

Search for new decays of the Λ_b^0 baryon at the LHCb experiment

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Abstract. High statistics collected by the LHCb experiment between 2011 and 2018 in proton-proton (pp) collisions at the Large Hadron Collider (LHC), jointly with the large cross-section of $b\bar{b}$ pairs production provides unique possibility for the search and study new decays of beauty hadrons. The results of search for new decays of the Λ_b^0 baryons are presented. In particular the decays $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$, $\Lambda_b^0 \rightarrow J/\psi \Lambda$, $\Lambda_b^0 \rightarrow \psi(2S) \Lambda$, $\Lambda_b^0 \rightarrow \psi(2S) p \pi^-$, $\Lambda_b^0 \rightarrow \chi_{c1}(3872) p K^-$ and $\Lambda_b^0 \rightarrow \Lambda \gamma$ are found and branching fraction ratios measurement for these decays are done. Also the study of the $\Lambda_b^0 \pi^+ \pi^-$ systems led to the observation of two new excited Λ_b^0 states, denoted as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, are found.

1 Introduction

High energy of pp collisions at the LHC, jointly with the large cross-section of the heavy b-quarks provides an access to the full range of b-hadrons including heavy Λ_b^0 baryons. This fact makes the study of beauty baryons not only an interesting but also a promising task for the LHCb collaboration.

The LHCb experiment [1] is one of the four main experiments at the LHC. It is designed to search for indirect manifestations of New Physics beyond the Standard Model (SM) through the study of CP-symmetry violation in decays of particles containing b- and c-quarks. Besides, there are researches in such areas like measurement of the unitarity triangle angles, search for rare decays of beauty hadrons, study of heavy hadrons properties and search for new particles. Thus, with all the advantages of the LHCb experiment the search for new beauty baryon decays is of particular interest for the experimental high energy physics. For the studies presented in this paper a different data samples collected between 2011 and 2018 at centre-of-mass energy 7, 8 and 13 TeV are used.

2 Observation of the $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ decay

The study of the decay channel $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$, $\Lambda_c^+ \rightarrow p K^- \pi^+$ is of high interest due to possible charmed dibaryon resonant states contributions. As discussed in reference [2], such states could manifest via the decay $\Lambda_b^0 \rightarrow \bar{p} + [cd][ud][ud] = \bar{p} + \mathcal{D}_c^+$, where \mathcal{D}_c^+ is the lightest charmed dibaryon state with a mass below $4682 \text{ MeV}/c^2$. The subsequent decay of the \mathcal{D}_c^+

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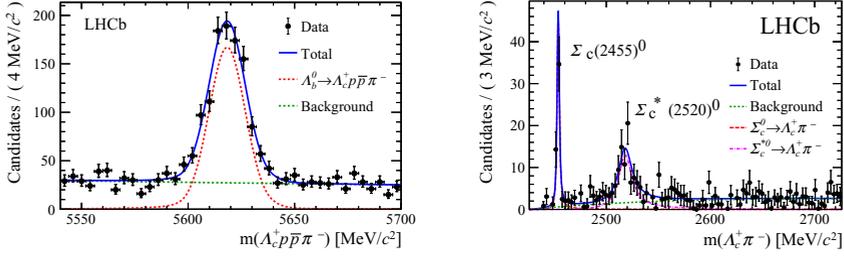


Figure 1. Mass distributions of the (left) $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ candidates and (right) of the $\Lambda_c^+ \pi^-$ system from the $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ decay. The $\Sigma_c(2455)^0$ and $\Sigma_c^*(2520)^0$ resonances are indicated. The fit to the data is shown as a blue continuous line, with the background component due to random combinations shown as a green dotted line, the Λ_c^0 and $\Sigma_c(2455)^0$ shapes are shown as a dashed red line, and the $\Sigma_c^*(2520)^0$ shape shown as a dash-dotted magenta line.

20 dibaryon could proceed either via quark rearrangement to the final state $p\Sigma_c^0$, with $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$
 21 decay, or via string breaking to a final state $\mathcal{P}_c^0(\bar{u}[cd][ud])$ involving a lighter, yet undiscovered
 22 \mathcal{P}_c^0 pentaquark state, $\mathcal{P}_c^+ \rightarrow \mathcal{P}_c^0(\bar{u}[cd][ud])p$, with $\mathcal{P}_c^0 \rightarrow \Lambda_c^+ \pi^-$ decay [2]. The discovery
 23 of any of these decay modes would test the predictions of quantum chromodynamics and
 24 the fundamental workings of the Standard Model.

The decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ is observed for the first time 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 decay of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ is used as the normalization channel. In those two decays, the Λ_c^+ baryon is reconstructed as a combination of $pK^- \pi^+$ particles. The fit to the mass distribution for the signal channel are shown in figure 1 (left). The signal yields are determined to be 926 ± 43 and $(167.00 \pm 0.50) \times 10^3$ for the $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decay modes, respectively. The ratio of branching fractions between $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decays is measured to be

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032,$$

25 where the first uncertainty is statistical and the second is systematic [3].

Two resonant structures are observed in the $\Lambda_c^+ \pi^-$ mass spectrum of the $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ decays, corresponding to the $\Sigma_c(2455)^0$ and $\Sigma_c^*(2520)^0$ states (see figure 1 (right)) with yields of 59 ± 10 and 104 ± 17 , respectively [3]. The ratios of branching fractions with respect to the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ are

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

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*0} p \bar{p}) \times \mathcal{B}(\Sigma_c^{*0} \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)} = 0.119 \pm 0.020 \pm 0.014.$$

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

29 **3 Observation of the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ and $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ decays**

30 The LHCb collaboration has observed several $\Lambda_b^0 \rightarrow J/\psi X$ [4–9] and $\Lambda_b^0 \rightarrow \psi(2S)X$
 31 decays [7, 10], where X indicates a final-state particle system. The ratios of

32 branching fractions of b-hadron decays into $J/\psi X$ and $\psi(2S)X$ (where X indicates a
 33 final-state particle system) provide useful information on the production of charmo-
 34 nia in b-hadron decays. These ratios can be used to test factorisation of ampli-
 35 tudes. The ATLAS collaboration has previously measured the ratio of the branching
 36 fractions to be $\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)/\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda) = 0.501 \pm 0.033$ (stat) ± 0.019 (syst) [11],
 37 where in both decays J/ψ and $\psi(2S)$ mesons are reconstructed using $\mu^+\mu^-$ fi-
 38 nal state and Λ hyperon is reconstructed using $p\pi^-$ final state. This result
 39 differs by 2.8σ from a theoretical prediction in the framework of the covari-
 40 ant quark model, $\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)/\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda) = 0.8 \pm 0.1$ [12, 13], and with simi-
 41 lar measurements in the B-systems, $\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)/\mathcal{B}(B^0 \rightarrow J/\psi K_S^0) = 0.66 \pm 0.06$ and
 42 $\mathcal{B}(B^+ \rightarrow \psi(2S)K^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+) = 0.615 \pm 0.019$ [14].

The ratio of branching fraction of $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$ decay relative to the branching fraction
 of $\Lambda_b^0 \rightarrow J/\psi\Lambda$ decay cancels most experimental uncertainties. A measurement with improved
 precision helps to better understand this possible discrepancy and sets new constraints on the
 available form-factor models [13]. This study is based on two data samples containing long
 and downstream tracks. These two types of tracks are defined as tracks including hits from the
 vertex detector (long) and tracks that do not include vertex detector hits (downstream) [1].
 Using pp collisions corresponding to 3 fb^{-1} integrated luminosity, recorded by the LHCb
 experiment at centre-of-mass energies of 7 and 8 TeV, the ratio of branching fractions is
 determined to be

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda)} = 0.513 \pm 0.023 \pm 0.016 \pm 0.011,$$

43 where the first uncertainty is statistical, the second is systematic and the third is related to the
 44 uncertainties of the known branching fractions of $\psi(2S)$ and J/ψ mesons to two leptons [15].
 45 This measurement is compatible within one standard deviation with the measurement from
 46 the ATLAS collaboration [11] and has a better precision. It confirms the discrepancy with the
 47 covariant quark model theory predictions [12, 13] and sets additional constraints on available
 48 models.

49 **4 Observation of the $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ decay**

The Cabibbo-suppressed decay $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ is observed for the first time using a data
 sample collected by the LHCb experiment in pp collisions corresponding to 1.0, 2.0 and
 1.9 fb^{-1} of integrated luminosity at centre-of-mass energies of 7, 8 and 13 TeV, respectively.
 The $\psi(2S)$ mesons are reconstructed in the $\mu^+\mu^-$ final state. The branching fraction with
 respect to that of the $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ decay mode is measured to be

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)p\pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)pK^-)} = (11.4 \pm 1.3 \pm 0.2) \times 10^{-2},$$

50 where the first uncertainty is statistical and the second is systematic [10]. The mass
 51 distributions for the selected $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ and $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ candidates are shown
 52 in figure 2. The signal yields are determined to be 121 ± 13 and 806 ± 29 for
 53 the $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ and $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ decay modes, respectively. The significance of
 54 the observed $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ decay is more than 9σ . The $\psi(2S)p$ and $\psi(2S)\pi^-$ mass spectra
 55 are investigated and no evidence for exotic resonances is found [10].

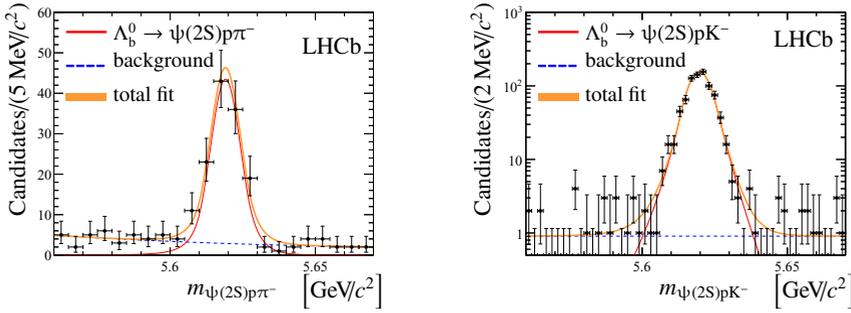


Figure 2. Mass distributions of the (left) $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$ and (right, in logarithmic scale) $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ candidates.

5 First observation of the $\chi_{c1}(3872)$ state in beauty baryon decay

$\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$

The $\chi_{c1}(3872)$ state, also known as $X(3872)$, was observed in 2003 by the Belle collaboration [16]. This discovery has attracted much interest in exotic charmonium spectroscopy since it was the first observation of an unexpected charmonium candidate.

The mass of the $\chi_{c1}(3872)$ state, its quantum numbers ($J^{PC} = 1^{++}$) [14] and the dipion mass spectrum in the decay $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ was also studied [17, 18]. Despite a large amount of experimental information, the nature of the $\chi_{c1}(3872)$ particle is still unclear and several theoretical models were proposed to describe it. It has been interpreted as a molecular state [19–21], tetraquark [22], $c\bar{c}g$ hybrid meson [23], vector glueball [24] or mixed state [25, 26]. Studies of radiative $\chi_{c1}(3872)$ decays [27–29] have reduced the number of possible interpretations of this state [30–32]. Thus far, the $\chi_{c1}(3872)$ particle has been widely studied in prompt hadroproduction [17, 33–35] and in the weak decays of beauty mesons, but never been observed in b-baryon decays [14]. In particular, observing Λ_b^0 decays involving the $\chi_{c1}(3872)$ state will allow comparison of their decay rates to the rates for conventional charmonium states, where, for instance, factorisation and spectator quarks assumptions may lead to different results depending on the nature of the $\chi_{c1}(3872)$ state.

Using pp collision data, collected with the LHCb detector and corresponding to 1.0, 2.0 and 1.9 fb^{-1} of integrated luminosity at the centre-of-mass energies of 7, 8, and 13 TeV, respectively, the decay $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ is observed for the first time. The $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ decay is used as the normalization channel. The both $\chi_{c1}(3872)$ and $\psi(2S)$ mesons are reconstructed using $J/\psi \pi^+ \pi^-$ final state. The J/ψ meson is reconstructed using $J/\psi \rightarrow \mu^+ \mu^-$ decay mode. Projections of the two-dimensional fit to the $J/\psi \pi^+ \pi^- pK^-$ and $J/\psi \pi^+ \pi^-$ mass distributions for the interval of $3.80 < m_{J/\psi \pi^+ \pi^-} < 3.95 \text{ GeV}/c^2$ are shown in figure 3. The signal yields are determined to be 55 ± 11 and 610 ± 30 for the $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ and $\Lambda_b^0 \rightarrow \psi(2S)pK^-$ decay modes, respectively. The statistical significance of the observed $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ signal is estimated to be 7.2σ .

The branching fraction of the $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ decay with respect to the normalization channel is measured to be

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)pK^-)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2},$$

where the first uncertainty is statistical and the second is systematic. It is found that the decay $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ mainly proceeds through two-body $\chi_{c1}(3872)\Lambda(1520)$ intermediate state [36].

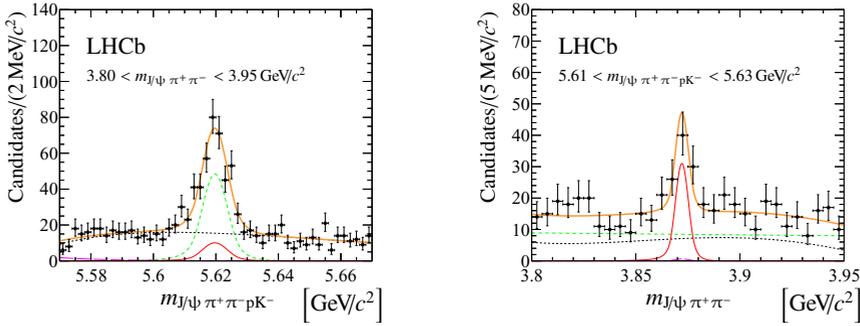


Figure 3. Projection of the two-dimensional distribution of (left) $J/\psi \pi^+ \pi^- pK^-$ and (right) $J/\psi \pi^+ \pi^-$ masses for the $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ candidates. A signal component, describing the true $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ decays (red), a component describing nonresonant $\Lambda_b^0 \rightarrow J/\psi \pi^+ \pi^- pK^-$ decays with no intermediate $\chi_{c1}(3872)$ state (NR) (green), a component describing random combinations of $\chi_{c1}(3872)$ state with pK^- pairs that are not Λ_b^0 decay products (magenta) and a combinatorial $J/\psi \pi^+ \pi^- pK^-$ component (black) are indicated.

6 First observation of the radiative beauty baryon decay $\Lambda_b^0 \rightarrow \Lambda \gamma$

The decay $\Lambda_b^0 \rightarrow \Lambda \gamma$, $\Lambda \rightarrow p\pi^-$ proceeds via the $b \rightarrow s\gamma$ flavour-changing neutral-current transition. This process is forbidden at tree level in the SM and is therefore sensitive to new particles entering the loop-level transition, which can modify decay properties. Radiative b-baryon decays have never been observed and offer a unique benchmark to measure the photon polarization due to the non-zero spin of the initial and final-state particles [37]. In particular, the $\Lambda_b^0 \rightarrow \Lambda \gamma$ decay has been proposed as a suitable mode for the study of the photon polarization, since the helicity of the Λ hyperon can be measured, giving access to the helicity structure of the $b \rightarrow s\gamma$ transition [38, 39].

Using a data sample of pp collisions corresponding to an integrated luminosity of 1.7 fb^{-1} collected by the LHCb experiment at a center-of-mass energy of 13 TeV the radiative decay $\Lambda_b^0 \rightarrow \Lambda \gamma$ is observed for the first time. The decay $B^0 \rightarrow K^*(892)^0 \gamma$ is used as the normalization channel. The signal yields are found to be 65 ± 13 (with significance of 5.6σ) and 32670 ± 290 for $\Lambda_b^0 \rightarrow \Lambda \gamma$ and $B^0 \rightarrow K^*(892)^0 \gamma$ decays, respectively. The branching fraction of the $\Lambda_b^0 \rightarrow \Lambda \gamma$ decay is measured exploiting the normalization mode and is found to be

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda \gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6},$$

where the quoted uncertainties are statistical, systematic and systematic from external inputs, respectively [40]. This is the first observation of the radiative decay of beauty baryon.

7 Observation of new resonances in the $\Lambda_b^0 \pi^+ \pi^-$ systems

In the constituent quark model [41, 42], baryons containing a beauty quark form multiplets according to the internal symmetries of flavour, spin, and parity [43]. Beyond the Λ_b^0 baryon, which is the lightest beauty baryon, a rich spectrum of radially and orbitally excited states is expected at higher masses. Several new baryon states have been discovered in recent years [44–48]. The spectrum of excited states decaying to the $\Lambda_b^0 \pi^+ \pi^-$ final state has already been studied by the LHCb experiment with the discovery of two narrow states [44], denoted $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$. The heavier of these states was later confirmed by the CDF collaboration [49]. Mass predictions for the ground-state beauty baryons and their orbital and radial excitations are given in many theoretical works, *e.g.*, [50–53]. In addition to the already

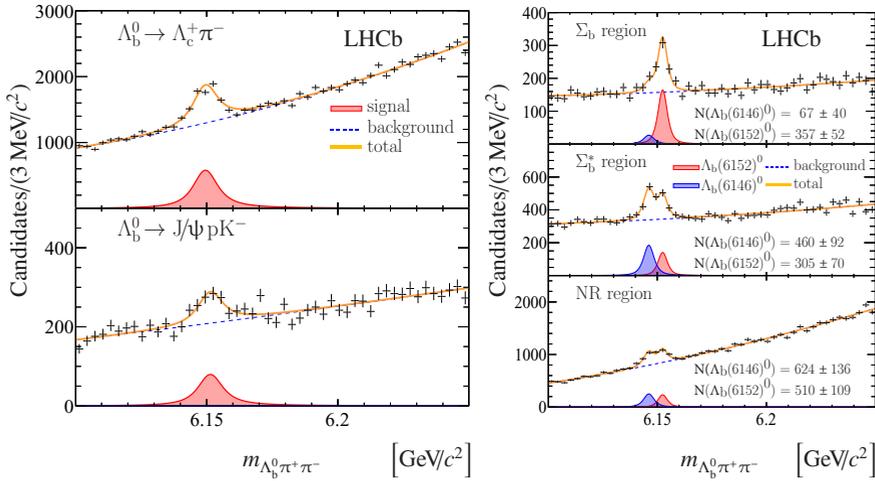


Figure 4. Mass distribution of selected $\Lambda_b^0 \pi^+ \pi^-$ candidates (left) for the (top) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and (bottom) $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay modes. Mass distributions of selected $\Lambda_b^0 \pi^+ \pi^-$ candidates for the three regions in $\Lambda_b^0 \pi^+ \pi^-$ mass (right): (top) Σ_b^+ , (middle) Σ_b^0 and (bottom) NR region. The signal yields of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ contributions in each region are shown.

107 observed doublet of first orbital excitations, more states are predicted in the mass region near
 108 or above $6.1 \text{ GeV}/c^2$.

The observation of a new structure in the $\Lambda_b^0 \pi^+ \pi^-$ spectrum using the full LHCb data set of pp collisions, corresponding to an integrated luminosity of 9 fb^{-1} , collected at $\sqrt{s} = 7, 8$ and 13 TeV is reported. In summary, a new structure with high statistical significance is observed in the $\Lambda_b^0 \pi^+ \pi^-$ mass spectrum using $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$, $\Lambda_c^+ \rightarrow p K^- \pi^+$ decays, and confirmed using a sample of Λ_b^0 baryons reconstructed through the $\Lambda_b^0 \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+ \mu^-$ decay. The mass distributions for selected $\Lambda_b^0 \pi^+ \pi^-$ candidates are shown in figure 4 (left). An analysis of the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra for the regions enriched by the $\Sigma_b^{(*)\pm}$ resonances suggests the interpretation of the structure as two almost degenerate narrow states, denoted as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$. The $\Lambda_b^0 \pi^+ \pi^-$ mass spectra in these three regions are shown in figure 4 (right). The masses and natural widths of these states are measured to be

$$\begin{aligned} m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}/c^2, \\ m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}/c^2, \\ \Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3 \text{ MeV}, \\ \Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3 \text{ MeV}, \end{aligned}$$

where the first uncertainty is statistical, the second systematic and the third for the mass measurements due to imprecise knowledge of the mass of the Λ_b^0 baryon [54]. The mass differences with respect to the Λ_b^0 mass are measured to be

$$\begin{aligned} m_{\Lambda_b(6146)^0} - m_{\Lambda_b^0} &= 526.55 \pm 0.33 \pm 0.10 \text{ MeV}/c^2, \\ m_{\Lambda_b(6152)^0} - m_{\Lambda_b^0} &= 532.89 \pm 0.26 \pm 0.10 \text{ MeV}/c^2, \end{aligned}$$

109 and the mass difference between the two states is measured to be $6.34 \pm 0.32 \pm 0.02 \text{ MeV}/c^2$.
110 The masses of the two states measured in this analysis are consistent with the predic-
111 tions for the doublet of $\Lambda_b(1D)^0$ states with quantum numbers (spin J and parity P)
112 $J^P = \frac{3}{2}^+$ and $\frac{5}{2}^+$ [50, 53].

113 8 Conclusion

114 Using proton-proton collision data collected by the LHCb experiment between 2011 and
115 2018 at centre-of-mass energies of 7, 8, and 13 TeV a number of new decays of the Λ_b^0
116 baryon are found. In particular the decays $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$, $\Lambda_b^0 \rightarrow J/\psi \Lambda$, $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$,
117 $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$, $\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$ and $\Lambda_b^0 \rightarrow \Lambda\gamma$ are observed and the branching fraction
118 ratios are measured. Also by studying of the $\Lambda_b^0 \pi^+ \pi^-$ systems two new excited states of the
119 Λ_b^0 baryon, denoted as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ are discovered.

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