

# Study of the $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$ decay

R. Aaij *et al.*<sup>\*</sup>  
(LHCb Collaboration)



(Received 20 April 2026; accepted 15 June 2026; published 13 July 2026)

The decay  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  is studied at LHCb for the first time using proton-proton collision data recorded by the LHCb experiment at a center-of-mass energy of  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $5.4 \text{ fb}^{-1}$ . The branching ratio relative to the decay  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  is measured to be  $[\mathcal{B}(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0)]/[\mathcal{B}(B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+)] = 0.53 \pm 0.05 \pm 0.05$  where the first uncertainty is statistical and the second is systematic. Evidence is found for contributions from two resonant states,  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$ , in the  $\Lambda_c^+ K_S^0$  system. The two states show a significance of  $3.9\sigma$  relative to the nonresonant hypothesis. These two  $\Xi_c^+$  states are consistent with being the isospin partners of the states observed in the  $\Lambda_c^+ K^-$  system.

DOI: 10.1103/jrkb-q3w6

## I. INTRODUCTION

Multibody  $B$ -meson decays exhibit a rich and complex phenomenology, much of which remains unexplored. The Large Hadron Collider, with its high production rate of heavy-flavor hadrons, provides an unprecedented opportunity to deepen the understanding of  $B$ -meson decays and to probe both strong and weak interactions with great precision. Final states involving two open-charm hadrons and a strange meson, arising from the  $b \rightarrow c\bar{c}s$  quark-level transitions, constitute a significant fraction of the total  $B$ -meson decay width [1]. These decays have proven to be particularly valuable in the discovery of both open- and hidden-charm exotic states, offering unique insights into QCD dynamics [2–8].

The study of the  $B \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K$  processes started with the observation of a structure at  $2930 \text{ MeV}/c^2$  in the  $\Lambda_c^+ K^-$  spectrum in  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decays<sup>1</sup> by the BABAR Collaboration [9], later confirmed by the Belle Collaboration [10]. This structure was subsequently studied using prompt  $\Lambda_c^+ K^-$  production in  $pp$  (proton-proton) collisions [11] and was resolved into two narrow states, namely  $\Xi_c(2923)^0$  and  $\Xi_c(2939)^0$ . Further analysis of the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decay at LHCb confirmed the existence of these two states in  $B$  decays [12], along with evidence for the existence of the additional state  $\Xi_c(2880)^0$ .

Moreover, a recent LHCb study of the prompt  $\Xi_c^+ \pi^- \pi^+$  production led to the discovery of the  $\Xi_c(2923)^+$ , along with confirmation of  $\Xi_c(2815)^+$ ,  $\Xi_c(2970)^+$ , and  $\Xi_c(3080)^+$  states [13]. These states, denoted as  $\Xi_c^{**}$ , represent excited states of the  $\Xi_c$  baryon, with their quantum numbers yet to be confirmed.

The isospin-partner channel  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  helps to form a more complete picture. The Belle Collaboration reported a  $3.9\sigma$  evidence of the charged  $\Xi_c(2930)^+$  state in the  $\Lambda_c^+ K_S^0$  spectrum [14], suggesting similar resonant structures in both  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  and  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decays. The corresponding Feynman diagrams of both nonresonant and excited-state contributions are illustrated in Fig. 1. The unique capabilities of the LHCb detector, combined with the large  $B$ -meson production rates in  $pp$  collisions, provide an ideal environment for detailed studies of these  $\Xi_c$  states.

Besides open-charm systems, charmoniumlike exotic states decaying to  $\Lambda_c^+ \bar{\Lambda}_c^-$  remain intriguing. The Belle Collaboration observed a near-threshold enhancement in  $e^+e^-$  collisions with initial-state radiation [15], later measured precisely by the BESIII Collaboration [16]. The recent study from BESIII does not support the resonant structure previously suggested by Belle [17]. Studies of baryon-pair systems in  $B$ -meson decays will provide further insight into this topic.

This paper describes a study of the  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decay, using  $pp$  collision data at a center-of-mass energy of  $\sqrt{s} = 13$  TeV collected by the LHCb detector, corresponding to an integrated luminosity of  $5.4 \text{ fb}^{-1}$ . The main goals are to measure the branching fraction relative to the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decay and to investigate potential  $\Xi_c^+$  excited states in the  $\Lambda_c^+ K_S^0$  spectrum in search of the isospin partners of established  $\Xi_c^{*0}$  states. Moreover,

<sup>\*</sup>Full author list given at the end of the article.

<sup>1</sup>Charge conjugate processes are implied throughout unless stated otherwise.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP<sup>3</sup>.

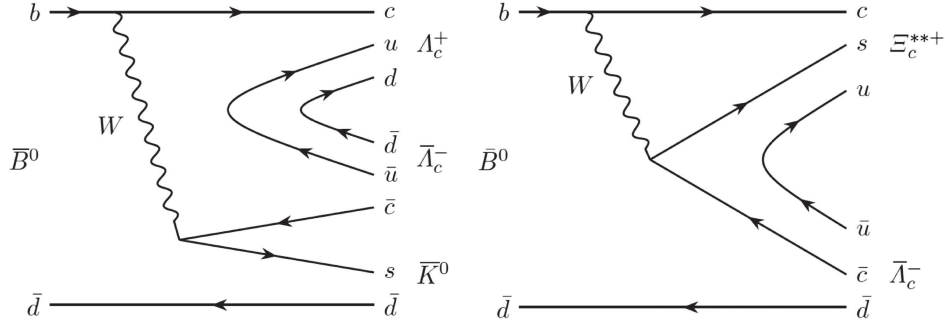


FIG. 1. Feynman diagrams for the  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decay through (left) nonresonant and (right)  $B^0 \rightarrow \bar{\Lambda}_c^- \Xi_c^{***+}$  processes.

the analysis also enables a search of possible charmonium-like exotic states decaying to  $\Lambda_c^+ \bar{\Lambda}_c^-$ .

## II. DETECTOR AND SIMULATION

The LHCb detector [18,19] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , specifically designed for studying  $b$  and  $c$  hadrons. Its tracking system consists 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 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  $p$  of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ $c$ . The momentum scale is calibrated using  $J/\psi \rightarrow \mu^+ \mu^-$  and  $B^+ \rightarrow J/\psi K^+$  decays [20,21] with a relative accuracy of  $3 \times 10^{-4}$ . The minimum distance of a track to a primary  $pp$  collision vertex (PV), the impact parameter, 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. Photons, electrons, and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors and an electromagnetic 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, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. At the hardware trigger stage, events are required to have a muon with high  $p_T$  or a hadron, photon, or electron with high transverse energy in the calorimeters. The software trigger requires a two-, three-, or four-track secondary vertex with a significant displacement from any primary  $pp$  interaction vertex. Data passing the trigger requirements undergo a centralized, offline processing step, to deliver physics-analysis-ready data across the entire LHCb physics program [22].

Simulation is required to model the effects of the detector acceptance and the imposed selection requirements. In the simulation,  $pp$  collisions are generated using Pythia [23] with a specific LHCb configuration [24]. Decays of unstable particles are described by EvtGen [25], in which final-state radiation is generated using PHOTOS [26]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [27] as described in Ref. [28]. The reconstructed signal decays in the simulation are required to be matched with the generated signal decays. To account for known imperfections in modeling the particle identification (PID) performance, the simulation is corrected using information from control samples in data [29]. The simulation samples are weighted to compensate for known differences with respect to the data in  $B$  production kinematics and track multiplicity, as well as trigger efficiencies. They are used to optimize selection criteria, model signal shapes, and compute efficiencies for branching fraction measurements.

## III. SELECTION

The reconstruction of  $B^0$  candidates combines two oppositely charged  $\Lambda_c$  baryons,<sup>2</sup> reconstructed through the  $\Lambda_c^+ \rightarrow p K^- \pi^+$  decay, with one  $K_S^0$  meson. Final-state particles from  $\Lambda_c$  decays are selected with  $p_T > 100$  MeV/ $c$  and required not to originate from any of the PVs. The  $\Lambda_c$  candidates are required to have a reconstructed mass within  $\pm 110$  MeV/ $c^2$  of the known mass [1]. Furthermore, they are required to have  $p_T > 1$  GeV/ $c$ , good vertex-fit quality, and the three  $\Lambda_c$  decay product tracks must have a maximum separation of 0.5 mm. At least one decay product from each  $\Lambda_c$  must have  $p_T > 500$  MeV/ $c$  and  $p > 5$  GeV/ $c$ .

Candidate  $K_S^0 \rightarrow \pi^+ \pi^-$  decays are reconstructed in two different categories: the first involving  $K_S^0$  mesons that decay early enough within the vertex detector such that the two charged pions are reconstructed using the full tracking system, and the second containing  $K_S^0$  mesons whose decay vertex is such that the pions can only be reconstructed with information from the tracking detectors placed downstream

<sup>2</sup>The notation  $\Lambda_c$  is used to represent both  $\Lambda_c^+$  and  $\bar{\Lambda}_c^-$ .

of the vertex detector. The pion tracks of the two categories are referred to as “long” and “downstream” tracks, respectively. The  $K_S^0$  candidates that use long-track pairs (LL) or downstream-track pairs (DD) are treated separately in the event reconstruction chain, with LL candidates offering superior mass and momentum resolution and DD candidates providing higher yields. The  $K_S^0$  candidates are selected requiring the invariant mass of the pion pair in the range  $[465, 530]$  MeV/ $c^2$  for DD candidates and  $[478, 517]$  MeV/ $c^2$  for LL candidates, corresponding to five times the  $K_S^0$  mass resolution in each category. The  $K_S^0$  candidates are required to have a decay vertex that is significantly displaced from the primary vertex.

For the selection of the control channel  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$ , the  $K^+$  candidates are required to have  $p_T > 500$  MeV/ $c$  and  $p > 5$  GeV/ $c$ . The  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  and  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  candidates are required to have a decay vertex of good quality, be consistent with being produced at the PV, and have decay time exceeding 0.2 ps. In addition, the final-state particles are required to satisfy supplementary PID, and mass windows are applied to the  $B$ -meson and  $\Lambda_c$  candidates. These selections suppress combinatorial background while preserving more than 95% of the signal efficiency.

In order to further reduce combinatorial background, a boosted decision tree (BDT) classifier [30,31], implemented in the TMVA toolkit [32], is used. The classifier is trained using candidate  $B$  decays from the high-mass sideband region  $[5400, 5800]$  MeV/ $c^2$  in data as a background proxy and simulated candidates as a signal proxy. The BDT incorporates several discriminating variables including those related to the  $B$  decay topology, PID information, and kinematic properties. The BDT training is performed independently for LL or DD reconstruction categories. The optimal BDT response threshold is determined by maximizing the estimated signal significance. Separate BDTs are optimized for the signal and control channels, with nearly identical selection criteria.

#### IV. SIGNAL YIELD DETERMINATION

The yields of signal and background contributions are determined via three-dimensional (3D) extended unbinned maximum-likelihood fits to the invariant masses of the reconstructed  $B^0$  and  $\Lambda_c$  candidates. For each invariant-mass distribution in  $M(\Lambda_c^+ \bar{\Lambda}_c^- K)$ ,  $M(pK^-\pi^+)$ , and  $M(\bar{p}K^+\pi^-)$ , the signal mass shape (labeled as  $S$ ) is modeled by a double-sided Crystal Ball function [33], and the combinatorial background shape (labeled as  $B$ ) is parametrized by a first-order polynomial function. A 3D fit is performed for both the signal and the control samples. The fit model is constructed as a sum of multiple terms, each of which is a direct product of one-dimensional functions representing each of the three mass distributions. Therefore, the function describing the signal is defined as

$S_{B^0} S_{\Lambda_c^+} S_{\bar{\Lambda}_c^-}$  while the background candidates can be divided into seven different categories:

Categories 1–3 (backgrounds containing genuine  $B^0$  decays):  $S_{B^0} B_{\Lambda_c^+} S_{\bar{\Lambda}_c^-}$ ,  $S_{B^0} S_{\Lambda_c^+} B_{\bar{\Lambda}_c^-}$ ,  $S_{B^0} B_{\Lambda_c^+} B_{\bar{\Lambda}_c^-}$ ;

Categories 4–6 (non- $B^0$  decays containing true  $\Lambda_c$  decays):  $B_{B^0} S_{\Lambda_c^+} S_{\bar{\Lambda}_c^-}$ ,  $B_{B^0} B_{\Lambda_c^+} S_{\bar{\Lambda}_c^-}$ ,  $B_{B^0} S_{\Lambda_c^+} B_{\bar{\Lambda}_c^-}$ ; and

Category 7 (pure combinatorial background):  $B_{B^0} B_{\Lambda_c^+} B_{\bar{\Lambda}_c^-}$ .

It is found that the backgrounds in categories 1–4 are negligible for the signal mode, while this is not the case for categories 5–7. All the tail parameters of the Crystal Ball functions are fixed to the values obtained from simulation and shared between the  $\Lambda_c^+$  and  $\bar{\Lambda}_c^-$  baryons. A similar fit strategy is used for the control mode. Separate fits are performed for LL and DD categories. The invariant-mass distributions of the selected  $B^0$  and  $\Lambda_c$  candidates after applying all the aforementioned selection requirements are shown in Fig. 2. The signal yields are determined to be  $148 \pm 14$  and  $62 \pm 9$  for DD and LL modes, respectively. The yields in the DD and LL modes are consistent with each other accounting for differences in efficiencies. The yield of the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decay is  $1335 \pm 43$ .

#### V. BRANCHING FRACTION

The ratio of branching fractions is defined as

$$\begin{aligned} & \frac{\mathcal{B}(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0)}{\mathcal{B}(B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+)} \\ &= \frac{N(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0)}{N(B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+)} \times \frac{\varepsilon(B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+)}{\varepsilon(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0)} \\ & \times \frac{1}{\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)} \times \frac{f_u}{f_d}, \end{aligned} \quad (1)$$

where  $N$ ,  $\varepsilon$ ,  $\mathcal{B}$ , and  $f_u/f_d$  denote the observed signal yields, the total experimental efficiencies, the branching fraction, and the ratio of hadronization fractions of  $b$  quarks to  $B^+$  and  $B^0$  mesons, respectively. The branching fraction  $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (69.20 \pm 0.05)\%$  is taken from Ref. [1]. The ratio  $f_u/f_d$  is assumed to be equal to unity [34]. The yields of the signal and control modes are obtained from the 3D fit described in Sec. IV, applied to candidates satisfying additional trigger requirements to reduce trigger-related uncertainties. The corresponding yields of signal and control modes are  $128 \pm 12$  and  $971 \pm 36$ , respectively. The total efficiencies are determined from simulation and defined as the product of efficiencies corresponding to detector acceptance, reconstruction, offline preselection, trigger and multivariate selection. Simulated samples are weighted to ensure distributions in the key variables match those in data. A data-driven correction for tracking efficiency is applied. The tracking efficiency for charged tracks is estimated using data, and the difference between simulation and data is obtained from a correction table as a function of the momentum of the

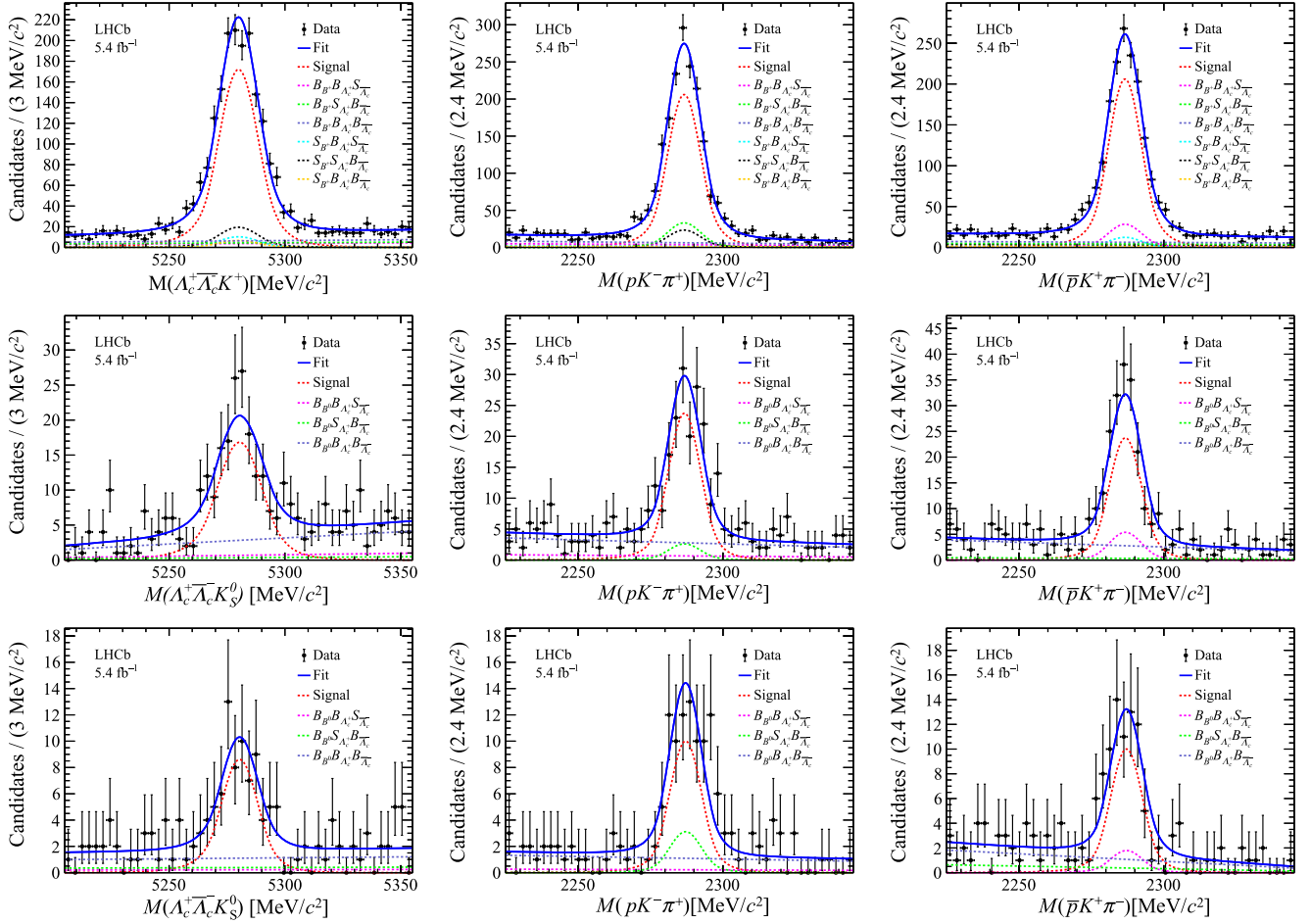


FIG. 2. Fits to the (top row)  $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ , (middle row)  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  DD, and (bottom row) LL categories. The projections along  $M(\Lambda_c^+ \bar{\Lambda}_c^- K^-)$ ,  $M(pK^- \pi^+)$ , and  $M(\bar{p}K^+ \pi^-)$  are shown in left, middle, and right columns, respectively.

track, its pseudorapidity, and the track multiplicity of the event. The total efficiencies of the signal and control decays are  $(1.21 \pm 0.01) \times 10^{-4}$  and  $(3.36 \pm 0.02) \times 10^{-4}$ , respectively, where the uncertainties are statistical only.

The systematic uncertainties on the relative branching fraction measurement, apart from external inputs, are related to the signal yields and efficiencies. Due to the similar topology of the signal and control decays, many sources of systematic uncertainties either cancel or are largely suppressed in the ratio of branching fractions. The remaining systematic uncertainties are outlined below and summarized in Table I.

The determination of the signal yields in the  $B^0$  and  $B^+$  decay channels is affected by the choice of the fit models for the various components. For the  $B$ -meson mass distribution, the Hypatia function [35] and the sum of two Gaussian functions are considered as alternative models for the signal component. For the  $\Lambda_c$  baryon mass peaks, a sum of three Gaussian functions is considered as the alternative model. The correlation between  $B$  and  $\Lambda_c$  masses is ignored in the baseline fit, and the correlation effect is studied by refitting the  $B$  mass while constraining the  $\Lambda_c$  mass to its

known value [1]. Regarding the fit assumption, the reconstructed  $B$ -mass distribution ( $S_B$ ) for backgrounds is allowed to differ from that of the signal component. Therefore, separate signal  $B$  shapes for different components are studied in alternative fits. In addition to this, the fitting ranges for both  $B$  and  $\Lambda_c$  masses are varied.

TABLE I. Sources of systematic uncertainties on the branching ratio measurement.

| Source                 | Relative uncertainty (%) |
|------------------------|--------------------------|
| Signal model           | 3.3                      |
| Mass correlation       | 2.9                      |
| Fit assumption         | 1.9                      |
| Fit range              | 1.2                      |
| Simulation sample size | 3.2                      |
| Weighting              | 6.2                      |
| Tracking efficiency    | 0.8                      |
| Hadronic interaction   | 1.7                      |
| Total                  | 8.7                      |

The systematic uncertainties in the efficiency estimation arise from the limited size of the simulation samples and imperfect simulation of the track reconstruction and the detector response. The uncertainty due to weighting of the simulated samples for the track multiplicity is estimated using pseudoexperiments. In each pseudoexperiment, the applied weight in each track multiplicity bin is varied according to a Gaussian distribution, whose mean and width are taken from the baseline correction factor and its associated uncertainty, respectively. A fit with a Gaussian function is performed to the distribution of deviations of the recalculated efficiency. The resulting width is assigned as the corresponding systematic uncertainty. The tracking efficiency correction is validated using the same method and the associated uncertainty is found to be negligible. In addition, the final states of the signal mode and the control mode differ by one track, hence an additional relative uncertainty for the tracking efficiency is considered. Possible effects from intermediate resonances are taken into account by weighting the phase-space variables to match the distribution in data, and the resulting variation is assigned as the systematic uncertainty are included in the weighting systematic uncertainty.

Uncertainties of 1.1% and 1.4% due to hadronic interactions are assigned for kaons and pions to account for the uncertainties in material budget and interaction cross section in simulations [36] for different particle types, in both signal and control decays.

Additional sources of systematic uncertainties are considered but found negligible. The PID efficiency is obtained from calibration data in separate regions of momentum and pseudorapidity. Systematic uncertainties are assessed through pseudoexperiments and by varying the limits of these regions. Potential background contamination in the simulation is evaluated by fitting simulated samples without matching requirements to the generated signals. All related systematic effects are found to be negligible for both signal and control channels.

## VI. INTERMEDIATE RESONANCES

To study the intermediate states with improved mass resolution while enhancing signal purity, stringent mass requirements are imposed on the  $B^0$  candidates in range of [5230, 5330] MeV/ $c^2$  and the  $\Lambda_c$  candidates in range of [2255, 2315] MeV/ $c^2$ . Subsequently kinematic quantities are recalculated with the  $\Lambda_c^+$  and  $K_S^0$  candidate masses constrained to their established values. The signal channel  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  is a self-conjugate decay process, where excited charged  $\Xi_c^{*+}$  states are expected to contribute to both the  $\Lambda_c^+ K_S^0$  and  $\bar{\Lambda}_c^- K_S^0$  invariant-mass spectra. The projection of the  $\Lambda_c^+ K_S^0$  and  $\bar{\Lambda}_c^- K_S^0$  invariant-mass spectra, denoted  $\Lambda_c K_S^0$ , is shown in Fig. 3 for the combined LL and DD samples, together with the result of an unbinned

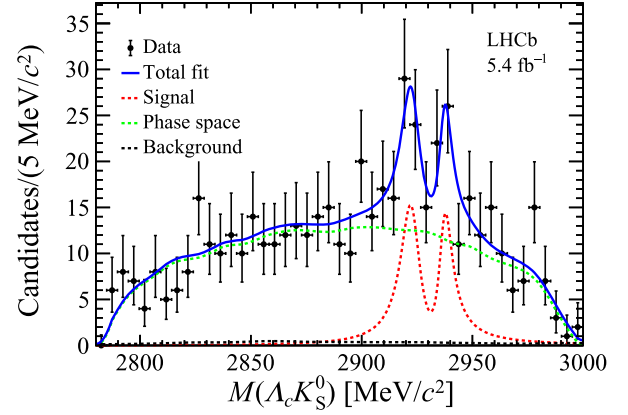


FIG. 3. Fit to the  $\Lambda_c K_S^0$  mass spectrum considering  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  states.

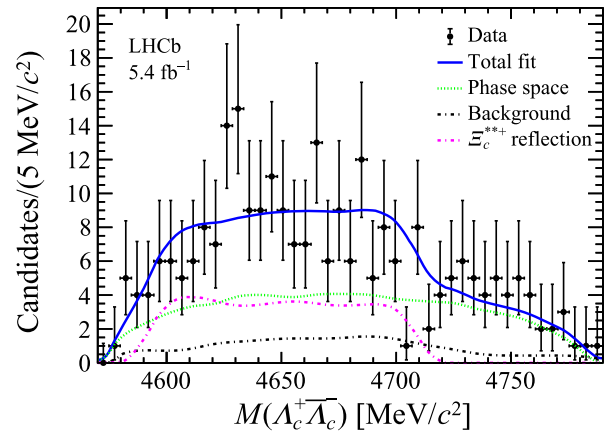


FIG. 4. Fit to the  $\Lambda_c^+ \bar{\Lambda}_c^-$  mass spectrum.

maximum-likelihood fit that includes two  $\Xi_c^{*+}$  states, as detailed below.

The  $\Lambda_c^+ \bar{\Lambda}_c^-$  invariant-mass spectra are shown in Fig. 4. The fit components are similar to those used in the fit of  $\Lambda_c K_S^0$  combination. In this case, a contribution due to the reflection of the  $\Xi_c^{*+}$  states is included, with the shape determined from a phase-space generator-level simulation of  $B^0 \rightarrow \bar{\Lambda}_c^- \Xi_c^{*+}$  decays. No significant structure emerges within the current statistical precision.

The fit model for the  $\Lambda_c K_S^0$  mass spectrum is constructed as

$$f(M) = g_{\Xi_c^{*+}} f_{\Xi_c^{*+}} \otimes G(0, \sigma_{\text{res}}) + g_{\text{bkg}} f_{\text{bkg}} + (1 - g_{\Xi_c^{*+}} - g_{\text{bkg}}) f_{\text{phsp}}, \quad (2)$$

where  $g_{\Xi_c^{*+}}$  and  $g_{\text{bkg}}$  are the fractional yields of  $\Xi_c^{*+}$  and background, respectively, leaving  $(1 - g_{\Xi_c^{*+}} - g_{\text{bkg}})$  as the fraction of the nonresonant component. The function  $f_{\Xi_c^{*+}}$  represents the probability density function of excited  $\Xi_c^{*+}$  states and  $G(0, \sigma_{\text{res}})$  is a Gaussian function parametrizing

the detector resolution. Separate detector resolutions are used for the DD and LL subsamples. To combine these two subsamples, the weight factors for DD and LL are based on the statistical precision in the considered intervals. The resolution shows dependence on the variable  $M(\Lambda_c K_S^0)$  which is modeled by a second-order polynomial function whose parameters are determined from simulation. The background shape  $f_{\text{bkg}}$  is determined from the data excluding the  $B^0$  and  $\Lambda_c$  mass regions. The shape of the nonresonant component  $f_{\text{phsp}}$  is obtained from simulation of pure phase-space  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decays.

In the baseline fit, the sum of  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  contributions is modeled as

$$f_{\Xi_c^{**}} = pq(|\mathcal{M}_{\Xi_c(2923)^+}|^2 + \alpha^2 |\mathcal{M}_{\Xi_c(2939)^+}|^2), \quad (3)$$

where  $p$  is the  $\Xi_c^{**}$  momentum in the  $B^0$  rest frame,  $q$  is the  $\Lambda_c$  (or  $K_S^0$ ) momentum in the  $\Xi_c^{**}$  rest frame, and  $\alpha$  quantifies the relative contribution of the two peaks. The amplitude  $\mathcal{M}$  is parametrized using Blatt-Weisskopf barrier factors [37]  $B_L$  and a relativistic Breit-Wigner (RBW) function [38], defined as

$$\text{RBW}(M) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)}, \quad (4)$$

$$\Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \left(\frac{M_0}{M}\right) B_L^2, \quad (5)$$

where  $q_0$  is the value of the momentum  $q$  at the resonance peak, and  $L$  is the orbital angular momentum between the  $\Lambda_c$  and  $K_S^0$  hadrons. The parameters  $M_0$  and  $\Gamma_0$  denote the pole mass and width, which are determined from the fit. The  $B_L$  factors are evaluated assuming an effective radius of the resonant state of 3 GeV<sup>-1</sup> [11], corresponding to approximately 0.6 fm [39].

Due to the limited signal yields, the quantum numbers of the  $\Xi_c^{**}$  states cannot be determined. The spin-parity ( $J^P$ ) assignments in this paper follow the same configuration as in the previous study of  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decays [12], with the orbital angular momentum between  $\Lambda_c$  and  $K_S^0$  set to 2 and the  $J^P$  of both  $\Xi_c^+$  states assumed to be  $\frac{3}{2}^-$  [40]. Given the  $K_S^0$  and  $\Lambda_c$  particles have  $J^P = 0^-$  and  $\frac{1}{2}^+$ , respectively, the  $P$ -parity of  $\Xi_c^+$  is consequently determined to be negative. This provides a baseline model, allowing for subsequent comparison with the models that incorporate interference. Alternative hypotheses of S-wave and P-wave configurations are considered as part of the systematic uncertainty evaluation.

The  $M(\Lambda_c K_S^0)$  mass distribution is shown in Fig. 3, together with the result of the baseline fit, which includes contributions from both the  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  states. Their combined yield is  $86 \pm 22$ , while their mass and width are reported in Table II. The significance of the

TABLE II. Measured masses and widths of the  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  states.

| State           | Mass (MeV/ $c^2$ )       | Width (MeV/ $c^2$ )    |
|-----------------|--------------------------|------------------------|
| $\Xi_c(2923)^+$ | $2923.1 \pm 1.8 \pm 0.8$ | $11.6 \pm 5.2 \pm 2.6$ |
| $\Xi_c(2939)^+$ | $2937.5 \pm 1.6 \pm 0.9$ | $7.1 \pm 4.1 \pm 2.4$  |

two-resonance structure with respect to the background-only hypothesis is evaluated using Wilks's theorem [41] and found to be  $3.9\sigma$ . When the null hypothesis is set to a single peak, allowing for changes in both the peak mass and its width, the significance of the two-resonance structure is reduced to  $1.7\sigma$ .

Systematic uncertainties on the mass and width measurements from various sources are studied. Multiple alternative assumptions on the fit parameters are tested to determine the possible uncertainties related to the choice of the signal model. The effective radius of  $\Xi_c^+$  resonances is changed to 2.0 and 4.0 GeV<sup>-1</sup>. Alternative spin-parity assignments of the two  $\Xi_c^+$  states,  $J^P = \frac{1}{2}^+, \frac{1}{2}^-, \frac{3}{2}^+$ , or  $\frac{3}{2}^-$ , are considered. Different resonances with the same spin parity that are close in mass can interfere. To account for this, Eq. (3) is replaced with the coherent sum

$$pq|\mathcal{M}_{\Xi_c(2923)^+} + \alpha e^{i\theta} \mathcal{M}_{\Xi_c(2939)^+}|^2, \quad (6)$$

where  $\alpha$  is a free parameter in the fit. The relative phase  $\theta$  is scanned in the range of  $[-\pi, \pi]$  to determine a related systematic uncertainty. The background yields are constrained to the results of the baseline fit using Gaussian priors. The maximum variation of the fit results for each alternative model assumption described above is assigned as the corresponding uncertainty and added in quadrature to the total systematic uncertainty.

To study possible biases on the measured mass and width of the  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  states, 1000 pseudoexperiments are performed in which all fit parameters, except the masses and widths, are fixed. Each pseudosample is generated according to the baseline fit result where the total number of signal and background candidate yields are fluctuated according to Poisson distributions. The deviations between the mean values obtained from the pseudoexperiment results and the generated values are evaluated. The deviations are smaller than the statistical uncertainties and are considered in the systematic uncertainty determination.

The systematic uncertainty associated with the modeling of the mass-resolution parameter is evaluated using an alternative second-order polynomial, obtained by fitting the mass-resolution dependence with a different binning. In addition, several other sources of systematic uncertainty only affect the mass measurement. These include the momentum uncertainty, evaluated by shifting the momentum scale used in the reconstruction of charged tracks by a factor of  $3 \times 10^{-4}$  [11,21] in simulated decays, and the

TABLE III. Summary of systematic uncertainties on the masses and widths of the  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  states.

| Source           | $\Xi_c(2923)^+$      |                           | $\Xi_c(2939)^+$      |                           |
|------------------|----------------------|---------------------------|----------------------|---------------------------|
|                  | $M$<br>(MeV/ $c^2$ ) | $\Gamma$<br>(MeV/ $c^2$ ) | $M$<br>(MeV/ $c^2$ ) | $\Gamma$<br>(MeV/ $c^2$ ) |
| Model assumption | 0.75                 | 1.20                      | 0.82                 | 1.20                      |
| Fit procedure    | 0.38                 | 2.32                      | 0.37                 | 2.08                      |
| Mass resolution  | 0.00                 | 0.02                      | 0.08                 | 0.03                      |
| Momentum scaling | 0.04                 | ...                       | 0.05                 | ...                       |
| Energy loss      | 0.04                 | ...                       | 0.04                 | ...                       |
| Total            | 0.84                 | 2.61                      | 0.91                 | 2.40                      |

imperfect modeling of the energy loss in the detector material [42]. The deviation from the baseline fit is assigned as the systematic uncertainty.

A summary of the systematic uncertainties is listed in Table III. The uncertainties from different sources are added in quadrature to give the total systematic uncertainty.

## VII. RESULTS AND SUMMARY

The  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decay is studied at LHCb using  $pp$  collision data collected at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $5.4 \text{ fb}^{-1}$ . The branching ratio of the  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decay is measured relative to  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  as

$$\frac{\mathcal{B}(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0)}{\mathcal{B}(B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+)} = 0.53 \pm 0.05 \pm 0.05,$$

where the uncertainties are statistical and systematic, respectively. Using the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  branching fraction from Ref. [1], the branching fraction of the  $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0$  decay is determined to be

$$\mathcal{B}(B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K_S^0) = (2.60 \pm 0.26 \pm 0.23 \pm 0.37) \times 10^{-4},$$

where the third uncertainty is due to the external branching fraction of the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decay [1]. This result is the most precise measurement to date.

The fit to the  $\Lambda_c K_S^0$  mass spectrum shows evidence for the  $\Xi_c(2923)^+$  and  $\Xi_c(2939)^+$  resonances with a significance of  $3.9\sigma$ . Both the masses and widths are consistent with

measurements from the isospin-partner decay  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  [12] and from prompt measurements in  $\Xi_c \rightarrow \Lambda_c^+ K^-$  decays [11]. No significant structure is seen in the  $\Lambda_c^+ \bar{\Lambda}_c^-$  spectrum.

## ACKNOWLEDGMENTS

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 LHCb institutes. We acknowledge support from CERN and from the national agencies: ARC (Australia); CAPES, CNPq, FAPERJ, and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 and CEA (France); BMFTR, DFG, and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICIU and AEI (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (U.S.). We acknowledge the computing resources that are provided by ARDC (Australia), CBPF (Brazil), CERN, IHEP, and LZU (China), IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), Polish WLCG (Poland), IFIN-HH (Romania), PIC (Spain), CSCS (Switzerland), GridPP (United Kingdom), and NSF (U.S.). 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 RTP (Australia), Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP (China); Minciencias (Colombia); EPLANET, Marie Skłodowska-Curie Actions, ERC, and NextGenerationEU (European Union); A\*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Alexander-von-Humboldt Foundation (Germany); ICSC (Italy); Severo Ochoa and María de Maeztu Units of Excellence, GVA, XuntaGal, GENCAT, InTalent-Inditex, and Prog. Atracción Talento CM (Spain); the Leverhulme Trust, the Royal Society, and UKRI (United Kingdom).

## DATA AVAILABILITY

All LHCb scientific output is published in journals, with preliminary results made available in Conference Reports. All are Open Access, without restriction on use beyond the standard conditions agreed by CERN. Data associated with the plots in this publication are made available on the CERN document server [43].

- [1] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [2] R. Aaij *et al.* (LHCb Collaboration), Model-independent study of structure in  $B^+ \rightarrow D^+ D^- K^+$  decays, *Phys. Rev. Lett.* **125**, 242001 (2020).
- [3] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of the  $B^+ \rightarrow D^+ D^- K^+$  decay, *Phys. Rev. D* **102**, 112003 (2020).
- [4] R. Aaij *et al.* (LHCb Collaboration), Observation of a resonant structure near the  $D_s^+ D_s^-$  threshold in the  $B^+ \rightarrow D_s^+ D_s^- K^+$  decay, *Phys. Rev. Lett.* **131**, 071901 (2023).
- [5] R. Aaij *et al.* (LHCb Collaboration), First observation of the  $B^+ \rightarrow D_s^+ D_s^- K^+$  decay, *Phys. Rev. D* **108**, 034012 (2023).
- [6] R. Aaij *et al.* (LHCb Collaboration), First observation of a doubly charged tetraquark candidate and its neutral partner, *Phys. Rev. Lett.* **131**, 041902 (2023).
- [7] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of  $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$  and  $B^+ \rightarrow D^- D_s^+ \pi^+$  decays, *Phys. Rev. D* **108**, 012017 (2023).
- [8] R. Aaij *et al.* (LHCb Collaboration), Observation of new charmonium or charmoniumlike states in  $B^+ \rightarrow D^{*\pm} D^\mp K^+$  decays, *Phys. Rev. Lett.* **133**, 131902 (2024).
- [9] B. Aubert *et al.* (BABAR Collaboration), A study of  $\bar{B} \rightarrow \Xi_c^- \bar{\Lambda}_c^-$  and  $\bar{B} \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- \bar{K}$  decays at BABAR, *Phys. Rev. D* **77**, 031101 (2008).
- [10] Y. B. Li *et al.* (Belle Collaboration), Observation of  $\Xi_c(2930)^0$  and updated measurement of  $B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^-$  at Belle, *Eur. Phys. J. C* **78**, 252 (2018).
- [11] R. Aaij *et al.* (LHCb Collaboration), Observation of new  $\Xi_c^0$  baryons decaying to  $\Lambda_c^+ K^-$ , *Phys. Rev. Lett.* **124**, 222001 (2020).
- [12] R. Aaij *et al.* (LHCb Collaboration), Study of the  $B^+ \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^+$  decay, *Phys. Rev. D* **108**, 012020 (2023).
- [13] R. Aaij *et al.* (LHCb Collaboration), Observation of a new charmed baryon decaying to  $\Xi_c^+ \pi^+ \pi^-$ , *Phys. Rev. Lett.* **135**, 161901 (2025).
- [14] Y. B. Li *et al.* (Belle Collaboration), Evidence of a structure in  $\bar{K}^0 \Lambda_c^+$  consistent with a charged  $\Xi_c(2930)^+$ , and updated measurement of  $\bar{B}^0 \rightarrow \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$  at Belle, *Eur. Phys. J. C* **78**, 928 (2018).
- [15] G. Pakhlova *et al.* (Belle Collaboration), Observation of a near-threshold enhancement in the  $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$  cross section using initial-state radiation, *Phys. Rev. Lett.* **101**, 172001 (2008).
- [16] M. Ablikim *et al.* (BESIII Collaboration), Precision measurement of the  $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$  cross section near threshold, *Phys. Rev. Lett.* **120**, 132001 (2018).
- [17] M. Ablikim *et al.* (BESIII Collaboration), Measurement of energy-dependent pair-production cross section and electromagnetic form factors of a charmed baryon, *Phys. Rev. Lett.* **131**, 191901 (2023).
- [18] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [19] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [20] R. Aaij *et al.* (LHCb Collaboration), Measurements of the  $\Lambda_b^0$ ,  $\Xi_b^-$ , and  $\Omega_b^-$  baryon masses, *Phys. Rev. Lett.* **110**, 182001 (2013).
- [21] R. Aaij *et al.* (LHCb Collaboration), Precision measurement of  $D$  meson mass differences, *J. High Energy Phys.* **06** (2013) 065.
- [22] N. Grieser *et al.*, The LHCb stripping project: Sustainable legacy data processing for high-energy physics, *Comput. Software Big. Sci.* **9**, 21 (2025).
- [23] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008); T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [24] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [25] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [26] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in C++: Technical and physics documentation, *Comput. Phys. Commun.* **199**, 86 (2016).
- [27] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006); S. Agostinelli *et al.* (Geant4 Collaboration), Geant4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [28] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [29] R. Aaij *et al.*, Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2, *Eur. Phys. J. Tech. Instrum.* **6**, 1 (2019).
- [30] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth International Group, Belmont, California, USA, 1984).
- [31] 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).
- [32] H. Voss, A. Hoecker, J. Stelzer, and F. Tegenfeldt, TMVA—toolkit for multivariate data analysis with ROOT, *Proc. Sci. ACAT2007* (2007) 040; A. Hoecker *et al.*, TMVA 4—Toolkit for multivariate data analysis with ROOT. Users guide, [arXiv:physics/0703039](https://arxiv.org/abs/physics/0703039).
- [33] 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 [Report No. DESY-F31-86-02].
- [34] Y. Amhis *et al.*, Averages of b-hadron, c-hadron, and -lepton properties as of 2018, *Eur. Phys. J. C* **81**, 226 (2020).
- [35] D. Martínez Santos and F. Dupertuis, Mass distributions marginalized over per-event errors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **764**, 150 (2014).
- [36] M. De Cian *et al.*, Measurement of the track finding efficiency, Reports No. LHCb-PUB-2011-025, No. CERN-LHCb-PUB-2011-025, CERN, Geneva, 2012, <https://cds.cern.ch/record/1402577>.
- [37] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Springer, New York, 1952).

- [38] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of  $B^+ \rightarrow J/\psi \phi K^+$  decays, *Phys. Rev. D* **95**, 012002 (2017).
- [39] R. Aaij *et al.* (LHCb Collaboration), Observation of two new  $\Xi_b^-$  baryon resonances, *Phys. Rev. Lett.* **114**, 062004 (2015).
- [40] K.-L. Wang, L.-Y. Xiao, and X.-H. Zhong, Understanding the newly observed  $\Xi_c^0$  states through their decays, *Phys. Rev. D* **102**, 034029 (2020).
- [41] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011); **73**, 2501(E) (2013).
- [42] R. Aaij *et al.* (LHCb Collaboration), Prompt  $K_S^0$  production in  $pp$  collisions at  $\sqrt{s} = 0.9$  TeV, *Phys. Lett. B* **693**, 69 (2010).
- [43] <https://cds.cern.ch/record/2959314>.

R. Aaij<sup>38</sup>, M. Abdelfatah<sup>69</sup>, A. S. W. Abdelmotteleb<sup>57</sup>, C. Abellan Beteta<sup>51</sup>, F. Abudinén<sup>59</sup>, T. Ackernley<sup>61</sup>, A. A. Adefisoye<sup>69</sup>, B. Adeva<sup>47</sup>, M. Adinolfi<sup>55</sup>, P. Adlarson<sup>87</sup>, C. Agapopoulou<sup>14</sup>, C. A. Aidala<sup>89</sup>, Z. Ajaltouni<sup>11</sup>, S. Akar<sup>11</sup>, K. Akiba<sup>38</sup>, P. Albicocco<sup>28</sup>, J. Albrecht<sup>19,b</sup>, R. Aleksiejunas<sup>81</sup>, F. Alessio<sup>49</sup>, P. Alvarez Cartelle<sup>56,47</sup>, R. Amalric<sup>16</sup>, S. Amato<sup>3</sup>, J. L. Amey<sup>55</sup>, Y. Amhis<sup>14</sup>, L. An<sup>6</sup>, L. Anderlini<sup>27</sup>, M. Andersson<sup>51</sup>, P. Andreola<sup>51</sup>, M. Andreotti<sup>26</sup>, S. Andres Estrada<sup>44</sup>, A. Anelli<sup>31,c</sup>, D. Ao<sup>7</sup>, C. Arata<sup>12</sup>, F. Archilli<sup>37</sup>, Z. Areg<sup>69</sup>, M. Argenton<sup>26</sup>, S. Argüedas Cuendis<sup>9,49</sup>, L. Arnone<sup>31,c</sup>, M. Artuso<sup>69</sup>, E. Aslanides<sup>13</sup>, R. Ataíde Da Silva<sup>50</sup>, M. Atzeni<sup>65</sup>, B. Audurier<sup>12</sup>, J. A. Authier<sup>15</sup>, D. Bacher<sup>64</sup>, I. Bachiller Perea<sup>50</sup>, S. Bachmann<sup>22</sup>, M. Bachmayer<sup>50</sup>, J. J. Back<sup>57</sup>, Z. B. Bai<sup>8</sup>, P. Baladron Rodriguez<sup>47</sup>, V. Balagura<sup>15</sup>, A. Balboni<sup>26</sup>, W. Baldini<sup>26</sup>, Z. Baldwin<sup>79</sup>, L. Balzani<sup>19</sup>, H. Bao<sup>7</sup>, J. Baptista de Souza Leite<sup>2</sup>, C. Barbero Pretel<sup>47,12</sup>, M. Barbetti<sup>27</sup>, I. R. Barbosa<sup>70</sup>, R. J. Barlow<sup>63,a</sup>, M. Barnyakov<sup>25</sup>, S. Barsuk<sup>14</sup>, W. Barter<sup>59</sup>, J. Bartz<sup>69</sup>, S. Bashir<sup>40</sup>, B. Batsukh<sup>82</sup>, P. B. Battista<sup>14</sup>, A. Bavarchee<sup>80</sup>, A. Bay<sup>50</sup>, A. Beck<sup>65</sup>, M. Becker<sup>19</sup>, F. Bedeschi<sup>35</sup>, I. B. Bediaga<sup>2</sup>, N. A. Behling<sup>19</sup>, S. Belin<sup>47</sup>, A. Bellavista<sup>25</sup>, I. Belov<sup>29</sup>, I. Belyaev<sup>36</sup>, G. Benane<sup>13</sup>, G. Bencivenni<sup>28</sup>, E. Ben-Haim<sup>16</sup>, R. Bernet<sup>51</sup>, A. Bertolin<sup>33</sup>, F. Betti<sup>59</sup>, J. Bex<sup>56</sup>, O. Bezshyyko<sup>88</sup>, S. Bhattacharya<sup>80</sup>, M. S. Bieker<sup>18</sup>, N. V. Biesuz<sup>26</sup>, A. Biolchini<sup>38</sup>, M. Birch<sup>62</sup>, F. C. R. Bishop<sup>10</sup>, A. Bitadze<sup>63</sup>, A. Bizzeti<sup>27,d</sup>, T. Blake<sup>57,e</sup>, F. Blanc<sup>50</sup>, J. E. Blank<sup>19</sup>, S. Blusk<sup>69</sup>, J. A. Boelhauve<sup>19</sup>, O. Boente Garcia<sup>49</sup>, T. Boettcher<sup>90</sup>, A. Bohare<sup>59</sup>, C. Bolognani<sup>19</sup>, R. Bolzonella<sup>26,f</sup>, R. B. Bonacci<sup>1</sup>, A. Bordelius<sup>49</sup>, F. Borgato<sup>33,49</sup>, S. Borghi<sup>63</sup>, M. Borsato<sup>31,c</sup>, J. T. Borsuk<sup>86</sup>, E. Bottalico<sup>61</sup>, S. A. Bouchiba<sup>50</sup>, M. Bovill<sup>64</sup>, T. J. V. Bowcock<sup>61</sup>, A. Boyer<sup>49</sup>, C. Bozzi<sup>26</sup>, J. D. Brandenburg<sup>91</sup>, A. Brea Rodriguez<sup>50</sup>, N. Breer<sup>19</sup>, C. Breitfeld<sup>19</sup>, J. Brodzicka<sup>41</sup>, J. Brown<sup>61</sup>, D. Brundu<sup>32</sup>, E. Buchanan<sup>59</sup>, M. Burgos Marcos<sup>84</sup>, C. Burr<sup>49</sup>, C. Buti<sup>27</sup>, J. S. Butter<sup>56</sup>, J. Buytaert<sup>49</sup>, W. Byczynski<sup>49</sup>, S. Cadeddu<sup>32</sup>, H. Cai<sup>75</sup>, Y. Cai<sup>5</sup>, A. Caillet<sup>16</sup>, R. Calabrese<sup>26,f</sup>, L. Calefice<sup>45</sup>, M. Calvi<sup>31,c</sup>, M. Calvo Gomez<sup>46</sup>, P. Camargo Magalhaes<sup>2,g</sup>, J. I. Cambon Bouzas<sup>47</sup>, P. Campana<sup>28</sup>, A. C. Campos<sup>3</sup>, A. F. Campoverde Quezada<sup>7</sup>, Y. Cao<sup>6</sup>, S. Capelli<sup>31,c</sup>, M. Caporale<sup>25</sup>, L. Capriotti<sup>26</sup>, R. Caravaca-Mora<sup>9</sup>, A. Carbone<sup>25,h</sup>, L. Carcedo Salgado<sup>47</sup>, R. Cardinale<sup>29,i</sup>, A. Cardini<sup>32</sup>, P. Carniti<sup>31</sup>, L. Carus<sup>22</sup>, A. Casais Vidal<sup>65</sup>, R. Caspary<sup>22</sup>, G. Casse<sup>61</sup>, M. Cattaneo<sup>49</sup>, G. Cavallero<sup>26</sup>, V. Cavallini<sup>26,f</sup>, S. Celani<sup>49</sup>, I. Celestino<sup>35,j</sup>, S. Cesare<sup>49,k</sup>, A. J. Chadwick<sup>61</sup>, I. Chahrour<sup>89</sup>, M. Charles<sup>16</sup>, Ph. Charpentier<sup>49</sup>, E. Chatzianagnostou<sup>38</sup>, R. Cheaib<sup>80</sup>, M. Chefdeville<sup>10</sup>, C. Chen<sup>57</sup>, J. Chen<sup>50</sup>, S. Chen<sup>5</sup>, Z. Chen<sup>7</sup>, A. Chen Hu<sup>62</sup>, M. Cherif<sup>12</sup>, A. Chernov<sup>41</sup>, S. Chernyshenko<sup>53</sup>, X. Chiotopoulos<sup>84</sup>, G. Chizhik<sup>1</sup>, V. Chobanova<sup>44</sup>, M. Chrzasczcz<sup>41</sup>, V. Chulikov<sup>28,49,36</sup>, P. Ciambone<sup>28</sup>, X. Cid Vidal<sup>47</sup>, G. Ciezarek<sup>49</sup>, P. Cifra<sup>49</sup>, P. E. L. Clarke<sup>59</sup>, M. Clemencic<sup>49</sup>, H. V. Cliff<sup>56</sup>, J. Closier<sup>49</sup>, C. Cocha Toapaxi<sup>22</sup>, V. Coco<sup>49</sup>, J. Cogan<sup>13</sup>, E. Cogneras<sup>11</sup>, L. Cojocariu<sup>43</sup>, S. Collaviti<sup>50</sup>, P. Collins<sup>49</sup>, T. Colombo<sup>49</sup>, M. Colonna<sup>19</sup>, A. Comerma-Montells<sup>45</sup>, L. Congedo<sup>24</sup>, J. Connaughton<sup>57</sup>, A. Contu<sup>32</sup>, N. Cooke<sup>60</sup>, G. Cordova<sup>35,j</sup>, C. Coronel<sup>66</sup>, I. Corredoira<sup>12</sup>, A. Correia<sup>16</sup>, G. Corti<sup>49</sup>, G. C. Costantino<sup>61</sup>, J. Cotte Meldrum<sup>55</sup>, B. Couturier<sup>49</sup>, D. C. Craik<sup>51</sup>, N. Crepet<sup>14</sup>, M. Cruz Torres<sup>2,l</sup>, M. Cubero Campos<sup>9</sup>, E. Curras Rivera<sup>50</sup>, R. Currie<sup>59</sup>, C. L. Da Silva<sup>68</sup>, X. Dai<sup>4</sup>, E. Dall'Occo<sup>49</sup>, J. Dalseno<sup>44</sup>, C. D'Ambrosio<sup>62</sup>, J. Daniel<sup>11</sup>, G. Darze<sup>3</sup>, A. Davidson<sup>57</sup>, J. E. Davies<sup>63</sup>, O. De Aguiar Francisco<sup>63</sup>, C. De Angelis<sup>32,m</sup>, F. De Benedetti<sup>49</sup>, J. de Boer<sup>38</sup>, K. De Bruyn<sup>83</sup>, S. De Capua<sup>63</sup>, M. De Cian<sup>63</sup>, U. De Freitas Carneiro Da Graca<sup>2</sup>, E. De Lucia<sup>28</sup>, J. M. De Miranda<sup>2</sup>, L. De Paula<sup>3</sup>, M. De Serio<sup>24,n</sup>, P. De Simone<sup>28</sup>, F. De Vellis<sup>19</sup>, J. A. de Vries<sup>84</sup>, F. Debernardis<sup>24</sup>, D. Decamp<sup>10</sup>, S. Dekkers<sup>1</sup>, L. Del Buono<sup>16</sup>, B. Delaney<sup>65</sup>, J. Deng<sup>8</sup>, V. Denysenko<sup>51</sup>, O. Deschamps<sup>11</sup>, F. Dettori<sup>32,m</sup>, B. Dey<sup>80</sup>, P. Di Nezza<sup>28</sup>, S. Ding<sup>69</sup>, Y. Ding<sup>50</sup>, L. Dittmann<sup>22</sup>, A. D. Docheva<sup>60</sup>, A. Doheny<sup>57</sup>, C. Dong<sup>4,o</sup>, F. Dordei<sup>32</sup>, A. C. dos Reis<sup>2</sup>, A. D. Dowling<sup>69</sup>, L. Dreyfus<sup>13</sup>

W. Duan<sup>73</sup>, P. Duda<sup>86</sup>, L. Dufour<sup>50</sup>, V. Duk<sup>34</sup>, P. Durante<sup>49</sup>, M. M. Duras<sup>86</sup>, J. M. Durham<sup>68</sup>, O. D. Durmus<sup>80</sup>, A. Dziurda<sup>41</sup>, S. Easo<sup>58</sup>, E. Eckstein<sup>18</sup>, U. Egede<sup>1</sup>, S. Eisenhardt<sup>59</sup>, E. Ejopu<sup>61</sup>, L. Eklund<sup>87</sup>, M. Elashri<sup>66</sup>, D. Elizondo Blanco<sup>19</sup>, J. Ellbracht<sup>19</sup>, S. Ely<sup>62</sup>, A. Ene<sup>43</sup>, J. Eschle<sup>69</sup>, T. Evans<sup>38</sup>, F. Fabiano<sup>14</sup>, S. Faghih<sup>66</sup>, L. N. Falcao<sup>31,c</sup>, B. Fang<sup>7</sup>, R. Fantechi<sup>35</sup>, L. Fantini<sup>34,p</sup>, M. Faria<sup>50</sup>, K. Farmer<sup>59</sup>, F. Fassin<sup>83,38</sup>, D. Fazzini<sup>31,c</sup>, L. Felkowski<sup>86</sup>, C. Feng<sup>6</sup>, M. Feng<sup>5,7</sup>, A. Fernandez Casani<sup>48</sup>, M. Fernandez Gomez<sup>47</sup>, A. D. Fernez<sup>67</sup>, F. Ferrari<sup>25,h</sup>, F. Ferreira Rodrigues<sup>3</sup>, M. Ferrillo<sup>51</sup>, M. Ferro-Luzzi<sup>49</sup>, R. A. Fini<sup>24</sup>, M. Fiorini<sup>26,f</sup>, M. Firlej<sup>40</sup>, K. L. Fischer<sup>64</sup>, D. S. Fitzgerald<sup>89</sup>, C. Fitzpatrick<sup>63</sup>, T. Fiutowski<sup>40</sup>, F. Fleuret<sup>15</sup>, A. Fomin<sup>52</sup>, M. Fontana<sup>25,49</sup>, L. A. Foreman<sup>63</sup>, R. Forty<sup>49</sup>, D. Foulds-Holt<sup>59</sup>, V. Franco Lima<sup>3</sup>, M. Franco Sevilla<sup>67</sup>, M. Frank<sup>49</sup>, E. Franzoso<sup>26,f</sup>, G. Frau<sup>63</sup>, C. Frei<sup>49</sup>, D. A. Friday<sup>63,49</sup>, J. Fu<sup>7</sup>, Q. Führling<sup>19,56,b</sup>, T. Fulghesu<sup>13</sup>, G. Galati<sup>24,n</sup>, M. D. Galati<sup>38</sup>, A. Gallas Torreira<sup>47</sup>, D. Galli<sup>25,h</sup>, S. Gambetta<sup>59</sup>, M. Gandelman<sup>3</sup>, P. Gandini<sup>30</sup>, B. Ganie<sup>63</sup>, H. Gao<sup>7</sup>, R. Gao<sup>64</sup>, T. Q. Gao<sup>56</sup>, Y. Gao<sup>8</sup>, Y. Gao<sup>6</sup>, Y. Gao<sup>8</sup>, L. M. Garcia Martin<sup>50</sup>, P. Garcia Moreno<sup>45</sup>, J. García Pardiñas<sup>65</sup>, P. Gardner<sup>67</sup>, L. Garrido<sup>45</sup>, C. Gaspar<sup>49</sup>, A. Gavrikov<sup>33</sup>, L. L. Gerken<sup>19</sup>, E. Gersabeck<sup>20</sup>, M. Gersabeck<sup>20</sup>, T. Gershon<sup>57</sup>, S. Ghizzo<sup>29,i</sup>, Z. Ghorbanimoghaddam<sup>55</sup>, F. I. Giasemis<sup>16,q</sup>, V. Gibson<sup>56</sup>, H. K. Giemza<sup>42</sup>, A. L. Gilman<sup>66</sup>, M. Giovannetti<sup>28</sup>, A. Gioventù<sup>47</sup>, L. Girardey<sup>63,58</sup>, M. A. Giza<sup>41</sup>, F. C. Glaser<sup>22,14</sup>, V. V. Gligorov<sup>16</sup>, C. Göbel<sup>70</sup>, L. Golinka-Bezshyyko<sup>88</sup>, E. Golobardes<sup>46</sup>, A. Golutvin<sup>62,49</sup>, S. Gomez Fernandez<sup>45</sup>, W. Gomulka<sup>40</sup>, F. Goncalves Abrantes<sup>64</sup>, I. Gonçalves Vaz<sup>49</sup>, M. Goncerz<sup>41</sup>, G. Gong<sup>4,o</sup>, J. A. Gooding<sup>19</sup>, C. Gotti<sup>31</sup>, E. Govorkova<sup>65</sup>, J. P. Grabowski<sup>30</sup>, L. A. Granado Cardoso<sup>49</sup>, E. Graugés<sup>45</sup>, E. Graverini<sup>35,50,r</sup>, L. Grazette<sup>57</sup>, G. Graziani<sup>27</sup>, A. T. Grecu<sup>43</sup>, N. A. Grieser<sup>66</sup>, L. Grillo<sup>60</sup>, C. Gu<sup>15</sup>, M. Guarise<sup>26</sup>, L. Guerry<sup>11</sup>, A.-K. Guseinov<sup>50</sup>, Y. Guz<sup>6</sup>, T. Gys<sup>49</sup>, K. Habermann<sup>18</sup>, T. Hadavizadeh<sup>1</sup>, C. Hadjivasiliou<sup>67</sup>, G. Haefeli<sup>50</sup>, C. Haen<sup>49</sup>, S. Haken<sup>56</sup>, G. Hallett<sup>57</sup>, P. M. Hamilton<sup>67</sup>, Q. Han<sup>33</sup>, X. Han<sup>22,49</sup>, S. Hansmann-Menzemer<sup>22</sup>, N. Harnew<sup>64</sup>, T. J. Harris<sup>1</sup>, M. Hartmann<sup>14</sup>, S. Hashmi<sup>40</sup>, J. He<sup>7,s</sup>, N. Heatley<sup>14</sup>, A. Hedes<sup>63</sup>, F. Hemmer<sup>49</sup>, C. Henderson<sup>66</sup>, R. Henderson<sup>14</sup>, R. D. L. Henderson<sup>1</sup>, A. M. Hennequin<sup>49</sup>, K. Hennessy<sup>61</sup>, J. Herd<sup>62</sup>, P. Herrero Gascon<sup>22</sup>, J. Heuel<sup>17</sup>, A. Heyn<sup>13</sup>, A. Hicheur<sup>3</sup>, G. Hijano Mendizabal<sup>51</sup>, J. Horswill<sup>63</sup>, R. Hou<sup>8</sup>, Y. Hou<sup>11</sup>, D. C. Houston<sup>60</sup>, N. Howarth<sup>61</sup>, W. Hu<sup>7,s</sup>, X. Hu<sup>4</sup>, W. Hulsbergen<sup>38</sup>, R. J. Hunter<sup>57</sup>, D. Hutchcroft<sup>61</sup>, M. Idzik<sup>40</sup>, P. Ilten<sup>66</sup>, A. Iohner<sup>10</sup>, H. Jage<sup>17</sup>, S. J. Jaimes Elles<sup>77,48,49</sup>, S. Jakobsen<sup>49</sup>, T. Jakoubek<sup>78</sup>, E. Jans<sup>38</sup>, A. Jawahery<sup>67</sup>, C. Jayaweera<sup>54</sup>, A. Jelavic<sup>1</sup>, V. Jevtic<sup>19</sup>, Z. Jia<sup>16</sup>, E. Jiang<sup>67</sup>, X. Jiang<sup>5,7</sup>, Y. Jiang<sup>7</sup>, Y. J. Jiang<sup>6</sup>, E. Jimenez Moya<sup>9</sup>, N. Jindal<sup>91</sup>, M. John<sup>64</sup>, A. John Rubesh Rajan<sup>23</sup>, D. Johnson<sup>54</sup>, C. R. Jones<sup>56</sup>, S. Joshi<sup>42</sup>, B. Jost<sup>49</sup>, J. Juan Castella<sup>56</sup>, N. Jurik<sup>49</sup>, I. Juszczak<sup>41</sup>, K. Kalecinska<sup>40</sup>, D. Kaminaris<sup>50</sup>, S. Kandybei<sup>52</sup>, M. Kane<sup>59</sup>, Y. Kang<sup>4,o</sup>, C. Kar<sup>11</sup>, M. Karacson<sup>49</sup>, A. Kauniskangas<sup>50</sup>, J. W. Kautz<sup>66</sup>, M. K. Kazanecki<sup>41</sup>, F. Keizer<sup>49</sup>, M. Kenzie<sup>56</sup>, T. Ketel<sup>38</sup>, B. Khanji<sup>69</sup>, S. Kholodenko<sup>62,49</sup>, G. Khreich<sup>14</sup>, F. Kiraz<sup>14</sup>, T. Kirm<sup>17</sup>, V. S. Kirsebom<sup>31,c</sup>, S. Klaver<sup>39</sup>, N. Kleijne<sup>35,j</sup>, A. Kleimenova<sup>50</sup>, D. K. Klekots<sup>88</sup>, K. Klimaszewski<sup>42</sup>, M. R. Kmiec<sup>42</sup>, T. Knospe<sup>19</sup>, R. Kolb<sup>22</sup>, S. Kolliiev<sup>53</sup>, L. Kolk<sup>19</sup>, A. Konoplyannikov<sup>6</sup>, P. Kopciwicz<sup>49</sup>, P. Koppenburg<sup>38</sup>, A. Korchin<sup>52</sup>, I. Kostiuik<sup>38</sup>, O. Kot<sup>53</sup>, S. Kotriakhova<sup>6</sup>, E. Kowalczyk<sup>67</sup>, O. Kravcov<sup>81</sup>, M. Kreps<sup>57</sup>, W. Krupa<sup>49</sup>, W. Krzemien<sup>42</sup>, O. Kshyvanskyi<sup>53</sup>, S. Kubis<sup>86</sup>, M. Kucharczyk<sup>41</sup>, A. Kupsc<sup>87</sup>, V. Kushnir<sup>52</sup>, B. Kutsenko<sup>13</sup>, J. Kvapil<sup>68</sup>, I. Kyryllin<sup>52</sup>, D. Lacarrere<sup>49</sup>, P. Laguarda Gonzalez<sup>45</sup>, A. Lai<sup>32</sup>, A. Lampis<sup>32</sup>, D. Lancierini<sup>62</sup>, C. Landesa Gomez<sup>47</sup>, J. J. Lane<sup>1</sup>, G. Lanfranchi<sup>28</sup>, C. Langenbruch<sup>22</sup>, J. Langer<sup>19</sup>, T. Latham<sup>57</sup>, F. Lazzari<sup>35,r</sup>, C. Lazzeroni<sup>54</sup>, R. Le Gac<sup>13</sup>, H. Lee<sup>61</sup>, R. Lefèvre<sup>11</sup>, M. Lehuraux<sup>57</sup>, E. Lemos Cid<sup>49</sup>, O. Leroy<sup>13</sup>, T. Lesiak<sup>41</sup>, E. D. Lesser<sup>49</sup>, B. Leverington<sup>22</sup>, A. Li<sup>4,o</sup>, C. Li<sup>4</sup>, C. Li<sup>13</sup>, H. Li<sup>73</sup>, J. Li<sup>8</sup>, K. Li<sup>76</sup>, L. Li<sup>63</sup>, P. Li<sup>7</sup>, P.-R. Li<sup>74</sup>, Q. Li<sup>5,7</sup>, T. Li<sup>72</sup>, T. Li<sup>73</sup>, Y. Li<sup>8</sup>, Y. Li<sup>5</sup>, Y. Li<sup>4</sup>, Z. Lian<sup>4,o</sup>, Q. Liang<sup>8</sup>, X. Liang<sup>69</sup>, Z. Liang<sup>32</sup>, S. Libralon<sup>48</sup>, A. Lightbody<sup>12</sup>, C. Lin<sup>7</sup>, T. Lin<sup>58</sup>, R. Lindner<sup>49</sup>, H. Linton<sup>62</sup>, R. Litvinov<sup>66</sup>, D. Liu<sup>8</sup>, F. L. Liu<sup>1</sup>, G. Liu<sup>73</sup>, K. Liu<sup>74</sup>, S. Liu<sup>5</sup>, W. Liu<sup>8</sup>, Y. Liu<sup>59</sup>, Y. Liu<sup>74</sup>, Y. L. Liu<sup>62</sup>, G. Loachamin Ordonez<sup>70</sup>, I. Lobo<sup>1</sup>, A. Lobo Salvia<sup>10</sup>, A. Loi<sup>32</sup>, T. Long<sup>56</sup>, F. C. L. Lopes<sup>2,g</sup>, J. H. Lopes<sup>3</sup>, A. Lopez Huertas<sup>45</sup>, C. Lopez Iribarnegaray<sup>47</sup>, Q. Lu<sup>15</sup>, C. Lucarelli<sup>49</sup>, D. Lucchesi<sup>33,t</sup>, M. Lucio Martinez<sup>48</sup>, Y. Luo<sup>6</sup>, A. Lupato<sup>33,u</sup>, M. Lupberger<sup>20</sup>, E. Luppi<sup>26,f</sup>, K. Lynch<sup>23</sup>, S. Lyu<sup>6</sup>, X.-R. Lyu<sup>7</sup>, H. Ma<sup>72</sup>, S. Maccolini<sup>49</sup>, F. Machefert<sup>14</sup>, F. Maciuc<sup>43</sup>, B. Mack<sup>69</sup>, I. Mackay<sup>64</sup>, L. M. Mackey<sup>69</sup>, L. R. Madhan Mohan<sup>56</sup>, M. J. Madurai<sup>54</sup>, D. Magdalinski<sup>38</sup>, J. J. Malczewski<sup>41</sup>, S. Malde<sup>64</sup>, L. Malentacca<sup>49</sup>, G. Manca<sup>32,m</sup>, G. Mancinelli<sup>13</sup>, C. Mancuso<sup>14</sup>, R. Manera Escalero<sup>45</sup>, A. Mangalasseri<sup>80</sup>, F. M. Manganella<sup>37</sup>, D. Manuzzi<sup>25</sup>, D. Marangotto<sup>30,k</sup>, J. F. Marchand<sup>10</sup>, R. Marchevski<sup>50</sup>, U. Marconi<sup>25</sup>, E. Mariani<sup>16</sup>, S. Mariani<sup>49</sup>, C. Marin Benito<sup>45</sup>, J. Marks<sup>22</sup>

- A. M. Marshall<sup>55</sup> L. Martel<sup>64</sup> G. Martelli<sup>34</sup> G. Martellotti<sup>36</sup> L. Martinazzoli<sup>49</sup> M. Martinelli<sup>31,c</sup>  
D. Martinez Gomez<sup>83</sup> D. Martinez Santos<sup>44</sup> F. Martinez Vidal<sup>48</sup> A. Martorell i Granollers<sup>46</sup> A. Massafferri<sup>2</sup>  
R. Matev<sup>49</sup> A. Mathad<sup>49</sup> C. Matteuzzi<sup>69</sup> K. R. Mattioli<sup>15</sup> A. Mauri<sup>62</sup> E. Maurice<sup>15</sup> J. Mauricio<sup>45</sup>  
P. Mayencourt<sup>50</sup> J. Mazorra de Cos<sup>48</sup> M. Mazurek<sup>42</sup> D. Mazzanti Tarancon<sup>45</sup> M. McCann<sup>62</sup> N. T. McHugh<sup>60</sup>  
A. McNab<sup>63</sup> R. McNulty<sup>23</sup> B. Meadows<sup>66</sup> D. Melnychuk<sup>42</sup> D. Mendoza Granada<sup>16</sup>  
P. Menendez Valdes Perez<sup>47</sup> F. M. Meng<sup>4,o</sup> M. Merk<sup>38,84</sup> A. Merli<sup>50,30</sup> L. Meyer Garcia<sup>67</sup> D. Miao<sup>5,7</sup>  
H. Miao<sup>7</sup> M. Mikhayenko<sup>79</sup> D. A. Milanes<sup>85</sup> A. Minotti<sup>31,c</sup> E. Minucci<sup>28</sup> B. Mitreska<sup>63</sup> D. S. Mitzel<sup>19</sup>  
R. Mocanu<sup>43</sup> A. Modak<sup>58</sup> L. Moeser<sup>19</sup> R. D. Moise<sup>17</sup> E. F. Molina Cardenas<sup>89</sup> T. Mombächer<sup>47</sup> M. Monk<sup>56</sup>  
T. Monnard<sup>50</sup> S. Monteil<sup>11</sup> A. Morcillo Gomez<sup>47</sup> G. Morello<sup>28</sup> M. J. Morello<sup>35,j</sup> M. P. Morgenthaler<sup>22</sup>  
A. Moro<sup>31,c</sup> J. Moron<sup>40</sup> W. Morren<sup>38</sup> A. B. Morris<sup>81,49</sup> A. G. Morris<sup>13</sup> R. Mountain<sup>69</sup> Z. Mu<sup>6</sup>  
E. Muhammad<sup>57</sup> F. Muheim<sup>59</sup> M. Mulder<sup>19</sup> K. Müller<sup>51</sup> F. Muñoz-Rojas<sup>9</sup> V. Mytrochenko<sup>52</sup> P. Naik<sup>61</sup>  
T. Nakada<sup>50</sup> R. Nandakumar<sup>58</sup> G. Napoletano<sup>50</sup> I. Nasteva<sup>3</sup> M. Needham<sup>59</sup> N. Neri<sup>30,k</sup> S. Neubert<sup>18</sup>  
N. Neufeld<sup>49</sup> J. Nicolini<sup>49</sup> D. Nicotra<sup>84</sup> E. M. Niel<sup>15</sup> L. Nisi<sup>19</sup> Q. Niu<sup>74</sup> B. K. Njoki<sup>49</sup> P. Nogarolli<sup>3</sup>  
P. Nogga<sup>18</sup> C. Normand<sup>47</sup> J. Novoa Fernandez<sup>47</sup> G. Nowak<sup>66</sup> C. Nunez<sup>89</sup> H. N. Nur<sup>60</sup>  
A. Oblakowska-Mucha<sup>40</sup> T. Oeser<sup>17</sup> O. Okhrimenko<sup>53</sup> R. Oldeman<sup>32,m</sup> F. Oliva<sup>59,49</sup> E. Olivart Pino<sup>45</sup>  
M. Olocco<sup>19</sup> R. H. O'Neil<sup>49</sup> J. S. Ordonez Soto<sup>11</sup> D. Osthus<sup>19</sup> J. M. Otalora Goicochea<sup>3</sup> P. Owen<sup>51</sup>  
A. Oyanguren<sup>48</sup> O. Ozcelik<sup>49</sup> F. Paciolla<sup>35,v</sup> A. Padee<sup>42</sup> K. O. Padeken<sup>18</sup> B. Pagare<sup>47</sup> T. Pajero<sup>49</sup>  
A. Palano<sup>24</sup> L. Palini<sup>30</sup> M. Palutan<sup>28</sup> C. Pan<sup>75</sup> X. Pan<sup>4,o</sup> S. Panebianco<sup>12</sup> S. Paniskaki<sup>49,33</sup> L. Paolucci<sup>63</sup>  
A. Papanestis<sup>58</sup> M. Pappagallo<sup>24,n</sup> L. L. Pappalardo<sup>26</sup> C. Pappenheimer<sup>66</sup> C. Parkes<sup>63</sup> D. Parmar<sup>79</sup>  
G. Passaleva<sup>27</sup> D. Passaro<sup>35,j</sup> A. Pastore<sup>24</sup> M. Patel<sup>62</sup> J. Patoc<sup>64</sup> C. Patrignani<sup>25,h</sup> A. Paul<sup>69</sup> C. J. Pawley<sup>84</sup>  
A. Pellegrino<sup>38</sup> J. Peng<sup>5,7</sup> X. Peng<sup>74</sup> M. Pepe Altarelli<sup>28</sup> S. Perazzini<sup>25</sup> H. Pereira Da Costa<sup>68</sup>  
M. Pereira Martinez<sup>47</sup> A. Pereiro Castro<sup>47</sup> C. Perez<sup>46</sup> P. Perret<sup>11</sup> A. Perrevoort<sup>83</sup> A. Perro<sup>49</sup> M. J. Peters<sup>66</sup>  
K. Petridis<sup>55</sup> A. Petrolini<sup>29,i</sup> S. Pezzulo<sup>29,i</sup> J. P. Pfaller<sup>66</sup> H. Pham<sup>69</sup> L. Pica<sup>35,j</sup> M. Piccini<sup>34</sup> L. Piccolo<sup>32</sup>  
B. Pietrzyk<sup>10</sup> R. N. Pilato<sup>61</sup> D. Pinci<sup>36</sup> F. Pisani<sup>49</sup> M. Pizzichemi<sup>31,49,c</sup> V. M. Placinta<sup>43</sup> M. Plo Casasus<sup>47</sup>  
T. Poeschl<sup>49</sup> F. Polci<sup>16</sup> M. Poli Lener<sup>28</sup> A. Poluektov<sup>13</sup> I. Polyakov<sup>63</sup> E. Polcarpo<sup>3</sup> S. Ponce<sup>49</sup>  
D. Popov<sup>7,49</sup> K. Popp<sup>19</sup> K. Prasanth<sup>59</sup> C. Prouve<sup>44</sup> D. Provenzano<sup>32,49,m</sup> V. Pugatch<sup>53</sup> A. Puicercus Gomez<sup>49</sup>  
G. Punzi<sup>35,r</sup> J. R. Pybus<sup>68</sup> Q. Qian<sup>6</sup> W. Qian<sup>7</sup> N. Qin<sup>4,o</sup> R. Quagliani<sup>49</sup> R. I. Rabadan Trejo<sup>57</sup> R. Racz<sup>81</sup>  
J. H. Rademacker<sup>55</sup> M. Rama<sup>35</sup> M. Ramírez García<sup>89</sup> V. Ramos De Oliveira<sup>70</sup> M. Ramos Pernas<sup>49</sup>  
M. S. Rangel<sup>3</sup> G. Raven<sup>39</sup> M. Rebollo De Miguel<sup>48</sup> F. Redi<sup>30,u</sup> J. Reich<sup>55</sup> F. Reiss<sup>20</sup> Z. Ren<sup>7</sup> P. K. Resmi<sup>64</sup>  
M. Ribalda Galvez<sup>45</sup> R. Ribatti<sup>50</sup> G. Ricart<sup>12</sup> D. Riccardi<sup>35,j</sup> S. Ricciardi<sup>58</sup> K. Richardson<sup>65</sup>  
M. Richardson-Slipper<sup>56</sup> F. Riehn<sup>19</sup> K. Rinnert<sup>61</sup> P. Robbe<sup>14,49</sup> G. Robertson<sup>60</sup> E. Rodrigues<sup>61</sup>  
A. Rodriguez Alvarez<sup>45</sup> E. Rodriguez Fernandez<sup>47</sup> J. A. Rodriguez Lopez<sup>77</sup> E. Rodriguez Rodriguez<sup>49</sup>  
J. Roensch<sup>19</sup> A. Rogovskiy<sup>58</sup> D. L. Rolf<sup>19</sup> P. Roloff<sup>49</sup> V. Romanovskiy<sup>66</sup> A. Romero Vidal<sup>47</sup>  
G. Romolini<sup>26,49</sup> F. Ronchetti<sup>50</sup> T. Rong<sup>6</sup> M. Rotondo<sup>28</sup> M. S. Rudolph<sup>69</sup> M. Ruiz Diaz<sup>22</sup>  
R. A. Ruiz Fernandez<sup>47</sup> J. Ruiz Vidal<sup>84</sup> J. J. Saavedra-Arias<sup>9</sup> J. J. Saborido Silva<sup>47</sup> S. E. R. Sacha Emile R.  
D. Sahoo<sup>80</sup> N. Sahoo<sup>54</sup> B. Saitta<sup>32</sup> M. Salomoni<sup>31,49,c</sup> I. Sanderswood<sup>48</sup> R. Santacesaria<sup>36</sup>  
C. Santamarina Rios<sup>47</sup> M. Santimaria<sup>28</sup> L. Santoro<sup>2</sup> E. Santovetti<sup>37</sup> A. Saputi<sup>26,49</sup> A. Sarnatskiy<sup>83</sup>  
G. Sarpis<sup>49</sup> M. Sarpis<sup>81</sup> C. Satriano<sup>36</sup> A. Satta<sup>37</sup> M. Saur<sup>74</sup> H. Sazak<sup>17</sup> F. Sborzacchi<sup>49,28</sup> A. Scarabotto<sup>19</sup>  
S. Schael<sup>17</sup> S. Scherl<sup>61</sup> M. Schiller<sup>22</sup> H. Schindler<sup>49</sup> M. Schmelling<sup>21</sup> B. Schmidt<sup>49</sup> N. Schmidt<sup>68</sup>  
S. Schmitt<sup>65</sup> H. Schmitz<sup>18</sup> O. Schneider<sup>50</sup> A. Schopper<sup>62</sup> N. Schulte<sup>19</sup> M. H. Schune<sup>14</sup> G. Schwering<sup>17</sup>  
B. Sciascia<sup>28</sup> A. Sciuccati<sup>49</sup> G. Scriven<sup>84</sup> I. Segal<sup>79</sup> S. Sellam<sup>47</sup> T. Senger<sup>51</sup> M. Senghi Soares<sup>39</sup>  
A. Sergi<sup>29,i</sup> N. Serra<sup>51</sup> L. Sestini<sup>27</sup> B. Sevilla Sanjuan<sup>46</sup> Y. Shang<sup>6</sup> D. M. Shangase<sup>89</sup> R. S. Sharma<sup>69</sup>  
L. Shchutska<sup>50</sup> T. Shears<sup>61</sup> J. Shen<sup>6</sup> Z. Shen<sup>38</sup> S. Sheng<sup>50</sup> B. Shi<sup>7</sup> J. Shi<sup>56</sup> Q. Shi<sup>7</sup> W. S. Shi<sup>73</sup>  
E. Shmanin<sup>25</sup> R. Silva Coutinho<sup>2</sup> G. Simi<sup>33,t</sup> S. Simone<sup>24,n</sup> M. Singha<sup>80</sup> I. Siral<sup>50</sup> N. Skidmore<sup>57</sup>  
T. Skwarnicki<sup>69</sup> M. W. Slater<sup>54</sup> E. Smith<sup>65</sup> M. Smith<sup>62</sup> L. Soares Lavra<sup>59</sup> M. D. Sokoloff<sup>66</sup> F. J. P. Soler<sup>60</sup>  
A. Solomin<sup>55</sup> K. Solovieva<sup>20</sup> N. S. Sommerfeld<sup>18</sup> R. Song<sup>1</sup> Y. Song<sup>50</sup> Y. Song<sup>4,o</sup> Y. S. Song<sup>6</sup>  
F. L. Souza De Almeida<sup>45</sup> B. Souza De Paula<sup>3</sup> K. M. Sowa<sup>40</sup> E. Spadaro Norella<sup>29,i</sup> E. Spedicato<sup>25</sup>  
J. G. Speer<sup>19</sup> P. Spradlin<sup>60</sup> F. Stagni<sup>49</sup> M. Stahl<sup>79</sup> S. Stahl<sup>49</sup> S. Stanislaus<sup>64</sup> M. Stefaniak<sup>91</sup> O. Steinkamp<sup>51</sup>  
Y. Su<sup>7</sup> F. Suljik<sup>64</sup> J. Sun<sup>32</sup> J. Sun<sup>63</sup> L. Sun<sup>75</sup> D. Sundfeld<sup>2</sup> W. Sutcliffe<sup>51</sup> P. Svihra<sup>78</sup> V. Svintozelskiy<sup>48</sup>

K. Swientek<sup>40</sup>, F. Swystun<sup>56</sup>, A. Szabelski<sup>42</sup>, T. Szumlak<sup>40</sup>, Y. Tan<sup>4</sup>, Y. Tang<sup>75</sup>, Y. T. Tang<sup>7</sup>, M. D. Tat<sup>22</sup>,  
 J. A. Teixeira Jimenez<sup>47</sup>, F. Terzuoli<sup>35,v</sup>, F. Teubert<sup>49</sup>, E. Thomas<sup>49</sup>, D. J. D. Thompson<sup>54</sup>,  
 A. R. Thomson-Strong<sup>59</sup>, H. Tilquin<sup>62</sup>, V. Tisserand<sup>10</sup>, S. T'Jampens<sup>10</sup>, M. Tobin<sup>5,49</sup>, T. T. Todorov<sup>20</sup>,  
 L. Tomassetti<sup>26,f</sup>, G. Tonani<sup>30</sup>, X. Tong<sup>6</sup>, T. Tork<sup>30</sup>, L. Toscano<sup>19</sup>, D. Y. Tou<sup>4,o</sup>, C. Trippel<sup>46</sup>, G. Tuci<sup>22</sup>,  
 N. Tuning<sup>38</sup>, L. H. Uecker<sup>22</sup>, A. Ukleja<sup>40</sup>, D. J. Unverzagt<sup>22</sup>, A. Upadhyay<sup>49</sup>, B. Urbach<sup>59</sup>, A. Usachov<sup>38</sup>,  
 U. Uwer<sup>22</sup>, V. Vagnoni<sup>25,49</sup>, A. Vaitkevicius<sup>81</sup>, V. Valcarce Cadenas<sup>47</sup>, G. Valenti<sup>25</sup>, N. Valls Canudas<sup>49</sup>,  
 J. van Eldik<sup>49</sup>, H. Van Hecke<sup>68</sup>, E. van Herwijnen<sup>62</sup>, C. B. Van Hulse<sup>47,w</sup>, R. Van Laak<sup>50</sup>, M. van Veghel<sup>84</sup>,  
 G. Vasquez<sup>51</sup>, R. Vazquez Gomez<sup>45</sup>, P. Vazquez Regueiro<sup>47</sup>, C. Vázquez Sierra<sup>44</sup>, S. Vecchi<sup>26</sup>, J. Velilla Serna<sup>48</sup>,  
 J. J. Velthuis<sup>55</sup>, M. Veltri<sup>27,x</sup>, A. Venkateswaran<sup>50</sup>, M. Verdoglia<sup>32</sup>, M. Vesterinen<sup>57</sup>, W. Vetens<sup>69</sup>,  
 D. Vico Benet<sup>64</sup>, P. Vidrier Villalba<sup>45</sup>, M. Vieites Diaz<sup>47</sup>, X. Vilasis-Cardona<sup>46</sup>, E. Vilella Figueras<sup>61</sup>, A. Villa<sup>50</sup>,  
 P. Vincent<sup>16</sup>, B. Vivacqua<sup>3</sup>, F. C. Volle<sup>54</sup>, D. vom Bruch<sup>13</sup>, K. Vos<sup>84</sup>, C. Vrahas<sup>59</sup>, J. Wagner<sup>19</sup>, J. Walsh<sup>35</sup>,  
 N. Walter<sup>49</sup>, E. J. Walton<sup>1</sup>, G. Wan<sup>6</sup>, A. Wang<sup>7</sup>, B. Wang<sup>5</sup>, C. Wang<sup>22</sup>, G. Wang<sup>8</sup>, H. Wang<sup>74</sup>, J. Wang<sup>7</sup>,  
 J. Wang<sup>5</sup>, J. Wang<sup>4,o</sup>, J. Wang<sup>75</sup>, M. Wang<sup>49</sup>, N. W. Wang<sup>7</sup>, R. Wang<sup>55</sup>, X. Wang<sup>8</sup>, X. Wang<sup>73</sup>,  
 X. W. Wang<sup>62</sup>, Y. Wang<sup>76</sup>, Y. Wang<sup>6</sup>, Y. H. Wang<sup>74</sup>, Z. Wang<sup>14</sup>, Z. Wang<sup>30</sup>, J. A. Ward<sup>57,1</sup>, M. Waterlaet<sup>49</sup>,  
 N. K. Watson<sup>54</sup>, D. Websdale<sup>62</sup>, Y. Wei<sup>6</sup>, Z. Weida<sup>7</sup>, J. Wendel<sup>44</sup>, B. D. C. Westhenry<sup>55</sup>, C. White<sup>56</sup>,  
 M. Whitehead<sup>60</sup>, E. Whiter<sup>54</sup>, A. R. Wiederhold<sup>63</sup>, D. Wiedner<sup>19</sup>, M. A. Wiegertjes<sup>38</sup>, C. Wild<sup>64</sup>,  
 G. Wilkinson<sup>64,49</sup>, M. K. Wilkinson<sup>66</sup>, M. Williams<sup>65</sup>, M. J. Williams<sup>49</sup>, M. R. J. Williams<sup>59</sup>, R. Williams<sup>56</sup>,  
 S. Williams<sup>55</sup>, Z. Williams<sup>55</sup>, F. F. Wilson<sup>58</sup>, M. Winn<sup>12</sup>, W. Wislicki<sup>42</sup>, M. Witek<sup>41</sup>, L. Witola<sup>19</sup>, T. Wolf<sup>22</sup>,  
 E. Wood<sup>56</sup>, G. Wormser<sup>14</sup>, S. A. Wotton<sup>56</sup>, H. Wu<sup>69</sup>, J. Wu<sup>8</sup>, X. Wu<sup>75</sup>, Y. Wu<sup>6,56</sup>, Z. Wu<sup>7</sup>, K. Wyllie<sup>49</sup>,  
 S. Xian<sup>73</sup>, Z. Xiang<sup>5</sup>, Y. Xie<sup>8</sup>, T. X. Xing<sup>30</sup>, A. Xu<sup>35,j</sup>, L. Xu<sup>4,o</sup>, M. Xu<sup>49</sup>, R. Xu<sup>89</sup>, Z. Xu<sup>49</sup>, Z. Xu<sup>7</sup>, Z. Xu<sup>5</sup>,  
 S. Yadav<sup>26</sup>, K. Yang<sup>62</sup>, X. Yang<sup>6</sup>, Y. Yang<sup>7</sup>, Y. Yang<sup>80</sup>, Z. Yang<sup>6</sup>, Z. Yang<sup>4</sup>, H. Yeung<sup>63</sup>, H. Yin<sup>8</sup>, X. Yin<sup>7</sup>,  
 C. Y. Yu<sup>6</sup>, J. Yu<sup>72</sup>, X. Yuan<sup>5</sup>, Y. Yuan<sup>5,7</sup>, J. A. Zamora Saa<sup>71</sup>, M. Zavertyaev<sup>21</sup>, M. Zdybal<sup>41</sup>, F. Zenesini<sup>25</sup>,  
 C. Zeng<sup>5,7</sup>, M. Zeng<sup>4,o</sup>, S. H. Zeng<sup>55</sup>, C. Zhang<sup>6</sup>, D. Zhang<sup>8</sup>, J. Zhang<sup>7</sup>, L. Zhang<sup>4,o</sup>, R. Zhang<sup>8</sup>, S. Zhang<sup>64</sup>,  
 S. L. Zhang<sup>72</sup>, Y. Zhang<sup>6</sup>, Z. Zhang<sup>4,o</sup>, Y. Zhao<sup>22</sup>, A. Zhelezov<sup>22</sup>, S. Z. Zheng<sup>6</sup>, X. Z. Zheng<sup>4,o</sup>, Y. Zheng<sup>7</sup>,  
 T. Zhou<sup>6</sup>, X. Zhou<sup>8</sup>, V. Zhovkovska<sup>57</sup>, L. Z. Zhu<sup>59</sup>, X. Zhu<sup>4,o</sup>, X. Zhu<sup>8</sup>, Y. Zhu<sup>17</sup>, V. Zhukov<sup>17</sup>, J. Zhuo<sup>48</sup>,  
 D. Zuliani<sup>33,t</sup> and G. Zunica<sup>28</sup>

(LHCb Collaboration)

<sup>1</sup>*School of Physics and Astronomy, Monash University, Melbourne, Australia*

<sup>2</sup>*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*

<sup>3</sup>*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

<sup>4</sup>*Department of Engineering Physics, Tsinghua University, Beijing, China*

<sup>5</sup>*Institute Of High Energy Physics (IHEP), Beijing, China*

<sup>6</sup>*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

<sup>7</sup>*University of Chinese Academy of Sciences, Beijing, China*

<sup>8</sup>*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*

<sup>9</sup>*Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica*

<sup>10</sup>*Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*

<sup>11</sup>*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*

<sup>12</sup>*Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Gif-Sur-Yvette, France*

<sup>13</sup>*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

<sup>14</sup>*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*

<sup>15</sup>*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*

<sup>16</sup>*Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), Sorbonne Université, CNRS/IN2P3, Paris, France*

<sup>17</sup>*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*

<sup>18</sup>*Universität Bonn—Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*

<sup>19</sup>*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*

<sup>20</sup>*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*

<sup>21</sup>*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

<sup>22</sup>*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

- <sup>23</sup>*School of Physics, University College Dublin, Dublin, Ireland*  
<sup>24</sup>*INFN Sezione di Bari, Bari, Italy*  
<sup>25</sup>*INFN Sezione di Bologna, Bologna, Italy*  
<sup>26</sup>*INFN Sezione di Ferrara, Ferrara, Italy*  
<sup>27</sup>*INFN Sezione di Firenze, Firenze, Italy*  
<sup>28</sup>*INFN Laboratori Nazionali di Frascati, Frascati, Italy*  
<sup>29</sup>*INFN Sezione di Genova, Genova, Italy*  
<sup>30</sup>*INFN Sezione di Milano, Milano, Italy*  
<sup>31</sup>*INFN Sezione di Milano-Bicocca, Milano, Italy*  
<sup>32</sup>*INFN Sezione di Cagliari, Monserrato, Italy*  
<sup>33</sup>*INFN Sezione di Padova, Padova, Italy*  
<sup>34</sup>*INFN Sezione di Perugia, Perugia, Italy*  
<sup>35</sup>*INFN Sezione di Pisa, Pisa, Italy*  
<sup>36</sup>*INFN Sezione di Roma La Sapienza, Roma, Italy*  
<sup>37</sup>*INFN Sezione di Roma Tor Vergata, Roma, Italy*  
<sup>38</sup>*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*  
<sup>39</sup>*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*  
<sup>40</sup>*AGH—University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland*  
<sup>41</sup>*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*  
<sup>42</sup>*National Center for Nuclear Research (NCBJ), Warsaw, Poland*  
<sup>43</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*  
<sup>44</sup>*Universidad de Coruña, A Coruña, Spain*  
<sup>45</sup>*ICCUB, Universitat de Barcelona, Barcelona, Spain*  
<sup>46</sup>*La Salle, Universitat Ramon Llull, Barcelona, Spain*  
<sup>47</sup>*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*  
<sup>48</sup>*Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*  
<sup>49</sup>*European Organization for Nuclear Research (CERN), Geneva, Switzerland*  
<sup>50</sup>*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*  
<sup>51</sup>*Physik-Institut, Universität Zürich, Zürich, Switzerland*  
<sup>52</sup>*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*  
<sup>53</sup>*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*  
<sup>54</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*  
<sup>55</sup>*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*  
<sup>56</sup>*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*  
<sup>57</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*  
<sup>58</sup>*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*  
<sup>59</sup>*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*  
<sup>60</sup>*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*  
<sup>61</sup>*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*  
<sup>62</sup>*Imperial College London, London, United Kingdom*  
<sup>63</sup>*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*  
<sup>64</sup>*Department of Physics, University of Oxford, Oxford, United Kingdom*  
<sup>65</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*  
<sup>66</sup>*University of Cincinnati, Cincinnati, Ohio, USA*  
<sup>67</sup>*University of Maryland, College Park, Maryland, USA*  
<sup>68</sup>*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*  
<sup>69</sup>*Syracuse University, Syracuse, New York, USA*  
<sup>70</sup>*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)*  
<sup>71</sup>*Universidad Andres Bello, Santiago, Chile (associated with Physik-Institut, Universität Zürich, Zürich, Switzerland)*  
<sup>72</sup>*School of Physics and Electronics, Hunan University, Changsha City, China (associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)*  
<sup>73</sup>*State Key Laboratory of Nuclear Physics and Technology, South China Normal University, Guangzhou, China (associated with Department of Engineering Physics, Tsinghua University, Beijing, China)*  
<sup>74</sup>*Lanzhou University, Lanzhou, China (associated with Institute Of High Energy Physics (IHEP), Beijing, China)*  
<sup>75</sup>*School of Physics and Technology, Wuhan University, Wuhan, China (associated with Department of Engineering Physics, Tsinghua University, Beijing, China)*

- <sup>76</sup>*Henan Normal University, Xinxiang, China (associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)*
- <sup>77</sup>*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), Sorbonne Université, CNRS/IN2P3, Paris, France)*
- <sup>78</sup>*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic (associated with Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom)*
- <sup>79</sup>*Ruhr Universitaet Bochum, Fakultät f. Physik und Astronomie, Bochum, Germany (associated with Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany)*
- <sup>80</sup>*Eotvos Lorand University, Budapest, Hungary (associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)*
- <sup>81</sup>*Faculty of Physics, Vilnius University, Vilnius, Lithuania (associated with Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany)*
- <sup>82</sup>*Institute of Physics and Technology, Ulan Bator, Mongolia (associated with Institute Of High Energy Physics (IHEP), Beijing, China)*
- <sup>83</sup>*Van Swinderen Institute, University of Groningen, Groningen, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
- <sup>84</sup>*Universiteit Maastricht, Maastricht, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
- <sup>85</sup>*Universidad de Ingeniería y Tecnología (UTEC), Lima, Peru (associated with Massachusetts Institute of Technology, Cambridge, Massachusetts, USA)*
- <sup>86</sup>*Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland (associated with Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland)*
- <sup>87</sup>*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden (associated with School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)*
- <sup>88</sup>*Taras Schevchenko University of Kyiv, Faculty of Physics, Kyiv, Ukraine (associated with Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France)*
- <sup>89</sup>*University of Michigan, Ann Arbor, Michigan, USA (associated with Syracuse University, Syracuse, NewYork, USA)*
- <sup>90</sup>*Indiana University, Bloomington, USA (associated with Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA)*
- <sup>91</sup>*Ohio State University, Columbus, USA (associated with Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA)*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Lamarr Institute for Machine Learning and Artificial Intelligence, Dortmund, Germany.

<sup>c</sup>Also at Università degli Studi di Milano-Bicocca, Milano, Italy.

<sup>d</sup>Also at Università di Modena e Reggio Emilia, Modena, Italy.

<sup>e</sup>Also at Department of Physics and Astronomy, University of Victoria, Victoria, Canada.

<sup>f</sup>Also at Università di Ferrara, Ferrara, Italy.

<sup>g</sup>Also at Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil.

<sup>h</sup>Also at Università di Bologna, Bologna, Italy.

<sup>i</sup>Also at Università di Genova, Genova, Italy.

<sup>j</sup>Also at Scuola Normale Superiore, Pisa, Italy.

<sup>k</sup>Also at Università degli Studi di Milano, Milano, Italy.

<sup>l</sup>Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras.

<sup>m</sup>Also at Università di Cagliari, Cagliari, Italy.

<sup>n</sup>Also at Università di Bari, Bari, Italy.

<sup>o</sup>Also at Center for High Energy Physics, Tsinghua University, Beijing, China.

<sup>p</sup>Also at Università di Perugia, Perugia, Italy.

<sup>q</sup>Also at LIP6, Sorbonne Université, Paris, France.

<sup>r</sup>Also at Università di Pisa, Pisa, Italy.

<sup>s</sup>Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.

<sup>t</sup>Also at Università di Padova, Padova, Italy.

<sup>u</sup>Also at Università di Bergamo, Bergamo, Italy.

<sup>v</sup>Also at Università di Siena, Siena, Italy.

<sup>w</sup>Also at Universidad de Alcalá, Alcalá de Henares, Spain.

<sup>x</sup>Also at Università di Urbino, Urbino, Italy.