Production of open heavy flavor hadrons in pPb collisions at LHCb

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Outline

• Introduction

• The LHCb experiment

• Open heavy flavor measurements in pPb collisions
  
  ➢ $D^0$ production at $\sqrt{s_{NN}} = 5$ TeV [JHEP 10 (2017) 090]
  
  ➢ $\Lambda_c^+$ production at $\sqrt{s_{NN}} = 5$ TeV [LHCb-PAPER-2018-021]
  
  ➢ Beauty production at $\sqrt{s_{NN}} = 8.16$ TeV [PRD 99 (2019) 052011]

• Summary
Introduction

• Unique probe in heavy-ion collisions
  ➢ $m_Q \gg \Lambda_{QCD}$, allows perturbative calculations
  ➢ $t_{\text{prod}} \ll t_{\text{QGP}}$, experience whole time evolution of collision

• Study also cold nuclear matter effects
  ➢ Modification of parton distribution functions: nPDF or CGC
  ➢ Energy-loss with (in)coherent small-angle gluon radiation
  ➢ Interacting with co-moving particles

• Heavy flavor measurements
  ➢ Particle correlations
  ➢ Kinematics, track multiplicity and species dependence
  ➢ Variations in collision systems
LHCb experiment

Precision measurements in $b, c$ flavor sectors

$\tau(H_b) \sim 1.5$ ps, $\tau(H_c) \sim 0.1 - 1$ ps

**Vertex Locator** (vertex reconstruction)

- Impact parameter resolution: $(15 + 29/p_T) \mu$m
- Time resolution: 45 fs, resolving HF decay vertex

**Tracking system** (particle reconstruction)

- $\epsilon$(Tracking) $\sim 96$
- $\delta p/p \sim 0.5\%-1\%$ (5-200 GeV)
- $\sigma(m_{B \rightarrow hh}) \approx 22$ MeV

Decays: $b \rightarrow c \rightarrow s (K^\pm)$;
Baryon $\rightarrow$ proton

**RICH detectors** ($K/\pi/p$ separation)

- $\epsilon(K \rightarrow K) \sim 95\%$ for $r(\pi \rightarrow K) \sim 5\%$

**Magnet**
Bending power: 4 Tm

**pp collision point**
LHCb proton-lead data taking

- 2013 pPb runs: collected about 2 nb\(^{-1}\) data at \(\sqrt{s_{NN}} = 5\) TeV

- 2016 pPb runs: collected about 30 nb\(^{-1}\) data at \(\sqrt{s_{NN}} = 8.16\) TeV

Proton and lead beam inverted \(\rightarrow\) two beam configurations

- LHCb collected collisions in either proton (positive rapidity) or lead beam (negative rapidity) direction
Measurements with pPb collisions

- $D^0$ production at $\sqrt{s_{\text{NN}}} = 5$ TeV  
  [JHEP 10 (2017) 090]
- $\Lambda_c^+$ production at $\sqrt{s_{\text{NN}}} = 5$ TeV  
  [JHEP 02 (2019) 102]
- Beauty production at $\sqrt{s_{\text{NN}}} = 8.16$ TeV  
  [PRD 99 (2019) 052011]
Prompt $D^0$ in pPb data

- $D^0$ fully reconstructed through $D^0 \rightarrow K^\mp \pi^\pm$ decays
- Prompt and secondary $D^0$ yields separated using impact parameter w.r.t. PV
- Reconstruction and particle ID efficiency calibrated using data
- Measurement down to zero-$p_T$
Forward-backward ratio

- Comparing production in proton and lead beam directions

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

- \( R_{FB} \) indicates significant production asymmetry between p- and Pb-beam direction
  - Asymmetry increases with rapidity and decreases at high \( p_T \)
  - Data consistent with predictions with various nPDF sets

\[ 2.5 < |y| < 4.0 \quad \text{LHCb} \quad \sqrt{s_{NN}} = 5 \text{ TeV} \]

\[ p_T < 10 \text{GeV/c} \quad \text{LHCb} \quad \sqrt{s_{NN}} = 5 \text{ TeV} \]

\[ D^0 \quad p_T \quad |y^*| \]
Strong suppression at positive rapidity (~30%), compatible with no suppression and hint of enhancement $\rightarrow$ different nuclear modification in proton and lead beam direction

JHEP 04 (2009) 065, EPJ C77 (2017) 1

CGC: PR D91 (2015) 114005
arXiv:1706.06728
Similar nuclear modification for $D^0$ and $J/\psi$: $\frac{R_{pPb}(J/\psi)}{R_{pPb}(D^0)} \approx 1$; $\psi(2S)$ more suppressed.

JHEP 04 (2009) 065, EPJ C77 (2017) 1
CGC: PR D91 (2015) 114005
arXiv:1706.06728
• Suppression-enhancement pattern predicted by nPDFs
• At positive rapidity region also consistent with CGC, with a proper saturation scale
$R_{pA}$: double differential

LHCb
Pb$p$, $\sqrt{s_{NN}}$=5 TeV

Decreasing with $y$ (Pb to p beam direction)
Increasing with $p_T$
**Nuclear modification factor**

• Observation described by calculations using nPDFs or the CGC model (p-direction)
• Data help to reduce nPDF uncertainties
  - Complexities: scale uncertainties, other nuclear effects

JHEP 04 (2009) 065, EPJ C77 (2017) 1

CGC: PR D91 (2015) 114005  
arXiv:1706.06728

PRL 121 (2018) 052004

+ arXiv:1906.02512
Prompt $\Lambda_c^+$ in pPb data

- Studied in $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays, also high signal purity. $\sim 11/4K$ signals at positive/negative rapidity
- Same strategy as prompt $D^0$ analysis

Forward-backward ratio consistent with calculations using nPDF, however large uncertainty bands on both data and calculations
Baryon over meson ratio

- Most nPDF uncertainties cancel out, sensitive to charm quark fragmentation

- $\Lambda_c^+/D^0$ similar in p and Pb beam directions
- Generally consistent with expectations from $pp$ data $\Lambda_c^+/D^0 \sim 0.3$, hint of discrepancy at high $p_T$ for proton beam direction
- Tensions between LHCb and ALICE?

Analyses with new data essential!
Beauty hadron production

- Beauty fragmentation fractions in pPb data
- $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}, \sim 30 \text{ nb}^{-1} \text{ (positive + negative rapidity)}$
- Exclusive decay modes: $B^+ \to J/\psi K^+, \bar{D}^0 \pi^+, B^0 \to D^- \pi^+, \Lambda_b^0 \to \Lambda_c^+ \pi^-$

### Signal yields

<table>
<thead>
<tr>
<th>Decay</th>
<th>pPb</th>
<th>PbP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to \bar{D}^0 \pi^+$</td>
<td>$1958 \pm 54$</td>
<td>$1806 \pm 55$</td>
</tr>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>$883 \pm 32$</td>
<td>$907 \pm 33$</td>
</tr>
<tr>
<td>$B^0 \to D^- \pi^+$</td>
<td>$1151 \pm 38$</td>
<td>$889 \pm 34$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to \Lambda_c^+ \pi^-$</td>
<td>$484 \pm 24$</td>
<td>$399 \pm 23$</td>
</tr>
</tbody>
</table>
Cross-sections

- $B^+$ cross-section studied in $J/\psi K^+$ and $\bar{D}^0 \pi^+$ modes consistent, systematic effects under control. Precision improved in weighted average.

Statistics limited for $p_T < 2$ GeV, excluded for measurements.
• Probing relative $b$-quark fragmentation into different beauty hadrons

- $B^0/B^+$ ratio independent of $y$ and $p_T$, about 1-$\sigma$ away from unity (isospin symmetry), explained by systematic uncertainties.
- $\Lambda_b^0/B^0 \approx 40\%$, decreasing with $p_T$, no hint of strong rapidity dependence. Similar to results in LHCb $pp$ data [JHEP 08 (2014) 143]
- $\Lambda_b^0/B^0$ ratio reaches LEP data at high $p_T$, $0.20 \pm 0.02$ [arXiv:1612.07233]
- Production at positive rapidity $\approx 25\%$ lower compared with negative rapidity
- No evidence of $p_T$ dependence with current precision
- In good agreement with the calculation using different nPDF sets.
- $R_{FB}$ for $B^+$, $B^0$ and $\Lambda_b^0$ are compatible
Pattern consistent with $R_{pA}$ of $D^0$ hadron

Significant suppression ($\approx 25\%$) in positive rapidity, suppression decreased at large $p_T$

Consistent with unity at negative rapidity

Measurements in good agreement with $J/\psi$-from-$b$ decay data [PLB74 (2017) 159] and calculations using nPDF sets

Experimental uncertainties smaller than nPDF
\( \Lambda_b^0 \) and \( B^0 \) relative modification

- Ratio of \( R_{pA} \) between \( \Lambda_b^0 \) and \( B^0 \) hadrons

Consistent with unity in all kinematic bins \( \Rightarrow b \)-quark fragmentation function similar in pPb and pp collisions
Statistical uncertainty dominated, demanding more statistics to understand better
Summary and outlook

• LHCb has made unique contributions to heavy ion studies

• Studied production of $D^0, \Lambda_c^+, \Lambda_b^0$ baryon
  
  ➢ Precise data for prompt $D^0$ down to zero $p_T$: strong suppression in proton beam direction. Moderate nuclear effect at lead beam direction, hint of enhancement for extreme rapidity
  
  ➢ Prompt $\Lambda_c^+/D^0$ cross-section ratio consistent with expectation at low $p_T$, possible discrepancy at high $p_T$ at positive rapidity
  
  ➢ First measurement of beauty hadrons using exclusive hadronic states. Nuclear effect for $B^+$ consistent with $J/\psi$-from-$b$ data and similar to $D^0$ mesons.
  
  ➢ First direct measurement of $\Lambda_b^0$ baryon in heavy ion collisions, similar suppression compared to beauty mesons

• Millions of charm hadrons to be explored in new data ($\sqrt{s_{NN}} = 8.16$ TeV)
  
  ➢ $D^{0/+, D_s^+, \Lambda_c^+, \Xi_c^{+/0} \ldots$, Di-charm, correlations, track multiplicity dependence

• Improvement of beauty yields studying more decay modes

Thank you for your attention
Additional material
Separation from prompt and detached

Pseudo-decay time of $\psi$

$$t_z = \frac{(Z_{J/\Psi} - Z_{PV}) \times M_{J/\Psi}}{\sum}$$

IP of $D^0$

From B

prompt
LHCb experiment
Aiming for precision measurements in $b, c$ sectors

**Vertex Locator** (vertex reconstruction)
- IP resolution: 20µm
- Decay time resolution: 45 fs ($\tau_B \sim 1.5$ ps)

**RICH detectors** ($K/\pi/p$ separation)
- $\epsilon(K \rightarrow K) \sim 95\%$
- Mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$

**Calorimeters (ECAL, HCAL)** ($e/\gamma$ identification)
- $\delta E/E \sim 1\% + 10\% \sqrt{E}$ (GeV)

**Tracking system, TT T1-T3** (particle reconstruction)
- $\epsilon$(Tracking) $\sim 96\%$
- $\delta p/p \sim 0.5\% - 1\%$ (5-200 GeV)
- $\sigma(m_{B \rightarrow hh}) \approx 22$ MeV

**Bending magnet**
- Bending power: 4 Tm

**Herschel**
- -7.5m, -20m, -114m

**Muon system** ($\mu$ identification)
- $\epsilon(\mu \rightarrow \mu) \sim 97\%$
- Mis-ID $\epsilon(\mu \rightarrow \mu) \sim 1 - 3\%$

**250 mrad**

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LHCb experiment

Decays: $b \rightarrow c \rightarrow s \,(K^{\pm})$; Baryon $\rightarrow$ proton

**RICH detectors ($K/\pi/p$ separation)**
- $\epsilon(K \rightarrow K) \sim 95\%$ for $r(\pi \rightarrow K) \sim 5\%$

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JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

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EPS-HEP 2019
Prompt $D^0$ cross-section

- Differential cross-sections
$R_{pA}$: double differential

- Fixing $p_T$ region, $R_{pA}$ increases from proton to lead beam direction
- For the same $y$, $R_{pA}$ increases with $p_T$, from strong suppression to moderate suppression for positive rapidity, small suppression at very low $p_T$ and hint of enhancement at high $p_T$
- Large enhancement when getting closer to lead beam rapidity
Open charm vs charmonium

• (Double) ratios

JHEP 10 (2017) 090

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Charm baryons over mesons

- Ratios

\[ R_{A_c^+/D^0} \]

LHCb

\[ p\text{Pb } \sqrt{s_{NN}} = 5 \text{ TeV} \]

\[ 2.0 < p_T < 10.0 \text{ GeV}/c \]

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Baryon over meson ratio

- Overall scale is different in LHCb and ALICE in $pp$ collisions
- Unexpected rapidity dependence

![Graphs showing the baryon over meson ratio for LHCb and ALICE in $pp$ collisions.](image)

JHEP 04 (2018) 108
JHEP 10 (2017) 090
Cross-sections (cont.)

Similar $p_T$ and $y$ distributions for $B^+$, $B^0$ and $\Lambda_b^0$ hadrons
Forward backward ratio

Principle Results

- The magnitude of $R_{FB}$ for $B^+$, $B^0$ and $\Lambda_b^0$ are compatible.

**Graphical Representation:**
- Two plots showing the forward-backward ratio $R_{FB}$ for $B^+$ and $p_{T}$, with data points and shaded regions indicating the range of values for $2 < p_T < 20 \text{ GeV/c}$.

**Notation and Symbols:**
- $R_{FB}$: Forward-backward ratio
- $B^+$, $B^0$, $\Lambda_b^0$: Particle species
- $p_{T}$: Transverse momentum
- LHCb: Longitudinal Chromatic Bubbles
- $\sqrt{s_{NN}} = 8.16 \text{ TeV}$: Center-of-mass energy
$B_s^0 \rightarrow D_s^- \pi^+$ mass

![Graph 1](Fwd: N_{sig} \sim 270)

![Graph 2](Bwd: N_{sig} \sim 220)

Signal yield much smaller due to small production and branching fraction. Due to smaller $f_{B_s^0}$ and $B(B_s^0 \rightarrow D_s^- \pi^+) \times B(D_s^- \rightarrow K^+ K^- \pi^+)$