Charmonium production measurements in Pb-Pb collisions with ALICE at the LHC

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For the ALICE Collaboration

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Content

Physics motivation

The ALICE detector

$J/\psi \rightarrow \mu\mu (2.5 < y < 4.0)$:
- Analysis
- Results

$\psi(2S) \rightarrow \mu\mu (2.5 < y < 4.0)$:
- Analysis
- Results

Conclusions
Charmonium in A-A

- Ultrarelativistic heavy-ion collisions $\rightarrow$ high energy densities.
- Quark-Gluon-Plasma: deconfined state of quarks and gluons.

Charmonium as a probe of deconfinement:

- Created in the early stages of the collision.  
  - PLB 178(1986) 416
- Suppressed by Debye screening.  
  - PRD 64(2001) 094015
- Different radii & binding energies $\rightarrow$ sequential suppression.
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Charmonium production in A-A previously studied by various experiments:

\[ R_{AA} = \frac{Y_{AA}}{<N_{coll}> Y_{pp}} \]

- RHIC & SPS: significant J/ψ suppression beyond the Cold Nuclear Matter effects. [EPJ C71(2011) 1534]
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$$ R_{AA} = \frac{Y_{A-A}^{J/\psi}}{<N_{\text{Coll}}>} Y_{pp}^{J/\psi} $$

- RHIC & SPS: significant J/ψ suppression beyond the Cold Nuclear Matter effects.
- RHIC: larger suppression at forward than at mid rapidity.

PRD 64(2001) 094015

PRL 98(2007) 232301
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What can we expect at the LHC?

- New collision energy regime
  - larger suppression?
- $N_{cc\bar{c}}$/central collision $\approx 10 \times$ RHIC
  - new source of $J/\psi$ production from recombination of $c\bar{c}$ pairs?

Charmonium

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The ALICE detector

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The ALICE detector

Central barrel $|y| < 0.9$
down to $p_T = 0$

Charmonia: $e^+ e^- \text{ channel}$

Fiorella Fionda’s talk

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The ALICE detector

Muon Spectrometer: 
2.5 < y < 4.0
down to $p_T = 0$

Charmonia: 
$\mu^+ \mu^-$ channel
pp reference and Pb-Pb data set

**pp collisions**: results at $\sqrt{s} = 7$ and 2.76 TeV.

$2.5 < y < 4.0$: NRQCD calculations describe the measured $d^2\sigma/dydp_T$ at $\sqrt{s} = 7$ and 2.76 TeV.

Results at $\sqrt{s} = 2.76$ TeV (same energy as Pb-Pb collisions) are used as reference.

pp reference is the main source of systematics in the $R_{AA}$: 9%. 

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**pp reference and Pb-Pb data set**

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$J/\psi, \psi(2S) \rightarrow \mu\mu$ in **Pb-Pb collisions**:

Dimuon events from the muon trigger, $L_{\text{int}} \approx 70$ μb$^{-1}$.

Centrality estimation is based on a Glauber model fit of the V0 amplitude.
\[ J/\psi \rightarrow \mu\mu \text{ in Pb-Pb: analysis} \]

Yield extracted by fitting the invariant mass spectrum of unlike-sign dimuons:

- **Signal:** modified Crystal Ball with different line shapes.
- **Background:** different functions with and w/o background subtraction (event mixing technique).

Results are then combined to extract a weighted mean \( N_{J/\psi} \) and the systematic uncertainties on signal extraction.
$J/\psi \rightarrow \mu\mu$ in Pb-Pb: analysis

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Acceptance \( \times \) efficiency values are obtained by embedding MC \( J/\psi \) into real events.

Weak centrality dependence.
Results: $J/\psi$ $R_{AA}$ vs centrality

- No significant centrality dependence for $N_{\text{part}} > 70$. 
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- No significant centrality dependence for $N_{\text{part}} > 70$.
- $R_{AA}^{\text{ALICE}} \sim 3 \times R_{AA}^{\text{PHENIX}}$ for $N_{\text{part}} > 250$. 

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No significant centrality dependence for \( N_{\text{part}} > 100 \).

\[ R_{AA}^{\text{ALICE}} \sim 3 \times R_{AA}^{\text{PHENIX}} \] for \( N_{\text{part}} > 250 \).

Statistical Hadronisation Model: prediction for two \( d\sigma_{c\bar{c}}/dy \) in Pb-Pb.

Transport Models: different rate equations of \( J/\psi \) dissociation and regeneration in QGP.

Shadowing plus comovers plus recombination model.  

Need to measure \( \sigma_{c\bar{c}} \).
Results: $J/\psi$ $R_{AA}$ vs centrality, $y$ bins

$R_{AA}$ decreases by 40% from $y = 2.5$ to $y = 4$. Similar centrality behavior for different forward rapidity ranges.
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$R_{AA}$ decreases by 40% from $y = 2.5$ to $y = 4$.

Shadowing accounts for only a fraction of the suppression at forward $y$.

Similar centrality behavior for different forward rapidity ranges.

Shadowing + comovers + recombination model does not reproduce the data for $3.5 < y < 4$.

A measurement of the Cold Nuclear Matter effects is needed!

Igor Lakomov’s talk

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Results: $J/\psi$ $R_{AA}$ vs centrality, $p_T$ bins

- No centrality dependence for low-$p_T$ $J/\psi$ ($0 < p_T < 2$ GeV/c) when $N_{\text{part}} > 100$.
Results: $J/\psi$ $R_{AA}$ vs centrality, $p_T$ bins

- No centrality dependence for low-$p_T$ $J/\psi$ ($0 < p_T < 2$ GeV/c) when $N_{\text{part}} > 100$.


- Transport Models predictions in good agreement with the data:
  - Around 50% of the low-$p_T$ $J/\psi$ in the most central collisions are produced by regeneration.
  - For high-$p_T$ $J/\psi$, contribution from regeneration is very small.
Results: $J/\psi$ $R_{AA}$ vs $p_T$, centrality bins

Stronger suppression for high-$p_T$ $J/\psi$.

Stronger $p_T$ dependence for central collisions (0-20%).
Results: $J/\psi$ $R_{AA}$ vs $p_T$, centrality bins

Stronger suppression for high-$p_T$ $J/\psi$.

Very good agreement with Transport Models.

Stronger $p_T$ dependence for central collisions (0-20%).

Discrepancy between model and data at low-$p_T$ in peripheral collisions (40-90%).

According to Transport Models: regeneration at work in the low-$p_T$ regime.
Results: $J/\psi < p_T$>

$< p_T >$ values were obtained by fitting

$$\frac{d^2 N}{dy dp_T} \propto \frac{p_T}{[1 + (p_T / p_0)^2]^n}$$

in three different centrality bins.
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$$\frac{d^2N}{dydp_T} \propto \frac{p_T}{\left[1+(p_T/p_0)^2\right]^n}$$

in three different centrality bins.

ALICE: clear decrease of $< p_T >$ with increasing $N_{\text{part}}$.

Striking difference with respect to lower energy results (PHENIX)!

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ψ(2S) → μμ

ψ(2S) analysis suffers from low statistics, both in pp and Pb-Pb.

Signal extraction only possible in 2 $p_T$ bins:
- $0 < p_T < 3$ GeV/c: 20-40%, 40-60% and 60-90%.
- $3 < p_T < 8$ GeV/c: 0-20% and 20-60%.

S/B in Pb-Pb: between 0.01 and 0.3 from 20-40% to 60-90% centrality.
$\psi(2S) \rightarrow \mu\mu$

ALICE used pp at $\sqrt{s} = 7$ TeV as reference: small $\sqrt{s}$ and $y$ dependence from $[\psi(2S) / J/ψ]_{pp}$ results by CDF, LHCb and CMS taken into account in the systematic uncertainty ($\sim 15\%$).

Dashed lines show the error on the pp reference: CMS used pp at $\sqrt{s} = 2.76$ TeV.

Signal extraction and MC inputs for Acceptance x Efficiency corrections are the main source of systematics (some others vanish in the double ratio).

No decisive conclusion on the $\psi(2S)$ enhancement/suppression vs $N_{\text{part}}$ due to large statistical and systematic uncertainties.

ALICE excludes large enhancement in the most central collisions.
Conclusions

- ALICE Pb-Pb results vs $N_{\text{part}}$ show a different behavior relative to RHIC energies:
  - Flat centrality dependence ($N_{\text{part}} > 70$).
  - $R_{AA}^{\text{ALICE}} \sim 3 \times R_{AA}^{\text{PHENIX}}$ for the most central collisions.

- Stronger suppression for high-$p_T$ $J/\psi$ relative to the low-$p_T$ ones.

- $<p_T>$ decreases with increasing collision centrality, opposite behavior compared to lower energy results (PHENIX).

- Comparisons to models and RHIC results point to (re)generation.

- Important to measure Cold Nuclear Matter effects and $\sigma_{c\bar{c}}$.

- $\psi(2S)$: No firm conclusion on enhancement/suppression with respect to $J/\psi$, but a strong enhancement in central Pb-Pb collisions seems unlikely.
BACKUP
The ALICE Muon Spectrometer

Located in the forward rapidity region and with a full azimuthal coverage, it is composed by:

• Absorbers:
  a) Front absorber.- Absorbs hadrons, photons and electrons.
  b) Beam shield.- Protects from particles produced at large $\gamma$.
  c) Iron wall.- Absorbs hadrons that punch-through the frontal absorber.

• Magnetic dipole.- 3 T·m integrated magnetic field, bends charged particles allowing to extract the sign of their electric charge and momentum.

• Tracking chambers.- Spatial resolution, in bending coordinate, better than 100 $\mu$m in order to identify and disentangle the $\Upsilon$ family (100 MeV resolution).

• Trigger chambers.- Timing resolution of 1-2 ns and latency of 700 ns (LØ trigger), can trigger likesign and unlikesign events.
$R_{AA}$ vs Centrality, $y$ bins

- Inclusive $J/\psi$, $0<p_T<8$ GeV/c
- $Pb-Pb | s_{NN}=2.76$ TeV, $L=70 \mu b^{-1}$, global sys. = $\pm 6\%$

- $2.5<y<3$
- $3<y<3.5$
- $3.5<y<4$

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$R_{AA}$ vs Centrality, $p_T$ bins

\begin{align*}
\text{Inclusive J/ψ, } 2.5<y<4 & \\
Pb-Pb | s_{NN}=2.76 \text{ TeV, } L=70 \mu \text{b}^{-1}, \text{ global sys.}=\pm 6\% \\
0<p_T<2 \text{ GeV/c} & \\
2<p_T<5 \text{ GeV/c} & \\
5<p_T<8 \text{ GeV/c} &
\end{align*}
$R_{AA}$ vs $p_T$, centrality bins
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Concept</th>
<th>Value (%)</th>
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<tr>
<td>Luminosity pp</td>
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<tr>
<td>R factor pp</td>
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<td>Normalization (MUL $\rightarrow$ MB)</td>
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<tr>
<td>Trigger</td>
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</tr>
<tr>
<td>Tracking</td>
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<tr>
<td>Matching</td>
<td>2.0</td>
</tr>
<tr>
<td>MC input</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Systematic uncertainties


Unc. systematics: n J/ψ + T_{AA} + Tracking + Trigger.


In the plots:
Statistics: vertical line at each point.
Unc. systematics: shaded area at each point.
Systematic uncertainties

Unc. systematics: \( n \ J/\psi \).

P.C. systematics: MC input + Matching + Tracking + Trigger + TAA +
unc. \( J/\psi \) pp.

Unc. systematics: \( n \ J/\psi + \text{unc.} \ J/\psi \) pp.

P.C. systematics: MC input + Matching + Tracking + Trigger + TAA.


Statistics: \( n \ J/\psi + J/\psi \) pp.

In the plots:
Statistics: vertical line.
Unc. systematics: shaded area at each point.
P.C. systematics: boxes at each point,
Non-prompt fraction of the inclusive $J/\psi$ yield in $pp$ at mid rapidity ($f_B$):

CDF vs CMS: increase of 5% and $p_T$ independent.

Assume:

1. Linear increase of $f_B(\sqrt{s})$.
2. It does not depend on the $y$ region.

$b$-hadron suppression factor in Pb-Pb ($q$)? $R_{AA}^D \approx 0.3$ for $2 < p_T < 16$ GeV/c

⇒ ‘Dead cone effect’: $R_{AA}^B > R_{AA}^D$.

$0.2 < q < 1$ is used
Effect of non-prompt $J/\psi$ on $R_{AA}$

$$R_{AA}^{\text{prompt}}(p_T) = \frac{R_{AA}^{\text{incl}} - f_B q}{1 - f_B}$$  \(\Rightarrow\) small effect on the inclusive $J/\psi$ $R_{AA}$ results.

Similar study can be carried out for $R_{AA}$ vs $y$: LHCb shows $f_B(y)$ decreases with increasing rapidity.

\(\Rightarrow\) Difference between inclusive and prompt $R_{AA}$ well within errors.

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Theoretical models

Statistical hadronization
Thermal model with $T=164$ MeV, $\mu = 1$ MeV (from particle ratio fits).
All charm produced in the initial hard-scatterings.
Charmonium production at phase boundary.

Transport Model by Rapp & Zhao
Boltzmann transport equation for the $J/\psi$.
$V_{FB}$ adjusted to measured $dN_{ch}/d\eta$.
$\sigma_{cc}|_{y=3.25} \approx 0.5$ mb.
Shadowing: 30% suppression in the most central collisions.
No Croning effect and $\sigma_{Abs} = 0$.
10% of $J/\psi \leftarrow B$ and no quenching.

Transport Model by Liu et al.
Boltzmann transport equation for the $J/\psi$.
$\sigma_{c\bar{c}}|_{y=3.25} \approx 0.38$ mb.
EKS98 shadowing and $\sigma_{Abs} = 0$.
10% of $J/\psi \leftarrow B$ and $R_{AA} (b) = 0.4$ for all $p_T$ range.
J/ψ photo-production

Clear deviation, at low- $p_T$ for semi and peripheral collisions, to the expected J/ψ hadro-production.

J/ψ photo-production could be responsible of this excess.

More than 50% of the J/ψ from photo-production have a $p_T$ in the 0-200 MeV/c range.

Only ~ 1% of the J/ψ from hadro-production have a $p_T < 200$ MeV.
$J/\psi < p_T^2$