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

**Irina Nasteva on behalf of the LHCb collaboration**
Instituto de Física, Universidade Federal do Rio de Janeiro
Av. Athos da Silveira Ramos 149, CT bloco A, Cidade Universitária
Rio de Janeiro, RJ 21941-972, Brazil

E-mail: irina.nasteva@cern.ch

**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 $\Lambda_b^0$ and $\Xi_b^0$ baryons to the final states $\Lambda h^+ h'^-$ ($h^{(\prime)} = \pi$ or $K$) results in the first observation of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and $\Lambda_b^0 \to \Lambda K^+ K^-$ decays and measurements of their branching fractions and $CP$ asymmetries, as well as evidence of the $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ decay and limits on the branching fractions of $\Xi_b^0$ baryon decays. The first observation of $\Lambda_b^0 \to \Lambda\phi$ decay is also reported and the branching fraction and triple-product asymmetries are measured. The search for $\Lambda_b^0 \to \Lambda\eta'$ and $\Lambda_b^0 \to \Lambda\eta$ decays yields evidence for the latter and upper limits on the former. A measurement of the branching fraction of $B_s^0 \to \phi\phi$ decay and a limit on the $B^0 \to \phi\phi$ mode are also presented. The decay $B_s^0 \to K_S^0 K^*(892)^0$ 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 $b \to u$ tree and flavour-changing neutral current $b \to s, d$ 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 $B_s^0 \to \phi\phi$ ($B^0 \to K_S^0\phi$, $B^0 \to K^{*0}\phi$) where no $CP$ violation has been found so far [1, 2, 3, 4], and $\Lambda_b^0 \to \Lambda\phi$ 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 $1\,\text{fb}^{-1}$ of integrated luminosity collected at centre-of-mass energy of 7 TeV in 2011 and $2\,\text{fb}^{-1}$ 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

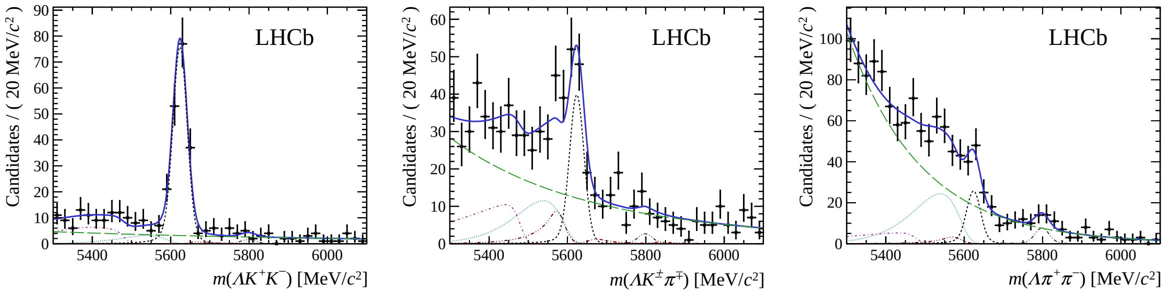


**Figure 1.** Results of the invariant mass fits for (left) $\Lambda K^+K^-$, (middle) $\Lambda K^\pm\pi^\mp$, and (right) $\Lambda\pi^+\pi^-$ final states. The total result of the fit is superomposed as a solid blue line, the $\Lambda_b^0$ ($\Xi_b^0$) decay as a short-dashed black (double dot-dashed grey) line, cross-feed as triple dot-dashed brown lines, the combinatorial background as a long-dashed green line, and partially reconstructed background components with either a missing neutral pion as a dot-dashed purple line or a missing soft photon as a dotted cyan line. From [8].

background from misidentified particles. Possible contributions from $b$-hadron decays with intermediate $\Lambda_c^+$, $\Xi_c^+$ or $D^0$ particles are removed by excluding the corresponding regions in phase space. In some of the analyses, these charm decays are retained separately as control channels for the normalisation of branching fraction measurements, while in others different modes with high yields and similar final states to the signal are used as control channels.

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].

Long-lived particles such as $\Lambda$ and $K_S^0$ 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 $K_S^0/\Lambda$ particles that decay early enough 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, and are therefore treated separately.

## 3. Observations of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and $\Lambda_b^0 \to \Lambda K^+K^-$ decays and searches for other decays of $\Lambda_b^0$ and $\Xi_b^0$ to $\Lambda h^+h'^-$ 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 $\Lambda_b^0$ and $\Xi_b^0$ baryons to the final states $\Lambda h^+h'^-$, with $h^{(\prime)} = \pi$ or $K$. The $\Lambda$ baryon is reconstructed in its decay $\Lambda \to p\pi^-$. The charm decay $\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-$ 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 $\Lambda K^+K^-$, $\Lambda K^\pm\pi^\mp$, and $\Lambda\pi^+\pi^-$ final states with the fit results overlaid. The decay modes $\Lambda_b^0 \to \Lambda K^+\pi^-$, and $\Lambda_b^0 \to \Lambda K^+K^-$ are observed for the first time with significances of $8.1\,\sigma$ and $15.8\,\sigma$, respectively, including the effects of systematic uncertainties on the yields. Evidence is seen for the $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ mode with a total significance of $4.7\,\sigma$. The dominant systematic uncertainties are due to the fit model, efficiency estimation and the yield of the normalisation channel.

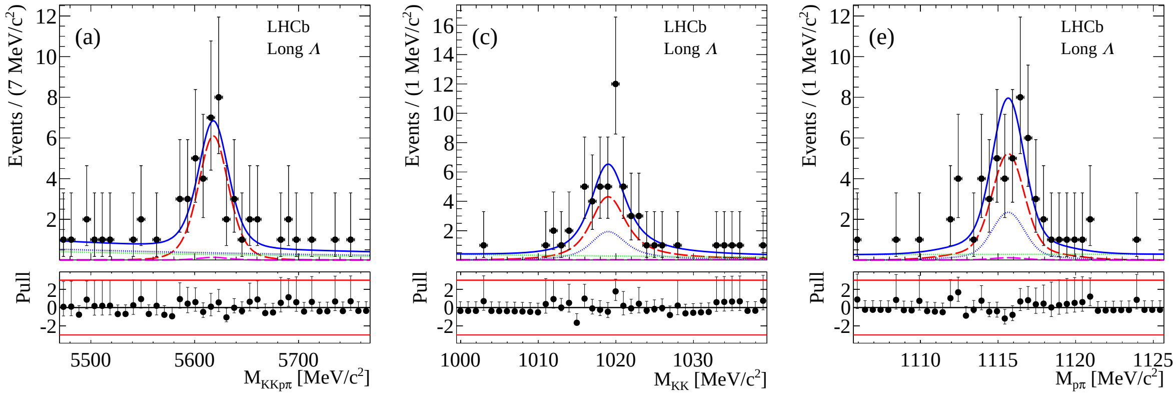


**Figure 2.** Fit projections to the (left) $p\pi^-K^+K^-$, (middle) $K^+K^-$and (right) $p\pi^-$invariant masses of the long dataset of $\Lambda_b^0 \to \Lambda\phi$ candidates. The total fit is given by the blue solid line, the $\Lambda_b^0 \to \Lambda\phi$ signal by the red dashed line, the $\Lambda_b^0 \to \Lambda K^+K^-$ non-resonant component by the magenta dashed line, and the $\phi + \Lambda$ and pure combinatorial fit components by the blue and green dotted lines, respectively. From [10].

The absolute branching fractions are measured using the normalisation channel to be

$$\begin{aligned}
\mathcal{B}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) &= (4.6 \pm 1.2\,(\text{stat}) \pm 1.4\,(\text{syst}) \pm 0.6\,(\text{norm})) \times 10^{-6}\,, \\
\mathcal{B}(\Lambda_b^0 \to \Lambda K^+\pi^-) &= (5.6 \pm 0.8\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 0.7\,(\text{norm})) \times 10^{-6}\,, \\
\mathcal{B}(\Lambda_b^0 \to \Lambda K^+K^-) &= (15.9 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 2.0\,(\text{norm})) \times 10^{-6}\,,
\end{aligned}$$

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 $\Xi_b^0$ modes are compatible with zero. The results are translated into limits on the product of their branching fractions and the ratio of fragmentation fractions $f_{\Xi_b^0}$ and $f_{\Lambda_b^0}$ that give the probability for a $b$ quark to hadronise into either a $\Xi_b^0$ or $\Lambda_b^0$,

$$\begin{aligned}
f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda\pi^+\pi^-) &< 1.7\ (2.1) \times 10^{-6} \text{ at } 90\ (95)\,\%\text{ confidence level}\,, \\
f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^-\pi^+) &< 0.8\ (1.0) \times 10^{-6} \text{ at } 90\ (95)\,\%\text{ confidence level}\,, \\
f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^+K^-) &< 0.3\ (0.4) \times 10^{-6} \text{ at } 90\ (95)\,\%\text{ confidence level}\,.
\end{aligned}$$

The two $\Lambda_b^0$ modes with highest yields offer the possibility to search for *CP* violation, as has been seen in the corresponding three-body $B^\pm$ decays [9]. The raw asymmetries are obtained from efficiency-corrected yields of $\Lambda_b^0$ and $\overline{\Lambda}_b^0$ 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

$$\begin{aligned}
\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) &= -0.53 \pm 0.23\,(\text{stat}) \pm 0.11\,(\text{syst})\,, \\
\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) &= -0.28 \pm 0.10\,(\text{stat}) \pm 0.07\,(\text{syst})\,,
\end{aligned}$$

consistent with the conservation of *CP* symmetry.

## 4. Observation of the $\Lambda_b^0 \to \Lambda\phi$ decay

This analysis presents the search for the quasi-two-body $\Lambda_b^0 \to \Lambda\phi$ decay [10]. The $\phi$ mesons are reconstructed as $\phi \to K^+K^-$, and the $\Lambda$ baryons as $\Lambda \to p\pi^-$. The $B^0 \to K_S^0\phi$ decay mode is used as a normalisation channel, with $K_S^0 \to \pi^+\pi^-$.

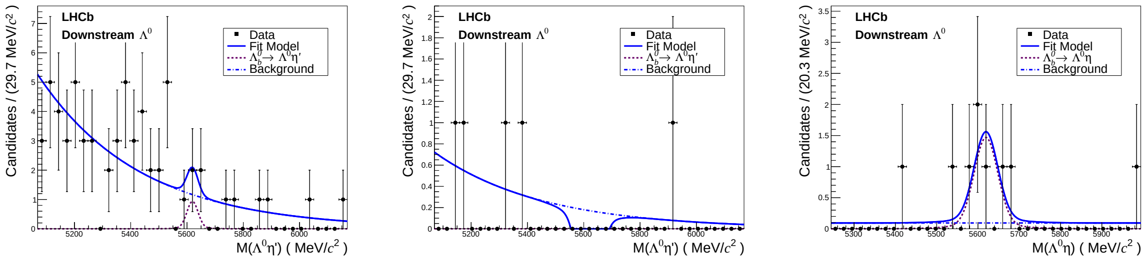


**Figure 3.** Invariant mass distributions of the (left) $\Lambda_b^0 \to \Lambda\eta'$ ($\eta' \to \pi^+\pi^-\gamma$), (middle) $\Lambda_b^0 \to \Lambda\eta'$ ($\eta' \to \pi^+\pi^-\eta$) and (right) $\Lambda_b^0 \to \Lambda\eta$ ($\eta \to \pi^+\pi^-\pi^0$) downstream candidates. The blue lines show the total fit, the dashed purple lines the signals, and the dash-dotted blue lines the background. From [11].

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 Fig. 2 for the signal mode. The resulting signal yield of $89 \pm 13$ events represents the first observation of $\Lambda_b^0 \to \Lambda\phi$ decay, with a total significance of $5.9\sigma$. The branching fraction is measured to be

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\phi) = \left(5.18 \pm 1.04\,(\text{stat}) \pm 0.35\,(\text{syst})\,^{+0.50}_{-0.43}\,(\text{norm}) \pm 0.44\,(f_d/f_{\Lambda_b^0})\right) \times 10^{-6}.$$

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 $\Lambda_b^0 \to \Lambda\phi$ 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 $\mathcal{A}^{c,s}_{\Lambda,\phi}$ are measured from fits to the subsets of the data where where the observables are positive and negative. The $T$-odd triple-product asymmetries are obtained to be

$$\mathcal{A}^c_\Lambda = -0.22 \pm 0.12\,(\text{stat}) \pm 0.06\,(\text{syst}), \qquad \mathcal{A}^s_\Lambda = \phantom{-}0.13 \pm 0.12\,(\text{stat}) \pm 0.05\,(\text{syst}),$$
$$\mathcal{A}^c_\phi = -0.01 \pm 0.12\,(\text{stat}) \pm 0.03\,(\text{syst}), \qquad \mathcal{A}^s_\phi = -0.07 \pm 0.12\,(\text{stat}) \pm 0.01\,(\text{syst}),$$

and are consistent with zero.

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

The search for the as yet unobserved $\Lambda_b^0 \to \Lambda\eta'$ and $\Lambda_b^0 \to \Lambda\eta$ 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 $b \to s$ loop diagram for both $\Lambda_b^0 \to \Lambda\eta'$ and $\Lambda_b^0 \to \Lambda\eta$ decays, $\Lambda_b^0 \to \Lambda\eta'$ 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 $B^0 \to K^0_S\eta'$ mode is used as a normalisation channel for the measurement of the branching fractions. The decays are reconstructed as $\Lambda \to p\pi^-$, $K^0_S \to \pi^+\pi^-$, $\eta'$ candidates as $\eta' \to \pi^+\pi^-\gamma$ and $\eta' \to \pi^+\pi^-\eta$ (with $\eta \to \gamma\gamma$), and $\eta$ candidates as $\eta \to \pi^+\pi^-\pi^0$ (with $\pi^0 \to \gamma\gamma$). The signal invariant mass distributions are shown in Fig. 3. No significant signal is observed for $\Lambda_b^0 \to \Lambda\eta'$ decays, while the $\Lambda_b^0 \to \Lambda\eta$ yield is $5.3 \pm 3.8$ events which represents evidence with a significance of $3.0\sigma$.

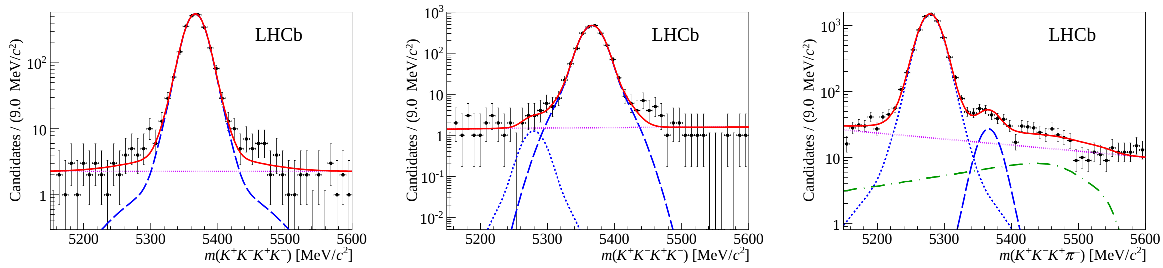


**Figure 4.** Distribution of (left) $K^+K^-K^+K^-$ mass, (middle) $K^+K^-K^+K^-$ mass with a tighter selection applied, and (right) $K^+K^-K^+\pi^-$ mass of $B^0_{(s)} \to \phi\phi$ candidates. The total fitted function is shown by the red solid line, the $B^0_s \to \phi\phi$ component by the blue long-dashed line, $B^0 \to \phi\phi$ by the blue short-dashed line, and the combinatorial background by the (purple) dotted line. On the right plot, the short-dashed line shows the $B^0 \to \phi K^*$, the long-dashed line $B^0_s \to \phi \overline{K}^*(892)^0$, and the dashed line $\Lambda^0_b \to \phi p \pi^-$ and $\Lambda^0_b \to \phi p K^-$ contributions. From [13].

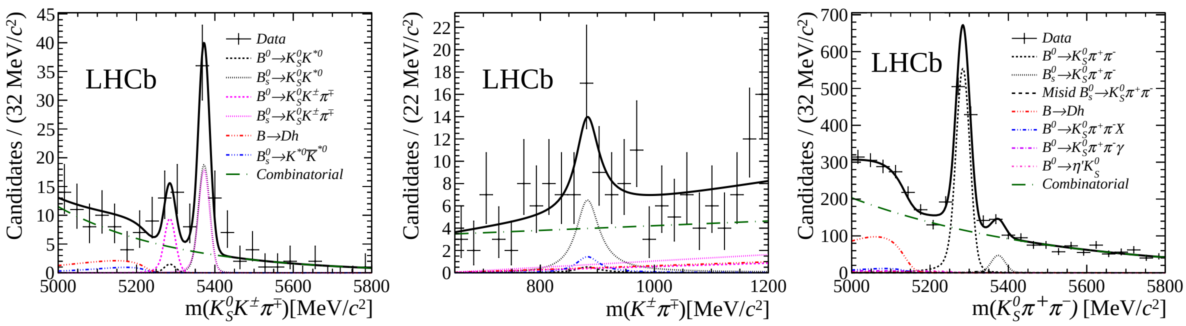


**Figure 5.** Distributions of (left) $K^0_S K^\pm \pi^\mp$ mass, (middle) $K^\pm\pi^\mp$ mass and (right) $K^0_S\pi^+\pi^-$ mass for downstream $B^0_{(s)} \to K^0_S K^*(892)^0$ candidates, with the overall fit represented by the solid black line, the $B^0$ ($B^0_s$) signal components by the black short-dashed (dotted) lines, the combinatorial background by the green long-dash dotted line, and the rest of the fit components as shown in the legends. From [15].

A branching fraction measurement is performed using the normalisation channel, where a limit is placed for $\Lambda^0_b \to \Lambda\eta'$ decays and 68% CL intervals are calculated for $\Lambda^0_b \to \Lambda\eta$ decays,

$$\mathcal{B}(\Lambda^0_b \to \Lambda\eta') < 3.1 \times 10^{-6} \text{ at 90\% CL}\,, \qquad \mathcal{B}(\Lambda^0_b \to \Lambda\eta) = (9.3^{+7.3}_{-5.3}) \times 10^{-6}\,.$$

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

## 6. Measurement of the $B^0_s \to \phi\phi$ branching fraction and search for $B^0 \to \phi\phi$ decay

In this study [13], a branching fraction measurement of $B^0_s \to \phi\phi$ 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 Fig. 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 $\mathcal{B}(B^0 \to \phi\phi) < 2.8\,(3.4) \times 10^{-8}$ at 90 (95)% CL, and provides a constraint on possible new physics contributions [14].

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

$$\mathcal{B}(B^0_s \to \phi\phi) = (1.84 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.11\,(f_s/f_d) \pm 0.12\,(\text{norm})) \times 10^{-5}\,,$$

representing the most precise measurement of this quantity to date.

## 7. Observation of $B_s^0 \to K_S^0 K^*(892)^0$ decay

The branching fraction measurement of $B_s^0 \to K_S^0 K^*(892)^0$ 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 $B_{(s)}^0 \to K_S^0 h^\pm h'^\mp$ decays, including first observation of the decay $B_s^0 \to K_S^0 K^\pm \pi^\mp$ [16]. In this analysis the resonant structure in the $K^+\pi^-$ invariant mass region around $1\,\mathrm{GeV}/c^2$ 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 Fig. 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 $K^0\overline{K}^{*0}$ or $\overline{K}^0 K^{*0}$,

$$\begin{aligned}
\mathcal{B}(B_s^0 \to \bar{K}^0 K^*(892)^0) + \mathcal{B}(B_s^0 \to K^0 \bar{K}^*(892)^0) &= (16.4 \pm 3.4 \pm 1.9 \pm 1.0 \pm 0.7) \times 10^{-6}\,, \\
\mathcal{B}(B^0 \to \bar{K}^0 K^*(892)^0) + \mathcal{B}(B^0 \to K^0 \bar{K}^*(892)^0) &< 0.96\ (1.04) \times 10^{-6} \text{ at } 90\%\ (95\%)\ \mathrm{CL}\,,
\end{aligned}$$

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 $\Lambda_b^0$ decays to $\Lambda K^+\pi^-$, $\Lambda K^+K^-$ and $\Lambda\phi$ states, and of $B_s^0 \to K_S^0 K^*(892)^0$ 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

Financial support from CNPq and George Mason University is gratefully acknowledged.


## References


[1] Aaij R *et al.* (LHCb collaboration) 2014 *Phys. Rev.* **D90** 052011 (*Preprint* 1407.2222)
[2] Aaij R *et al.* (LHCb collaboration) 2013 *Phys. Rev. Lett.* **110** 241802 (*Preprint* 1303.7125)
[3] Abe K *et al.* (Belle) 2003 *Phys. Rev. Lett.* **91** 261602 (*Preprint* hep-ex/0308035)
[4] Aaij R *et al.* (LHCb collaboration) 2014 *JHEP* **05** 069 (*Preprint* 1403.2888)
[5] Alves Jr A A *et al.* (LHCb) 2008 *JINST* **3** S08005
[6] Aaij R *et al.* (LHCb collaboration) 2015 *Int. J. Mod. Phys.* **A30** 1530022 (*Preprint* 1412.6352)
[7] Olive K A *et al.* (Particle Data Group) 2014 *Chin. Phys.* **C38** 090001
[8] Aaij R *et al.* (LHCb collaboration) 2016 *JHEP* **05** 081 (*Preprint* 1603.00413)
[9] Aaij R *et al.* (LHCb collaboration) 2014 *Phys. Rev.* **D90** 112004 (*Preprint* 1408.5373)
[10] Aaij R *et al.* (LHCb collaboration) 2016 *Phys. Lett.* **B759** 282 (*Preprint* 1603.02870)
[11] Aaij R *et al.* (LHCb collaboration) 2015 *JHEP* **09** 006 (*Preprint* 1505.03295)
[12] Di Donato C, Ricciardi G and Bigi I 2012 *Phys. Rev.* **D85** 013016 (*Preprint* 1105.3557)
[13] Aaij R *et al.* (LHCb collaboration) 2015 *JHEP* **10** 053 (*Preprint* 1508.00788)
[14] Bar-Shalom S, Eilam G and Yang Y D 2003 *Phys. Rev.* **D67** 014007 (*Preprint* hep-ph/0201244)
[15] Aaij R *et al.* (LHCb collaboration) 2016 *JHEP* **01** 012 (*Preprint* 1506.08634)
[16] Aaij R *et al.* (LHCb collaboration) 2013 *JHEP* **10** 143 (*Preprint* 1307.7648)