Observation of the decay \( \Lambda_b^0 \to \Lambda_c^+ p \overline{p} \pi^- \)

Citation for published version:
Clarke, P, Cowan, G, Eisenhardt, S, Gambetta, S, Muheim, F, Needham, M, Playfer, S, Collaboration, LHC & Pappagallo, M 2018, 'Observation of the decay \( \Lambda_b^0 \to \Lambda_c^+ p \overline{p} \pi^- \)', Physics Letters B, vol. B784, pp. 101-111. https://doi.org/10.1016/j.physletb.2018.07.033

Digital Object Identifier (DOI):
10.1016/j.physletb.2018.07.033

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Physics Letters B

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$

LHCb Collaboration

**A R T I C L E   I N F O**

Article history:
Received 27 April 2018
Received in revised form 29 June 2018
Accepted 17 July 2018
Available online 25 July 2018

Editor: W.-D. Schlatter

**A B S T R A C T**

The decay $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ is observed using pp collision data collected with the LHCb detector at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb$^{-1}$. The ratio of branching fractions between $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decays is measured to be $\text{BR}(\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-) / \text{BR}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 0.0540 \pm 0.0023 \pm 0.0032$.

Two resonant structures are observed in the $\Lambda_c^+ \pi^-$ mass spectrum of the $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ decays, corresponding to the $\Sigma_c(2455)^0$ and $\Sigma_c(2520)^0$ states. The ratios of branching fractions with respect to the decay $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ are

$$\frac{\text{BR}(\Lambda_b^0 \to \Sigma_c^0 p \bar{p}) \times \text{BR}(\Sigma_c^0 \to \Lambda_c^+ \pi^-)}{\text{BR}(\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-)} = 0.089 \pm 0.015 \pm 0.006,$$

$$\frac{\text{BR}(\Lambda_b^0 \to \Sigma_c^0 p \bar{p}) \times \text{BR}(\Sigma_c^0 \to \Lambda_c^+ \pi^-)}{\text{BR}(\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-)} = 0.119 \pm 0.020 \pm 0.014.$$ 

In all of the above results, the first uncertainty is statistical and the second is systematic. The phase space is also examined for the presence of dibaryon resonances. No evidence for such resonances is found.

© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP$^3$.

1. Introduction

The quark model of Gell-Mann [1] and Zweig [2] classifies mesons ($qq$) and baryons ($qqq$) into multiplets, and also allows for hadrons with more than the minimal quark contents. In 2015, LHCb observed two pentaquark states in the decay $\Lambda_b^0 \to J/\psi p K^-$ [3]. In the decay channel $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$, charmed dibaryon resonant states could be present. As discussed in Ref. [4], such states could manifest via the decay $\Lambda_b^0 \to \bar{p} + [cd][ud][ud] = \bar{p} + D_s^0$, where $D_s^0$ is the dibaryon state with a mass below 4682 MeV/c$^2$. The subsequent decay of the $D_s^0$ dibaryon could proceed either via quark rearrangement to the final state $p \Sigma_c^0$, with $\Sigma_c^0 \to \Lambda_c^+ \pi^-$, or via string breaking to the final state $p \Sigma_c^0(\bar{u}(cd)[ud])$, which could involve a lighter, yet undiscovered $\Xi_b^0$ pentaquark state, $\Xi_b^0 \to p \Sigma_c^0(\bar{u}(cd)[ud])$, with $p \Sigma_c^0 \to \Lambda_c^+ \pi^-$. The discovery of any of these decay modes would test the predictions of quantum chromodynamics and the fundamental workings of the Standard Model.

In this Letter, the first observation of the decay $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$, referred to as the signal channel, is reported. A measurement is made of its branching fraction relative to the normalisation channel $\Lambda_b^0 \to \Lambda_c^+ \pi^-$. Resonance structures within the $\Lambda_c^+ p \bar{p} \pi^-$ system are also investigated. While no evidence for dibaryon resonances is found, significant contributions from the $\Sigma_c(2455)^0$ and $\Sigma_c(2520)^0$ resonances are found in the $\Lambda_c^+ \pi^-$ invariant mass spectrum. The ratios of branching fractions between decays via these resonances, hereinafter denoted as $\Sigma_c^0$ and $\Sigma_c^0$ and the $\Lambda_c^+ p \bar{p} \pi^-$ inclusive decay are also reported. The measurements in this Letter are based on a data sample of pp collisions collected with the LHCb detector at centre-of-mass energies of $\sqrt{s} = 7$ TeV in 2011 and $\sqrt{s} = 8$ TeV in 2012, corresponding to an integrated luminosity of 3 fb$^{-1}$.

2. Detector and simulation

The LHCb detector [5,6] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip ver-
t = m_\phi L/p$, is required to be greater than 0.2 ps, where $m_\phi$ is the mass, $L$ is the decay length and $p$ is the momentum of the $Λ^0$ candidate. The $Λ^+_c$ candidate is also required to have at least one final-state particle in the decay chain with $p_T > 1.7$ GeV/c, $p > 10$ GeV/c, and have at least one track significantly inconsistent with originating from the associated PV by requiring the track to have $d_0 > 16$. Final-state tracks of signal and normalisation channel candidates must pass strict particle-identification requirements based on the RICH detectors, calorimeters and muon stations. A constrained fit [16] is applied to the candidate decay chain for both the signal and the normalisation channels, requiring the $Λ^0$ candidate to come from the associated PV and constraining the $Λ^+_c$ particle to its known mass [15]. In the case of the search of the resonant contributions, the mass of the $Λ^0$ candidate is also constrained to the known mass [15].

Trigger signals are associated with reconstructed particles from the decays of the signal channel or of the normalisation channel. Selection requirements can therefore be made on the trigger selection itself and on whether the decision was due to the reconstructed candidate decay, other particles produced in the $pp$ collision, or a combination of the two. This association makes it possible to use a data-driven method for the correction and systematic uncertainty estimation on the trigger efficiencies [7]. To take advantage of the similarity between the signal and the normalisation channels, which helps to minimize the systematic uncertainty on the ratio of their efficiencies, candidates are classified in one of the following two hardware trigger categories. In the first category, called Triggered On Signal (TOS), the candidate must include a hadron consistent with originating from the decay of a $Λ^+_c$ candidate and which deposited enough transverse energy in the calorimeter to satisfy the hardware trigger requirements. The typical value of the transverse energy threshold is around $3.5$ GeV/c$^2$. As the $Λ^+_c$ baryon is a $Λ^0$ decay product for both the signal and the normalisation channels, this choice minimizes the difference between the $Λ^0$ decay modes. The second category, called Triggered Independent of Signal (TIS), comprises events which satisfied the hardware trigger through signatures unassociated with the complete $Λ^0$ decay chains, either due to a muon with high $p_T$, or a hadron, photon, or electron with high transverse energy deposited in the calorimeters. The efficiencies of the TIS and TOS requirements are different, so the data are divided into two statistically independent samples, one TIS, and the other TOS and not TIS, which will be referred to as TOS for the rest of this Letter.

The so-called cross-feed backgrounds, contributing under the peak of the invariant mass of the normalisation channel or of the signal channel from the $B^0(D^+ \rightarrow D^+ \phi \pi^- \pi^+)$ and $B^0(D^0 \rightarrow D^0 \phi \pi^- \pi^+)$ decays, respectively, with $D^+(D^+_s) \rightarrow K^+ K^- \pi^+$ or $D^0 \rightarrow K^- \pi^+ \pi^0$, where either the kaon or pion is misidentified as a proton, are explicitly vetoed when both of the following two conditions are satisfied. First, the mass hypothesis of the proton from the $Λ^+_c$ candidate is replaced with either the kaon or pion hypothesis, and the resulting invariant mass of the combination is consistent with the known $D^+(D^+_s)$ mass [15] within ±15 MeV/c$^2$. Second, the invariant mass of the $Λ^+_c$ candidate is set to the known $D^+(D^+_s)$ mass [15], and the resulting invariant mass of the $Λ^0$ candidate is consistent with the known $B^0(D^0)$ mass [15] within ±25 MeV/c$^2$ for $Λ^0 \rightarrow Λ^+_c p \pi^- \pi^-$ decays, and within ±45 MeV/c$^2$ for $Λ^0 \rightarrow Λ^+_c \pi^- \pi^-$ decays.

Further background reduction is achieved using a multivariate analysis based on a gradient boosted decision tree (BDTG) [17]. The BDTG is trained using twelve variables: the vertex-fit quality of the $Λ^+_c$ and $Λ^0$ candidates, the decay-vertex displacement along the beamline between the $Λ^0$ and $Λ^+_c$ candidates, the displacement between the decay vertex of the $Λ^0$ candidate and
the associated PV, the $\chi^2_0$ of the $\Lambda_b^0$ candidate, the angle between the reconstructed $\Lambda_b^0$ momentum and the direction of flight from the associated PV to the decay vertex, the smallest $p_t$ and smallest $\chi^2_0$ among the three $\Lambda_b^0$ decay products, the $p_t$ and $\chi^2_0$ of the pion originating directly from the $\Lambda_b^0$ decay, and the smallest $p_t$ and smallest $\chi^2_0$ between the $p$ and $\bar{p}$ originating directly from the $\Lambda_b^0$ decay. The BDTG training is performed using simulated samples for the signal, and data distributions for the background, with reconstructed invariant mass well above the known $\Lambda_b^0$ mass [15]. Cross-feed backgrounds from the decays $\Lambda_b^0 \rightarrow \Lambda^+_b K^- \pi^-$, $\Phi^0 \rightarrow \Lambda^+_b \pi^+ \pi^-$ and $\Phi^0 \rightarrow \Lambda^+_b \bar{p} K^+ \pi^-$ are explicitly vetoed during the BDTG-training process by requiring the difference between the reconstructed $b$-hadron mass and its known mass to be greater than $\pm 30$ MeV/$c^2$. The BDTG selection is optimized for the figure of merit $S/\sqrt{S+B}$, where $S$ and $B$ are the expected signal and background yields within $\pm 30$ MeV/$c^2$ of the known $\Lambda_b^0$ mass [15]. The initial value of $S$ and $B$ without BDTG selection is obtained from the $\Lambda_b^0$ mass spectrum in data. No improvement in the normalisation channel is found using a similar procedure, therefore no BDTG selection is applied. A systematic uncertainty is assessed for this choice in Section 6.

Due to the large number of final-state particles in the $\Lambda_b^0$ decays, particles with the same charge may share track segments, representing a possible background. These tracks are referred to as clones, and are suppressed by requiring that the opening angle between any same-charged tracks in the candidate is larger than 0.5 mrad. This selection removes 2% of candidates in the signal sample and 0.1% in the normalisation sample. If multiple $\Lambda_b^0$ candidates are reconstructed in one single event, one candidate is chosen at random in the following two cases. First, if the proton from the $\Lambda_b^0$ decays is exchanged with that directly from the $\Lambda_b^0$ decays, forming two candidates with nearly the same $\Lambda_b^0$ mass. Second, if a track from one candidate shares a segment with a track from another candidate. With these criteria, 2.5% of candidates in the signal sample and 0.1% in the normalisation sample are vetoed. After these selections, 0.8% of events in the signal sample and 0.2% in the normalisation sample contain multiple $\Lambda_b^0$ candidates. These remaining multiple candidates mainly originate from the random combinations of the final-state tracks, and have a negligible influence on the estimation of the signal yields. No further vetoes on these candidates are applied.

4. Efficiencies

The total efficiencies of the signal and the normalisation decays are given by

$$\epsilon_{total} = \epsilon_a \cdot \epsilon_{recon} \cdot \epsilon_{sel} \cdot \epsilon_{trig} \cdot \epsilon_{PID}$$

where $\epsilon_a$ represents the geometrical acceptance of the LHCb detector, $\epsilon_{recon} \cdot \epsilon_{sel}$ is the efficiency of reconstruction and selection calculated on candidates in the acceptance, $\epsilon_{trig}$ is the trigger efficiency of the selected candidates, and $\epsilon_{PID}$ is the particle-identification efficiency. All efficiencies except $\epsilon_{PID}$ and $\epsilon_{trig}$ are determined from simulation. The particle-identification efficiency is determined from calibration data specific to each data-taking year, binned in momentum and pseudorapidity of the track in question, as well as in the multiplicity of the event [10]. The trigger efficiency is determined from a combination of simulation and data-driven techniques where the agreement between data and simulation is explicitly verified using the normalisation sample satisfying the TIS requirement. All efficiencies are calculated separately for the TIS and TOS trigger samples, and for data-taking year, due to the difference in centre-of-mass energies.

Agreement between data and simulation is improved by applying a per-candidate weight to the $p_t$ and rapidity, $y$, of the $\Lambda_b^0$ baryon in simulated events to match the normalisation sample in the TIS category, which is largely independent of trigger conditions. The $p_t$ and $y$ distributions of $\Lambda_b^0$ produced in $pp$ collision are identical for the signal and the normalisation channels, so the same per-candidate weights are applied to the signal sample. The simulated $\chi^2_0$ of the final-state particles and the vertex-fit $\chi^2$ of $\Lambda_b^0$ candidates are weighted to reproduce the data distributions. The ratio between the efficiencies of the signal and the normalisation channels, $\epsilon_s$, is $(10.00 \pm 0.12)%$ for the TIS sample and $(11.39 \pm 0.22)%$ for the TOS sample, including uncertainties due to the limited size of the simulated sample.

5. Fit model and the ratio of branching fractions

The yields in both the signal and the normalisation channels are determined from an unbinned extended maximum-likelihood fit to the corresponding invariant-mass spectra with both the TIS and TOS samples combined. The signal is modelled by a sum of two Crystal Ball functions [19] with a common mean of the Gaussian core, and with the tail parameters fixed from simulation. For both the signal and the normalisation channels, the background from random combinations of final-state particles is described by an exponential function, whose parameters are left free in the fits and are independent between the signal and the normalisation channels. For the normalisation channel, background from the $\Lambda_b^0 \rightarrow \Lambda^+_b \rho^- \pi^+$ decays, with $\rho^- \rightarrow \pi^- \pi^0$ is modelled by the convolution of an empirical threshold function with a Gaussian resolution. The contribution due to misidentification of the kaon to pion from $\Lambda_b^0 \rightarrow \Lambda^+_b K^-$ is modelled by a sum of two Crystal Ball functions. The parameters of these two background sources are taken from simulation. The fits to the invariant-mass distributions for the signal and the normalisation channels are shown in Fig. 1. In this figure, the TIS and TOS samples are combined. From these fits, 926 ± 43 $\Lambda_b^0 \rightarrow \Lambda^+_b p \bar{p} \pi^-$ and $(167.00 \pm 0.50) \times 10^3$ $\Lambda_b^0 \rightarrow \Lambda^+_b \pi^- \pi^-$ decays are observed.

To determine the ratio of branching fractions $\frac{B(\Lambda_b^0 \rightarrow \Lambda^+_b \rho^- \pi^+)}{B(\Lambda_b^0 \rightarrow \Lambda^+_b \pi^- \pi^-)}$, indicated in the following by $B_r$, a simultaneous fit is performed to the signal and the normalisation channels, each divided into the two independent trigger categories. The yield of the normalisation sample, $N(\Lambda_b^0 \rightarrow \Lambda^+_b \pi^- \pi^-)$, is a free parameter in the fits, whereas the yield of the signal sample is calculated as $N(\Lambda_b^0 \rightarrow \Lambda^+_b \rho^- \pi^+) = B_r \times \epsilon_s \times N(\Lambda_b^0 \rightarrow \Lambda^+_b \pi^- \pi^-)$, where $\epsilon_s$ is the ratio between the total efficiency of the $\Lambda_b^0 \rightarrow \Lambda^+_b \rho^- \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda^+_b \pi^- \pi^-$ decays. The ratio of branching fractions $B_r$ is the same for the TIS and TOS subsamples and is measured to be $B_r = 0.0542 \pm 0.0023$. The corresponding signal yields are 677 ± 29 for the TIS subsample and 259 ± 11 for the TOS subsample; the yields in the normalisation sample are $(124.9 \pm 0.4) \times 10^3$ for the TIS subsample and $(41.9 \pm 0.2) \times 10^3$ for the TOS subsample.

6. Systematic uncertainties

The systematic uncertainties on the measurement of the ratio of branching fractions are listed in Table 1. The total systematic uncertainty is determined from the sum in quadrature of all terms. First, the uncertainty related to the background modelling is considered. In the signal sample, the exponential function is replaced with a second-order polynomial for the background component. For the normalisation channel, the model is varied by using the sum of two exponential functions. The resulting uncertainty on the ratio of branching fractions is 0.6%. The uncertainties due to the $\Lambda_b^0 \rightarrow \Lambda^+_b K^- \pi^+$ shape parameters are assessed by increasing the
width of the Crystal Ball functions by 10%, corresponding to two standard deviations, resulting in a change of 0.1%. The uncertainty due to the $\Lambda_c^0 \to \Lambda_c^+ \rho^-$ contribution is estimated by varying the shape parameters by one standard deviation, resulting in an uncertainty of 0.4%. The total uncertainty on the ratio of the branching fractions due to the background modelling is 0.7%.

The signal-model parameterization is changed to a single Hypatia function [20], where the mean and width are allowed to float and all other parameters are taken from simulation, resulting in an uncertainty of 0.1%.

The uncertainty on the relative efficiency of the particle identification is assessed by generating pseudoexperiments. For each pseudoexperiment, efficiencies in different momentum, pseudorapidity and multiplicity bins are determined from independent Gaussian distributions with mean values equal to the nominal efficiencies and widths corresponding to their uncertainties. This procedure is repeated 1000 times, and the width of the resulting efficiency is taken as the systematic uncertainty. This procedure, performed separately for the TIS and TOS samples, results in a 0.13% uncertainty for both samples. Binning effects on the efficiency are estimated by halving the bin size of the momentum distributions, resulting in a relative change of 0.2% for the TIS sample and 0.1% for the TOS sample. The total uncertainty on the relative efficiency for the TIS and TOS samples is 0.24% and 0.16%, respectively, corresponding to an uncertainty of 0.3% on the ratio of the branching fractions.

Tracking efficiencies are determined with simulated events weighted to match the kinematic properties of dedicated calibration samples. The weights are determined as a function of the kinematic variables, separately for each data-taking year [21]. The kinematic properties of the $\Lambda_c^+$ decay products are similar for the signal and the normalisation samples and therefore provide minor contributions to the total tracking efficiency ratio. The dominant contribution to the systematic uncertainty comes from the knowledge of the $p$ and $\bar{p}$ tracking efficiencies, whose systematic uncertainties are fully correlated. The efficiency correction procedure gives a change in efficiency of 2.0% for the TIS sample and 1.4% for the TOS sample, yielding a total correction factor of 0.985 for the ratio of branching fractions, and a systematic uncertainty of 0.4% for each of the $p$ and $\bar{p}$ mainly stemming from the finite size of the calibration sample [21].

Due to distinct trigger requirements, the kinematic acceptance of the calibration samples differs slightly from the signal and the normalisation channels. A nonnegligible fraction of candidates have final-state particles in a kinematic range outside of the regions covered by the calibration samples. About 20% of the candidates from both channels fall in this category due to the low-momentum pion from the $\Lambda_c^+$ decay. In addition, 10% of the candidates from the signal channel are also affected, mainly due to the pion originating from the $\Lambda_c^0$ decay. For all of these outside-range candidates, the efficiency correction in the nearest available bin is used. As the effects for $\Lambda_c^+$ decays cancel in the relative efficiency, only the additional 10% candidates in the signal channel contribute a 0.7% uncertainty on the relative efficiency.

Hadrronic interactions with the LHCb detector contribute an additional uncertainty of 2.2% on the ratio of the branching fractions.

---

### Table 1

Summary of systematic uncertainties and correction factors to the ratio of branching fractions measurement. All uncertainties are given as a percentage of the ratio of branching fractions.

| Source                                           | Uncertainty (%) | Correction factor |
|--------------------------------------------------|-----------------|------------------|
| Background fit model                             | 0.7             | –                |
| Signal fit model                                 | 0.1             | –                |
| PID efficiency                                   | 0.3             | –                |
| Tracking efficiency calibration                  | 0.8             | 0.985            |
| Kinematic range of final-state tracks            | 0.7             | –                |
| Hadron interaction                               | 4.4             | –                |
| $p_T$, $\gamma$ weighting                        | 1.0             | –                |
| Trigger efficiency                               | 2.9             | –                |
| Simulated sample size                            | 1.3             | –                |
| Candidates with clone tracks and multiple candidates | 0.2             | –                |
| Veto of the reflection background                 | 0.4             | –                |
| $\Lambda_c^+$ Dalitz weighting                   | 0.2             | 0.984            |
| $\Lambda_c^+$ polarization                      | 0.3             | 0.987            |
| Resonant structures                              | 1.8             | 1.041            |
| Total                                            | 6.0             | 0.996            |

---

Fig. 1. Invariant mass distributions of the (a) $\Lambda_c^0 \to \Lambda_c^+ pp\pi^-$ and (b) $\Lambda_c^0 \to \Lambda_c^+ \pi^-$ candidates. Fit results are overlaid as a solid blue line. For (a), the red dotted line represents the signal component and the green dotted line the background due to random combinations. For (b), the red dotted line is the signal component, the green dotted line is the random combination background, the purple dashed line is the contribution from $\Lambda_c^0 \to \Lambda_c^+ \rho^-$ and the brown dashed-dotted line represents the contribution from $\Lambda_c^0 \to \Lambda_c^+ K^-$. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)
for each $p$ or $\overline{p}$ (4.4% in total), which is obtained from simulation, accounting for the imperfect knowledge of material budget of the LHCb detector [22].

Per-candidate weights depending on $p_T$ and $y$ of the $A^0_b$ baryon are applied in simulated events to improve the agreements between data and simulation. Systematic uncertainties for the weighting due to the finite size of the normalisation sample are assessed with pseudoexperiments. In each pseudoexperiment, the weights are varied within their uncertainties, and the results are propagated to the ratio of branching fractions. The standard deviation of the obtained distributions is taken as a systematic uncertainty, resulting in 0.65% for the TIS sample and 0.65% for the TOS sample. The systematic uncertainties due to the binning scheme of the weighting in $p_T$ and $y$ are estimated by halving the bin size, or using the gradient boosting [23] [24], which is an unbinned method of weighting, to check the changes on the relative efficiencies. The resulting systematic uncertainties are 0.43% for the TIS sample and 1.5% for the TOS sample. After propagation through the entire fit procedure, this results in an uncertainty of 1.0% on the ratio of the branching fractions.

Trigger efficiencies for the TOS samples are also assessed using pseudoexperiments which are propagated to the final measurement, resulting in a final uncertainty of 0.1%. The trigger efficiency of the TIS sample is taken from simulation. Its systematic uncertainty is computed from the difference between the TIS efficiency taken from data and simulation for events which are triggered both on the $A^0_b$ candidate and also on other tracks unassociated to the signal decay. As a result, a systematic uncertainty of 3.9% is assigned for the relative trigger efficiency of the TIS sample, corresponding to an uncertainty of 2.9% on the ratio of the branching fractions.

The effect of the finite size of the simulated samples is assessed by considering the possible variation of the efficiency with weighted samples in a bin of $p_T$ and rapidity of the $A^0_b$ candidate, and the corresponding systematic uncertainty on the efficiency of the signal or normalisation channel, TIS or TOS sample, is given by

$$\sigma_\varepsilon = \sqrt{\sum_i \varepsilon_i(1 - \varepsilon_i)N_iw_i^2/\sum_i N_iw_i^2},$$

where for each bin $i$, $N_i$ is the number of candidates, $w_i$ is the single event weight, and $\varepsilon_i$ is the single event efficiency. The total uncertainty on the relative efficiency for the TIS and TOS samples is 1.2% and 1.9%, respectively, corresponding to an uncertainty of 1.3% on the ratio of the branching fractions.

The uncertainty due to the removal of candidates reconstructed with clone tracks and multiple candidates is assessed by applying the same procedure to simulation, resulting in a difference of 0.2%. Vetoes on the invariant mass of possible cross-feed backgrounds may bias the signal mass distributions. An uncertainty of 0.4% is determined by changing the fit range of the normalisation sample to begin at 5450 MeV/$c^2$, instead of 5350 MeV/$c^2$.

The agreement between data and simulation in the $A^0_b \rightarrow pK^-\pi^+$ decay is also tested by comparing the Dalitz plot distributions. The normalisation sample is weighted in the $m^2(pK^-)$ versus $m^2(K^-\pi^+)$ plane. Due to the smaller sample size of the signal channel, weights obtained from the normalisation channel are applied to the signal. The resulting procedure renders all distributions consistent within one statistical standard deviation. The difference in the ratio of branching fractions is 1.3% smaller than the nominal result, providing a correction factor of 0.984. An uncertainty of 0.2% is determined by using an alternative binning scheme and varying the Dalitz-plot weights by their statistical uncertainties.

The polarization of the $A^0_b$ particles has been measured to be consistent with zero [25], but the weak decay of the $A^0_b$ baryon may induce a polarization in the $A^0_b$ system. In the simulation, it is assumed that the $A^0_b$ particle is unpolarized, leading to a difference in angular distributions between simulation and data. A possible effect due to the $A^0_b$ polarization is assessed by applying a weighting procedure to the distribution of the $A^0_b$ helicity angle, which is defined as the angle between the $A^0_b$ flight direction in the $A^0_b$ rest frame and the direction of the $pK^-\pi^+$ pair in the $A^0_b$ rest frame. This weight is obtained through a comparison between the angular distributions in simulation and data for the signal and the normalisation channels individually. Applying this weight to both the signal and the normalisation channels does not change the efficiency with respect to any of the other possible angles, and leads to a change of 1.1% in the relative efficiency for the TOS sample and 1.4% for the TIS sample. Propagation of these uncertainties leads to a correction factor of 0.987 on the ratio of the branching fractions. An uncertainty of 0.3% is determined by using an alternative binning scheme and varying the single-candidate weights by their statistical uncertainties.

Simulated data are generated using a phase-space model for the $A^0_b$ decay, which does not take into account possible resonances in the $A^0_b p\overline{p}\pi^-\pi^-$ system. Upon inspection, clear signals from the $\Sigma^0$ and $\Sigma^{0*}$ resonances are found, as described in Section 7. To assess the effect of these resonances, the simulation is weighted to reproduce the data. Weights are applied in two invariant mass dimensions, namely the $A^0_b\pi^-\pi^-$ invariant mass and another invariant mass of any two or three body combination. Among these weighting strategies, applying weights in $m(A^0_b\pi^-\pi^-)$ and $m(p\overline{p}\pi^-)$ (option 1) leads to the smallest $p_T$, while weights in $m(A^0_b\pi^-\pi^-)$ and $m(p\overline{p}\pi^-)$ (option 2) leads to the largest $p_T$. A correction factor is computed as the average of the central values of the ratio of branching fractions for the two options divided by the nominal branching fraction, with an uncertainty determined by half the difference between the two ratios of branching fractions. This leads to a correction factor of 1.041 and a resulting systematic uncertainty of 1.8%.

Uncertainties due to the use of the BDTG are tested by repeating the BDTG training and selection procedure to the normalisation channel without variables related to the $p\overline{p}$ pair; the ratio of branching fractions is found to be consistent.

### 7. Resonance structures in the $A^0_b\pi^-\pi^-$ mass spectrum

As the resonant structure of $A^0_b \rightarrow A^0_b p\overline{p}\pi^-\pi^-$ decays is unexplored, the resonances in the $A^0_b\pi^-\pi^-$ system are studied. An unbinned maximum-likelihood fit of the $A^0_b\pi^-\pi^-$ mass is performed for those candidates which pass all the selection criteria for the signal $A^0_b \rightarrow A^0_b p\overline{p}\pi^-\pi^-$ decays, to determine if there are resonant contributions. In this case the $A^0_b$ candidate is constrained to its known mass [15] when obtaining the $A^0_b\pi^-\pi^-$ invariant mass spectrum.

The signal shapes of the $\Sigma^0$ and $\Sigma^{0*}$ resonances are given as the modulus squared of the relativistic Breit–Wigner function [15].

$$|\text{BW}(m|M_0, \Gamma_0)|^2 = \left|1/(M_0^2 - m^2 - iM_0\Gamma(m))\right|^2,$$

multiplied by $m\Gamma(m)$, and convolved with a Gaussian resolution determined from simulation. Here, $M_0$ is the known value of the $\Sigma^0$ or $\Sigma^{0*}$ mass [15], $m$ is the $A^0_b\pi^-\pi^-$ invariant mass, and $\Gamma_0$ is the mass-independent width of the resonance, namely 1.83 MeV/$c^2$ for the $\Sigma^0$ and 15.3 MeV/$c^2$ for the $\Sigma^{0*}$ resonance. The mass-dependent width is given by
The existence of dibaryon resonances, \( \mathcal{R}_n^+ \rightarrow p \Sigma^0_n \), is investigated in the \( \Lambda_c^+ \pi^- \) mass spectrum of background-subtracted data. The full \( m(\Lambda_c^+ \pi^-) \) spectrum is considered, while the signal regions of \( \Sigma_c^0 \) and \( \Sigma_c^{*0} \) resonances are defined by the ranges \( 2450 < m(\Lambda_c^+ \pi^-) < 2458 \text{ MeV}/c^2 \) and \( 2488 < m(\Lambda_c^+ \pi^-) < 2549 \text{ MeV}/c^2 \), respectively. The background is subtracted with the sPlot technique [27]. No peaking structures are observed in the distributions shown in Fig. 3. The two-dimensional distribution of \( m(\Lambda_c^+ \pi^-) \) versus \( m(\Lambda_c^+ \pi^-) \) has been checked and does not exhibit any clear structure.

9. Conclusion

The first observation of the decay \( \Lambda_b^0 \rightarrow \Lambda_c^+ p \Sigma^- \) is presented. The ratio of the branching fractions using the decay \( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \) as the normalisation channel is measured to be

\[
\frac{B(\Lambda_b^0 \rightarrow \Lambda_c^+ p \Sigma^-)}{B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032,
\]

using data corresponding to an integrated luminosity of 3 fb\(^{-1}\) collected during 2011 and 2012 with the LHCb detector. Contributions from the \( \Sigma_c(2455)^0 \) and \( \Sigma_c^*(2520)^0 \) resonances are observed, and the ratios of their branching fractions with respect to the \( \Lambda_b^0 \rightarrow \Lambda_c^+ p \Sigma^- \) decays are measured to be

\[
\begin{align*}
\frac{B(\Lambda_b^0 \rightarrow \Sigma_c^0 p \bar{p} \pi^-)}{B(\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-)} &= 0.089 \pm 0.015 \pm 0.006, \\
\frac{B(\Lambda_b^0 \rightarrow \Sigma_c^{*0} p \bar{p} \pi^-)}{B(\Sigma_c^{*0} \rightarrow \Lambda_c^+ \pi^-)} &= 0.119 \pm 0.020 \pm 0.014.
\end{align*}
\]

In all of the above results, the first uncertainty is statistical and the second is systematic.

The mass spectra of the \( \Lambda_c^+ p \pi^- \) final state are also inspected for possible dibaryon resonances, but no evidence of peaking structures is observed.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (The Netherlands); MNI SW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); Mineco (Spain); SNSF and SER (Switzerland); NSU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom), RIKKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA).
Fig. 3. Background-subtracted mass spectrum of the $\Lambda^+_c \pi^- p$ system from the decay $\Lambda^0_c \to \Lambda^+_c p \pi^- n$ in (a) the full $\Lambda^+_c \pi^- n$ mass spectrum, (b) the signal region of the $\Sigma^0$ resonance, and (c) the signal region of the $\Sigma^0$ resonance. In all figures, the black points are data and the red points are simulated events where the $\Lambda^+_c$ baryon decays to the $\Lambda^+_c \pi^- n$ final state (a) based on a uniform-phase-space model, (b) through the $\Sigma^0$ resonance and (c) through the $\Sigma^0$ resonance. No evident peaking shapes are visible.

We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Sklodowska-Curie Actions and ERC (European Union), ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France), Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China), RFBR, RSF and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, the Royal Society, the English-Speaking Union and the Leverhulme Trust (United Kingdom).

References

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. 8 (1964) 213.

[2] G. Zweig, An SU(3) model for strong interaction symmetry and its breaking, CERN-TH-401, 1964.

[3] LHCb Collaboration, R. Aaij, et al., Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda^0_c \to J/\psi pK^-\pi^+$ decays, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414.

[4] L. Maiani, A.D. Polosa, V. Riquer, From pentaquarks to dibaryons in $\Lambda^0_c(5620)^+$ decays, Phys. Lett. B 750 (2015) 37, arXiv:1508.04459.

[5] LHCb Collaboration, A.A. Alves Jr. et al., The LHCb detector at the LHC, J. Instrum. 3 (2008) S08005.

[6] LHCb Collaboration, R. Aaij, et al., LHCb detector performance, Int. J. Mod. Phys. A 30 (2015) 1530022, arXiv:1412.6352.

[7] R. Aaij, et al., The LHCb trigger and its performance in 2011, J. Instrum. 8 (2013) P04022, arXiv:1211.3055.

[8] V.V. Gligorov, M. Williams, Efficient, reliable and fast high-level triggering using a boosted decision tree, J. Instrum. 8 (2013) P01023, arXiv:1210.6681.

[9] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820; T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, arXiv:hep-ph/0603175.

[10] I. Belyaev, et al., Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. 331 (2011) 032047.

[11] D.J. Lange, The EvGen particle decay simulation package, Nucl. Instrum. Methods A 462 (2001) 152.

LHCb Collaboration

R. Aaij 43, B. Adeva 39, M. Adinolfi 48, Z. Ajaltouni 5, S. Akar 59, P. Albicocchi 49, J. Albrecht 10, F. Alessio 40, M. Alexander 53, A. Alfonso-Albero 38, S. Ali 43, G. Alkhazov 31, P. Alvarez Cartelle 55, A.A. Alves Jr. 59, S. Amato 2, S. Amerio 23, Y. Amhis 7, L. An 3, L. Anderlini 18, G. Andreassi 41, M. Andreotti 17,8, J.E. Andrews 60, R.B. Appleby 16, F. Archilli 43, P. d’Argent 12, J. Arnau Romeu 6, A. Artamonov 37, M. Artuso 61, E. Aslanides 6, M. Atzeni 42, G. Auriemma 26, S. Bachmann 12, J.J. Back 50, S. Baker 55, V. Balagura 27,28, W. Baldini 17, A. Baranov 35, R.J. Barlow 56, S. Barsuk 7, W. Barter 36, F. Baryshnikov 32, V. Batozskaya 29, V. Battista 41, A. Bay 41, J. Beddow 53, F. Bedeschi 24, I. Bediaga 1, A. Beiter 61, L.J. Bel 43, N. Beliy 62, V. Bellee 41, N. Belloli 21, K. Belous 37, I. Belyaev 32,40, E. Ben-Haim 8, G. Bencivenni 19, S. Benson 43, S. Beranek 9, A. Berezhnov 33, R. Bernet 42, D. Berninghoff 12, E. Bertholet 8, A. Bertolin 23,
