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

LHCb collaboration†

Abstract

We report 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. A study of the structure suggests its interpretation as a superposition of two almost degenerate narrow states. The masses and widths of these states are measured to be

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

with a mass splitting of $\Delta m = 6.34 \pm 0.32 \pm 0.02 \text{ MeV}$, where the first uncertainty is statistical, the second systematic and the third derives from the knowledge of the mass of the $\Lambda_b^0$ baryon. The measured masses and widths of these new excited states suggest their possible interpretation as a doublet of $\Lambda_b(1D)^0$ states.


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In the constituent quark model \cite{1,2}, baryons containing a beauty quark form multiplets according to the internal symmetries of flavour, spin, and parity \cite{3}. Beyond the $\Lambda_b^0$ 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 \cite{4–8}. The spectrum of excited states decaying to the $\Lambda_b^0\pi^+\pi^-\pi^0$ final state has already been studied by the LHCb experiment with the discovery of two narrow states \cite{4}, denoted $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$. The heavier of these states was later confirmed by the CDF collaboration \cite{9}. Mass predictions for the ground-state beauty baryons and their orbital and radial excitations are given in many theoretical works, \textit{e.g.}, \cite{10–13}. In addition to the already observed doublet of first orbital excitations, more states are predicted in the mass region near or above 6.1 GeV.

In this Letter, we document the study of the $\Lambda_b^0\pi^+\pi^-$ spectrum (charge conjugation is implied throughout this article) in the extended mass region between 6.10 and 6.25 GeV, using pp collision data collected by the LHCb experiment at centre-of-mass energies of 7, 8, and 13 TeV. The combined data set corresponds to an integrated luminosity of 9 fb$^{-1}$.

The LHCb detector \cite{14,15} 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 \cite{16}, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes \cite{17} 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 \cite{18,19}. The relative accuracy of this procedure is estimated to be $3 \times 10^{-4}$ using samples of other fully reconstructed b-hadron, $K_S^0$, and narrow $\Upsilon(1S)$ resonance decays. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors \cite{20}. The online event selection is performed by a trigger \cite{21} 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. The software trigger requires a two-, three- or four-track secondary vertex with significant displacement from all primary pp interaction vertices. A multivariate algorithm \cite{22} is used for the identification of secondary vertices consistent with the decay of a b hadron. Simulated data samples are produced using the software packages described in Refs. \cite{23–27}.

Samples of $\Lambda_b^0$ candidates are formed from $\Lambda_c^+\pi^-$ combinations, where the $\Lambda_c^+$ baryon is reconstructed in the $pK^-\pi^+$ final state. All charged final-state particles are required to have particle-identification information consistent with their respective mass hypotheses. Misreconstructed tracks are suppressed by the use of a neural network \cite{25}. To suppress prompt background, the $\Lambda_b^0$ decay products are required to have significant $\chi^2_{IP}$, with respect to all PVs in the event, where $\chi^2_{IP}$ of a particle is the difference in $\chi^2$ of the vertex fit of a given PV, when the particle is included or excluded from the fit. The reconstructed $\Lambda_c^+$ vertex is required to have a good fit quality and to be significantly displaced from all PVs. The reconstructed $\Lambda_c^+$ mass must be within a mass window of $\pm 25$ MeV of the known

\textsuperscript{1}Natural units with $c = \hbar = 1$ are used throughout this Letter.
value \[29\]. Pion candidates are combined with \(\Lambda_c^+\) candidates to form \(\Lambda_b^0\) candidates, requiring good vertex-fit quality and separation of the \(\Lambda_b^0\) decay point from any PV in the event. A Boosted Decision Tree (BDT) discriminant \[30\] is used to further reduce the background level. The BDT exploits fifteen variables, including kinematic variables of the \(\Lambda_c^+\) and \(\Lambda_b^0\) candidates, the lifetime of the \(\Lambda_b^0\) candidate, kinematic variables and quality of particle identification for the final-state pions, kaons and protons, and variables describing the consistency of the selected candidates with the \(\Lambda_b^0 \to \Lambda_c^+\pi^-\) decay of a \(\Lambda_b^0\) baryon \[32\]. The BDT is trained using background-subtracted \[33\] \(\Lambda_b^0\) candidates as a signal sample and \(\Lambda_b^0\) candidates from the data sidebands, in the \(\Lambda_c^+\pi^-\) mass range 5.7 < \(m_{\Lambda_c^+\pi^-}\) < 6.1 GeV, as a background sample. The \(k\)-fold cross-validation technique with \(k=11\) is used in the BDT training \[34\]. The use of a multivariate discriminant allows the malle level of \(\Lambda_b^0\) background candidates in the analysis to be reduced by a further factor of two, keeping almost 100% efficiency for the signal. The resulting yield of \(\Lambda_b^0 \to \Lambda_c^+\pi^-\) decays is (892.8 ± 1.2) \(\times 10^3\). A sample of \(\Lambda_b^0 \to J/\psi pK^-\) candidates, with \(J/\psi \to \mu^+\mu^-\), is also selected in a similar way as a cross-check. The yield for this decay mode is smaller, corresponding to (217.5 ± 0.7) \(\times 10^3\) decays. The mass spectra of the selected \(\Lambda_b^0 \to \Lambda_c^+\pi^-\) and \(\Lambda_b^0 \to J/\psi pK^-\) candidates are shown in Fig. SI of the Supplemental Material of this Letter.

The selected \(\Lambda_b^0\) candidates are combined with pairs of pions compatible with originating from the same PV as the \(\Lambda_b^0\) candidate. Only pion pairs with \(p_T^2 \pi^- > 500\) MeV are used, to suppress the otherwise large combinatorial background from soft dipion combinations. This background is further reduced by using a dedicated BDT discriminant tuned on each of the two samples with \(\Lambda_b^0 \to \Lambda_c^+\pi^-\) and \(\Lambda_b^0 \to J/\psi pK^-\) decays. It exploits the transverse momentum of the \(\Lambda_b^0\pi^+\pi^-\) combination, the \(\chi^2\) value for the \(\Lambda_b^0\pi^+\pi^-\) vertex, the transverse momenta of both individual pions and the pion pair, as well as particle-identification and reconstruction-quality \[28\] variables for both pions. The BDT is trained on simulated samples of excited beauty baryons with a mass of 6.15 GeV as signal and same-sign \(\Lambda_b^0\pi^+\pi^-\) combinations in data, with \(m_{\Lambda_b^0\pi^+\pi^-} < 6.22\) GeV, as background.

In order to improve the \(\Lambda_b^0\pi^+\pi^-\) mass resolution, the \(\Lambda_b^0\pi^+\pi^-\) combinations are refitted constraining the masses of the \(\Lambda_c^+\) baryon (or \(J/\psi\) meson) to their known values \[29\] and requiring consistency of the \(\Lambda_b^0\pi^+\pi^-\) vertex with the PV associated with the \(\Lambda_b^0\) candidate \[32\]. The mass of the \(\Lambda_b^0\) baryon in the fit is constrained to the central value of \(m_{\Lambda_b^0} = 5618.62 ± 0.16 ± 0.13\) MeV \[35\], obtained from a combination of the measurements of the \(\Lambda_b^0\) mass in \(\Lambda_b^0 \to \chi_{c1}\p K^-\) \[35\], \(\Lambda_b^0 \to \psi(2S)pK^-\), \(\Lambda_b^0 \to J/\psi\pi^+\pi^-pK^-\), \[36\] and \(\Lambda_b^0 \to J/\psi\Lambda\) decay modes \[18\] \[37\] by the LHCb collaboration. The mass distributions for selected \(\Lambda_b^0\pi^+\pi^-\) candidates are shown in Fig. 1. Only \(\Lambda_b^0\) candidates with a mass within \(±50\) (20) MeV (approximately three times the resolution) of the known \(\Lambda_b^0\) mass for \(\Lambda_b^0 \to \Lambda_c^+\pi^-\) candidates (\(\Lambda_b^0 \to J/\psi pK^-\)) are used. There is a clear excess of \(\Lambda_b^0\pi^+\pi^-\) candidates around 6.15 GeV over the background for both \(\Lambda_b^0\) decay modes. The excess is initially treated as originating from a single broad state. The distributions are parameterised by the sum of signal and background components. The signal component is modelled by a relativistic S-wave Breit–Wigner function with Blatt–Weisskopf form factors \[38\]. The relativistic Breit–Wigner function is convolved with the detector resolution described by the sum of two Gaussian functions with common mean and parameters, which are fixed from simulation. The obtained effective resolution is 1.7 MeV. The background component is parameterised with a second-order polynomial function. Extended unbinned maximum-likelihood fits to the \(\Lambda_b^0\pi^+\pi^-\) mass spectra are shown
The mass and width of the structure agree between the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to J/\psi p K^-$ samples. The statistical significance for the signals is estimated using Wilks' theorem [39]. It is found to exceed twenty-six and nine standard deviations for

in Fig. [1]. The corresponding parameters of interest are listed in Table [1].

Table 1: The yields, $N$, masses, $m$, and natural widths, $\Gamma$, from the fits of a single broad state to the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra.

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda_b^0 \to \Lambda_c^+ \pi^-$ mode</th>
<th>$\Lambda_b^0 \to J/\psi p K^-$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\Lambda_b^0 \pi^+ \pi^-}$</td>
<td>3117 $\pm$ 240</td>
<td>431 $\pm$ 97</td>
</tr>
<tr>
<td>$m$ [MeV]</td>
<td>6149.6 $\pm$ 0.3</td>
<td>6151.5 $\pm$ 1.0</td>
</tr>
<tr>
<td>$\Gamma$ [MeV]</td>
<td>9.6 $\pm$ 1.0</td>
<td>9.7 $\pm$ 2.9</td>
</tr>
</tbody>
</table>
the $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ and $\Lambda^0_b \rightarrow J/\psi p K^-$ decay modes, respectively. The fitted parameters exhibit very modest dependence on the choice of the orbital momentum for the relativistic Breit–Wigner function and the Blatt–Weiskopf breakup momenta [38].

Since the mass of the new structure is above the $\Sigma^*_b(\pm)\pi^\mp$ kinematic thresholds, the $\Lambda^0_b \pi^+ \pi^-$ decay modes, respectively. The fitted parameters exhibit very modest dependence on the choice of the orbital momentum for the relativistic Breit–Wigner function and the Blatt–Weiskopf breakup momenta [38].

The mass spectrum is investigated in $\Lambda^0_b \pi^\pm$ mass regions populated by the $\Sigma^*_b(\pm)$ resonances. The data are split into three nonoverlapping regions: candidates with a $\Lambda^0_b \pi^\pm$ mass within the natural width of the known $\Sigma^*_b$ mass; candidates with a $\Lambda^0_b \pi^\pm$ mass within the natural width of the known $\Sigma^*_b$ mass; and the remaining nonresonant (NR) region. The $\Lambda^0_b \pi^+ \pi^-$ mass spectra in these three regions are shown in Fig. 2. Only the larger sample of $\Lambda^0_b$ candidates selected via the $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ decay mode is used here and in the remainder of this Letter. The spectra in the $\Sigma^*_b$ and $\Sigma^*_{b}$ regions look different and suggest the presence of two narrow peaks.

Doublets of orbitally excited states are predicted in the mass region near the observed peaks [10–13]. The spins and parities of the states in the doublet determine the lowest allowed orbital angular momentum in the two-body $\Sigma^*_b(\pm)\pi^\mp$ transition. The intensities of the transitions can be enhanced or suppressed depending on the angular momentum assignment. Heavy quark effective theory (HQET) also predicts different decay rates of the doublet members to the $\Sigma^*_b\pi^\mp$ and $\Sigma^*_b\pi^\mp$ final states [40]. To probe the two-resonance hypothesis, a simultaneous fit to the mass spectra in the three $\Lambda^0_b \pi^\pm$ mass regions is performed. For each region, the fit function consists of two signal components and a background component described by a second-order polynomial function. The signal components are modelled by relativistic Breit–Wigner functions convolved with the detector resolution. For the $\Sigma^*_b$ region, the signal components describe two-body intermediate states $\Sigma^*_b\pi^\mp$ in P- and D-wave for the low-mass and high-mass states, respectively. For the $\Sigma^*_{b}$ region, S- and P-wave are chosen for decays of low- and high-mass states, respectively. These choices are motivated by the possible interpretation of the new states as a doublet of $\Lambda_0(1D)^0$ states [10–13]. The masses and widths of the two states are taken as common parameters for the three regions, while the other parameters, namely the signal and background yields and background shape parameters, are allowed to vary independently. The two signal components are added incoherently, assuming interference effects are negligible, since a coherent production of the states in the complex environment of pp interactions is unlikely.

The results of the simultaneous extended unbinned maximum-likelihood fit to the $\Lambda^0_b \pi^+ \pi^-$ mass spectra in the three $\Lambda^0_b \pi^\pm$ mass regions are shown in Fig. 2. The two-signal hypothesis is favoured with respect to the single-signal hypothesis with a statistical significance exceeding seven standard deviations. The masses, $m$, and the natural widths, $\Gamma$, of the two narrow states, referred to hereafter as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, are measured to be

\[
\begin{align*}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \text{ MeV}, \\
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \text{ MeV}, \\
\Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \text{ MeV}, \\
\Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \text{ MeV},
\end{align*}
\]

with a mass splitting of $\Delta m = 6.34 \pm 0.32 \text{ MeV}$, where the uncertainties are statistical only. While these new states are denoted as $\Lambda_b$, their interpretation as other excited beauty baryons, such as neutral $\Sigma^0_b$ states, cannot be excluded.
To probe further the resonance structure of the $\Lambda_b(6146)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ and $\Lambda_b(6152)^0 \rightarrow \Lambda_b^0 \pi^+ \pi^-$ decays, the background-subtracted $\Lambda_b^0 \pi^\pm$ mass spectra are studied. The sPlot technique [33] is used here; it projects out the signal components from the combined signal-plus-background densities using $m_{\Lambda_b^0 \pi^\pm}$ as a discriminating variable. The resulting $\Lambda_b^0 \pi^\pm$ mass spectra are shown in Fig. 3. The spectra are fit with three components, describing the contributions from $\Sigma_b^\pm$, $\Sigma_b^{*\pm}$ and nonresonant decays. Relativistic S- and P-wave Breit–Wigner functions are used to describe $\Sigma_b^\pm \rightarrow \Lambda_b^0 \pi^\pm$ and

Figure 2: Mass distributions of selected $\Lambda_b^0 \pi^+ \pi^-$ candidates for the three regions in $\Lambda_b^0 \pi^\pm$ mass: (top) $\Sigma_b$, (middle) $\Sigma_b^{*}$ and (bottom) nonresonant (NR) region.
The nonresonant component is parameterised as a product of two-from-three-body decay phase space functions and a first-order polynomial function. The masses and widths of the $\Sigma_b^{(*)\pm}$ states are fixed to their known values. The results of extended unbinned maximum-likelihood fits to the background-subtracted $\Lambda_b^0 \pi^\pm$ mass distributions are shown in Fig. 3 and are presented in Table S3 of the Supplemental Material. Significant $\Lambda_b(6152)^0 \rightarrow \Sigma_b^{\pm} \pi^\mp$ and $\Lambda_b(6152)^0 \rightarrow \Sigma_b^{*\pm} \pi^\mp$ signals are observed, accounting for approximately one-third and one-quarter of the signal decays in the sample, respectively. The statistical significance of the contributions is in excess of seven and five standard deviations, respectively. For the $\Lambda_b(6146)^0$ state, $\Lambda_b(6146)^0 \rightarrow \Sigma_b^{*\pm} \pi^\mp$ decays account for about half of the observed decay rate with a statistical significance in excess of six standard deviations.
Table 2: Summary of the systematic uncertainties for the masses, $m$, and widths, $\Gamma$, of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states. All values are in keV.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Lambda_b(6146)^0$</th>
<th>$\Lambda_b(6152)^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m$</td>
<td>$\Gamma$</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>80</td>
<td>$-$</td>
</tr>
<tr>
<td>Signal model</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Resolution model</td>
<td>15</td>
<td>270</td>
</tr>
<tr>
<td>Background model</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>280</td>
</tr>
<tr>
<td>Including $\Lambda_b^0$ mass systematic</td>
<td>220</td>
<td>280</td>
</tr>
</tbody>
</table>

deviations. No significant $\Lambda_b(6146)^0 \rightarrow \Sigma_b^{\pm}\pi^\mp$ signals are observed.

Several sources of systematic uncertainty are considered. The most important source of systematic uncertainty on the mass measurements derives from the knowledge of the momentum scale. This uncertainty is evaluated by varying the momentum scale within its known uncertainty [19] and rerunning the mass fit. The second uncertainty arises from the assumed parameters of the Breit–Wigner functions. To estimate this uncertainty, the orbital angular momentum is changed from $L = 0$ to 2 for all signal components and the Blatt–Weisskopf breakup radii are varied from $1.5$ to $5 \text{ GeV}^{-1}$. Since the states are narrow and far from the thresholds, the fitted masses and widths have only very small dependency on the assumed parameters. The maximal changes to the fitted parameters with respect to the baseline fit are assigned as systematic uncertainties. The impact of the background model is evaluated by varying the order of the polynomial functions from two to four. A further source of uncertainty on the determination of the natural widths arises from known differences in resolution between data and simulation. This effect is assessed by varying conservatively the width of the resolution function by $\pm 10\%$, based on previous studies [5,7,42–45].

The different sources of systematic uncertainty are summarised in Table 2. In all cases they are smaller than the statistical uncertainties. A large part of the systematic uncertainty cancels for the mass splitting, $\Delta m$, between the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states. The remaining systematic uncertainty for $\Delta m$ is $20 \text{ keV}$. An additional uncertainty arises due to the value of the $\Lambda_b^0$ mass used in the constrained fit. The statistical uncertainty on the $\Lambda_b^0$ mass introduces an uncertainty of $0.16 \text{ MeV}$ on the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ masses. This uncertainty is quoted separately. The systematic uncertainty on the constraint is correlated, through the momentum scale, with the masses measured in this analysis and is instead included in the final systematic uncertainty in Table 2.

In summary, a new structure with high statistical significance is observed in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum using $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ decays, and confirmed using a sample of $\Lambda_b^0$ baryons reconstructed through the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay. An analysis of the $\Lambda_b^0\pi^+\pi^-$ mass spectra for the regions enriched by the $\Sigma_b^{(s)\pm}$ 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 masses and natural widths of these states are measured to
be

\begin{align*}
  m_{\Lambda_b(6146)^0} & = \ 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}, \\
  m_{\Lambda_b(6152)^0} & = \ 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}, \\
  \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{align*}

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 \( \Lambda_b^0 \) baryon. The mass differences with respect to the \( \Lambda_b^0 \) mass are measured to be

\begin{align*}
  m_{\Lambda_b(6146)^0} - m_{\Lambda_b^0} & = \ 526.55 \pm 0.33 \pm 0.10 \text{ MeV}, \\
  m_{\Lambda_b(6152)^0} - m_{\Lambda_b^0} & = \ 532.89 \pm 0.26 \pm 0.10 \text{ MeV},
\end{align*}

and the mass difference between the two states is measured to be \( 6.34 \pm 0.32 \pm 0.02 \text{ MeV} \).

The masses of the two states measured in this analysis are consistent with the predictions for the doublet of \( \Lambda_b(1D)^0 \) states with quantum numbers (spin \( J \) and parity \( P \)) \( J^P = \frac{3}{2}^+ \) and \( \frac{5}{2}^+ \) \[10, 13\]. Similar natural widths are expected for the two states of the doublet in HQET \[40\]. The observed decay pattern, where one of the states decays to both \( \Sigma_b \) with \( J^P = \frac{1}{2}^+ \) and \( \Sigma_b^* \) with \( J^P = \frac{3}{2}^+ \), while the other decays primarily to \( \Sigma_b^* \), is also consistent with the above assignment. However, the interpretation of these states as excited \( \Sigma_b^0 \) states cannot be excluded.

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References


[36] LHCb collaboration, R. Aaij et al., *Observation of $\Lambda_b^0 \to \psi(2S) p K^-$ and $\Lambda_b^0 \to J/\psi \pi^+ \pi^- p K^-$ decays and a measurement of the $\Lambda_b^0$ baryon mass*, JHEP 05 (2016) 132, arXiv:1603.06961.


[44] LHCb collaboration, R. Aaij et al., *$\chi_{c1}$ and $\chi_{c2}$ resonance parameters with the decays $\chi_{c1,c2} \to J/\psi \mu^+ \mu^-$*, Phys. Rev. Lett. 119 (2017) 221801, arXiv:1709.04247.

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† Deceased
Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system

Supplemental Material

The $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ candidates

The mass distributions for selected $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi pK^-$ candidates are shown in Fig. S1. The distributions are fit with a sum of a signal and a background component. The signal component is parameterised by a modified Gaussian function with power-law tails on both sides of the peak, while the background is parameterised by the product of an exponential function and a second-order polynomial function. The signal yields are listed in Table S1.

![Mass distribution of selected $\Lambda_b^0$ candidates](image)

Figure S1: Mass distribution of selected $\Lambda_b^0$ candidates from the (top) $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and (bottom) $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay modes.
Table S1: The signal yields for $\Lambda_b^0 \to \Lambda^+_c \pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N$ [10^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \to \Lambda^+_c \pi^-$</td>
<td>892.8 ± 1.2</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to J/\psi pK^-$</td>
<td>217.5 ± 0.7</td>
</tr>
</tbody>
</table>

Results of the simultaneous fit to $\Lambda_b^0 \pi^+ \pi^-$ mass spectra in the three $\Lambda_b^0 \pi^\pm$ mass regions

The yields of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ signals from the simultaneous extended unbinned maximum-likelihood fit to the $\Lambda_b^0 \pi^+ \pi^-$ mass spectra in the three $\Lambda_b^0 \pi^\pm$ mass regions are presented in Table S2.

Table S2: The yields of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ signals in the three $\Lambda_b^0 \pi^\pm$ mass regions.

<table>
<thead>
<tr>
<th>$\Sigma_b$ region</th>
<th>$\Sigma_b^*$ region</th>
<th>NR region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\Lambda_b(6146)^0}$</td>
<td>67 ± 40</td>
<td>460 ± 92</td>
</tr>
<tr>
<td>$N_{\Lambda_b(6152)^0}$</td>
<td>357 ± 52</td>
<td>305 ± 70</td>
</tr>
</tbody>
</table>

Results of the fits to background-subtracted $\Lambda_b^0 \pi^\pm$ mass spectra

The yield of $\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$ and $\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$ decays, determined from fits to the background-subtracted $\Lambda_b^0 \pi^\pm$ mass distributions, are summarized in Table S3.

Table S3: The yields, $N$, and statistical significance, $S_W$, of the $\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$ and $\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$ signals from the fits to the background-subtracted $\Lambda_b^0 \pi^\pm$ mass distributions.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N$</th>
<th>$S_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>213 ± 44</td>
<td>7.8σ</td>
</tr>
<tr>
<td>$\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>208 ± 43</td>
<td>7.6σ</td>
</tr>
<tr>
<td>$\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>163 ± 45</td>
<td>5.3σ</td>
</tr>
<tr>
<td>$\Lambda_b(6152)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>141 ± 45</td>
<td>4.5σ</td>
</tr>
<tr>
<td>$\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>53 ± 30</td>
<td>2.3σ</td>
</tr>
<tr>
<td>$\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>0 ± 20</td>
<td>—</td>
</tr>
<tr>
<td>$\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>285 ± 51</td>
<td>8.4σ</td>
</tr>
<tr>
<td>$\Lambda_b(6146)^0 \to \Sigma_b^{(*)\pm} \pi^\mp$</td>
<td>227 ± 52</td>
<td>6.3σ</td>
</tr>
</tbody>
</table>