Heavy flavor production at LHCb

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Selected measurements

• Observation of new resonances in $\Lambda_b^0\pi^+\pi^-$  NEW!
  LHCb-PAPER-2019-025

• Observation of an excited $B_c^+$ state
  PRL 122 (2019) 232001

• Measurement of $b$-hadron fractions at 13 TeV
  arXiv:1902.06794

• Measurement of the mass and production rate of $\Xi_b^-$ baryons
  PRD 99 (2019) 052006

• Measurement of $\Upsilon$ production at 13 TeV
  JHEP 07 (2018) 134

Recent, omitted in this talk:
• Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state
  JHEP 07 (2019) 035
• Forward HQ production at the LHC
• Forward region $2 < \eta < 5$, ~4% of solid angle, but ~40% of HQ production x-section

• Complementary cross-section measurements and overlap in terms of rapidity and $p_T$
• Key detector systems for production measurements: vertex reconstruction (VELO), particle identification (Muon detector, RICHs, Calorimeters), flexible trigger

LHCb: single arm forward spectrometer
Heavy flavor production: motivation

- Variety of measurements
  - **Spectroscopy and production** of b-baryons
  - **Open heavy flavor** production and polarization
  - **Quarkonium** production and polarization
  - Associated production

- Important study for QCD, both perturbative and non-perturbative
  - **Tests of QCD** predictions
  - Determination of **non perturbative parameters**

- Required for MC tuning ➔ inputs for precision flavor physics measurements

- Precise knowledge of SM background for New Physics searches
Observation of new resonances in $\Lambda_b^0 \pi^+ \pi^-$

- Previous study of $\Lambda_b^0$ spectrum at LHCb using data sample of 1 fb$^{-1}$
  - discovery of $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ PRL 109 (2012) 172003
- Later confirmed by CDF PRD 88 (2013) 071101

- New results available with Run I+II data sample of 9 fb$^{-1}$
- Two $\Lambda_b^0$ decay modes considered: $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K$

Clear excess around 6.15 GeV in both distributions
Observation of new resonances in $\Lambda_b^0\pi^+\pi^-$

- The $\Lambda_b^0\pi^+\pi^-$ inv. mass distribution is studied in regions of $\Lambda_b^0\pi^+$ inv. mass: resonant ($\Sigma_b^+$ and $\Sigma_b^{*+}$) and non-resonant

Two peaks hypothesis favoured with $7\sigma$ significance

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Observation of new resonances in $\Lambda_b^0\pi^+\pi^-$

- The mass distribution is studied in regions of $\Lambda_b^0\pi^+$ mass: resonant ($\Sigma_b^+$ and $\Sigma_b^{*+}$) and non-resonant

- Background subtracted $\Lambda_b^0\pi^+$ inv. mass distributions:

\[
\Lambda_b(6152)^0 \rightarrow \Lambda_b^0\pi^+\pi^-
\]

\[
\Lambda_b(6146)^0 \rightarrow \Lambda_b^0\pi^+\pi^-
\]

Different decay rates via $\Sigma_b^+$ and $\Sigma_b^{*+}$ for observed states

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Observation of new resonances in $\Lambda_b^0 \pi^+ \pi^-$

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• Results:

\[
\begin{align*}
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \text{ MeV} \\
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \text{ MeV} \\
\Delta m &= 6.34 \pm 0.32 \text{ MeV} \\
\Gamma_{\Lambda_b(6152)^0} &= 2.11 \pm 0.81 \text{ MeV} \\
\Gamma_{\Lambda_b(6146)^0} &= 2.90 \pm 1.28 \text{ MeV}
\end{align*}
\]

• Possible interpretation of the new states as a doublet of $\Lambda_b(1D)^0$ states with $J^P = \frac{3^+}{2}$ and $\frac{5^+}{2}$

EPJA 51 (2015) 82
PRD 34 (1986) 2809
Observation of an excited $B_c^+$ state

- Two states observed by CMS PRL122 (2019) 132001
- LHCb analysis: Run I+II data sample of 8.5 $fb^{-1}$
- Reconstructed via $B_c^*(2S) \rightarrow (B_c^+ \rightarrow J/\psi \pi^+)\pi^+\pi^-$

Masses are measured to be

$6841.2 \pm 0.6 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 \text{ (}B_c^+\text{) MeV/c}^2$

$6872.1 \pm 1.3 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 \text{ (}B_c^+\text{) MeV/c}^2$

$\Rightarrow$ Consistent with expectations of $B_c(2^3S_1)$ and $B_c(2^1S_1)$ e.g. PRD 86 (2012) 094510

$\Rightarrow$ Confirms first observation by CMS
Measurement of $b$-hadron fractions at 13 TeV

- Data sample: part of Run II, $1.67 \text{ fb}^{-1}$
- Inclusive semileptonic decays to $H_c X \mu \nu$ are used to reconstruct $b$-hadrons
- 2D fit to distinguish signal and background in decays to $H_c h X \mu \nu$:

\[ B_s^0 \rightarrow D_0 K^{\pm} X \mu \nu \]  
\[ D_{s1}^{*+}, D_{s2}^{*+} \text{ nonresonant background} \]

\[ \Lambda_b^0 \rightarrow D_0 p^{(-)} X \mu \nu \]  
\[ \Lambda_c^{+} (2860), \Lambda_c^{+} (2880), \Lambda_c^{+} (2940) \text{ nonresonant background} \]
Measurement of $b$-hadron fractions at 13 TeV

arXiv:1902.06794

• First measurement of $b$-hadron fractions at 13 TeV

\[
\frac{f_s}{f_u + f_d} = 0.122 \pm 0.006
\]

\[
\frac{f_{A_b^0}}{f_u + f_d} = 0.259 \pm 0.018
\]

• Fragmentation fractions extracted as function of $p_T$

Fit by linear function

Fit by exponential function
Measurement of the mass and production rate of $\Xi_b^-$ baryons

- Run I+II data sample of 1 $fb^{-1}$ at 7 TeV, 2 $fb^{-1}$ at 8 TeV and 1.6 $fb^{-1}$ at 13 TeV
- $\Xi_b^-$ reconstructed via $\Xi_b^- \rightarrow J/\psi \Xi^-$, normalization: $\Lambda^0_b \rightarrow J/\psi \Lambda$

Results – first measurement of $\Xi_b^-$ production

\[
\frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)}{\mathcal{B}(\Lambda^0_b \rightarrow J/\psi \Lambda)} \left( \frac{\Xi^- \rightarrow \Lambda \pi^-}{\Xi^- \rightarrow \Lambda \pi^-} \right) = (10.8 \pm 0.9 \pm 0.8) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}]
\]

\[
\frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)}{\mathcal{B}(\Lambda^0_b \rightarrow J/\psi \Lambda)} \left( \frac{\Xi^- \rightarrow \Lambda \pi^-}{\Xi^- \rightarrow \Lambda \pi^-} \right) = (13.1 \pm 1.1 \pm 1.0) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}]
\]
Measurement of the mass and production rate of $\Xi_b^-$ baryons

- Assuming SU(3) symmetry, the fragmentation fraction is obtained

\[
\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}]
\]
\[
\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}]
\]
due to SU(3) symmetry breaking

- No significant production asymmetry observed

\[
A_{\text{prod}}(\Xi_b^-) = (1.1 \pm 5.6)\% \quad [\sqrt{s} = 7, 8 \text{ TeV}],
\]
\[
A_{\text{prod}}(\Xi_b^-) = (-3.9 \pm 4.9)\% \quad [\sqrt{s} = 13 \text{ TeV}].
\]

- The most precise measurement of $\Xi_b^-$ mass

\[
m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17 \text{ MeV}/c^2
\]
Measurement of Υ production at 13 TeV

• Data sample of $277 \, pb^{-1}$ collected at $\sqrt{s} = 13$ TeV
• Clean signals from Υ(1$S$), Υ(2$S$) and Υ(3$S$) using decays to $\mu^+\mu^-$

Absolute production is measured

\[
\begin{align*}
\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) \times \sigma(\Upsilon(1S), 0 < p_T < 15 \, GeV/c, 2 < y < 4.5) &= 4687 \pm 10 \pm 294 \, pb \\
\mathcal{B}(\Upsilon(2S) \rightarrow \mu^+\mu^-) \times \sigma(\Upsilon(2S), 0 < p_T < 15 \, GeV/c, 2 < y < 4.5) &= 1134 \pm 6 \pm 71 \, pb \\
\mathcal{B}(\Upsilon(3S) \rightarrow \mu^+\mu^-) \times \sigma(\Upsilon(3S), 0 < p_T < 15 \, GeV/c, 2 < y < 4.5) &= 561 \pm 4 \pm 36 \, pb
\end{align*}
\]
Measurement of $\Upsilon$ production at 13 TeV

- $p_T$ and $y$–differential and double differential cross-sections measured
- Results compared to Non Relativistic QCD prediction


JHEP 07 (2018) 134

- The 13/8 TeV ratios measured
Summary

Significant LHCb contribution to study heavy flavour production and spectroscopy:

• Observation of new excited $\Lambda_b^0$ resonances
  *provides tests of quark model*

• Observation of excited $B_c^+$ resonances
  *precision tests of lattice predictions*

• Measurement of $B_s^0$ and $\Lambda_b^0$ fractions
  *important for measurements of BR of their decay modes*

• First measurement of $\Xi_b^-$ production and
  the most precise measurement of its mass

• Measurement of $\Upsilon$ production at 13 TeV
  *provides tests of NRQCD*

More results in progress with Run II data
Stay tuned!