Charmonium production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with ALICE

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On behalf of the ALICE Collaboration

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Outline

- Introduction

- ALICE detector

- Analysis technique

Inclusive $J/\psi$ $R_{AA}$ at $\sqrt{s_{NN}} = 5.02$ TeV in Pb-Pb collisions versus centrality and transverse momentum

- Using pp cross section at $\sqrt{s} = 5.02$ TeV as $R_{AA}$ reference
- Comparison to the results at $\sqrt{s_{NN}} = 2.76$ TeV
- Comparison to the theoretical models

- The results are available in CERN-EP-2016-162 and are published in arXiv:1606.08197
→ Quarkonium suppression:
  • Quarkonium states are expected to be dissociated in a hot medium by color screening.
  • Differences in the binding energies lead to a sequential melting of the states with increasing temperature (T. Matsui and H. Satz, PLB 178 (1986) 416).

→ Quarkonium (re)combination:
  • Increasing the collision energy, the $c\bar{c}$ pair multiplicity increases.
  • Enhanced quarkonium production via (re)combination at hadronization or during QGP stage.
Quarkonium in ALICE can be measured in two ways:

**Central Barrel:** \( J/\psi \rightarrow e^+e^- \)

- \(|y| < 0.9\)
- Electrons tracked using ITS and TPC
- Particle identification: TPC (+TOF)

**Forward muon arm:** \( J/\psi \rightarrow \mu^+\mu^- \)

- \(2.5 < y < 4\)
- Muons identified and tracked in the muon spectrometer

- Acceptance coverage in both \(y\) regions down to zero \(p_T\)
- The ALICE results presented in this talk refer to inclusive \(J/\psi\).
ALICE J/ψ Run-1 results in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Centrality dependence of the J/ψ inclusive $R_{AA}$ studied by ALICE at both central and forward rapidities down to zero $p_T$.

ALICE results:
- Clear J/ψ suppression with almost no centrality dependence for $N_{\text{part}} > 100$.

Comparison with PHENIX:
- ALICE results show weaker centrality dependence and smaller suppression for central events, behaviour expected in a (re)combination scenario.

ALICE Coll. PLB 734 (2014) 314

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ALICE Coll. PLB 734 (2014) 314
The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy.

- Hint for J/ψ flow at the LHC while $v_2 \sim 0$ at RHIC [PRL. 111, 052301 (2013)] (even if with large uncertainties).
- Qualitative agreement with transport models including regeneration.
→ Excess of J/$\psi$ at very low $p_T$ observed in peripheral Pb-Pb collisions.

→ Photoproduction of J/$\psi$ in Pb-Pb collisions with $b < 2R$ was proposed to be at the origin of this excess. The cut $p_T > 0.3$ GeV/$c$ removes ~75% of photoproduced J/$\psi$. 

**Low $p_T$ J/$\psi**
ALICE J/ψ Run-2 results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

CERN-EP-2016-162
arXiv:1606.08197
Results from 2015 data set, based on dimuon triggered events

Integrated luminosity ~ 225 $\mu$b$^{-1}$

Event selection:
Rejection of beam gas and electromagnetic interactions (V0 and ZDC)
SPD used for vertex determination

Centrality selection:
Estimate based on a Glauber model fit of the V0 amplitude

Muon track selection:
• Muon trigger matching
• $-4 < \eta_{\mu} < -2.5$
• $17.6 < R_{abs} < 89.5$ cm
  ($R_{abs} =$ track position at the absorber end)
• $2.5 < y_{\mu\mu} < 4$
The statistics is now ~ 7 times higher w.r.t. Run-1.

\[ \text{J/}\psi \rightarrow \mu^+\mu^- \text{ signal} \]

J/\psi yield extracted fitting the opposite sign dimuon invariant mass spectrum.

Signal is extracted with a extended Crystal Ball function or a pseudo-Gaussian function.

Background: phenomenological fits of the inv. mass spectrum or subtraction of the background evaluated from event mixing.

Results obtained with different techniques are combined to extract \(<N_{\text{J/}\psi}>\) and to evaluate systematic uncertainties.
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$p_T < 12 \text{ GeV/c, centrality bins}$

arXiv:1606.08197
ALICE took data at $\sqrt{s} = 5.02$ TeV during 4 days in November 2015.

We collected a luminosity of 106.3 nb$^{-1}$.

The analysis technique adopted is similar to the one of Pb-Pb collisions.

We use these data as reference for the $J/\psi R_{AA}$ in Pb-Pb collisions.

Integrated cross section ($p_{T} < 12$ GeV/c): $5.61 \pm 0.08$ (stat.) $\pm 0.28$ (syst.) $\mu$b.

The integrated and differential cross sections are in very good agreement with the interpolation values used for p-Pb results at $\sqrt{s_{NN}} = 5.02$ TeV.
Inclusive $J/\psi$ $R_{AA}$ vs centrality

- High statistics collected in 2015 allows the $R_{AA}$ measurement in narrow centrality bins.

- Clear $J/\psi$ suppression with almost no centrality dependence above $N_{part} \sim 100$.

- $R_{AA}^{0-90\%} (0 < p_T < 8 \text{ GeV/c}) = 0.66 \pm 0.01 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$.

- $R_{AA}$ at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ was $0.58 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (syst.)}$.

- A systematic difference of $\sim 15\%$ is visible w.r.t. $R_{AA}$ at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. Effect is within the uncertainties of the measurement.

- The $R_{AA}$ of prompt $J/\psi$ would be about $10\%$ higher if $R_{AA(\text{non-prompt})} = 0$ and about $5\% \ (1\%)$ smaller if $R_{AA(\text{non-prompt})} = 1$ for central (peripheral) collisions.
For most calculations a better agreement with the data is found when considering their upper limit.

For transport models this corresponds to the absence of nuclear shadowing, which can be clearly considered as an extreme assumption.

$\rightarrow p_T > 0.3$ GeV/c cut removes about 80% of photoproduced $J/\psi$.

$\rightarrow R_{AA}$ is compared with the theoretical calculations: statistical, transport and comovers approaches.

$\rightarrow$ Large uncertainties due to the choice of input parameters in particular $\sigma_{c\bar{c}}$.

Stat. hadronization: NPA 904-905 (2013) 535c

arXiv:1606.08197
The double ratio for most central events is $1.17 \pm 0.04$ (stat.) $\pm 0.20$ (syst.).

Data are, within uncertainties, compatible with the theoretical models, and show no clear centrality dependence.

By doing the double ratio, some uncertainties on the models cancel out.

With the measurement, the $T_{AA}$ uncertainty is cancelled.

The error bands on the models correspond to a variation by 5% of the $c\bar{c}$ cross section.

Contribution from non-prompt $J/\psi$ varies the double ratio by 2%.

The double ratio for most central events is $1.17 \pm 0.04$ (stat.) $\pm 0.20$ (syst.).

Data are, within uncertainties, compatible with the theoretical models, and show no clear centrality dependence.
Inclusive $J/\psi \, R_{AA}$ vs $p_T$

$\rightarrow$ $R_{AA}$ measurement now extended up to 12 GeV/$c$.

$\rightarrow$ Less suppression at low with respect to high $p_T$, with stronger $p_T$ dependence for central events as expected from models with strong regeneration component.

$\rightarrow$ Hint for an increase of $R_{AA}$ with $\sqrt{s_{NN}}$ is visible in $2 < p_T < 6$ GeV/$c$.

arXiv:1606.08197
The J/$\psi$ cross section has been measured both integrated and in $p_T$ bins in pp collisions at $\sqrt{s} = 5.02$ TeV.

The inclusive J/$\psi$ nuclear modification factor has been measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity, down to $p_T = 0$.

The centrality and $p_T$ dependence of $R_{AA}$ have been studied:

- $R_{AA}$ shows an increase of the suppression with centrality up to $N_{\text{part}} \sim 100$ followed by a saturation.
- The $p_T$ dependence of $R_{AA}$ exhibits an increase at low $p_T$.

Comparing the $R_{AA}$ at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV:

- A difference by ~ 15% is observed, without a clear centrality dependence.
- As a function of $p_T$, a hint for an increase of $R_{AA}$ is visible in $2 < p_T < 6$ GeV/$c$.

These results are described by theoretical calculations and they support a picture of J/$\psi$ suppression and regeneration in a QGP.
Thank you
## Summary of systematic uncertainties (Pb-Pb)

<table>
<thead>
<tr>
<th>Source</th>
<th>0-90%, $p_T &lt;12\text{GeV/c}$</th>
<th>0-20%, vs $p_T$</th>
<th>Vs centrality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>1.8%</td>
<td>1.2-3.1%</td>
<td>1.6-2.8%</td>
</tr>
<tr>
<td>MC input</td>
<td>2%</td>
<td>2%</td>
<td>2%*</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>3%</td>
<td>3%+1%</td>
<td>3%*+1% (central)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>3.6%</td>
<td>1.5-4.8%+1%</td>
<td>3.6%*+1% (central)</td>
</tr>
<tr>
<td>Matching efficiency</td>
<td>1%</td>
<td>1%</td>
<td>1%*</td>
</tr>
<tr>
<td>$&lt;T_{\text{AA}}&gt;$</td>
<td>3.2%</td>
<td>3.2%*</td>
<td>3.1-7.6%</td>
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<tr>
<td>$F_{\text{norm}}$</td>
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<td>0.5%*</td>
<td>0.5%*</td>
</tr>
<tr>
<td>Centrality</td>
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<td>0.1%*</td>
<td>0-6.6%</td>
</tr>
<tr>
<td>pp reference (stat.)</td>
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<td>3-20%</td>
<td>1.5%*</td>
</tr>
<tr>
<td>pp reference (syst.)</td>
<td>5.0%</td>
<td>3-10% + 2.1%*</td>
<td>4.9%*</td>
</tr>
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</table>

* correlated error
# Summary of systematic uncertainties (pp)

<table>
<thead>
<tr>
<th>Source</th>
<th>$0 &lt; p_T &lt; 12$ GeV/c</th>
<th>$V_s p_T$</th>
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<tr>
<td>Signal extraction</td>
<td>3%</td>
<td>1.5-9.3%</td>
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<tr>
<td>MC input</td>
<td>2%</td>
<td>0.7-1.5%</td>
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<tr>
<td>Tracking efficiency</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.8%</td>
<td>1.5-1.8%</td>
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<tr>
<td>Matching efficiency</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Luminosity</td>
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<td>2.1%*</td>
</tr>
<tr>
<td>BR</td>
<td>0.5%</td>
<td>0.5%*</td>
</tr>
</tbody>
</table>

* correlated error
Inclusive $J/\psi$ $R_{AA}$ vs centrality

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>
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<tr>
<td>Transport(Rapp)</td>
<td>0.57 mb</td>
<td>3.14 $\mu$b</td>
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<td>EPS09</td>
</tr>
<tr>
<td>Transport(Zhou)</td>
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<td>3.5 $\mu$b</td>
<td>-</td>
<td>EPS09</td>
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<td>Stat. hadronization</td>
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<td>-</td>
<td>-</td>
<td>EPS09</td>
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<tr>
<td>Comovers</td>
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<td>3.53 $\mu$b</td>
<td>0.65 mb</td>
<td>Glauber-Gribov theory</td>
</tr>
</tbody>
</table>
Good agreement between ALICE and CMS data.

Large statistical and systematic uncertainties prevent a firm conclusion on the $\psi(2S)$ trend vs centrality.
The $R_{AA}$ of prompt $J/\psi$ would be about 10% higher if $R_{AA(\text{non-prompt})} = 0$ and about 5% (1%) smaller if $R_{AA(\text{non-prompt})} = 1$ for central (peripheral) collisions.

The prompt $J/\psi$ $R_{AA}$ is expected to be 7% larger (2% smaller) for $p_T < 1$ GeV/$c$ and 30% larger (55% smaller) for $10 < p_T < 12$ GeV/$c$ when the beauty contribution is fully (not) suppressed.