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Roel Aaij, Carlos Abellán Beteta, Thomas Ackernley, Bernardo Adeva, Marco Adinolfi, Hossein Afsharnia, Christine Angela Aidala, Salvatore Aiola, Ziad Ajaltouni, Simon Akar, et al.

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# Observation of new $\Xi_c^0$ baryons decaying to $\Lambda_c^+ K^-$

LHCb collaboration<sup>†</sup>

## Abstract

The  $\Lambda_c^+ K^-$  mass spectrum is studied with a data sample of  $pp$  collisions at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of  $5.6 \text{ fb}^{-1}$  collected by the LHCb experiment. Three  $\Xi_c^0$  states are observed with a large significance and their masses and natural widths are measured to be

$$\begin{aligned}
 m(\Xi_c(2923)^0) &= 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \text{ MeV}, \\
 \Gamma(\Xi_c(2923)^0) &= 7.1 \pm 0.8 \pm 1.8 \text{ MeV}, \\
 m(\Xi_c(2939)^0) &= 2938.55 \pm 0.21 \pm 0.17 \pm 0.14 \text{ MeV}, \\
 \Gamma(\Xi_c(2939)^0) &= 10.2 \pm 0.8 \pm 1.1 \text{ MeV}, \\
 m(\Xi_c(2965)^0) &= 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \text{ MeV}, \\
 \Gamma(\Xi_c(2965)^0) &= 14.1 \pm 0.9 \pm 1.3 \text{ MeV},
 \end{aligned}$$

where the uncertainties are statistical, systematic, and due to the limited knowledge of the  $\Lambda_c^+$  mass. The  $\Xi_c(2923)^0$  and  $\Xi_c(2939)^0$  baryons are new states. The  $\Xi_c(2965)^0$  state is in the vicinity of the known  $\Xi_c(2970)^0$  baryon; however, their masses and natural widths differ significantly.

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<sup>†</sup>Authors are listed at the end of this paper.



Singly charmed baryons are composed of a charm quark and two light quarks. Due to the large mass difference between the charm and the lighter quarks, these baryons provide an insight into the spectrum of states using symmetries described by the Heavy Quark Effective Theory [1,2]. Numerous theoretical predictions of the properties of heavy baryons, containing either a charm or a beauty quark, have been made in recent years [3–13]. In many of these models, the heavy quark interacts with a lighter diquark, which is treated as a single object. Other predictions are based on Lattice QCD calculations [14].

In 2017, the LHCb collaboration reported the observation of five new narrow  $\Omega_c^0$  baryons decaying to the  $\Xi_c^+ K^-$  final state [15], four of which were later confirmed by the Belle collaboration [16]. It is currently not understood why the natural widths of these resonances are small [17,18], although a similar trend has recently been observed in the excited  $\Omega_b^-$  states decaying to  $\Xi_b^0 K^-$  [19]. Investigating a different charmed mass spectrum could lead to a better understanding of this feature.

A natural extension to the  $\Xi_c^+ K^-$  analysis is the study of the  $\Lambda_c^+ K^-$  spectrum. The BaBar collaboration was the first to observe a structure in the  $\Lambda_c^+ K^-$  mass spectrum in  $B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^-$  decays peaking at 2.93 GeV in 2007 [20]. However, it was not interpreted as a new state due to the absence of an amplitude analysis. Unless otherwise stated, charge-conjugate processes are implicitly included, and natural units with  $\hbar = c = 1$  are used throughout. Later that year another analysis was published [21], looking at strongly interacting prompt decays of charm-strange baryons to several final states, one of which was  $\Lambda_c^+ K^-$ . No resonances were reported in the  $\Lambda_c^+ K^-$  mass spectrum. The Belle collaboration also reported the study of  $B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^-$  decays [22]. A peaking structure was observed in the  $\Lambda_c^+ K^-$  mass spectrum compatible with the results of Ref. [20] and interpreted as a new  $\Xi_c^0$  baryon, dubbed  $\Xi_c(2930)^0$ . Similarly, evidence of the isospin partner  $\Xi_c(2930)^+$  in  $\bar{B}^0 \rightarrow \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$  decays has been claimed [23].

This letter presents a search for excited  $\Xi_c^0$  baryons, hereafter referred to as  $\Xi_c^{**0}$ , in the  $\Lambda_c^+ K^-$  spectrum in a mass region around the  $\Xi_c(2930)^0$  state, with the  $\Lambda_c^+$  baryons reconstructed in the  $p K^- \pi^+$  final state. Defining  $\Delta M \equiv m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m(K^-)$ , the region considered is  $\Delta M < 300$  MeV. The data are collected in  $pp$  collisions with the LHCb detector at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $5.6 \text{ fb}^{-1}$ .

The LHCb detector [24,25] 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 elements that are particularly relevant to this analysis are: a silicon-strip vertex detector surrounding the  $pp$  interaction region that allows  $c$  and  $b$  hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of the momentum of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. 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 two-level software stage, which applies a full event reconstruction [26,27]. Simulated data samples are produced with the software packages described in Refs. [28–32] and are used to optimise the selection requirements, to quantify the invariant-mass resolution, and to model physics processes which may constitute peaking backgrounds in the analysis.

Candidate  $\Lambda_c^+$  baryons are formed from the combination of three tracks of good quality which are inconsistent with originating from any primary proton-proton interaction vertex (PV) and have large transverse momentum ( $p_T$ ). Particle identification (PID)

requirements are imposed on all three tracks to suppress combinatorial background and misidentified charm-meson decays. The  $\Lambda_c^+$  candidates are required to have  $p_T > 2$  GeV and are constrained to originate from the associated PV by requiring a small  $\chi_{\text{IP}}^2$ , defined as the difference between the vertex-fit  $\chi^2$  of the PV reconstructed with and without the candidate in question. The  $\Lambda_c^+$  vertex must also be displaced from the associated PV such that the  $\Lambda_c^+$  decay time is longer than 0.3 ps. A multivariate classifier based on a boosted decision tree (BDT) algorithm [33, 34] implemented in the TMVA toolkit [35] is used to further improve the  $\Lambda_c^+$  signal purity. The input variables given to the BDT are the  $\chi^2$  value of the  $\Lambda_c^+$  decay-vertex fit, the  $\Lambda_c^+$  flight distance between the production and decay vertex, the angle between the  $\Lambda_c^+$  momentum vector and the line that joins the  $\Lambda_c^+$  decay vertex with its associated PV, the  $\chi_{\text{IP}}^2$  and  $p_T$  of the  $\Lambda_c^+$  candidate, and the  $\chi_{\text{IP}}^2$  and PID responses of the  $\Lambda_c^+$  decay particles. The background sample used in the BDT training consists of the lower and upper sidebands of the  $pK^-\pi^+$  invariant mass distribution, 2230 – 2250 MeV and 2320 – 2340 MeV, respectively. The signal sample used is the  $\Lambda_c^+$  sample in data after subtracting the background by means of the *sPlot* technique [36], exploiting  $m(pK^-\pi^+)$  as discriminating variable. The training of the multivariate algorithm is carried out by using 20 000 candidates of the reconstructed  $\Lambda_c^+$  candidates from the data recorded in 2016. The requirement on the BDT response is determined using 200 000  $\Lambda_c^+$  candidates by maximising the figure of merit  $S/\sqrt{S+B}$ , where  $S$  is the  $\Lambda_c^+$  signal yield extracted from a fit to the mass spectrum of  $\Lambda_c^+$  candidates passing a given BDT requirement and  $B$  is expected background yield. The value for  $B$  is extrapolated by scaling the background yield over the full mass range of the fit to a  $\pm 15$  MeV mass range around the  $\Lambda_c^+$  peak.

Misidentified  $D^+ \rightarrow K^-\pi^+\pi^+$ ,  $D^+ \rightarrow K^+K^-\pi^+$  and  $D_s^+ \rightarrow K^+K^-\pi^+$  background decays are observed after changing the mass hypothesis of the proton into a kaon or a pion. These background components are reduced by employing a tighter PID selection and requiring the invariant mass  $m(K^+K^-)$  to differ by at least 10 MeV from the known  $\phi(1020)$  mass [37]. Removing all candidates in mass windows around the  $D_{(s)}^+$  mass distributions would result in a large loss of signal efficiency and therefore is not implemented. However, it is checked that the results of the analysis are stable when these background components are removed fully. About 125 million  $\Lambda_c^+$  signal decays are selected for further analysis with a purity of 93%. The invariant-mass distribution of 20% of the  $\Lambda_c^+$  candidates satisfying these selection requirements is shown in Fig. 1.

The  $\Xi_c^{*0}$  candidates are formed from  $\Lambda_c^+K^-$  combinations, where the  $\Lambda_c^+$  candidate mass is required to be within 20 MeV of the known  $\Lambda_c^+$  mass [37]. Each  $\Lambda_c^+$  candidate is combined with a  $K^-$  candidate that is consistent with originating from the associated PV. The  $\Lambda_c^+$  and  $K^-$  particles are fitted to a common vertex, which is required to be consistent with the associated PV.

The main contribution to the combinatorial background in the  $\Lambda_c^+K^-$  mass spectrum is due to the large number of kaon candidates from the PV. The signal to background ratio is improved by optimising the PID criteria of the  $K^-$  candidates and the  $p_T$  requirement on the  $\Xi_c^{*0}$  candidates using the figure of merit  $\epsilon/(\sqrt{B_P} + 5/2)$  [38]. Here,  $\epsilon$  is the efficiency determined using simulated  $\Xi_c(2930)^0 \rightarrow \Lambda_c^+K^-$  decays, and  $B_P$  is the number of  $\Lambda_c^+K^-$  candidates in the mass region  $260 < \Delta M < 290$  MeV, corresponding to the background expected in a mass window around the expected  $\Xi_c(2930)^0$  signal, with width  $\Gamma(\Xi_c(2930)^0) = 26 \pm 8$  MeV [37]. Based on the optimisation above, the  $p_T$  of the  $\Xi_c^0$  candidates is required to be larger than 7350 MeV, and the kaon PID is required to satisfy

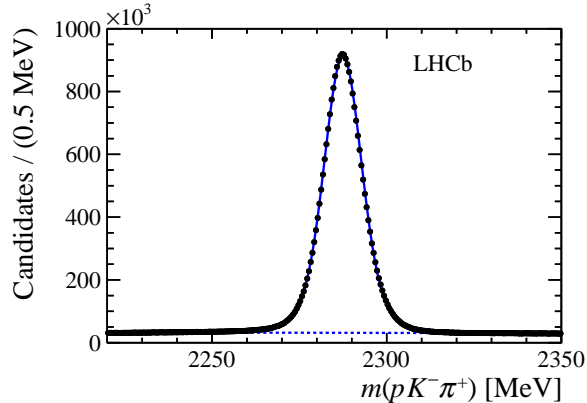


Figure 1: Distribution of the reconstructed invariant mass  $m(pK^-\pi^+)$  for 20% of the candidates in the  $\Lambda_c^+$  sample passing the selection described in the text. The solid blue curve shows the result of the fit, and the dashed blue line indicates the background component of the fit.

a tight criterion. The fraction of events with multiple candidates is found to be 0.88% in the entire  $\Delta M$  range. All candidates are included in the analysis.

The resulting  $\Delta M$  distribution of the signal candidates is shown in Fig. 2, where a fit to the data is superimposed. Three narrow structures are observed in the  $\Lambda_c^+ K^-$  candidate spectrum. These peaking structures are not seen in the wrong-sign (WS)  $\Lambda_c^+ K^+$  candidates or  $\Lambda_c^+$  sideband distributions. The  $\Delta M$  distribution also shows a broad structure to the left of the three narrow structures consistent with being partially reconstructed  $\Xi_c(3055) \rightarrow \Sigma_c(2455)(\rightarrow \Lambda_c^+ \pi) K^-$  and  $\Xi_c(3080) \rightarrow \Sigma_c(2455)(\rightarrow \Lambda_c^+ \pi) K^-$  decays, where the pion is not reconstructed.

An unbinned maximum-likelihood fit, henceforth denoted the reference fit, is performed to the  $\Delta M$  distribution to measure the parameters of each peak. The background is modelled by an empirical function of the form  $\Delta M^a \times \exp(-b \times \Delta M)$ , where  $a$  and  $b$  vary freely. Each signal peak is described by an  $S$ -wave relativistic Breit–Wigner function convolved with a mass-resolution function. The experimental mass resolution is determined using simulated  $\Xi_c^{*0} \rightarrow \Lambda_c^+ K^-$  decays at several  $\Xi_c^{*0}$  masses. In the  $\Delta M$  interval where the three narrow peaks occur, the mass resolution varies between 1.7 and 2.2 MeV. Simulated data are also generated to determine the shape of partially reconstructed  $\Xi_c(3055)$  and  $\Xi_c(3080)$  decays. The shapes of these contributions are allowed to shift in  $\Delta M$  by the uncertainties in the decay-product masses, where the shift is Gaussian constrained. From isospin symmetry, the yields of the components are constrained to be twice as large as the corresponding  $\Xi_c(3055)^0$  and  $\Xi_c(3080)^0$  components. The fit model outlined so far does not accurately describe the data in the mass region close to the kinematic threshold, and thus an additional component is considered. There are no known decays of  $\Sigma_c(2455)(\rightarrow \Lambda_c^+ \pi) K^-$  or  $\Sigma_c(2520)(\rightarrow \Lambda_c^+ \pi) K^-$  which could enter the sample as partially reconstructed components at  $\Delta M \simeq 0$ . It is observed that the missing component is consistent with being due to the partial reconstruction of the state that peaks around  $\Delta M \simeq 140$  MeV when it decays directly to the  $\Lambda_c^+ K^- \pi^+$  final state without any intermediate resonance. The shape of these partially reconstructed decays is taken from simulated samples generated using the RapidSim package [39] and the yield is a free parameter in the fit.

The  $\Delta M$  distribution with the fit to the data superimposed is shown in Fig. 2(a). The

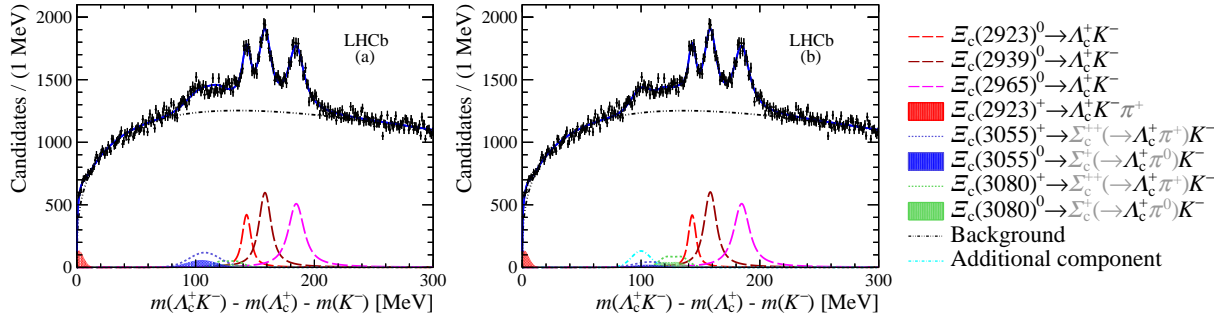


Figure 2: Distributions of the reconstructed invariant-mass difference  $\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m(K^-)$  for all candidates passing the selection requirements described in the text. The black symbols show the selected signal candidates. The result of a fit, described in the text, is overlaid (solid blue line). In plot (a) the reference fit is shown. Plot (b) shows an alternative description to the data, where an additional Gaussian component given by the cyan dot-dashed line is added to the fit model around  $\Delta M \simeq 100$  MeV. The missing child particles in the reconstruction are indicated in grey in the legend.

Table 1: Peak positions in the invariant-mass difference distribution  $\Delta M$ , natural widths  $\Gamma$ , signal yields and local significances of the three mass peaks obtained from the fit to the  $\Lambda_c^+ K^-$  mass spectrum, where the systematic uncertainties are statistical.

Peak of $\Delta M$ [MeV]	$\Gamma$ [MeV]	Signal yields
$142.91 \pm 0.25$	$7.1 \pm 0.8$	$5400 \pm 400$
$158.45 \pm 0.21$	$10.2 \pm 0.8$	$10400 \pm 600$
$184.75 \pm 0.26$	$14.1 \pm 0.9$	$11700 \pm 600$

goodness-of-fit value is  $\chi^2/\text{ndof} = 301/(300 - 19) = 1.07$ , where ndof is the number of the degrees of freedom. Table 1 shows the results for the parameters of the signal peaks of the reference fit, hereafter named  $\Xi_c(2923)^0$ ,  $\Xi_c(2939)^0$  and  $\Xi_c(2965)^0$ .

To validate the presence of the signal components and test the stability of the fit parameters, several additional checks are performed. The data are fitted in samples according to the year of data-taking and to different data-taking conditions depending on the LHCb magnet configuration. The  $\Lambda_c^+ K^-$  sample and its charge conjugate are also studied separately. The results are consistent among all samples.

The data and the reference fit show the least compatibility in the region around  $\Delta M \simeq 100$  MeV. This may be due to a mismodelling of the partially reconstructed distributions, but it could also be due to the presence of further new  $\Xi_c^{*0}$  baryon states. Figure 2(b) shows the  $\Delta M$  distribution for the signal sample where an additional component, parametrized by an empirical Gaussian function, has been added to the reference fit. This fit has a goodness-of-fit value of  $\chi^2/\text{ndof} = 278/(300 - 22) = 1.00$ . As a cross-check, this structure is tested in subsamples of the data set divided by data-taking year, and showed an inconsistency in the scaling of the yield with respect to the integrated luminosity. Furthermore, the feed-down components are highly suppressed when this contribution is included. More data are required to understand the cause of this additional structure. It is accounted for when calculating the systematic uncertainties.

Table 2: Summary of the contributions to the systematic uncertainties on the resonance parameters. Absolute deviations from the nominal fit are quoted.

Source	$\Xi_c(2923)^0$		$\Xi_c(2939)^0$		$\Xi_c(2965)^0$	
	$m$ [MeV]	$\Gamma$ [MeV]	$m$ [MeV]	$\Gamma$ [MeV]	$m$ [MeV]	$\Gamma$ [MeV]
Alternative fit model	0.15	1.6	0.14	0.4	0.04	1.1
Resonance interferences	0.08	0.7	0.06	1.0	0.11	0.7
Momentum-scale	0.04	–	0.05	–	0.06	–
Energy losses	0.04	–	0.04	–	0.04	–
Resolution calibration	–	0.6	–	0.2	–	0.3
Total	0.20	1.8	0.17	1.1	0.14	1.3

Several sources of systematic uncertainty may affect the measured parameters. The fit model uncertainty is evaluated by replacing the background model by an alternative function, consisting of a combination of the wrong-sign  $m(\Lambda_c^+ K^+)$  invariant-mass distribution shape and the shape obtained from candidates in the  $\Lambda_c^+$  sideband. In addition, the choice of the relativistic Breit–Wigner model is changed by setting the values of the angular momentum  $L$  between the child particles to  $L = 1, 2$  and separately varying the Blatt–Weisskopf factors [40] from 2 to 4  $\text{GeV}^{-1}$ . Furthermore, the fit is adapted to include any partially reconstructed decays  $\Xi_c^{**} \rightarrow \Sigma_c(2455/2520)(\rightarrow \Lambda_c^+ \pi) K^-$  that are found to not contribute significantly to the reference fit. Finally, deviations in fit parameters between the reference fit and the fit shown in Fig. 2(b) are included in the fit model uncertainty. The largest deviation from the reference fit is quoted as the systematic uncertainty for the fit model. Resonances with the same spin-parity that are close in mass can interfere. An interference term is introduced between neighbouring resonances, for one pair of resonances at a time. With the interference term, the lineshape takes the form  $A = |c_j \text{BW}_j + c_k \text{BW}_k e^{i\phi}|^2$  where  $j$  and  $k$  denote the two resonances,  $\text{BW}_{j,k}$  are Breit–Wigner functions and  $c_{j,k}$  and  $\phi$  are free real parameters. The largest difference between the reference fit and a fit where resonance interference is allowed is used as the systematic uncertainty. In addition, several other sources of systematic uncertainty only affect the mass measurement. These include the momentum-scale uncertainty, evaluated by shifting the momentum-scale of charged tracks by  $\pm 0.03\%$  [41] in simulated decays, and the imperfect modelling of the energy loss in the detector material, resulting in a systematic uncertainty of 0.04 MeV [42]. Finally, a systematic uncertainty is attributed to the width measurement, to account for the fact that the simulation may not reproduce the absolute mass resolution perfectly. The corresponding systematic uncertainty is obtained by the change in the width when the value of the resolution, determined on simulated data, is varied by 10% [43]. The systematic uncertainties are summarised in Table 2 and in Table 3 their measured masses and natural widths are summarised.

The observations described in this letter and the lack of any  $\Xi_c(2930)^0$  signal indicates that the broad bump observed in  $B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^-$  decays [20, 22] might be due to the overlap of two narrower states, such as the  $\Xi_c(2923)^0$  and  $\Xi_c(2939)^0$  baryons. The  $\Xi_c(2965)^0$  baryon is in the vicinity of the known  $\Xi_c(2970)^0$  baryon, which has been observed in different decay modes,  $\Sigma_c(2455)^0 K_S^0$  [21],  $\Xi_c'^+ \pi^-$  [44] and  $\Xi_c(2645)^+ \pi^-$  [45]. Furthermore, the  $\Xi_c(2965)^0$  resonance has a natural width and mass which differs significantly from that of the  $\Xi_c(2970)^0$  baryon,  $\Gamma(\Xi_c(2970)^0) = 28.1_{-4.0}^{+3.4} \text{ MeV}$

Table 3: Summary of the parameters for the studied states, showing the measured  $\Delta M$  values, the masses and the natural widths, where the first uncertainty is statistical and the second uncertainty is systematic. For the mass measurement, the third uncertainty denotes the uncertainty on the known  $\Lambda_c^+$  mass [37].

Resonance	Peak of $\Delta M$ [MeV]	Mass [MeV]	$\Gamma$ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

and  $m(\Xi_c(2970)^0) = 2967.8_{-0.7}^{+0.9}$  MeV [37]. Further studies are required to establish whether the  $\Xi_c(2965)^0$  state is indeed a different baryon. The equal spacing rule [46, 47] succeeded to predict the mass of the  $\Omega$  baryon and holds for other flavour multiplets such as the sextet of the  $J^P = 3/2^+$  charmed ground states:

$$m(\Omega_c(2770)^0) - m(\Xi_c(2645)^0) \simeq m(\Xi_c(2645)^0) - m(\Sigma_c(2520)^0) \simeq 125 \text{ MeV}.$$

It is noted that the rule also seems to hold for the  $\Xi_c(2923)^0$ ,  $\Xi_c(2939)^0$  and  $\Xi_c(2965)^0$  baryons within a precision of a few MeV:

$$\begin{aligned} m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) &\simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \simeq 125 \text{ MeV}, \\ m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) &\simeq 125 \text{ MeV}, \\ m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) &\simeq 125 \text{ MeV}. \end{aligned}$$

This pattern may indicate that the new states reported in this analysis are related to the excited  $\Omega_c^0$  baryons observed in the  $\Xi_c^+ K^-$  spectrum. Measurements of spin-parities will be crucial to confirm whether they belong to the same flavour multiplets.

In summary,  $pp$  collision data collected by the LHCb experiment at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $5.6 \text{ fb}^{-1}$ , are used to search for excited  $\Xi_c^0$  resonances in the  $\Lambda_c^+ K^-$  mass spectrum. Three different  $\Xi_c^0$  baryons,  $\Xi_c(2923)^0$ ,  $\Xi_c(2939)^0$  and  $\Xi_c(2965)^0$ , are unambiguously observed. The two baryons at lower mass are observed for the first time, while an investigation of additional final states is required to establish whether the  $\Xi_c(2965)^0$  and  $\Xi_c(2970)^0$  states are different baryons.

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R. Aaij<sup>31</sup>, C. Abellán Beteta<sup>49</sup>, T. Ackernley<sup>59</sup>, B. Adeva<sup>45</sup>, M. Adinolfi<sup>53</sup>, H. Afsharnia<sup>9</sup>, C.A. Aidala<sup>81</sup>, S. Aiola<sup>25</sup>, Z. Ajaltouni<sup>9</sup>, S. Akar<sup>66</sup>, J. Albrecht<sup>14</sup>, F. Alessio<sup>47</sup>, M. Alexander<sup>58</sup>, A. Alfonso Alberio<sup>44</sup>, G. Alkhazov<sup>37</sup>, P. Alvarez Cartelle<sup>60</sup>, A.A. Alves Jr<sup>45</sup>, S. Amato<sup>2</sup>, Y. Amhis<sup>11</sup>, L. An<sup>21</sup>, L. Anderlini<sup>21</sup>, G. Andreassi<sup>48</sup>, M. Andreotti<sup>20</sup>, F. Archilli<sup>16</sup>, A. Artamonov<sup>43</sup>, M. Artuso<sup>67</sup>, K. Arzymatov<sup>41</sup>, E. Aslanides<sup>10</sup>, M. Atzeni<sup>49</sup>, B. Audurier<sup>11</sup>, S. Bachmann<sup>16</sup>, J.J. Back<sup>55</sup>, S. Baker<sup>60</sup>, V. Balagura<sup>11,b</sup>, W. Baldini<sup>20</sup>, J. Baptista Leite<sup>1</sup>, R.J. Barlow<sup>61</sup>, S. Barsuk<sup>11</sup>, W. Barter<sup>60</sup>, M. Bartolini<sup>23,47,h</sup>, F. Baryshnikov<sup>78</sup>, J.M. Basels<sup>13</sup>, G. Bassi<sup>28</sup>, V. Batozskaya<sup>35</sup>, B. Batsukh<sup>67</sup>, A. Battig<sup>14</sup>, A. Bay<sup>48</sup>, M. Becker<sup>14</sup>, F. Bedeschi<sup>28</sup>, I. Bediaga<sup>1</sup>, A. Beiter<sup>67</sup>, V. Belavin<sup>41</sup>, S. Belin<sup>26</sup>, V. Bellec<sup>48</sup>, K. Belous<sup>43</sup>, I. Belyaev<sup>38</sup>, G. Bencivenni<sup>22</sup>, E. Ben-Haim<sup>12</sup>, S. Benson<sup>31</sup>, A. Berezhnoy<sup>39</sup>, R. Bernet<sup>49</sup>, D. Berninghoff<sup>16</sup>, H.C. Bernstein<sup>67</sup>, C. Bertella<sup>47</sup>, E. Bertholet<sup>12</sup>, A. Bertolin<sup>27</sup>, C. Betancourt<sup>49</sup>, F. Betti<sup>19,e</sup>, M.O. Bettler<sup>54</sup>, I.a. Bezshyiko<sup>49</sup>, S. Bhasin<sup>53</sup>, J. Bhom<sup>33</sup>, M.S. Bieker<sup>14</sup>, S. Bifani<sup>52</sup>, P. Billoir<sup>12</sup>, A. Bizzeti<sup>21,t</sup>, M. Bjørn<sup>62</sup>, M.P. Blago<sup>47</sup>, T. Blake<sup>55</sup>, F. Blanc<sup>48</sup>, S. Blusk<sup>67</sup>, D. Bobulska<sup>58</sup>, V. Bocci<sup>30</sup>, O. Boente Garcia<sup>45</sup>, T. Boettcher<sup>63</sup>, A. Boldyrev<sup>79</sup>, A. Bondar<sup>42,w</sup>, N. Bondar<sup>37,47</sup>, S. Borghi<sup>61</sup>, M. Borisyak<sup>41</sup>, M. Borsato<sup>16</sup>, J.T. Borsuk<sup>33</sup>, T.J.V. Bowcock<sup>59</sup>, A. Boyer<sup>47</sup>, C. Bozzi<sup>20</sup>, M.J. Bradley<sup>60</sup>, S. Braun<sup>65</sup>, A. Brea Rodriguez<sup>45</sup>, M. Brodski<sup>47</sup>, J. Brodzicka<sup>33</sup>, A. Brossa Gonzalo<sup>55</sup>, D. Brundu<sup>26</sup>, E. Buchanan<sup>53</sup>, A. Büchler-Germann<sup>49</sup>, A. Buonaura<sup>49</sup>, C. Burr<sup>47</sup>, A. Bursche<sup>26</sup>, A. Butkevich<sup>40</sup>, J.S. Butter<sup>31</sup>, J. Buytaert<sup>47</sup>, W. Byczynski<sup>47</sup>, S. Cadeddu<sup>26</sup>, H. Cai<sup>72</sup>, R. Calabrese<sup>20,g</sup>, L. Calero Diaz<sup>22</sup>, S. Cali<sup>22</sup>, R. Calladine<sup>52</sup>, M. Calvi<sup>24,i</sup>, M. Calvo Gomez<sup>44,l</sup>, P. Camargo Magalhaes<sup>53</sup>, A. Camboni<sup>44,l</sup>, P. Campana<sup>22</sup>, D.H. Campora Perez<sup>31</sup>, A.F. Campoverde Quezada<sup>5</sup>, L. Capriotti<sup>19,e</sup>, A. Carbone<sup>19,e</sup>, G. Carboni<sup>29</sup>, R. Cardinale<sup>23,h</sup>, A. Cardini<sup>26</sup>, I. Carli<sup>6</sup>, P. Carniti<sup>24,i</sup>, K. Carvalho Akiba<sup>31</sup>, A. Casais Vidal<sup>45</sup>, G. Casse<sup>59</sup>, M. Cattaneo<sup>47</sup>, G. Cavallero<sup>47</sup>, S. Celani<sup>48</sup>, R. Cenci<sup>28,o</sup>, J. Cerasoli<sup>10</sup>, M.G. Chapman<sup>53</sup>, M. Charles<sup>12</sup>, Ph. Charpentier<sup>47</sup>, G. Chatzikonstantinidis<sup>52</sup>, M. Chefdeville<sup>8</sup>, V. Chekalina<sup>41</sup>, C. Chen<sup>3</sup>, S. Chen<sup>26</sup>, A. Chernov<sup>33</sup>, S.-G. Chitic<sup>47</sup>, V. Chobanova<sup>45</sup>, S. Cholak<sup>48</sup>, M. 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P. Gandini<sup>25</sup>, Y. Gao<sup>4</sup>, L.M. Garcia Martin<sup>46</sup>, J. García Pardiñas<sup>49</sup>, B. Garcia Plana<sup>45</sup>,  
 F.A. Garcia Rosales<sup>11</sup>, L. Garrido<sup>44</sup>, D. Gascon<sup>44</sup>, C. Gaspar<sup>47</sup>, D. Gerick<sup>16</sup>, E. Gersabeck<sup>61</sup>,  
 M. Gersabeck<sup>61</sup>, T. Gershon<sup>55</sup>, D. Gerstel<sup>10</sup>, Ph. Ghez<sup>8</sup>, V. Gibson<sup>54</sup>, A. Gioventù<sup>45</sup>,  
 P. Gironella Gironell<sup>44</sup>, L. Giubega<sup>36</sup>, C. Giugliano<sup>20</sup>, K. Gizdov<sup>57</sup>, V.V. Gligorov<sup>12</sup>, C. Göbel<sup>70</sup>,  
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 I.V. Gorelov<sup>39</sup>, C. Gotti<sup>24,i</sup>, E. Govorkova<sup>31</sup>, J.P. Grabowski<sup>16</sup>, R. Graciani Diaz<sup>44</sup>,  
 T. Grammatico<sup>12</sup>, L.A. Granado Cardoso<sup>47</sup>, E. Graugés<sup>44</sup>, E. Graverini<sup>48</sup>, G. Graziani<sup>21</sup>,  
 A. Grecu<sup>36</sup>, R. Greim<sup>31</sup>, P. Griffith<sup>20</sup>, L. Grillo<sup>61</sup>, L. Gruber<sup>47</sup>, B.R. Gruberg Cazon<sup>62</sup>, C. Gu<sup>3</sup>,  
 M. Guarise<sup>20</sup>, E. Gushchin<sup>40</sup>, A. Guth<sup>13</sup>, Yu. Guz<sup>43,47</sup>, T. Gys<sup>47</sup>, P. A. Gnther<sup>16</sup>,  
 T. Hadavizadeh<sup>62</sup>, G. Haefeli<sup>48</sup>, C. Haen<sup>47</sup>, S.C. Haines<sup>54</sup>, P.M. Hamilton<sup>65</sup>, Q. Han<sup>7</sup>, X. Han<sup>16</sup>,  
 T.H. Hancock<sup>62</sup>, S. Hansmann-Menzemer<sup>16</sup>, N. Harnew<sup>62</sup>, T. Harrison<sup>59</sup>, R. Hart<sup>31</sup>, C. Hasse<sup>14</sup>,  
 M. Hatch<sup>47</sup>, J. He<sup>5</sup>, M. Hecker<sup>60</sup>, K. Heijhoff<sup>31</sup>, K. Heinicke<sup>14</sup>, A.M. Hennequin<sup>47</sup>,  
 K. Hennessy<sup>59</sup>, L. Henry<sup>25,46</sup>, J. Heuel<sup>13</sup>, A. Hicheur<sup>68</sup>, D. Hill<sup>62</sup>, M. Hilton<sup>61</sup>, P.H. Hopchev<sup>48</sup>,  
 J. Hu<sup>16</sup>, J. Hu<sup>71</sup>, W. Hu<sup>7</sup>, W. Huang<sup>5</sup>, W. Hulsbergen<sup>31</sup>, T. Humair<sup>60</sup>, R.J. Hunter<sup>55</sup>,  
 M. Hushchyn<sup>79</sup>, D. Hutchcroft<sup>59</sup>, D. Hynds<sup>31</sup>, P. Ibis<sup>14</sup>, M. Idzik<sup>34</sup>, P. Ilten<sup>52</sup>, A. Inglessi<sup>37</sup>,  
 K. Ivshin<sup>37</sup>, R. Jacobsson<sup>47</sup>, S. Jakobsen<sup>47</sup>, E. Jans<sup>31</sup>, B.K. Jashal<sup>46</sup>, A. Jawahery<sup>65</sup>,  
 V. Jevtic<sup>14</sup>, F. Jiang<sup>3</sup>, M. John<sup>62</sup>, D. Johnson<sup>47</sup>, C.R. Jones<sup>54</sup>, B. Jost<sup>47</sup>, N. Jurik<sup>62</sup>,  
 S. Kandybei<sup>50</sup>, M. Karacson<sup>47</sup>, J.M. Kariuki<sup>53</sup>, N. Kazeev<sup>79</sup>, M. Kecke<sup>16</sup>, F. Keizer<sup>54,47</sup>,  
 M. Kelsey<sup>67</sup>, M. Kenzie<sup>55</sup>, T. Ketel<sup>32</sup>, B. Khanji<sup>47</sup>, A. Kharisova<sup>80</sup>, K.E. Kim<sup>67</sup>, T. Kirn<sup>13</sup>,  
 V.S. Kirsobom<sup>48</sup>, S. Klaver<sup>22</sup>, K. Klimaszewski<sup>35</sup>, S. Koliiev<sup>51</sup>, A. Kondybayeva<sup>78</sup>,  
 A. Konoplyannikov<sup>38</sup>, P. Kopciwicz<sup>34</sup>, R. Kopečna<sup>16</sup>, P. Koppenburg<sup>31</sup>, M. Korolev<sup>39</sup>,  
 I. Kostiuk<sup>31,51</sup>, O. Kot<sup>51</sup>, S. Kotriakhova<sup>37</sup>, L. Kravchuk<sup>40</sup>, R.D. Krawczyk<sup>47</sup>, M. Kreps<sup>55</sup>,  
 F. Kress<sup>60</sup>, S. Kretzschmar<sup>13</sup>, P. Krokovny<sup>42,w</sup>, W. Krupa<sup>34</sup>, W. Krzemien<sup>35</sup>, W. Kucewicz<sup>33,k</sup>,  
 M. Kucharczyk<sup>33</sup>, V. Kudryavtsev<sup>42,w</sup>, H.S. Kuindersma<sup>31</sup>, G.J. Kunde<sup>66</sup>, T. Kvaratskheliya<sup>38</sup>,  
 D. Lacarrere<sup>47</sup>, G. Lafferty<sup>61</sup>, A. Lai<sup>26</sup>, D. Lancierini<sup>49</sup>, J.J. Lane<sup>61</sup>, G. Lanfranchi<sup>22</sup>,  
 C. Langenbruch<sup>13</sup>, O. Lantwin<sup>49,78</sup>, T. Latham<sup>55</sup>, F. Lazzari<sup>28,u</sup>, R. Le Gac<sup>10</sup>, S.H. Lee<sup>81</sup>,  
 R. Lefèvre<sup>9</sup>, A. Leflat<sup>39,47</sup>, O. Leroy<sup>10</sup>, T. Lesiak<sup>33</sup>, B. Leverington<sup>16</sup>, H. Li<sup>71</sup>, L. Li<sup>62</sup>, X. Li<sup>66</sup>,  
 Y. Li<sup>6</sup>, Z. Li<sup>67</sup>, X. Liang<sup>67</sup>, T. Lin<sup>60</sup>, R. Lindner<sup>47</sup>, V. Lisovskyi<sup>14</sup>, G. Liu<sup>71</sup>, X. Liu<sup>3</sup>, D. Loh<sup>55</sup>,  
 A. Loi<sup>26</sup>, J. Lomba Castro<sup>45</sup>, I. Longstaff<sup>58</sup>, J.H. Lopes<sup>2</sup>, G. Loustau<sup>49</sup>, G.H. Lovell<sup>54</sup>, Y. Lu<sup>6</sup>,  
 D. Lucchesi<sup>27,n</sup>, M. Lucio Martinez<sup>31</sup>, Y. Luo<sup>3</sup>, A. Lupato<sup>61</sup>, E. Luppi<sup>20,g</sup>, O. Lupton<sup>55</sup>,  
 A. Lusiani<sup>28,s</sup>, X. Lyu<sup>5</sup>, S. Maccolini<sup>19,e</sup>, F. Machefert<sup>11</sup>, F. Maciuc<sup>36</sup>, V. Macko<sup>48</sup>,  
 P. Mackowiak<sup>14</sup>, S. Maddrell-Mander<sup>53</sup>, L.R. Madhan Mohan<sup>53</sup>, O. Maev<sup>37</sup>, A. Maevskiy<sup>79</sup>,  
 D. Maisuzenko<sup>37</sup>, M.W. Majewski<sup>34</sup>, S. Malde<sup>62</sup>, B. Malecki<sup>47</sup>, A. Malinin<sup>77</sup>, T. Maltsev<sup>42,w</sup>,  
 H. Malygina<sup>16</sup>, G. Manca<sup>26,f</sup>, G. Mancinelli<sup>10</sup>, R. Manera Escalero<sup>44</sup>, D. Manuzzi<sup>19,e</sup>,  
 D. Marangotto<sup>25,p</sup>, J. Maratas<sup>9,v</sup>, J.F. Marchand<sup>8</sup>, U. Marconi<sup>19</sup>, S. Mariani<sup>21,47,21</sup>,  
 C. Marin Benito<sup>11</sup>, M. Marinangeli<sup>48</sup>, P. Marino<sup>48</sup>, J. Marks<sup>16</sup>, P.J. Marshall<sup>59</sup>, G. Martellotti<sup>30</sup>,  
 L. Martinazzoli<sup>47</sup>, M. Martinelli<sup>24,i</sup>, D. Martinez Santos<sup>45</sup>, F. Martinez Vidal<sup>46</sup>, A. Massafferri<sup>1</sup>,  
 M. Materok<sup>13</sup>, R. Matev<sup>47</sup>, A. Mathad<sup>49</sup>, Z. Mathe<sup>47</sup>, V. Matiunin<sup>38</sup>, C. Matteuzzi<sup>24</sup>,  
 K.R. Mattioli<sup>81</sup>, A. Mauri<sup>49</sup>, E. Maurice<sup>11,b</sup>, M. McCann<sup>60</sup>, L. Mcconnell<sup>17</sup>, A. McNab<sup>61</sup>,  
 R. McNulty<sup>17</sup>, J.V. Mead<sup>59</sup>, B. Meadows<sup>64</sup>, C. Meaux<sup>10</sup>, G. Meier<sup>14</sup>, N. Meinert<sup>74</sup>,  
 D. Melnychuk<sup>35</sup>, S. Meloni<sup>24,i</sup>, M. Merk<sup>31</sup>, A. Merli<sup>25</sup>, L. Meyer Garcia<sup>2</sup>, M. Mikhasenko<sup>47</sup>,  
 D.A. Milanes<sup>73</sup>, E. Millard<sup>55</sup>, M.-N. Minard<sup>8</sup>, O. Mineev<sup>38</sup>, L. Minzoni<sup>20</sup>, S.E. Mitchell<sup>57</sup>,  
 B. Mitreska<sup>61</sup>, D.S. Mitzel<sup>47</sup>, A. Mödden<sup>14</sup>, A. Mogini<sup>12</sup>, R.D. Moise<sup>60</sup>, T. Mombächer<sup>14</sup>,  
 I.A. Monroy<sup>73</sup>, S. Monteil<sup>9</sup>, M. Morandin<sup>27</sup>, G. Morello<sup>22</sup>, M.J. Morello<sup>28,s</sup>, J. Moron<sup>34</sup>,  
 A.B. Morris<sup>10</sup>, A.G. Morris<sup>55</sup>, R. Mountain<sup>67</sup>, H. Mu<sup>3</sup>, F. Muheim<sup>57</sup>, M. Mukherjee<sup>7</sup>,  
 M. Mulder<sup>47</sup>, D. Müller<sup>47</sup>, K. Müller<sup>49</sup>, C.H. Murphy<sup>62</sup>, D. Murray<sup>61</sup>, P. Muzzetto<sup>26</sup>, P. Naik<sup>53</sup>,  
 T. Nakada<sup>48</sup>, R. Nandakumar<sup>56</sup>, T. Nanut<sup>48</sup>, I. Nasteva<sup>2</sup>, M. Needham<sup>57</sup>, I. Neri<sup>20</sup>, N. Neri<sup>25,p</sup>,  
 S. Neubert<sup>16</sup>, N. Neufeld<sup>47</sup>, R. Newcombe<sup>60</sup>, T.D. Nguyen<sup>48</sup>, C. Nguyen-Mau<sup>48,m</sup>, E.M. Niel<sup>11</sup>,  
 S. Nieswand<sup>13</sup>, N. Nikitin<sup>39</sup>, N.S. Nolte<sup>47</sup>, C. Nunez<sup>81</sup>, A. Oblakowska-Mucha<sup>34</sup>, V. Obraztsov<sup>43</sup>,  
 S. Ogilvy<sup>58</sup>, D.P. O'Hanlon<sup>53</sup>, R. Oldeman<sup>26,f</sup>, C.J.G. Onderwater<sup>75</sup>, J. D. Osborn<sup>81</sup>,

A. Ossowska<sup>33</sup>, J.M. Otalora Goicochea<sup>2</sup>, T. Ovsiannikova<sup>38</sup>, P. Owen<sup>49</sup>, A. Oyanguren<sup>46</sup>,  
 P.R. Pais<sup>48</sup>, T. Pajero<sup>28,47,28,s</sup>, A. Palano<sup>18</sup>, M. Palutan<sup>22</sup>, G. Panshin<sup>80</sup>, A. Papanestis<sup>56</sup>,  
 M. Pappagallo<sup>57</sup>, L.L. Pappalardo<sup>20</sup>, C. Pappenheimer<sup>64</sup>, W. Parker<sup>65</sup>, C. Parkes<sup>61</sup>,  
 C.J. Parkinson<sup>45</sup>, G. Passaleva<sup>21,47</sup>, A. Pastore<sup>18</sup>, M. Patel<sup>60</sup>, C. Patrignani<sup>19,e</sup>, A. Pearce<sup>47</sup>,  
 A. Pellegrino<sup>31</sup>, M. Pepe Altarelli<sup>47</sup>, S. Perazzini<sup>19</sup>, D. Pereima<sup>38</sup>, P. Perret<sup>9</sup>, K. Petridis<sup>53</sup>,  
 A. Petrolini<sup>23,h</sup>, A. Petrov<sup>77</sup>, S. Petrucci<sup>57</sup>, M. Petruzzo<sup>25,p</sup>, B. Pietrzyk<sup>8</sup>, G. Pietrzyk<sup>48</sup>,  
 M. Pili<sup>62</sup>, D. Pinci<sup>30</sup>, J. Pinzino<sup>47</sup>, F. Pisani<sup>19</sup>, A. Piucci<sup>16</sup>, V. Placinta<sup>36</sup>, S. Playfer<sup>57</sup>,  
 J. Plews<sup>52</sup>, M. Plo Casasus<sup>45</sup>, F. Polci<sup>12</sup>, M. Poli Lener<sup>22</sup>, M. Poliakov<sup>67</sup>, A. Poluektov<sup>10</sup>,  
 N. Polukhina<sup>78,c</sup>, I. Polyakov<sup>67</sup>, E. Polycarpo<sup>2</sup>, G.J. Pomery<sup>53</sup>, S. Ponce<sup>47</sup>, A. Popov<sup>43</sup>,  
 D. Popov<sup>52</sup>, S. Poslavskii<sup>43</sup>, K. Prasanth<sup>33</sup>, L. Promberger<sup>47</sup>, C. Prouve<sup>45</sup>, V. Pugatch<sup>51</sup>,  
 A. Puig Navarro<sup>49</sup>, H. Pullen<sup>62</sup>, G. Punzi<sup>28,o</sup>, W. Qian<sup>5</sup>, J. Qin<sup>5</sup>, R. Quagliani<sup>12</sup>, B. Quintana<sup>8</sup>,  
 N.V. Raab<sup>17</sup>, R.I. Rabadan Trejo<sup>10</sup>, B. Rachwal<sup>34</sup>, J.H. Rademacker<sup>53</sup>, M. Rama<sup>28</sup>,  
 M. Ramos Pernas<sup>45</sup>, M.S. Rangel<sup>2</sup>, F. Ratnikov<sup>41,79</sup>, G. Raven<sup>32</sup>, M. Reboud<sup>8</sup>, F. Redi<sup>48</sup>,  
 F. Reiss<sup>12</sup>, C. Remon Alepuz<sup>46</sup>, Z. Ren<sup>3</sup>, V. Renaudin<sup>62</sup>, S. Ricciardi<sup>56</sup>, D.S. Richards<sup>56</sup>,  
 S. Richards<sup>53</sup>, K. Rinnert<sup>59</sup>, P. Robbe<sup>11</sup>, A. Robert<sup>12</sup>, A.B. Rodrigues<sup>48</sup>, E. Rodrigues<sup>59</sup>,  
 J.A. Rodriguez Lopez<sup>73</sup>, M. Roehrken<sup>47</sup>, A. Rollings<sup>62</sup>, V. Romanovskiy<sup>43</sup>, M. Romero Lamas<sup>45</sup>,  
 A. Romero Vidal<sup>45</sup>, J.D. Roth<sup>81</sup>, M. Rotondo<sup>22</sup>, M.S. Rudolph<sup>67</sup>, T. Ruf<sup>47</sup>, J. Ruiz Vidal<sup>46</sup>,  
 A. Ryzhikov<sup>79</sup>, J. Ryzka<sup>34</sup>, J.J. Saborido Silva<sup>45</sup>, N. Sagidova<sup>37</sup>, N. Sahoo<sup>55</sup>, B. Saitta<sup>26,f</sup>,  
 C. Sanchez Gras<sup>31</sup>, C. Sanchez Mayordomo<sup>46</sup>, R. Santacesaria<sup>30</sup>, C. Santamarina Rios<sup>45</sup>,  
 M. Santimaria<sup>22</sup>, E. Santovetti<sup>29,j</sup>, G. Sarpis<sup>61</sup>, M. Sarpis<sup>16</sup>, A. Sarti<sup>30</sup>, C. Satriano<sup>30,r</sup>,  
 A. Satta<sup>29</sup>, M. Saur<sup>5</sup>, D. Savrina<sup>38,39</sup>, L.G. Scantlebury Smead<sup>62</sup>, S. Schael<sup>13</sup>, M. Schellenberg<sup>14</sup>,  
 M. Schiller<sup>58</sup>, H. Schindler<sup>47</sup>, M. Schmelling<sup>15</sup>, T. Schmelzer<sup>14</sup>, B. Schmidt<sup>47</sup>, O. Schneider<sup>48</sup>,  
 A. Schopper<sup>47</sup>, H.F. Schreiner<sup>64</sup>, M. Schubiger<sup>31</sup>, S. Schulte<sup>48</sup>, M.H. Schune<sup>11</sup>, R. Schwemmer<sup>47</sup>,  
 B. Sciascia<sup>22</sup>, A. Sciubba<sup>22</sup>, S. Sellam<sup>68</sup>, A. Semennikov<sup>38</sup>, A. Sergi<sup>52,47</sup>, N. Serra<sup>49</sup>,  
 J. Serrano<sup>10</sup>, L. Sestini<sup>27</sup>, A. Seuthe<sup>14</sup>, P. Seyfert<sup>47</sup>, D.M. Shangase<sup>81</sup>, M. Shapkin<sup>43</sup>,  
 L. Shchutska<sup>48</sup>, T. Shears<sup>59</sup>, L. Shekhtman<sup>42,w</sup>, V. Shevchenko<sup>77</sup>, E. Shmanin<sup>78</sup>,  
 J.D. Shupperd<sup>67</sup>, B.G. Siddi<sup>20</sup>, R. Silva Coutinho<sup>49</sup>, L. Silva de Oliveira<sup>2</sup>, G. Simi<sup>27,n</sup>,  
 S. Simone<sup>18,d</sup>, I. Skiba<sup>20</sup>, N. Skidmore<sup>16</sup>, T. Skwarnicki<sup>67</sup>, M.W. Slater<sup>52</sup>, J.G. Smeaton<sup>54</sup>,  
 A. Smetkina<sup>38</sup>, E. Smith<sup>13</sup>, I.T. Smith<sup>57</sup>, M. Smith<sup>60</sup>, A. Snoch<sup>31</sup>, M. Soares<sup>19</sup>,  
 L. Soares Lavra<sup>9</sup>, M.D. Sokoloff<sup>64</sup>, F.J.P. Soler<sup>58</sup>, B. Souza De Paula<sup>2</sup>, B. Spaan<sup>14</sup>,  
 E. Spadaro Norella<sup>25,p</sup>, P. Spradlin<sup>58</sup>, F. Stagni<sup>47</sup>, M. Stahl<sup>64</sup>, S. Stahl<sup>47</sup>, P. Steffen<sup>48</sup>,  
 O. Steinkamp<sup>49,78</sup>, S. Stemmle<sup>16</sup>, O. Stenyakin<sup>43</sup>, M. Stepanova<sup>37</sup>, H. Stevens<sup>14</sup>, S. Stone<sup>67</sup>,  
 S. Stracka<sup>28</sup>, M.E. Stramaglia<sup>48</sup>, M. Straticiu<sup>36</sup>, S. Strovk<sup>80</sup>, J. Sun<sup>26</sup>, L. Sun<sup>72</sup>, Y. Sun<sup>65</sup>,  
 P. Svihra<sup>61</sup>, K. Swientek<sup>34</sup>, A. Szabelski<sup>35</sup>, T. Szumlak<sup>34</sup>, M. Szymanski<sup>47</sup>, S. Taneja<sup>61</sup>,  
 Z. Tang<sup>3</sup>, T. Tekampe<sup>14</sup>, F. Teubert<sup>47</sup>, E. Thomas<sup>47</sup>, K.A. Thomson<sup>59</sup>, M.J. Tilley<sup>60</sup>,  
 V. Tisserand<sup>9</sup>, S. T'Jampens<sup>8</sup>, M. Tobin<sup>6</sup>, S. Tolk<sup>47</sup>, L. Tomassetti<sup>20,g</sup>, D. Torres Machado<sup>1</sup>,  
 D.Y. Tou<sup>12</sup>, E. Tournefier<sup>8</sup>, M. Traill<sup>58</sup>, M.T. Tran<sup>48</sup>, E. Trifonova<sup>78</sup>, C. Trippl<sup>48</sup>,  
 A. Tsaregorodtsev<sup>10</sup>, G. Tuci<sup>28,o</sup>, A. Tully<sup>48</sup>, N. Tuning<sup>31</sup>, A. Ukleja<sup>35</sup>, A. Usachov<sup>31</sup>,  
 A. Ustyuzhanin<sup>41,79</sup>, U. Uwer<sup>16</sup>, A. Vagner<sup>80</sup>, V. Vagnoni<sup>19</sup>, A. Valassi<sup>47</sup>, G. Valenti<sup>19</sup>,  
 M. van Beuzekom<sup>31</sup>, H. Van Hecke<sup>66</sup>, E. van Herwijnen<sup>47</sup>, C.B. Van Hulse<sup>17</sup>, M. van Veghel<sup>75</sup>,  
 R. Vazquez Gomez<sup>44</sup>, P. Vazquez Regueiro<sup>45</sup>, C. Vázquez Sierra<sup>31</sup>, S. Vecchi<sup>20</sup>, J.J. Velthuis<sup>53</sup>,  
 M. Veltri<sup>21,q</sup>, A. Venkateswaran<sup>67</sup>, M. Veronesi<sup>31</sup>, M. Vesterinen<sup>55</sup>, J.V. Viana Barbosa<sup>47</sup>,  
 D. Vieira<sup>64</sup>, M. Vieites Diaz<sup>48</sup>, H. Viemann<sup>74</sup>, X. Vilasis-Cardona<sup>44,l</sup>, G. Vitali<sup>28</sup>,  
 A. Vitkovskiy<sup>31</sup>, A. Vollhardt<sup>49</sup>, D. Vom Bruch<sup>12</sup>, A. Vorobyev<sup>37</sup>, V. Vorobyev<sup>42,w</sup>,  
 N. Voropaev<sup>37</sup>, R. Waldi<sup>74</sup>, J. Walsh<sup>28</sup>, J. Wang<sup>3</sup>, J. Wang<sup>72</sup>, J. Wang<sup>6</sup>, M. Wang<sup>3</sup>, Y. Wang<sup>7</sup>,  
 Z. Wang<sup>49</sup>, D.R. Ward<sup>54</sup>, H.M. Wark<sup>59</sup>, N.K. Watson<sup>52</sup>, D. Websdale<sup>60</sup>, A. Weiden<sup>49</sup>,  
 C. Weisser<sup>63</sup>, B.D.C. Westhenry<sup>53</sup>, D.J. White<sup>61</sup>, M. Whitehead<sup>53</sup>, D. Wiedner<sup>14</sup>,  
 G. Wilkinson<sup>62</sup>, M. Wilkinson<sup>67</sup>, I. Williams<sup>54</sup>, M. Williams<sup>63</sup>, M.R.J. Williams<sup>61</sup>,  
 T. Williams<sup>52</sup>, F.F. Wilson<sup>56</sup>, W. Wislicki<sup>35</sup>, M. Witek<sup>33</sup>, L. Witola<sup>16</sup>, G. Wormser<sup>11</sup>,  
 S.A. Wotton<sup>54</sup>, H. Wu<sup>67</sup>, K. Wyllie<sup>47</sup>, Z. Xiang<sup>5</sup>, D. Xiao<sup>7</sup>, Y. Xie<sup>7</sup>, H. Xing<sup>71</sup>, A. Xu<sup>4</sup>, J. Xu<sup>5</sup>,

L. Xu<sup>3</sup>, M. Xu<sup>7</sup>, Q. Xu<sup>5</sup>, Z. Xu<sup>4</sup>, Z. Xu<sup>5</sup>, Z. Yang<sup>3</sup>, Z. Yang<sup>65</sup>, Y. Yao<sup>67</sup>, L.E. Yeomans<sup>59</sup>, H. Yin<sup>7</sup>, J. Yu<sup>7</sup>, X. Yuan<sup>67</sup>, O. Yushchenko<sup>43</sup>, K.A. Zarebski<sup>52</sup>, M. Zavertyaev<sup>15,c</sup>, M. Zdybal<sup>33</sup>, M. Zeng<sup>3</sup>, D. Zhang<sup>7</sup>, L. Zhang<sup>3</sup>, S. Zhang<sup>4</sup>, W.C. Zhang<sup>3,y</sup>, Y. Zhang<sup>47</sup>, A. Zhelezov<sup>16</sup>, Y. Zheng<sup>5</sup>, X. Zhou<sup>5</sup>, Y. Zhou<sup>5</sup>, X. Zhu<sup>3</sup>, V. Zhukov<sup>13,39</sup>, J.B. Zonneveld<sup>57</sup>, S. Zucchelli<sup>19,e</sup>.

<sup>1</sup>*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*

<sup>2</sup>*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

<sup>3</sup>*Center for High Energy Physics, Tsinghua University, Beijing, China*

<sup>4</sup>*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

<sup>5</sup>*University of Chinese Academy of Sciences, Beijing, China*

<sup>6</sup>*Institute Of High Energy Physics (IHEP), Beijing, China*

<sup>7</sup>*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*

<sup>8</sup>*Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*

<sup>9</sup>*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*

<sup>10</sup>*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

<sup>11</sup>*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*

<sup>12</sup>*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*

<sup>13</sup>*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*

<sup>14</sup>*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*

<sup>15</sup>*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

<sup>16</sup>*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

<sup>17</sup>*School of Physics, University College Dublin, Dublin, Ireland*

<sup>18</sup>*INFN Sezione di Bari, Bari, Italy*

<sup>19</sup>*INFN Sezione di Bologna, Bologna, Italy*

<sup>20</sup>*INFN Sezione di Ferrara, Ferrara, Italy*

<sup>21</sup>*INFN Sezione di Firenze, Firenze, Italy*

<sup>22</sup>*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

<sup>23</sup>*INFN Sezione di Genova, Genova, Italy*

<sup>24</sup>*INFN Sezione di Milano-Bicocca, Milano, Italy*

<sup>25</sup>*INFN Sezione di Milano, Milano, Italy*

<sup>26</sup>*INFN Sezione di Cagliari, Monserrato, Italy*

<sup>27</sup>*INFN Sezione di Padova, Padova, Italy*

<sup>28</sup>*INFN Sezione di Pisa, Pisa, Italy*

<sup>29</sup>*INFN Sezione di Roma Tor Vergata, Roma, Italy*

<sup>30</sup>*INFN Sezione di Roma La Sapienza, Roma, Italy*

<sup>31</sup>*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*

<sup>32</sup>*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*

<sup>33</sup>*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*

<sup>34</sup>*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*

<sup>35</sup>*National Center for Nuclear Research (NCBJ), Warsaw, Poland*

<sup>36</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

<sup>37</sup>*Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia*

<sup>38</sup>*Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia, Moscow, Russia*

<sup>39</sup>*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*

<sup>40</sup>*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*

<sup>41</sup>*Yandex School of Data Analysis, Moscow, Russia*

<sup>42</sup>*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*

<sup>43</sup>*Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia*

<sup>44</sup>*ICCUB, Universitat de Barcelona, Barcelona, Spain*

<sup>45</sup>*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*

- <sup>46</sup> *Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- <sup>47</sup> *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- <sup>48</sup> *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- <sup>49</sup> *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- <sup>50</sup> *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- <sup>51</sup> *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- <sup>52</sup> *University of Birmingham, Birmingham, United Kingdom*
- <sup>53</sup> *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- <sup>54</sup> *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>55</sup> *Department of Physics, University of Warwick, Coventry, United Kingdom*
- <sup>56</sup> *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>57</sup> *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- <sup>58</sup> *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- <sup>59</sup> *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- <sup>60</sup> *Imperial College London, London, United Kingdom*
- <sup>61</sup> *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- <sup>62</sup> *Department of Physics, University of Oxford, Oxford, United Kingdom*
- <sup>63</sup> *Massachusetts Institute of Technology, Cambridge, MA, United States*
- <sup>64</sup> *University of Cincinnati, Cincinnati, OH, United States*
- <sup>65</sup> *University of Maryland, College Park, MD, United States*
- <sup>66</sup> *Los Alamos National Laboratory (LANL), Los Alamos, United States*
- <sup>67</sup> *Syracuse University, Syracuse, NY, United States*
- <sup>68</sup> *Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria, associated to <sup>2</sup>*
- <sup>69</sup> *School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to <sup>55</sup>*
- <sup>70</sup> *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to <sup>2</sup>*
- <sup>71</sup> *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to <sup>3</sup>*
- <sup>72</sup> *School of Physics and Technology, Wuhan University, Wuhan, China, associated to <sup>3</sup>*
- <sup>73</sup> *Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia, associated to <sup>12</sup>*
- <sup>74</sup> *Institut für Physik, Universität Rostock, Rostock, Germany, associated to <sup>16</sup>*
- <sup>75</sup> *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to <sup>31</sup>*
- <sup>76</sup> *Universiteit Maastricht, Maastricht, Netherlands, associated to <sup>31</sup>*
- <sup>77</sup> *National Research Centre Kurchatov Institute, Moscow, Russia, associated to <sup>38</sup>*
- <sup>78</sup> *National University of Science and Technology "MISIS", Moscow, Russia, associated to <sup>38</sup>*
- <sup>79</sup> *National Research University Higher School of Economics, Moscow, Russia, associated to <sup>41</sup>*
- <sup>80</sup> *National Research Tomsk Polytechnic University, Tomsk, Russia, associated to <sup>38</sup>*
- <sup>81</sup> *University of Michigan, Ann Arbor, United States, associated to <sup>67</sup>*

<sup>a</sup> *Universidade Federal do Triângulo Mineiro (UFMT), Uberaba-MG, Brazil*

<sup>b</sup> *Laboratoire Leprince-Ringuet, Palaiseau, France*

<sup>c</sup> *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*

<sup>d</sup> *Università di Bari, Bari, Italy*

<sup>e</sup> *Università di Bologna, Bologna, Italy*

<sup>f</sup> *Università di Cagliari, Cagliari, Italy*

<sup>g</sup> *Università di Ferrara, Ferrara, Italy*

<sup>h</sup> *Università di Genova, Genova, Italy*

<sup>i</sup> *Università di Milano Bicocca, Milano, Italy*

<sup>j</sup> *Università di Roma Tor Vergata, Roma, Italy*

<sup>k</sup> *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland*

<sup>l</sup> *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*

<sup>m</sup> *Hanoi University of Science, Hanoi, Vietnam*

<sup>n</sup> *Università di Padova, Padova, Italy*

<sup>o</sup> *Università di Pisa, Pisa, Italy*

<sup>p</sup> *Università degli Studi di Milano, Milano, Italy*

<sup>q</sup> *Università di Urbino, Urbino, Italy*

<sup>r</sup> *Università della Basilicata, Potenza, Italy*

<sup>s</sup> *Scuola Normale Superiore, Pisa, Italy*

<sup>t</sup> *Università di Modena e Reggio Emilia, Modena, Italy*

<sup>u</sup> *Università di Siena, Siena, Italy*

<sup>v</sup> *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*

<sup>w</sup> *Novosibirsk State University, Novosibirsk, Russia*

<sup>x</sup> *INFN Sezione di Trieste, Trieste, Italy*

<sup>y</sup> *School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China*

<sup>z</sup> *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*