Observation of Two Resonances in the $\Lambda_b^0\pi^\pm$ Systems and Precise Measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ Properties

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The first observation of two structures consistent with resonances in the final states $\Lambda_b^0\pi^-$ and $\Lambda_b^0\pi^+$ is reported using samples of pp collision data collected by the LHCb experiment at $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}. The ground states $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ are also confirmed and their masses and widths are precisely measured.

Bottom baryons are composed of a b quark and two lighter quarks (bqq'). In the constituent quark model [1,2], such baryon states form multiplets according to the symmetries of their flavor, spin, and spatial wave functions [3]. The Λ_b^0 baryon is the lightest of the bottom baryons and forms an isospin (I) singlet (bud) with spin-parity $J^P = \frac{1}{2}^+$. Two $I = 1$ triplets with $J^P = \frac{1}{2}^+$ (Σ_b) and $J^P = \frac{3}{2}^+$ (Σ_b^*) are expected, with the spin of the flavor-symmetric qq' diquark $S_{qq'} = 1$. Four of those six states, the $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ baryons (uub and ddb), have been observed by the CDF collaboration [4,5] and reported briefly in a previous LHCb paper [6]. Beyond these ground states, radially and orbitally excited states are expected at higher masses, but only a few excited baryons have been observed in the bottom sector [7–10]. The search for and study of these states will cast light on the internal mechanisms governing the dynamics of the constituent quarks [11,12].

In this Letter, we report the observation of structures in both the $\Lambda_b^0\pi^+$ and $\Lambda_b^0\pi^-$ mass distributions (charge conjugation is implied throughout this Letter) using pp collision data collected by the LHCb experiment at $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}. We refer to these new states as $\Sigma_b(6097)^\pm$ in the rest of the Letter. We also measure precisely the masses and widths of the $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ ground states.

The LHCb detector [13,14] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the

pp interaction region [15], 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 [16] 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 (natural units with $c = \hbar = 1$ are used throughout this Letter). The momentum scale is calibrated using samples of $J/\psi \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [17,18]. The relative accuracy of this procedure is estimated to be 3×10^{-4} using samples of other fully reconstructed b hadrons, K_S^0, and narrow Υ resonance decays. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ μm, where p_T is the component of the momentum transverse to the beam in GeV. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [19]. The online event selection is performed by a trigger [20], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The software trigger requires a two-, three-, or four-track secondary vertex with significant displacement from all primary pp interaction vertices. A multivariate algorithm [21] is used for the identification of secondary vertices consistent with the decay of a b hadron. Simulated data samples are produced using the software packages described in Refs. [22–26].

Samples of Λ_b^0 candidates are formed from $\Lambda_c^+\pi^-$ combinations, where the Λ_c^+ baryon is reconstructed in the $pK^-\pi^+$ final state. All charged particles used to form the b-hadron candidates are required to have particle-identification information consistent with the appropriate mass hypothesis. Misreconstructed tracks are suppressed by the use of a neural network trained to discriminate

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between real and fake particles [27]. To suppress prompt background, all Λ_b^0 decay products are required to have significant χ_{IP}^2 with respect to all PVs in the event, where χ_{IP}^2 is the difference in χ^2 of the vertex fit of a given PV, when a particle is included or excluded from the fit. The reconstructed Λ_c^+ vertex is required to have a good fit quality and to be significantly displaced from all PVs in the event. The reconstructed Λ_c^+ mass must be within a mass window of ± 25 MeV of its known value [28]. Pion candidates that have large χ_{IP}^2 with respect to all PVs are combined with Λ_c^+ candidates to form Λ_b^0 candidates, requiring good vertex-fit quality and separation of the Λ_b^0 decay point from any PV in the event. A boosted decision tree (BDT) discriminant [29,30] is used to further reduce the background. The BDT exploits nineteen topological variables, including the χ_{IP}^2 and p_T values of all the particles in the decay chain, the χ^2 values of the Λ_b^0 and Λ_c^+ decay vertices, their flight-distance significance, and the angle between their momentum and direction of flight, defined by their production and decay vertices. The BDT is trained using simulated Λ_b^0 signal decays and Λ_b^0 candidates in data in the sideband $5800 < m(\Lambda_b^0) < 6000$ MeV. The signal candidates are refitted constraining the mass of the Λ_c^+ to its known value [28] in order to improve the mass resolution [31]. The mass distribution of the selected $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, $\Lambda_c^+ \to pK^-\pi^+$ candidates is shown in Fig. 1. The mass spectrum is fitted with an asymmetric resolution function for the signal component [32], plus a misreconstructed $\Lambda_b^0 \to \Lambda_c^+ K^-$ component whose yield is fixed relative to that of $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, an exponential function for the combinatorial background and an empirical function for partially reconstructed backgrounds as described in Ref. [32]. The resulting Λ_b^0 signal yield is $234\,270 \pm 900$.

The Λ_b^0 candidates contained in a ± 50 MeV window around the peak maximum are then combined with a prompt pion, hereafter referred to as $\pi_s^\pm$, to form $\Sigma_b^\pm \to \Lambda_b^0 \pi^\pm$ combinations (along with $\bar{\Sigma}_b^\mp \to \bar{\Lambda}_b^0 \pi^\mp$). Initially,
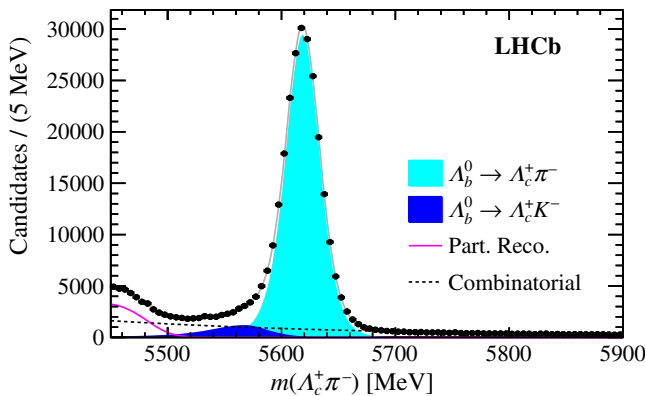
$p_T(\pi_s^\pm) > 200$ MeV and $Q \equiv m(\Lambda_b^0 \pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm) < 200$ MeV are required, where the $\Lambda_b^0 \pi^\pm$ mass is recomputed constraining the masses of the Λ_c^+ and Λ_b^0 baryons to their known values [28]. Then the search is extended to higher masses up to $Q = 600$ MeV, observing an additional peak in both $\Lambda_b^0 \pi^-$ and $\Lambda_b^0 \pi^+$ spectra. A tighter transverse momentum cut $p_T(\pi_s^\pm) > 1000$ MeV is applied to remove the background from prompt pions.

The signal yields and parameters of the $\Sigma_b^\pm$, $\Sigma_b^{*\pm}$, and $\Sigma_b(6097)^\pm$ resonances are determined with extended unbinned maximum-likelihood fits to the Q-value distribution. All signal components are modeled as relativistic Breit-Wigner functions [33] including Blatt-Weisskopf form factors [34] with a radius of 4 GeV^{-1}. The orbital angular momentum l between the Λ_b^0 baryon and $\pi_s^\pm$ candidate is taken to be 1 in all cases. The relativistic Breit-Wigner functions are convolved with the detector resolution and corrected for a small distortion in the shape induced by the p_T requirement on the $\pi_s^\pm$ meson. The resolution models are determined from simulation, in which the three signal resonances are generated at the Q values found in the data. The root-mean-square values of the resolution functions for Σ_b, Σ_b^*, and $\Sigma_b(6097)$ are 0.99, 1.13, and 2.35 MeV, respectively, all below the visible widths of the mass peaks and consistent with a resolution that scales as $\sqrt{Q}$. Different empirical parametrizations are used for the two mass ranges. For $0 < Q < 200$ MeV the background shape is described by a smooth threshold function [10,35,36], while for $0 < Q < 600$ MeV a sigmoid function is used, as in Refs. [37,38]. The background shapes are validated by using candidates in the data sidebands for a wide range of p_T requirements. All of the masses, widths, and yields are free to vary in the fit, as are the background parameters; the resolutions of the signal components are fixed to the values found in simulation. The fit models are validated with pseudoexperiments and no significant bias is found on any of the free parameters.

The fits to the data sample are shown in Fig. 2 and the resulting parameters of interest are summarized in Table I. The fit results are also used to determine mass differences and isospin splittings (given below). The two new peaks in $\Lambda_b^0 \pi^-$ and $\Lambda_b^0 \pi^+$ distributions have local statistical significances of 12.7σ and 12.6σ, respectively, based on the differences in log-likelihood between a fit with zero signal and the nominal fit.

Several sources of systematic uncertainty are considered. The dominant source of systematic uncertainty on the mass measurements comes from the knowledge of the momentum scale. This uncertainty is evaluated by adjusting the momentum scale by the 3×10^{-4} relative uncertainty from the calibration procedure [18] and rerunning the mass fit. This procedure is also validated using a control sample of approximately 3×10^6 $D^{*+} \to D^0 \pi^+$ decays, with $D^0 \to K^- \pi^+$. The momentum-scale uncertainties largely cancel in

FIG. 1. Mass distribution for the selected $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ candidates. The points show experimental data.
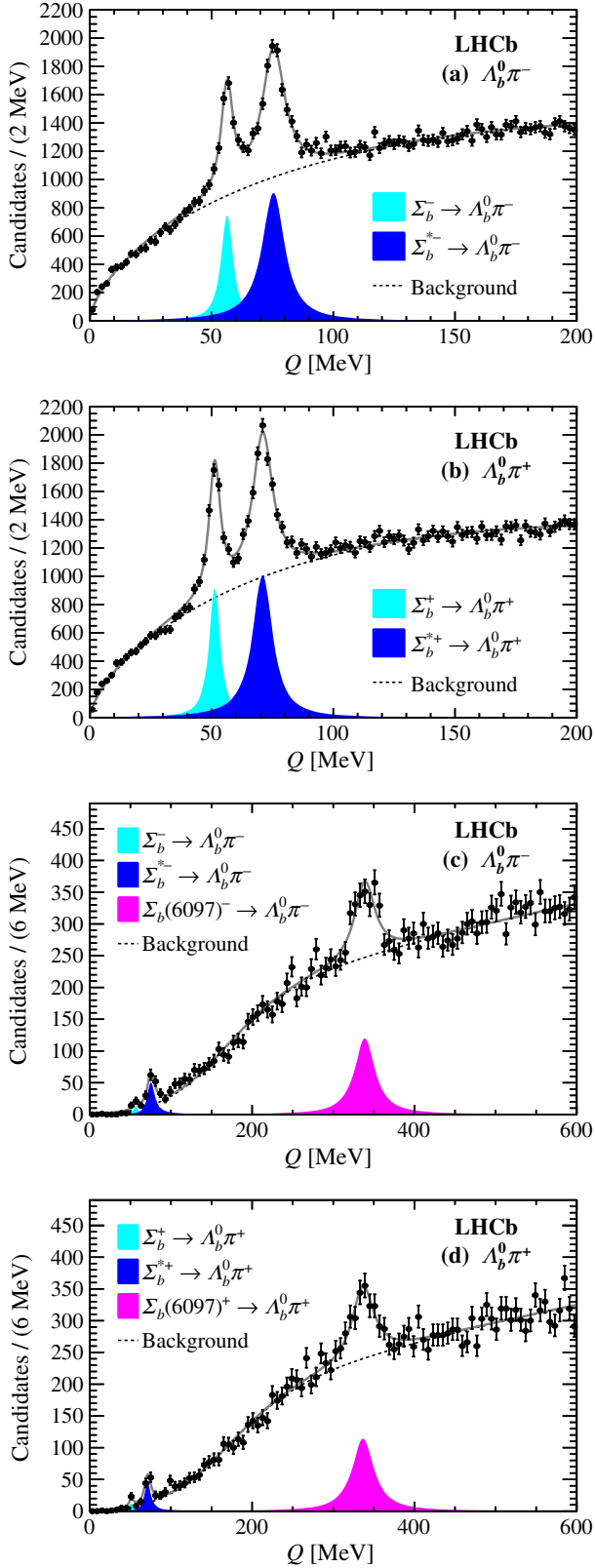
FIG. 2. Mass distribution for selected $\Lambda_b^0\pi^\pm$ candidates. The points show experimental data. The left (right) column shows $\Lambda_b^0\pi^-$ ($\Lambda_b^0\pi^+$) combinations. The top row shows the fits to the lower-mass states $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$. The lower row presents the fits to the new mass peaks with the requirement $p_T(\pi_s^\pm) > 1000$ MeV.

TABLE I. Summary of the results of the fits to the $Q \equiv m(\Lambda_b^0\pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$ mass spectra. Q_0 and Γ are the mean and the width of the Breit-Wigner function. The quoted uncertainties are statistical only.

State	Q_0 [MeV]	Γ [MeV]	Yield
Σ_b^-	56.45 ± 0.14	5.33 ± 0.42	3270 ± 180
Σ_b^{*-}	75.54 ± 0.17	10.68 ± 0.60	7460 ± 300
Σ_b^+	51.36 ± 0.11	4.83 ± 0.31	3670 ± 160
Σ_b^{*+}	71.09 ± 0.14	9.34 ± 0.47	7350 ± 260
$\Sigma_b(6097)^-$	338.8 ± 1.7	28.9 ± 4.2	880 ± 100
$\Sigma_b(6097)^+$	336.6 ± 1.7	31.0 ± 5.5	900 ± 110

the mass differences and splittings. A second uncertainty arises from the parameterization of the background and is estimated by varying the function used (e.g., polynomial background functions of different order and other empirical curves). An additional source of uncertainty on the determination of the natural widths arises from known differences in resolution between data and simulation. These are expected to agree within 5%, based on previous studies [8,10,36], and this assumption has been validated with the $D^{*+} \to D^0\pi^+$ control sample. Systematic uncertainties on the widths are assessed by varying the width of the resolution function by $\pm 5\%$. Further uncertainties on the masses and widths arise from the assumed Breit-Wigner parameters. The resonant states are assumed to decay to $\Lambda_b^0\pi^\pm$ with angular momentum $l = 1$. For the $\Sigma_b(6097)^\pm$ states, fits assuming $l = 0, 2, 3$ are also performed and the largest changes to the fitted parameters with respect to the

TABLE II. Summary of the systematic uncertainties on the measured masses and widths. Q_0 and Γ are the mean and the width of the Breit-Wigner function. All values are in MeV.

Source	Σ_b^-		Σ_b^{*-}		$\Sigma_b(6097)^-$	
	Q_0	Γ	Q_0	Γ	Q_0	Γ
p scale	0.046	0.036	0.047	0.071	0.130	0.013
Resolution	0.001	0.038	0.001	0.033	0.003	0.108
Spin assign.					0.370	0.462
Radius	0.003	0.101	0.010	0.017	0.080	0.081
Background	0.021	0.351	0.033	0.315	0.184	0.798
Total	0.051	0.369	0.058	0.325	0.440	0.932

Source	Σ_b^+		Σ_b^{*+}		$\Sigma_b(6097)^+$	
	Q_0	Γ	Q_0	Γ	Q_0	Γ
p scale	0.039	0.046	0.047	0.045	0.128	0.090
Resolution	0.001	0.040	0.001	0.038	0.002	0.086
Spin assign.					0.113	0.342
Radius	0.001	0.061	0.003	0.002	0.001	0.031
Background	0.027	0.357	0.026	0.256	0.207	0.598
Total	0.047	0.367	0.053	0.263	0.268	0.701

TABLE III. Masses and widths of the $\Sigma_b(6097)^\pm$, $\Sigma_b^{*\pm}$, and $\Sigma_b^\pm$ baryons. Isospin splittings $\Delta(X^\pm) = m(X^+) - m(X^-)$ and mass differences are also calculated. The first uncertainty is statistical, the second systematic. The systematic uncertainty on m includes the uncertainty from the knowledge of the Λ_b^0 mass [39].

Quantity	Value [MeV]		
$m[\Sigma_b(6097)^-]$	6098.0	1.7	0.5
$m[\Sigma_b(6097)^+]$	6095.8	1.7	0.4
$\Gamma[\Sigma_b(6097)^-]$	28.9	4.2	0.9
$\Gamma[\Sigma_b(6097)^+]$	31.0	5.5	0.7
$m(\Sigma_b^-)$	5815.64	0.14	0.24
$m(\Sigma_b^{*-})$	5834.73	0.17	0.25
$m(\Sigma_b^+)$	5810.55	0.11	0.23
$m(\Sigma_b^{*+})$	5830.28	0.14	0.24
$\Gamma(\Sigma_b^-)$	5.33	0.42	0.37
$\Gamma(\Sigma_b^{*-})$	10.68	0.60	0.33
$\Gamma(\Sigma_b^+)$	4.83	0.31	0.37
$\Gamma(\Sigma_b^{*+})$	9.34	0.47	0.26
$m(\Sigma_b^{*-}) - m(\Sigma_b^-)$	19.09	0.22	0.02
$m(\Sigma_b^{*+}) - m(\Sigma_b^+)$	19.73	0.18	0.01
$\Delta[\Sigma_b(6097)^\pm]$	−2.2	2.4	0.3
$\Delta(\Sigma_b^\pm)$	−5.09	0.18	0.01
$\Delta(\Sigma_b^{*\pm})$	−4.45	0.22	0.01

nominal fit are assigned as systematic uncertainties. The systematic uncertainties are summarized in Table II; in all cases they are much smaller than the statistical uncertainties. All numerical results for the measured masses and widths are presented in Table III. The mass values m are obtained using the most precise LHCb combination for the Λ_b^0 mass, $m(\Lambda_b^0) = 5619.62 \pm 0.16 \pm 0.13$ MeV [39], which dominates by far the current world average [40]. The correlated uncertainties, mainly deriving from the knowledge of the momentum scale which is a common source of systematic uncertainty in all LHCb mass measurements, are propagated as described in Ref. [41]. The isospin splitting of the new states is consistent with zero, although with large experimental uncertainty.

In summary, the first observation of two new mass peaks in the $\Lambda_b^0\pi^+$ and $\Lambda_b^0\pi^-$ systems is reported. These structures are consistent with single resonances described by relativistic Breit-Wigner functions. The ground-state $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ baryons are also confirmed and their masses and widths precisely measured. These values are in good agreement with those measured by the CDF Collaboration [5], with precision improved by a factor of 5. We also quote the mass differences and isospin splittings, for which most of the systematic uncertainties cancel.

In the heavy-quark limit, five $\Sigma_b(1P)$ states are expected. Several predictions of their masses have been made [11,12,42,43], but some or all of these states may be too wide to be accessible experimentally [42]. Since the expected density of baryon states is high, it cannot be excluded that the new structures seen are the superpositions

of more than one (near-)degenerate state. Taking into account that the predicted mass and width depend on the as-yet-unknown spin and parity, the newly observed structures are compatible with being $1P$ excitations. Other interpretations, such as molecular states, may also be possible [44].

[1] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).
[2] G. Zweig, CERN, Geneva, Technical Report No. CERN-TH-401, 1964.
[3] E. Klempt and J.-M. Richard, Rev. Mod. Phys. **82**, 1095 (2010).
[4] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 202001 (2007).
[5] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **85**, 092011 (2012).
[6] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 241801 (2015).
[7] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **109**, 172003 (2012).
[8] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **121**, 072002 (2018).

[9] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **108**, 252002 (2012).

[10] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **114**, 062004 (2015).

[11] K. Thakkar, Z. Shah, A. K. Rai, and P. C. Vinodkumar, Nucl. Phys. **A965**, 57 (2017).

[12] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D **84**, 014025 (2011).

[13] A. A. Alves, Jr. *et al.* (LHCb Collaboration), J. Instrum. **3**, S08005 (2008).

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

[15] R. Aaij *et al.*, J. Instrum. **9**, P09007 (2014).

[16] R. Arink *et al.*, J. Instrum. **9**, P01002 (2014).

[17] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 182001 (2013).

[18] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 06 (2013) 065.

[19] M. Adinolfi *et al.*, Eur. Phys. J. C **73**, 2431 (2013).

[20] R. Aaij *et al.*, J. Instrum. **8**, P04022 (2013).

[21] V. V. Gligorov and M. Williams, J. Instrum. **8**, P02013 (2013).

[22] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026; Comput. Phys. Commun. **178**, 852 (2008).

[23] I. Belyaev *et al.*, J. Phys. Conf. Ser. **331**, 032047 (2011).

[24] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[25] P. Golonka and Z. Was, Eur. Phys. J. C **45**, 97 (2006).

[26] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Dubois *et al.* (Geant4 Collaboration), IEEE Trans. Nucl. Sci. **53**, 270 (2006); S. Agostinelli *et al.* (Geant4 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[27] M. De Cian, S. Farry, P. Seyfert, and S. Stahl, Fast neural-net based fake track rejection in the LHCb reconstruction (2017), http://cdsweb.cern.ch/record/2255039.

[28] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

[29] B. P. Roe, H.-J. Yang, J. Zhu, Y. Liu, I. Stancu, and G. McGregor, Nucl. Instrum. Methods Phys. Res., Sect. A **543**, 577 (2005).

[30] Y. Freund and R. E. Schapire, J. Comput. Syst. Sci. **55**, 119 (1997).

[31] W. D. Hulsbergen, Nucl. Instrum. Methods Phys. Res., Sect. A **552**, 566 (2005).

[32] R. Aaij *et al.* (LHCb Collaboration), Phys. Lett. B **777**, 16 (2018).

[33] J. D. Jackson, Il Nuovo Cimento **34**, 1644 (1964).

[34] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Springer, New York, 1952).

[35] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 151803 (2013).

[36] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **118**, 182001 (2017).

[37] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 10 (2013) 115.

[38] R. Aaij *et al.* (LHCb Collaboration), Phys. Lett. B **714**, 215 (2012).

[39] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **119**, 062001 (2017).

[40] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

[41] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 05 (2016) 132.

[42] M. Karliner and J. L. Rosner, Phys. Rev. D **92**, 074026 (2015).

[43] M. Karliner and J. L. Rosner, arXiv:1808.07869.

[44] W. H. Liang, C. W. Xiao, and E. Oset, Phys. Rev. D **89**, 054023 (2014).

R. Aaij,[28] C. Abellán Beteta,[45] B. Adeva,[42] M. Adinolfi,[49] C. A. Aidala,[73] Z. Ajaltouni,[6] S. Akar,[60] P. Albicocco,[19] J. Albrecht,[11] F. Alessio,[43] M. Alexander,[54] A. Alfonso Albero,[41] G. Alkhazov,[34] P. Alvarez Cartelle,[56] A. A. Alves Jr,[42] S. Amato,[2] S. Amerio,[24] Y. Amhis,[8] L. An,[3] L. Anderlini,[18] G. Andreassi,[44] M. Andreotti,[17] J. E. Andrews,[61] R. B. Appleby,[57] F. Archilli,[28] J. Arnau Romeu,[7] A. Artamonov,[40] M. Artuso,[62] K. Arzymatov,[38] E. Aslanides,[7] M. Atzeni,[45] B. Audurier,[23] S. Bachmann,[13] J. J. Back,[51] S. Baker,[56] V. Balagura,[8,a] W. Baldini,[17] A. Baranov,[38] R. J. Barlow,[57] S. Barsuk,[8] W. Barter,[57] F. Baryshnikov,[70] V. Batozskaya,[32] B. Batsukh,[62] V. Battista,[44] A. Bay,[44] J. Beddow,[54] F. Bedeschi,[25] I. Bediaga,[1] A. Beiter,[62] L. J. Bel,[28] S. Belin,[23] N. Beliy,[4] V. Bellee,[44] N. Belloli,[21,b] K. Belous,[40] I. Belyaev,[35,43] G. Bencivenni,[19] E. Ben-Haim,[9] S. Benson,[28] S. Beranek,[10] A. Berezhnoy,[36] R. Bernet,[45] D. Berninghoff,[13] E. Bertholet,[9] A. Bertolin,[24] C. Betancourt,[45] F. Betti,[16,43] M. O. Bettler,[50] Ia. Bezshyiko,[45] S. Bhasin,[49] J. Bhom,[30] S. Bifani,[48] P. Billoir,[9] A. Birnkraut,[11] A. Bizzeti,[18,c] M. Bjørn,[58] M. P. Blago,[43] T. Blake,[51] F. Blanc,[44] S. Blusk,[62] D. Bobulska,[54] V. Bocci,[27] O. Boente Garcia,[42] T. Boettcher,[59] A. Bondar,[39,d] N. Bondar,[34] S. Borghi,[57,43] M. Borisyak,[38] M. Borsato,[42] F. Bossu,[8] M. Boubdir,[10] T. J. V. Bowcock,[55] C. Bozzi,[17,43] S. Braun,[13] M. Brodski,[43] J. Brodzicka,[30] A. Brossa Gonzalo,[51] D. Brundu,[23] E. Buchanan,[49] A. Buonaura,[45] C. Burr,[57] A. Bursche,[23] J. Buytaert,[43] W. Byczynski,[43] S. Cadeddu,[23] H. Cai,[64] R. Calabrese,[17,e] R. Calladine,[48] M. Calvi,[21,b] M. Calvo Gomez,[41,f] A. Camboni,[41,f] P. Campana,[19] D. H. Campora Perez,[43] L. Capriotti,[16] A. Carbone,[16,g] G. Carboni,[26] R. Cardinale,[20,h] A. Cardini,[23] P. Carniti,[21,b] L. Carson,[53] K. Carvalho Akiba,[2] G. Casse,[55] L. Cassina,[21] M. Cattaneo,[43] G. Cavallero,[20,h] R. Cenci,[25,i] D. Chamont,[8] M. G. Chapman,[49] M. Charles,[9] Ph. Charpentier,[43] G. Chatzikonstantinidis,[48] M. Chefdeville,[5] V. Chekalina,[38] C. Chen,[3] S. Chen,[23] S.-G. Chitic,[43] V. Chobanova,[42] M. Chrzaszcz,[43] A. Chubykin,[34] P. Ciambrone,[19] X. Cid Vidal,[42] G. Ciezarek,[43]

F. Cindolo,[16] P. E. L. Clarke,[53] M. Clemencic,[43] H. V. Cliff,[50] J. Closier,[43] V. Coco,[43] J. A. B. Coelho,[8] J. Cogan,[7] E. Cogneras,[6] L. Cojocariu,[33] P. Collins,[43] T. Colombo,[43] A. Comerma-Montells,[13] A. Contu,[23] G. Coombs,[43] S. Coquereau,[41] G. Corti,[43] M. Corvo,[17,e] C. M. Costa Sobral,[51] B. Couturier,[43] G. A. Cowan,[53] D. C. Craik,[59] A. Crocombe,[51] M. Cruz Torres,[1] R. Currie,[53] F. Da Cunha Marinho,[2] C. L. Da Silva,[74] E. Dall'Occo,[28] J. Dalseno,[49] C. D'Ambrosio,[43] A. Danilina,[35] P. d'Argent,[13] A. Davis,[3] O. De Aguiar Francisco,[43] K. De Bruyn,[43] S. De Capua,[57] M. De Cian,[44] J. M. De Miranda,[1] L. De Paula,[2] M. De Serio,[15,j] P. De Simone,[19] J. A. de Vries,[28] C. T. Dean,[54] D. Decamp,[5] L. Del Buono,[9] B. Delaney,[50] H.-P. Dembinski,[12] M. Demmer,[11] A. Dendek,[31] D. Derkach,[38] O. Deschamps,[6] F. Desse,[8] F. Dettori,[55] B. Dey,[65] A. Di Canto,[43] P. Di Nezza,[19] S. Didenko,[70] H. 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