New results on heavy flavour production in proton-nucleus collisions with the LHCb experiment

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LHCb detector

- LHCb - single armed forward spectrometer, located at LHC
- Acceptance $2 < \eta < 5$
- Proton-proton interaction at up to $\sqrt{s} = 13\text{TeV}$
- Physics goals:
  - CP violation in $b$ and $c$ sectors
  - general purpose physics in forward region

[2008 JINST 3 S08005]
Proton-ion setup at LHCb

\[ \text{Ion} = \frac{208}{82}\text{Pb} \]

Forward region:
- \( y^* = y_{\text{lab}} - 0.465 \)
- \( p\text{Pb}: \, 1.5 < y^* < 4.0 \)

Backward region:
- \( y^* = -(y_{\text{lab}} + 0.465) \)
- \( \text{Pbp}: \, -5.0 < y^* < -2.5 \)

2013 data taking: \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- 1.1 nb\(^{-1}\) (Fwd), 0.5 nb\(^{-1}\) (Bwd)

2016 data taking: \( \sqrt{s_{NN}} = 8.16 \text{ TeV} \)
- 13.6 nb\(^{-1}\) (Fwd), 20.8 nb\(^{-1}\) (Bwd)
Physics motivation

- Study of QCD in a yet barely explored regime
- Study of cold nuclear matter (CNM) effects and their disentangling from QGP effects
- Reference for nucleus-nucleus collisions
- Forward acceptance of LHCb allows to test unique phase space
  - $x_A$: momentum fraction carried by a parton inside the nucleon bound in the lead ion
  - sensitivity for very low as well as very high $x_A$-values
$D^0$ production in proton-lead collisions at 5.02 TeV

[arXiv:1707.02750]
(accepted by JHEP)
Signal Extraction

- 2013 pPb collision data, 5.02 TeV
- Reconstructed through $D^0 \rightarrow K^- \pi^+$ decays
- Simultaneous 2D fit to $D^0$ mass and impact parameter (IP)

**Mass distribution:**
- Signal: Crystal Ball
- Background: linear function

**IP distribution:**
- Prompt Signal: from simulation
- $D^0$ from $b$: from simulation
- Background: shape from sidebands

[arXiv:1707.02750]
Results: prompt $D^0$ total cross-sections in $pPb$

Forward:

$$\sigma_{\text{forward}}(p_T < 10 \ \text{GeV}/c, \ 1.5 < y^* < 4.0) = 230.6 \pm 0.5 \pm 13.0 \ \text{mb}$$

$$\sigma_{\text{forward}}(p_T < 10 \ \text{GeV}/c, \ 2.5 < y^* < 4.0) = 119.1 \pm 0.3 \pm 5.6 \ \text{mb}$$

Backward:

$$\sigma_{\text{backward}}(p_T < 10 \ \text{GeV}/c, \ -5.0 < y^* < -2.5) = 252.7 \pm 1.0 \pm 20.0 \ \text{mb}$$

$$\sigma_{\text{backward}}(p_T < 10 \ \text{GeV}/c, \ -4.0 < y^* < -2.5) = 175.5 \pm 0.6 \pm 14.4 \ \text{mb}$$
Results: prompt $D^0$ double differential cross-section

double-differential cross-section for prompt $D^0$ production in a given ($p_T$, $y^*$) bin

$$\frac{d^2\sigma}{dp_T dy^*} = \frac{N(D^0 \rightarrow K^{\mp}\pi^{\pm})}{\mathcal{L} \times \epsilon_{tot} \times B(D^0 \rightarrow K^{\mp}\pi^{\pm}) \times \Delta p_T \times \Delta y^*}$$
Results: prompt $D^0$ differential cross-section

- Sizeable forward-backward asymmetry
- Uncertainty is the quadratic sum of the statistical and systematic components
- Measurements are compared with theoretical calculations including different nuclear parton distribution functions

[arXiv:1707.02750]
Results: prompt $D^0$ nuclear modification factor

Nuclear modification factor is defined as:

$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}, \ A = 208$$

- Prompt $D^0$ in $pp$ at $\sqrt{s} = 5$ TeV was measured by LHCb [JHEP06(2017)147]

**Forward**

![Forward plot]

**Backward**

![Backward plot]
Results: prompt $D^0$ nuclear modification factor

Nuclear modification factor is defined as:

$$R_{ppb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2 \sigma_{ppb}(p_T, y^*)}{dp_T dy^*} / \frac{d^2 \sigma_{pp}(p_T, y^*)}{dp_T dy^*}, A = 208$$

- Nuclear modification factor smaller at forward rapidity
- Measurements consistent with theoretical calculations

[arXiv:1707.02750]
Results: Prompt $D^0$ forward-backward asymmetry

Forward-backward production ratio is defined as

$$R_{FB}(p_T, y^*) \equiv \frac{d^2\sigma_{pPb}(p_T, +|y^*|)/dp_Tdy^*}{d^2\sigma_{PbP}(p_T, -|y^*|)/dp_Tdy^*}$$

- **Common rapidity region** $2.5 < y^* < 4.0$
- **Significant forward-backward asymmetry observed**
- **Measurements consistent with theoretical calculations**

[arXiv:1707.02750]
J/ψ production in proton-lead collisions at 8.16 TeV

[arXiv:1706.07122]
(accepted by PLB)
Signal Extraction

- 2016 pPb collision data, 8.16 TeV
- Prompt J/ψ and J/ψ-from-b hadrons are extracted by simultaneous fit of mass and pseudo-proper time: $t_Z = (Z_{J/\psi} - Z_{PV}) \times M_{J/\psi} / p_Z$

**Mass distribution:**
Signal: Crystal Ball
Background: exponential

**$t_Z$ distribution:**
Signal: $\delta (t_Z)$ for prompt J/ψ;
Exponential for J/ψ-from-b.
Background: empirical function from sideband

**Total yields:**
- Prompt from-b:
  - Forward: $\sim 3.8 \times 10^5$; $\sim 6.7 \times 10^4$
  - Backward: $\sim 5.6 \times 10^5$; $\sim 7.1 \times 10^4$

[arXiv:1706.07122]
Results: $J/\psi$ total cross-sections in $p\text{Pb}$

Forward:

$$
\sigma_{\text{prompt } J/\psi}(1.5 < y^* < 4.0, \ p_T < 14\text{GeV}/c) = 1625 \pm 4 \pm 117 \mu\text{b},
$$

$$
\sigma_{J/\psi-\text{from-}b-\text{hadrons}}(1.5 < y^* < 4.0, \ p_T < 14\text{GeV}/c) = 276 \pm 2 \pm 20 \mu\text{b},
$$

Backward:

$$
\sigma_{\text{prompt } J/\psi}(-5.0 < y^* < -2.5, \ p_T < 14\text{GeV}/c) = 1692 \pm 4 \pm 182 \mu\text{b},
$$

$$
\sigma_{J/\psi-\text{from-}b-\text{hadrons}}(-5.0 < y^* < -2.5, \ p_T < 14\text{GeV}/c) = 209 \pm 1 \pm 22 \mu\text{b},
$$
Results: \( \psi \) double differential cross-section

double-differential cross-section for \( \psi \) production in a given \((p_T, y^*)\) bin

\[
\frac{d^2\sigma}{dp_T dy^*} = \frac{N(\psi \rightarrow \mu^+ \mu^-)}{\mathcal{L} \cdot \varepsilon_{tot} \cdot B \cdot \Delta p_T \cdot \Delta y^*}
\]

- \( N \): number of reconstructed prompt \( \psi \) or \( \psi \)-from-b;
- \( B \): branching fraction of \( \psi \rightarrow \mu^+ \mu^- \) decay (\( \sim 6\%) [PDG];

\[\text{arXiv:1706.07122}\]
Results: $J/\psi$ differential cross-section

- The cross-sections as a function of $y^*$, integrated over the $p_T$
- Sizeable forward-backward asymmetry
- Uncertainty is the quadratic sum of the statistical and systematic components

[arXiv:1706.07122]
Results: J/ψ differential cross-section

- The cross-section is compared with the reference cross-section for prompt J/ψ and J/ψ-from-b-hadrons production in pp collisions at $\sqrt{s} = 8.16$ TeV, multiplied by the Pb mass number $A = 208$.

- The cross-sections as a function of $p_T$, integrated over the range $1.5 < y^* < 4.0$ for pPb and $-5.0 < y^* < -2.5$ for PbPb.
Fraction of $\psi$-from-$b$ hadrons is defined by

$$f_b \equiv \frac{d^2 \sigma_{\psi\text{-from-}b\text{-hadrons}}}{dp_T dy^*}$$

Comparing $pp$ (black), forward (blue) and backward (red) configurations.

Similar trends.

But deviations at low $p_T$ highlight the differences in the nuclear effects on prompt $\psi$ and $\psi$-from-$b$ hadrons.
Results: Prompt $J/\psi$ nuclear modification factor

Nuclear modification factor is defined as:

$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_Tdy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_Tdy^*}, A = 208$$

- In Fwd: suppression at low $p_T$ up to 50%, converging to unity at high $p_T$
- In Bwd: $R_{pPb}$ closer to unity. Intriguing low values in Bwd at low $p_T$
- Overall agreement with theoretical models. Compatible with $pPb$ 5 TeV results.

$R_{pPb}$ vs. $p_T$, Forward  $R_{pPb}$ vs. $p_T$, Backward  $R_{pPb}$ vs. $y^*$

[arXiv:1706.07122]
Results: $J/\psi$-from-$b$ nuclear modification factor

Nuclear modification factor is defined as:

$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}, A = 208$$

- In Fwd: suppression at low $p_T$ up to 30%, converging to unity at high $p_T$
- In Bwd: $R_{pPb}$ slightly above unity
- Overall agreement with theoretical model. Compatible with $pPb$ 5 TeV results.

- $R_{pPb}$ vs. $p_T$, Forward
- $R_{pPb}$ vs. $p_T$, Backward
- $R_{pPb}$ vs. $y^*$
Results: J/ψ forward-backward asymmetry

Forward-backward production ratio is defined as

\[ R_{FB}(p_T, y^*) \equiv \frac{\frac{d^2\sigma_{pPb}(p_T, +|y^*|)}{dp_Tdy^*}}{\frac{d^2\sigma_{PbP}(p_T, -|y^*|)}{dp_Tdy^*}} \]

- Clear forward-backward asymmetry for prompt J/ψ, in particular at low \( p_T \)
- For J/ψ-from-b: \( R_{FB} \) is closer to unity
- Agreement with \( pPb \) 5 TeV data within uncertainties

![Plot of R_{FB} vs. p_T and R_{FB} vs. |y*|]

[arXiv:1706.07122]
Outlook and Conclusions
Outlook and Conclusions

- Production cross-sections of prompt $D^0$ in $\sqrt{s_{NN}} = 5.02$ TeV $p$Pb collisions, Prompt and non-prompt $J/\psi$ in $\sqrt{s_{NN}} = 8.16$ TeV $p$Pb collisions are measured as function of $p_T$ and $y^*$
- Nuclear modification factors and forward-backward asymmetry are measured
- These results can have an impact in constrain models for nuclear effects
- These results will be the reference for the analysis of nucleus-nucleus collisions
- More measurements with $\sqrt{s_{NN}} = 8.16$ TeV are still yet to come ($\psi(2S)$, $\Upsilon(nS)$, ...)

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Initial Stages
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Backup
Collision of $pp$ at 8.16 TeV reference

- $pp$ 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 [LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002]