Searches for Λ_b^0 and Ξ_b^0 decays to $K_S^0 p\pi^-$ and $K_S^0 pK^-$ final states with first observation of the $\Lambda_b^0 \to K_S^0 p\pi^-$ decay

R. Silva Coutinho
on behalf of the LHCb collaboration
Department of Physics, University of Warwick,
Coventry, CV4 7AL, United Kingdom

A search for previously unobserved decays of beauty baryons to the final states $K_S^0 p\pi^-$ and $K_S^0 pK^-$ is reported. The analysis is based on a data sample corresponding to an integrated luminosity of $1.0\,\mathrm{fb}^{-1}$ of pp collisions recorded by the LHCb experiment. The $\Lambda_b^0 \to K_S^0 p\pi^-$ decay is observed for the first time with a significance of $8.6\,\sigma$, and a measurement is made of the CP asymmetry, which is consistent with zero.

1 Introduction

The study of bottom baryon decays is still at an early stage. Among the possible $J^P = \frac{1}{2}^+$ ground states, no hadronic three-body decay to a charmless final state had been observed [1]. These channels provide interesting possibilities to study hadronic decays and search for CP violation effects, in particular asymmetries in the phase-space [2,3]. In contrast to three-body neutral B meson decays to charmless final states containing K_S^0 mesons, conservation of baryon number allows CP violation searches in baryonic decays without the need to identify the flavour of the initial state, which is of considerable benefit for analysis in LHCb. In this paper [4], searches for Λ_b^0 and Ξ_b^0 baryon decays to final states containing a K_S^0 meson, a proton and either a kaon or a pion, are reported. Intermediate states containing charmed hadrons are also investigated: $\Lambda_b^0 \to \Lambda_c^+(K_S^0 p)\pi^-$, $\Lambda_b^0 \to \Lambda_c^+(K_S^0 p)K^-$ and $\Lambda_b^0 \to D_s^-(K_S^0 K^-)p$ decays. The results are based on an integrated luminosity of $1\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ collected by the LHCb detector. The LHCb experiment [5] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks.

2 Analysis strategy for charmless three-body b-baryon decays

All branching fractions are measured relative to the control channel $B^0 \to K_S^0 \pi^+\pi^-$, and rely on existing measurements of the ratio of fragmentation fractions $f_{\Lambda_b^0}/f_d$ [6]. The b hadron decays are reconstructed by combining two charged tracks with a K_S^0 candidate. The K_S^0 are reconstructed in the $\pi^+\pi^-$ final state, and are classified into two categories: candidates that have hits in the vertex detector and in the tracking stations downstream of the dipole magnet ("Long" or "LL"); pions with track segments not found in the vertex detector, which use only the tracking stations downstream of the vertex detector ("Downstream" or "DD").

An initial set of loose requirements is applied to filter the events selected by the trigger. Further separation of signal from combinatorial background is achieved with a multivariate algorithm trained for each K_S^0 type using as reference the control channel. Remaining sources of background are further suppressed using particle identification criteria. The Λ_b^0 and Ξ_b^0 signal regions of the unobserved modes were not examinated until the analysis procedure has been finalised in order to avoid any bias in the selection. The optimal values for the selection criteria are chosen using a figure-of-merit which maximises the signal visibility (in standard deviations) [7].

A multibody decay can be composed of several intermediate quasi-two-body states and a nonresonant contribution. This reflects on how the population of events in the phase-space is driven by the dynamics of the decay process. Hence, the correct determination of the efficiency variation across the phase-space is of crucial importance for branching fraction measurements. In modes with significant yields, the efficiency is obtained by weighting the observed data using the *sPlot* technique [8]. For unobserved modes, the selection efficiency corresponds to the simulated distribution variation across the phase-space, and a systematic uncertainty is assigned.

3 Results

The results of the unbinned extended maximum likelihood fits to the invariant mass distributions for $\Lambda_b^0 \to K_S^0 p h^-$ and $\Lambda_b^0 \to \Lambda_c^+(\pi^+ K_S^0)h^-$ candidates, separated for each K_S^0 category, are shown respectively in figures 1 and 2. The significance of the yields for the charmless decays is found to be $8.6\,\sigma$ and $2.1\,\sigma$ for $\Lambda_b^0 \to K_S^0 p\pi^-$ and $\Lambda_b^0 \to K_S^0 pK^-$ decays, respectively. Moreover, the recent observation of the $\Lambda_b^0 \to \Lambda_c^+(\pi^+ K_S^0)K^-$ channel is confirmed and no significant signal is seen for the other channels. Finally, the phase-space distribution for $\Lambda_b^0 \to K_S^0 p\pi^-$ decays, shown in figure 3, is obtained using the *sPlot* technique and applying event-by-event efficiency corrections based on the position of the decay in the phase-space. A first inspection indicates a structure at low $p\pi^-$ invariant mass which may originate from an excited nucleon state.

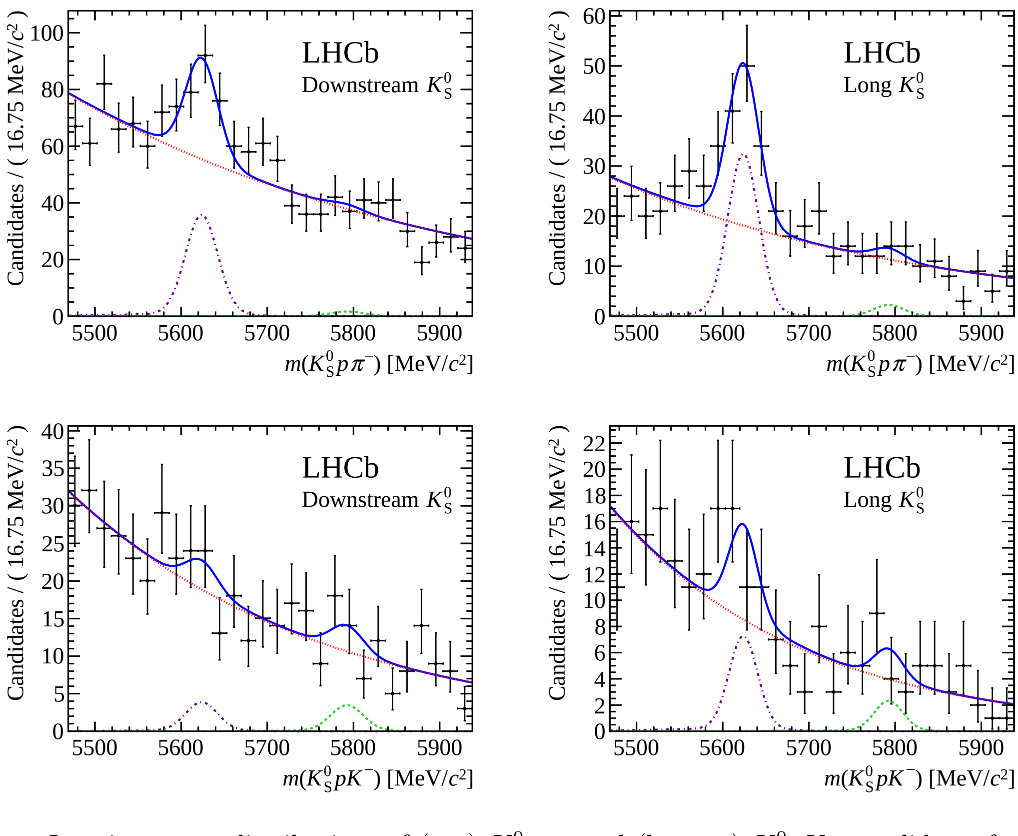

Figure 1 – Invariant mass distributions of (top) $K_S^0 p\pi^-$ and (bottom) $K_S^0 pK^-$ candidates for the (left) DD and (right) LL K_S^0 categories. Each significant component of the fit model is displayed: Λ_b^0 signal (violet dot-dashed), Ξ_b^0 signal (green dashed) and combinatorial background (red dotted). The overall fit is given by the solid blue line.

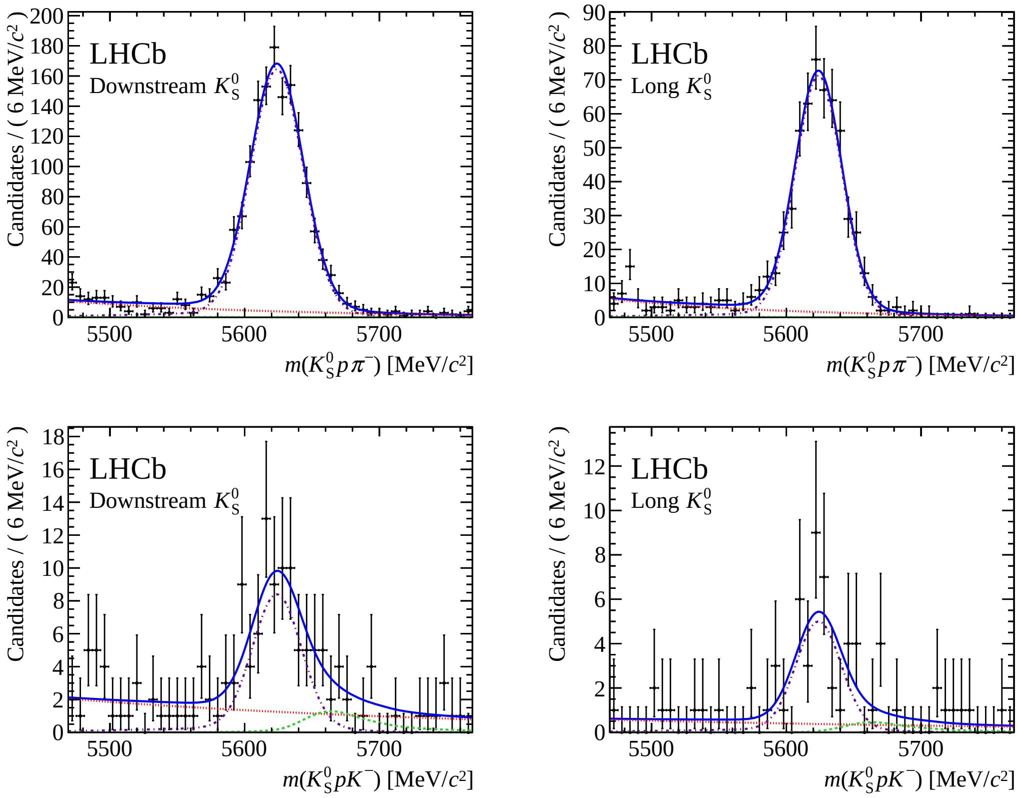

Figure 2 – Invariant mass distributions of (top) $\Lambda_b^0 \to \Lambda_c^+(\pi^+ K_S^0)\pi^-$ and (bottom) $\Lambda_b^0 \to \Lambda_c^+(\pi^+ K_S^0)K^-$ candidates for the (left) DD and (right) LL K_S^0 categories. Each significant component of the fit model is displayed: signal distributions (violet dot-dashed), signal cross-feed contributions (green dashed) and combinatorial background (red dotted). The overall fit is given by the solid blue line.

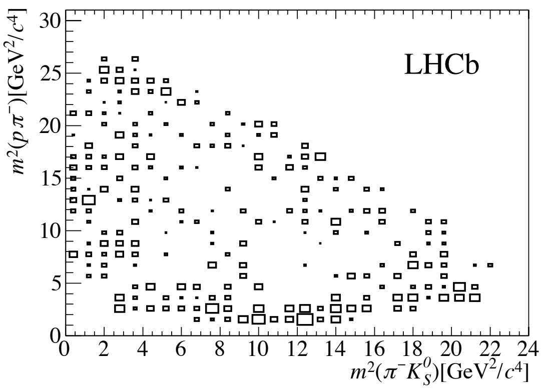

Figure 3 – Background-subtracted, efficiency-corrected phase-space distribution of $\Lambda_b^0 \to K_S^0 p\pi^-$ decays for DD and LL K_S^0 categories combined.

3.1 Branching fraction results

The absolute branching fractions are calculated using the measured branching fraction [1] of the normalisation channel $\mathcal{B}(B^0 \to K^0\pi^+\pi^-) = (4.96 \pm 0.20) \times 10^{-5}$. Each result is determined separately for each K_S^0 category and combined in a weighted average, where correlations in the systematic uncertainties are taken into account. Upper limits are placed on the unobserved modes by integrating the likelihood multiplied by a Bayesian prior, which is uniform in the region of positive branching fractions. The results are expressed in terms of final states containing either

K^0 or $\bar{K}^0$ mesons, according to the expectation for each decay,

$$
\begin{aligned}
\mathcal{B}(\Lambda_b^0 \to \bar{K}^0 p\pi^-) &= (1.26 \pm 0.19 \pm 0.09 \pm 0.34 \pm 0.05) \times 10^{-5}\,,\\
\mathcal{B}(\Lambda_b^0 \to K^0 pK^-) &< 3.5\ (4.0) \times 10^{-6} \ \text{ at } \ 90\,\%\ (95\,\%)\ \text{CL}\,,\\
f_{\Xi_b^0}/f_d \times \mathcal{B}(\Xi_b^0 \to \bar{K}^0 p\pi^-) &< 1.6\ (1.8) \times 10^{-6} \ \text{ at } \ 90\,\%\ (95\,\%)\ \text{CL}\,,\\
f_{\Xi_b^0}/f_d \times \mathcal{B}(\Xi_b^0 \to \bar{K}^0 pK^-) &< 1.1\ (1.2) \times 10^{-6} \ \text{ at } \ 90\,\%\ (95\,\%)\ \text{CL}\,,\\
\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) &= (5.97 \pm 0.28 \pm 0.34 \pm 0.70 \pm 0.24) \times 10^{-3}\,,\\
\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+K^-) &= (3.55 \pm 0.44 \pm 0.24 \pm 0.41 \pm 0.14) \times 10^{-4}\,,\\
\mathcal{B}(\Lambda_b^0 \to D_s^- p) &< 4.8\ (5.3) \times 10^{-4} \ \text{ at } \ 90\,\%\ (95\,\%)\ \text{CL}\,,
\end{aligned}
$$

where the uncertainties are statistical, systematic, from the ratio of fragmentation fractions $f_{\Lambda_b^0}/f_d$, and from the branching fraction of the normalisation channel, respectively.

3.2 Direct CP asymmetry

The significant signal observed for the $\Lambda_b^0 \to K_S^0 p\pi^-$ channel allows a measurement of its phase-space integrated CP asymmetry. To obtain the physical CP asymmetry, the raw asymmetry is obtained from the fit to data, and corrected by the production and detection asymmetries. These can be conveniently obtained from $\Lambda_b^0 \to \Lambda_c^+(\pi^+K_S^0)\pi^-$ decays, in which the expected CP violation is negligible. The phase-space integrated CP asymmetry is found to be

$$
\mathcal{A}^{CP}(\Lambda_b^0 \to \bar{K}^0 p\pi^-) = 0.22 \pm 0.13\,(\text{stat}) \pm 0.03\,(\text{syst})\,, \tag{1}
$$

which is consistent with zero.

4 Summary

Using a data sample collected by the LHCb experiment corresponding to an integrated luminosity of $1.0\,\text{fb}^{-1}$, searches for b-baryon decays to $K_S^0 p\pi^-$ and $K_S^0 pK^-$ are performed. The decay channel $\Lambda_b^0 \to K_S^0 p\pi^-$ is observed for the first time and its phase-space integrated CP asymmetry shows no significant deviation from zero. The first observation of a charmless three-body decay of a b baryon opens a new field of possible amplitude analyses and CP violation measurements that will be of great interest to study with larger data samples.

Acknowledgments

This work is funded in part by the European Research Council under FP7 and by the United Kingdom's Science and Technology Facilities Council.

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