

Results from LHCb in charmless b -baryon decays

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Since mostly unexplored, the heavy baryon sector is an interesting field where to search for new physics effects. Recent LHCb results in b -baryon decays to charmless final states are presented based on pp collision data collected in 2011 and 2012 at centre-of-mass energies of $\sqrt{s} = 7\text{TeV}$ and 8TeV , respectively. The total integrated luminosity collected is 3.0 fb^{-1} . New decays of b -baryons are presented and preliminary studies of CP violation are performed. The first evidence of CP violation in baryons is provided in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays by means of the triple-product correlation technique. All the other presented CP asymmetries are compatible with zero.

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1. Introduction

The ‘‘B-factories’’ BaBar and Belle have studied in detail the B^0 and B^\pm decays, however the heavy baryons sector (*i.e.* containing the b quark) still remains largely unexplored. Given the copious production of heavy baryons at the LHC, precision measurements have become possible in this field and the interest of scientific community is growing on this subject. Recently, studies of heavy baryons led to the measurement of $|V_{ub}|$ using $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$ decays [1], to the discovery of pentaquark using $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays [2] and also to the discoveries of $\Xi_b^{\prime-}$ and Ξ_b^{*0} baryonic states [3] and two orbitally excited Λ_b^{*0} states [4].

It is interesting to study baryon charmless decays, search new decay modes and measure their branching fraction, because in the Standard Model (SM) CP violation (CPV) is predicted to be particularly suppressed, as explained by the CKM flavour mixing mechanism. A significant excess of CPV with respect to the theoretical predictions would represent a proof of new physics beyond the SM. Within the mesonic sector, the CKM matrix in the SM describes the CPV results for B and K mesons. It is important to test CPV also in baryon decays to verify if the mechanism through which it is generated is the same as for mesons. This is a complementary test of the SM with respect to what has been already done with mesons. Indeed both mesons and baryons are governed by the same underlying short distance physics, with different spin and QCD structure, and it is interesting to compare the two results.

Four recent results from LHCb in the field of charmless b -hadron decays are here reviewed. All the analysis are performed on the full Run I datasample corresponding to an integrated luminosity of 3.0 fb^{-1} .

2. Study of $\Lambda_b^0(\Xi_b^0) \rightarrow \Lambda h^+ h^{(\prime)-}$ decays

An inclusive measurement of $\Lambda_b^0 \rightarrow \Lambda h^+ h^{(\prime)-}$ decays, where $h, h' \in \{K, \pi\}$, has been performed [5]. The analysis uses the abundant $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi$ control mode. The result of the maximum likelihood mass fit is shown in Figure 1. Signals for $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ and $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$ are ob-

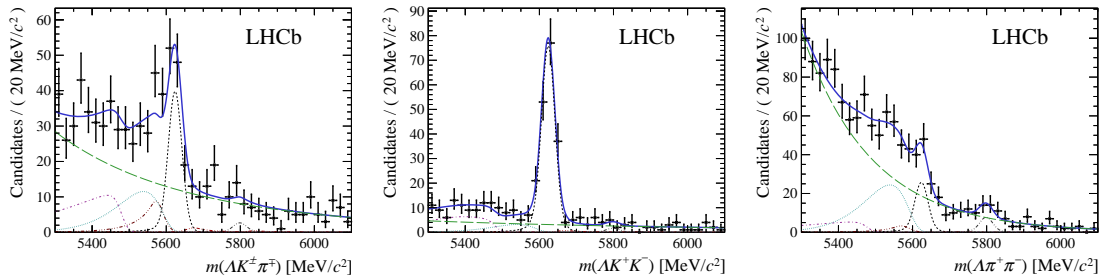


Figure 1: Results of the fit for the (left) $\Lambda K^\pm \pi^\pm$, (middle) $\Lambda K^+ K^-$ and (right) $\Lambda \pi^+ \pi^-$ final states. Superimposed on the data are the total result of the fit as a solid blue line, the $\Lambda_b^0(\Xi_b^0)$ signal contribution as a short-dashed black (double 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 with either a missing neutral pion as a dot-dashed purple line or a missing soft photon as a dotted cyan line.

served with a significance of 15.8σ and 8.1σ , respectively, where the systematic uncertainties

are also taken into account. There is strong evidence for $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$ (4.7σ) while the significance of the other modes is less than 3σ . The branching fractions are measured to be $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-) = (5.6 \pm 0.8 \pm 0.8 \pm 0.7) \times 10^{-6}$, $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda K^+ K^-) = (15.9 \pm 1.2 \pm 1.2 \pm 2.0) \times 10^{-6}$ and $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-) = (4.6 \pm 1.2 \pm 1.4 \pm 0.6) \times 10^{-6}$ where the first uncertainty is statistical, the second systematic and the third one is due to the precision with which the normalisation channel branching fraction is known. The significant yields observed in the $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ and $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$ decays allows for the determination of phase-space-integrated CP asymmetries. Those asymmetries are measured with respect to the control mode in order to cancel at first order the Λ_b^0 production and final state detection asymmetries. The CP asymmetries are then found to be $\mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-) = -0.53 \pm 0.23 \pm 0.11$ and $\mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+ K^-) = -0.28 \pm 0.10 \pm 0.07$ where the uncertainties are statistical and systematic, respectively. These are both consistent with zero, though will be interesting with larger dataset sizes.

3. Study of $\Lambda_b^0 \rightarrow \Lambda \phi$ decays

In addition, a search for the exclusive mode $\Lambda_b^0 \rightarrow \Lambda \phi$ is performed with LHCb data [6]. The approach is to fit in the three invariant mass dimensions ($M_{K^+K^- p\pi^-}, M_{K^+K^-}, M_{p\pi^-}$) depending if Λ baryon decayed inside (long) or outside (downstream) the vertex locator. This then allows for the different selection efficiencies and resolutions to be accounted for. All the projections are shown in Figure 2. The mass fit results in a yield of 89 ± 13 . The signal significance is

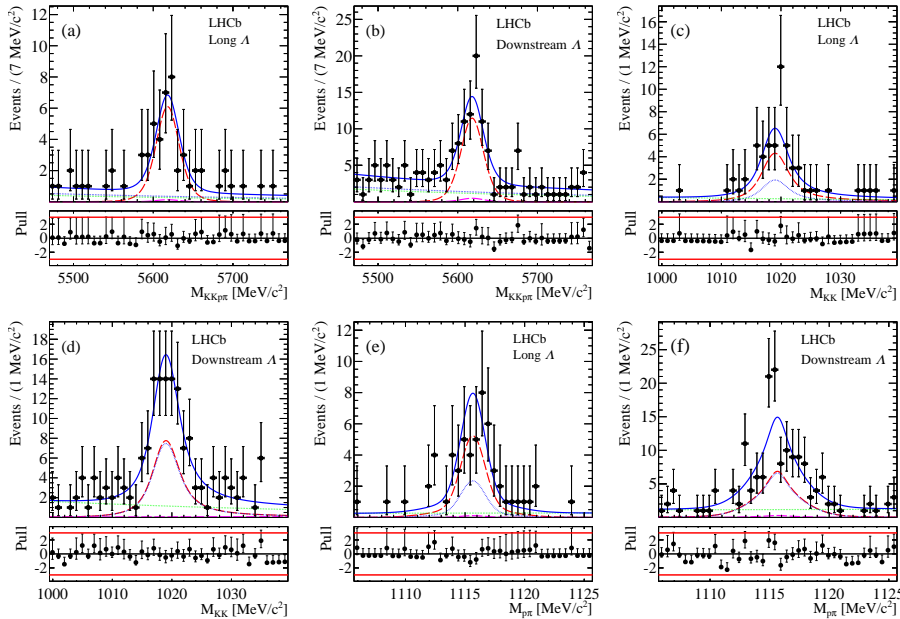


Figure 2: Fit projections to the $K^+K^- p\pi^-$ invariant mass in the (a) long and (b) downstream datasets, the K^+K^- invariant mass in the (c) long and (d) downstream datasets, and the $p\pi^-$ invariant mass in the (e) long and (f) downstream datasets. The total fit projection is given by the blue solid line. The blue and green dotted lines represents the $\phi + \Lambda$ and pure combinatorial fit components, respectively. The red and magenta dashed lines represent the $\Lambda_b^0 \rightarrow \Lambda \phi$ signal and the $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ non-resonant components, respectively. Black points represent the data. Data uncertainties are Poisson 68% confidence intervals.

calculated to be 5.9σ , including systematics uncertainties, representing a first observation. The measured branching fraction is $(5.18 \pm 1.04 \pm 0.35_{-0.62}^{+0.67}) \times 10^{-6}$, where the first uncertainty is statistical, the second is systematic, and the third is related to external inputs. Triple products asymmetries can also be computed in the $\Lambda_b^0 \rightarrow \Lambda \phi$ decay due to the spin structure of the decay. These have been performed following the formalism in [7]. Four triple products are possible, corresponding to $\cos \Phi_{\vec{n}_{\Lambda, \phi}}$ and $\sin \Phi_{\vec{n}_{\Lambda, \phi}}$, where $\Phi_{\vec{n}_{\Lambda, \phi}}$ is the azimuthal angle of the resonance decay planes with normal vector $\vec{n}_{\Lambda, \phi}$. The asymmetries $A_{\Lambda}^{c,s}$ and $A_{\phi}^{c,s}$, where c and s correspond to the cosine and sine respectively, are sensitive to CPV and measured to be $A_{\Lambda}^c = -0.22 \pm 0.12(\text{stat.}) \pm 0.06(\text{syst.})$, $A_{\Lambda}^s = 0.13 \pm 0.12(\text{stat.}) \pm 0.05(\text{syst.})$, $A_{\phi}^c = -0.01 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$ and $A_{\phi}^s = -0.07 \pm 0.12(\text{stat.}) \pm 0.01(\text{syst.})$, where systematic contributions mainly arise from the mass model. Everything is consistent with zero and no CPV evidence is found.

4. Study of $\Lambda_b^0 \rightarrow p h^- h^+ h^-$ decays

Using data from LHCb experiment CPV and P-violating (PV) asymmetries are studied in the decay angle distributions of $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$ [8]. In this analysis, scalar triple product of final-state particle momenta in the Λ_b^0 centre-of-mass frame are studied. These are defined as $C_{\hat{T}} = \mathbf{p}_p \cdot (\mathbf{p}_{h_1^-} \times \mathbf{p}_{h_2^+})$ for Λ_b^0 and $\bar{C}_{\hat{T}} = \mathbf{p}_{\bar{p}} \cdot (\mathbf{p}_{h_1^+} \times \mathbf{p}_{h_2^-})$ for $\bar{\Lambda}_b^0$, where h_1 and h_2 are final-state hadrons: $h_1 = \pi$ and $h_2 = K$ for $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$ and $h_1 = h_2 = \pi$ for $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$. In the latter case there is an inherent ambiguity in the choice of the pion for h_1 that is resolved by taking that with the larger momentum in the Λ_b^0 rest frame, referred to as π_{fast} . $A_{\hat{T}}$ ($\bar{A}_{\hat{T}}$) asymmetry can be defined based on the $C_{\hat{T}}$ ($-\bar{C}_{\hat{T}}$) sign for Λ_b^0 ($\bar{\Lambda}_b^0$). The sum $a_P^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$ is sensitive to PV while the difference $a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$ to CPV effects. The signal yields of $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$ are $6,646 \pm 105$ and $1,030 \pm 56$, respectively, and are extracted from fit shown in Figure 3, where the contribution of background also appear. This is the first observation of these decay modes. We measure the asymmetries

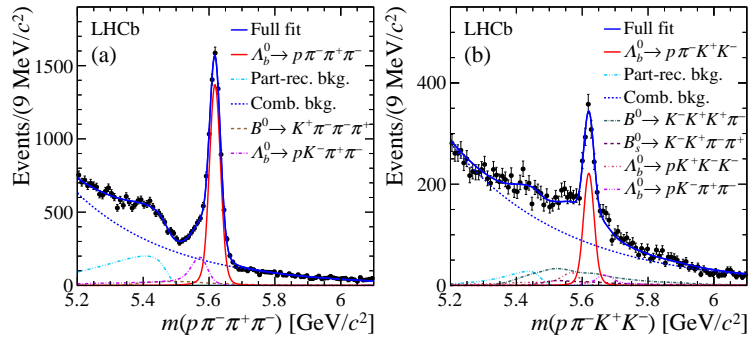


Figure 3: Reconstructed invariant mass fits for (a) $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ and (b) $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$ decays used to extract the signal yields. A fit is overlaid on the top of the data points as a blue line, with red solid (signal) and dotted lines (background) describing the projections of the fit for different contribution.

integrated in phase space obtaining $a_{CP}^{\hat{T}\text{-odd}} = 1.15 \pm 1.45 \pm 0.32(-0.93 \pm 4.54 \pm 0.42)$ and $a_P^{\hat{T}\text{-odd}} = -3.71 \pm 1.45 \pm 0.32(3.62 \pm 4.54 \pm 0.42)$ for $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ ($\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$), consistent with CP and P symmetry hypothesis. The asymmetries are also measured in region of phase space, with

different binning scheme to isolate regions according to the dominant resonant contributions and to exploits in more detail the interference of contributions which could be visible as a function of the angle Φ between the decay planes formed by the $p\pi_{fast}^-$ and the $p\pi_{slow}^-$ systems. The combined significance for the two binning schemes for CPV in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays is determined by means of a permutation test, taking into account correlations among the results. An overall p -value of 9.8×10^{-4} (3.3σ) is obtained for the CP -symmetry hypothesis, including systematic uncertainties. This represents the first evidence for CPV in the baryon sector. The observables measured in phase space for $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$ are consistent with CP and P symmetry.

5. Study of $\Xi_b^- \rightarrow ph^-h'^-$ decays

Large CPV effects have been observed in regions of the phase space of $B^- \rightarrow h^+h'^-h''-$ mesonic decays [9–11]. The baryonic partner is represented by $\Xi_b^- (\Omega_b^-) \rightarrow ph^-h'^-$ and it is therefore of great interest to search for these charmless b -baryon decays that may be used to investigate CPV effects. For the first time these decays are searched with the LHCb detector [12]. The result of the fit after the selection is shown in Figure 4. The decay $\Xi_b^- \rightarrow pK^-K^-$ is observed with a significance

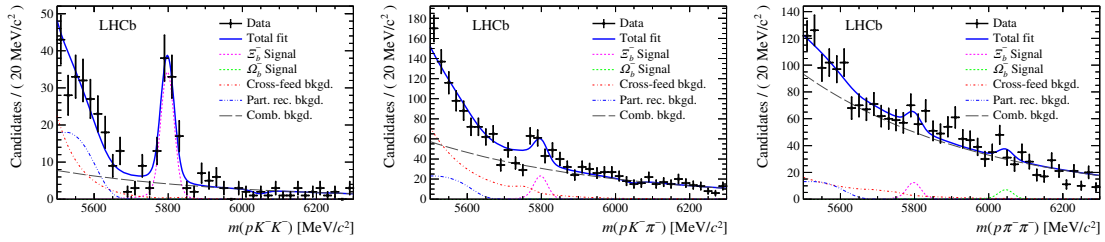


Figure 4: Mass distributions for b -hadron candidates in the (left) pK^-K^- , (center) $pK^-\pi^-$, (right) $p\pi^-\pi^-$. Results of the fits are shown with dark blue solid lines. Signals for $\Xi_b^- (\Omega_b^-)$ decays are shown with pink (light green) dashed lines, combinatorial backgrounds are shown with grey long-dashed lines, cross-feed backgrounds are shown with red dot-dashed lines, and partially reconstructed background are shown with dark blue double-dot-dashed lines.

of 8.7σ , and evidence at the level of 3.4σ is found for the $\Xi_b^- \rightarrow pK^-\pi^-$ decay. This is the first observation of a Ξ_b decay to a charmless final state. The measured branching ratio are

$$\frac{f_{\Xi_b^-} \mathcal{B}(\Xi_b^- \rightarrow pK^-K^-)}{f_u \mathcal{B}(B^- \rightarrow K^+K^-K^-)} = (2.65 \pm 0.35 \pm 0.47) \times 10^{-3},$$

$$\frac{\mathcal{B}(\Xi_b^- \rightarrow pK^-\pi^-)}{\mathcal{B}(\Xi_b^- \rightarrow pK^-K^-)} = 0.98 \pm 0.27 \pm 0.09$$

where the decay $\Xi_b^- \rightarrow pK^-K^-$ is measured with respect to the control sample $B^- \rightarrow K^+K^-K^-$. All the other Ξ_b^- and Ω_b^- signals are not statistically significant. For those modes an upper limit at 90 (95)% CL is given

$$\frac{f_{\Xi_b^-} \mathcal{B}(\Xi_b^- \rightarrow p\pi^-\pi^-)}{f_u \mathcal{B}(B^- \rightarrow K^+K^-K^-)} < 1.47(16.6) \times 10^{-4}, \quad \frac{f_{\Omega_b^-} \mathcal{B}(\Omega_b^- \rightarrow pK^-K^-)}{f_u \mathcal{B}(B^- \rightarrow K^+K^-K^-)} < 1.8(2.2) \times 10^{-4},$$

$$\frac{f_{\Omega_b^-} \mathcal{B}(\Omega_b^- \rightarrow pK^-\pi^-)}{f_u \mathcal{B}(B^- \rightarrow K^+K^-K^-)} < 5.1(6.2) \times 10^{-4}, \quad \frac{f_{\Omega_b^-} \mathcal{B}(\Omega_b^- \rightarrow p\pi^-\pi^-)}{f_u \mathcal{B}(B^- \rightarrow K^+K^-K^-)} < 10.9(12.4) \times 10^{-4}.$$

6. Conclusions

Four recent results from LHCb in the field of charmless b -baryon decays have been presented. The decay modes $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$, $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda \phi$ are observed for the first time and their branching fraction is measured. The phase-space integrated CP asymmetry parameters are measured for the $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ and $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$ decays, while several triple-product asymmetries are measured for the $\Lambda_b^0 \rightarrow \Lambda \phi$ decay. All these asymmetries are found to be compatible with zero. Triple-product asymmetries are measured for $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$ and $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ decays, observed for the first time, both integrated in phase space and in region of phase space. A deviation at 3.3σ from the CP symmetry hypothesis is found in regions of phase space for $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ decay. This represents the first evidence of CPV in baryon decays. All the other measured asymmetries don't show any deviation. The first observation of $\Xi_b^- \rightarrow p K^- K^-$ decay and the first evidence for $\Xi_b^- \rightarrow p K^- \pi^-$ decay have been obtained. This is the first observation of a Ξ_b decay to a charmless final state. These modes may be used in future to search for CP asymmetries in the b -baryon sector.

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