Heavy-flavor hadron production at LHCb

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Collisions in LHCb

Fixed target, LHCb only

\[ \sqrt{s_{NN}} = 13 \text{ TeV} \]
\[ \sqrt{s_{NN}} = 8 \text{ TeV} \]
\[ \sqrt{s_{NN}} = 7 \text{ TeV} \]

\[ \sqrt{s_{NN}} = 8.16 \text{ TeV} \]
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

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

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

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

\[ \sqrt{s_{NN}} = 110 \text{ GeV} \]
\[ \sqrt{s_{NN}} = 69 \text{ GeV} \]

+ short Xe+Xe run in 2017

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LHCb SMOG: fixed (gas) target

System for Measuring Overlap with Gas
- Inject He, Ne, Ar into VELO at $\sim 2 \times 10^{-7}$ mbar
- Designed to measure beam profile
- Allows data taking in fixed target mode

Collected data

<table>
<thead>
<tr>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>pNe</td>
<td>pHe</td>
<td>pAr</td>
<td>pAr</td>
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<tr>
<td>pAr</td>
<td>PbAr</td>
<td>pHe</td>
<td>pHe</td>
</tr>
<tr>
<td>pHe</td>
<td>pNe</td>
<td>pNe</td>
<td>PbNe</td>
</tr>
</tbody>
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Beam Energy
- 2500 GeV
- 4000 GeV
- 6500 GeV
**Forward spectrometer** fully instrumented in $2 < \eta < 5$

- Very good momentum and vertex resolution
  \[ \Delta p/p < 1 \% \text{ for } 0 < p < 200 \text{ GeV/c}, \Delta x \sim 20 \mu\text{m for high } p_T \text{ tracks} \]

- Good particle identification
  - $K$: $\sim 90 \%$ efficiency, mis-ID $< 5 \%$
  - $\mu$: $\sim 97 \%$ efficiency, mis-ID $\sim 1-3 \%$

- **Optimal:** $\mu, p, K^+, \pi^+$ produced inside Vertex Locator
- **Ok:** $K^0_S, \Lambda^0, \gamma, e, \pi^0$
- **Challenging:** stable neutral hadrons $n, K^0_L$
HeRSChel: forward scintillator

Carvalho Akiba et al. JINST 13 (2018) no.04, P04017

- Forward shower counters with acceptance $5 < |\eta| < 10$
- Better identification of diffractive events, important to identify CEP
Why heavy flavor?

Charm and Beauty

• Quark mass $\gg \Lambda_{\text{QCD}}$ acts as cut-off allowing pQCD calculations to low $p_T$
  • Tests of pQCD – FONLL calculations

fixed-order plus next-to-leading logs, see Cacciari et al. hep-ph/9803400

• Cross-sections sensitive to Parton Density Functions (PDFs)
  • Important input to theoretical calculations
  • Dominate uncertainties of predictions
  • Unexplored at low $x$

• Hadrons produced early in ion collisions
  • Experience evolution of nuclear medium
  • Probe nuclear medium via transport properties

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Heavy-ion physics to explore

**Hot nuclear matter in PbPb**
- Possible formation of **Quark Gluon Plasma (QGP)**

**Cold nuclear matter in pPb**
- Modified parton distribution function: nuclear PDF
- Absorption and coherent energy loss in nuclear matter
- Possible formation of Color Glass Condensate

**Study signatures separately in pp, pPb, PbPb to distinguish QGP effects**
- **p-p**: No nuclear effects
- **p-Pb**: Adds cold matter effects
- **Pb-Pb**: Adds hot matter effects
Nuclear effects & asymmetric acceptance

"forward"
Measured particles at $\eta > 0$
Probes low x in nuclear PDF

Probes high x in nuclear PDF

“backward”

Nuclear modification factor

$$R_{pPb} = \frac{\text{cross-section for } pPb}{A_{Pb} \times \text{cross-section for } pp}$$

No nuclear effects: $R_{pPb} = 1$

Forward-Backward (FB) ratio

$$R_{FB} = \frac{\text{cross-section for } pPb + \mid y \mid}{\text{cross-section for } pPb - \mid y \mid}$$
Recent results

Hadrons with charm

ψ(2S) in pp at 7,13 TeV
Asymmetry of D_{s}^{+/-} in pp at \( v_{s_{NN}} = 7,8 \) TeV
Prompt \( \Lambda_{c}^{+} \) in pPb at \( v_{s_{NN}} = 5 \) TeV
J/ψ, D^{0} in p(Ar,He) at \( v_{s_{NN}} = 87, 110 \) GeV

\textit{LHCb-PAPER-2018-049, submitted to JHEP}

JHEP 08 (2018) 008
JHEP 02 (2019) 102
arXiv:1810.07907, submitted to PRL

Hadrons with beauty

Y(nS)_{n=1,2,3} in pp at \( v_{s_{NN}} = 13 \) TeV
Y(nS)_{n=1,2,3} in pPb at \( v_{s_{NN}} = 8.16 \) TeV
B^{0}, B^{+}, \Lambda_{b}^{0} in pPb at \( v_{s_{NN}} = 8.16 \) TeV
\Xi_{b}^{-} in pp at \( v_{s} = 7,8,13 \) TeV

JHEP 07 (2018) 134
JHEP 11 (2018) 194
Hadrons with Charm
ψ(2S) in pp at 7,13 TeV

- ψ(2S) has negligible feed-down compared to J/ψ, easier to theoretically interpret
- Decay channel: ψ(2S) -> μμ
- Double differential cross-section in y, p_T for prompt ψ(2S) and ψ(2S) from b-decay
- Cross-section σ(pp → b̅b X) inferred
- Combined fit to invariant mass and pseudo decay time

\[ t_z = \frac{(z_{\psi(2S)} - z_{PV}) \times m_{\psi(2S)}}{p_z} \]

blue: prompt ψ(2S)    black line: from b-decay    green, magenta: backgrounds
\( \psi(2S) \) in pp at 7,13 TeV

- Overall good agreement with predictions, some deviation at low \( p_T \) for prompt \( \psi(2S) \)
- New measurement at 7 TeV supersedes earlier result based on smaller event sample
Asymmetry of $D_s^{+/−}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV

Expected asymmetry in charmed mesons with u and d
- c and c-bar hadronise differently due to the presence of u, d valence quarks
- c-bar preferably forms mesons, c can additionally form baryons with valence quarks

$D_s^{+/−}$ does not contain valence quarks, only indirect effect of asymmetry expected
- Sensitive test for non-perturbative QCD models
- Essential input for direct $CP$ violation in decays of $D_s^+$ mesons

Asymmetry

$$A_P(D_s^+) = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$$

Decay mode $D_s^+ \rightarrow \phi \pi^+$ with $\phi \rightarrow K^+K^-$, measurements includes $D_s^{+*} \rightarrow D_s^+ \gamma$ or $D_s^+ \pi^0$
Asymmetry of $D_s^{+/−}$ in pp at $\sqrt{s_{NN}} = 7,8$ TeV

- 3.3 $\sigma$ non-zero asymmetry in combined data
- No significant dependence on $\sqrt{s_{NN}}$, $y$, $p_T$
- PYTHIA 8.1 prediction is off and shows stronger dependence on $y$ and $p_T$ than data
Prompt \( \Lambda_c^+ \) in pPb at \( \sqrt{s_{NN}} = 5 \) TeV

- Double differential cross-section in \( y^* \), \( p_T \)
  - \( y^* \) ... rapidity in cms of colliding nucleons
- Cross-section ratios: Forward-backward, baryon-to-meson
- Decay channel \( \Lambda_c^+ \rightarrow p K^- \pi^+ \) used to measure \( \Lambda_c^+ \) yield
- Prompt \( \Lambda_c^+ \) determined from fit of \( \log(\chi^2_{IP}) \) distribution
  - \( \chi^2_{IP} \) ... difference in \( \chi^2 \) when fitting primary vertex with and without \( \Lambda_c^+ \) candidate

Combinatorial background for \( \log(\chi^2_{IP}) \) measured in sidebands
Prompt $\Lambda_c^+$ in pPb at $\sqrt{s_{NN}} = 5$ TeV

- FB ratios consistent with predictions
- Baryon-to-meson ratios
  - At forward rapidity lower at $p_T > 7$ GeV/c than predictions
  - Predictions slightly convex in $y^*$, ALICE + LHCb suggest more peaked shape at mid-rapidity
J/ψ, D0 in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV

- First study of charm in fixed-target mode
- J/ψ and D0 production in pAr(gas) and pHe(gas)
- Decay channels: D0 $\rightarrow$ K±π∓, J/ψ $\rightarrow$ µ±µ∓
- Differential cross-section in y and $p_T$
- Low background in invariant mass distributions
- Right: Total cross-sections
  - Data measured at y = [2, 4.6] extrapolated (about 10 % correction)
  - Measurements fill gap between 50 and 200 GeV
  - D0 to c c-bar with global fragmentation factor
  - Very high precision compared to other data

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$J/\psi$, $D^0$ in $p(\text{Ar,He})$ at $\sqrt{s_{NN}} = 87, 110$ GeV

HELAC-ONIA predictions differ in amplitude and shape
J/ψ, D⁰ in p(Ar,He) at $\sqrt{s_{NN}} = 87, 110$ GeV

- Substantial intrinsic valence-like charm content of the nucleon expected in some theories
- Would contribute at large Bjorken-x and could be visible in most backward bin of pHe data
- Data seem to agree with predictions without any intrinsic valence-like charm contribution
- No evidence of substantial intrinsic charm content of the nucleon observed

arXiv:1810.07907, submitted to PRL
Hadrons with Beauty
\[ \Upsilon(nS)_{n=1,2,3} \text{ in pp at } \sqrt{s_{NN}} = 13 \text{ TeV} \]

- Previous measurements (RHIC, LHC) showed increasing suppression of higher states ("melting")
- Decay channel: \[ \Upsilon(nS) \rightarrow \mu\mu \]
- Double diff. cross-section \[ d^2\sigma/dp_T\text{d}y \times B \] times muon branching fraction for \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \)
- Also computed ratios of 13 TeV data to 8 TeV data
$\Upsilon(nS)_{n=1,2,3}$ in pp at $\sqrt{s_{NN}} = 13$ TeV

- Good agreement with NRQCD predictions

![Graph showing differential cross-sections and ratios with $p_T$ and $y$](image)

- Enhanced suppression of $n>1$ states at low $p_T$
- No significant dependence observed on $y$

Ratios of 13 TeV data to 8 TeV data
- Consistently above unity
- Growths with $p_T$ and $y$ for all states
\( \Upsilon(nS)_{n=1,2,3} \) in pPb at \( \sqrt{s_{NN}} = 8.16 \) TeV

- 21x luminosity compared to previous LHC measurement at 5 TeV
- Decay channel: \( \Upsilon(nS) \rightarrow \mu\mu \)
- Double diff. cross-section \( d^2\sigma/dp_T dy \) for \( \Upsilon(1S) \) and \( \Upsilon(2S) \), integral for \( \Upsilon(3S) \); multiple ratios measured

- Nuclear modification \( R \) enhanced at low \( p_T \)
- Agreement with HELAC-Onia predictions at high \( p_T \)
- Some disagreement at low \( p_T \)
$\Upsilon(nS)_{n=1,2,3}$ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

"Suppression factor" $
\frac{[d^2\sigma/dp_Tdy^*] (\Upsilon(nS))}{[d^2\sigma/dp_Tdy^*] (\Upsilon(1S))}$

$nS_{pPb}/pPb = \frac{R(\Upsilon(nS))_{pPb}|_{Pbp}}{R(\Upsilon(nS))_{pp}}$

- Suppression of $n > 1$ states in good agreement with predictions and previous measurements
- Stronger suppression at low $p_T$
- Strongly enhanced suppression of $\Upsilon(3S)$ in pPb compared to pp at negative rapidity
**B^0, B^+, Λ^0_b in pPb at \( \sqrt{s_{NN}} = 8.16 \text{ TeV} \)**

- Double diff. cross-section \( d^2\sigma/dp_T dy \), see paper for many more plots & tables

\[
B^+ \rightarrow \bar{D}^0 \pi^+
\]
\[
\bar{D}^0 \rightarrow K^+\pi^-
\]
\[
B^0 \rightarrow D^- \pi^+
\]
\[
D^- \rightarrow K^+\pi^-\pi^-
\]

\[
\Lambda^0_b \rightarrow \Lambda_c^+ \pi^-
\]
\[
\Lambda_c^+ \rightarrow pK^-\pi^+
\]

Low backgrounds in invariant mass distributions
**B^0, B^+, Λ^0_b in pPb at \sqrt{s_{NN}} = 8.16 TeV**

### Nuclear effects

- Small effects in agreement with predictions
- Similar for all analyzed b-hadrons
- Comparable to non-prompt J/ψ from b-decays
- Smaller than for prompt J/ψ (as expected from b-mass > c-mass)
$\Xi_b^-$ in pp at $\sqrt{s} = 7,8,13$ TeV

- Measured production ratios, production asymmetry between $\Xi_b^-$ and $\Xi_b^+$, mass
- Decay channel $\Xi_b^- \to J/\psi \Xi^-$ and $\Xi^- \to \Lambda \pi^-$
- Measure production ratios instead of absolute branching fractions
  - Lack of knowledge of fragmentation fractions for decay products
  - Measure ratio to kinematically similar decay $\Lambda_b^0 \to J/\psi \Lambda$ instead (see next slide)
\[ R \equiv \frac{f_{\Xi^-_b}}{f_{\Lambda^0_b}} \frac{\mathcal{B}(\Xi^-_b \to J/\psi \Xi^-)}{\mathcal{B}(\Lambda^0_b \to J/\psi \Lambda)} = \frac{f_{\Xi^-_b}}{f_{\Lambda^0_b}} \frac{\Gamma(\Xi^-_b \to J/\psi \Xi^-) \tau_{\Xi^-_b}}{\Gamma(\Lambda^0_b \to J/\psi \Lambda) \tau_{\Lambda^0_b}} \]

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\[ \frac{f_{\Xi^-_b}}{f_{\Lambda^0_b}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}], \]

\[ \frac{f_{\Xi^-_b}}{f_{\Lambda^0_b}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}]. \]

- Production asymmetry of \( \Xi^-_b \) at 7,8 and 13 TeV compatible with zero (not shown)
- Mass of \( \Xi^-_b \) also measured relative to \( \Lambda^0_b \) to cancel uncertainty of momentum-calibration

\[ m(\Xi^-_b) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17 \text{ MeV}/c^2 \quad \text{(with PDG mass of } \Lambda^0_b) \]
Summary

• LHCb has rich and broad physics program:
  Many new and updated precise inclusive production cross-sections for c- and b-hadrons
  - $\psi(2S)$ in pp at 7,13 TeV 
  - Asymmetry of $D_s^{+/-}$ in pp at $\sqrt{s}_{NN} = 7,8$ TeV
  - Prompt $\Lambda_c^+$ in pPb at $\sqrt{s}_{NN} = 5$ TeV
  - $J/\psi$, $D^0$ in p(Ar,He) at $\sqrt{s}_{NN} = 87, 110$ GeV
  - $Y(nS)_{n=1,2,3}$ in pp at $\sqrt{s}_{NN} = 13$ TeV
  - $Y(nS)_{n=1,2,3}$ in pPb at $\sqrt{s}_{NN} = 8.16$ TeV
  - $B^0, B^+, \Lambda^0_b$ in pPb at $\sqrt{s}_{NN} = 8.16$ TeV
  - $\Xi_b^-$ in pp at $\sqrt{s} = 7,8,13$ TeV

• Comparison with predictions from pertubative QCD improve understanding of nuclear matter effects, mostly good agreement

• Cross-section ratios useful to reduce uncertainties on experimental and theory side

  CEP of $J/\psi$ and $\psi(2S)$ in pp at 13 TeV \textit{JHEP 10 (2018) 167}

Also see Marcin Kucharczyk talk at 11:05 on "Soft QCD and Central Exclusive Production at LHCb"
Backup
Central exclusive production

- Diffractive process: $pp \rightarrow pxp$, $X = \text{meson}$, protons remain intact
- Fusion of photon and pomeron
  - Photon (spin 1) + pomeron (spin 0) = vector meson (spin 1)
- pQCD calculations available for charmonium production
- Probes gluon PDF down to $x = 2 \times 10^{-6}$, possibly showing saturation effects

Experimental signature: no activity in LHCb except two muons, low activity in HeRSCheL

Results: Differential cross-sections in $y$ (MC corrected for fiducial acceptance to muons)
CEP of $J/\psi$, $\psi(2S)$ in pp at 13 TeV

Good agreement of data with NLO calculations

CEP cross-section $pp\rightarrow pXp$ are converted to photoproduction cross-section $\gamma p\rightarrow Xp$

Deviations from simple power-law observed for $\gamma p\rightarrow J/\psi p$, in agreement with JMRT prediction