Charmless $b$-meson and $b$-baryon decays at LHCb

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Abstract. The latest LHCb results for charmless $b$-meson and $b$-baryon decays, using Run I data collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV, are presented. The search for charmless three-body decays of the $\Lambda_0^b$ and $\Xi_0^b$ baryons to the final states $\Lambda h^+ h^-$ ($h^+ h^- = \pi$ or $K$) results in the first observation of $\Lambda_0^b \rightarrow \Lambda K^+ \pi^-$ and $\Lambda_0^b \rightarrow \Lambda K^+ K^-$ decays and measurements of their branching fractions and $CP$ asymmetries, as well as evidence of the $\Lambda_0^b \rightarrow \Lambda \pi^+ \pi^-$ decay and limits on the branching fractions of $\Xi_0^b$ baryon decays. The first observation of $\Lambda_0^b \rightarrow \Lambda \phi$ decay is also reported and the branching fraction and triple-product asymmetries are measured. The search for $\Lambda_0^b \rightarrow \Lambda \eta'$ and $\Lambda_0^b \rightarrow \Lambda \eta$ decays yields evidence for the latter and upper limits on the former. A measurement of the branching fraction of $B^0_s \rightarrow \phi \phi$ decay and a limit on the $B^0 \rightarrow \phi \phi$ mode are also presented. The decay $B^0 \rightarrow K^0_S K^* (892)^0$ is observed for the first time and its branching fraction measured.

1. Introduction
Decays of $b$-mesons and $b$-baryons to charmless final states proceed via $b \rightarrow u$ tree and flavour-changing neutral current $b \rightarrow s, d$ loop (penguin) transitions, both of which are suppressed in the Standard Model. The tree and penguin transition amplitudes are of similar size and have a relative weak phase, which can lead to $CP$ violation in decay. The possibility of new physics particles contributing to the loop makes these decay modes sensitive probes of new physics and motivates their branching fraction and $CP$ asymmetry measurements. The $CP$ asymmetries can be compared in corresponding $b$-meson and $b$-baryon decays, such as $B^0 \rightarrow \phi \phi$ ($B^0 \rightarrow K^0_S \phi$, $B^0 \rightarrow K^{*0} \phi$) where no $CP$ violation has been found so far [1], [2], [3], [4], and $\Lambda_0^b \rightarrow \Lambda \phi$ reported here. The sector of charmless $b$-baryon decays is almost unexplored and particular to LHCb.

2. Datasets and analysis strategies
The results presented in these proceedings are recent measurements, performed by the LHCb experiment in its Run I with a dataset corresponding to 1 fb$^{-1}$ of integrated luminosity collected at centre-of-mass energy of 7 TeV in 2011 and 2 fb$^{-1}$ at 8 TeV in 2012. The LHCb detector [5], [6] is a single-arm forward spectrometer designed for the study of particles containing $b$ or $c$ quarks.

The selection criteria for signal candidates share some common characteristics in the analyses of charmless $b$-hadron decays presented here. The selections are based on multivariate classifiers that exploit the kinematic properties of final-state particles and the topologies of three-body and quasi-two-body decays. In addition, particle identification requirements on charged hadrons, based primarily on information from ring-imaging Cherenkov detectors, are applied to reduce
Long-lived particles such as Λ and K0 can travel considerable distances and sometimes decay outside the acceptance of the LHCb vertex detector (VELO). They are therefore reconstructed in two categories: the first, referred to as “long”, involving K0/Λ particles that decay early for their decay products to be reconstructed in the VELO; and the second, referred to as “downstream”, containing those that decay later, such that track segments cannot be formed in the VELO. The two data categories have different vertex, momentum and mass resolutions, as “downstream”, containing those that decay later, such that track segments cannot be formed outside the acceptance of the LHCb vertex detector (VELO).

In order to extract the signal, control channel and background yields, fits are performed to the invariant masses of the selected candidates. The relative branching fractions with respect to a control channel are obtained as the product of the ratio of the yields and the ratio of the efficiencies for the two modes. The absolute branching fractions of the signal channels are then calculated by multiplying with the branching fractions of the control channel, taken from previous measurements or the PDG [7].

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3. Observations of Λ0 → ΛK+π− and Λ0 → ΛK+K− decays and searches for other decays of Λ0 and Ξ0 to Λh+h− final states

Few charmless decays of b-baryons have been studied to date. In this study [8], a search is performed for the charmless three-body decays of the Λ0 and Ξ0 baryons to the final states Λh+h−, with h(0) = π or K. The Λ baryon is reconstructed in its decay Λ → pπ−. The charm decay Λ0 → (Λπ+)Lambda+π− is used as a control mode.

A simultaneous fit is performed to all final states and the control mode. Figure 1 shows the invariant mass distributions of the ΛK+K−, ΛK±π∓, and Λπ±π∓ final states with the fit results overlaid. The decay modes Λ0 → ΛK+π−, and Λ0 → ΛK+K− are observed for the first time with significances of 8.1σ and 15.8σ, respectively, including the effects of systematic uncertainties on the yields. Evidence is seen for the Λ0 → Λπ+π− mode with a total significance of 4.7σ. The dominant systematic uncertainties are due to the fit model, efficiency estimation and the yield of the normalisation channel.
The absolute branching fractions are measured using the normalisation channel to be

\[
B(Λ^0_b → Λπ^+π^-) = (4.6 ± 1.2 \text{ (stat)} ± 1.4 \text{ (syst)} ± 0.6 \text{ (norm)}) \times 10^{-6},
\]

\[
B(Λ^0_b → ΛK^+π^-) = (5.6 ± 0.8 \text{ (stat)} ± 0.8 \text{ (syst)} ± 0.7 \text{ (norm)}) \times 10^{-6},
\]

\[
B(Λ^0_b → ΛK^-π^-) = (15.9 ± 1.2 \text{ (stat)} ± 1.2 \text{ (syst)} ± 2.0 \text{ (norm)}) \times 10^{-6},
\]

where the first quoted uncertainty is statistical, the second systematic, and the third is due to the normalisation mode branching fraction.

The measured yields of the corresponding Ξ_b^0 modes are compatible with zero. The results are translated into limits on the product of their branching fractions and the ratio of fragmentation fractions \(f_{Ξ_b^0}/f_{Λ_b^0}\) that give the probability for a \(b\) quark to hadronise into either a \(Ξ_b^0\) or \(Λ_b^0\),

\[
f_{Ξ_b^0}/f_{Λ_b^0} \times B(Ξ_b^0 → Λπ^+π^-) < 1.7 (2.1) \times 10^{-6} \text{ at 90 (95) } % \text{ confidence level},
\]

\[
f_{Ξ_b^0}/f_{Λ_b^0} \times B(Ξ_b^0 → ΛK^-π^-) < 0.8 (1.0) \times 10^{-6} \text{ at 90 (95) } % \text{ confidence level},
\]

\[
f_{Ξ_b^0}/f_{Λ_b^0} \times B(Ξ_b^0 → ΛK^+K^-) < 0.3 (0.4) \times 10^{-6} \text{ at 90 (95) } % \text{ confidence level}.
\]

The two \(Λ_b^0\) modes with highest yields offer the possibility to search for \(CP\) violation, as has been seen in the corresponding three-body \(B^±\) decays [9]. The raw asymmetries are obtained from efficiency-corrected yields of \(Λ_b^0\) and \(Λ_b^0\) fitted separately. The \(CP\) asymmetries are then calculated by correcting for the production and detection asymmetries using the control mode which has negligible \(CP\) violation. The measured \(CP\) asymmetries are

\[
A_{CP}(Λ_b^0 → ΛK^+π^-) = -0.53 ± 0.23 \text{ (stat)} ± 0.11 \text{ (syst)},
\]

\[
A_{CP}(Λ_b^0 → ΛK^-π^-) = -0.28 ± 0.10 \text{ (stat)} ± 0.07 \text{ (syst)},
\]

consistent with the conservation of \(CP\) symmetry.

4. Observation of the \(Λ_b^0 → Λϕ\) decay

This analysis presents the search for the quasi-two-body \(Λ_b^0 → Λϕ\) decay [10]. The \(ϕ\) mesons are reconstructed as \(ϕ → K^+K^-\), and the \(Λ\) baryons as \(Λ → pπ^-\). The \(B^0 → K_s^0ϕ\) decay mode is used as a normalisation channel, with \(K_s^0 → π^+π^-\).
A three-dimensional fit to the $p\pi^-K^+K^-$ ($\pi^+\pi^-K^+K^-$), $p\pi^-$ ($\pi^+\pi^-$) and $K^+K^-$ invariant masses is performed, as shown in Figure 2 for the signal mode. The resulting signal yield of $89 \pm 13$ events represents the first observation of $\Lambda_b^0 \rightarrow \Lambda\phi$ decay, with a total significance of 5.9$\sigma$. The branching fraction is measured to be

$$B(\Lambda_b^0 \rightarrow \Lambda\phi) = \left(5.18 \pm 1.04 \text{ (stat)} \pm 0.35 \text{ (syst)} \pm 0.44 \text{ (fd/f}_{\Lambda b}^0)\right) \times 10^{-6}.$$

Here the third and fourth uncertainties are due to the normalisation mode and the ratio of fragmentation fractions, respectively. The systematic uncertainty is dominated by the efficiency estimation and the fit model.

The $\Lambda_b^0 \rightarrow \Lambda\phi$ decay is a spin-$\frac{1}{2}$ to spin-$\frac{1}{2}$ plus vector meson transition, and five angles are needed to describe the decay. $CP$ violation in the decay can be probed without the need for a control channel, through $T$-odd triple products. The angles $\Phi_\Lambda$ ($\Phi_\phi$) are defined as the azimuthal angles of the final-state $K^+$ (proton) in the rest frame of the $\phi$ ($\Lambda$). The sines and cosines of these angles are odd under time reversal, and their corresponding asymmetries $A_{A,\phi}^{c,s}$ are measured from fits to the subsets of the data where the observables are positive and negative. The $T$-odd-triplet-product asymmetries are obtained to be

$$A_A^c = -0.22 \pm 0.12 \text{ (stat)} \pm 0.06 \text{ (syst)}, \quad A_\Lambda^{s} = 0.13 \pm 0.12 \text{ (stat)} \pm 0.05 \text{ (syst)},$$

$$A_\phi^c = -0.01 \pm 0.12 \text{ (stat)} \pm 0.03 \text{ (syst)}, \quad A_\phi^{s} = -0.07 \pm 0.12 \text{ (stat)} \pm 0.01 \text{ (syst)},$$

and are consistent with zero.

5. Search for $\Lambda_b^0 \rightarrow \Lambda\eta'$ and $\Lambda_b^0 \rightarrow \Lambda\eta$ decays

The search for the as yet unobserved $\Lambda_b^0 \rightarrow \Lambda\eta'$ and $\Lambda_b^0 \rightarrow \Lambda\eta$ decays is presented [11]. Decays to states with $\eta$ and $\eta'$ are sensitive to the mixing angle between light and strange quarks [12]. In addition to the dominant $b \rightarrow s$ loop diagram for both $\Lambda_b^0 \rightarrow \Lambda\eta'$ and $\Lambda_b^0 \rightarrow \Lambda\eta$ decays, $\Lambda_b^0 \rightarrow \Lambda\eta'$ decays have further contributions from non-spectator and anomalous diagrams, which can alter its branching fraction due to gluon mixing. Thus, branching fraction measurements are important to constrain the $\eta - \eta'$ mixing angles.

The $B^0 \rightarrow K_s^{0}\eta'$ mode is used as a normalisation channel for the measurement of the branching fractions. The decays are reconstructed as $\Lambda \rightarrow p\pi^-, K_0^{*}\rightarrow \pi^+\pi^-$, $\eta'$ candidates as $\eta' \rightarrow \pi^+\pi^-$ and $\eta' \rightarrow \pi^+\pi^-\eta$ (with $\eta \rightarrow \gamma\gamma$), and $\eta$ candidates as $\eta \rightarrow \pi^+\pi^-\pi^0$ (with $\pi^0 \rightarrow \gamma\gamma$). The signal invariant mass distributions are shown in Figure 3. No significant signal is observed for $\Lambda_b^0 \rightarrow \Lambda\eta'$ decays, while the $\Lambda_b^0 \rightarrow \Lambda\eta$ yield is $5.3 \pm 3.8$ events which represents evidence with a significance of 3.0$\sigma$. 

**Figure 3.** Invariant mass distributions of the (left) $\Lambda_b^0 \rightarrow \Lambda\eta'$ ($\eta' \rightarrow \pi^+\pi^-\gamma$), (middle) $\Lambda_b^0 \rightarrow \Lambda\eta'$ ($\eta' \rightarrow \pi^+\pi^-\eta$) and (right) $\Lambda_b^0 \rightarrow \Lambda\eta$ ($\eta \rightarrow \pi^+\pi^-\pi^0$) downstream candidates. The solid lines show the total fit, the dashed lines the signals, and the dash-dotted lines the background. From [11].
A branching fraction measurement is performed using the normalisation channel, where a limit is placed for \( \Lambda_b^0 \to \Lambda \eta' \) decays and 68% CL intervals are calculated for \( \Lambda_b^0 \to \Lambda \eta \) decays,

\[
B(\Lambda_b^0 \to \Lambda \eta') < 3.1 \times 10^{-6} \text{ at 90\% CL}, \quad B(\Lambda_b^0 \to \Lambda \eta) = (9.3^{+7.3}_{-5.3}) \times 10^{-6}.
\]

The results suggest the possible presence of gluonic mixing of \( \eta' \) mesons.

6. **Measurement of the \( B_s^0 \to \phi \phi \) branching fraction and search for \( B^0 \to \phi \phi \) decay**

In this study [13], a branching fraction measurement of \( B_s^0 \to \phi \phi \) decay and a search for the suppressed \( B^0 \to \phi \phi \) decay are performed, using \( B^0 \to \phi K^*(892)^0 \) as a control channel.

The invariant mass fits are shown in Figure 4, where the selection used in the \( B^0 \to \phi \phi \) search is optimised for sensitivity to that decay, but its yield is negligible. The upper limit on the branching ratio is obtained as \( B(B^0 \to \phi \phi) < 2.8 \times 10^{-8} \) at 90(95)% CL, and provides a constraint on possible new physics contributions [14].

The yields of the \( B_s^0 \to \phi \phi \) and control modes are corrected for the S-wave fractions of candidates, whose uncertainty is the largest systematic contribution. The branching fraction is

\[
B(B_s^0 \to \phi \phi) = (1.84 \pm 0.05 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.11 (f_s/f_d) \pm 0.12 \text{ (norm)}) \times 10^{-5},
\]
representing the most precise measurement of this quantity to date.

7. Observation of $B^0_s \to K_S^0 K^+(892)^0$ decay

The branching fraction measurement of $B_s^0 \to K^0_S K^+(892)^0$ and search for $B^0 \to K_S^0 K^+(892)^0$ decays [15] is performed using 2011 data and the $B^0 \to K_S^0 \pi^+ \pi^-$ mode for normalisation. The LHCb experiment has already measured inclusive $B^0_s \to K^0_S h^0 h^\pm$ decays, including first observation of the decay $B^0_s \to K^0_S K^+ \pi^-$ [16]. In this analysis the resonant structure in the $K^+ \pi^-$ invariant mass region around 1 GeV/$c^2$ is analysed to determine the number of decays that proceed through an intermediate $K^{*0}$ resonance.

A two-dimensional fit is performed to the $K_S^0 K^+ \pi^-$ and $K^+ \pi^-$ invariant masses in order to select the $K^*(892)^0$ resonant signal mode, as shown in Figure 5. The $B_s^0 \to K_S^0 K^*(892)^0$ decay is observed for the first time, with a total significance of 7.1 standard deviations. For the $B^0$ decay, the yields are negligible and an upper limit is determined. The results for the branching fractions are obtained in terms of the sum of final states with either $K^0 K^{*0}$ or $\bar{K}^0 K^{*0}$,

$$B(B_s^0 \to \bar{K}^0 K^*(892)^0) + B(B_s^0 \to K^0 \bar{K}^0 K^*(892)^0) = (16.4 \pm 3.4 \pm 1.9 \pm 1.0 \pm 0.7) \times 10^{-6},$$

$$B(B^0 \to K^0 K^*(892)^0) + B(B^0 \to K^0 \bar{K}^0 K^*(892)^0) < 0.96 (1.04) \times 10^{-6} \text{ at 90\% (95\%) CL},$$

where the first uncertainty is statistical, the second systematic, the third due to the ratio of the fragmentation fractions and the fourth due to the branching fraction of the normalisation mode.

8. Summary

Several recent searches for $b$-meson and $b$-baryon decays with the LHCb detector were presented, including the first observations of $\Lambda_0^0$ decays to $\Lambda K^+ \pi^-$, $\Lambda K^+ K^-$ and $\Lambda \phi$ states, and of $B^0_s \to K_S^0 K^*(892)^0$ decays. Branching ratio measurements were performed for these modes, and limits were set for the unobserved modes. The $CP$ asymmetries and $T$-odd triple-product asymmetries of some modes were measured to be consistent with zero. With the larger datasets being collected by LHCb during its Run II, the branching fraction and $CP$ violation measurements will be improved statistically, and new charmless $b$-hadron decay modes will become accessible.

Acknowledgments

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