Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum

LHCb collaboration†

Abstract

A new baryon state is observed in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum with high significance using a data sample of pp collisions, collected with the LHCb detector at centre-of-mass energies $\sqrt{s} = 7, 8$ and $13$ TeV, corresponding to an integrated luminosity of $9 \, \text{fb}^{-1}$. The mass and natural width of the new state are measured to be

\[
\begin{align*}
m & = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \, \text{MeV}, \\
\Gamma & = 72 \pm 11 \pm 2 \, \text{MeV},
\end{align*}
\]

where the first uncertainty is statistical and the second systematic. The third uncertainty for the mass is due to imprecise knowledge of the $\Lambda_b^0$ baryon mass. The new state is consistent with the first radial excitation of the $\Lambda_b^0$ baryon, the $\Lambda_b^{(2S)^0}$ resonance. Updated measurements of the masses and the upper limits on the natural widths of the previously observed $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states are also reported.

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1 Introduction

The constituent quark model [1,2] is very successful in describing and classifying the known hadrons based on their quantum numbers [3]. However, quantum chromodynamics that lies in the origin of the quark model, being a nonperturbative theory, does not predict hadron properties, namely masses and decay widths, from first principles. Alternative theoretical approaches are developed, such as heavy quark effective theory or lattice calculations. These approaches require verification with experiment in various regimes, e.g. testing the agreement with data for hadrons with different quark content and quantum numbers. Baryons, containing a beauty quark form a particular family of hadrons, where the experimental data are still scarce.

Excited beauty baryons with two light quarks and quark content $bqq'$, where $q, q' = u, d$, have been studied experimentally at the Tevatron and the LHC. The family of these baryons consists of the $\Lambda_b^0$ isosinglet and the $\Sigma_b$ and $\Sigma_b^*$ isotriplet states. The lightest charged $\Sigma_b^{(*)}\pi^\pm$ baryons have been observed by the CDF collaboration [4,5] in the $\Lambda_b^0\pi^\pm$ spectrum. The measurement of the masses and widths of those states was updated by the LHCb collaboration and the heavier $\Sigma_b(6097)^\pm$ states were discovered [6].

The spectrum of excited beauty baryons decaying to the $\Lambda_b^0\pi^+\pi^-$ final state near threshold has been studied by the LHCb collaboration using a data sample collected in 2011, which resulted in the discovery of two narrow states [7], denoted $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$. The most likely interpretation of these states is that they are a doublet of first orbital excitations in the $\Lambda_b^0$ system, with quantum numbers $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. The heavier of these states was later confirmed by the CDF collaboration [8]. A doublet of narrow states, $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, was also observed by LHCb collaboration [9]. The measured masses and widths of these states are compatible with the expectations for the $\Lambda_b(1D)^0$ doublet [10–13]. Recently, the CMS collaboration reported an evidence for a broad excess of events in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum in the region of 6040 – 6100 MeV corresponding to a statistical significance of four standard deviations [14].

The existence of additional states in the $\Lambda_b^0\pi^+\pi^-$ spectrum is predicted by the quark model [15–17], notably, in the region between the established narrow doublet states, with masses around 6.1 GeV. Quark-model predictions for the masses of the lightest $\Lambda_b$ and $\Sigma_b^{(*)}$ states are shown in Table 1.

This paper reports the observation of a new structure in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum, as well as updated measurements of the masses and widths of the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states with improved precision. The analysis uses pp collision data recorded by LHCb in 2011–2018 at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to an integrated luminosity of 1, 2 and 6 fb$^{-1}$, respectively.

2 The LHCb detector

The LHCb detector [19, 20] 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 vertex detector surrounding the pp interaction region [21], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and

$^1$Natural units are used through the paper with $c = \hbar = 1$. 

1
Table 1: Quark-model predictions for the masses of the lightest $\Lambda_b$ and $\Sigma_b^{(*)}$ states (in MeV).

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<tr>
<td>$\Lambda_b^0$</td>
<td>1S</td>
<td>$\frac{1}{2}^+$</td>
<td>5585</td>
<td>5612</td>
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<td>2S</td>
<td>$\frac{1}{2}^+$</td>
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<td>6107</td>
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</table>

three stations of silicon-strip detectors and straw drift tubes [22,23] placed downstream of the magnet. The tracking system provides a measurement of the momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV. The momentum scale of the tracking system is calibrated using samples of $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [24,25]. The relative accuracy of this procedure is estimated to be $3 \times 10^{-4}$ using samples of other fully reconstructed b-hadron, $K^0_S$, and narrow $\Upsilon(1S)$ resonance decays. Different types of charged hadrons are distinguished by the particle identification (PID) system using information from two ring-imaging Cherenkov detectors [26]. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [27].

The online event selection is performed by a trigger [28] which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. At the hardware trigger stage, events are required to have a muon with high transverse momentum, $p_T$, or a pair of opposite-sign muons with a requirement on the product of muon transverse momenta, or a hadron, photon or electron with high transverse energy in the calorimeters. The software trigger requires a two-, three- or four-track secondary vertex with at least one charged particle with a large $p_T$ and inconsistent with originating from any reconstructed primary pp collision vertex (PV) [29,30] or two muons of opposite charge forming a good-quality secondary vertex with a mass in excess of 2.7 GeV.

Simulation is required to model the effects of the detector acceptance, resolution, and selection requirements. In the simulation, pp collisions are generated using PYTHIA [31] with a specific LHCb configuration [32]. Decays of unstable particles are described by EvtGen [33], in which final-state radiation is generated using PHOTOS [34]. The interact-
tion of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit as described in Ref. [35].

3 Event selection

The $\Lambda_b^0$ candidates are reconstructed in the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays.\footnote{Inclusion of charge-conjugate states is implied throughout this paper.} The selection of the $\Lambda_b^0$ candidates is similar to that used in Ref. [9]. All charged final-state particles are required to be positively identified by the PID systems. To reduce the background from random combinations of tracks, only the tracks with large impact parameter with respect to all PVs in the event are used. The $\Lambda_c^+$ candidates are reconstructed in the $pK^-\pi^+$ final state. The $\Lambda_b^0 \rightarrow J/\psi pK^-$ candidates are created by combining the $J/\psi$ candidates formed of $\mu^+\mu^-$ pairs with kaon and proton tracks. The masses of the $\Lambda_c^+$ and $J/\psi$ candidates are required to be consistent with the known values of the masses of the respective states [3] and the $\Lambda_b^0$ candidate is required to have a good-quality vertex significantly displaced from all PVs.

Further suppression of the background is achieved by using a boosted decision tree (BDT) classifier [37, 38] implemented in the TMVA toolkit [39]. Two separate BDTs are used for the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ selections. The multivariate estimators are based on the kinematic properties, the reconstructed lifetime and vertex quality of the $\Lambda_b^0$ candidate and on variables describing the overall consistency of the selected candidates with the decay chain obtained from the kinematic fit described below [40]. In addition, the reconstructed lifetime and vertex quality of the $\Lambda_c^+ \rightarrow pK^-\pi^+$ candidate is used for the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ decay. The PID quality, transverse momentum and pseudorapidity of the proton and kaon candidates (for $\Lambda_b^0 \rightarrow J/\psi pK^-$) or $\pi^-$ candidate (for $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$) are also used. The BDT is trained using data, where the signal sample is taken from the range $5 - 5.85$ GeV in the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ mass distributions. A $k$-fold cross-validation technique is used to avoid introducing a bias in the evaluation [41]. A kinematic fit [40] is performed in order to improve the $\Lambda_b^0$ mass resolution. The momenta of the particles in the full decay chain are recomputed by constraining the $\Lambda_c^+$ or $J/\psi$ mass to their known values [3] and the $\Lambda_b^0$ baryon to originate from the associated PV. The mass distributions for the selected $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ candidates are shown in Fig. [1]. The $\Lambda_b^0$ signal yield is $(937.9 \pm 1.6) \times 10^3$ and $(223.0 \pm 0.6) \times 10^3$ for $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays, respectively.

Selected $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ ($\Lambda_b^0 \rightarrow J/\psi pK^-$) candidates with mass within $\pm 50$ (20) MeV from the known $\Lambda_b^0$ mass are combined with pairs of opposite and same-sign pion tracks. To reduce the large combinatorial background, four separate BDT classifiers are trained for the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ samples in the high-mass ($m_{\Lambda_c^+\pi^-} < 6.35$ GeV) and the low-mass ($m_{\Lambda_c^+\pi^-} < 5.95$ GeV) regions. The BDTs exploit the vertex quality, $\chi^2_{\text{vtx}}$, of the $\Lambda_b^0\pi\pi$ combination, its transverse momentum, the $p_T$ of the $\pi\pi$ pair, the $p_T$ of each pion, as well as their PID and track-reconstruction-quality variables. For the high-mass region, the $p_T$ of the dipion system is required to exceed 250 MeV. Simulated samples of excited $\Lambda_b^0$ baryons decaying into the $\Lambda_b^0\pi^+\pi^-$ final state are used as signal training samples, while the background training sample is taken from the same-sign $\Lambda_b^0\pi^+\pi^-$ combinations in data. For the low-mass region, simulated samples of $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ signal
decays are used, while for the high-mass region the simulated sample consists of decays of a narrow state with mass of 6.15 GeV and natural width of 7 MeV, and a broad state with mass of 6.08 GeV and natural width of 60 MeV. A $k$-fold cross-validation technique is used for training. A figure of merit $\varepsilon/(\frac{5}{2} + \sqrt{B})$ is used to optimise the requirement on the BDT estimator. The mass resolution is improved by a kinematic fit constraining the mass of the $pK^−π^+$ and $μ^+μ^−$ combinations to the known masses of the $Λ_c^+$ baryon and $J/ψ$ meson, respectively [3]. The mass of the $Λ_b^0$ baryon in the fit is constrained to the central value of $m_{Λ_b^0} = 5619.62 ± 0.16 ± 0.13$ MeV [45]. It is also required that the momentum vector of the $Λ_b^0$ candidate and the momenta of both pions points back to the associated pp interaction vertex.

4 Analysis of the high-mass region

The distributions of the $Λ_b^0π^+π^−$ and $Λ_b^0π^+π^−$ masses in the range $5.93 < m_{Λ_b^0ππ} < 6.23$ GeV for the $Λ_b^0 → Λ_c^+π^−$ sample with the high-mass BDT selection applied are shown in Fig. 2. The distributions of the same-sign $Λ_b^0π^+π^−$ combinations are dominated by random combinations of a $Λ_b^0$ baryon and two pions. The $Λ_b^0π^+π^−$ spectrum features the contributions of two narrow $Λ_b(6146)^0$ and $Λ_b(6152)^0$ states as well as a broad structure just below 6.1 GeV in addition to the smooth background. This new structure is referred to as $Λ_b^{∗0}$ hereafter. Figure 3 shows the same distributions for the $Λ_b^0 → J/ψ pK^−$ sample, where the same features are visible.

A simultaneous binned maximum-likelihood fit with a bin width of 200 keV is performed to the six distributions shown in Figs. 2 and 3 in order to determine the properties of the resonant shapes. Both signal and background $Λ_b^0ππ$ combinations could include contributions from intermediate $Σ_b^±$ and $Σ_b^{∗±}$ states. The fitting function for the $Λ_b^0π^+π^−$ spectra is the sum of five components: a combinatorial background, the two components corresponding to the combinations of $Σ_b^± → Λ_b^0π^±$ and $Σ_b^{∗±} → Λ_b^0π^±$ with the addition of a pion from the rest of the event, and three resonant contributions for the $Λ_b(6146)^0$, $Λ_b(6152)^0$ and $Λ_b^{∗0}$ states. The same-sign $Λ_b^0π^+π^−$ spectra are fitted with a function that
Figure 2: Mass spectra of selected (top) $\Lambda_b^0\pi^+\pi^-$, (middle) $\Lambda_b^0\pi^+\pi^+$ and (bottom) $\Lambda_b^0\pi^-\pi^-$ combinations for the $\Lambda_b^0 \rightarrow \Lambda^+_c\pi^-$ sample. A simultaneous fit, described in the text, is superimposed.

contains only the combinatorial, $\Sigma^+_b\pi^\pm$, and $\Sigma^{*\pm}_b\pi^\pm$ components.

The combinatorial background is parameterised with a positive, increasing third-order polynomial function, whose coefficients are left free to vary in the fit. The $\Sigma^+_b\pi$ and $\Sigma^{*\pm}_b\pi$ components are described by the product of a two-body phase-space function and an exponential function, accounting for the finite width of the $\Sigma^{(*)}_b$ states. The exponential factor is determined from the fit to the background-subtracted $\Sigma^{(*)}_b\pi$ mass distributions in the $6.16 < m_{\Lambda_b^0\pi\pi} < 6.40$ GeV range. The shapes of the $\Sigma^{(*)}_b\pi$ components are taken to be the same in all spectra. The combinatorial background shape is fixed to be the same in the opposite-sign $\Lambda_b^0\pi^+\pi^-$ and same-sign $\Lambda_b^0\pi^+\pi^\pm$ spectra, but is allowed to differ for the $\Lambda_b^0 \rightarrow \Lambda^+_c\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ samples. The yields of all background components are left free to vary in the fit.

The narrow $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ components are parameterised using relativistic Breit–Wigner distributions convolved with the experimental resolution. The detector
Figure 3: Mass spectra of selected (top) $\Lambda_b^0\pi^+\pi^-$, (middle) $\Lambda_b^0\pi^+\pi^+$ and (bottom) $\Lambda_b^0\pi^-\pi^-$ combinations for the $\Lambda_b^0 \to J/\psi pK^-$ sample. A simultaneous fit, described in the text, is superimposed.

The resolution function is described by the sum of two Gaussian functions with zero mean and parameters fixed from simulation. The obtained effective resolution increases from 0.5 MeV to 1.7 MeV when the $\Lambda_b^0\pi^+\pi^-$ mass grows from the mass of the $\Lambda_b(5912)^0$ state to that of the $\Lambda_b(6152)^0$ state. The masses and widths of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states are fixed to the values obtained in Ref. [9]. The $\Lambda_b^{*0}$ shape as a function of the $\Lambda_b^0\pi\pi$ mass $m$ is parameterised as

$$\mathcal{S}(m|m_0, \Gamma) \propto \frac{\Gamma \rho_3(m)}{(m_0^2 - m^2)^2 + m_0^2\Gamma^2 \left(\frac{\rho_3(m)}{\rho_3(m_0)}\right)^2},$$

(1)
The background-subtracted spectrum is consistent with the presence of relatively small contributions from $\Lambda_b^{*0} \rightarrow \Sigma_b^{*0}\pi^+$ and $\Lambda_b^{*0} \rightarrow \Lambda_b^0 J/\psi\pi^+\pi^-$ decays and a dominant contribution from nonresonant $\Lambda_b^{*0} \rightarrow \Lambda_b^0\pi^+\pi^-$ decays.

Table 2: Yields of excited baryons from the simultaneous fit to $\Lambda_b^0\pi\pi$ spectra with $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$.

<table>
<thead>
<tr>
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<th>$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$</th>
<th>$\Lambda_b^0 \rightarrow J/\psi pK^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^{*0}$</td>
<td>2570 ± 260</td>
<td>550 ± 80</td>
</tr>
<tr>
<td>$\Lambda_b(6146)^0$</td>
<td>520 ± 50</td>
<td>103 ± 22</td>
</tr>
<tr>
<td>$\Lambda_b(6152)^0$</td>
<td>480 ± 50</td>
<td>90 ± 21</td>
</tr>
</tbody>
</table>

where $\rho_3(m)$ is a three-body phase space of the $\Lambda_b^0\pi^+\pi^-$ system

$$
\rho_3(m) \equiv \frac{\pi^2}{4m^2} \int_{4m_b^2}^{(m-m_b)^2} \frac{dm_{\pi\pi}^2}{m_{\pi\pi}^2} \lambda^{1/2} \left( m_{\pi\pi}^2, m^2, m_{\Lambda_b^0}^2 \right) \lambda^{1/2} \left( m_{\pi\pi}^2, m_{\pi}^2, m_{K}^2 \right),
$$

$\lambda(x, y, z)$ stands for a Källén function \[46\], and $m_{\pi\pi}$ and $m_{\Lambda_b^0}$ denote the known masses of the charged $\pi$ meson and $\Lambda_b^0$ baryon, respectively. The mass, $m_0$, and width, $\Gamma$, of the $\Lambda_b^{*0}$ state are free parameters of the fit.

The yields of the fit components in the combined fit are reported in Table 2. The mass difference with respect to the $\Lambda_b^0$ baryon mass and the natural width of the $\Lambda_b^{*0}$ state are determined to be

$$
\Delta m_{\Lambda_b^{*0}} = 452.7 \pm 2.9 \text{ MeV},
$$

$$
\Gamma_{\Lambda_b^{*0}} = 72 \pm 11 \text{ MeV},
$$

where uncertainties are statistical only. The statistical significance of the $\Lambda_b^{*0}$ signal in $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ samples is obtained using Wilks’ theorem \[47\] and exceeds 14 and 7 standard deviations, respectively.

The earlier analysis of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states \[9\] has shown that a significant fraction of their decays into the $\Lambda_b^0\pi^+\pi^-$ final state proceeds via the intermediate $\Sigma_b^{*0}\pi^+$ and $\Sigma_b^{*0}\pi^-$ processes. Since the measured mass of the $\Lambda_b^{*0}$ state is above the $\Sigma_b\pi$ threshold, one might expect that this state decays via intermediate $\Sigma_b^{(*)}\pi^+$ states as well. However, performing the fits to the $\Sigma_b^{(*)}\pi$ mass spectra as was done in Ref. \[9\] is complicated by the fact that the $\Sigma_b^{(*)}\pi^+$ and $\Sigma_b^{(*)}\pi^-\pi^+$ kinematic regions overlap in the range of $\Lambda_b^0\pi^+\pi^-$ masses used for the $\Lambda_b^{*0}$ fit. Separating the contributions of the resonant and nonresonant $\Lambda_b^{*0}$ decays would require a full multidimensional fit in the $\Lambda_b^0\pi^+\pi^-$, $\Lambda_b^0\pi^+$, and $\Lambda_b^0\pi^-\pi^+$ masses, which is beyond the scope of this paper.

The $\Lambda_b^0\pi^+$ mass spectra from $\Lambda_b^0\pi^+\pi^-$ and $\Lambda_b^0\pi^+\pi^+$ combinations with $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ from the $\Lambda_b^{*0}$ signal-enhanced region $6.00 < m_{\Lambda_b^{*0}\pi\pi} < 6.14 \text{ GeV}$ are shown in Fig. 4. The $\Lambda_b^0\pi^±$ mass spectrum from the signal $\Lambda_b^{*0}$ decays is obtained assuming that the $\Lambda_b^0\pi^±$ spectra from the same-sign $\Lambda_b^0\pi^±\pi^±$ combinations represent the background. The background-subtracted spectrum is consistent with the presence of relatively small contributions from $\Lambda_b^{*0} \rightarrow \Sigma_b^{(*)}\pi^+$ and $\Lambda_b^{*0} \rightarrow \Sigma_b^{*0}\pi^+$ decays and a dominant contribution from nonresonant $\Lambda_b^{*0} \rightarrow \Lambda_b^0\pi^+\pi^-$ decays.
Figure 4: (Top) Spectra of $\Lambda^0_{b}\pi^\pm$ mass with $\Lambda^0_{b}\rightarrow \Lambda^+_c\pi^-$ for $\Lambda^0_{b}\pi^+\pi^-$ combinations (red points with error bars) and $\Lambda^0_{b}\pi^\pm\pi^\mp$ combinations (open blue histogram). (Bottom) Difference between $\Lambda^0_{b}\pi^+$ mass spectra from $\Lambda^0_{b}\pi^+\pi^-$ and $\Lambda^0_{b}\pi^\pm\pi^\mp$ combinations. The structures near 5.81 and 5.83 GeV correspond to the $\Sigma^\pm_{b}\rightarrow \Lambda^0_{b}\pi^\pm$ and $\Sigma^*\pm_{b}\rightarrow \Lambda^0_{b}\pi^\pm$ signals, respectively.

5 Analysis of the low-mass region

The $\Lambda^0_{b}\pi\pi$ mass spectra in the low-mass region $m_{\Lambda^0_{b}\pi\pi}<5.94$ GeV for $\Lambda^0_{b}\rightarrow \Lambda^+_c\pi^-$ and $\Lambda^0_{b}\rightarrow J/\psi pK^-$ samples are shown in Figs. 5 and 6, respectively. These distributions are used to measure the properties of the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states. A simultaneous binned fit, with narrow bins of 50 keV width, is performed to the six distributions with the sum of the two resonance components (in $\Lambda^0_{b}\pi^+\pi^-$ combinations only) and the combinatorial background component (in all six distributions). The combinatorial component is parameterised with a product of the three-body phase-space function and a positive polynomial function. The resonant components are given by relativistic $S$-wave Breit–Wigner lineshapes convolved with the resolution function obtained from simulation.
The shape of the combinatorial background is assumed to be the same in the opposite-sign \( \Lambda_b^0 \pi^+ \pi^- \) and same-sign \( \Lambda_b^0 \pi^\pm \pi^\mp \) spectra, but is allowed to differ for the \( \Lambda_b^0 \rightarrow \Lambda^+_c \pi^- \) and \( \Lambda_b^0 \rightarrow J/\psi pK^- \) samples. The results of the combined fit are presented in Table 3.

The natural widths of the \( \Lambda_b(5912)^0 \) and \( \Lambda_b(5920)^0 \) states are consistent with zero.

### 6 Systematic uncertainties

The systematic uncertainties of the mass and the width of the \( \Lambda_b^{**0} \) state and of the masses of the \( \Lambda_b(5912)^0 \) and \( \Lambda_b(5920)^0 \) states are summarised in Table 4.

A large uncertainty in the measurement of the \( \Lambda_b^{**0} \) parameters comes from the parameterisation of the \( \Lambda_b^{**0} \) signal distribution. The fit function from Eq. (1) describes three-body phase-space decays, while Fig. 4 suggests some contribution from decays via...
Figure 6: Mass spectra of selected (top) $\Lambda_b^0\pi^+\pi^-$, (middle) $\Lambda_b^0\pi^+\pi^+$ and (bottom) $\Lambda_b^0\pi^-\pi^-$ combinations for the $\Lambda_b^0 \rightarrow J/\psi p K^-$ sample. A simultaneous fit, described in the text, is superimposed.

Table 3: Results of the combined fit to the low-mass $\Lambda_b^0\pi\pi$ spectra.

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$</th>
<th>$\Lambda_b^0 \rightarrow J/\psi p K^-$</th>
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<tbody>
<tr>
<td>$N_{\Lambda_b(5912)^0}$</td>
<td>$234 \pm 17$</td>
<td>$57 \pm 9$</td>
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<tr>
<td>$N_{\Lambda_b(5920)^0}$</td>
<td>$843 \pm 33$</td>
<td>$204 \pm 17$</td>
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<tr>
<td>$\Delta m_{\Lambda_b(5912)^0}$ [MeV]</td>
<td>$292.582 \pm 0.029$</td>
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<td>$\Delta m_{\Lambda_b(5920)^0}$ [MeV]</td>
<td>$300.479 \pm 0.019$</td>
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<td>$m_{\Lambda_b(5920)^0} - m_{\Lambda_b(5912)^0}$ [MeV]</td>
<td>$7.896 \pm 0.034$</td>
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</table>
Table 4: Summary of systematic uncertainties for the mass difference with respect to the ground state $\Lambda_{b}^0$ and natural width of the $\Lambda_{b}^{*0}$ state and the mass-differences for the $\Lambda_{b}(5912)^0$ and $\Lambda_{b}(5920)^0$ states, $\Delta m_{\Lambda_{b}(1P)^0}$.

<table>
<thead>
<tr>
<th>Source</th>
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<th>$\Gamma_{\Lambda_{b}^{*0}}$ [MeV]</th>
<th>$\Delta m_{\Lambda_{b}(1P)^0}$ [MeV]</th>
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<tr>
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<td>–</td>
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</tbody>
</table>

The quasi-two-body phase-space functions $\rho_{\Sigma_{b}^{(*)}\pi}(m)$ for the decays via the intermediate $\Sigma_{b}^{(*)}\pi$ states are

$$
\rho_{\Sigma_{b}^{(*)}\pi}(m) = \left( \frac{m_{\Sigma_{b}^{(*)}}}{m} \right)^2 \left( \frac{2p}{\sqrt{s}} \right)^2 \left( \frac{2q}{1 + R^2 q^2} \right)^2 \int_{(m^2 + m_{\Sigma_{b}^{(*)}}^2)^2}^{(m_{\Sigma_{b}^{(*)}}^2 - s)^2} \frac{R^2 q^2}{1 + R^2 q^2} ds,
$$

$$
\Gamma'_{\Sigma_{b}^{(*)}}(s) = \left( \frac{m_{\Sigma_{b}^{(*)}}}{m_{\Sigma_{b}^{(*)}}^2} \right)^3 \left( \frac{q}{q_0} \right)^3 \left( \frac{1 + R^2 q_0^2}{1 + R^2 q^2} \right)^2,
$$

where $s$ stands for a squared mass of the $\Lambda_{b}^0\pi$ pair forming the $\Sigma_{b}^{(*)}$ resonance, $p$ denotes the momenta of the pion in the P-wave decay $\Lambda_{b}^{*0} \to \Sigma_{b}^{(*)}\pi$, $q$ denotes the momenta of the pion in the decay $\Sigma_{b}^{(*)} \to \Lambda_{b}^0\pi$, $q_0$ is the value of $q$ at $s = m_{\Sigma_{b}^{(*)}}^2$, $R = 3.5$ GeV$^{-1}$ corresponds to the breakup momentum of the P-wave Blatt–Weisskopf centrifugal barrier factor [48]. $m_{\Sigma_{b}^{(*)}}$ and $\Gamma_{\Sigma_{b}^{(*)}}$ are known mass and width of the $\Sigma_{b}^{(*)}$ states [6]. The function is reparameterised as

$$
\Gamma_{\text{NR}} = (1 - \alpha - \beta) \Gamma,
\Gamma_{\Sigma_{b}\pi} = \alpha \Gamma,
\Gamma_{\Sigma_{b}^*\pi} = \beta \Gamma,
$$
where the non-negative parameters $\alpha$ and $\beta$ account for the relative contributions from the $\Lambda_{b}^{*+0} \rightarrow \Sigma_{b}^{+0} \pi^{0}$ and $\Lambda_{b}^{*+0} \rightarrow \Sigma_{b}^{+0} \pi^{0}$ decays, respectively. A series of fits is performed with parameters $\alpha$ and $\beta$ varied within the ranges $0 \leq \alpha < 0.2$, $0 \leq \beta < 0.2$, and $\alpha + \beta \leq 0.3$, consistent with Fig. [4]. The mass of the $\Lambda_{b}^{*+0}$ state is found to be very stable with respect to such variations. The fitted mass does not change more than $0.5$ MeV while the fitted width increases up to $1.5$ MeV. These values are taken as systematic uncertainties due to the signal parameterisation. The nominal fit does not take the variations of the detector efficiency with the $\Lambda_{b}^{0} \pi^{+} \pi^{-}$ mass into account. An alternative fit is performed where the signal shape is multiplied by the efficiency function obtained from simulation. The difference with the nominal fit is added to the uncertainty on the signal parameterisation. Alternative parameterisations of the detector resolution functions, namely a symmetric variant of an Apollonios function [49], a double-sided Crystal Ball function [43], a modified Novosibirsk function [50, 51], a Student’s $t$-distribution and a hyperbolic secant function, cause negligible variation for the measured mass and width of the $\Lambda_{b}^{*+0}$ state. The signal parameterisation uncertainty in the measurement of the masses of the low-mass states is negligible.

The uncertainty in the combinatorial background shape parameterisation is accounted for by varying the degree of the polynomial functions from 3 to 4. The uncertainty in the $\Sigma_{b}\pi$ and $\Sigma_{b}^{*}\pi$ background functions is evaluated by modifying the parameters of the exponential parameterisation within the limits allowed by the fits to the background-subtracted $\Sigma_{b}^{(*)}\pi$ spectra. In order to assess a possible sensitivity of the fit parameters to the features of the background shape not accounted for by the variations mentioned above, fits are performed in narrower and broader $\Lambda_{b}^{0}\pi\pi$ regions and variations are included as an additional source of systematic uncertainty.

To assess the effect of the fixed parameters of the narrow $\Lambda_{b}(6146)^{0}$ and $\Lambda_{b}(6152)^{0}$ states from the previous analysis [9] in the higher-mass fit, the fits are performed with the masses and the widths of each of the two states left free to vary one by one. The resulting variations of the $\Lambda_{b}^{*+0}$ parameters are found to be negligible.

The effect of the calibration of the momentum scale is evaluated by varying the scale within its known uncertainty [7,9,25]. All systematic uncertainties for the mass difference $m_{\Lambda_{b}(5920)^{0}} - m_{\Lambda_{b}(5912)^{0}}$ are found to be negligible.

The upper limits on the natural widths of the $\Lambda_{b}(5912)^{0}$ and $\Lambda_{b}(5920)^{0}$ states are obtained by performing profile likelihood scans. In the calculation of the likelihood, the uncertainties in the knowledge of mass resolution are included by using various resolution models, as listed above, and by varying the mass-resolution scaling factor obtained from simulations within 5% [9,52,53] and the maximum upper limits across all variations are reported.

7 Results and summary

Using the LHCb data set taken in 2011–2018, corresponding to an integrated luminosity of $9$ fb$^{-1}$ collected in pp collisions at centre-of-mass energies of 7, 8 and 13 TeV, the $\Lambda_{b}^{0}\pi^{+}\pi^{-}$ mass spectrum is studied with $\Lambda_{b}^{0}$ baryons reconstructed in the $\Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+} \pi^{-}$ and $\Lambda_{b}^{0} \rightarrow J/\psi p K^{-}$ decay modes. A new broad resonance-like state is observed with a statistical significance exceeding 14 and 7 standard deviations for $\Lambda_{b}^{0}\pi^{+}\pi^{-}$ samples reconstructed using the $\Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+} \pi^{-}$ and $\Lambda_{b}^{0} \rightarrow J/\psi p K^{-}$ decay modes, respectively. The mass
difference with respect to the $\Lambda_b^0$ mass and natural width of the state are determined from a combined fit to both samples and are found to be

$$\Delta m_{\Lambda^*0} = 452.7 \pm 2.9 \pm 0.5 \text{ MeV},$$
$$\Gamma_{\Lambda^*0} = 72 \pm 11 \pm 2 \text{ MeV},$$

where the first uncertainty is statistical and the second systematic. Taking the mass of the $\Lambda_b^0$ baryon $m_{\Lambda_b^0} = 5619.62 \pm 0.16 \pm 0.13 \text{ MeV}$, obtained by a combination of measurements at the LHCb experiment in $\Lambda_b^0 \to \chi_{c1}pK^-$ [45], $\Lambda_b^0 \to \psi(2S)pK^-$, $\Lambda_b^0 \to J/\psi\pi^+\pi^-pK^-$ [54] and $\Lambda_b^0 \to J/\psi\Lambda$ decay modes [24,55], and accounting for the correlated systematic uncertainty, the mass of the $\Lambda^*0$ state is found to be

$$m_{\Lambda^*0} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV},$$

where the last uncertainty is due to that on the mass of the $\Lambda_b^0$ baryon. The new resonance is consistent with the broad excess of events reported by the CMS collaboration [14] and the measured mass and width agree with expectations for the $\Lambda_b(2S)^0$ state [15–17,56,57].

Several excited $\Sigma_b(1P)$ states are expected with a mass close to the measured value, but the partial decay widths for $\Sigma_b(1P)$ states into $\Lambda_b^0\pi\pi$ are predicted to be very small [58]. If the observed broad peak corresponds to the $\Sigma_b(1P)^+(0)^*$ state, two peaks with similar masses and widths and significantly larger yields should be visible in the $\Lambda_b^0\pi^\mp$ mass spectra due to decays of the charged isospin partners $\Sigma_b(1P)^+(0)^*\to\Lambda_b^0\pi^\mp$. However, no signs of states with such a mass and width, and large production yields are observed in the analysis of the $\Lambda_b^0\pi^\mp$ mass spectra; the observed $\Sigma_b(6097)^\pm$ states have significantly smaller natural width and relatively small yields [6]. It cannot be excluded that the observed broad structure corresponds to a superposition of more than one narrow states, but the interpretation of these states as excited $\Sigma_b$ resonances is disfavoured.

The mass differences for the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states with respect to the mass of the $\Lambda_b^0$ baryon are measured to be

$$\Delta m_{\Lambda_b(5912)^0} = 292.589 \pm 0.029 \pm 0.010 \text{ MeV},$$
$$\Delta m_{\Lambda_b(5920)^0} = 300.492 \pm 0.019 \pm 0.010 \text{ MeV},$$

and the corresponding masses are

$$m_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21 \text{ MeV},$$
$$m_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21 \text{ MeV},$$

where the last uncertainty is due to imprecise knowledge of the $\Lambda_b^0$ mass. The mass splitting between the narrow states is

$$m_{\Lambda_b(5920)^0} - m_{\Lambda_b(5912)^0} = 7.896 \pm 0.034 \text{ MeV}.$$

The following upper limits on the natural widths are obtained:

$$\Gamma_{\Lambda_b(5912)^0} < 0.25 (0.28) \text{ MeV},$$
$$\Gamma_{\Lambda_b(5920)^0} < 0.19 (0.20) \text{ MeV},$$

at 90% (95%) confidence level, respectively. The measurements of the parameters of the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states are about four times more precise and supersede those reported in Ref. [7].
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