First observation of the decay $\Lambda_b^0 \to \eta_c(1S)pK^-$

R. Aaij et al.*
(LHCb Collaboration)

(Received 22 July 2020; accepted 3 November 2020; published 22 December 2020)

The decay $\Lambda_b^0 \to \eta_c(1S)pK^-$ is observed for the first time using a data sample of proton-proton collisions, corresponding to an integrated luminosity of 5.5 fb$^{-1}$, collected with the LHCb experiment at a center-of-mass energy of 13 TeV. The branching fraction of the decay is measured, using the $\Lambda_b^0 \to J/\psi pK^-$ decay as a normalization mode, to be $B(\Lambda_b^0 \to \eta_c(1S)pK^-) = (1.06 \pm 0.16 \pm 0.06^{+0.22}_{-0.19}) \times 10^{-4}$, where the quoted uncertainties are statistical, systematic and due to external inputs, respectively. A study of the $\eta_c(1S)p$ mass spectrum is performed to search for the $P_c(4312)^+ \to \Lambda_cK^0$ pentaquark state. No evidence is observed and an upper limit of $\frac{B(\Lambda_b^0 \to P_c(4312)^+K^-) \times B(P_c(4312)^+ \to \eta_c(1S)p)}{B(\Lambda_b^0 \to \eta_c(1S)pK^-)} < 0.24$ is obtained at the 95% confidence level.

DOI: 10.1103/PhysRevD.102.112012

The existence of baryons comprising four quarks and an antiquark was proposed by Gell-Mann [1] and Zweig [2]. Hereafter, these states are referred to as pentaquarks [3]. Two pentaquark candidates were observed in the $J/\psi p$ system of $\Lambda_b^0 \to J/\psi pK^-$ decays [4]. These candidates were labeled $P_c(4450)^+$ and $P_c(4380)^+$. Using a larger data sample of $\Lambda_b^0 \to J/\psi pK^-$ decays, a new pentaquark state, $P_c(4312)^+$, was observed, and the broad $P_c(4450)^+$ structure resolved into two narrower overlapping structures, labeled $P_c(4440)^+$ and $P_c(4457)^+$ [5]. Many theoretical models have been proposed to describe the dynamics of the observed states, including tightly bound $duucc\bar{c}$ pentaquark states [6–12], baryon-meson molecular states [13–21], or peaking structures due to triangle-diagram processes [22–25]. More experimental and theoretical scrutiny is required to verify these models.

The yet-unobserved $\Lambda_b^0 \to \eta_c pK^-$ decay, where $\eta_c$ refers to the $\eta_c(1S)$ meson, can provide a unique approach to search for new pentaquarks, and to study the observed states. It has been predicted that a $D\Sigma_c$ molecular state, with a mass of around 4265 MeV/$c^2$, can contribute to the decay $\Lambda_b^0 \to \eta_c pK^-$ via $\eta_c p$ final-state interactions [26].

The observed $P_c(4312)^+$ state could be such a molecular state [27], since its mass is close to the $D\Sigma_c$ threshold [5].

The study of the $\Lambda_b^0 \to \eta_c pK^-$ decay provides a new way to test the binding mechanism of pentaquark states, as the predicted ratio of the branching fractions for a pentaquark decaying into $\eta_c p$ compared to the $J/\psi p$ final states depends on the pentaquark model. The branching fraction of $P_c(4312)^+ \to \eta_c p$ is predicted to be 3 times larger than that of the $J/\psi p$ decay mode if the $P_c(4312)^+$ state is a $D\Sigma_c$ molecule [13–15].

This paper presents the first observation of the $\Lambda_b^0 \to \eta_c pK^-$ decay, with the $\eta_c$ meson reconstructed using the $\eta_c \to p\bar{p}$ decay mode, and reports a search for the $P_c(4312)^+$ pentaquark state in the $\eta_c p$ system. The analysis uses the decay $\Lambda_b^0 \to J/\psi pK^-$ as a normalization channel, where the $J/\psi p$ meson decays to $p\bar{p}$. The data sample used in this analysis corresponds to an integrated luminosity of 5.5 fb$^{-1}$, collected with the LHCb experiment in proton-proton collisions at $\sqrt{s} = 13$ TeV between 2016 and 2018.

In the $B$-meson sector, heavy quark effective theory [28,29] predicts that the decay rates of the $B \to \eta_c X$ and $B \to J/\psi X$ channels are of the same order of magnitude. Experimental results are in good agreement with this expectation [30]. Studying the branching fraction ratio between the $\Lambda_b^0 \to \eta_c pK^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays will provide the first comparison of $b$-baryon decay rates to the $\eta_c X$ and $J/\psi X$ final states, and help to test whether the presence of an additional spectator quark modifies the final-state interactions in a non-negligible way.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, and is described in detail in Refs. [31,32]. The detector includes a silicon-strip vertex detector surrounding the proton-proton...
interaction region, tracking stations on either side of a dipole magnet, ring-imaging Cherenkov (RICH) detectors, calorimeters and muon chambers. The online event selection is performed by a trigger [33], 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 a significant displacement from any primary vertex (PV) that is consistent with originating from the decay of a b hadron [34].

Simulated data samples as described in Refs. [35–40], are used to optimize the event selection, determine the efficiency of the reconstruction and event selection, and to constrain the fit model which determines the signal yield. The simulated \( \Lambda_b^0 \to \eta_c p K^- \) and \( \Lambda_b^0 \to J/\psi p K^- \) decays are generated based on a uniform phase-space model. The simulated decays are also weighted to match the \( \Lambda_b^0 \) momentum spectrum and Dalitz-plot distribution in the data, as described later in this paper.

The \( \Lambda_b^0 \to \eta_c (\to p \bar{p}) p K^- \), and \( \Lambda_b^0 \to J/\psi (\to p \bar{p}) p K^- \) candidates are reconstructed and selected using the same selection criteria, with a \( p_\text{T} \) mass window of [2800, 3200] MeV/c\(^2\) that covers both the \( \eta_c \) and \( J/\psi \) mass regions. In the following, the notation \([c\bar{c}]\) will be used to refer to both the \( \eta_c \) and the \( J/\psi \) candidates from \( \Lambda_b^0 \) baryon decays. Particle identification (PID) variables in the simulation are calibrated using large data samples of kinematically identified protons and kaons, originating from \( \Lambda_b^0 \to \Lambda^+_c (\to p K^- \pi^+) \pi^- \) and \( D^0 \to K^- \pi^+ \pi^- \) decays.

The offline event selection is performed using a preselection, followed by a requirement on the response of a boosted decision tree (BDT) classifier [41,42]. In the preselection, each track is required to be of good quality. Kaons and protons are both required to have \( p_\text{T} > 300 \) MeV/c, where \( p_\text{T} \) is the component of the momentum transverse to the beam. Protons are also required to have a momentum larger than 10 GeV/c\(^2\), such that the kaons and protons can be distinguished by the RICH detectors. The sum of the \( p_\text{T} \) of the proton and kaon from the \( \Lambda_b^0 \) baryon is required to be larger than 900 MeV/c. The \([c\bar{c}]\) candidate is required to have a good-quality vertex.

The \( \Lambda_b^0 \) candidate must have a good-quality decay vertex that is significantly displaced from every PV, and have \( \chi^2_{\text{IP}} < 25 \) with respect to the associated PV. Here, \( \chi^2_{\text{IP}} \) is defined as the \( \chi^2 \) difference between the vertex fit of a PV reconstructed with or without the particle in question, and the associated PV is the one with the smallest \( \chi^2_{\text{IP}} \) value. The angle between the reconstructed momentum vector of the \( \Lambda_b^0 \) candidate and the line connecting the associated PV and the \( \Lambda_b^0 \) decay vertex, \( \theta_{\Lambda_b^0} \), is required to satisfy \( \cos(\theta_{\Lambda_b^0}) > 0.9999 \).

Contamination from \( B^0 \to p \bar{p} K^+ K^- \) and \( B^0 \to p \bar{p} K^+ \pi^- \) decays, where a kaon or pion is misidentified as a proton, is removed by applying strict particle identification requirements on candidates with a mass within \( \pm 50 \) MeV/c\(^2\) around the known \( B^0 \) or \( B^0 \) mass [30] after assigning a kaon or pion mass hypothesis to the proton. Backgrounds from \( \phi(1020) \to K^+ K^- \) and \( D^0 \to K^+ K^- \) decays, where one of the kaons is misidentified as a proton and the \( \Lambda_b^0 \) candidate is formed by combining the particles with a \([c\bar{c}]\) candidate from elsewhere in the event, are also observed. These contributions are removed by placing stricter particle-identification requirements on candidates with a \( pK^- \) mass within \( \pm 10 \) MeV/c\(^2\) (\( \pm 20 \) MeV/c\(^2\)) of the known \( \phi(1020) \) \( (D^0) \) mass, after assigning a kaon mass hypothesis [30] to the proton.

After the preselection, further separation between the signal and combinatorial backgrounds originating from a random combination of final-state particles is achieved by using a BDT classifier. The classifier uses the following input variables: the \( p_\text{T} \) of the \( \Lambda_b^0 \) candidate, and of the kaon and proton directly from the \( \Lambda_b^0 \) decay; the \( \chi^2_{\text{IP}} \) of the \( \Lambda_b^0 \) candidate, the \([c\bar{c}]\) candidate, and the kaon and proton directly from the \( \Lambda_b^0 \) decay; the smallest values of both the \( p_\text{T} \) and \( \chi^2_{\text{IP}} \) of the \([c\bar{c}]\) decay products; the significance of the displacement of the \( \Lambda_b^0 \) vertex with respect to the associated PV; the vertex-fit \( \chi^2 \) of the \( \Lambda_b^0 \) candidate; the \( \theta_{\Lambda_b^0} \) angle; and the PID information of the final-state particles. The BDT is trained using simulated \( \Lambda_b^0 \to \eta_c p K^- \) decays for the signal, and the data candidates in the \( p \bar{p} p \bar{K}^- \) invariant-mass sideband above 5800 MeV/c\(^2\) for the background. The requirement on the BDT response is optimized by maximizing the figure of merit \( e_{\text{sig}}^2 / (a/2 + \sqrt{N_{\text{bkg}}}) \) [43], where \( e_{\text{sig}} \) is the BDT selection efficiency estimated using the simulated \( \Lambda_b^0 \to \eta_c p K^- \) sample, \( a = 5 \) is the target significance for the signal in standard deviations, and \( N_{\text{bkg}} \) is the expected yield of background with \( p \bar{p} p \bar{K}^- \) masses in the ranges \( m(p \bar{p}) \in [2951.4, 3015.4] \) MeV/c\(^2\) and \( m(p \bar{p} p K^-) \in [5585, 5655] \) MeV/c\(^2\), respectively. The background yields are estimated using the \( p \bar{p} p K^- \) and \( p \bar{p} \) invariant-mass sidebands in the data. The BDT response requirement provides about 70% signal efficiency and suppresses the background by a factor of approximately 100. After the BDT selection, a background in the normalization channel is observed due to swapping the proton from the \( \Lambda_b^0 \) decay with a proton from the \( J/\psi \) decay. This contribution is removed by requiring the invariant mass of the system formed by the proton from the \( \Lambda_b^0 \) baryon and the antiproton from the \( J/\psi \) meson to be inconsistent with the known \( J/\psi \) mass [30]. The \( p \bar{p} p K^- \) and \( p \bar{p} \) invariant-mass spectra of the selected data are displayed in Fig. 1.

A two-dimensional unbinned maximum-likelihood fit to the \( p \bar{p} p K^- \) and \( p \bar{p} \) invariant-mass distributions is performed to determine the signal yield. The \( p \bar{p} K^- \) mass spectra of the signal and normalization channels are described using the same model, sharing the shape
parameters. The signal is modeled by the sum of two Crystal Ball (CB) functions [44] with common peak positions. The tail parameters of the CB functions are determined from simulation, while the mean and width of the Gaussian cores are freely varying in the fit to the data. The \( p\bar{p} \) mass spectrum is described with a relativistic Breit-Wigner function [45] convolved with a Gaussian resolution function for the \( \eta_c \), and is described with the sum of two CB functions with common peak positions for the \( J/\psi \) decay. When modeling the \( m(\rho) \) spectrum, the correlation between \( m(p\bar{p}pK^-) \) and \( m(\rho) \) needs to be taken into account. The width (peak) parameter of the resolution function of the signal channel, and the width (peak) parameters of the Gaussian cores for the normalization channel, are parametrized as second-order (first-order) polynomial functions of \( m(p\bar{p}pK^-) \); the coefficients of these polynomial functions are calibrated using simulated samples.

For the two-dimensional mass spectrum of the background components, it is assumed that \( m(p\bar{p}pK^-) \) and \( m(\rho) \) are uncorrelated, which is corroborated using the background-dominated data sample before the BDT selection is applied. For background from \( \Lambda_b^0 \to p\bar{p}pK^- \) decays but with the \( p\bar{p} \) pair not originating from a \( \eta_c \) or \( J/\psi \) resonance, the \( m(\rho) \) spectrum is described using an exponential function, and the \( m(p\bar{p}pK^-) \) spectrum is described using the same model as the signal but the parameters of the distribution are allowed to take different values in the fit. For background with a \( [c\bar{c}] \to p\bar{p} \) process but not from a \( \Lambda_b^0 \) decay, the \( m(p\bar{p}pK^-) \) distribution is described using an exponential function, and the \( m(\rho) \) spectrum is modeled by Breit-Wigner functions that are each convolved with a separate Gaussian function to describe the \( \eta_c \) and \( J/\psi \) resonances. In the fit, a Gaussian constraint of 31.9 ± 0.7 MeV/c\(^2\) [30] is applied to the natural width of the \( \eta_c \) meson for both the signal and background components. For combinatorial backgrounds, both the \( m(p\bar{p}pK^-) \) and \( m(\rho) \) spectra are described using exponential functions. The background shape due to swapping the two protons in the \( \Lambda_b^0 \to \eta_c(\to p\bar{p})pK^- \) decay shares the same shape in \( m(p\bar{p}pK^-) \) as the signal channel, while the \( m(\rho) \) shape, and the relative yield with respect to the signal component of the signal channel, are determined from simulation. Given the limited yield of \( \Lambda_b^0 \to \eta_c pK^- \) decays expected in this data sample, the interference between the \( \Lambda_b^0 \to \eta_c pK^- \) and nonresonant \( \Lambda_b^0 \to p\bar{p}pK^- \) decays is not considered. An amplitude analysis of a larger data set is needed to have sensitivity to such interference effects.

The \( m(p\bar{p}pK^-) \) and \( m(\rho) \) distributions of the selected candidates are presented in Fig. 1, with the one-dimensional projections of the fit overlaid. The yields of the signal and normalization modes are \( N(\Lambda_b^0 \to \eta_c pK^-) = 173 \pm 25 \) and \( N(\Lambda_b^0 \to J/\psi pK^-) = 804 \pm 31 \), respectively, where the uncertainties are statistical only. To estimate the signal significance, a two-dimensional fit without the contribution from the \( \Lambda_b^0 \to \eta_c pK^- \) decay is performed. The difference in log-likelihood between this and the nominal fit is found to be 29.4. Based on the assumption of a \( \chi^2 \) distribution with one degree of freedom, the statistical significance of the \( \Lambda_b^0 \to \eta_c pK^- \) decay with respect to the background-only hypothesis, expressed in Gaussian standard deviations, is 7.7\sigma.

The ratio of the branching fraction between the \( \Lambda_b^0 \to \eta_c pK^- \) and \( \Lambda_b^0 \to J/\psi pK^- \) decays is given by

\[
\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = \frac{N(\Lambda_b^0 \to \eta_c pK^-)}{N(\Lambda_b^0 \to J/\psi pK^-)} \times \frac{e(\Lambda_b^0 \to J/\psi pK^-)}{e(\Lambda_b^0 \to \eta_c pK^-)} \times \frac{\mathcal{B}(J/\psi \to p\bar{p})}{\mathcal{B}(\eta_c \to p\bar{p})},
\]

where \( N \) represents the yield of the decay given in the parentheses, determined from a fit to the invariant-mass spectrum and \( e \) is the efficiency accounting for the detector geometrical acceptance, reconstruction and event

![Image](image-url)
selection. The known values of the branching fractions, \( B \), of the \( \Lambda_b^0 \rightarrow J/\psi pK^- \), \( J/\psi \rightarrow p\bar{p} \) [30] and \( \eta_c \rightarrow p\bar{p} \) decays [46] are used as external inputs for the measurement of \( B (\Lambda_b^0 \rightarrow \eta_c pK^-) \).

The efficiencies of the detector geometrical acceptance, reconstruction and event selections are determined from simulation. The agreement between data and simulation is improved by weighting the two-dimensional \( (p, p_T) \) distribution of the \( \Lambda_b^0 \) baryons in simulation. The weights are obtained using a comparison between a large sample of data and simulated events from \( \Lambda_b^0 \rightarrow J/\psi pK^- \) decays, where the \( J/\psi \) meson is reconstructed through its decay \( J/\psi \rightarrow \mu^+\mu^- \). The distributions of \( m(pK^-) \) and \( m(\bar{c}c[p]) \) in the simulation for signal and normalization channels are also weighted to match the corresponding distributions observed in data, where the data distributions are obtained using the sPlot technique [47] with \( m(p\bar{p}pK^-) \) and \( m(p\bar{p}) \) as the discriminating variables. The ratio between the overall efficiencies of the signal and normalization channels is \( 0.95 \pm 0.02 \), where the uncertainty accounts only for the finite yields of the simulated events. The ratio of branching fractions between the \( \Lambda_b^0 \rightarrow \eta_c pK^- \) and \( \Lambda_b^0 \rightarrow J/\psi pK^- \) decays is obtained as

\[
\frac{B(\Lambda_b^0 \rightarrow \eta_c pK^-)}{B(\Lambda_b^0 \rightarrow J/\psi pK^-)} = 0.333 \pm 0.050,
\]

where the quoted uncertainty is statistical only.

A search for a \( P_c(4312)^+ \rightarrow \eta_c p \) contribution to the \( \Lambda_b^0 \rightarrow \eta_c pK^- \) decay is performed by projecting out the background-subtracted \( \eta_c p \) mass spectrum using the sPlot technique. The resulting \( \eta_c p \) and \( J/\psi p \) mass distributions are shown in Fig. 2. A weighted unbinned maximum-likelihood fit [48] is applied to the \( \eta_c p \) mass spectrum, where the data is described as the incoherent sum of \( P_c(4312)^+ \rightarrow \eta_c p \) decays and a nonresonant \( \eta_c p \) contribution. The \( P_c(4312)^+ \) resonance is modeled using a relativistic Breit-Wigner function [45], with parameters obtained from Ref. [5], and is convolved with the sum of two Gaussian resolution functions whose shape parameters are determined from simulation. The contribution from \( \Lambda_b^0 \rightarrow \eta_c pK^- \) decays with a nonresonant \( \eta_c p \) system is modeled using simulated events generated with a uniform phase-space model. The fit projection is shown in Fig. 2(a).

The yield of the \( P_c(4312)^+ \) state is determined to be \( 16.4^{+12.8}_{-9.3} \) (stat.) \( \pm 4 \) (syst.). The systematic uncertainty on the yield is estimated by using alternative models to describe the \( \Lambda_b^0 \) component without \( \eta_c p \) resonances, and varying the mass and width of the \( P_c(4312)^+ \) state based on their uncertainties from Ref. [5]. To consider the potential influence of the interference between the \( P_c(4312)^+ \) component and reflections from \( \Lambda^+ \rightarrow pK^- \) resonances, several \( \Lambda_b^0 \rightarrow J/\psi pK^- \) samples are generated based on the result of a full amplitude fit to the \( \Lambda_b^0 \rightarrow J/\psi(p\rightarrow \mu^+\mu^-)pK^- \) sample used in Ref. [5], with a different scale factor assigned on the \( P_c(4312)^+ \) amplitude to account for a change in its contribution. A fit is performed to these simulated \( J/\psi p \) mass spectra, using the same description for the \( P_c(4312)^+ \) contribution as that in the fit model of the background-subtracted \( \eta_c p \) mass spectrum. The largest relative difference between the \( P_c(4312)^+ \) relative contribution obtained from the fit and its true value in the simulated samples is taken as a systematic uncertainty for this potential interference.

The difference of the log-likelihood between the nominal fit and a fit with the \( P_c(4312)^+ \) yield fixed to zero is 2.4. Since all of the shape parameters of the \( P_c(4312)^+ \) component are fixed in the nominal fit, the statistical

![FIG. 2. The invariant-mass spectra of (a) the \( \eta_c p \) system of the \( \Lambda_b^0 \rightarrow \eta_c pK^- \) decays and (b) the \( J/\psi p \) system of the \( \Lambda_b^0 \rightarrow J/\psi pK^- \) decays. The black points represent the background-subtracted data and the red points correspond to the expectation from a simulation generated according to a uniform phase-space model. The blue solid line in panel (a) shows the fit projection of the \( \eta_c p \) mass spectrum including the contribution from a \( P_c(4312)^+ \) resonance in the mass range \([4000, 4400]\) MeV/c^2.](image-url)
significance of the $P_c(4312)^+$ state is $2.2\sigma$. Defining the relative $P_c(4312)^+$ contribution analogous to that which is used in Ref. [5] as

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to P_c(4312)^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)} \mathcal{B}(P_c(4312)^+ \to \eta_c p).$$  \hspace{1cm} (2)$$
a 95\% confidence level upper limit of $R < 0.24$ is obtained from the likelihood profile distribution. The search to the $P_c(4440)^+$ and $P_c(4457)^+$ states is not performed in this paper, as they will together perform like a broad structure under the limited sample size [4], which cannot be disentangled from the reflections from the $\Lambda_b^0 \to \Lambda^+\eta_c$, $\Lambda^+ \to p^- K^-$ decay chain without a full amplitude analysis.

Sources of systematic uncertainty on the $\Lambda_b^0 \to \eta_c p K^-$ branching fraction arise from the fitting procedure and limited knowledge of the efficiencies, and are summarized in Table I. Pseudoexperiments are used to estimate the effects due to parameters determined from simulation. Systematic uncertainties on the fit model are evaluated by using alternative fit models where: the exponential functions are replaced by Chebyshev polynomials; the contributions from genuine $\Lambda_b^0$ decays in the $m(p\bar{p}K^-)$ spectrum are modeled by the Hypatia distribution [49]; the resolution of the $\eta_c$ peaking structure in the $m(p\bar{p})$ spectrum is replaced by the average resolution of the CB functions describing the $\omega$ and the shape parameters of the $\Lambda_b^0$ peak in the $\Lambda_b^0 \to \eta_c p K^-$ decay without the $\eta_c$ or $J/\psi$ resonances are fixed to be the same as those of the signal and the normalization decays. Pseudoexperiments are used to estimate the potential bias of the fit yields, which is found to be negligible compared to the statistical uncertainties. Based on each alternative fit model described above, the significance of the $\Lambda_b^0 \to \eta_c p K^-$ is reestimated. The smallest significance found is approximately $7.7\sigma$. This is the first observation of this decay mode.

Uncertainties on the efficiency ratio between the signal and normalization channels are largely canceled due to the similarity of these two decay modes. For the estimation of systematic uncertainties related to the weighting procedure of $m(\bar{c}c|p)$, $m(pK^-)$ and $(p, p_T)$ of the $\Lambda_b^0$ decays in simulation, pseudoexperiments are used to propagate the uncertainties of single-event weights, originating from the finite yield of the samples used to obtain the weights, to the uncertainty of the overall efficiency ratio; an alternative binning scheme is used to estimate the uncertainty due to the choice of binning in the weighting procedure; and the negative weights, given by the $s$Plot technique due to statistical fluctuations, are set to zero to recalculate the overall efficiency ratio. A systematic uncertainty is also assigned for the finite size of the simulated samples used for the efficiency estimation.

The total systematic uncertainty of the $\Lambda_b^0 \to \eta_c p K^-$ branching fraction measurement is obtained by adding the above contributions in quadrature, leading to a value of $5.8\%$, and details are given in Table I. The dominant contribution is the uncertainty related to the fit model. The limited knowledge of the branching fractions of the $\Lambda_b^0 \to J/\psi p K^-$, $J/\psi \to p\bar{p}$ and $\eta_c \to p\bar{p}$ decays [30] is also considered as an external source that contributes to the total uncertainty.

The background-subtracted data distributions of $m(\bar{c}c|p)$ for the signal and normalization channels are shown in Fig. 2, with the distributions of simulated events overlaid. The background subtraction is based on the $s$Plot technique [47], with $m(p\bar{p}K^-)$ and $m(p\bar{p})$ as the discriminating variables. No significant peaking structures are seen. The fractions of the $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ contributions to the $\Lambda_b^0 \to J/\psi p K^-$ decays are only roughly $0.3\%$, $1.1\%$ and $0.5\%$, respectively [5], and given the limited $\Lambda_b^0 \to J/\psi p K^-$ yields of this analysis, it is not surprising that these $P_c$ contributions are not observed.

In summary, the first observation of the decay $\Lambda_b^0 \to \eta_c p K^-$ has been reported using proton-proton collision data collected with the LHCb experiment, corresponding to an integrated luminosity of $5.5$ fb$^{-1}$. The significance of this observation, over the background-only hypothesis, is $7.7$ standard deviations. The branching fraction ratio between the $\Lambda_b^0 \to \eta_c p K^-$ and $\Lambda_b^0 \to J/\psi p K^-$ decays is measured to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.333 \pm 0.050(\text{stat.}) \pm 0.019(\text{syst.}) \pm 0.032(\mathcal{B}),$$

where the first uncertainty is statistical, the second is systematic, and the last is due to the uncertainty on the branching fractions of the $\eta_c \to p\bar{p}$ and $J/\psi \to p\bar{p}$ decays. Using this ratio, the branching fraction of the $\Lambda_b^0 \to \eta_c p K^-$ decay is determined to be

$$\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-) = (1.06 \pm 0.16(\text{stat.})) \times (10^{-4}),$$

$$\pm 0.06(\text{syst.})^{+0.22}_{-0.19}(\mathcal{B}) \times 10^{-4},$$

Another uncertainty that is evaluated is the uncertainty on the ratio of the $\Lambda_b^0 \to \eta_c p K^-$ to $\eta_c p K^-$ branching fraction, and is estimated to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\eta_c p K^-)} = (1.00 \pm 0.12(\text{stat.})) \times 10^{-4},$$

$$\pm 0.06(\text{syst.})^{+0.23}_{-0.18}(\mathcal{B}) \times 10^{-4},$$

$$\pm 0.06(\text{syst.})^{+0.22}_{-0.19}(\mathcal{B}) \times 10^{-4},$$

TABLE I. Summary of the uncertainties on the branching fraction ratio $\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)/\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)$. The total systematic uncertainty is obtained by summing the individual contributions in quadrature.

| Source | Uncertainty (%) |
|--------|-----------------|
| $\Lambda_b^0 p$ and $p_T$ distributions | 1.0 |
| $m(pK^-)$ and $m(\bar{c}c|p)$ distributions | 3.2 |
| Fit model | 4.0 |
| Finite simulated sample sizes | 2.5 |
| Total systematic uncertainty | 5.8 |
| Statistical uncertainty | 13.6 |
| $\mathcal{B}(\bar{c}c \to p\bar{p})$ | 9.6 |

112012-5
where the third uncertainty also depends on the branching fraction of the $\Lambda_c^0 \to J/\psi pK^-$ decay.

The observation of this decay opens up a new line of investigation in searching for pentaquarks in the $\eta_c p$ system. If the $P_c(4312)^+$ state is a $D\Sigma_c$ molecule and the predictions of Refs. [13–15] are accurate, a value of $R_{D\Sigma_c} \sim 0.03$ would be expected, based on the $P_c(4312)^+$ relative contribution in $\Lambda_c^0 \to J/\psi pK^-$ decays [5] and the above result for $B(\Lambda_c^0 \to \eta_c pK^-)/B(\Lambda_c^0 \to J/\psi pK^-)$. The 95% confidence level upper limit obtained in this analysis, $R < 0.24$, does not exclude this molecular interpretation for the $P_c(4312)^+$ state. A further amplitude analysis with a larger data sample is required for a more quantitative comparison to theoretical predictions [13–15]. By using an upgraded LHCb detector with improved trigger conditions and larger data samples collected, there are good prospects for using this decay to shed light on the binding mechanism of the recently observed pentaquark states [5].

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the accelerator departments for the excellent performance of the states [5].

We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNISW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, Thousand Talents Program, and Sci. & Tech. Program of Guangzhou (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom).

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964).
[2] G. Zweig, An SU$_3$ model for strong interaction symmetry and its breaking; Version 2, CERN-TH-412, CERN, Geneva, 1964, http://cds.cern.ch/record/570209.
[3] H. J. Lipkin, New possibilities for exotic hadrons- anti-charmed strange baryons, Phys. Lett. **B 195**, 484 (1987).
[4] R. Aaij et al. (LHCb Collaboration), Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_c^0 \to J/\psi pK^-$ Decays, Phys. Rev. Lett. **115**, 072001 (2015).
[5] R. Aaij et al. (LHCb Collaboration), Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of Two-Peak Structure of the $P_c^+(4450)^+$, Phys. Rev. Lett. **122**, 222001 (2019).
[6] L. Maiani, A. D. Polosa, and V. Riquer, The new pentaquarks in the diquark model, Phys. Lett. B **749**, 289 (2015).
[7] R. F. Lebed, The pentaquark candidates in the dynamical diquark picture, Phys. Lett. B **749**, 454 (2015).
[8] V. V. Anisovich et al., Pentaquarks and resonances in the $pJ/\psi$ spectrum, arXiv:1507.07562.
[9] G.-N. Li, X.-G. He, and M. He, Some predictions of diquark model for hidden charm pentaquark discovered at the LHCb, J. High Energy Phys. **12** (2015) 128.
[10] R. Ghosh, A. Bhattacharya, and B. Chakrabarti, A study on $P_c^+(4380)$ and $P_c^0$ in the quasi particle diquark model, Phys. Part. Nucl. Lett. **14**, 550 (2017).
[11] Z.-G. Wang, Analysis of $P_c(4380)$ and $P_c(4450)$ as pentaquark states in the diquark model with QCD sum rules, Eur. Phys. J. C **76**, 70 (2016).
[12] R. Zhu and C.-F. Qiao, Pentaquark states in a diquark-triquark model, Phys. Lett. B **756**, 259 (2016).
[13] M. B. Voloshin, Some decay properties of hidden-charm pentaquarks as baryon-meson molecules, Phys. Rev. D **100**, 034020 (2019).
[14] S. Sakai, H.-J. Jing, and F.-K. Guo, Decays of $P_c$ into $J/\psi N$ and $\eta_c N$ with heavy quark spin symmetry, Phys. Rev. D **100**, 074007 (2019).
[15] G.-J. Wang, L.-Y. Xiao, R. Chen, X.-H. Liu, X. Liu, and S.-L. Zhu, Probing hidden-charm decay properties of $P_c$ states in a molecular scenario, Phys. Rev. D **102**, 036012 (2020).
[16] M. Karliner and J. L. Rosner, New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules, Phys. Rev. Lett. **115**, 122001 (2015).
[17] R. Chen, X. Liu, X.-Q. Li, and S.-L. Zhu, Identifying Exotic Hidden-Charm Pentaquarks, Phys. Rev. Lett. **115**, 132002 (2015).
[18] H.-X. Chen, W. Chen, X. Liu, T. G. Steele, and S.-L. Zhu, Towards Exotic Hidden-Charm Pentaquarks in QCD, Phys. Rev. Lett. **115**, 172001 (2015).
[19] L. Roca, J. Nieves, and E. Oset, LHCb pentaquark as a $\bar{D}^*\Sigma_c - D\Sigma_c^*$ molecular state, Phys. Rev. D **92**, 094003 (2015).
FIRST OBSERVATION OF THE DECAY $\Lambda_{b0}^{\ast} \rightarrow \eta_c(1S)pK^- \ldots$

PHYS. REV. D 102, 112012 (2020)

[20] J. He, $\vec{D}\Sigma_c^-$ and $\vec{D}^\ast\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks, Phys. Lett. B 753, 547 (2016).

[21] H. Huang, C. Deng, J. Ping, and F. Wang, Possible pentaquarks with heavy quarks, Eur. Phys. J. C 76, 624 (2016).

[22] F.-K. Guo, U.-G. Meißner, W. Wang, and Z. Yang, How to reveal the exotic nature of the $P_c(4450)$, Phys. Rev. D 92, 071502 (2015).

[23] U.-G. Meißner and J. A. Oller, Testing the $\chi^0_1\rho$ composite nature of the $P_c(4450)$, Phys. Lett. B 751, 59 (2015).

[24] X.-H. Liu, Q. Wang, and Q. Zhao, Understanding the newly observed heavy pentaquark candidates, Phys. Lett. B 757, 231 (2016).

[25] M. Mikhasenko, A triangle singularity and the LHCb pentaquarks, arXiv:1507.06552.

[26] J.-J. Xie, W.-H. Liang, and E. Oset, Hidden charm pentaquark and $\Lambda(1405)$ in the $\Lambda_b^0 \rightarrow \eta_cK^-p(\pi\Sigma)$ reaction, Phys. Lett. B 777, 447 (2018).

[27] J.-J. Wu, T.-S. H. Lee, and B.-S. Zou, Nucleon resonances with hidden charm in $\rho\gamma$ reactions, Phys. Rev. C 100, 035206 (2019).

[28] N.G. Deshpande and J. Trampetic, Exclusive and semi-inclusive B decays based on $b \rightarrow s\eta_c$ transition, Phys. Lett. B 339, 270 (1994).

[29] M. R. Ahmady and R. R. Mendel, A theoretical prediction for exclusive decays $B \rightarrow K(K^*)\eta_c$, Z. Phys. C 65, 263 (1995).

[30] M. Tanabashi et al. (Particle Data Group), Review of particle physics, Phys. Rev. D 98, 030001 (2018); and 2019 update.

[31] A.A. Alves, Jr. et al. (LHCb Collaboration), The LHCb detector at the LHC, J. Instrum. 3, S08005 (2008).

[32] R. Aaij et al. (LHCb Collaboration), LHCb detector performance, Int. J. Mod. Phys. A 30, 1530022 (2015).

[33] R. Aaij et al., Performance of the LHCb trigger and full real-time reconstruction in Run 2 of the LHC, J. Instrum. 14, P04013 (2019).

[34] V.V. Gilgorov and M. Williams, Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree, J. Instrum. 8, P02013 (2013).

[35] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to pyTHIA 8.1, Comput. Phys. Commun. 178, 852 (2008).

[36] I. Belyaev et al., Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. 331, 032047 (2011).

[37] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).

[38] P. Golonka and Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays, Eur. Phys. J. C 45, 97 (2006).

[39] J. Allison et al. (Geant4 Collaboration), GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53, 270 (2006).

[40] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranzi, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, J. Phys. Conf. Ser. 331, 032023 (2011).

[41] Y. Freund and R.E. Schapire, A decision-theoretic generalization of on-line learning and an application to boosting, J. Comput. Syst. Sci. 55, 119 (1997).

[42] H. Voss, A. Hoecker, J. Stelzer, and F. Tegenfeldt, TMVA, The toolkit for multivariate data analysis with ROOT, Proc. Sci., ACAT2007 (2007) 040.

[43] G. Punzi, Sensitivity of searches for new signals and its optimization, eConf C030908, MODT002 (2003), arXiv: physics/0308063.

[44] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02, https://inspirehep.net/literature/230779.

[45] J. D. Jackson, Remarks on the phenomenological analysis of resonances, Nuovo Cimento 34, 1644 (1964).

[46] F.A. Zyla et al. (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

[47] M. Pivk and F.R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Methods Phys. Res., Sect. A 555, 356 (2005).

[48] Y. Xie, sFit: A method for background subtraction in maximum likelihood fit, arXiv:0905.0724.

[49] D. Martinez Santos and F. Dupertuis, Mass distributions marginalized over per-event errors, Nucl. Instrum. Methods Phys. Res., Sect. A 764, 150 (2014).
FIRST OBSERVATION OF THE DECAY $\Lambda_b^0 \to \eta_c(1S)pK^- \cdots$  

**Phys. Rev. D** **102**, 112012 (2020)
(LHCb Collaboration)

1 Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2 Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3 Center for High Energy Physics, Tsinghua University, Beijing, China
4 School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
5 University of Chinese Academy of Sciences, Beijing, China
6 Institute Of High Energy Physics (IHEP), Beijing, China
7 Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China
8 Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France
9 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
10 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
11 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
12 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
13 J. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
14 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
15 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
16 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
17 School of Physics, University College Dublin, Dublin, Ireland
18 INFN Sezione di Bari, Bari, Italy
19 INFN Sezione di Bologna, Bologna, Italy
20 INFN Sezione di Ferrara, Ferrara, Italy
21 INFN Sezione di Firenze, Firenze, Italy
22 INFN Laboratori Nazionali di Frascati, Frascati, Italy
23 INFN Sezione di Genova, Genova, Italy
24 INFN Sezione di Milano-Bicocca, Milano, Italy
25 INFN Sezione di Milano, Milano, Italy
26 INFN Sezione di Cagliari, Monserrato, Italy
27 Universita degli Studi di Padova, Universita e INFN, Padova, Padova, Italy
28 INFN Sezione di Pisa, Pisa, Italy
29 INFN Sezione di Roma Tor Vergata, Roma, Italy
30 INFN Sezione di Roma La Sapienza, Roma, Italy
31 Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
32 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
33 AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
34 National Center for Nuclear Research (NCBJ), Warsaw, Poland

112012-10

R. AAIJ et al.

PHYS. REV. D 102, 112012 (2020)
FIRST OBSERVATION OF THE DECAY $\Lambda^0_{b \rightarrow \eta_c(1S)pK^-} \ldots$

PHYS. REV. D 102, 112012 (2020)
National Research Centre Kurchatov Institute, Moscow, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia, Moscow, Russia)

National University of Science and Technology “MISIS”, Moscow, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia, Moscow, Russia)

National Research University Higher School of Economics, Moscow, Russia
(associated with Yandex School of Data Analysis, Moscow, Russia)

National Research Tomsk Polytechnic University, Tomsk, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia, Moscow, Russia)

University of Michigan, Ann Arbor, USA
(associated with Syracuse University, Syracuse, New York, USA)

Also at Laboratoire Leprince-Ringuet, Palaiseau, France.

Also at Università di Genova, Genova, Italy.

Also at Università di Bologna, Bologna, Italy.

Also at Università di Modena e Reggio Emilia, Modena, Italy.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Università di Ferrara, Ferrara, Italy.

Also at Università di Milano Bicocca, Milano, Italy.

Also at DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

Also at Universidad Nacional Autonoma de Honduras, Tegucigalpa, Honduras.

Also at Università di Bari, Bari, Italy.

Also at Università di Cagliari, Cagliari, Italy.

Also at INFN Sezione di Trieste, Trieste, Italy.

Also at Università degli Studi di Milano, Milano, Italy.

Also at Università di Roma Tor Vergata, Roma, Italy.

Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

Also at AGH—University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

Also at Università di Siena, Siena, Italy.

Also at Università di Padova, Padova, Italy.

Also at Scuola Normale Superiore, Pisa, Italy.

Also at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.

Also at Università di Firenze, Firenze, Italy.

Also at Hanoi University of Science, Hanoi, Vietnam.

Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.

Also at Università di Pisa, Pisa, Italy.

Also at Università della Basilicata, Potenza, Italy.

Also at Università di Urbino, Urbino, Italy.