Charmonium production in Pb-Pb and p-Pb collisions at forward rapidity measured with ALICE

Mohamad Tarhini, IPN-Orsay
For the ALICE collaboration
• Introduction and ALICE detector
  
  • Results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
  
  • Results in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
  
  • Summary
Introduction and motivation

Original proposal:
- Measurement of charmonium production in heavy-ion collisions is a probe for the de-confinement aspect of the QGP \[1\]
  - Sequential dissociation of different charmonium states can serve as a QGP thermometer

But:
- If there are enough c\bar{c} pairs, charmonium can be (re)generated \[2,3\]
  - (re)generation is treated in different ways in different models
    - How to distinguish between models?
      - $R_{AA}$, $J/\psi$ elliptic flow ($v_2$), $J/\psi \ <p_T>$, $\psi(2s)/J/\psi$
      - c\bar{c} cross section is a key ingredient

Other ingredients:
- Effects of cold nuclear matter (CNM) on the charmonium production and c\bar{c} cross section
  - Need for (p-A)-like data
- Different sources of charmonium production (inclusive = prompt + non-prompt)
• Inclusive charmonia are reconstructed via their \textit{dimuon decay} down to zero $p_T$

See the talk by Tonatiuh Bustamante (today, parallel session 1.3) on the $(J/\psi \rightarrow e^+e^-)$ results at mid-rapidity

• In the $v_2$ analysis, the event plane is determined using V0 or SPD
• In Pb-Pb collisions, the centrality is estimated by a MC Glauber \textsuperscript{1} fit of the V0 amplitude

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\textbf{muon spectrometer}

$$-4 < \eta < -2.5$$

\textbf{Pb-Pb at } $\sqrt{s_{NN}} = 5.02$ TeV

$\mathcal{L}_{\text{int}} \sim 225 \mu$b\textsuperscript{-1}

[Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV: $\mathcal{L}_{\text{int}} \sim 70 \mu$b\textsuperscript{-1}]

\textbf{p-Pb at } $\sqrt{s_{NN}} = 8.16$ TeV

$\mathcal{L}_{\text{int}} \sim 8.7$ nb\textsuperscript{-1}

[p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV: $\mathcal{L}_{\text{int}} \sim 5$ nb\textsuperscript{-1}]

\textbf{Pb-p at } $\sqrt{s_{NN}} = 8.16$ TeV

$\mathcal{L}_{\text{int}} \sim 12.9$ nb\textsuperscript{-1}

[Pb-p at $\sqrt{s_{NN}} = 5.02$ TeV: $\mathcal{L}_{\text{int}} \sim 5.8$ nb\textsuperscript{-1}]

\textsuperscript{1} PRL. 116 (2016) 222302
Charmonium reconstruction

- **Main single muon selections:**
  - $-4 < \eta_\mu < -2.5$
  - Matching between trigger and tracker

- **Muon pair selections:**
  - $2.5 < y < 4$
  - Opposite sign charges

- The signal is extracted by fitting the dimuon invariant mass distribution with (background+signal) functions
  - Different signal and background shapes are considered
  - Event mixing is also used in Pb-Pb collisions to subtract the combinatorial background

- Number of charmonium candidates are further corrected by the detector acceptance times efficiency obtained via MC simulations
\[ R_{AA} \text{ Pb-Pb at } \sqrt{s_{NN}} = 5.02 \text{ TeV: } R_{AA} 0-90\%(0<p_T<8 \text{ GeV/c}) = 0.66 \pm 0.01 \text{(stat.)} \pm 0.05 \text{(syst.)} \]  

\[ R_{AA} \text{ Pb-Pb at } \sqrt{s_{NN}} = 2.76 \text{ TeV: } R_{AA} 0-90\%(0<p_T<8 \text{ GeV/c}) = 0.58 \pm 0.01 \text{(stat.)} \pm 0.09 \text{(syst.)} \]

- A measured pp cross section is used in the \( R_{AA} \) calculation.

See poster (C01) by Benjamin Audurier for more details.

- Clear \( J/\psi \) suppression and almost no centrality dependence for \( N_{\text{part}} > 100 \) (centrality < 50%)
- The precision of the measurement is improved with respect to \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) data.
- A systematic difference of \( \sim 15\% \) between the \( R_{AA} \) at two energies.
  - The increase is within the uncertainties.
Results are compared with calculations based on different models:

- Two transport models (TM1 [1] and TM2 [2]): continuous interplay between dissociation and (re)generation
- **Statistical hadronisation model** [3]: all J/ψ are dissociated in the plasma. (Re)generation occurs at the phase boundary
- **Comover model (CIM)** [4]: J/ψ are suppressed via interaction with a parton co-moving medium. (Re)generation added as a gain term

**Measurement is precise enough to constrain the models**

\[ \langle N_{\text{part}} \rangle \]

$J/\psi R_{AA} \text{ vs centrality (comparison with models)}$

- $p_T > 0.3 \text{ GeV/c to remove possible J/ψ photo-production contribution} \ [5]$
- Brackets represent maximum remaining contribution

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For central events, the suppression is smaller at lower $p_T$.

$R_{AA}$ shows a stronger centrality dependence at high $p_T$.

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

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $2.5 < y < 4$

- $0.3 < p_T < 2$ GeV/$c$
- $2 < p_T < 5$ GeV/$c$
- $5 < p_T < 8$ GeV/$c$
- $8 < p_T < 12$ GeV/$c$
• For central events, the suppression is smaller at lower $p_T$
  • This behaviour is reproduced by models that include $J/\psi$ (re)generation (for instance TM1 [1])
• $R_{AA}$ shows a stronger centrality dependence at high $p_T$

**J/\psi R_{AA} vs Centrality (in $p_T$ ranges)**

- Rapidity dependence of the $R_{AA}$ is studied in three centrality ranges

- A negligible rapidity dependence of the $R_{AA}$ in different centrality and $p_T$ ranges

- Would be interesting to have comparison with model calculations!
Charm quarks, if thermalised in the QGP, should exhibit the elliptic flow generated in this phase.

- Non zero $v_2$ for re-generated $J/\psi$

A non zero $J/\psi$ $v_2$ seen in semi-central collisions (20-40%) [7.6 $\sigma$ significance in $4 < p_T < 6$ GeV/c]
J/$\psi$ elliptic flow ($v_2$)

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![Graph showing J/$\psi$ elliptic flow ($v_2$) vs $p_T$]

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- Similar measured $v_2$ values for hidden and open charm (see Anastasia Barbano talk at 16:50)
Charm quarks, if thermalised in the QGP, should exhibit the elliptic flow generated in this phase
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A non zero J/$\psi$ $v_2$ seen in semi-central collisions (20-40%) [7.6 $\sigma$ significance in $4 < p_T < 6$ GeV/$c$]
- Precision is significantly increased in run-2 measurement with respect to run-1
- Similar measured $v_2$ values for hidden and open charm
- Models have difficulties to reproduce the measured J/$\psi$ $v_2$ in the measured $p_T$ interval
• The J/ψ $<p_T>$ and the $r_{AA}$ are complementary observables to the $R_{AA}$ and the $v_2$ 

• The J/ψ $<p_T>$ is smaller in central events than in peripheral ones → (re)generation 

• The results of $r_{AA}$ at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV [1] are compatible within uncertainties 

• Discrepancies are seen in some centralities (e.g. $> 3 \sigma$ for 30-40 %) between the measurements and calculations based on TM1[2] model
• The ratios between different charmonium states are essential to discriminate between different models.

![Graph showing $R_{AA}$ for ALICE inclusive $J/\psi$, $\psi(2S)$, Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $2.5<y<4$, $0<p_T<8$ GeV/c.](image)

- For the bins with too small $\psi(2S)$ significance, an upper limit with 95% CL is calculated.

- The $\psi(2S)$ is more suppressed than the $J/\psi$ in semi-central and central collisions.
• The ratios between different charmonium states are essential to discriminate between different models.

**Graph:**

- ALICE: Inclusive
  - $3 < p_T < 8$ GeV/$c$
  - $2.5 < y < 4$

- CMS: Prompt
  - $3 < p_T < 30$ GeV/$c$
  - $1.6 < y < 2.4$

**Equation:**

$$R_{AA}(\psi(2S)) / R_{AA}(J/\psi)$$

**Legend:**

- J/$\psi$, $\psi(2S)$, Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
- ALICE, $3 < p_T < 8$ GeV/$c$, $2.5 < y < 4.0$, Inclusive (Preliminary)
- CMS, $3 < p_T < 30$ GeV/$c$, $1.6 < y < 2.4$, Prompt only (arXiv:1611.01438)

**Notes:**

- Upper limits include global uncertainties.

• The results of the double ratio at $\sqrt{s_{NN}} = 5.02$ TeV are compatible within uncertainties with the ones from CMS [1]
**New** J/ψ in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

- The inclusive J/ψ $R_{pPb}$ has been measured in p-Pb and Pb-p collisions at the new energy of $\sqrt{s_{NN}} = 8.16$ TeV
- ALICE [1] and LHCb [2] pp data at $\sqrt{s_{NN}} = 8$ TeV are used as a reference to calculate the $R_{pPb}$

- Clear suppression at positive rapidities, and compatible with unity at negative rapidity
- The $R_{pPb}$ measured at $\sqrt{s_{NN}} = 8.16$ TeV is similar to the one measured at $\sqrt{s_{NN}} = 5.02$ TeV [3]
J/ψ in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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- Different models (shadowing, energy loss, CGC) can describe well the data
J/ψ in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- The $p_T$ reach of the $R_{pPb}$ has been extended to 20 GeV/c
- The suppression is higher at low $p_T$ for the positive rapidity range
**J/ψ in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV**

- The $p_T$ reach of the $R_{pPb}$ has been extended to 20 GeV/c
- The suppression is higher at low $p_T$ for the positive rapidity range
- Different models (shadowing, energy loss, CGC) can describe well the data in the two rapidity ranges
Summary

- **J/ψ results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV**
  - $R_{AA}$ as a function of centrality, rapidity and transverse momentum
  - Elliptic flow
  - Average $p_T$
- Results compared to models calculations and to results at $\sqrt{s_{NN}} = 2.76$ TeV
- High precision measurement can constrain the models

- The $\psi(2s)$ is more suppressed than the $J/ψ$ in central and semi-central collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- The $J/ψ$ $R_{p-Pb}$ at $\sqrt{s_{NN}} = 8.16$ TeV has been measured as a function of rapidity and transverse momentum
  - Clear suppression at positive rapidity and low $p_T$
  - $R_{p-Pb}$ can be described by different CNM effects
Extra Slides
$J/\psi$ $R_{AA}$ Vs $p_T$
Charmonia decay schemes:

<table>
<thead>
<tr>
<th>State</th>
<th>J/Ψ</th>
<th>(\chi_c)</th>
<th>(\Psi')</th>
<th>(\Upsilon)</th>
<th>(\chi_b)</th>
<th>(\Upsilon')</th>
<th>(\chi_b')</th>
<th>(\Upsilon'')</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta E) [GeV]</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>(\Delta M) [GeV]</td>
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<td>-0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>radius [fm]</td>
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<td>0.36</td>
<td>0.45</td>
<td>0.14</td>
<td>0.22</td>
<td>0.28</td>
<td>0.34</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Inclusive $J/\psi \rightarrow \mu^+\mu^-$, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au $\sqrt{s_{NN}} = 0.2$ TeV

- ALICE, $2.5 < y < 4$, 0-20% global syst. = ±8%
- PHENIX, $1.2 < |y| < 2.2$, 0-20% global syst. = ±10%
Excess at very low pT
**Signal extraction**

**ALICE Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV**

$L_{int} \approx 225 \ \mu b^{-1}$

**Centrality 0-10 %**

$\chi^2/\text{ndf} = 1.10, \ S/B_{3\sigma} = 0.10$

**Mixed-event background subtracted**

**Centrality 70-80 %**

$\chi^2/\text{ndf} = 0.82, \ S/B_{3\sigma} = 3.52$

**Mixed-event background subtracted**

**Centrality 0-10 %**

$\chi^2/\text{ndf} = 0.93$

**Centrality 70-80 %**

$\chi^2/\text{ndf} = 0.85$
J/Ψ elliptic flow ($v_2$) extraction

- For each muons pair, calculate $\langle \cos 2(\Phi_{\mu\mu} - \Psi) \rangle$ in bins of invariant mass (B)

- Using S/B parameters from the J/Ψ signal extraction (A), fit the distribution with:
  
  $$v_2(m_{\mu\mu}) = v_2^J/\Psi(m_{\mu\mu}) + v_2^{bkgd}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})]$$

- $\Psi$ and $\phi_{\mu\mu}$ are the azimuthal angle of the event plane and the muon pairs

- $\Psi$ is determined using two different detectors (V0A and SPD) that cover two different pseudo-rapidity ranges and do not overlap with the muon spectrometer acceptance

First method

Second method

- Extract the J/psi signal in bins of $\Delta \varphi = \Psi - \phi_{\mu\mu}$ (C)

- Fit the distribution with: $N_0[ (1+2v_2)\cos 2(\Delta \varphi) ]$
v2 @ 2.76 TeV

- ALICE (Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV), centrality 20%-60%, $2.5 < y < 4.0$
- Y. Liu et al., b thermalized
- Y. Liu et al., b not thermalized
- X. Zhao et al., b thermalized

Significance 2.2 sigma

Global syst. = ± 1.4%
pp cross section at 5.02 TeV

\[ d^2\sigma / dp_T dy \ (\text{mb/(GeV/c)}) \]

- ALICE inclusive $J/\psi$, $2.5 < y < 4$
- pp $\sqrt{s} = 5.02$ TeV
- $L_{int} = 106.3 \text{ nb}^{-1} \pm 2.1\%$
- BR uncert.: 0.6%

\[ d\sigma / dy \ (\text{mb}) \]

- ALICE inclusive $J/\psi$
- pp $\sqrt{s} = 5.02$ TeV, $p_T < 12$ GeV/c
- $L_{int} = 106.3 \text{ nb}^{-1} \pm 2.1\%$
- BR uncert.: 0.6%

NRQCD, Y-Q. Ma et al.
+ FONLL M. Cacciari et al.

NRQCD + CGC, Y-Q. Ma et al.
+ FONLL M. Cacciari et al.
rAA at 2.76 TeV