Study of $J/\psi$ production and cold nuclear matter effects in p-Pb collisions

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Outline

1. The LHCb p-Pb run
2. Quarkonium production in pA
3. Conclusions
Covers only 4% of the solid angle, but captures $\sim 25\%$ of the heavy quark cross-section in pp collisions.
**LHCb in a nutshell**

**Impact parameter resolution:** 20 µm

**Proper time resolution:** $\Delta \tau = 45 \text{ fs}$ for $B^0_s \rightarrow J/\psi \Phi$ and $B^0_s \rightarrow D^+_s \pi$

**Momentum resolution:** $\Delta p/p = 0.4\% - 0.6\%$ (5 GeV/c - 100 GeV/c)

**Mass resolution:** $\Delta m = 8 \text{ MeV}/c^2$ for $B \rightarrow J/\psi X$ constrained $J/\psi$ mass.

**RICH $\pi$-K separation:**

- $\epsilon(K \rightarrow K) \sim 95\%$ mis-id
- $\epsilon(\pi \rightarrow K) \sim 5\%$

**Muon ID:**

- $\epsilon(\mu \rightarrow \mu) \sim 97\%$ mis-id
- $\epsilon(\pi \rightarrow \mu) \sim 1\% - 3\%$

**E.m. energy resolution:**

$\Delta E/E = 1\% \oplus 10\%/\sqrt{E \text{ (GeV)}}$

**Figure:**

- LHCb
- $\sqrt{s} = 8 \text{ TeV}$

**Graphs:**

Beam configurations

Rapidity coverage:
- **Forward direction** (p-Pb):
  - \( y = +0.47 \)
  - pA: \( 1.5 < y < 4.5 \)
- **Backward direction** (Pb-p):
  - \( y = -0.47 \)
  - pA: \( -5.5 < y < -2.5 \)

- Common frame for the measurements: \( 2.5 < |y| < 4.0 \)
- Center-of-mass energy: \( \sqrt{s} = 5 \text{ TeV} \)
2013 p-Pb data taking

- Four different data taking periods: p-Pb / Pb-p, magnet up, magnet down
- Instantaneous luminosity: $45 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$
- Low pile-up: $\sim 1$ primary interaction per event.

Integrated luminosity after data quality:
- p-Pb $\sim 1.1 \text{ nb}^{-1}$
- Pb-p $\sim 0.5 \text{ nb}^{-1}$
p-Pb events at LHCb

- Higher track multiplicity in Pb-p as expected.
- Magnet polarities agree for both beam configurations.
- All plots unless stated from J. High Energy Phys. 02 (2014) 072
Why pA physics at LHCb?

- pA collisions interesting both in itself and in understanding heavy ion collisions.
- Allows factorizing the QGP effects from Cold Nuclear Matter effects.
- Insight into yet unexplored region of QCD.

- LHCb with its unique rapidity coverage can play an important role.
- Measurements can constrain PDF at low x, $Q^2$. 

![Graph showing $Q^2$ vs $x_A$]
Quarkonium production in pA

Heavy flavour and quarkonium important probes of the QGP energy loss mechanisms, medium transport properties, quark deconfinement, and temperature

Cold Nuclear Matter (CNM) effects

- Production of heavy quarkonia suppressed at large rapidity in pA collisions.

Nuclear Modification Factor

- $N_{coll} = A$ in pA collisions.
- Forward-Backward asymmetry:
  - pp $J/\psi$ cross section uncertainties cancel out.

$$R_{pA}(y, \sqrt{s_{NN}}) = \frac{1}{N_{coll}} \frac{d\sigma_{pA}(y, \sqrt{s_{NN}})/dy}{d\sigma_{pp}(y, \sqrt{s_{NN}})/dy}$$

$$R_{FP}(y, \sqrt{s_{NN}}) = \frac{R_{pPb}(+|y|, \sqrt{s_{NN}})}{R_{pPb}(-|y|, \sqrt{s_{NN}})}$$
**J/ψ** production in pA

- Three sources of **J/ψ** prompt and non prompt:
  - Direct production
  - Feed down from heavier $c\bar{c}$ states: $\psi(2S)$, $\chi_{c0}$, $\chi_{c1}$...
  - From $b$ hadrons decays.

- Analysis strategy same as for pp collisions:
  - Reconstruct **J/ψ** from 2 muons.
  - Measure separately the production cross section in bins of transverse momentum and rapidity for prompt and non-prompt **J/ψ**.
  - Separate prompt and non-prompt using pseudo propertime:

\[
\sigma = \frac{N(\psi \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \epsilon \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}
\]

\[
t_z = (z_{J/\psi} - z_{PV}) \times \frac{M_{J/\psi}}{p_z}
\]
**J/ψ** signal extraction

Yields of prompt **J/ψ** and **J/ψ** from b extracted from simultaneous fit of mass and pseudo propertime

\[ t_z = (Z_{J/ψ} - Z_{PV}) \times \frac{M_{J/ψ}}{p_z} \]

**Mass fits**
- Signal by Crystal Ball
- background by exponential

**Propertime fit:**
- Prompt signal by \(\delta\)–function
- Non-prompt signal by exponential
- Background by empirical function from sidebands.
Double differential $J/\psi$ cross sections

\[ \frac{d\sigma}{dp_T dy} = \frac{N(J/\psi \rightarrow \mu^+ \mu^-)}{\mathcal{L} \times \epsilon \times B(J/\psi \rightarrow \mu^+ \mu^-) \times \hat{p}_T \times \hat{y}} \]

\[ \epsilon_{tot} = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{trg} \sim 45\% \]

- $\epsilon_{acc} \times \epsilon_{rec}$ including detection, reconstruction and selection estimated from simulation.
- $\epsilon_{trg}$ obtained from the minimum-bias sample collected in the data.
- In the efficiency estimation no polarization for the $J/\psi$ is assumed.

Double differential cross section in pA:

![Graphs showing double differential cross sections for pA collisions.](image-url)
Single differential $J/\psi$ cross sections
### Summary of systematic uncertainties

#### Correlated between bins:

<table>
<thead>
<tr>
<th>Source of the uncertainty</th>
<th>Forward %</th>
<th>Backward %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fit from checking dimuon mass with double Crystal Ball</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Radiative tail with dimuon mass below signal region</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Muon identification from “tag and probe”</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Track reconstruction efficiency from pp/pA multiplicity difference</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity calibration</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Branching ratio from PDG</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

#### Uncorrelated between bins:

<table>
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<th>Source of the uncertainty</th>
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<th>Backward %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y-p_T$ binning</td>
<td>0.1-8.7</td>
<td>0.1-6.1</td>
</tr>
<tr>
<td>Reweighting of track multiplicity in simulation comp. to no reweighting</td>
<td>0.1-3.0</td>
<td>0.2-4.3</td>
</tr>
<tr>
<td>$t_Z$ fit on non-prompt $J/\psi$ by extraction with $s - Plot$</td>
<td>0.2-12.0</td>
<td>0.2-13.0</td>
</tr>
</tbody>
</table>

- Systematics dominated by fit model, luminosity and agreement between data and simulation
- No uncertainty assigned to unknown $J/\psi$ polarization but effect measured to be small.
Reference $J/\psi$ pp cross section at $E_{CM} = 5$ TeV

Input to the determination of the nuclear modification factor.
- Interpolation from measurements at 2.76 TeV, 7 TeV and 8 TeV.
- Rescaling from $2.0 < y < 4.5$ to the common rapidity range $2.5 < y < 4.0$ ($\sim$60%).
- Three different functions used to interpolate.

$$(\sqrt{s}/p_0)^{p_1}$$

$$p_0 + \sqrt{s}p_1$$

$$p_0 \left(1 - \exp \left(\sqrt{s}p_1\right)\right)$$

- Power law extrapolations used.
- Functions checked against predictions from LO-CEM and FONLL.
Nuclear Modification Factor

- Strong dependence on rapidity.
- Non prompt less affected than prompt $J/\psi$.
- B hadrons less affected by cold nuclear effects $\Rightarrow$ dependance on mass $\Rightarrow$ Measure for upsilon.
- Agreement with theoretical predictions, even though these are affected by large uncertainty.
- Precision insufficient to distinguish nuclear effects with/out saturation.

Theoretical predictions from: JHEP 03 (2013) 122, JHEP 05 (2013) 155
Forward-Backward asymmetry

- Uncertainties from proton-proton cross section cancel out.
- Clear difference between prompt $J/\psi$ and $J/\psi$ from $b$. 

![Graphs showing forward-backward asymmetry](image-url)
Study of pA collisions is important to better understand Cold Nuclear Matter effects and for probing some yet unexplored QCD physics phenomena.

LHCb has recorded $\sim 1.8\text{nb}^{-1}$ p-Pb collisions in a unique kinematic range.

$J/\psi$ production cross section measured as function of $p_T$ and $y$.

Nuclear Modification Factor and Forward-Backward production asymmetry also measured as function of $p_T$ and $y$.

Clear $J/\psi$ suppression observed in agreement with theory.

Further analyses planned with the pA sample.

Looking forward to a $10 \times$ increase in luminosity in Run II.