J/ψ production in p-Pb collisions with at the LHC

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*on behalf of the ALICE collaboration

Strangeness in Quark Matter 2013, Birmingham, 21-27.07.2013
Outline

✧ Physics motivation

✧ Analysis

✧ Results
  ❖ Forward to Backward ratio $R_{FB}^{J/\psi}$ integrated and vs $p_T$, vs $y_{cms}$
  ❖ Nuclear modification factor $R_{pPb}^{J/\psi}$ integrated and vs $y$

✧ Summary and outlook
Physics motivation

- Elementary collision
  No nuclear matter effects

- Cold nuclear matter effects – without Quark-Gluon Plasma (QGP)

- Hot nuclear matter effects – related to QGP formation

> To disentangle hot and cold nuclear matter (CNM) p-Pb measurements are needed as an intermediate step between Pb-Pb and benchmark pp collisions.

*See the talk of Lizardo Valencia Palomo
Cold nuclear matter effects

In p-Pb different kinds of nuclear matter effects can be considered:

1. **Initial-state**
   - gluon shadowing[1] (or saturation[2]): at high energies gluons start shadowing each other (or recombining).
   - At LHC energies large shadowing is expected.

2. **Coherent energy loss** [4]: gluon radiates a soft gluon.
   - The amount of medium-induced gluon radiation defines the strength of the J/ψ suppression.

3. **Final-state**
   - nuclear absorption: J/ψ pre-resonant state destruction by colliding nucleons.
   - At the LHC at mid- and forward rapidity in p-Pb the ccbar pair spends a very short time within cold nuclear matter, due to the large Lorentz gamma of the colliding nuclei. Consequently, nuclear absorption is then expected to be negligible [5].

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[5] Lourenco et al., JHEP 0902:014, 2009
ALICE detector

See the talk of Fiorella Fionda

Muon spectrometer

$2.5 < y < 4.0$

Central barrel

$|y| < 0.9$
Event selection and analysis cuts

- **Event selection**
  - MB trigger: Coincidence of the two sides of VZERO: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$
  - MB trigger efficiency ~99% for NSD events
  - Rejection of beam-gas and electromagnetic interactions
  - SPD used for vertex determination

- **Dimuon trigger**
  - Coincidence of minimum bias (MB) interaction with two opposite sign muon tracks detected in the trigger chambers of the Muon spectrometer

- **The following cuts (standard for J/ψ analysis) were also applied:**
  - Muon trigger matching
  - $-4 < \eta_\mu < -2.5$
  - $17.6 \text{ cm} < R_{\text{abs}} < 89.5 \text{ cm}$, where $R_{\text{abs}}$ – track radial position at the absorber end
  - Unlike sign dimuon
  - $2.5 < y_{\mu\mu}^{\text{lab}} < 4$
Main observables \((R_{pPb}, R_{Pbp})\)

- Nuclear modification factor \(R_{pPb}\) and \(R_{Pbp}\)

\[
R_{pPb}^{J/\psi} = \frac{Y_{pPb}}{\left\langle T_{pPb} \right\rangle \sigma_{pp}^{J/\psi \rightarrow \mu^+\mu^-}}, \quad Y_{pPb} = \frac{N_{J/\psi \rightarrow \mu^+\mu^-}}{(A \times \varepsilon) N_{MB}}
\]

\(R_{pPb}\) and \(R_{Pbp}\) are computed in the range \(2.5 < y_{lab} < 4\)

\(T_{pPb} = 0.0983 \pm 0.0034 \text{ mb}^{-1}\) – nuclear overlap function

- Shift in \(y_{cms}\) and rapidity coverage

LHC beam asymmetry \((E_{Pb}=1.58\cdot A \text{ TeV}, E_p=4 \text{ TeV})\) => \(|\Delta y|_{\text{cms}} = 0.5 \log(Z_{Pb}A_p/Z_pA_{Pb}) = 0.465\)

- \(p\)-Pb: \(2.03 < y_{cms} < 3.53\)
  \(8.1\times10^{-5} > \chi_{Bjorken} > 1.8\times10^{-5}\)

- Pb-\(p\): \(-4.46 < y_{cms} < -2.96\)
  \(5.3\times10^{-2} > \chi_{Bjorken} > 1.2\times10^{-2}\)
Main observables ($R_{FB}$)

**Forward to Backward ratio $R_{FB}$**

$$R_{FB}^{J/\psi} = \frac{R_{pPb}}{R_{PbP}}$$

- $R_{FB}$ is computed in the $y_{cms}$ range common to both $p$-$Pb$ and $Pb$-$p$: $2.96 < y_{cms} < 3.53$
- which corresponds to the following range in lab.system:
  - $p$-$Pb$: $3.43 < y_{lab} < 4$
  - $3.2 \times 10^{-5} > x_{Bjorken} > 1.8 \times 10^{-5}$
  - $Pb$-$p$: $-3.07 < y_{lab} < -2.5$
  - $2.1 \times 10^{-2} > x_{Bjorken} > 1.2 \times 10^{-2}$

In that case $T_{PbP}$ and the pp cross-section cancel out in the ratio:

$$R_{FB}^{J/\psi} = \frac{Y_{Forward \ pPb}}{Y_{Backward \ pPb}} = \frac{N_{Forward \ J/\psi \rightarrow \mu^+\mu^-}}{(Acc \times \varepsilon)^{Forward \ MB} N_{Forward \ MB}} \times \frac{(Acc \times \varepsilon)^{Backward \ J/\psi \rightarrow \mu^+\mu^-}}{N_{Backward \ MB}}$$
Signal extraction (and its syst. unc.) is based on fits of dimuon inv.mass distribution by varying:

1. **Signal shape**: Extended Crystal Ball (CB2) or other pseudo-Gaussian functions (tails tuned on the corresponding Monte Carlo (MC))
2. **Background shape**: Variable Width Gaussian (VWG) or Pol2*Exp (or Pol4*Exp)
3. **Fitting range**

These plots are examples of the fit with **CB2+VWG**.
Acceptance x Efficiency

- **Average J/ψ acceptance x efficiency:**
  - p-Pb: ~25% in 2.03<y_{cms}<3.53
  - Pb-p: ~17% in -4.46<y_{cms}<-2.96
  - Difference in AccxEff between p-Pb and Pb-p is due to different efficiency of detector in two periods of data-taking

- **Systematic uncertainties** on acceptance inputs uncorrelated vs $p_T$, $y$ and collision system (different physics)
## Summary on the syst. uncertainties

<table>
<thead>
<tr>
<th>Source of systematic uncertainty:</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>1-4%</td>
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<td><strong>Total syst. uncertainty</strong></td>
<td><strong>7-12%</strong></td>
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*(ranges correspond to values obtained in $y$ or $p_T$ bins)*
\[ d^2\sigma_{J/\psi}/dydp_T \]

\[ \sigma_{J/\psi \rightarrow \mu^+\mu^-}^{pPb} = \frac{N_{J/\psi \rightarrow \mu^+\mu^-}}{L_{int} \times Acc \times \varepsilon \times BR_{J/\psi \rightarrow \mu^+\mu^-}} \]

\[ L_{int} = \frac{N_{MB}}{\sigma_{MB}} \]

\( \checkmark \) \( \sigma_{MB} \) obtained using VdM scans:

2.08 b ± 3.4% for p-Pb period
2.12 b ± 3.2% for Pb-p period

\( L_{int}^{pPb} = 5.0 \text{ nb}^{-1}; L_{int}^{Pbp} = 5.8 \text{ nb}^{-1} \)

One can calculate \( \langle p_T \rangle \mid_{0-15 \text{ GeV/c}} \):

\( \checkmark \) \( \langle p_T \rangle = 2.77 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c} \)

\( \checkmark \) \( \langle p_T \rangle = 2.47 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c} \)

\( p-Pb \sqrt{s_{NN}} = 5.02 \text{ TeV, inclusive } J/\psi \rightarrow \mu^+\mu^- \):

- 2.03 \( \frac{<y>}{\text{CMS}} \) < 3.53 \( (L_{int} = 5.0 \text{ nb}^{-1}) \)
- -4.46 \( \frac{<y>}{\text{CMS}} \) < -2.96 \( (L_{int} = 5.8 \text{ nb}^{-1}) \)
\( d\sigma_{J/\psi}/dy \)

- **Correlated uncertainties** (brackets): luminosity, normalization factor, BR
- **Uncorrelated uncertainties** (filled boxes): matching, trigger efficiency, tracking, acc. inputs, signal extraction
- **Statistical uncertainties** (line)

Cross-sections are higher in the backward rapidity region (Pb-p).

\[
\frac{d\sigma_{ppb}}{dy} = 588 \pm 4 \ (\text{stat.}) \pm 38 \ (\text{syst.}) \ \mu b
\]

\[
\frac{d\sigma_{pbp}}{dy} = 644 \pm 5 \ (\text{stat.}) \pm 51 \ (\text{syst.}) \ \mu b
\]

**Luminosity** is correlated within p-Pb or Pb-p, but not within the two systems.
Integrated $R_{FB}$

$R_{FB} = 0.60 \pm 0.01$ (stat.) $\pm 0.06$ (syst.)

- The uncertainty is small
- Pure shadowing slightly overestimates the data
- Model including energy loss contribution is rather good
Comparison with theoretical models confirms previous observations done on the $y$-integrated results.

Calculations including both shadowing and energy loss seems consistent with the data.
A sizeable $p_T$-dependence of $R_{FB}$ is seen.

Stronger suppression is found at low $p_T$.

Theoretical models including energy loss show strong nuclear matter effects at low $p_T$ in fair agreement with the data.

The observed $p_T$-dependence is smoother than expected in coherent energy loss models.
Phenomenological interpolation of the inclusive $J/\psi$ x-section to pp collisions at $\sqrt{s_{NN}}=5.02$ TeV from CDF, RHIC and LHC (2.76 and 7 TeV) based on the paper from arXiv:1103.2394v3.

① Energy dependence: pp cross-section at mid-rapidity

Calculations performed using a Monte Carlo toy.

Parametrization with a power-law shape.

\[
\left. \frac{d\sigma_{pp}^{J/\psi \to \mu^+\mu^-}}{dy} \right|_{y=0} = 362 \pm 6\,\text{(stat.)}^{+55}_{-37}\,\text{(syst.)}\,\text{nb}
\]

② Rapidity dependence

Based on a universal, energy independent gaussian shape.

③ Systematic uncertainties

Evaluated within 2.5$\sigma$ in order to include most of the uncertainties from FONLL and CEM LO interpolation.

\[
\frac{d\sigma_{pp}^{J/\psi \to \mu^+\mu^-}}{dy} \bigg|_{2.03 < y_{c ms} < 3.53} = 231^{+41}_{-32}\,\text{(syst.)}\,\text{nb}
\]
\[
\frac{d\sigma_{pp}^{J/\psi \to \mu^+\mu^-}}{dy} \bigg|_{-4.46 < y_{c ms} < -2.96} = 159^{+40}_{-27}\,\text{(syst.)}\,\text{nb}
\]
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<tr>
<td>$y$-dependence of pp interpolation @ $\sqrt{s_{NN}} = 5.02$ TeV</td>
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*(ranges correspond to values obtained in $y$ or $p_T$ bins)*
$R_{pPb}$ and $R_{Pbp}$ integrated

$R_{pPb}$ ($2.03 < y_{\text{cms}} < 3.53$) = $0.732 \pm 0.005\text{(stat)} \pm 0.059\text{(syst)} + 0.131\text{(syst. ref)} - 0.101\text{(syst.ref)}$

$R_{pPb}$ ($-4.46 < y_{\text{cms}} <-2.96$) = $1.160 \pm 0.010\text{ (stat)} \pm 0.096\text{(syst)} + 0.296\text{(syst. ref)} - 0.198\text{(syst.ref)}$

**Error bars:**

- boxes around the points: uncorrelated
- $[\ ]$: partially correlated
- grey box around unity: fully correlated

- Large uncertainty (correlated and uncorrelated) from pp interpolation
- At forward rapidity, data in-between shadowing and energy loss models
- Color Glass Condensate (CGC) model underestimates the data
At backward rapidity, models including coherent parton energy loss show a slightly steeper pattern than the one observed in data.

Results dominated by a large uncertainty from pp interpolation.

Error bars:
- boxes around the points: uncorrelated
- [: partially correlated
- grey box around unity: fully correlated
ALICE has measured inclusive $J/\psi$ production in p-Pb run in backward and forward rapidity regions at $\sqrt{s_{_{NN}}} = 5.02$ TeV. Many interesting results are obtained:

- Measured strong $p_T$ dependence of $R_{FB}$ with a decrease at low $p_T$ is in a fair agreement with models including coherent energy loss contribution.

- $R_{pPb}$ and $R_{Pbp}$ show an increase of suppression towards forward rapidity in agreement with energy loss model and/or shadowing model EPS09 NLO.

- pure nuclear shadowing and/or energy loss seem to reasonably describe the data, indicating that final state absorption may indeed be negligible at LHC energies.
...and outlook

- Many other interesting results are under study: $R_{pPb}$ vs centrality, $\Psi(2S)$ yield...

Stay tuned...

Thank you for your attention!
Backup slides
Signal extraction in $p_T$ bins

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Signal extraction in $y$ bins

Inclusive $J/\psi \to \mu^+\mu^-$

- $2.04 < y_{cms} < 2.29$
  - $N_{J/\psi} = 4118 \pm 151$
  - $S/B (\pm 3\sigma)_{J/\psi} = 1.8$

- $2.29 < y_{cms} < 2.54$
  - $N_{J/\psi} = 13422 \pm 239$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.1$

- $2.54 < y_{cms} < 2.79$
  - $N_{J/\psi} = 16801 \pm 246$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.3$

$p_T > 0$

- $2.79 < y_{cms} < 3.04$
  - $N_{J/\psi} = 14981 \pm 217$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.5$

- $3.04 < y_{cms} < 3.29$
  - $N_{J/\psi} = 10002 \pm 178$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.8$

- $3.29 < y_{cms} < 3.54$
  - $N_{J/\psi} = 3239 \pm 112$
  - $S/B (\pm 3\sigma)_{J/\psi} = 3.6$

$p_T > 0$

- $3.71 < y_{cms} < 3.96$
  - $N_{J/\psi} = 13938 \pm 225$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.2$

- $3.96 < y_{cms} < 4.21$
  - $N_{J/\psi} = 7065 \pm 134$
  - $S/B (\pm 3\sigma)_{J/\psi} = 3.3$

- $4.21 < y_{cms} < 4.46$
  - $N_{J/\psi} = 11645 \pm 190$
  - $S/B (\pm 3\sigma)_{J/\psi} = 2.6$

- $4.46 < y_{cms} < 4.71$
  - $N_{J/\psi} = 4107 \pm 171$
  - $S/B (\pm 3\sigma)_{J/\psi} = 1.4$

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\[ \frac{d^2 \sigma_{J/\psi}}{dp_T dy} \text{ and } \langle p_T \rangle \text{ in full } y\text{-range} \]

From the \( \frac{d^2 \sigma}{dy dp_T} \) distributions one can calculate the mean \( p_T \) in the full \( y \)-range.

- \( \langle p_T \rangle |_{0-15 \text{ GeV/c}} = 2.77 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \) GeV/c in p-Pb
- \( \langle p_T \rangle |_{0-15 \text{ GeV/c}} = 2.47 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \) GeV/c in Pb-p

- \( \langle p_T \rangle \) is higher in p-Pb than in pp at \( \sqrt{s_{NN}} = 7 \text{ TeV} \)
- \( \langle p_T \rangle \) in Pb-p is close to the one in pp at \( \sqrt{s_{NN}} = 7 \text{ TeV} \)
From the $d^2\sigma/dydp_T$ distributions one can calculate the mean $p_T$ in the common $y$-range:

- $<p_T>|_{0-15 \text{ GeV/c}} = 2.71 \pm 0.02^{\text{stat.}} \pm 0.03^{\text{syst.}} \text{ GeV/c in p-Pb}$
  - compare to $<p_T>|_{0-15 \text{ GeV/c}} = 2.77 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c in the full y-range}$

- $<p_T>|_{0-15 \text{ GeV/c}} = 2.56 \pm 0.01^{\text{stat.}} \pm 0.03^{\text{syst.}} \text{ GeV/c in Pb-p}$
  - compare to $<p_T>|_{0-15 \text{ GeV/c}} = 2.47 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c in the full y-range}$
Interpolation of $\sigma_{J/\psi}^{pp}$ at $\sqrt{s_{NN}} = 5.02$ TeV

Energy dependence

Rapidity dependence
Signal shapes functions

CB extended

\[
f(x; N, \bar{x}, \sigma, \alpha, n, \alpha', n') = N \cdot \begin{cases} 
\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{(x-\bar{x})}{\sigma} > -\alpha \\
A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{(x-\bar{x})}{\sigma} \leq -\alpha \\
C \cdot (D + \frac{x-\bar{x}}{\sigma})^{-n'}, & \text{for } \frac{(x-\bar{x})}{\sigma} \geq \alpha' 
\end{cases}
\]

\[
A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)
\]
\[
B = \frac{n}{|\alpha|} - |\alpha|
\]
\[
C = \left(\frac{n'}{|\alpha'|}\right)^{n'} \cdot \exp\left(-\frac{|\alpha'|^2}{2}\right)
\]
\[
D = \frac{n'}{|\alpha'|} - |\alpha'|
\]

NA60 function

\[
f(x; N, \bar{x}, \sigma, x_1, x_2, p_1, ..., p_6) = N \cdot \exp\left(-\frac{(x-\bar{x})^2}{2\sigma_{NA60}^2}\right)
\]

\[
\sigma_{NA60} = \begin{cases} 
\sigma \cdot \left(1 + p_1 (x_1 - x)^{p_2 - p_3 \sqrt{x_1 - x}}\right), & \text{for } x < x_1 \\
\sigma, & \text{for } x_1 \leq x < x_2 \\
\sigma \cdot \left(1 + p_4 (x - x_2)^{p_5 - p_6 \sqrt{x - x_2}}\right), & \text{for } x \geq x_2 
\end{cases}
\]

- Parameters \( N, \sigma, x \) are left free in the data
- All the other parameters are fixed on the tuned MC

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29
Visible disagreement in results.
- Only half of statistics analyzed by LHCb.
- Difference in cross-sections seems to be the main source of the discrepancy.
- Work in progress on understanding the discrepancy between experiments.
Comparison of ALICE results with LHCb - 2

Visible disagreement in results.
Same conclusions as in the previous slide.
Work in progress on understanding the discrepancy between experiments.

ALICE uncertainties:

◊ Statistical uncertainties (line)

◊ Systematic uncertainties:
  * Corr. uncertainties (brackets): luminosity, normalization factor, BR
    (Luminosity is correlated within p-Pb or Pb-p, but not within the two systems)
  * Uncorr. uncertainties (filled boxes): matching, trigger, tracking, acc. inputs, signal extraction