonium:

• no B hadron feed-down
• smaller gluon shadowing effects
• negligible (re)combination
• more robust theoretical predictions due to the higher b quark mass

with a drawback...smaller production cross-section

Clear suppression of $\Upsilon$ states in PbPb with respect to pp collisions
Sequential suppression observed at LHC in Run 1:

\[ R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)} \]

- \( R_{AA}(\Upsilon(1S)) = 0.43 \pm 0.03 \pm 0.07 \)
- \( R_{AA}(\Upsilon(2S)) = 0.13 \pm 0.03 \pm 0.02 \)
- \( R_{AA}(\Upsilon(3S)) < 0.14 \) at 95% CL

Centrality dependent suppression for \( \Upsilon(1S) \) and \( \Upsilon(2S) \)

At LHC \( \Upsilon(1S) \) is already suppressed in semiperipheral collisions, while at RHIC only in the central ones

Feed-down from excited states + CNM are enough to explain the observed \( \Upsilon(1S) \) suppression?
no $p_T$ or $y$ dependence of the $\Upsilon(1S)$ and $\Upsilon(2S)$ suppressions
models reproduce the $p_T$ and centrality dependence
rapidity description still needs tuning
Centrality dependent $\Upsilon(1S) R_{AA}$ suppression observed also at $\sqrt{s_{NN}}=5.02\text{TeV}$

No firm conclusion on the $R_{AA}$ energy dependence within the current uncertainties
Different trend in data and theory for most forward-y?
Quarkonium in p-A collisions
J/ψ affected by CNM effects, with a strong $y$ and $p_T$ dependence: $\rightarrow R_{pA}$ decreases towards forward $y$

data consistent with shadowing and coherent parton energy loss models

agreement with CGC depends on implementation

good agreement between ALICE and LHCb (similar kinematic range)

different behavior at mid-$y$ for low and high $p_T$ J/ψ
mid and fw-γ: suppression increases vs centrality and is larger at low $p_T$
backward-γ: hint for increasing $Q_{pA}$ vs centrality, with rather flat $p_T$ trend

Shadowing and coherent energy loss models in fair agreement with data
\( \psi(2S) \) production in pA

- \( \psi(2S) \) suppression is stronger than the \( J/\psi \) one, both at RHIC and LHC

- unexpected since time spent by the cc in the nucleus (\( \tau_c \)) is shorter than charmonium formation time (\( \tau_f \))

- shadowing and energy loss, almost identical for \( J/\psi \) and \( \psi(2S) \), do not account for the different suppression

Only models including QGP + hadron resonance gas or comovers describe the stronger \( \psi(2S) \) suppression
No significant rapidity dependence of $\Upsilon$(1S) $R_{pA}$ (ALICE and LHCb agree within uncertainties)

Shadowing and energy loss models are compatible at forward-$y$ At backward-$y$ smaller anti-shadowing is suggested


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**p-Pb vs pp @mid-γ:**
Stronger excited states suppression with respect to γ(1S)
Initial state effects similar for the three γ states
→ Final states effects in p-Pb?

**p-Pb vs PbPb @mid-γ:**
even stronger suppression of excited states in PbPb

→ ALICE (and LHCb) observes:

\[ \frac{Y(2S)/Y(1S)}{Y(3S)/Y(1S)} \]


\[ \frac{X}{Y} \]

2.03<\(y\)<3.53: 0.27±0.08±0.04 (2012)
-4.46<\(y\)<-2.96: 0.26±0.09±0.04

compatible with pp results
0.26 ± 0.08 (ALICE, pp@7TeV)

→ Rapidity dependent final state effects at play?
Conclusions

Run1 results at $\sqrt{s}=2.76$TeV highlight the role of suppression and recombination mechanisms at play on the various quarkonium states.

First Run2 results at $\sqrt{s}=5.02$TeV confirm the picture, showing a rather similar suppression level.

Interplay of shadowing and energy loss describes $J/\psi$ and $\Upsilon$ production.

Comover-like effects seem to affect excited quarkonium states.

Thanks!
Conclusions

Run1 results at $\sqrt{s}=2.76\,\text{TeV}$ highlight the role of suppression and recombination mechanisms at play on the various quarkonium states. First Run2 results at $\sqrt{s}=5.02\,\text{TeV}$ confirm the picture, showing a rather similar suppression level. Interplay of shadowing and energy loss describes $J/\psi$ and $\Upsilon$ production. Comover-like effects seem to affect excited quarkonium states.

Other new results from Run2 eagerly awaited!!!

Thanks!

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Backup slides
the original idea: quarkonium production suppressed via color screening in the QGP

sequential melting
differences in the quarkonium binding energies lead to a sequential melting with increasing temperature

Quarkonium as QGP thermometer

PHENIX, Phys.Rev C91, 024913

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Evolution of $J/\psi \langle p_T^2 \rangle$

**r_{AA}** centrality evolution strongly depends on $\sqrt{s}$

decreasing $r_{AA}$ trend, observed at LHC
→ due to (re)combination, which dominates $J/\psi$ production at low $p_T$

transport models, already describing $J/\psi \ R_{AA}$, also reproduce the $r_{AA}$ evolution

---

ALICE inclusive $J/\psi \rightarrow \mu^+\mu^-$, 2.5<y<4
- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, global syst. = 4%

PHENIX inclusive $J/\psi \rightarrow \mu^+\mu^-$, 1.2<|y|<2.2
- Au-Au and Cu-Cu $\sqrt{s_{NN}} = 0.2$ TeV, global syst. = 3%

NA50 inclusive $J/\psi \rightarrow \mu^+\mu^-$, 0<y<1
- Pb-Pb $\sqrt{s_{NN}} = 0.017$ TeV, global syst. = 3%

Transport model calculations
Strong $R_{AA}$ enhancement in peripheral collisions for $0<p_T<0.3$ GeV/c

- significance of the excess is $5.4 \,(3.4)\sigma$ in 70-90% (50-70%)
- behaviour not predicted by transport models
- excess might be due to coherent $J/\psi$ photoproduction in PbPb (as measured also in UPC)

If excess is “removed” requiring $p_T^{J/\psi}>0.3$ GeV/c, ALICE $R_{AA}$ lowers by 20% at maximum (in the most peripheral bin)
2.76 TeV

ALICE, inclusive $J/\psi \rightarrow \mu^+\mu^-$, $p_{T} = 2.76$ TeV and Au-Au $s_{NN} = 0.2$ TeV

- ALICE, 2.5$ < y < 4$, 0-20%
  - global syst. = ± 8%
- PHENIX, 1.2$ < y < 2.2$, 0-20%
  - global syst. = ± 10%

Rapp Zhuang

5.02 TeV

ALICE, inclusive $J/\psi \rightarrow \mu^+\mu^-$

- Pb-Pb $s_{NN} = 5.02$ TeV, 0-20%
- Pb-Pb $s_{NN} = 2.76$ TeV, 0-20%
- Transport $s_{NN} = 5.02$ TeV (TM1, Du and Rapp)

TM1
TM2
**Multi-differential J/ψ studies**

- $p_T$-centrality multi-differential studies allows detailed comparison with theory models

0-20%

Model provide a fair description of the data, even if with different balance of primordial/regeneration components

Still rather large theory uncertainties: models will benefit from precise measurement of $\sigma_{cc}$ and CNM effects

Zhao et al., Nucl.Phys.A859 (2011) 114


ALICE, arXiv:1506.08804

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The contribution of $J/\psi$ from (re)combination should lead to a significant elliptic flow

ALICE: qualitative agreement with transport models including regeneration

CMS: path-length dependence suppression effect?

ALICE, PRL 111(2013) 162301

CMS-PAS-HIN-12-001

STAR, PRL 052301(2013)

Hint for $J/\psi$ flow at LHC, contrary to $v_2 \sim 0$ observed at RHIC!

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LHC Run-2 J/ψ results

ALICE, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
Inclusive $J/\psi \rightarrow \mu^+\mu^-$
$2.5 < y < 4$, $0.3 < p_T < 8$ GeV/$c$

<table>
<thead>
<tr>
<th>model</th>
<th>$\sigma_{c\bar{c}}$</th>
<th>N-N $\sigma_{J/\psi}$</th>
<th>comover $\sigma_{J/\psi}$</th>
<th>Shadowing</th>
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</thead>
<tbody>
<tr>
<td>Transport(Rapp)</td>
<td>0.57 mb</td>
<td>3.14 $\mu$b</td>
<td>-</td>
<td>EPS09</td>
</tr>
<tr>
<td>Transport(Zhou)</td>
<td>0.82 mb</td>
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<td>EPS09</td>
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<td>Stat. hadronization</td>
<td>0.45 mb</td>
<td>-</td>
<td>-</td>
<td>EPS09</td>
</tr>
<tr>
<td>Comovers</td>
<td>[0.45,0.7] mb</td>
<td>3.53 $\mu$b</td>
<td>0.65 mb</td>
<td>Glauber-Gribov theory</td>
</tr>
</tbody>
</table>
**Forward-to-Backward Ratio:**

\[
R_{FB}(p_T, y) = \frac{\frac{d^2\sigma(p_T, y > 0)}{dp_T dy}}{\frac{d^2\sigma(p_T, y < 0)}{dp_T dy}} = \frac{\text{p-going (x } \sim 10^{-4})}{\text{Pb-going (x } \sim 10^{-2})}
\]
Once CNM effects are measured in pPb, what can we learn on J/ψ production in PbPb?

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

we get rid of CNM effects with AA / pA x Ap

CNM effects not enough to explain PbPb data at high \( p_T \)

Evidence for hot matter effects in Pb-Pb!
ψ(2S) production in pA

Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA.

Low energy ψ(2S) p-A results from NA50, E866 and HERA-B:

**mid-y** (x_F~0):
- ψ(2S) suppression stronger than J/ψ one, interpreted via pair break-up
- fully formed resonances traversing the nucleus

**forward-y** (high x_F):
- suppression becomes identical
- dominated by energy loss

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**ψ(2S) versus crossing time**

Forward-$y$: $\tau_c \ll \tau_f$

Interaction with nuclear matter cannot play a role.

Backward-$y$: $\tau_c \approx \tau_f$

Indication of effects related to break-up in the nucleus?
Comparison to theoretical models

QGP+hadron resonance gas (Rapp) or comovers models (Ferreiro) reasonably describe both $J/\psi$ and $\psi(2S)$ suppression at RHIC and LHC.

$J/\psi$ → small suppression beyond CNM effects

$\psi(2S)$ → strongly affected by comovers due to its larger size → comovers more important in the A-going direction.
Similar suppression trend observed versus centrality, by both ALICE and PHENIX

QGP+hadron resonance gas (Rapp) or comovers models (Ferreiro) describe the observed suppression.
Y\(\text{vs}\ \text{ev. activity}\)

- Y\((nS)\)/Y\((1S)\) ratios fall with event-activity
  - Is the multiplicity affecting the Y\((nS)\)?
  - Are the Y\((nS)\) produced differently with multiplicity?

CMS
$Y$ compared to theory