Observation of the decay $\Lambda_b^0 \to \psi(2S)p\pi^-$

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

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right)} = (11.4 \pm 1.3 \pm 0.2)\%,$$

where the first uncertainty is statistical and the second is systematic. The $\psi(2S)p$ and $\psi(2S)\pi^-$ mass spectra are investigated and no evidence for exotic resonances is found.

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Contents

1   Introduction

The Λ_b^0 baryon is the isospin-singlet ground state of a bound system of a beauty quark and two light quarks. The high production rate of b quarks at the Large Hadron Collider (LHC) [1–5], along with the excellent mass resolution and hadron-identification capabilities of the LHCb detector, give access to a variety of decay channels of the Λ_b^0 baryon, including multibody, rare, charmless and semileptonic decays [6–25]. The high signal yield of the $\Lambda_b^0 \to J/\psi\, pK^-$ decay [15] facilitated a precise measurement of the Λ_b^0 lifetime [26], while the relatively low energy released in the $\Lambda_b^0 \to \psi(2S)pK^-$ and $\Lambda_b^0 \to \chi_c pK^-$ decays allowed for precise measurements of the Λ_b^0 mass [16, 22]. A six-dimensional amplitude analysis of the $\Lambda_b^0 \to J/\psi\, pK^-$ decay resulted in the observation of the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquark states decaying into the $J/\psi\, p$ final state [27]. Later, these states were confirmed using a model-independent technique [28]. Subsequently, an analysis of Cabibbo-suppressed $\Lambda_b^0 \to J/\psi\, p\pi^-$ decays found evidence for contributions from the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquarks and from the $Z_c(4200)^-$ tetraquark [29].

The first observation of Λ_b^0 decays to the excited charmonium state $\psi(2S)$ was made in the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay mode by the ATLAS collaboration [30]. Later, the decay $\Lambda_b^0 \to \psi(2S)pK^-$ was observed by the LHCb collaboration [16]. The Cabibbo-suppressed analogue of the latter decay, $\Lambda_b^0 \to \psi(2S)p\pi^-$, is of particular interest because of possible contributions from exotic states in both the $\psi(2S)p$ system, similar to the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquark states, and in the $\psi(2S)\pi^-$ system, analogous to the charged charmonium-like state $Z_c(4430)^-$ studied in detail by the Belle and LHCb collaborations in $B \to \psi(2S)\pi^- K$ decays [31–35]. Depending on the nature of a proposed exotic state, its coupling with the $\psi(2S)$ meson can be larger than with the J/ψ meson. For example,

the decay rate of the X(3872) particle to the $\psi(2S)\gamma$ final state was found to exceed the corresponding decay rate to the $J/\psi\gamma$ final state [36, 37].

This paper reports the first observation of the decay $\Lambda_b^0 \to \psi(2S)p\pi^-$ using a data sample collected by the LHCb experiment in proton-proton collisions corresponding to 1.0, 2.0 and $1.9\,\text{fb}^{-1}$ of integrated luminosity at centre-of-mass energies of 7, 8 and 13 TeV, respectively. A measurement is made of the $\Lambda_b^0 \to \psi(2S)p\pi^-$ branching fraction relative to that of the Cabibbo-favoured decay $\Lambda_b^0 \to \psi(2S)pK^-$,

$$R_{\pi/K} \equiv \frac{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right)}, \tag{1.1}$$

where the $\psi(2S)$ mesons are reconstructed in the $\mu^+\mu^-$ final state. Throughout this paper the inclusion of charge-conjugated processes is implied.

2 Detector and simulation

The LHCb detector [38, 39] is a single-arm forward spectrometer covering the pseudo-rapidity 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, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\,\text{Tm}$, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at $200\,\text{GeV}/c$. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)\,\mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICH). Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger [40], 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 hardware trigger selects muon candidates with high transverse momentum or dimuon candidates with high value of the product of the p_T of each muon. The subsequent software trigger is composed of two stages, the first of which performs a partial event reconstruction, while full event reconstruction is done at the second stage. In the software trigger, each pair of oppositely charged muons forming a good-quality two-track vertex is required to be significantly displaced from all PVs and the mass of the pair is required to exceed $2.7\,\text{GeV}/c^2$.

The techniques used in this analysis are validated using simulated events. In the simulation, pp collisions are generated using PYTHIA [41] with a specific LHCb configuration [42]. Decays of hadronic particles are described by EVTGEN [43], in which final-state radiation

is generated using PHOTOS [44]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [45, 46] as described in ref. [47].

3   Event selection

The signal $\Lambda_b^0 \to \psi(2S)p\pi^-$ and the normalization $\Lambda_b^0 \to \psi(2S)pK^-$ decays are both reconstructed using the decay mode $\psi(2S) \to \mu^+\mu^-$. Similar selection criteria, based on those used in ref. [16], are applied to both channels.

Muon, proton, pion and kaon candidates are identified using combined information from the RICH, calorimeter and muon detectors. They are required to have a transverse momentum larger than 550, 900, 500 and 200 MeV/c, respectively. To allow for an efficient particle identification, kaons and pions are required to have a momentum between 3.2 and 150 GeV/c, whilst protons must have a momentum between 10 and 150 GeV/c. To reduce the combinatorial background due to particles produced in the pp interaction, only tracks that are inconsistent with originating from a PV are used.

Pairs of oppositely charged muons consistent with originating from a common vertex are combined to form $\psi(2S) \to \mu^+\mu^-$ candidates. The mass of the dimuon candidate is required to be between 3.67 and 3.70 GeV/c^2, where the asymmetric mass range around the known $\psi(2S)$ mass [48] is chosen to account for final-state radiation. The position of the reconstructed dimuon vertex is required to be inconsistent with that of any of the reconstructed PVs.

To form signal (normalization) Λ_b^0 candidates, the selected $\psi(2S)$ candidates are combined with a proton and a pion (kaon) of opposite charges. Each Λ_b^0 candidate is associated with the PV with respect to which it has the smallest χ_{IP}^2, where χ_{IP}^2 is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the particle under consideration. To improve the Λ_b^0 mass resolution, a kinematic fit [49] is performed. This fit constrains the four charged final-state particles to form common vertex, the mass of the $\mu^+\mu^-$ combination to the known $\psi(2S)$ mass and the Λ_b^0 candidate to originate from the associated PV. A good quality of this fit is required to further suppress combinatorial background. In addition, the measured decay time of the Λ_b^0 candidate, calculated with respect to the associated PV, is required to be between 0.2 and 2.0 mm/c to suppress poorly reconstructed candidates and background from particles originating from the PV.

To suppress cross-feed from $B^0 \to \psi(2S)K^+\pi^-$ decays with the positively charged kaon (negatively charged pion) misidentified as a proton (antiproton) for the signal (normalization) channel, a veto is applied on the Λ_b^0 candidate mass recalculated with a kaon (pion) mass hypothesis for the proton. Any candidate with a recalculated mass consistent with the nominal B^0 mass is rejected. A similar veto is applied to suppress cross-feed from $B_s^0 \to \psi(2S)K^-K^+$ decays with the positively charged kaon misidentified as a proton, and additionally for the signal channel, the negatively charged kaon misidentified as a pion. Finally, to suppress cross-feed from the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay, followed by a $\Lambda \to p\pi^-$ decay, candidates with a pπ^- mass that is consistent with the nominal Λ mass [48] are rejected.
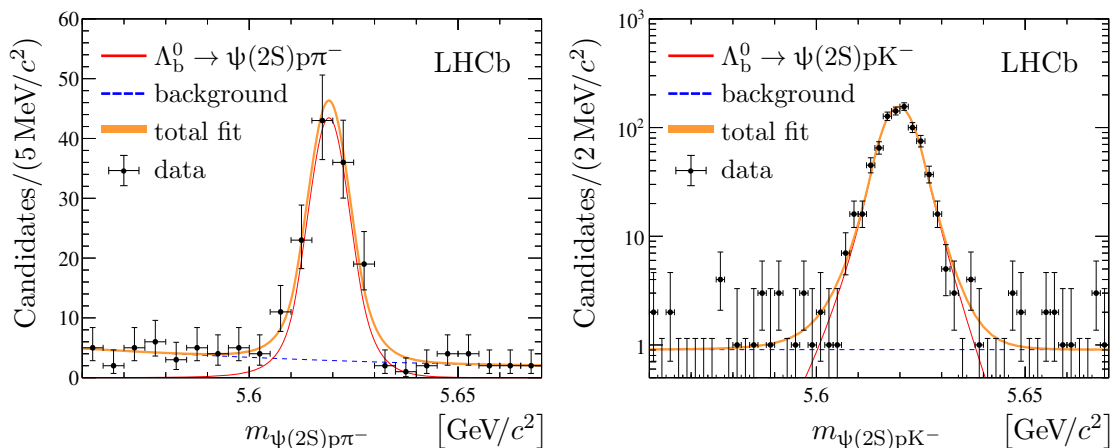
Figure 1. Mass distributions of the (left) $\Lambda_b^0 \to \psi(2S)p\pi^-$ and (right) $\Lambda_b^0 \to \psi(2S)pK^-$ candidates.

4 Signal yields and efficiencies

The mass distributions for the selected $\Lambda_b^0 \to \psi(2S)p\pi^-$ and $\Lambda_b^0 \to \psi(2S)pK^-$ candidates are shown in figure 1. The signal yields are determined using unbinned extended maximum-likelihood fits to these distributions. For each distribution the Λ_b^0 component is described by a modified Gaussian function with power-law tails on both sides [50, 51]. The tail parameters are fixed to values obtained from simulation, and the peak position and resolution of the Gaussian function are free to vary in the fit. The combinatorial background component is described by a monotonic second-order polynomial function with positive curvature. The resolution parameters obtained from the fits are found to be $5.23 \pm 0.55\,\mathrm{MeV}/c^2$ for the $\Lambda_b^0 \to \psi(2S)p\pi^-$ channel and $3.96 \pm 0.13\,\mathrm{MeV}/c^2$ for the $\Lambda_b^0 \to \psi(2S)pK^-$ channel, which are in good agreement with expectations from simulation. The signal yields are determined to be 121 ± 13 and 806 ± 29 for the $\Lambda_b^0 \to \psi(2S)p\pi^-$ and $\Lambda_b^0 \to \psi(2S)pK^-$ decay modes, respectively.

The resonance structure of the $\Lambda_b^0 \to \psi(2S)p\pi^-$ decay is investigated using the *sPlot* technique [52] for background subtraction, with the reconstructed $\psi(2S)p\pi^-$ mass as the discriminating variable. The background-subtracted mass distributions of $\psi(2S)p$, $\psi(2S)\pi^-$ and $p\pi^-$ combinations are shown in figure 2, along with those obtained from simulated decays generated according to a phase-space model. The $\psi(2S)p$ and $\psi(2S)\pi^-$ mass distributions show no evidence for contributions from exotic states. The mass distribution of the $p\pi^-$ combination differs from the phase-space model, indicating possible contributions from excited N^0 and Δ^0 states. Further studies with a larger data sample will provide a deeper insight into the underlying structure of the $\Lambda_b^0 \to \psi(2S)p\pi^-$ decay.

The ratio of branching fractions $R_{\pi/K}$, defined in eq. (1.1), is measured as

$$R_{\pi/K} = \frac{N_{\Lambda_b^0 \to \psi(2S)p\pi^-}}{N_{\Lambda_b^0 \to \psi(2S)pK^-}} \frac{\varepsilon_{\Lambda_b^0 \to \psi(2S)pK^-}}{\varepsilon_{\Lambda_b^0 \to \psi(2S)p\pi^-}}, \qquad (4.1)$$
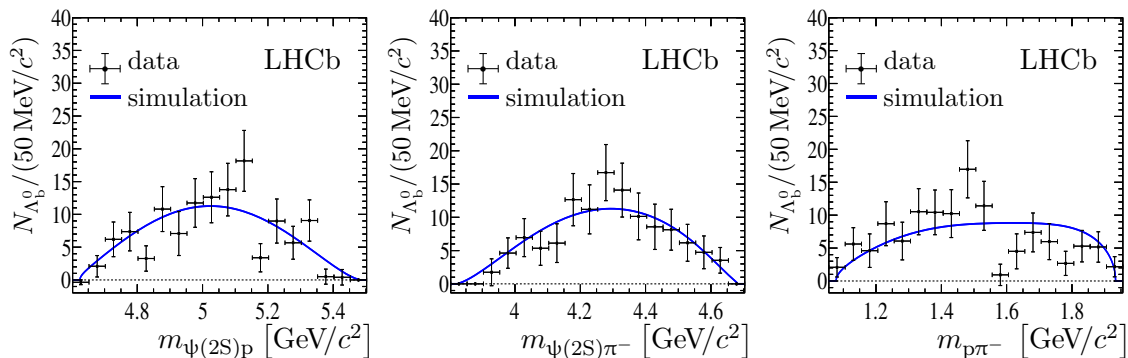
Figure 2. Background-subtracted mass distributions of the (left) $\psi(2S)p$, (centre) $\psi(2S)\pi^-$ and (right) $p\pi^+$ combinations in the $\Lambda_b^0 \to \psi(2S)p\pi^-$ decay compared with distributions obtained from a phase-space simulation.

where N represents the measured yield and ε denotes the efficiency of the corresponding decay. The efficiency is defined as the product of the geometric acceptance and the detection, reconstruction, selection and trigger efficiencies. The hadron-identification efficiencies as functions of kinematics and the event multiplicity are determined from data using the following calibration samples of low-background decays: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $K_S^0 \to \pi^+\pi^-$ and $D_s^+ \to \phi(\to K^+K^-)\pi^+$ for kaons and pions; and $\Lambda \to p\pi^-$ and $\Lambda_c^+ \to pK^+\pi^-$ for protons [53, 54]. The remaining efficiencies are determined using simulation. The p_T and rapidity spectra and the lifetime of the Λ_b^0 baryons in simulated samples are adjusted to match those observed in a high-yield low-background sample of reconstructed $\Lambda_b^0 \to J/\psi\, pK^-$ decays. The simulated samples are produced according to a phase-space decay model. The simulated $\Lambda_b^0 \to \psi(2S)pK^-$ decays are corrected to reproduce the pK^- mass and $\cos\theta_{pK^-}$ distributions observed in data, where θ_{pK^-} is the helicity angle of the pK^- system, defined as the angle between the momentum vectors of the kaon and Λ_b^0 baryon in the pK^- rest frame. To account for imperfections in the simulation of charged tracks, corrections obtained using data-driven techniques are also applied [55].

The efficiencies are determined separately for each data-taking period and are combined according to the corresponding luminosity [56] for each period and the known production cross-section of $b\bar{b}$ pairs in the LHCb acceptance [1–5]. The ratio of the total efficiency of the normalization channel to that of the signal channel is determined to be

$$\frac{\varepsilon_{\Lambda_b^0\to\psi(2S)pK^-}}{\varepsilon_{\Lambda_b^0\to\psi(2S)p\pi^-}} = 0.761 \pm 0.004\,, \tag{4.2}$$

where only the uncertainty that arises from the sizes of the simulated samples is given. Additional sources of uncertainty are discussed in the following section. The kaon identification efficiency, entering into $\varepsilon_{\Lambda_b^0\to\psi(2S)pK^-}$, is the main factor causing non-equality of the total efficiencies for the signal and normalization channels.

5 Systematic uncertainties

Since the signal and normalization decay channels have similar kinematics and topologies, most systematic uncertainties cancel in the ratio $R_{\pi/K}$, e.g. those related to muon identification. The remaining contributions to the systematic uncertainty are listed in table 1 and discussed below.

To estimate the systematic uncertainty related to the fit model, pseudoexperiments are sampled from the baseline fit models with all parameters fixed from those obtained from the fits to the data. For each pseudoexperiment fits are performed with a number of alternative models for the signal and background components and the ratio $R_{\pi/K}$ is computed. A generalized Student's t-distribution [57] and an Apollonios function [58] are used as alternative models for the signal component, while polynomial functions of the second and the third order with various constraints for monotonicity and convexity are used as alternative backgrounds. The maximum relative bias found for $R_{\pi/K}$ is 0.7%, which is assigned as a relative systematic uncertainty.

The uncertainty related to the imperfect knowledge of the Λ_b^0 decay model used for the simulation of the $\Lambda_b^0 \to \psi(2S)pK^-$ decays is estimated by varying the correction factors obtained from kinematic distributions observed in data. Changing these correction factors within their statistical uncertainties causes a negligible variation of the efficiency $\varepsilon_{\Lambda_b^0 \to \psi(2S)pK^-}$. For the $\Lambda_b^0 \to \psi(2S)p\pi^-$ signal decays the observed two-body mass distributions are in agreement with the phase-space model used in the simulation. The corresponding uncertainty due to the unknown decay kinematics of the $\Lambda_b^0 \to \psi(2S)p\pi^-$ signal decays is small and therefore neglected.

An additional uncertainty arises from the differences between data and simulation, in particular those affecting the efficiency for the reconstruction of charged-particle tracks. The small difference in the track-finding efficiency between data and simulation is corrected using a data-driven technique [55]. The uncertainties in these correction factors together with the uncertainties in the hadron-identification efficiencies, related to the finite size of the calibration samples [53, 54], are propagated to the ratio of total efficiencies by means of pseudoexperiments. This results in a systematic uncertainty of 0.2% associated with the track reconstruction and hadron identification.

The systematic uncertainty on the efficiency of the trigger has been previously studied using high-yield $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$ decays by comparing ratios of trigger efficiencies in data and simulation [59]. Based on these comparisons a relative uncertainty of 1.1% is assigned.

Another source of uncertainty is the potential disagreement between data and simulation in the estimation of efficiencies, due to effects not considered above. This is studied using a high-yield low-background sample of $\Lambda_b^0 \to J/\psi pK^-$ decays, by varying the selection criteria in ranges that lead to as much as $\pm 20\%$ differences in the measured signal yields. The resulting variations in the efficiency-corrected yields do not exceed 1% for all inspected selection criteria. The value of 1% is taken as a corresponding systematic uncertainty.

Finally, the 0.5% relative uncertainty in the ratio of efficiencies from eq. (4.2) is assigned as a systematic uncertainty due to the finite size of the simulated samples.

Source	Uncertainty [%]
Fit model	0.7
Track reconstruction and hadron identification	0.2
Trigger	1.1
Selection criteria	1.0
Size of the simulation samples	0.5
Total	1.7

Table 1. Relative systematic uncertainties for the ratio of branching fractions. The total uncertainty is the quadratic sum of the individual contributions.

6   Results and summary

The Cabibbo-suppressed decay $\Lambda_b^0 \to \psi(2S)p\pi^-$ is observed using a data sample collected by the LHCb experiment in proton-proton collisions corresponding to 1.0, 2.0 and $1.9\,\mathrm{fb}^{-1}$ of integrated luminosity at centre-of-mass energies of 7, 8 and 13 TeV, respectively. The observed yield of $\Lambda_b^0 \to \psi(2S)p\pi^-$ decays is 121 ± 13. Using the $\Lambda_b^0 \to \psi(2S)pK^-$ decay as a normalization channel, the ratio of the branching fractions is measured to be

$$R_{\pi/\mathrm{K}} = \frac{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right)} = (11.4 \pm 1.3 \pm 0.2)\%\,,$$

where the first uncertainty is statistical and the second is systematic. Neglecting the resonance structures in the $\Lambda_b^0 \to \psi(2S)p\pi^-$ and $\Lambda_b^0 \to \psi(2S)pK^-$ decays, the calculated value for the ratio $R_{\pi/\mathrm{K}}$ is

$$R_{\pi/\mathrm{K}}^{\mathrm{th}} \approx \frac{\Phi_3\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)}{\Phi_3\left(\Lambda_b^0 \to \psi(2S)pK^-\right)} \times \tan^2\theta_\mathrm{C} \simeq 11\%\,,$$

where Φ_3 denotes the full three-body phase-space and θ_C is the Cabibbo angle [60]. The measured value is in a good agreement with this estimate.

The branching fraction $\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)$ is calculated using the value of $\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right) = \left(6.29 \pm 0.23 \pm 0.14_{-0.90}^{+1.14}\right) \times 10^{-5}$ [16] as

$$\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right) = \left(7.17 \pm 0.82 \pm 0.33_{-1.03}^{+1.30}\right) \times 10^{-6}\,,$$

where the first uncertainty is statistical, the second systematic (including the statistical and systematic uncertainties from $\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right)$) and the third arises from the uncertainties in the branching fractions of the $\Lambda_b^0 \to J/\psi\,pK^-$, $\psi(2S) \to J/\psi\,\pi^+\pi^-$, $\psi(2S) \to e^+e^-$ and $J/\psi \to e^+e^-$ decays [48].

The $\psi(2S)p$ and $\psi(2S)\pi^-$ mass spectra are investigated and no evidence for contributions from exotic states is found. With a larger data sample a detailed amplitude analysis of this decay could be performed, making it possible to search for small contributions from exotic states.

Acknowledgments

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