$J/\psi$ production in proton-lead collisions at 8 TeV with the LHCb detector

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Motivation

- Measurements of non-deconfinement effects in proton-nucleus collisions:
  - nuclear PDF,
  - saturation,
  - coherent energy loss.
- Important prerequisite for other measurements:
  - \( \psi(2S) \) and \( \chi_c \): density effects on excited states?
  - Drell-Yan: disentangle shadowing to energy loss.
- Unique opportunity for precise measurements of \( J/\psi \)-from-\( b \) hadrons.
- In 2016 higher energy and larger statistics (\( \sqrt{s} = 8.16 \text{ TeV}, \int \mathcal{L} dt \sim 35 \text{ nb}^{-1} \)) than in 2013 (\( \sqrt{s} = 5.02 \text{ TeV}, \int \mathcal{L} dt \sim 2 \text{ nb}^{-1} \)) [1].

• LHCb [1] – forward spectrometer, located at LHC.
• Acceptance $2 < \eta < 5$
• Proton-proton interaction at up to $\sqrt{s} = 13$ TeV, $\mathcal{L} = 4 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$.
• Goal: CP violation and rare decays of $B$-mesons.

• Resolutions [2]:
  • spatial (PV position): $\sim 16$ $\mu$m;
  • decay time: $\sim 50$ fs;
  • track’s momentum: 0.5–0.4%;
  • mass (FWHM): $\sim 13$ MeV ($J/\psi$);
  • particle identification: $\sim 96%$.

2016 heavy ion run:
Ion = $^{208}$Pb, $\sqrt{s_{NN}} = 8.16$ TeV, Integrated luminosity: 13.6 nb$^{-1}$ (Fwd), 20.8 nb$^{-1}$ (Bwd).

Monte Carlo samples: EPOS-LHC. $J/\psi$ from PYTHIA8 injected into each event [1].

Signal Extraction

- \( J/\psi \rightarrow \mu^+\mu^- \)
- Prompt \( J/\psi \)
- and \( J/\psi \)-from-\( b \) hadrons are extracted by simultaneous fit of mass and pseudo-proper time:
  \[ t_z = (Z_{J/\psi} - Z_{PV}) \cdot M_{J/\psi}/p_Z \]

- Mass distributions:
  - Signal: Crystal-Ball.
  - Bkg: exponential.

- \( t_z \) distributions:
  - Signal: \( \delta(t_z) \) for prompt \( J/\psi \);
    Exponential for \( J/\psi \)-from-\( b \).
  - Bkg: empirical function from sideband.

- Total yields:
  - Prompt from-\( b \)
  - Forward: \( \sim 3.8 \cdot 10^5 \); \( \sim 6.7 \cdot 10^4 \)
  - Backward: \( \sim 5.6 \cdot 10^5 \); \( \sim 7.1 \cdot 10^4 \)
\[
\frac{d^2\sigma}{dp_T \ dy^*} = \frac{N}{\Delta p_T \cdot \Delta y^* \cdot \epsilon \cdot B \cdot L}
\]

- \(N\) – number of reconstructed prompt \(J/\psi\) or \(J/\psi\)-from-\(b\);
- \(\Delta p_T = 1\ \text{GeV}/c\) – transverse momentum bin widths;
- \(\Delta y = 0.5\) – rapidity bin widths;
- \(\epsilon\) – total efficiency;
- \(B\) – branching fraction of \(J/\psi \rightarrow \mu^+\mu^-\) decay (\(\sim 6\%\)) [PDG];
- \(L\) – integrated luminosity.
Results: $f_b$

Fraction of $J/\psi$-from-$b$ hadrons:

$$f_b = \frac{\frac{d^2 \sigma_{J/\psi-\text{from-}b}}{dp_T dy^*}}{\frac{d^2 \sigma_{\text{Prompt} J/\psi}}{dp_T dy^*} + \frac{d^2 \sigma_{J/\psi-\text{from-}b}}{dp_T dy^*}}.$$ 

- Comparing $p-p$ (black), forward (blue) and backward (red) configurations.
- Similar trends.
- But deviations at low $p_T$ highlight the differences in the nuclear effects on prompt $J/\psi$ and $J/\psi$-from-$b$ hadrons.
- Advantage: most systematic uncertainties cancel.
Results: $p-p@8.16$TeV reference

- $p-p$ measurements at 8.16 TeV not available.
- Estimated based on interpolation (in energy), extrapolation (in rapidity outside $pp$ coverage) of measurements at 7, 8 and 13 TeV.
- These methods were validated with ALICE and LHCb data [1]

Results: Nuclear Modification Factors: Prompt $J/\psi$

$$R_{p\text{Pb}}(p_T, y^*) = \frac{\frac{d^2\sigma}{dp_T dy^*}_{p\text{Pb}}}{208 \cdot \frac{d^2\sigma}{dp_T dy^*}_{pp}}$$

- In Fwd: suppression at low $p_T$ up to 50%, converging to unity at high $p_T$.
- In Bwd: $R_{p\text{Pb}}$ closer to unity.
- Intriguing low values in Bwd at low $p_T$.
- Overall agreement with models:
  - Collinear factorization: nuclear PDF (HELAC) [1].
  - Color-Glass Condensate (CGC) [2].
  - Coherent energy loss [3].
- Compatible with $p$-Pb@5TeV results.


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Results: Nuclear Modification Factors: $J/\psi$-from-$b$

$$R_{pPb}(p_T, y^*) = \frac{\frac{d^2\sigma}{dp_T\,dy^*}}{208 \cdot \frac{d^2\sigma}{dp_T\,dy^*}}_{pp}$$

- In Fwd: suppression at low $p_T$ up to 30%, converting to unity at high $p_T$.
- In Bwd: $R_{pPb}$ above unity, $p_T$ dependence.
- Overall agreement with Model: FONLL with EPS09NLO [1].
- Compatible with $p$-Pb@5TeV results.
- Unprecedented precision.

Results: Forward-Backward Asymmetry

\[ R_{FB}(p_T, |y^*|) = \frac{d^2\sigma}{dp_T dy^*}(p_T, y^*)/\frac{d^2\sigma}{dp_T dy^*}(p_T, -y^*) \]

- Clear forward-backward asymmetry for prompt \( J/\psi \), in particular at low \( p_T \).
- For \( J/\psi \)-from-\( b \): \( R_{FB} \) is closer to unity.
- Agreement with \( p\text{-}p\text{-}\text{Pb}@5\text{TeV} \) data within uncertainties
- Total uncertainty ~ 10%
- Advantage: no \( pp \)-reference needed; many uncertainties cancel.
Conclusions

• Prompt and non-prompt $J/\psi$ production cross-sections as function of $p_T$ and $y^*$ are measured.
• Nuclear modification factors and Forward-backward backward asymmetry are measured as well.
• Unprecedented precision for prompt $J/\psi$ and most significantly for $J/\psi$-from-$b$.
• These results can have an impact in constraining models for nuclear effects.
• These results will be the reference for the analysis of higher charmonium states.