Evidence of charged $\Xi_c(2930)$ and updated measurement of $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$ at Belle

Y. B. Li,68 C. P. Shen,2 I. Adachi,19,15 H. Aihara,81 S. Al Said,77,38 D. M. Asner,4 T. Aushev,54 R. Ayad,77 V. Babu,78 I. Badhrees,77,37 S. Bahinipati,24 Y. Ban,68 V. Bansal,66 P. Behera,27 C. Beleño,14 V. Bhardwaj,23 B. Bhuyan,25 J. Biswal,34 A. Bobrov,5,64 A. Bozek,61 M. Bracko,49,34 T. E. Browder,39 L. Cao,36 D. Červenkov,6 P. Chang,60 V. Chekelian,50 A. Chen,58 B. G. Cheon,17 K. Chilikin,44 K. Cho,39 S.-K. Choi,16 Y. Choi,75 S. Choudhury,26 D. Cinabro,85 S. Cunliffe,9 N. Dash,24 S. Di Carlo,42 J. Dingfelder,3 Z. Doležal,6 T. V. Dong,19,15 Z. Drásal,6 S. Eidemüller,5,64 D. Epifanov,5,64 J. E. Fast,66 B. G. Fulsom,66 R. Garg,67 V. Gaur,84 N. Gabyshev,5,64 A. Garmash,5,64 M. Gelb,36 A. Giri,26 P. Goldenzweig,36 B. Golob,45,34 J. Haba,19,15 K. Hayasaka,63 S. Hirose,55 W.-S. Hou,60 T. Iijima,56,55 K. Inami,55 G. Inguglia,9 A. Ishikawa,80 R. Itoh,10,15 M. Iwasaki,65 Y. Iwasaki,19 W. W. Jacobs,28 I. Jaegle,10 H. B. Jeon,41 S. Jia,2 Y. Jin,81 K. K. Joo,7 A. B. Kaliyar,27 K. H. Kang,41 Y. Kato,55 T. Kawasaki,63 D. Y. Kim,73 J. B. Kim,40 S. H. Kim,17 K. Kinoshita,8 P. Kodyś,6 S. Korpar,49,34 D. Kotchetkov,18 P. Križan,45,34 R. Kroeger,52 P. Krokovny,5,64 T. Kuhn,46 Y.-J. Kwon,87 J. S. Lange,12 I. S. Lee,17 S. C. Lee,41 L. K. Li,29 L. Li Gioi,50 J. Libby,27 D. Liventsev,84,19 T. Luo,11 D. Matvienko,5,64,44 M. Merola,31,57 H. Miyata,63 R. Mizuk,44,53,54 H. K. Moon,40 T. Mori,55 R. Mussa,32 E. Nakano,65 T. Nant,34 K. J. Nath,25 Z. Natkaniec,61 M. Nayak,85,19 N. K. Nisar,69 S. Nishida,19,15 K. Nishimura,18 K. Ogawa,63 S. Okuno,35 H. Oto,62,63 P. Pakhlov,44,53 G. Pakhlova,44,54 B. Pal,4 S. Pardi,31 H. Park,41 S. Paul,79 T. K. Pedlar,47 R. Pestotnik,34 L. E. Piilonen,84 V. Popov,44,54 E. Prencipe,21 A. Rostomyan,9 G. Russo,31 Y. Sakai,18,15 M. Salehi,48,46 S. Sandilya,8 L. Santelj,19 T. Samuki,80 V. Savinov,69 O. Schneider,53 G. Schnell,1,22 C. Schwanda,30 Y. Seino,53 K. Senyo,56 O. Seon,55 M. E. Sevior,51 T.-A. Shibata,82 J.-G. Shi,50 E. Solovieva,44,54 M. Starić,34 J. F. Strube,66 M. Sumihama,13 T. Suniyoshi,83 M. Takizawa,72,20,70 U. Tamponi,32 K. Tanaka,35 F. Tchenchi,51 M. Uchida,82 T. Uglov,44,54 Y. Unno,17 S. Uno,19,15 Y. Usov,5,64 C. Van Hulse,1 R. Van Tonder,56 G. Varner,18 K. E. Varvel,76 V. Vorobyev,5,64,44 E. Waheed,51 B. Wang,8 C. H. Wang,59 M.-Z. Wang,60 P. Wang,29 X. L. Wang,11 S. Watanuki,80 E. Widmann,74 E. Won,40 H. Ye,5 J. Yelton,10 J. H. Yin,29 C. Z. Yuan,29 Y. Yusa,63 Z. P. Zhang,71 V. Zhilich,5,64 V. Zhukova,44,53 and V. Zhulanov5,64

(The Belle Collaboration)

1University of the Basque Country UPV/EHU, 48080 Bilbao
2Beihang University, Beijing 100191
3University of Bonn, 53115 Bonn
4Brookhaven National Laboratory, Upton, New York 11973
5Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090
6Faculty of Mathematics and Physics, Charles University, 121 16 Prague
7Chonnam National University, Kwangju 660-701
8University of Cincinnati, Cincinnati, Ohio 45221
9Deutsches Elektronen-Synchrotron, 22607 Hamburg
10University of Florida, Gainesville, Florida 32611
11Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443
12Justus-Liebig-Universität Gießen, 35392 Gießen
13Hokkaido University, Sapporo 060-0810
14University of Hawaii, Honolulu, Hawaii 96822
15High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
16J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
17Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
18Institute of High Energy Physics, Vienna 1050
We report evidence for the charged charmed-strange baryon $\Xi_c^+(2930)$ with a signal significance of 3.9σ. The charged $\Xi_c^+(2930)$ is found in its decay to $K^0\Lambda_c^+$ in the substructure of $B^0 \rightarrow K^0\Lambda_c^+$ decays. The measured mass and width are $[2942\pm 4.4\text{(stat.)} \pm 1.6\text{(syst.)}]$ MeV/c² and $[14.8 \pm 8.8\text{(stat.)} \pm 7.1\text{(syst.)}]$ MeV, respectively, and the product branching fraction is $B(B^0 \rightarrow \Xi_c^+(2930)\Lambda_c^+)B(\Xi_c^+(2930) \rightarrow K^0\Lambda_c^+) = [2.28 \pm 0.49\text{(stat.)} \pm 0.29\text{(syst.)}] \times 10^{-4}$. We also measure $B(B^0 \rightarrow K^0\Lambda_c^+) = [3.84 \pm 0.73\text{(stat.)} \pm 0.48\text{(syst.)}] \times 10^{-4}$ with greater precision than previous
The study of the excited states of charmed and bottom baryons is important as they offer an excellent laboratory for testing the heavy-quark symmetry of the c and b quarks and the chiral symmetry of the light quarks. At present, the particle data group (PDG) lists ten charmed-strange baryons [1]. Among these, $\Xi_c(2930)$ and $\Xi_c(3123)$ are relatively less established and evidence for them is poor [1]. For most of these excited $\Xi_c$ states the spins and parities have not been determined by experiments due to limited statistics.

Theoretically, the mass spectrum of excited charmed baryons has been computed in many models, including quark potential models [2–6], the relativistic flux tube model [7, 8], the coupled channel model [9], the Quantum Chromodynamics (QCD) sum rule [10–14], Regge phenomenology [15], the constituent quark model [16, 17], and lattice QCD [18, 19]. The strong decays of excited $\Xi_c$ baryons have also been studied in many models [20–26]. In these models, some possible $J^P$ assignments of these excited $\Xi_c$ have been performed. While many new excited charmed baryons have been discovered in experiments in recent years, and there has been much theoretical work devoted to study the nature of charmed baryon internal structure and quark organization, further effort (and cooperation) from both experimentalists and theorists is needed to make progress in this area.

Very recently, Belle reported the first observation of the $\Xi_c(2930)^0$ charmed-strange baryon with a significance greater than 5σ by study of the substructure in $B^- \to K^- \Lambda_c^+ \Lambda_c^-$ decays [27]. The measured mass and width of the $\Xi_c(2930)^0$ were found to be $[2928.9 \pm 3.0(\text{stat.}) \pm 12.0(\text{syst.})]$ MeV/$c^2$ and $[19.5 \pm 8.4(\text{stat.}) \pm 7.9(\text{syst.})]$ MeV, respectively. As the isospin of the $\Xi_c$ state is 1/2 and the neutral $\Xi_c(2930)$ has been found, it is natural to search for the charged partner in the substructure in $B^0 \to K^0 \Lambda_c^+ \Lambda_c^-$ decays [28].

BaBar and Belle have previously studied $B^0 \to K^0 \Lambda_c^+ \Lambda_c^-$ decays using data samples of $230 \times 10^6$ and $386 \times 10^6$ $BB$ pairs, and found signals of 1.4σ and 6.6σ significances, respectively [29, 30]. Neither experiment searched for possible intermediate states in the $K^0_\Lambda L_c$ system. The full Belle data sample of $(772 \pm 11) \times 10^6$ $BB$ pairs permits an improved study of $B^0 \to K^0 \Lambda_c^+ \Lambda_c^-$ and a search for the charged $\Xi_c(2930)$ in the decay mode $K^0 \Lambda_c$.

The $\Lambda_c^+ \Lambda_c^-$ system is interesting because (1) Belle has observed the $Y(4630)$ in the initial state radiation (ISR) process $e^+e^- \to \gamma_{\text{ISR}} \Lambda_c^+ \Lambda_c^-$ and measured a mass and width of $[4634.4^{+8}_{-7}(\text{stat.})^{+5}_{-8}(\text{syst.})]$ MeV/$c^2$ and $[92^{+40}_{-24}(\text{stat.})^{+10}_{-21}(\text{syst.})]$ MeV, respectively [31]; (2) Belle has also observed the $Y(4660)$ in $e^+e^- \to \gamma_{\text{ISR}} \pi^+ \pi^- \rho^0$ with a measured mass and width of $[4652 \pm 10(\text{stat.}) \pm 8(\text{syst.})]$ MeV/$c^2$ and $[68 \pm 11(\text{stat.}) \pm 1(\text{syst.})]$ MeV, respectively [32, 33]. As the masses and widths of the $Y(4630)$ and $Y(4660)$ are close to each other, many theoretical explanations assume they are the same state [34–36]. In Refs. [37, 38], the authors predicted a $Y(4660)$ spin partner—a $f_0(980)p_c(2S)$ bound state denoted the $Y_9$—with a mass and width of $(4613 \pm 4)$ MeV/$c^2$ and around $30$ MeV, respectively, with the assumption that the $Y(4660)$ is an $f_0(980)\rho^0$ bound state [36, 38]. Belle has searched for these states in the substructure of $B^- \to K^- \Lambda_c^+ \Lambda_c^-$ decays, and no clear signals were observed [27]. The corresponding $B^0$ decay mode can also be used to study the $\Lambda_c^+ \Lambda_c^-$ invariant mass.

In this letter, we perform an updated measurement of $B^0 \to K^0 \Lambda_c^+ \Lambda_c^-$ and find the $\Xi_c(2930)^+\Xi_c(2930)^-$ signal, which we denote as $\Xi_c(2930)^+\Xi_c(2930)^-$ hereafter, with a significance of $3.9\sigma$. This analysis is based on the full data sample collected at the $\Upsilon(4S)$ resonance by the Belle detector [39] at the KEKB asymmetric energy electron-positron collider [40].

The Belle detector is a large solid angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return yoke located outside the coil is instrumented to detect $K_L^0$ mesons and to identify muons. A detailed description of the Belle detector can be found in Ref. [39]. Simulated signal events with $B$ meson decays are generated using EVTGEN [41], while the inclusive decays are generated via PYTHIA [42]. These events are processed by a detector simulation based on GEANT3 [43]. Inclusive Monte Carlo (MC) samples of $\Upsilon(4S) \to BB$ ($B = B^+$ or $B^0$) and $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events at $\sqrt{s} = 10.58$ GeV, corresponding to more than 5 times the integrated luminosity of the data, are used to check the backgrounds.

In our analysis of $B^0 \to K^0 \Lambda_c^+ \Lambda_c^-$, the $K^0$ is reconstructed via its decay $K^0_S \to \pi^+ \pi^-$, and $\Lambda_c^+$ candidates are reconstructed in the $\Lambda_c^+ \to pK^- \pi^+$, $pK^0_S$, and $\Lambda^0(\to p\pi^- \pi^+)$ decay channels. A $\Lambda_c^+$ and $\Lambda_c^-$, together with a $K^0_S$, are combined to reconstruct a $B$ candidate,
with at least one required to have been reconstructed via the \( pK^+\pi^- \) or \( \bar{p}K^+\pi^- \) decay process.

For well reconstructed charged tracks, except for those from \( \Lambda \to p\pi^- \) and \( K_S^0 \to \pi^+\pi^- \) decays, the impact parameters perpendicular to and along the beam direction with respect to the nominal interaction point are required to be less than 0.5 cm and 4 cm, respectively, and the transverse momentum in the laboratory frame is required to be larger than 0.1 GeV/c. The information from different detector subsystems including specific ionization in the CDC, time measurements in the TOF and response of the ACC is combined to form the likelihood \( \mathcal{L}_i \) of the track for particle species \( i \), where \( i = \pi, K \) or \( p \) [44]. Except for the charged tracks from \( \Lambda \to p\pi^- \) and \( K_S^0 \to \pi^+\pi^- \) decays, tracks with a likelihood ratio \( R_K = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6 \) are identified as kaons, while tracks with \( R_K < 0.4 \) are treated as pions. The kaon (pion) identification efficiency is about 94% (97%), while 5% (3%) of the kaons (pions) are misidentified as pions/kaons with an efficiency of about 98%; fewer than 1% of the pions/kaons are misidentified as protons/anti-protons.

The \( K_S^0 \) candidates are reconstructed from pairs of oppositely-charged tracks, treated as pions, and identified by a multivariate analysis with a neural network [45] based on two sets of input variables [46]. Candidate \( \Lambda \) baryons are reconstructed in the decay \( \Lambda \to p\pi^- \) and selected if the \( \pi^+\pi^- \) invariant mass is within 5 MeV/c\(^2\) (5\(\sigma\)) of the \( \Lambda \) nominal mass [1].

A vertex fit to the \( B \) candidates is performed and the one with the minimum \( \chi^2_{\text{vertex}}/n.d.f. \) from the vertex fit is selected as the signal \( B \) candidate if there is more than one \( B \) candidate in an event, where \( n.d.f. \) is the number of degrees of freedom of the vertex fit. The \( \chi^2_{\text{vertex}}/n.d.f. < 15 \) is required, providing a selection efficiency above 96%. As the continuum background level is very low, further continuum suppression is not necessary.

The \( B \) candidates are identified using the beam-energy constrained mass \( M_{bc} \) and the mass difference \( \Delta M_B \). The beam-energy constrained mass is defined as \( M_{bc} \equiv \sqrt{E_{\text{beam}}^2/c^2 - (\sum \vec{p}_i)^2/c} \), where \( E_{\text{beam}} \) is the beam energy and \( \vec{p}_i \) are the three-momenta of the \( B \)-meson decay products, all defined in the center-of-mass system (CMS) of the \( e^+e^- \) collision. The mass difference is defined as \( \Delta M_B \equiv M_B - m_B \), where \( M_B \) is the invariant mass of the \( B \) candidate and \( m_B \) is the nominal \( B \)-meson mass [1]. The \( B \) signal region is defined as \( \Delta M_B < 0.018 \text{ GeV/c}^2 \) and \( M_{bc} > 5.272 \text{ GeV/c}^2 (\sim 2.5\sigma) \) which is shown as the central box in the distribution of \( \Delta M_B \) versus \( M_{bc} \) in Fig. 1.

The scatter plot of \( M_{\bar{\Lambda}^-} \) versus \( M_{\Lambda^+} \) is shown in the left panel of Fig. 1 for the selected \( B^0 \to K_S^0 \Lambda^+_c \bar{\Lambda}^-_c \) data candidates in the \( B \) signal region, and clear \( \Lambda^+_c \) and \( \bar{\Lambda}^-_c \) signals are observed. According to the signal MC simulation, the mass resolution of \( \Lambda_c \) candidates is almost independent of the \( \Lambda_c \) decay mode. The \( \Lambda_c \) signal region is defined as \( |m_{\Lambda_c} - m_{\Lambda_c^0}| < 12 \text{ MeV/c}^2 (\sim 2.5\sigma) \) for all \( \Lambda_c \) decay modes illustrated by the central green box in the Fig. 1 (left panel), where \( m_{\Lambda_c} \) is the nominal mass of the \( \Lambda_c \) baryon [1]. To estimate the non-\( \Lambda_c \) backgrounds, we define the \( \Lambda^+_c \) and \( \bar{\Lambda}^-_c \) mass sidebands as half of the total number of events in the four red sideband regions minus one quarter of the total number of events in the four blue sideband regions as shown in Fig. 1 (left panel).

![FIG. 1: Signal-enhanced distributions of \( M(\Lambda^-_c) \) versus \( M(\Lambda^+_c) \) (left panel) and of \( \Delta M_{B_0} \) versus \( M_{bc} \) (right panel) from the selected \( B^0 \to K^0 \Lambda^+_c \bar{\Lambda}^-_c \) candidates, summing over all three reconstructed \( \Lambda_c \) decay modes. Each panel shows the events falling in the solid green signal region of the other panel. The dashed red and blue boxes in the left panel show the \( \Lambda_c \) sideband regions described in the text, which are used for the estimation of the non-\( \Lambda_c \) background.](image-url)

To extract the \( B^0 \to K^0 \Lambda^+_c \bar{\Lambda}^-_c \) signal yields, we perform an unбинed two-dimensional (2D) simultaneous extended maximum likelihood fit to the \( \Delta M_B \) versus \( M_{bc} \) distributions for the three reconstructed \( \Lambda_c \) decay modes. A Gaussian function for the signal shape plus an ARGUS function [47] for the background is used to fit the \( M_{bc} \) distribution, while the sum of a double-Gaussian function for the signal plus a first-order polynomial for the background are used to fit the \( \Delta M_B \) distribution. Due to limited statistics, all the parameters of the Gaussian functions are fixed to the values from the fits to the individual MC signal distributions, and the relative signal yields among the three final states are fixed according to the relative branching fraction between the final states and the detection acceptance and efficiency of the intermediate states.

The projections of \( M_{bc} \) and \( \Delta M_B \) summed over the three reconstructed \( \Lambda_c \) decay modes in \( \Lambda_c \) signal region, together with the fitted results, are shown in Fig. 2. There are 34.9 ± 6.6 signal events with a statistical signal significance above 8.3\(\sigma\), and we extract the branching fraction of \( B(B^0 \to K^0 \Lambda^+_c \bar{\Lambda}^-_c) = [3.84 \pm 0.73(\text{stat.})] \times 10^{-4} \).

After applying all selection criteria above, the Dalitz
As the statistical signal significance of each \( Y \) state is less than 3\( \sigma \), assuming that the number of signal events follows a Poisson distribution with a uniform prior probability density function, 90% C.L. Bayesian upper limits on \( B(B^0 \to K^0 Y)B(Y \to \Lambda_c^+ \Lambda_c^-) \) are determined to be \( 3.2 \times 10^{-4} \) and \( 4.9 \times 10^{-5} \) for \( Y = Y_1 \) and \( Y = Y_2 \) and \( Y(4600) \), respectively, by solving the equation

\[
\int_0^{m_{B^0}} L(B) dB / \int_0^{m_{B^0}} L(B) dB = 0.9, \quad B = \frac{\varepsilon_{\text{all}} N_{Y \to B(B_l \to pK^- \pi^+)}(Y \to \Lambda_c^+ \Lambda_c^-)}{n_Y \Gamma_{Y \to B(B_l \to pK^- \pi^+)} \varepsilon_l},
\]

where \( n_Y \) is the number of \( Y \) signal events; and \( \varepsilon_{\text{all}} = \sum_i \varepsilon_i \times \Gamma_i / \Gamma(pK^- \pi^+) \) (\( \varepsilon_i \) being the detection efficiency from MC simulation for mode \( i \) ). To take the systematic uncertainty into account, the above likelihood is convolved with a Gaussian function whose width equals the total systematic uncertainty discussed below.

The \( M_{\Lambda_c^+ \Lambda_c^-} \) spectrum is shown in Fig. 4, where the shaded cyan histogram is from the normalized \( \Lambda_c^+ \) and \( \Lambda_c^- \) mass sidebands. No signals of \( Y_1 \) or \( Y(4600) \) are evident. An unbinned extended maximum likelihood fit is applied to the \( \Lambda_c^+ \Lambda_c^- \) mass spectrum to extract the signal yields of the \( Y_1 \) and \( Y(4600) \) in \( B \) decays separately. In the fit, the signal shape of the \( Y_1 \) or \( Y(4600) \) is obtained from MC simulation directly, with the input parameters \( M_{Y_1} = 4616 \text{ MeV}/c^2 \) and \( \Gamma_{Y_1} = 30 \text{ MeV} \) for \( Y_1 \) [36], and \( M_{Y(4600)} = 4643 \text{ MeV}/c^2 \) and \( \Gamma_{Y(4600)} = 72 \text{ MeV} \) for \( Y(4600) \) [1]; a third-order polynomial is used to describe all other contributions. The fit results are shown in Figs. 4(a) and 4(b) for the \( Y_1 \) and \( Y(4600) \), respectively. From the fits, we obtain \( (18.1 \pm 8.4) Y_1 \) and \( (28.1 \pm 11.1) Y(4600) \) signal events each with a signal statistical significance of 2.3\( \sigma \).

The sum of the projections of \( M_{K^0 \Lambda_c^+} \) and \( M_{K^0 \Lambda_c^-} \) mass spectra, denoted \( M_{K^0 \Lambda_c} \), is shown in Fig. 5. The shaded histogram is from the normalized \( \Lambda_c^+ \) and \( \Lambda_c^- \) mass sidebands, which is consistent with the contributions from normalized \( e^+ e^- \to q \bar{q} \) and \( Y(4S) \to B \bar{B} \) generic MC samples. Therefore, the estimate from the normalized \( \Lambda_c^+ \) and \( \Lambda_c^- \) mass sidebands is taken to represent the total background, neglecting the small possible contribution of background with real \( \Lambda_c^+ \) and \( \Lambda_c^- \) mass sidebands.

An unbinned simultaneous extended maximum likelihood fit is performed to the \( K^0 \Lambda_c \), invariant mass spectra for the total selected signal candidates and the \( \Lambda_c^+ \) and \( \Lambda_c^- \) mass sidebands. The following components are included in the fit: an S-wave Breit-Wigner (BW) function convolved with a Gaussian function with the phase space factor and efficiency curve included (the mass resolution of the Gaussian function being fixed to 5.36 MeV/c^2 from the signal MC simulation) is taken as the \( \Xi_c(2930)^\pm \) signal shape; a broader structure obtained by MC simulation is used to represent the reflection of the \( \Xi_c(2930)^\pm \); direct three-body \( B^0 \to K^0 \Lambda_c^+ \Lambda_c^- \) decays are modeled by
the MC-simulated shape distributed uniformly in phase space; a second-order polynomial is used to represent the \( \Lambda^+ \) and \( \bar{\Lambda}^- \) mass-sideband distribution, which is normalized to represent the total background in the signal events in the fit. In the above fit, the signal yields of the \( \Xi_c(2930)\pm \) and the corresponding reflection are constrained to be the same.

The fit results are shown in Fig. 5, where the solid blue line is the best fit, and the solid violet line is the total non-\( \Xi_c(2930)\pm \) backgrounds including the fitted phase space, the reflection of the \( \Xi_c(2930)\pm \), and the fitted sideband shape. The yields of the \( \Xi_c(2930)\pm \) signal and the phase-space contribution are \( N_{\Xi_c(2930)} = 21.2 \pm 4.6 \) and \( N_{\text{phsp}} = 18.3 \pm 4.6 \). The fitted mass and width are \( M_{\Xi_c(2930)} = [2942.3 \pm 4.4 \text{(stat.)}] \text{MeV}/c^2 \) and \( \Gamma_{\Xi_c(2930)} = [14.8 \pm 8.8 \text{(stat.)}] \text{MeV} \), respectively, where the correction of 2.8 MeV/c^2 has been applied on \( \Xi_c(2930)\pm \) mass, determined using the input and output mass difference by MC simulation. The statistical significance of the \( \Xi_c(2930)\pm \) signal is 4.1\( \sigma \), calculated from the difference of the logarithmic likelihoods [48], \(-2\ln(L_0/L_{\text{max}}) = 23.1\), where \( L_0 \) and \( L_{\text{max}} \) are the maximized likelihoods without and with a signal component, respectively, taking into account the difference in the number of degrees of freedom (\( \Delta \text{n.d.f.} = 3 \)).

The signal significance remains at 3.9\( \sigma \) when convolving the likelihood profile with a Gaussian function of width \( \Gamma \), which equals the total systematic uncertainty from detection efficiency, fitting procedure, and intermediate states’ branching fractions. Alternative fits to the \( K_0^0 \Lambda_c \) mass spectra are performed (a) using a first-order or third-order polynomial as the background shape; (b) changing the \( \Xi_c(2930)\pm \) mass resolution by \( \pm 10\% \); and (c) using an energy-dependent BW function as the \( \Xi_c(2930)\pm \) signal shape. The signal \( \Xi_c(2930)\pm \) mass significance is larger than 3.5\( \sigma \) in all cases.

The product of \( B(B^0 \rightarrow \Xi_c(2930)^+ \Lambda^-) \) and \( B(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \) is \( ([2.28 \pm 0.49 \text{(stat.)}] \times 10^{-4} \) calculated as \( N_{\Xi_c(2930)} \times [(\varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Lambda^+ \rightarrow p K^- \pi^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \times \varepsilon_{\Xi_c(2930)} \times N_{B^0 B^0} \mathcal{B}(\Xi_c(2930)^+ \rightarrow K^0 \bar{\Lambda}^+) \).
there are many theoretical possibilities. We expect this study to be repeated with a much larger data sample to be collected by the Belle II experiment. There are no significant signals seen in the \( \Lambda_c^+ \bar{\Lambda}_c^- \) mass spectrum. We place 90\% C.L. upper limits for the \( Y(4660) \) and its theoretically predicted spin partner \( Y_0 \) of \( B(\bar{B}^0 \rightarrow K^0 Y(4660))B(Y(4660) \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-) < 3.2 \times 10^{-4} \) and \( B(\bar{B}^0 \rightarrow K^0 Y_0)B(Y_0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-) < 4.9 \times 10^{-4} \) [49].

We thank the KEKB group for the excellent operation of the accelerator; the KEK cryogenics group for the efficient operation of the solenoid; and the KEK computer group, the National Institute of Informatics, and the Pacific Northwest National Laboratory (PNNL) Environmental Molecular Sciences Laboratory (EMSL) computing group for valuable computing and Science Information NETwork 5 (SINET5) network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council; Austrian Science Fund under Grant No. P 26794-N20; the National Natural Science Foundation of China under Contracts No. 11435013, No. 11475187, No. 11521505, No. 11575017, No. 11675166, No. 11705209; No. 11761141009; Key Research Program of Frontier Sciences, Chinese Academy of Sciences (CAS), Grant No. QYZDJ-SSW-SLH011; the CAS Center for Excellence in Particle Physics (CCEPP); Fudan University Grant No. JIH5913023, No. IDH5913011/003, No. JIH5913024, No. IDH5913011/002; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. LTT17020; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft, the Excellence Cluster Universe, and the VolkswagenStiftung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; National Research Foundation (NRF) of Korea Grants No. 2014R1A2A2A01005286, No.2015R1A2A2A01003280, No.2015H1A2A1033649, No.2016R1D1A1B01010135, No.2016K1A1A7A09005603, No.2016R1D1A1B02012900; Radiation Science Research Institute, Foreign Large-size Research Facility Application Supporting project and the Global Science Experimental Data Hub Center of the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Foundation for Basic Research; the Slovenian Research Agency; Ikerbasque, Basque Foundation for Science, Basque Government (No. IT956-16) and Ministry of Economy and Competitiveness (MINECO) (Juan de la Cierva), Spain; the Swiss National Science Foundation; the Ministry of Education and the Ministry of Science and Technology of Taiwan; and the United States Department of Energy.

### Table I: Relative systematic uncertainties (%) in the branching fraction measurements

| Branching fraction | DER | Fit | \( \Delta \Lambda \) decays | \( N_{B^0 \bar{B}^0} \) | Sum |
|-------------------|-----|-----|-------------------------|----------------|-----|
| \( B_1 \)         | 5.28 | 4.20 | 10.5                    | 1.82           | 12.6 |
| \( B_2 \)         | 5.31 | 5.10 | 10.5                    | 1.82           | 12.9 |
| \( B_3 \)         | 5.28 | 10.1 | 10.5                    | 1.82           | 15.6 |
| \( B_4 \)         | 5.27 | 25.3 | 10.5                    | 1.82           | 27.9 |

By changing the background shape, the differences of 0.5 MeV/c^2 and 1.3 MeV in the measured \( \Xi_c(2930)^\pm \) mass and width, respectively, are taken as systematic uncertainties. Assuming all the sources are independent, we add them in quadrature to obtain the total systematic uncertainties on the \( \Xi_c(2930)^\pm \) mass and width of 1.6 MeV/c^2 and 7.1 MeV, respectively.

In summary, using \( (772 \pm 11) \times 10^6 B \bar{B} \) pairs, we perform an updated analysis of \( B^0 \rightarrow K^0 \Lambda_c^+ \bar{\Lambda}_c^- \) decays. There is evidence at the 3.9\% level of the charged baryon state \( \Xi_c(2930)^\pm \) in the \( \Xi_c(2930)^\pm \) mass spectrum. The measured mass and width are \( \Delta m_{\Xi_c(2930)^\pm} = [2942.3 \pm 4.4(\text{stat.}) \pm 1.6(\text{syst.})] \) MeV/c^2 and \( \Gamma_{\Xi_c(2930)^\pm} = [14.8 \pm 8.8(\text{stat.}) \pm 7.1(\text{syst.})] \) MeV. The mass and width difference between neutral [27] and charged \( \Xi_c(2930)^\pm \) are \( \Delta m = [-13.4 \pm 5.3(\text{stat.})^{+1.8}_{-1.2}(\text{syst.})] \) MeV/c^2 and \( \Delta \Gamma = [4.7 \pm 12.2(\text{stat.})^{+5.2}_{-10.0}(\text{syst.})] \) MeV, respectively. The branching fraction is \( B(B^0 \rightarrow K^0 \Lambda_c^+ \bar{\Lambda}_c^-) = [3.84 \pm 0.73(\text{stat.}) \pm 0.48(\text{syst.})] \times 10^{-4} \), which is consistent with the world average value of \( (4.3 \pm 2.2) \times 10^{-4} \) but with improved precision. We measure the product branching fraction \( B(\bar{B}^0 \rightarrow \Xi_c(2930)^+ \bar{\Lambda}_c^-)B(\Xi_c(2930)^+ \rightarrow K^0 \Lambda_c^+) = [2.28 \pm 0.28(\text{stat.}) \pm 0.29(\text{syst.})] \times 10^{-4} \). We do not perform an angular correlation analysis to determine the spin parity of the \( \Xi_c(2930)^\pm \) due to the limited statistics. We are not able to identify the nature of \( \Xi_c(2930)^\pm \) with the spin parity not determined since...
and the National Science Foundation.

[1] C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016) and 2017 update.
[2] A. Majethiya, B. Patel, and P.C. Vinodkumar, Eur. Phys. J. A 38, 307 (2008).
[3] S. Migura, D. Merten, B. Metsch, and H. R. Petry, Eur. Phys. J. A 28, 41 (2006).
[4] H. Garcilazo, J. Vijande, and A. Valcarce, J. Phys. G 34, 961 (2007).
[5] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Lett. B 659, 612 (2008).
[6] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D 84, 014025 (2011).
[7] B. Chen, K. W. Wei, and A. Zhang, Eur. Phys. J. A 51, 82 (2015).
[8] B. Chen, D. X. Wang, and A. Zhang, Chin. Phys. C 33, 1327 (2009).
[9] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo, and R. G. E. Timmermans, Phys. Rev. D 85, 114032 (2012).
[10] Z. G. Wang, Eur. Phys. J. A 45, 267 (2010).
[11] Z. G. Wang, Eur. Phys. J. C 75, 359 (2015).
[12] D. D. Ye, Z. Zhao, and A. Zhang, Phys. Rev. D 96, 114009 (2017).
[13] T. M. Aliev, K. Azizi and H. Sundu, arXiv:1803.04002.
[14] H. X. Chen, W. Chen, Q. Mao, A. Hosaka, X. Liu, and S.L. Zhu, Phys. Rev. D 91, 054034 (2015).
[15] X. H. Guo, K. W. Wei, and X. H. Wu, Phys. Rev. D 78, 506005 (2008).
[16] K. L. Wang, Y. X. Yao, X. H. Zhong, and Q. Zhao, Phys. Rev. D 96, 116016 (2017).
[17] B. Chen, K. W. Wei, X. Liu, and T. Matsuki, Eur. Phys. J. C 77, 154 (2017).
[18] M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, arXiv:1311.4806.
[19] M. Padmanath and N. Mathur, arXiv:1508.07168.
[20] B. Chen, X. Liu, and A. Zhang, Phys. Rev. D 95, 074022 (2017).
[21] H. Y. Cheng and C. K. Chua, Phys. Rev. D 75, 014006 (2007).
[22] H. Y. Cheng and C. K. Chua, Phys. Rev. D 92, 074014 (2015).
[23] C. Chen, X. L. Chen, X. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D 75, 094017 (2007).
[24] L. H. Liu, L. Y. Xiao, and X. H. Zhong, Phys. Rev. D 86, 034024 (2012).
[25] Z. Zhao, D. D. Ye, and A. Zhang, Phys. Rev. D 94, 114020 (2016).
[26] H. X. Chen, Q. Mao, W. Chen, A. Hosaka, X. Liu, and S. L. Zhu, Phys. Rev. D 95, 094008 (2017).
[27] Y. B. Li et al. (Belle Collaboration), Eur. Phys. J. C 78, 252 (2018).
[28] Inclusion of charge conjugate states is implicit unless otherwise stated.
[29] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 77, 031101 (2008).
[30] N. Gabyshchev et al. (Belle Collaboration), Phys. Rev. Lett. 97, 202003 (2006).
[31] G. Pakhlova et al. (Belle Collaboration), Phys. Rev. Lett. 101, 172001 (2008).
[32] X. L. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 99, 142002 (2007).
[33] X. L. Wang et al. (Belle Collaboration), Phys. Rev. D 91, 112007 (2015).
[34] D. V. Bugg, J. Phys. G 36, 075002 (2009).
[35] G. Cotugno, R. Faccini, A. D. Polosa, and C. Sabelli, Phys. Rev. Lett. 104, 132005 (2010).
[36] F. K. Guo, J. Haidenbauer, C. Hanhart, and U. G. Meißner, Phys. Rev. D 82, 094008 (2010).
[37] F. K. Guo, C. Hanhart, and U. G. Meißner, Phys. Lett. B 665, 26 (2008).
[38] F. K. Guo, C. Hanhart, and U. G. Meißner, Phys. Rev. Lett. 102, 242004 (2009).
[39] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002); also, see detector section in J. Brodzicka et al., Prog. Theor. Exp. Phys. (2012) 04D001.
[40] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume; T. Abe et al., Prog. Theor. Exp. Phys. (2013) 03A001 and following articles up to 03A011.
[41] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).
[42] T. Sjöstrand et al., Comput. Phys. Commun. 135, 238 (2001).
[43] R. Brun et al., GEANT, CERN Report No. DD/EE/84-1 (1984).
[44] E. Nakano, Nucl. Instrum. Methods Phys. Res., Sect. A 494, 402 (2002).
[45] M. Feindt and U. Kerzel, Nucl. Instrum. Methods Phys. Res., Sect. A 559, 190 (2006).
[46] H. Nakano, PhD Thesis, Tohoku University (2014) Chapter 4, unpublished, https://tohoku.repo.nii.ac.jp/?action=pages_view_main&active_action=repository_view_main_item_detail&item_id=70563&item_no=1&page_id=33&block_id=38.
[47] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 229, 304 (1989).
[48] S. S. Wilks, Ann. Math. Stat. 9, 60 (1938).
[49] Considering the possible change of $B({\Lambda}_c^+ \to pK^-\pi^+)$ in the future, we provide $B(B^0 \to K^0{\Lambda}_c^+\bar{\Lambda}_c^-)B({\Lambda}_c^+ \to pK^-\pi^+)^2 = (1.55 \pm 0.29 \pm 0.11) \times 10^{-6}$ and $B(B^0 \to \Xi_c(2930)\bar{\Lambda}_c^-)B(\Xi_c(2930)^+ \to K^0{\Lambda}_c^+)B({\Lambda}_c^+ \to pK^-\pi^+)^2 = (9.18 \pm 0.72) \times 10^{-7}$, where the first errors are statistical and the second systematic with the uncertainty on $B({\Lambda}_c^+ \to pK^-\pi^+)$ omitted. The 90% C.L. upper limits on $B(B^0 \to K^0Y(4660))B(Y(4660) \to {\Lambda}_c^+\bar{\Lambda}_c^-)B({\Lambda}_c^+ \to pK^-\pi^+)^2$ and $B(B^0 \to K^0Y_0)B(Y_0 \to {\Lambda}_c^+\bar{\Lambda}_c^-)B({\Lambda}_c^+ \to pK^-\pi^+)^2$ are $2.0 \times 10^{-6}$ and $1.3 \times 10^{-6}$, respectively.