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In recent years, there has been significant progress in the study of the charmed baryon spectrum, mainly from the Belle and BaBar experiments. In the charmed strange baryon sector, a number of excited states ($\Xi^*_c$) have been observed. Belle reported evidence for two excited states ($\Xi^*_c(3055)^+, \Xi^*_c(3080)^+$) into $\Lambda D^0$. We also perform a combined analysis of the $\Lambda D^0$ and $\Sigma^*_{c} K^-$ decay modes to measure the ratios of branching fractions, masses with improved accuracy. We measure the ratios of branching fractions $B(\Xi^*_c(3055)^+ \rightarrow \Lambda D^0)/B(\Xi^*_c(3055)^+ \rightarrow \Sigma^*_{c} K^-) = 5.99 \pm 1.01 \pm 0.76$, $B(\Xi^*_c(3080)^+ \rightarrow \Lambda D^0)/B(\Xi^*_c(3080)^+ \rightarrow \Sigma^*_{c} K^-) = 1.29 \pm 0.30 \pm 0.15$, and $B(\Xi^*_c(3080)^+ \rightarrow \Sigma^*_{c} K^-) = 1.07 \pm 0.27 \pm 0.01$, where the uncertainties are statistical and systematic. The analysis is performed using a 980 fb$^{-1}$ data sample collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider.

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I. INTRODUCTION

In recent years, there has been significant progress in the study of the charmed baryon spectrum, mainly from
cited states, $\Xi_c(2980)$ and $\Xi_c(3080)$, in the $\Lambda^+_c K^- \pi^+$ and $\Lambda^+_c K^0 \pi^+$ final states [2]. These states have been confirmed by BaBar [6]. In the same paper, BaBar also claimed evidence for two resonances, the $\Xi_c(3055)^+$ and the $\Xi_c(3123)^+$, observed in the $\Sigma^{++}K^-$ and $\Sigma^{*+}K^-$ final states. Recently, Belle confirmed the existence of the $\Xi_c(3055)^+$, but no evidence was found for the $\Xi_c(3123)^+$ [4]. As discussed in Refs. [10, 11], the decay pattern of charmed baryons provides an important contribution to our understanding of the nature of the states. To date, all measurements of $\Xi^+_c$ baryons were performed using decays in which the charm quark is contained in the final-state baryon. Measurements of final states in which the charm quark is part of the final state meson provide complementary information.

In this paper, we report studies of $\Xi^+_c$ baryons decaying to the $\Lambda D^+$ and $\Lambda D^0$ final states using a data sample with an integrated luminosity of 980 fb$^{-1}$ collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We find significant signals for $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ decays into $\Lambda D^+$. In the $\Lambda D^0$ final state, we report observation of the $\Xi_c(3055)^0$. These measurements constitute the first observation and evidence for $\Lambda^+_c$ baryons decay-constitute the first observation and evidence for $\Lambda^+_c$ baryons decay-

The remaining sections of the paper are organized as follows. In Sections II and III, we describe the data sample and event selections. In Section IV, observations and measurements of $\Xi^+_c$ baryons in the $\Lambda D^+$ and $\Lambda D^0$ final states are presented. In Section V, the combined analysis with the $\Sigma^+_c K^-$ and $\Sigma^{*+}K^-$ final states to measure the ratios of branching fractions and to improve the accuracy of the mass and width measurements.

The selection of charged hadrons is based on information from the tracking system (SVD and CDC) and hadron identification system (CDC, ACC, and TOF). The charged hadrons that are not associated with the $\Lambda$ candidate are required to have a point of closest approach to the interaction point that is within 2 cm along the z axis and within 0.2 cm in the transverse ($r$-$\phi$) plane. The $z$ axis is opposite the positron beam direction. For each track, likelihood values $L_p$, $L_K$, and $L_\pi$ are provided by the hadron identification system, based on the ionization losses in the CDC, the number of detected Cherenkov photons in the ACC, and the time-of-flight measured by the TOF. The likelihood ratio is defined as $L(i:j) = L_i/(L_i + L_j)$. A track is identified as a proton if the likelihood ratios $L(p: \pi)$ and $L(p: K)$ are greater than 0.6, or as a kaon if the likelihood ratios $L(K: \pi)$ and $L(K: p)$ are greater than 0.6, or as a pion if the likelihood ratios $L(\pi: K)$ and $L(\pi: p)$ are greater than 0.6. In addition, an electron likelihood is provided based on information from the ECL, ACC, and CDC [13]. A track with an electron likelihood greater than 0.95 is rejected.

The momentum-averaged efficiencies of hadron identification are about 90%, 90%, and 93% for pions, kaons, and protons, respectively. The momentum-averaged probability to misidentify a pion as a kaon is about 9%, to misidentify a kaon as a pion about 10%, and to misidentify a pion or kaon as a proton about 5%. The $\pi^0$ candidates are reconstructed from pairs of photons whose invariant mass ($M_{\gamma\gamma}$) satisfies $120$ MeV/$c^2 < M_{\gamma\gamma} < 150$ MeV/$c^2$, which corresponds to $\pm 2.5 \sigma$ (where $\sigma$ is the
one-standard-deviation of the resolution). The energy of each photon in the laboratory frame is required to be greater than 50 MeV and the energy of the π0 candidate in the laboratory frame is required to be greater than 500 MeV. The D+ candidates are selected by requiring \(|M(K^-\pi^+\pi^+) - m_{D+}| < 12 \text{ MeV}/c^2\), where \(m_{D+}\) is the D+ mass [19]. The D0 candidates for each decay mode of the D0 are selected by requiring \(|M(K^-\pi^+) - m_{D0}| < 14 \text{ MeV}/c^2\), \(|M(K^-\pi^+\pi^-) - m_{D0}| < 11 \text{ MeV}/c^2\), and \(|M(K^-\pi^+\pi^-) - m_{D0}| < 27 \text{ MeV}/c^2\), where \(m_{D0}\) is the D0 mass. These mass ranges correspond to \(\pm 2\sigma\). To improve the momentum resolution, the daughter particles are fitted to a common vertex together with an invariant mass constrained to the D+ or D0 mass. The Λ candidates are selected using cuts on four parameters: the angular difference between the Λ flight direction and the direction pointing from IP to the decay vertex in the transverse plane; the distance between each track and the IP in the transverse plane; the distance between the decay vertex and the IP in the transverse plane; and the displacement along z of the closest-approach points of the two tracks to the beam axis. Also, the invariant mass of a Λ candidate is required to be within 3 MeV/c^2 of the Λ mass, which corresponds to \(\pm 3\sigma\). Excited charmed baryons are known to be produced with much higher average momenta than the combinatorial background. We thus require \(x_p\) to be greater than 0.7 for the ΛD+ and 0.8 for the ΛD0 modes.

IV. OBSERVATION OF Ξc \(\to\) ΛD DECAYS

Figure 1 shows the ΛD invariant-mass (M(ΛD)) distributions for data after the application of all the selection criteria; signals near 3055 and 3080 MeV/c^2 are seen. We do not observe any such peaks in the distributions in wrong-sign ΛD combinations, in data from the D meson mass sideband, nor in MC events that do not include these resonances. Hereinafter, Ξc baryons corresponding to these peaks are referred to as Ξc(3055) and Ξc(3080). In order to evaluate the masses, widths, and statistical significances of the Ξc states, we apply an unbinned extended maximum likelihood (UML) fit to the mass spectra in the invariant mass range of 3.0–3.2 GeV/c^2. For the ΛD0 mode, the fit is performed simultaneously for the three different D0 decay modes, with their relative yields fixed using the product of their known branching fractions [19] and detection efficiencies. The masses and widths of the Ξc states are constrained to be the same for all modes. The detection efficiencies for the Ξc(3055) and Ξc(3080) are found to exhibit no difference within the statistical precision of the MC sample, which is smaller than 1%. Therefore, we use common efficiency values for these states. The relative yields are fixed to \(K^-\pi^+:K^-\pi^+\pi^-\pi^-:K^-\pi^+\pi^0 = 1.00:1.30:1.15\). The probability density functions (PDF) for the Ξc components are represented by convolutions of Breit-Wigner shapes with Gaussian distributions to take the intrinsic invariant mass resolution, \(\sigma_{\text{res}}\), into account. Using the signal MC events, we determine \(\sigma_{\text{res}}\) for the ΛD+ mode to be 1.1 MeV/c^2 for the Ξc(3055)+ and 1.3 MeV/c^2 for the Ξc(3080)+. In the ΛD0 mode, we determine \(\sigma_{\text{res}}\) to be 1.1 and 2.0 MeV/c^2 for the D0 decay mode without and with π0, respectively for the Ξc(3055) and 1.3 and 2.2 MeV/c^2 for the Ξc(3080). The masses, widths and yields of the Ξc states are treated as free parameters. A third-order Chebyshev polynomial is used to model the PDF for the combinatorial background. The statistical significance is evaluated from \(-2\ln(L_0/\mathcal{L})\), where \(L_0\) is the likelihood for the fit without (with) the signal component. When we evaluate \(L_0\) for one of the Ξc states, the other Ξc state is included in the fit. The \(-2\ln(L_0/\mathcal{L})\) values are 144.6 for the Ξc(3055)+, 30.0 for the Ξc(3080)+, 83.1 for the Ξc(3055)0, and 6.6 for the Ξc(3080)0. By taking into account the change by 3 of the number of degrees of freedom in the UML fit associated with the inclusion of the Ξc states, the statistical significances are 11.7σ, 4.8σ, 8.6σ, and 1.7σ for the Ξc(3055)+, Ξc(3080)+, Ξc(3055)0, and Ξc(3080)0, respectively. The peak for the Ξc(3080)0 is not statistically significant.

We estimate the systematic uncertainty of the masses and widths of Ξc(3055)0, Ξc(3055)+ and Ξc(3080)+ in the ΛD+ decay mode as the changes produced by giving reasonable variations to the fitting technique. The stability of the background shape is checked by changing the fit region and background PDF. The maximum deviation from the nominal fit is taken as the systematic uncertainty. To check the uncertainty due to \(\sigma_{\text{res}}\), the ratio \(r_\sigma = \sigma_{\text{MC}}^D/\sigma_{\text{data}}^D\) is evaluated, where \(\sigma_{\text{MC}}^D\) and \(\sigma_{\text{data}}^D\) are the D0 mass resolution for MC and data. For the ΛD0 mode, \(r_\sigma = 1.16, 1.16\) and 1.08 for the D0 final state of K−π+, K−π+π−π− and K−π+π0, respectively. We evaluate the uncertainty by fitting data with \(\sigma_{\text{res}}\) scaled by 16% for all the decay modes. To check the uncertainty on the mass due to a possible mis-calibration of the momentum and energy measurements, we check the reconstructed D0 masses for both data and signal MC. In each mode, the peak position is observed to have a distinct but small deviation from the world average. However, these deviations are well reproduced by the MC and, because of the mass-constrained fit, have little effect on the determination of the masses of the Ξc baryons. In the signal MC, the differences between the input and output masses of the Ξc baryons is less than 0.1 MeV/c^2 for all D0 decay modes. We assign a systematic uncertainty of 0.1 MeV/c^2 on the mass measurements. We perform fits that include the interference of the Ξc(3055) and Ξc(3080) by introducing the phase between two Breit-Wigner amplitudes. The systematic uncertainties are summarized in Table I. The fit result for the Ξc(3080)+ width is (1.4 ± 1.8) MeV, which is consistent with zero. Therefore, we set a 90% confidence level upper limit on the width. We redo the fit by changing the width; the width for which the likelihood ratio \(-2\ln(\mathcal{L}/\mathcal{L}_{0\Gamma})\) is 2.7, where \(\mathcal{L}_{0\Gamma}\) is the likelihood with
We also measure the ratio of branching fractions, branching fraction values are taken from Ref. [19]. Other
\[ R_{\Sigma^c K} = R_{\text{yield}(\Sigma^c K)} \times \frac{(B \times \epsilon)_{\Sigma^c K}}{(B \times \epsilon)_{\Sigma^c K}} \]  
where \( R_{\text{yield}(\Sigma^c K)} \) is the ratio of yields of \( \Xi_c(3080)^+ \) in the \( \Sigma_c^{*+} K^- \) decay mode and \( \Sigma_c^{*+} K^- \) decay modes. \( (B \times \epsilon)_{\Sigma^c K} \) shares the form of Eq. (3) for \( (B \times \epsilon)_{\Sigma^c K} \) after replacing the reconstruction efficiency for \( \Sigma_c^{*+} K^- \) with that for \( \Sigma_c^{*+} K^- \). The data set used for the \( \Sigma_c^{*+} K^- \) and \( \Sigma_c^{*+} K^- \) decay modes is the same as that for the \( \Delta^+ \) mode. Event selections are the same as those in Ref. [9]. A \( \Sigma_c^{*+} \) or \( \Sigma_c^{*+} \) candidate is reconstructed via its decay into \( \Delta^+ \pi^+ \); the \( \Lambda^c_+ \) candidate here is reconstructed via its decay into \( p K^- \pi^+ \) and \( p K^0 \). Note that the requirement \( x_p > 0.7 \) is the same as that for the \( \Delta^+ \) mode and so it is possible to directly compare the three decay modes. To obtain \( R_{\text{yield}} \) and to measure the width of the \( \Xi_c(3055)^+ \) and \( \Xi_c(3080)^+ \) with greater accuracy than is possible using a single decay mode, we perform a simultaneous UML fit with the widths of the \( \Xi_c^* \) states constrained to be the same among the three decay modes, as discussed in the previous section. The masses are not constrained because we find inconsistency for the mass of the \( \Xi_c(3080)^+ \) among the three decay modes. We also fit the mass distribution of the \( \Sigma_c^{*+} \) sideband region, defined as \( |M(\Lambda^c_+ \pi^+) - (m_{\Lambda^c_+} + 15 \text{ MeV}/c^2)| < 5 \text{ MeV}/c^2 \), where \( m_{\Lambda^c_+}^+ \) is the \( \Sigma_c^{*+} \) mass, to subtract the contribution from non-resonant \( \Lambda^c_+ K^- \pi^+ \) decays in the signal region. We subtract half of the yield found in the sideband regions because the mass range of the sideband region is double the width of the \( \Sigma_c^{*+} \) signal region. It is difficult to define the \( \Sigma_c^{*+} \) sideband regions because the maximum mass that is possible for combinations to contribute to the \( \Xi_c(3080)^+ \) is only slightly higher than the \( \Sigma_c^{*+} \) mass, and a low mass sideband would overlap with the \( \Sigma_c^{*+} \) region. Thus, we estimate the contribution under the \( \Sigma_c^{*+} \) by scaling the yield in the \( \Sigma_c^{*+} \) sideband regions by 2.9, a factor estimated using signal MC. We assume no interference between \( \Sigma_c^{*+} K^- \) or \( \Sigma_c^{*+} K^- \) with non-resonant \( \Lambda^c_+ K^- \pi^+ \). The PDFs and fit region for the \( \Delta^+ \) are the same as those described in Section IV. The fit conditions for the \( \Sigma_c^{*+} K^- \) and \( \Sigma_c^{*+} K^- \) modes are the same as in Ref. [9]. For the fit to the events from the \( \Sigma_c^{*+} \) sideband region, we use the 3.0–3.2 GeV/c\(^2\) \( \Sigma_c^{*+} K^- \) mass range. The \( \Xi_c \) contributions are represented by a Gaussian-convolved Breit-Wigner with the same mass resolution of the \( \Xi_c \) states as that used for the \( \Sigma_c^{*+} \) signal region. The combinatorial background is represented by a second-order Chebyshev polynomial. Figure 2 shows the results of the simultaneous fit.

The following systematic uncertainties are taken into account for the combined analysis for the measurements of the ratios of branching fractions and width. The systematic uncertainty due to the pion- and kaon-identification efficiency is estimated from the ratio of the yields of the \( D^{*+} \to D^0 \pi^+ \), \( D^0 \to K^- \pi^+ \) with and without the pion- and kaon-identification requirements for data and MC. The difference of the ratio between data and MC is used to correct the efficiency and the statis-
FIG. 1: $M(\Lambda D)$ distributions. Points with statistical error bars are data. Blue solid lines show the fit results. The red dashed, magenta dotted, and black dashed-dotted lines show the $\Xi_c(3055)$ signal, the $\Xi_c(3080)$ signal, and the background components, respectively. (a) $M(\Lambda D^+)$ distribution; $M(\Lambda D^0)$ distributions for the (b) $K^-\pi^+$, (c) $K^-\pi^+\pi^0\pi^-$, and (d) $K^-\pi^+\pi^0 D^0$ decay modes.

| Source                  | $M_{\Xi_c(3055)^0}$ | $M_{\Xi_c(3080)^+}$ | $\Gamma_{\Xi_c(3055)^0}$ | $\Gamma_{\Xi_c(3080)^+}$ | $M_{\Xi_c(3055)^+}$ | $\Gamma_{\Xi_c(3055)^+}$ | $M_{\Xi_c(3080)^+}$ | $\Gamma_{\Xi_c(3080)^+}$ |
|-------------------------|----------------------|----------------------|--------------------------|--------------------------|----------------------|--------------------------|----------------------|--------------------------|
| Background shape        | 0.6                  | 0.0                  | 1.0                      | 0.1                      | 1.5                  | 0.1                      | 0.0                  | 0.0                      |
| Resolution              | 0.0                  | 0.0                  | 0.2                      | 0.0                      | 0.2                  | 0.0                      | 0.0                  | 0.0                      |
| Mass scale              | 0.1                  | 0.0                  | 0.1                      | 0.0                      | 0.0                  | 0.1                      | 0.1                  | 0.1                      |
| Interference            | 0.1                  | 0.3                  | 0.1                      | 0.1                      | 0.1                  | 0.1                      | 0.1                  | 0.1                      |
| Total                   | 0.6                  | 1.1                  | 0.2                      | 1.5                      | 0.1                  | 0.1                      | 0.1                  | 0.1                      |

The systematic uncertainty of this correction is treated as the systematic uncertainty. We conservatively assume no correlation in the systematic uncertainty for pion and kaon identification between $\Lambda D^+$ and $\Sigma_c^{++}K^-$ decay modes as the momentum ranges for these decay modes are distinct; the systematic uncertainty for $\Sigma_c^{++}K^-$ and $\Sigma_c^{+++}K^-$ cancel. The systematic uncertainty due to the efficiency of proton identification is determined using the ratio of the yields of the $\Lambda \to p\pi^-$ with and without the proton identification requirement. The difference of the ratio between data and MC is used to correct the efficiency and the statistical uncertainty of this correction is regarded as the systematic uncertainty. The systematic uncertainty due to the reconstruction efficiency of the $\Lambda$ is determined using the yield ratio of $B \to \Lambda K^+$ with and without the $\Lambda$ selection cut as a function of momenta of $\Lambda$. By taking the weighted average of the momentum, it is estimated to be 3%. The uncertainties of the branching fractions [19, 20] are included as systematic uncertainties. The stability of the background shape is checked by changing the fit region and background PDF. The maximum deviation from the nominal fit among the various changes is regarded as the systematic uncertainty. To assess the uncertainty due to $\sigma_{\text{res}}, r_{\sigma}$ is evaluated as $\sigma_{\text{data}}^{MC}/\sigma_{\text{data}} = 1.15$ for the $\Lambda D^+$ mode and $\sigma_{\Lambda_c^+}^{MC}/\sigma_{\Lambda_c^+}^{\text{data}} = 1.08$ for the $\Sigma_c^{++}K^-$; we
TABLE II: Summary of the masses, widths and significances of the Ξ^+_c baryons measured in the ΛD modes. The first error is statistical and the second is systematic. We set a 90% confidence level upper limit for the width of Ξ_c(3080)^+.

| Resonance     | Mass (MeV/c^2) | Width (MeV) | Significance (σ) |
|---------------|----------------|-------------|------------------|
| Ξ_c(3055)^+   | 3059.0 ± 0.5 ± 0.6 | 6.4 ± 2.1 ± 1.1 | 8.6              |
| Ξ_c(3055)^+   | 3055.8 ± 0.4 ± 0.2 | 7.0 ± 1.2 ± 1.5 | 11.7             |
| Ξ_c(3080)^+   | 3079.6 ± 0.4 ± 0.1 | < 6.3         | 4.8              |

FIG. 2: The simultaneous fit results. Points with error bars are data. The blue solid lines show the fit result. The red dashed, magenta dotted, green dotted, and black dash-dotted lines show the contributions from the Ξ_c(3055)^+, Ξ_c(3080)^+, Ξ_c(2980)^+, and background, respectively. (a) M(ΛD^+), (b) M(Σ_c^+ K^-), (c) M(Λ_c^+ K^- π^+) for the Σ_c^+ sideband region, and (d) M(Σ_c^*+ K^-).

We perform a fit with σ_res scaled by a factor of r_σ and use the difference of the result from the nominal fit as the systematic uncertainty. To check the uncertainty due to a possible mis-calibration of momentum and energy measurements, we evaluate the difference between the reconstructed and nominal D^+ and Λ_c^+ masses for both data and MC. In data, the reconstructed D^+ mass differs from the world average [19] by 0.1 MeV/c^2 whereas, in the MC, the D^+ mass differs by 0.2 MeV/c^2. No deviation is observed for Λ_c^+ for both data and MC. In the signal MC, the difference of the input and output Ξ_c^* masses in the ΛD^+ mode is 0.1 MeV/c^2, which is smaller than the deviation observed in the D^+ mass because of the mass-constrained fit. We conservatively assign the systematic uncertainty of 0.1 MeV/c^2 on the mass measurement. Table III summarizes the systematic uncertainties. Table IV summarizes the measurement of yields and widths of the Ξ_c(3055)^+ and Ξ_c(3080)^+ and Table V summarizes the values related to the ratio of branching fractions measurements.
TABLE III: Summary of the systematic uncertainties for the width (MeV) and ratio of branching fraction ratios (%) measurements from the combined analysis.

| Source                | \( \Gamma_{\Xi_c(3055)}^+ \) | \( R_{B(\Lambda D)} \) for \( \Xi_c(3055)^+ \) | \( \Gamma_{\Xi_c(3080)}^+ \) | \( R_{B(\Lambda D)} \) for \( \Xi_c(3080)^+ \) | \( R_{B(\Sigma^-K)} \) |
|-----------------------|-------------------------------|---------------------------------|-------------------------------|---------------------------------|----------------------|
| \( \pi Kp \) identification | -                             | 1.4                             | -                             | 1.4                             | -                    |
| A identification      | -                             | 3.0                             | -                             | 3.0                             | -                    |
| Branching fractions   | -                             | 5.7                             | -                             | 5.7                             | -                    |
| Background shape      | 1.5                           | 13.1                            | 0.4                           | 9.7                             | 1.0                  |
| Resolution            | 0.2                           | 2.1                             | 0.2                           | 1.6                             | 0.5                  |
| Mass scale            | 0.0                           | 0.0                             | 0.0                           | 0.0                             | 0.0                  |
| Total                 | 1.5                           | 14.9                            | 0.4                           | 12.0                            | 1.1                  |

TABLE IV: Summary of results from the simultaneous fits to the \( \Lambda D^+ \) and \( \Sigma_c^{++}K^- \) modes.

| Resonance | Width (MeV) | Yield for \( \Delta D^+ \) | Yield for \( \Sigma_c^{++}K^- \) | Yield for sideband | Yield for \( \Sigma_c^{++}K^- \) |
|-----------|-------------|-----------------------------|---------------------------------|-------------------|-----------------------------|
| \( \Xi_c(3055)^+ \) | 7.8 ± 1.2 ± 1.5 | 721 ± 90 | 173 ± 30 | 21 ± 18 | - |
| \( \Xi_c(3080)^+ \) | 5.0 ± 0.7 ± 0.4 | 186 ± 40 | 176 ± 23 | 20 ± 12 | 234 ± 30 |

VI. SUMMARY AND CONCLUSIONS

We present studies of \( \Xi_c \) baryons decaying into the \( \Lambda D^+ \) and \( \Delta D^0 \) final states. We report the first observation of the \( \Xi_c(3055)^0 \) in the \( \Delta D^0 \) mode with a significance of 8.6\( \sigma \). The mass and width of the \( \Xi_c(3055)^0 \) are measured to be (3059.0±0.5±0.6) MeV/c\(^2\) and (6.4±2.1±1.1) MeV, respectively. We report the first observation of the \( \Xi_c(3055)^+ \) decay and evidence for the \( \Xi_c(3080)^0 \) in the \( \Lambda D^+ \) final state. The mass and width of the \( \Xi_c(3055)^+ \) obtained from the \( \Delta D \) final states only are (3055.8±0.4±0.2) MeV/c\(^2\) and (7.0±1.2±1.5) MeV, respectively, and those for \( \Xi_c(3080)^+ \) are (3079.6±0.4±0.1) MeV/c\(^2\) and < 6.3 MeV, respectively. The measured values for \( \Xi_c(3055)^+ \) are more accurate than the world average thanks to the high statistics in this decay mode.

We perform a combined analysis of these particles by comparing their decays into \( \Delta D^+ \) with those into \( \Sigma_c^{++}K^- \) and \( \Sigma_c^{++}K^- \). We measure the ratios of branching fractions: \( B(\Xi_c(3055)^+ \to \Delta D^+)/B(\Xi_c(3055)^+ \to \Sigma_c^{++}K^-) = 5.09 ± 0.11 ± 0.76 \), \( B(\Xi_c(3080)^+ \to \Delta D^+)/B(\Xi_c(3080)^+ \to \Sigma_c^{++}K^-) = 1.29 ± 0.30 ± 0.15 \), and \( B(\Xi_c(3080)^+ \to \Sigma_c^{++}K^-)/B(\Xi_c(3080)^+ \to \Sigma_c^{++}K^-) = 1.07 ± 0.27 ± 0.01 \). The width of the \( \Xi_c(3055)^+ \) is (7.8±1.2±1.5) MeV and that of the \( \Xi_c(3080)^+ \) is (3.0±0.7±0.4) MeV. We take the weighted average of the measurements in the different decay modes to find the masses of the \( \Xi_c(3055)^+ \) and \( \Xi_c(3080)^+ \) to be (3055.9±0.4) MeV/c\(^2\) and (3077.9±0.9) MeV/c\(^2\), respectively, where the uncertainties are scaled by \( \sqrt{\chi^2/(N-1)} \) to account for small inconsistencies in the \( N \) individual measurements. The uncertainties on the masses incorporate the statistical and systematic values. The masses and widths of \( \Xi_c(3055)^+ \) and \( \Xi_c(3080)^+ \), after combining other decay modes, supersede our previous measurements [9].

Our measurements provide information on the nature of these baryons. For instance, the chiral quark model has been used to identify the \( \Xi_c(3055) \) as the D-wave excitation in the N=2 shell, and predicts \( B(\Xi_c(3055) \to \Sigma_c^0K^+)B(\Xi_c(3055) \to AD) = 2.3:0.1 \) or \( 5.6:0.0 \), depending on the possible excitation modes [1]. It further identifies the \( \Xi_c(3080) \) as an S-wave excitation mode of the \( \Xi_c \) in N=2 shell and predicts that its decay into \( \Delta D \) is forbidden. Both of these predictions are in contradiction with our measurements. Further experimental and theoretical work is needed to understand these baryons.

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TABLE V: Summary of the values related to the measurements of the ratio of branching fractions. The branching fraction values are taken from Ref. [14, 20]. For the ratios of branching fractions, the first error is statistical and second is systematic.

| Variable                                                                 | Value                  |
|-------------------------------------------------------------------------|------------------------|
| $B(D^+ \rightarrow K^-(\pi^+\pi^-))$                                   | 0.0913 ± 0.0019         |
| $B(\Lambda \rightarrow p\pi^-)$                                         | 0.639 ± 0.005           |
| $B(\Lambda^+_c \rightarrow pK^-\pi^+)$                                 | 0.0684 ± 0.036          |
| $B(K^0_S \rightarrow \pi^+\pi^-)$                                      | 0.6920 ± 0.0005         |
| $B(\Lambda^+_c \rightarrow pK^0_S)/B(\Lambda^+_c \rightarrow pK^-\pi^+)$| 0.24 ± 0.02             |

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