Decays of beauty to double open-charm hadrons at LHCb

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on behalf of the LHCb collaboration

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Outline

General overview of
Hadron Spectroscopy at LHCb
given by Zan this morning

This talk covers two
brand-new analyses:

Observation of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$
and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays [LHCb-PAPER-2023-034]

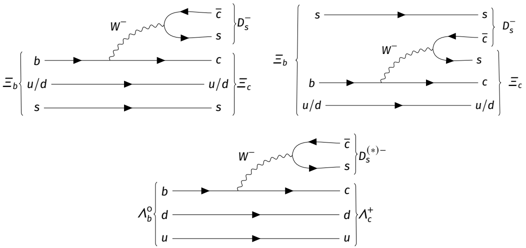
Observation of $\Xi_b^0 \to \Xi_c^+ D_s^-$
and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays [LHCb-PAPER-2023-017].

Motivation

- Beauty to double open-charm decays probe factorization assumptions in HQET; their application is contestable due to the presence of two heavy quarks in the final state.
- Predictions of decay widths / branching fractions ($\mathcal{B}$) exist for the two-body $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$, $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays, but not for $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$.

Reference	$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$
T. Mannel and W. Roberts [Z. Phys. C 59, 179]	0.75
H.-Y. Cheng [Phys. Rev. D 56, 2799]	0.83
A. K. Giri, L. Maharana, and R. Mohanta [Mod. Phys. Lett. A 13, 23]	1.54
Fayyazuddin and Riazuddin [Phys. Rev. D 58, 014016]	1.46
R. Mohanta *et al.* [Prog. Theor. Phys. 101, 959]	1.84
J. Zhu, Z.-T. Wei, and H.-W. Ke [Phys. Rev. D 99, 054020]	0.85
Z.-X. Zhao [Chinese Phys. C 42 093101]	1.49
W.-H. Liang and E. Oset [Eur. Phys. J. C 78, 528]	1.23
T. Gutsche *et al.* [Phys. Rev. D 98, 074011]	1.70
H.-W. Ke, N. Hao, and X.-Q. Li [Eur. Phys. J. C 79, 540]	1.51
C.-K. Chua [Phys. Rev. D 100, 034025]	1.47
S. Rahmani, H. Hassanabadi, and J. Kříž [Eur. Phys. J. C 80, 636]	1.29
Y.-W. Pan, M.-Z. Liu, and L.-S. Geng [arXiv:2309.12050]	2.25

Reference	$\frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$	$\frac{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}$
H.-Y. Cheng [Phys. Rev. D 56, 2799]	1.06	
Z.-X. Zhao [Chinese Phys. C 42 093101]	1.00	1.06
C.-K. Chua [Phys. Rev. D 100, 034025]	0.91	0.97

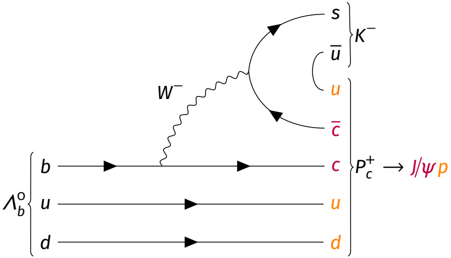


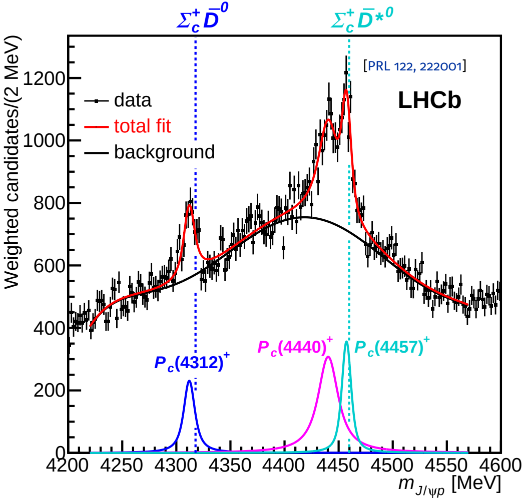
Motivation for $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$

[PRL 115, 072001], [PRL 117, 082002] [PRL 117, 082003]

- Search for P_c^+s, seen in $\Lambda_b^0 \to J/\psi p K^-$ and $\Lambda_b^0 \to J/\psi p \pi^-$, in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$

[PRL 122, 222001]





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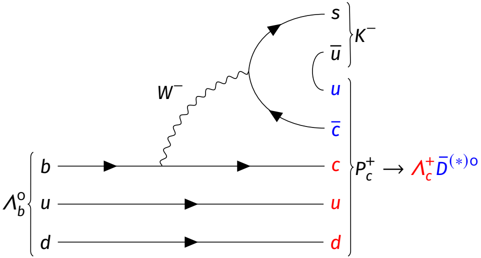


- $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b^0 \to J/\psi p K^-$ directly comparable, since P_c^+ production the same.
- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)$ gauges predictions:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = \frac{f_{J/\psi p}(P_c^+)}{f_{\Lambda_c^+ \bar{D}^{(*)0}}(P_c^+)} \cdot \frac{\mathcal{B}(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0})}{\mathcal{B}(P_c^+ \to J/\psi p)}.$$

$f_X(P_c^+)$ denotes the measured fit-fraction of P_c^+ in channel X

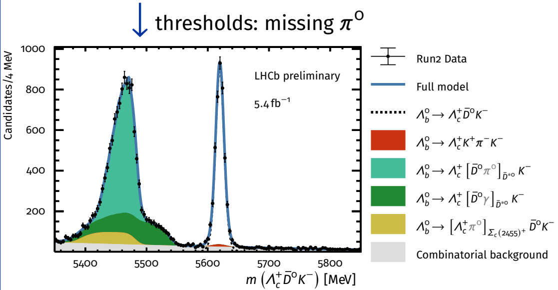
- Theory/pheno calculates $\dfrac{\mathcal{B}(P_c \to \Lambda_c^+ \bar{D}^{(*)})}{\mathcal{B}(P_c \to J/\psi N)}$

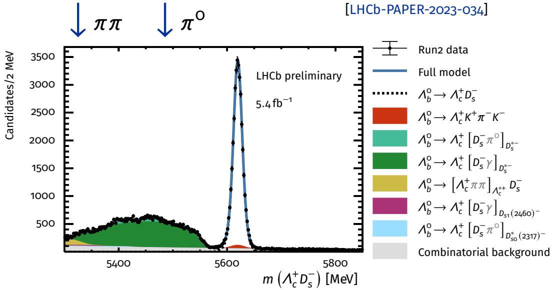
  $\rightsquigarrow$ sensitivity estimate of $f_{\Lambda_c^+ \bar{D}^{(*)0}}(P_c^+)$.

- ... or wait for future measurement of $f_{\Lambda_c^+ \bar{D}^{(*)0}}(P_c^+)$ to compare models.

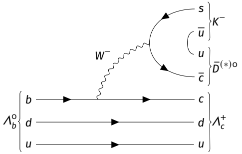
$\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$

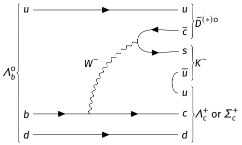
[LHCb-PAPER-2023-034]





- Measure $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})$ through partial reconstruction π^0 or γ from $\bar{D}^{*0}$ or D_s^{*-} decays not reconstructed.
- Shapes of partially reconstructed decays determined by kinematics **and dynamics** *i.e.* amplitude composition.
- $\Delta I = 1$ of spectator diquark forbids $\Lambda_b^0 \to \Sigma_c^+ D_s^-$ [Phys. Lett. B450, 250].
- $\Lambda_b^0 \to \Sigma_c^+ \bar{D}^0 K^-$ color-suppressed. Enhanced by $\Xi_c^{*0} \bar{D}^0$, P_c^+?





Analysis strategy

- Reconstruct both $\Lambda_c^+ \bar{D}^0 K^-$ and $\Lambda_c^+ D_s^-$ candidates in $pK^-\pi^+K^+\pi^-K^-$ final state
  $\Lambda_c^+ \to pK^-\pi^+, \bar{D}^0 \to K^+\pi^-, D_s^- \to K^-K^+\pi^-$.
- Measure $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \frac{N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-}}{N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}} \frac{\varepsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-}}{\varepsilon^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-}} \frac{\mathcal{B}(D_s^- \to K^-K^+\pi^-)}{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}$
- Datasets: Full 5.4 fb^{-1} Run 2 data.
  Dedicated simulation (MC) samples.
- In principle an easy analysis:
  Cut, Count, Correct.

Challenges of $\Lambda_c^+ \bar{D}^0 K^-$ and $\Lambda_c^+ D_s^-$ vs. $J/\psi pK^-$

Final state: 6 hadrons vs. 2 hadrons and 2 muons.
Hadronic hardware- and L1 triggers much less efficient than Dimuon triggers.
Many more combinatorial backgrounds.

- Same reconstruction and trigger selection of $\Lambda_c^+ \bar{D}^0 K^-$ and $\Lambda_c^+ D_s^-$ candidates;
  Different topological and particle identification (PID) requirements offline.
- Dedicated BDT for $\Lambda_c^+ \to pK^-\pi^+$ decays [PRL 112, 202001]; otherwise cutbased.
- Systematics from fit, multiple candidates, MC weighting, MC and calibration statistics.
- Validate result with 4 selection strategies, 3 bkg subtraction- and 3 weighting methods.

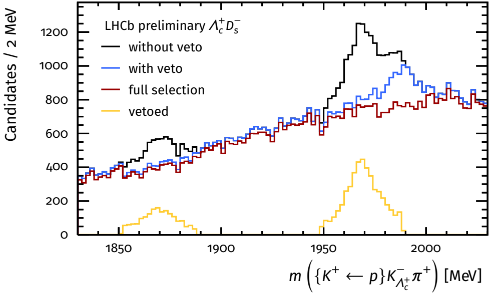
Selection highlight

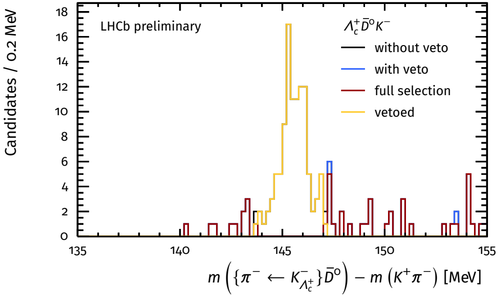
- Extensive veto selections underline complexity of $\Lambda_c^+\bar{D}^0K^-$ and $\Lambda_c^+D_s^-$ selection.
- Use PID information to efficiently suppress backgrounds validated by different selection strategies.

Explicitly rejected physics backgrounds. Some backgrounds are present only in the $\Lambda_c^+\bar{D}^0K^-$ or $\Lambda_c^+D_s^-$ systems, others in both. A particle, $M_{\rm misID}$, that decays through a real particle, a, which is reconstructed as a particle with different mass hypothesis, b, is denoted as $M_{\rm misID} \to \{a \leftarrow b\}X$, where X corresponds to the rest of the decay. As there are two K^- in the final state, the subscripts "Λ_c^+", and "com" (for companion) or "D_s^-" denote the assignment in the nominal $\Lambda_c^+\bar{D}^0K^-$ or $\Lambda_c^+D_s^-$ reconstruction chain.

$\Lambda_c^+\bar{D}^0K^-$	$\Lambda_c^+D_s^-$	Both
$\phi \to \{K^+ \leftarrow p\}K^-_{\rm com}$	$D^- \to \{\pi^- \leftarrow K^-_{D_s^-}\}K^+\pi^-$	$\phi \to \{K^+ \leftarrow p\}K^-_{\Lambda_c^+}$
$D^{*+} \to \left[\{\pi^+ \leftarrow p\}K^-_{\rm com}\right]_{D^0}\pi^+$	$\bar{\Lambda}_c^- \to \{\bar{p} \leftarrow K^-_{D_s^-}\}K^+\pi^-$	$D^+_{(s)} \to \{K^+ \leftarrow p\}K^-_{\Lambda_c^+}\pi^+$
$D^{*+} \to \left[\{K^+ \leftarrow p\}K^-_{\rm com}\right]_{D^0}\pi^+$	$\Lambda_c^+ \to \{\pi^+ \leftarrow p\}K^-_{\Lambda_c^+}\{p \leftarrow \pi^+\}$	$D^+ \to \{\pi^+ \leftarrow p\}K^-_{\Lambda_c^+}\pi^+$
$D^{*-} \to \{\pi^- \leftarrow K^-_{\rm com}\}\bar{D}^0$		$D^{*+} \to \left[\{\pi^+ \leftarrow p\}K^-_{\Lambda_c^+}\right]_{D^0}\pi^+$
$D^{*-} \to \{\pi^- \leftarrow K^-_{\Lambda_c^+}\}\bar{D}^0$		$D^{*+} \to \left[\{K^+ \leftarrow p\}K^-_{\Lambda_c^+}\right]_{D^0}\pi^+$

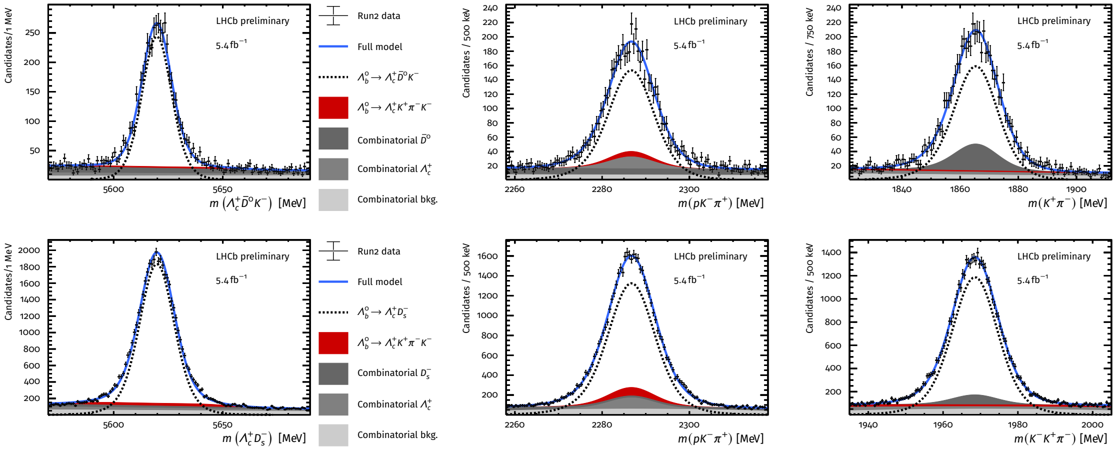
[LHCb-PAPER-2023-034]





- 3D fits determine charm mass requirements and normalization of $\Lambda_b^0 \to \Lambda_c^+ K^+ \pi^- K^-$.
- Linear dependency of $\Lambda_b^0 \to \Lambda_c^+ K^+ \pi^- K^-$ PDF in $m(\Lambda_c^+ \bar{D}^0 K^-)$ or $m(\Lambda_c^+ D_s^-)$ to $m(K^+\pi^-)$ or $m(K^- K^+ \pi^-)$ because of mass constraint.

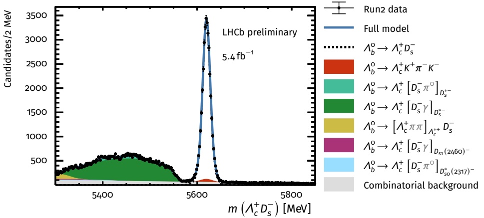
[LHCb-PAPER-2023-034]

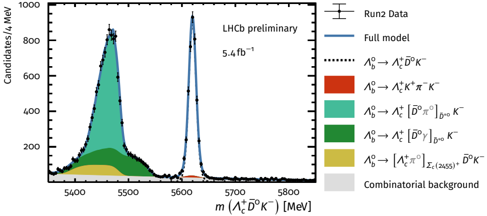


Baseline mass fits

- Analytical models for $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$, $\Lambda_b^0 \to \Lambda_c^+ D_{s0}^*(2317)^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_{s1}(2460)^-$.
- Normalizations of $\Lambda_b^0 \to \Lambda_c^+ D_{s0}^*(2317)^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_{s1}(2460)^-$ constrained from corresponding B meson decays and predicted baryon-meson ratios [Phys. Rev. D 69, 094002].
- $\Lambda_b^0 \to \Sigma_c^+ \bar{D}^0 K^-$, $\Lambda_b^0 \to \Lambda_c^+ D_s^- \pi\pi$ and $\Lambda_b^0 \to \Lambda_c^+ K^+ \pi^- K^-$ use kernel density (KDE) PDFs [Comput. Phys. Commun. 136, 198] from fast simulation (RapidSim [Comput. Phys. Commun. 214, 239]/AmpGen).
- Sum of $\Lambda_b^0 \to \Lambda_c^+ \left[\bar{D}^0 \pi^0\right]_{\bar{D}^{*0}} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ \left[\bar{D}^0 \gamma\right]_{\bar{D}^{*0}} K^-$ KDE PDFs from full simulation multiplied by polynomial for imperfectly modeled decay dynamics/efficiency.

[LHCb-PAPER-2023-034]





$$N^{\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}} = 46\,400 \pm 500\,(\text{stat.}), \quad N^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 35\,450^{+200}_{-210}\,(\text{stat.}),$$

$$N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-} = 10\,560^{+310}_{-290}\,(\text{stat.}), \quad N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-} = 4010 \pm 70\,(\text{stat.}).$$

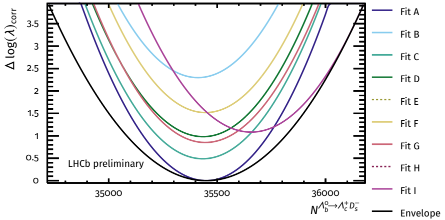
- Efficiency ratios are evaluated using simulation, corrected in production- and decay kinematics and track multiplicity.
- Data-driven calibration of the BDT response for $\Lambda_c^+ \to pK^-\pi^+$ decays [PRL 112, 202001].
- Validated by using different methods for the correction of simulated data, and by choosing selection requirements that probe certain aspects of the efficiency calculation.

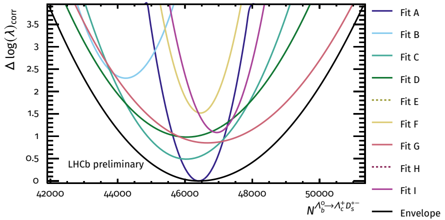
$$\epsilon^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-} / \epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 0.809 \pm 0.006 \text{ (MC stat.)},$$
$$\epsilon^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-} / \epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 0.689 \pm 0.005 \text{ (MC stat.)},$$
$$\epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}} / \epsilon^{\Lambda_b^0 \to \Lambda_c^+ D_s^-} = 0.785 \pm 0.005 \text{ (MC stat.)}.$$

Systematic uncertainties

- Fit model: use discrete profiling [JINST 10 P04015].
  - Likelihoods corrected for number of parameters and pulls of fit-constraints.
  - Baseline fit has best corrected likelihood.
  - Vary 9 model choices for discrete profiling.
  - Approximate likelihoods with bifurcated parabolas $\rightsquigarrow$ calculate envelope analytically.

[LHCb-PAPER-2023-034]





Source / relative to	$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^0K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)}$ [%]	$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^{*0}K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)}$ [%]	$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^{*-})}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)}$ [%]
Fit model	$^{+0.5}_{-0.6}$	$^{+2.8}_{-3.0}$	$^{+3.6}_{-3.3}$
Weighting	0.1	0.1	0.0
Multiple candidates	0.0	0.0	0.1
Size of simulated samples	0.4	0.3	0.2
Size of generated samples	0.6	0.6	0.6
Total	0.9	$^{+2.9}_{-3.1}$	$^{+3.7}_{-3.3}$
Statistical	1.8	2.8	1.3

Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.1908^{+0.0036}_{-0.0034}\,(\text{stat.})^{+0.0016}_{-0.0018}\,(\text{sys.}) \pm 0.0038(\mathcal{B}),$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.589^{+0.018}_{-0.017}\,(\text{stat.})^{+0.017}_{-0.018}\,(\text{sys.}) \pm 0.012(\mathcal{B}),$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022\,(\text{stat.})^{+0.061}_{-0.055}\,(\text{sys.}).$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)} = 3.09^{+0.11}_{-0.10}\,(\text{stat.})^{+0.09}_{-0.10}\,(\text{sys.}).$$

compatible with several predictions shown earlier.

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \cdot \frac{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}{\mathcal{B}(D_s^- \to K^-K^+\pi^-)} = 0.1400^{+0.0026}_{-0.0025}\,(\text{stat.})^{+0.0012}_{-0.0013}\,(\text{sys.}),$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \cdot \frac{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}{\mathcal{B}(D_s^- \to K^-K^+\pi^-)} = 0.432^{+0.013}_{-0.012}\,(\text{stat.}) \pm 0.013\,(\text{sys.}).$$

Corollary

- Reminder: $\dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = \dfrac{f_{J/\psi p}(P_c^+)}{f_{\Lambda_c^+ \bar{D}^{(*)0}}(P_c^+)} \cdot \dfrac{\mathcal{B}(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0})}{\mathcal{B}(P_c^+ \to J/\psi p)}$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009},$$

Yields $\Lambda_b^0 \to J/\psi p K^-$ $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$

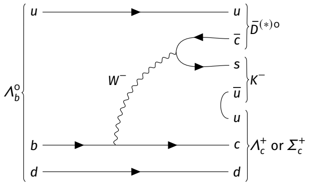
$N^{\Lambda_b^0 \to J/\psi p K^-} \approx 250\,000$ [PRL 122, 222001]

$N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-} \approx 4000$, $N^{\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-} \approx 10\,000$

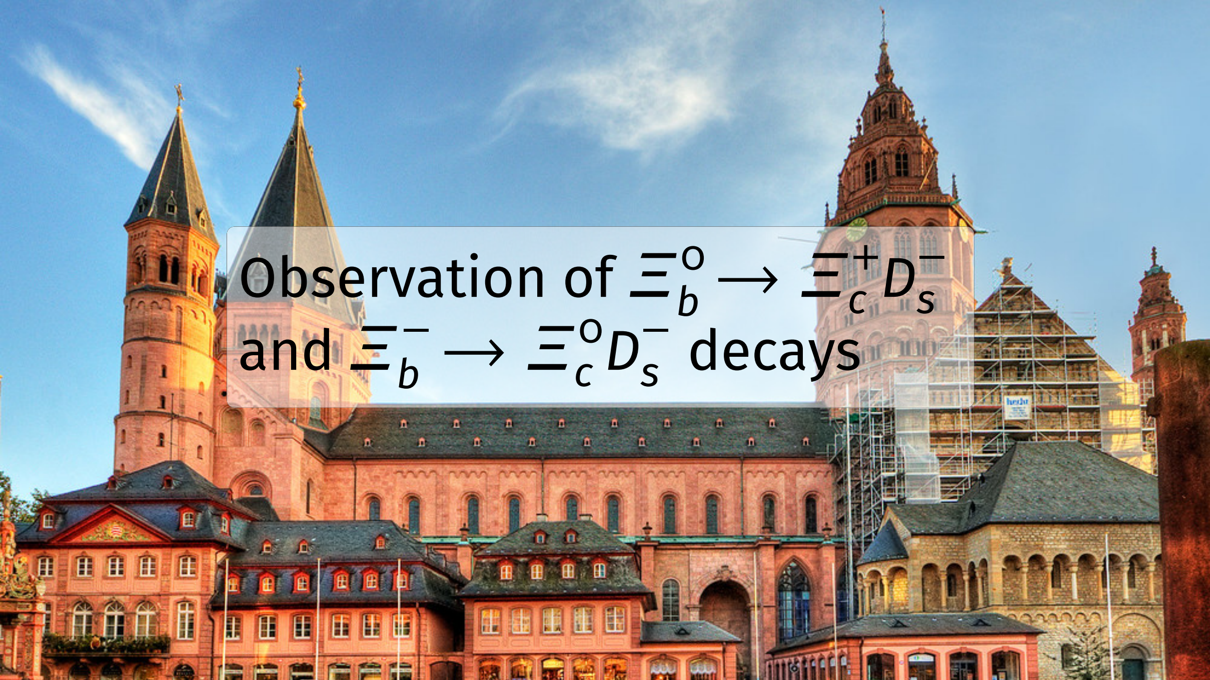
- Comparing $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)$ to mesonic counterpart allows to estimate size/strength of color-suppressed amplitudes; which are absent for meson decays [Phys. Rev. D 106, 054029].

- Define $\mathcal{DR}^{(*)}(M_b) \equiv \left[\dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}\right] \Big/ \left[\dfrac{\mathcal{B}(M_b \to M_c \bar{D}^{(*)0} K^-)}{\mathcal{B}(M_b \to M_c D_s^-)}\right].$

$$\mathcal{DR}(\bar{B}^0) = 1.29 \pm 0.20, \qquad \mathcal{DR}^*(\bar{B}^0) = 1.28 \pm 0.19,$$
$$\mathcal{DR}(B^-) = 1.20 \pm 0.30, \qquad \mathcal{DR}^*(B^-) = 0.87 \pm 0.12,$$
$$\mathcal{DR}(B_c^-) = 1.3 \pm 0.5, \qquad \mathcal{DR}^*(B_c^-) = 0.8 \pm 0.4.$$



Observation of $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays



- Reconstruct $\Xi_c^+ D_s^-$ and $\Lambda_c^+ D_s^-$ candidates in $pK^-\pi^+K^+\pi^-K^-$ final state. Ξ_c^0 adds third K^-.
- Measure $\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) \equiv \frac{\sigma(\Xi_b^0)}{\sigma(\Lambda_b^0)} \times \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \frac{N(\Xi_b^0 \to \Xi_c^+ D_s^-)}{N(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \frac{\varepsilon(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\varepsilon(\Xi_b^0 \to \Xi_c^+ D_s^-)} \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}$

$$\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) \equiv \frac{\sigma(\Xi_b^-)}{\sigma(\Lambda_b^0)} \times \frac{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \frac{N(\Xi_b^- \to \Xi_c^0 D_s^-)}{N(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \frac{\varepsilon(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\varepsilon(\Xi_b^- \to \Xi_c^0 D_s^-)} \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+)}$$

$$\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right) \equiv \frac{\sigma(\Xi_b^0)}{\sigma(\Xi_b^-)} \times \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)} = \frac{N(\Xi_b^0 \to \Xi_c^+ D_s^-)}{N(\Xi_b^- \to \Xi_c^0 D_s^-)} \frac{\varepsilon(\Xi_b^- \to \Xi_c^0 D_s^-)}{\varepsilon(\Xi_b^0 \to \Xi_c^+ D_s^-)} \frac{\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}$$

- Direct measure of fragmentation fraction ratios $\left(\frac{\sigma(\Xi_b)}{\sigma(\Lambda_b^0)}\right)$ assuming $\frac{\mathcal{B}(\Xi_b \to \Xi_c D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1$.
- Analysis additionally measures Λ_b^0 and Ξ_b masses. Not covered here.

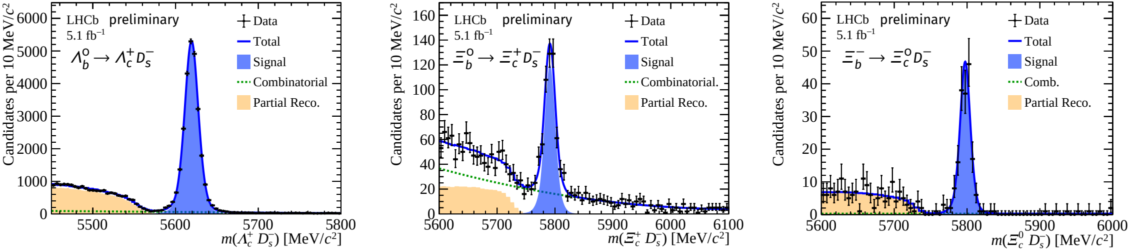
- Reconstruction and trigger efficiencies do not cancel to first order as before, due to differences in lifetime, kinematics ($\Xi_c/\Lambda_c^+/\Xi_b/\Lambda_b^0$) and/or additional track (Ξ_c^0).
- Veto ϕ, D_s^+, D^+, D^0 from proton misidentification, Λ_c^+ from a misidentified K^+.
- Train dedicated gradient BDT classifier maximizing $S/\sqrt{S+B}$ with expected signal/background yields S/B.
- Efficiencies are taken from simulation, corrected for PID responses, track reconstruction efficiency, production- and decay-kinematics and track multiplicity.

$$\frac{\varepsilon(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\varepsilon(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.101 \pm 0.010\,(\text{MC stat.}),$$
$$\frac{\varepsilon(\Xi_b^- \to \Xi_c^0 D_s^-)}{\varepsilon(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.515 \pm 0.005\,(\text{MC stat.}),$$
$$\frac{\varepsilon(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\varepsilon(\Xi_b^- \to \Xi_c^0 D_s^-)} = 2.138 \pm 0.017\,(\text{MC stat.}).$$

Mass fits

- Partially reconstructed signal consistent with $\Lambda_b^0/\Xi_b \rightarrow \Lambda_c^+/\Xi_c D_s^{*-}$ with $D_s^{*-} \rightarrow D_s^- \gamma$.
- Simulated samples with D_s^{*-} helicities ± 1 and 0 model partially reconstructed decays.
- Fractions of $\Lambda_b^0/\Xi_b \rightarrow \Lambda_c^+/\Xi_c K^- K^+ \pi^-$ decays $f_{\text{single } c}$ estimated from sidebands.

[LHCb-PAPER-2023-017]



$$N(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-}) = 26\,090 \pm 170\,(\text{stat.}), \quad f_{\text{single } c}(\Lambda_b^0) = (5.70 \pm 0.13\,(\text{stat.}))\%,$$
$$N(\Xi_b^0 \rightarrow \Xi_c^+ D_s^-) = 462 \pm 29\,(\text{stat.}), \quad f_{\text{single } c}(\Lambda_b^0) = (8.39 \pm 1.75\,(\text{stat.}))\%,$$
$$N(\Xi_b^- \rightarrow \Xi_c^0 D_s^-) = 175 \pm 14\,(\text{stat.}), \quad f_{\text{single } c}(\Lambda_b^0) = (6.44 \pm 10.48\,(\text{stat.}))\%.$$

- Fit model: vary signal and background model, remove partially reconstructed signal by adjusting fitted mass range. Take maximum deviation as uncertainty.
- Single charm background fraction $f_{\text{single } c}$ from different sideband region.
- Corrections to simulations dominated by weighting to match data in track multiplicity, production- and decay-kinematics; uncertainties evaluated with pseudoexperiments.

Source / relative to	$\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right)$ [%]	$\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right)$ [%]	$\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right)$ [%]
Fit model	2.7	1.3	3.4
$f_{\text{single } c}$	2.0	1.6	2.5
Limited simulation sample size	0.9	1.0	0.8
Trigger efficiency	1.5	1.5	1.5
Reconstruction efficiency	0.1	1.6	1.7
Corrections to simulations	1.3	4.3	4.3
Total	3.8	5.4	6.5

$$\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) = (15.8 \pm 1.1\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 7.7\,(\mathcal{B}))\%$$

$$\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) = (16.9 \pm 1.3\,(\text{stat.}) \pm 0.9\,(\text{sys.}) \pm 4.3\,(\mathcal{B}))\%$$

$$\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right) = (94 \pm 10\,(\text{stat.}) \pm 6\,(\text{sys.}) \pm 51\,(\mathcal{B}))\%$$

- $\mathcal{R}(\Xi_b^0/\Xi_b^-)$ consistent with $SU(3)$ flavour symmetry.
- Closing in on ratio of Λ_b^0 and Ξ_b fragmentation fractions.
- Related LHCb measurements

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.88 \pm 0.04 \pm 0.03)\%\ (\sqrt{s} = 7, 8\,\text{TeV})$$ [Phys. Rev. Lett. 113, 032001]

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = (10.8 \pm 0.9 \pm 0.8)\%\ (7, 8\,\text{TeV}),\ \ (13.1 \pm 1.1 \pm 1.0)\%(13\,\text{TeV})$$ [Phys. Rev. D 99, 052006]

Conclusion and Outlook

- LHCb is capable of reconstructing fully hadronic beauty to double open-charm decays with 6 and 7 particles in the final state, reaching down to percent-level precision!
- The presented branching fractions probe factorization assumptions in effective theories.
- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-)$ needed for upcoming pentaquark searches in these channels.
- $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays are valuable input to Ξ_b / Λ_b^0 fragmentation fractions.
- Great improvement of reconstruction and trigger efficiencies for fully hadronic decays in Run 3, due to triggerless readout of detector.