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Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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A study of excited Λ_b^0 baryons is reported, based on a data sample collected in 2016–2018 with the CMS detector at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of up to $140\,\text{fb}^{-1}$. The existence of four excited Λ_b^0 states: $\Lambda_b^0(5912)^0$, $\Lambda_b^0(5920)^0$, $\Lambda_b^0(6146)^0$, and $\Lambda_b^0(6152)^0$ in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum is confirmed, and their masses are measured. The $\Lambda_b^0\pi^+\pi^-$ mass distribution exhibits a broad excess of events in the region of 6040–6100 MeV, whose origin cannot be discerned with the present data.

1. Introduction

Studies of excited baryonic states are an important aspect of hadron spectroscopy and help to shed light on the mechanisms responsible for dynamics of quarks and baryon formation. In particular, spectroscopy of baryons that contain a heavy-flavor quark, such as the Λ_b^0 baryon, can test predictions of heavy-quark effective theory [1]. A number of theoretical calculations exist for various orbital and radial excitations of the ground state baryons containing a b quark [2–16], including those of the Λ_b^0 baryon. In general, there are a number of excited Λ_b^0 baryon states predicted in the 5.9–6.4 GeV mass range. However, predictions are very diverse in terms of the specific mass spectrum and do not point to any common narrow mass region in which to search for these excited states. As an additional complication, the widths and the production cross sections of various excited states are generally unknown. This situation makes experimental searches for excited heavy-quark baryons both challenging and important for testing various theoretical models.

The existence of two narrow excited Λ_b^0 states, $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$, in the $\Lambda_b^0\pi^+\pi^-$ invariant mass spectrum near the kinematic threshold was reported by the LHCb Collaboration in 2012 [17] (charge-conjugate states are implied throughout this Letter). The measured masses are $M(\Lambda_b^0(5912)^0) = 5911.97 \pm 0.67\,\text{MeV}$ and $M(\Lambda_b^0(5920)^0) = 5919.77 \pm 0.67\,\text{MeV}$, and the respective natural widths were found to be below 0.83 and 0.75 MeV at 95% confidence level. The latter state was confirmed by the CDF Collaboration [18] soon thereafter with the mass measured to be $M(\Lambda_b^0(5920)^0) = 5919.22 \pm 0.76\,\text{MeV}$. The precision of these measurements was limited by the large uncertainty in the Λ_b^0 mass at the time; the current world-average values $M(\Lambda_b^0(5912)^0) = 5912.20 \pm 0.21\,\text{MeV}$ and $M(\Lambda_b^0(5920)^0) = 5919.92 \pm 0.19\,\text{MeV}$ [19] are based on the updated Λ_b^0 mass measurement [20,21]. Recently, the LHCb experiment has also presented an observation of two narrow higher-mass states in the $\Lambda_b^0\pi^+\pi^-$ spectrum, with the following masses and widths [22]: $M(\Lambda_b^0(6146)^0) = 6146.17 \pm 0.43\,\text{MeV}$, $\Gamma(\Lambda_b^0(6146)^0) = 2.9 \pm 1.3\,\text{MeV}$, and $M(\Lambda_b^0(6152)^0) = 6152.51 \pm 0.38\,\text{MeV}$, $\Gamma(\Lambda_b^0(6152)^0) = 2.1 \pm 0.9\,\text{MeV}$.

In this Letter, a study of the $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution in the 5900–6400 GeV range by the CMS Collaboration is reported. Both the $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$ states near the kinematic threshold are confirmed and their masses are measured. In addition, the $\Lambda_b^0\pi^+\pi^-$ distribution is investigated in the higher-mass region and signals consistent with the $\Lambda_b^0(6146)^0$ and $\Lambda_b^0(6152)^0$ states are observed. The ground state baryon Λ_b^0 is reconstructed via its decays into the $\mathrm{J}/\psi\Lambda$ and $\psi(2\mathrm{S})\Lambda$ channels. The analysis uses the proton-proton (pp) collision data recorded

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with the CMS detector in 2016–2018, during the CERN LHC Run 2 at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of up to $140\,\text{fb}^{-1}$.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

Events of interest are selected using a two-tiered trigger system [24]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The L1 trigger used in the analysis required at least two muons. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. The set of HLT algorithms used in the analysis requires two opposite-sign (OS) muons with various pseudorapidity η and transverse momentum p_{T} thresholds, compatible with being produced in the dimuon decays of J/ψ or $\psi(2\mathrm{S})$ mesons. Given that no single trigger algorithm is dedicated to the decay signature of interest, the analysis uses a combination of several triggers, with integrated luminosities up to $140\,\text{fb}^{-1}$.

3. Event selection

The event selection begins by requiring two OS muons passing the CMS soft-muon identification criteria [25] with $p_{\mathrm{T}} > 3\,\text{GeV}$ and $|\eta| < 2.2$. The muons must form a common vertex with a χ^2 fit probability (P_{vtx}) greater than 1%. The dimuon invariant mass is required to satisfy $2.90 < M(\mu^+\mu^-) < 3.95\,\text{GeV}$. If $M(\mu^+\mu^-)$ is below 3.4 GeV, the dimuon system is considered to be a J/ψ candidate, or a $\psi(2\mathrm{S})$ candidate otherwise.

Another $\psi(2\mathrm{S})$ decay channel is also used to increase the signal yield: $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. Two additional, high purity [26], OS tracks, assumed to be pions and labeled $\pi_{\psi(2\mathrm{S})}$, are required to have $p_{\mathrm{T}} > 0.35\,\text{GeV}$. They are fit to a common vertex with a J/ψ candidate, using a world-average J/ψ meson mass [19] constraint. The invariant mass of the J/ψ candidate and the two tracks must satisfy the requirement $3672 < M(\mathrm{J}/\psi\pi^+\pi^-) < 3700\,\text{MeV}$, corresponding to a window centered on the world-average $\psi(2\mathrm{S})$ meson mass, with a half-width of approximately three times the corresponding mass resolution.

A Λ candidate is formed from a displaced two-prong vertex, assuming the decay $\Lambda \to \mathrm{p}\pi^-$, as described in Ref. [27]. The $\mathrm{p}\pi^-$ invariant mass is required to be within $\pm 10\,\text{MeV}$ of the world-average Λ baryon mass m_{Λ}^{PDG} [19], which corresponds to approximately three times the Λ candidate mass resolution. The two tracks are refitted with their invariant mass constrained to m_{Λ}^{PDG}, and the obtained Λ candidate is required to have $P_{\text{vtx}} > 1\%$.

To form the Λ_{b}^0 candidates, the J/ψ or $\psi(2\mathrm{S})$ candidate and the Λ candidate are fit to a common vertex with $P_{\text{vtx}} > 1\%$, where the world-average J/ψ or $\psi(2\mathrm{S})$ mass [19] constraint is applied to the muon pair. In the case of the $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-$ decay channel, only the $\mathrm{J}/\psi \to \mu^+\mu^-$ mass constraint is used.

The primary vertex (PV) associated with the Λ_{b}^0 candidate is selected among all the reconstructed vertices by requiring the smallest angle between the reconstructed Λ_{b}^0 candidate momentum and the vector pointing from this vertex to the Λ_{b}^0 decay vertex. The PV is then refitted after removing the tracks associated with the Λ and either the J/ψ or $\psi(2\mathrm{S})$ candidates. The decay length of the Λ_{b}^0 candidate in the transverse plane, L_{xy}, is computed as the two-dimensional distance between the PV and the Λ_{b}^0 decay vertex, and is required to exceed three times its uncertainty. This selection helps to suppress the combinatorial background. In addition, the transverse momentum of the Λ_{b}^0 candidate is required to be well aligned with the transverse displacement vector: $\cos\alpha > 0.99$, where α is the angle between the projections on the plane transverse to the beams of the Λ_{b}^0 candidate momentum and of the vector connecting the PV with the Λ_{b}^0 decay vertex. The numbers of Λ_{b}^0 signal candidates after these requirements are about 39 000, 3400, and 4300 for the $\mathrm{J}/\psi\Lambda$, $\psi(2\mathrm{S})\Lambda$ ($\psi(2\mathrm{S}) \to \mu^+\mu^-$), and $\psi(2\mathrm{S})\Lambda$ ($\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-$) channels, respectively.

The $\Lambda_{\mathrm{b}}^0\pi^+\pi^-$ candidates are formed by combining the selected Λ_{b}^0 candidates with two OS tracks originating from the PV, as in Refs. [28–30], since the lifetime of excited Λ_{b}^0 states is expected to be negligible, resulting in prompt decays. Combinations of a Λ_{b}^0 candidate with two prompt same-sign (SS) pions are used as a control channel and form the SS control region, as opposed to the OS signal region. The higher-p_{T} pion of the pair is labeled $\pi_1^\pm$ and the lower-p_{T} pion $\pi_2^\pm$. To improve the $\Lambda_{\mathrm{b}}^0\pi^+\pi^-$ invariant mass resolution, all tracks forming the PV and the selected Λ_{b}^0 candidate, taken as a single "pseudo-track" with the momentum, its uncertainty, and the assigned mass equal to those of the Λ_{b}^0 candidate, are refit to a common vertex. The $\Lambda_{\mathrm{b}}^0\pi^+\pi^-$ invariant mass $m_{\Lambda_{\mathrm{b}}^0\pi^+\pi^-}$ is then calculated using the momenta of particles returned by this vertex fit through the relation $m_{\Lambda_{\mathrm{b}}^0\pi^+\pi^-} = M(\Lambda_{\mathrm{b}}^0\pi^+\pi^-) - M(\Lambda_{\mathrm{b}}^0) + m_{\Lambda_{\mathrm{b}}^0}^{\text{PDG}}$, where $m_{\Lambda_{\mathrm{b}}^0}^{\text{PDG}} = 5619.60 \pm 0.17\,\text{MeV}$ is the world-average Λ_{b}^0 baryon mass [19]. The PV refitting procedure improves the $\Lambda_{\mathrm{b}}^0\pi^+\pi^-$ mass resolution by up to 50%. Unless specified otherwise, multiple $\Lambda_{\mathrm{b}}^0\pi^+\pi^-$ candidates found in the same event are not discarded.

4. Simulated samples and selection optimization

Several simulated signal samples with different masses of excited Λ_{b}^0 states are used in the analysis. The PYTHIA 8.230 package [31] is used to simulate the production of the excited Λ_{b}^0 states. The Σ_b^0 baryon, with a modified mass value, is used as a proxy for an excited Λ_{b}^0 baryon. The decays are described with EVTGEN 1.6.0 [32]. Final-state photon radiation is included in EVTGEN using PHOTOS [33,34]. Generated events are then passed to a detailed GEANT4-based simulation [35] of the CMS detector, followed by the same trigger and reconstruction algorithms used for collision data. The simulation includes effects from multiple pp interactions in the same or nearby bunch crossings (pileup) with the multiplicity distribution matching that observed in data.

Simulated samples are used to optimize the selection criteria using the Punzi figure of merit [36], i.e., optimizing the value of $S/(\frac{5}{2} + \sqrt{B})$, where S is the simulated signal yield and B is the expected background, as estimated using the SS control region. This optimization scheme is independent of the signal normalization.

The selection requirements are optimized separately for the low-mass $m_{\Lambda_{\mathrm{b}}^0\pi^+\pi^-} < 5950\,\text{MeV}$ and high-mass $5950 < m_{\Lambda_{\mathrm{b}}^0\pi^+\pi^-} < 6400\,\text{MeV}$ regions, using the $\Lambda_{\mathrm{b}}^0(5912)^0$ and $\Lambda_{\mathrm{b}}^0(6150)^0$ simulated signal samples, respectively. For the low-mass region, the optimized criteria are: $p_{\mathrm{T}}(\pi_2^\pm) > 0.3\,\text{GeV}$, $p_{\mathrm{T}}(\pi_1^\pm) > 0.35\,\text{GeV}$, $\cos\alpha >$

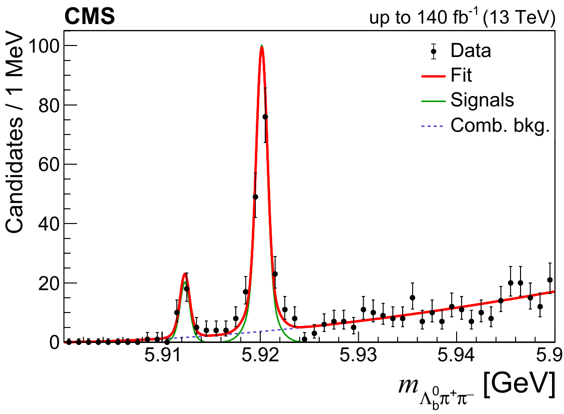

Fig. 1. Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates near threshold. The vertical bars on the data points display the statistical uncertainties in the data. The overall fit result is shown by the thick solid line, with the thin and dashed lines representing the signal and combinatorial background components, respectively.

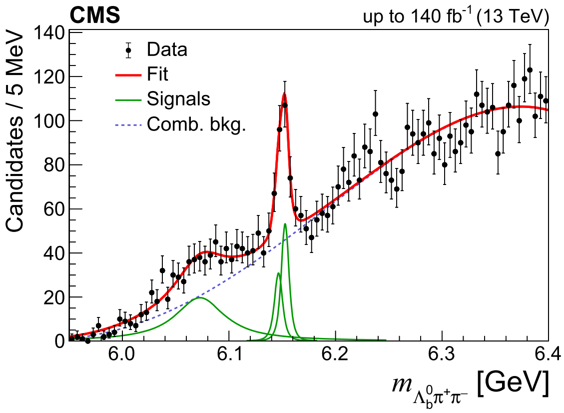

Fig. 2. Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates in the high-mass region. The vertical bars on the data points represent the statistical uncertainties in the data. The overall fit result is shown by the thick solid line. The thin lines present the contributions from the two signal peaks and the broad enhancement. The dashed line displays the combinatorial background.

0.995, $\cos\alpha^{3D} > 0.995$, and $p_T(\pi_{\psi(2S)}) > 0.4\,\text{GeV}$, where α^{3D} is a three-dimensional analog of the angle α. For the high-mass region, the optimized requirements are found to be $p_T(\pi_2^\pm) > 0.7\,\text{GeV}$, $p_T(\pi_1^\mp) > 1.4\,\text{GeV}$, $p_T(\Lambda_b^0) > 16\,\text{GeV}$, $P_{vtx}(\Lambda_b^0) > 2\%$, and $P_{vtx}(\Lambda_b^0\pi^+\pi^-) > 8\%$. In the high-mass region, due to higher backgrounds, if multiple excited Λ_b^0 candidates in an event pass the above requirements, only the highest p_T candidate is kept. In the low-mass region the average number of candidates per event is very close to one, while in the high-mass region it is around two.

5. Observed $\Lambda_b^0\pi^+\pi^-$ invariant mass spectra

The observed invariant mass distribution $m_{\Lambda_b^0\pi^+\pi^-}$ of the selected signal candidates near the threshold is shown in Fig. 1. The two narrow peaks corresponding to the $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$ baryons are modeled with double-Gaussian functions with the resolution parameters fixed to those obtained in simulation (effective resolutions are about 0.6 and 0.8 MeV). The background is modeled with a threshold function $(x - x_0)^\beta$, where x_0 is the mass threshold value. The value of β, as well as the masses and normalizations of the two signal functions, are free parameters of an unbinned maximum-likelihood fit to data. The best-fit signal yields are 28.4 ± 5.8 and 159 ± 14 events, and the measured masses are $5912.32 \pm 0.12\,\text{MeV}$ and $5920.16 \pm 0.07\,\text{MeV}$, respectively, where the uncertainties are statistical only. The presence of each of the peaks is established with a statistical significance of 5.7 and well over 6 standard deviations (σ), for the $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$ states, respectively, thereby confirming the existence of these two baryon states. The significances have been evaluated with the likelihood-ratio technique by applying the one- and two-peak signal hypotheses. The likelihood ratios are evaluated using an asymptotic formula [37,38]. The means and resolution parameters of the two peaks are allowed to vary in the fit within the Gaussian constraints from Ref. [19] and the simulation. The significance of the $\Lambda_b^0(5912)^0$ state varies between 5.4 and 5.7σ with the variations in the fit model used to estimate the systematic uncertainties, as detailed in Section 6; the significance of the $\Lambda_b^0(5920)^0$ state remains well above 6σ.

Higher masses in the $m_{\Lambda_b^0\pi^+\pi^-}$ distribution are studied as well, as shown in Fig. 2. A narrow peak at approximately 6150 MeV is evident, consistent with an overlap of the $\Lambda_b^0(6146)^0$ and $\Lambda_b^0(6152)^0$ signals, as well as a broad enhancement in the region below 6100 MeV. None of these features are present in the SS control region, as shown in the supplemental material [URL will be inserted by publisher].

A number of cross-checks have been performed to understand if the broad enhancement can be the result of a kinematic reflection or produced by a background process. It was found that the enhancement is not compatible with the partially reconstructed decays of $\Lambda_b^0(6146)^0$ or $\Lambda_b^0(6152)^0$ states into $\Lambda_b^0\pi^+\pi^-\pi^0$ (where the π^0 is lost). To check if it can be due to some other state decaying into the $\Lambda_b^0 K^\pm\pi^\mp$ channels, the $\Lambda_b^0 K\pi$ invariant mass distributions are obtained by substituting the pion mass with the kaon mass. No significant enhancements over the smooth background are found. The $m_{\Lambda_b^0\pi^+\pi^-}$ background distribution is found to be in agreement between the SS and OS regions in the simulation and does not show any enhancement in the 6000–6100 MeV mass region. The two-dimensional distributions of the $\Lambda_b^0\pi^+\pi^-$ mass versus the $\Lambda_b^0\pi^+$ and $\Lambda_b^0\pi^-$ masses from data are shown in the supplemental material [URL will be inserted by publisher]. If the $\Lambda_b^0\pi^\pm$ invariant mass ranges corresponding to the Σ_b^-, Σ_b^+, Σ_b^{*-}, and Σ_b^{*+} baryons are vetoed, the SS and OS mass distributions in data are found to be in agreement in the region below 6100 MeV and do not exhibit a broad enhancement, as shown in the supplemental material [URL will be inserted by publisher]. This suggests that the broad excess might be related to the intermediate $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ baryon states, although the current size of the data set does not allow this hypothesis to be tested.

The observed $m_{\Lambda_b^0\pi^+\pi^-}$ distribution in the high-mass region is fit with a sum of three signal functions and a smooth background function obtained by multiplying the threshold function $(x - x_0)^\beta$ by a first-order polynomial. The signal function describing the broad structure below 6100 MeV is a single Breit–Wigner function convolved with a double-Gaussian resolution function obtained from simulation. The narrow peak around 6150 MeV is modeled with the sum of two Breit–Wigner functions, each convolved with a double-Gaussian resolution function obtained from simulation, having an effective mass resolution of about 3.8 MeV. The natural widths of the two signals are fixed to those measured by the LHCb Collaboration [22]. The fit results for the yields and masses, respectively, are 301 ± 72 and $6073 \pm 5\,\text{MeV}$ for the broad enhancement, 70 ± 35 and $6146.5 \pm 1.9\,\text{MeV}$ for the $\Lambda_b^0(6146)^0$, and 113 ± 35 and $6152.7 \pm 1.1\,\text{MeV}$ for the $\Lambda_b^0(6152)^0$. The measured natural width of the broad excess is $55 \pm 11\,(\text{stat})\,\text{MeV}$. While this work was under the journal review, a similar structure, consistent with the one reported here and possibly a new baryon state, has been observed by the LHCb Collaboration [39].

Using the likelihood-ratio technique and the one- versus two-peak hypotheses, the presence of two peaks has a statistical significance of 0.4σ, indicating that the data are also consistent with a single peak at 6150 MeV. For the double-peak hypothesis, the natural widths of the two states are allowed to vary in the fit within the Gaussian constraints from the LHCb measurement [22]. In the single-peak hypothesis, the mass and the natural width of the signal peak are free parameters of the fit. In both cases, the mass resolution is allowed to float in the fit within its Gaussian uncertainty estimated from simulation. The local statistical significance of the single-peak hypothesis with respect to the background-only hypothesis is found to be over 6σ in the baseline fit, and varies between 5.4 and 6.5σ with the changes in the fit range and the model used to estimate the systematic uncertainties, as detailed in Section 6. The broad enhancement has a local statistical significance of about 4σ. Resonances with masses between 6200 and 6400 MeV have been also considered in the fit model and no significant excess was found. The present amount of data does not allow us to perform conclusive studies of $\Sigma_b^{*\pm} \to \Lambda_b^0\pi^\pm$ decay contributions to the resonances decaying into $\Lambda_b^0\pi^+\pi^-$.

6. Systematic uncertainties

Several sources of systematic uncertainties in the measured masses are considered. To evaluate the systematic uncertainties related to the choice of the fit model, several alternative signal and background functions are tested. Uncertainties related to the choice of the signal and background models are evaluated separately. The systematic uncertainty in each measurement is calculated as the maximum deviation of the observed mass value from the baseline fit result. The alternative signal model corresponds to a single-Gaussian resolution function; the alternative background models for the low- and high-mass regions are first- and second-order polynomials, respectively, multiplied by the same threshold function as in the baseline fit.

For the high-mass region, the nature of the broad excess below 6100 MeV is unclear, therefore an additional fit is performed in the region $m_{\Lambda_b^0\pi^+\pi^-} > 6100$ MeV, and the observed deviations from the baseline fit result in the measured masses are taken as the systematic uncertainties related to the possible presence of the broad resonance.

The systematic uncertainty from the choice of the fit range is evaluated by extending the range up to 6650 MeV. The observed deviations in the measured masses are taken as the systematic uncertainties. The systematic uncertainties due to fit range variations are negligible for the $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$ states.

In the baseline fits of the $m_{\Lambda_b^0\pi^+\pi^-}$ distributions, the mass resolutions are fixed to those estimated from simulated event samples. The systematic uncertainty associated with a possible differences between data and simulation is calculated using the following procedure. The mass resolutions are compared between data and simulation for the copious $\Lambda_b^0 \to \mathrm{J}/\psi\,\Lambda$ signal: they are, respectively, 15.25 and 15.78 MeV, corresponding to a difference of 3.5%. This difference is considered to be the uncertainty in the resolution due to the data-simulation difference. To estimate the effect of this uncertainty on the measured masses, the baseline fits are redone with the resolutions increased or decreased by 3.5%, and the largest deviation in the measured masses from the baseline fit results is considered as the systematic uncertainty due to the mass resolution.

The measured masses of the $\Lambda_b^0(6146)^0$ and $\Lambda_b^0(6152)^0$ states have an additional systematic uncertainty due to the fact that their natural widths were fixed in the nominal fit to the values reported by LHCb. To estimate the respective uncertainty, the nominal fit is repeated with the natural widths fixed to the central values obtained by LHCb plus or minus the corresponding uncertainties (in total 8 additional fits are performed).

A potential bias in the mass measurement due to a possible misalignment of the tracker detectors has been evaluated by comparing distributions obtained in 2016, 2017, and 2018 running periods, which is a reasonable comparison, given that an important fraction of the CMS tracking detector was replaced between the 2016 and 2017 data taking. As expected, the alignment of the detector leads to a negligible systematic uncertainty in the results reported in this Letter.

The various systematic uncertainties are summarized in Table 1, together with the total uncertainties calculated as the quadratic sum of the individual sources.

7. Summary

In summary, using the pp collision data recorded with the CMS detector at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of up to 140 fb^{-1}, the existence of the $\Lambda_b^0(5912)^0$ and $\Lambda_b^0(5920)^0$ baryons is confirmed. Their masses, with respect to the Λ_b^0 mass, are measured to be $292.72 \pm 0.12 \pm 0.01$ MeV and $300.56 \pm 0.07 \pm 0.01$ MeV, respectively, where the first uncertainty is statistical and the second is systematic. By adding the known Λ_b^0 mass of 5619.60 ± 0.17 MeV [19], we report the mass measurements

$$M(\Lambda_b^0(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\mathrm{MeV},$$

$$M(\Lambda_b^0(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\mathrm{MeV},$$

where the third uncertainty is the uncertainty in the world-average Λ_b^0 mass. The obtained values are consistent with the world-average values and have similar precision.

In addition, the $\Lambda_b^0\pi^+\pi^-$ invariant mass spectrum is investigated in the mass range up to 6400 MeV. A narrow peak is observed with a mass close to 6150 MeV, with a significance over 5 standard deviations, consistent with the superposition of the $\Lambda_b^0(6146)^0$ and $\Lambda_b^0(6152)^0$ baryons recently observed by the LHCb Collaboration [22]. The masses of these states are measured to be

$$M(\Lambda_b^0(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\mathrm{MeV},$$

$$M(\Lambda_b^0(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\mathrm{MeV},$$

where the first uncertainty is statistical, the second is systematic, and the third is the uncertainty in the world-average Λ_b^0 mass value. The corresponding mass differences with respect to the Λ_b^0 mass are

$$M(\Lambda_b^0(6146)^0) - M(\Lambda_b^0) = 526.9 \pm 1.9 \pm 0.8\,\mathrm{MeV},$$

$$M(\Lambda_b^0(6152)^0) - M(\Lambda_b^0) = 533.1 \pm 1.1 \pm 0.4\,\mathrm{MeV}.$$

These measurements are not as precise as, but are in good agreement with the LHCb results [22].

In addition, a broad excess of events is observed in the region 6040–6100 MeV, not present in the same-sign $\Lambda_b^0\pi^\pm\pi^\pm$ distribution. If it is fit with a single Breit-Wigner function, the returned mass and width are $6073 \pm 5\,(\mathrm{stat})$ MeV and $55 \pm 11\,(\mathrm{stat})$ MeV. However, it is not excluded that this enhancement is an overlap of more than one state with close masses or is created by the partially reconstructed decays of higher-mass states. More data are needed to elucidate the nature of this excess.

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Table 1
Systematic uncertainties (in MeV) in the measured masses. A dash means that the corresponding uncertainty is negligible, and "N/A" means that it does not apply.

Source	$M(\Lambda_b^0(5912)^0)$	$M(\Lambda_b^0(5920)^0)$	$M(\Lambda_b^0(6146)^0)$	$M(\Lambda_b^0(6152)^0)$
Signal model	0.005	0.011	0.21	0.23
Background model	0.004	–	0.16	0.14
Inclusion of the broad excess region	N/A	N/A	0.35	0.14
Fit range	–	–	0.40	0.02
Mass resolution	0.007	0.001	0.01	0.09
Knowledge of Γ	N/A	N/A	0.43	0.26
Total	0.009	0.011	0.77	0.41

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Appendix A. Supplementary material

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