Measurement of charmonia production in heavy-ion collisions with the ATLAS detector

Jorge López
for the ATLAS Collaboration

XXVI International Conference on Ultrarelativistic Heavy-Ion Collisions
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Why measure charmonia?

• Charmonia:
  - Bound states of charm and anti-charm quarks, like $J/\psi$ and $\psi(2S)$ mesons.
  - Two production mechanisms:
    - **Prompt** production from hard-scattering and very short time decays.
    - **Non-Prompt** production dominated by b-hadron decays.
  - A unique probe to study the hot, dense system created in heavy ion collisions.

• Many related issues:
  - **Cold nuclear matter** effects:
    - PDF modification inside nucleus
    - Initial stage energy loss
    - Nuclear absorption/dissociation
  - **Hot nuclear matter** effects:
    - Suppression by color screening
    - Regeneration via statistical recombination
    - Medium induced energy loss
    - Feed down of excited states of charmonium and B-hadrons

Jorge López - Measurement of charmonia production in heavy-ion collisions with the ATLAS detector - QM2017
The ATLAS Experiment at the LHC

2013 $p+Pb$ 5.02 TeV, 28 nb$^{-1}$  
2013 $pp$ 2.76 TeV, 4 pb$^{-1}$  
2015 $Pb+Pb$ 5.02 TeV, 0.42 nb$^{-1}$  
2015 $pp$ 5.02 TeV, 25 pb$^{-1}$  
2016 $p+Pb$ 8.16 TeV, 0.17 pb$^{-1}$

Forward Calorimeters (FCal) at $3.1 < |\eta| < 4.9$: Centrality determination.
ATLAS $J/\psi$ and $\psi(2S)$ measurements

- May 2015, $J/\psi$ paper
  - ATLAS Collaboration, Phys. Rev. C 92, 034904
  - p+Pb 5.02 TeV

- June 2015, $J/\psi$ and $\psi(2S)$
  - ATLAS-CONF-2015-023
  - p+Pb 5.02 TeV and pp 2.76 TeV

- September 2016, $J/\psi$ and $\psi(2S)$
  - ATLAS-CONF-2016-109 (updated)
  - Pb+Pb 5.02 TeV and pp 5.02 TeV

Published paper compatible with new analysis for $J/\psi$ and $\psi(2S)$ in p+Pb

See Poster: Charmonia production in Pb+Pb at 5.02 TeV
Sebastian Tapia
Data Analysis Method

- Charmonia production studied via the $\mu\mu$ decay channel.
- Trigger:
  - p+Pb: 2 muons with $p_T > 2$ GeV, at least one muon from L1.
  - Pb+Pb: 2 muons with $p_T > 4$ GeV, at least one muon from L1.
- Kinematic range:
  - p+Pb: $8.5 < p_T^{(dimuon)} < 30$ GeV, $|y^*| < 1.5$
  - Pb+Pb: $9 < p_T^{(dimuon)} < 40$ GeV, $|y| < 2$, Centrality 0 - 80%
- Observable determination:
  - Two dimensional weighted unbinned, maximum likelihood fits
  - Dimuons weighted to correct for trigger, reconstruction and acceptance.
  - Extraction of prompt and non prompt fraction of measured yields.
Simultaneous fit method

\[ PDF(m, \tau) = \sum_{i=1}^{7} k_i f_i(m) \cdot h_i(\tau) \otimes g(\tau) \]
Simultaneous fit method

<table>
<thead>
<tr>
<th>i</th>
<th>Type</th>
<th>Source</th>
<th>$f_i(m)$</th>
<th>$h_i(\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$J/\psi$</td>
<td>P</td>
<td>$\omega_i CB_1(m) + (1 - \omega_i)G_1(m)$</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>2</td>
<td>$J/\psi$</td>
<td>NP</td>
<td>$\omega_i CB_1(m) + (1 - \omega_i)G_1(m)$</td>
<td>$E_1(\tau)$</td>
</tr>
<tr>
<td>3</td>
<td>$\psi(2S)$</td>
<td>P</td>
<td>$\omega_i CB_2(m) + (1 - \omega_i)G_2(m)$</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>4</td>
<td>$\psi(2S)$</td>
<td>NP</td>
<td>$\omega_i CB_2(m) + (1 - \omega_i)G_2(m)$</td>
<td>$E_2(\tau)$</td>
</tr>
<tr>
<td>5</td>
<td>Bkg</td>
<td>P</td>
<td>flat</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>6</td>
<td>Bkg</td>
<td>NP</td>
<td>$E_3(m)$</td>
<td>$E_4(\tau)$</td>
</tr>
<tr>
<td>7</td>
<td>Bkg</td>
<td>NP</td>
<td>$E_5(m)$</td>
<td>$E_6(\mid\tau\mid)$</td>
</tr>
</tbody>
</table>

Pseudo-proper decay time

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$$

PDF($m$, $\tau$) = $\sum_{i=1}^{7} \kappa_i f_i(m) \cdot h_i(\tau) \otimes g(\tau)$
**$J/\psi$ non-prompt fraction vs $p_T$**

$$\text{Non-Prompt Fraction} = \frac{N_{\text{Non-Prompt} \ J/\psi (p_T, y)}}{N_{\text{Total} \ J/\psi (p_T, y)}}$$

---

ATLAS Preliminary

- $pp$ $\sqrt{s} = 5.02$ TeV, $\int L dt = 25$ pb$^{-1}$
- $J/\psi$ Non-Prompt Fraction
  - $0.00 < \mid y \mid < 0.75$
  - $0.75 < \mid y \mid < 1.50$
  - $1.50 < \mid y \mid < 2.00$

ATLAS

- 2013 $p+$Pb, 28.1 nb$^{-1}$
- $\sqrt{s_{NN}} = 5.02$ TeV

No rapidity dependence, $pp$ and $p+$Pb are compatible
J/ψ non-prompt fraction vs $p_T$

Non prompt fraction for several centrality slices in Pb+Pb

ATLAS Preliminary

PbPb $\sqrt{s_{NN}} = 5.02$ TeV, 0.42 nb$^{-1}$

J/ψ, |y| < 2.0

No centrality dependence
**J/ψ non-prompt fraction vs p_T**

Non-Prompt Fraction = \frac{N_{Non-Prompt \ J/\psi}(p_T, y)}{N_{Total \ J/\psi}(p_T, y)}

---

**ATLAS Preliminary**

*pp* \( \sqrt{s} = 5.02 \text{ TeV}, \int L dt = 25 \text{ pb}^{-1} \)

J/ψ Non-Prompt Fraction

- 0.00 < |y| < 0.75
- 0.75 < |y| < 1.50
- 1.50 < |y| < 2.00

**ATLAS**

2013 p+Pb, 28.1 nb^{-1}

\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

**No rapidity dependence, pp and p+Pb are compatible**
$J/\psi$ non-prompt fraction vs $p_T$

Non prompt fraction for several centrality slices in Pb+Pb

Slight difference with pp at low and high $p_T$. Greater suppression for prompt than non prompt.
Nuclear modification factor $R_{pPb}$

**Prompt $J/\psi$**

$$R_{pPb} = \frac{1}{A^{Pb}} \frac{d^2\sigma^{p+Pb}_{\psi}}{dy^* dp_T} / \frac{d^2\sigma^{pp}_{\psi}}{dy dp_T}$$

- **pp reference** is interpolated from 2.76 TeV, 7 TeV and 8 TeV

ATLAS-CONF-2015-023

No $p_T$ or rapidity dependence observed, $R_{pPb}$ is consistent with unity
Nuclear modification factor $R_{ppPb}$

Non-Prompt $J/\psi$

Non-Prompt $J/\psi$

-1.5 $< y^* < 1.5$

$ATLAS$ Preliminary

$p+Pb \sqrt{s_{NN}} = 5.02$ TeV

$R_{pp}$

$p_T$ [GeV]

0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

10 15 20 25 30

Rapidity

$y^*$

0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

$-1.5 -1 -0.5 0 0.5 1 1.5$

$R_{ppPb}$ is consistent with unity

No $p_T$ or rapidity dependence observed, $R_{ppPb}$ is consistent with unity

ATLAS-CONF-2015-023

pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV

Jorge López - Measurement of charmonia production in heavy-ion collisions with the ATLAS detector - QM2017
Nuclear modification factor $R_{pPb}$

**Prompt $\psi(2S)$**

No $p_T$ or rapidity dependence observed, $R_{pPb}$ is consistent with unity

pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV  ATLAS-CONF-2015-023
Number of Z bosons scale with number of nucleon-nucleon interactions.

Ratio of yields provide a test of production scaling independent of geometric models.

Check of the centrality dependence by normalizing to the number of Z bosons

$N_\psi/N_Z$ vs. $E_{T}^{FCal}$

$J/\psi$ to $Z$ ratio independent of event activity
$\psi(2S)$ to $Z$ yield ratio

Prompt $\psi(2S)$ has a decreasing trend with respect to event activity

ATLAS Preliminary

$p+\text{Pb } \sqrt{s_{NN}} = 5.02\text{ TeV}$

$10 < p_T^{\psi} < 30\text{ GeV}$

$-1.5 < y_\psi^* < 1.5$

$-3.0 < y_Z^* < 2.0$

ATLAS-CONF-2015-023
$J/\psi$ nuclear modification factor $R_{AA}$

$$R_{AA} = \frac{N^{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}.$$ 

### ATLAS Preliminary

**Prompt $J/\psi$**

- $\sqrt{s_{NN}} = 5.02$ TeV
- $0.42 \text{ nb}^{-1}$
- $pp, \sqrt{s} = 5.02$ TeV
- $25 \text{ pb}^{-1}$
- $|y| < 2$
- 0-80% centrality

**Suppression shows $p_T$ dependence only for prompt $J/\psi$**

### ATLAS Preliminary

**Non-Prompt $J/\psi$**

- $\sqrt{s_{NN}} = 5.02$ TeV
- $0.42 \text{ nb}^{-1}$
- $pp, \sqrt{s} = 5.02$ TeV
- $25 \text{ pb}^{-1}$
- $|y| < 2$
- 0-80% centrality

ATLAS-CONF-2016-109

Jorge López - Measurement of charmonia production in heavy-ion collisions with the ATLAS detector - QM2017
$J/\psi$ nuclear modification factor $R_{AA}$

No significant rapidity dependence
**J/ψ** nuclear modification factor $R_{AA}$

- $R_{AA}$ strongly dependent on collision centrality.
- Suppression pattern and magnitude are very similar for both production mechanisms.
$\psi(2S)$ to $J/\psi$ double ratio in Pb+Pb

- Stronger suppression of prompt $\psi(2S)$ with respect to $J/\psi$.
- Non prompt double ratio consistent with unity. Consistent with $B$-mesons decaying outside the nuclear medium.
$J/\psi$ decay produced in association with four jets collected during $p+Pb$ run at 8.16 TeV (2016 data)

$p+Pb$ $\sqrt{s_{NN}} = 8.16$ TeV

$m_{\mu^+\mu^-} = 3.09$ GeV, $P_T^{\mu^+\mu^-} = 50.9$ GeV

$p_{T^{\text{jet1}}} = 48.5$ GeV, $p_{T^{\text{jet2}}} = 31.4$ GeV

$p_{T^{\text{jet3}}} = 28.3$ GeV, $p_{T^{\text{jet4}}} = 23.3$ GeV

$\sum E_T^{\text{Pb}} = 57$ GeV
2016 p+Pb run dimuon spectrum

Events / Bin Width [GeV⁻¹]

ATLAS Preliminary
2016 p+Pb 0.17 pb⁻¹
√s_{NN} = 8.16 TeV

m_{μ⁺μ⁻} [GeV]
Charmonia production in p+Pb and Pb+Pb collisions are presented.
Separation of prompt and non-prompt ($b$) components.
For $J/\psi$ and $\psi(2S)$:
- $R_{pPb}$ and $R_{AA}$ show no significant rapidity dependence.
- $R_{AA}$ for prompt and non-prompt components have different behavior as a function of $p_T$.
- $R_{pPb}$ has no significant dependence on centrality.
- Prompt and non-prompt $R_{AA}$ strongly dependent on centrality.
- Prompt $\psi(2S)$ is suppressed with respect to $J/\psi$ in Pb+Pb.
- Non-prompt component does not indicate suppression of $\psi(2S)$ with respect to $J/\psi$.

A factor of six more pPb data at 8.16 TeV collected in the last run, stay tuned for new results
Additional Slides
Acceptance map for $J/\psi$ and $\psi(S)$ analyses
Simultaneous fit method definitions

<table>
<thead>
<tr>
<th>i</th>
<th>Type</th>
<th>Source</th>
<th>( f_i(m) )</th>
<th>( h_i(\tau) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( J/\psi )</td>
<td>P</td>
<td>( \omega_1 CB_1(m) + (1 - \omega_1)G_1(m) )</td>
<td>( \delta(\tau) )</td>
</tr>
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<td>NP</td>
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<td>flat</td>
<td>( \delta(\tau) )</td>
</tr>
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<td>NP</td>
<td>( E_5(m) )</td>
<td>( E_6(</td>
</tr>
</tbody>
</table>

CB: Crystal ball function
G: Gaussian
E: Exponential
\( \delta \): Delta Function
\( g \): Double Gaussian

Pseudo-proper decay time

\[
\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}
\]

\( L_{xy} \) = projection of decay length on the transverse plane
p+Pb systematic uncertainties summary

Table 3 summaries the contributions of each systematic uncertainty herein explained.

<table>
<thead>
<tr>
<th>source</th>
<th>$J/\psi$ cross section (%)</th>
<th>$\psi$(2S) cross section (%)</th>
<th>non-prompt fraction (%)</th>
<th>$\psi$(2S) to $J/\psi$ ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ + Pb Luminosity</td>
<td>2.7</td>
<td>2.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$pp$ Luminosity</td>
<td>3.1</td>
<td>3.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ID efficiency</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reco efficiency</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.3</td>
<td>0.01 – 0.05</td>
<td>0.01 – 0.05</td>
</tr>
<tr>
<td>EF trigger efficiency</td>
<td>1 – 5</td>
<td>1 – 5</td>
<td>0.1 – 1</td>
<td>0.1 – 1</td>
</tr>
<tr>
<td>EF trigger non-closure</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L1 trigger efficiency</td>
<td>1 – 5</td>
<td>1 – 5</td>
<td>0.1 – 1</td>
<td>0.1 – 1</td>
</tr>
<tr>
<td>Fit model</td>
<td>2 – 10</td>
<td>5 – 80</td>
<td>5 – 30</td>
<td>5 – 20</td>
</tr>
</tbody>
</table>

Table 3: Summary of systematic uncertainties on different observables.
# Pb+Pb systematic uncertainties summary

<table>
<thead>
<tr>
<th>Source</th>
<th>$J/\psi$ Pb+Pb yield</th>
<th>$J/\psi$ pp cross section</th>
<th>$R_{AA}^{J/\psi}$</th>
<th>$R_{AA}^{\psi(2S)}/R_{AA}^{\psi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>11 - 18 %</td>
<td>5 %</td>
<td>12 - 19 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>13 - 27 %</td>
<td>6 %</td>
<td>14 - 28 %</td>
<td>6 %</td>
</tr>
<tr>
<td>Migration</td>
<td>&lt; 2 %</td>
<td>–</td>
<td>&lt; 2 %</td>
<td>–</td>
</tr>
<tr>
<td>Fitting</td>
<td>2 %</td>
<td>1 %</td>
<td>2 %</td>
<td>8 %</td>
</tr>
</tbody>
</table>

Table 3: Systematic uncertainties of the $J/\psi$ yield determination and $\psi(2S)/J/\psi$ ratio measured in Pb+Pb collisions.
## Centrality in Pb+Pb

<table>
<thead>
<tr>
<th>Centrality [%]</th>
<th>$\langle T_{AA} \rangle$ [mb$^{-1}$]</th>
<th>$\langle N_{part} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>23.35 ± 0.20</td>
<td>358.8 ± 2.2</td>
</tr>
<tr>
<td>10-20</td>
<td>14.33 ± 0.17</td>
<td>264.0 ± 2.8</td>
</tr>
<tr>
<td>20-30</td>
<td>8.63 ± 0.17</td>
<td>189.1 ± 2.7</td>
</tr>
<tr>
<td>30-40</td>
<td>4.94 ± 0.15</td>
<td>131.4 ± 2.5</td>
</tr>
<tr>
<td>40-50</td>
<td>2.63 ± 0.11</td>
<td>86.9 ± 2.3</td>
</tr>
<tr>
<td>50-60</td>
<td>1.27 ± 0.07</td>
<td>53.9 ± 1.9</td>
</tr>
<tr>
<td>60-70</td>
<td>0.56 ± 0.04</td>
<td>30.5 ± 1.5</td>
</tr>
<tr>
<td>70-80</td>
<td>0.22 ± 0.02</td>
<td>15.3 ± 1.0</td>
</tr>
</tbody>
</table>

Table 1: The $\langle T_{AA} \rangle$ and $\langle N_{part} \rangle$ values and their uncertainties in each centrality bin.
Comparison of J/ψ Analyses in p+Pb

• Common elements
  - Same pPb data sample, same triggers, same secondary di-muon vertex fitting.
  - Same muon selection criteria and reconstruction efficiency corrections.
  - Same version of J/ψ acceptance map.

• Elements that are different
  - Included ψ(2S) in fit model; fit model was kept as similar as possible to 7 TeV and 8 TeV pp analyses to reduce interpolation uncertainties.
  - Included 2.76 TeV pp data for calculation of RpPb
  - Finer binned high-level trigger efficiency
  - Centrality dependence was studied using several centrality estimators
Definition of $y^*$

$p+Pb$

$y^* = - (y_{lab} + 0.465) \quad \text{Run period A}$

$y^* = y_{lab} - 0.465 \quad \text{Run period B}$

$y^*$ defined as positive in the proton beam direction
Link to ATLAS Public Results


Abstract

The suppression of heavy charmonia states in heavy-ion collisions is a phenomenon understood as a consequence of QGP formation in the hot, dense system formed in heavy ion collisions at the LHC. In addition to hot matter effects in heavy-ion collisions, cold nuclear effects may also affect heavy charmonia production. Therefore, a full assessment requires detailed studies on the effects present in both A+A and p+A collisions. Based on p+Pb data collected in 2013 and pp and Pb+Pb data collected in 2015 at the LHC, the ATLAS experiment has studied prompt and non-prompt J/psi and psi(2S) productions via the di-muon decay final states. The production and excited-to-ground state ratios of heavy charmonia measured in both p+Pb and Pb+Pb collision data with respect to that measured in pp collision data will be presented in intervals of transverse momentum, rapidity and centrality.