Recent results on charmed baryons from Belle

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On behalf of Belle Collaboration

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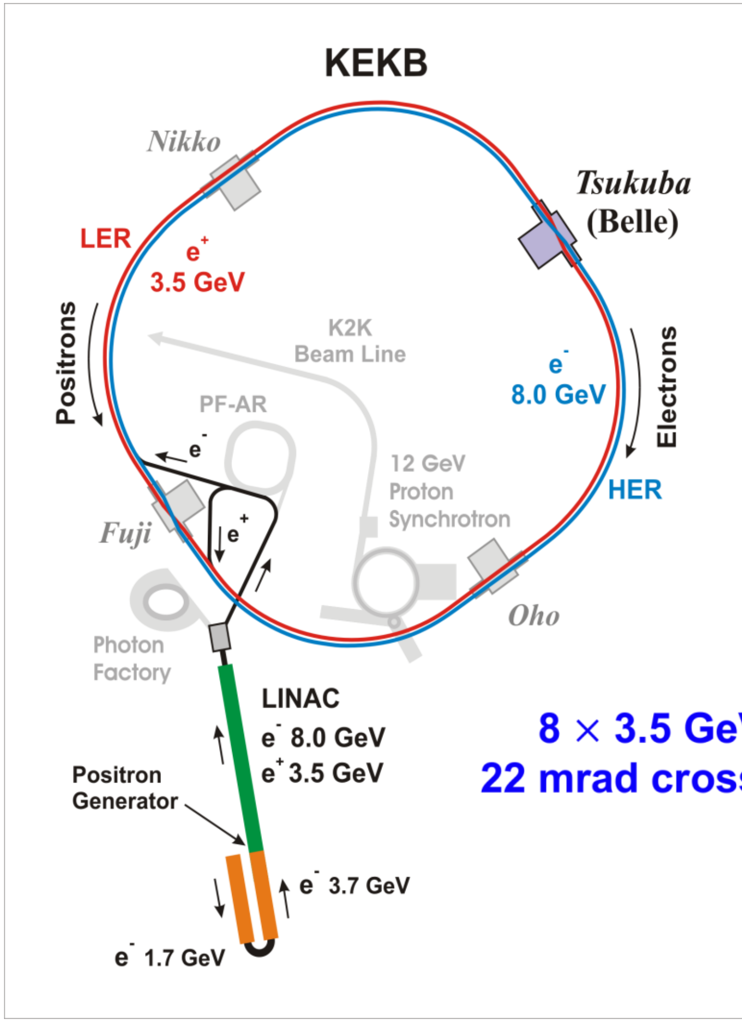
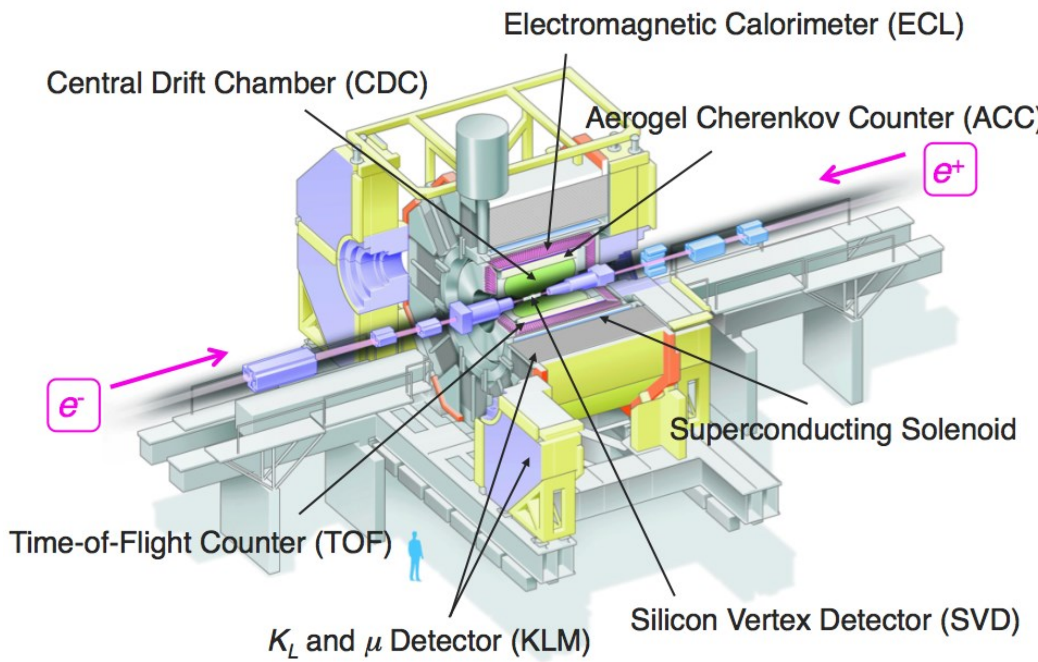
Belle Experiment and data samples



8 × 3.5 GeV
22 mrad crossing



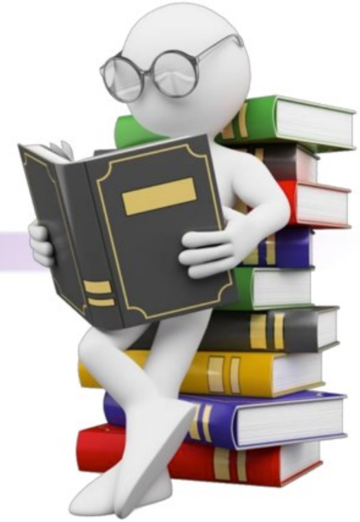
Data taking: 1999 – 2010

On/Off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 1 ab^{-1}

772M $B\bar{B}$ events @$\Upsilon(4S)$

Selected topics



1. Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$ and $\Sigma^+\eta'$

2. Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

3. Mass and width of $\Lambda_c(2625)^+$ and branching fractions of

$\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

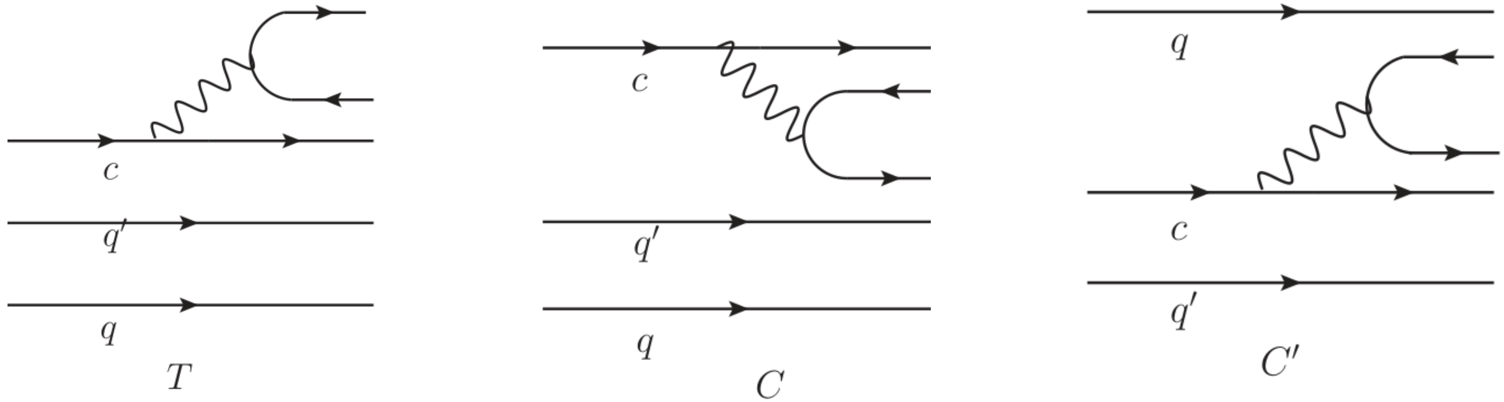
4. Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-(\Omega^-)K^+$

1. Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$ and $\Sigma^+\eta'$

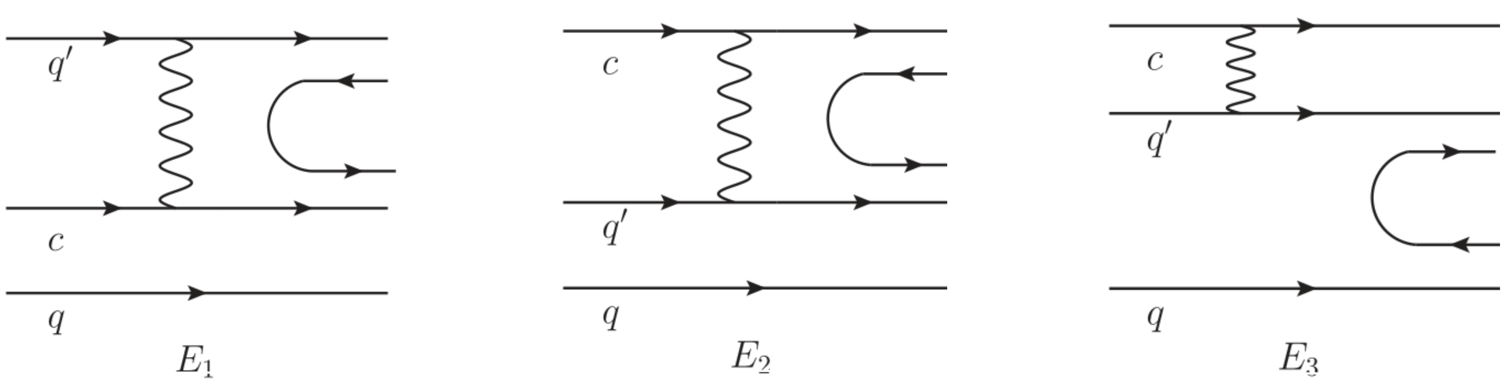
PRD 107, 032003 (2023)

Motivation 1

- For the charmed baryon weak decays: $B_c \to B + M$, there are six topological diagrams. Among them, T and C are factorizable, while C′ and E_{1-3} are nonfactorizable. All the nonfactorizable diagrams contribute to $\Lambda_c^+ \to \Sigma^+\eta(\eta')$.



external W-emission T · internal W-emission C · inner W-emission C'



W-exchange diagrams E_1 E_2 E_3

1. Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$ and $\Sigma^+\eta'$

PRD 107, 032003 (2023)

Motivation 2

- Theoretical predictions on the branching fractions and asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\eta(\eta')$ vary across.

- Branching fractions of $\Lambda_c^+ \to \Sigma^+\eta(\eta')$ are measured with large uncertainty ($\delta B/B$>40%) [PDG]. Decay asymmetry parameters for these two modes have never been measured.

Decay	Körner CCQM	Xu Pole	Cheng CA	Cheng Pole	Ivanov CCQM	Żenczykowski Pole	Sharma CA	Zou CA	Geng SU(3)	Experiment
$\Lambda_c^+ \to \Sigma^+\eta$	0.16				0.11	0.90	0.57	0.74	0.32 ± 0.13	0.44 ± 0.20
$\Lambda_c^+ \to \Sigma^+\eta'$	1.28				0.12	0.11	0.10		1.44 ± 0.56	1.5 ± 0.6
$\Lambda_c^+ \to \Sigma^+\eta$	0.33				0.55	0	-0.91	-0.95	-0.40 ± 0.47	
$\Lambda_c^+ \to \Sigma^+\eta'$	-0.45				-0.05	-0.91	0.78		$1.00^{+0.00}_{-0.17}$	

Branching fractions

Asymmetry parameters

1. Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$ and $\Sigma^+\eta'$

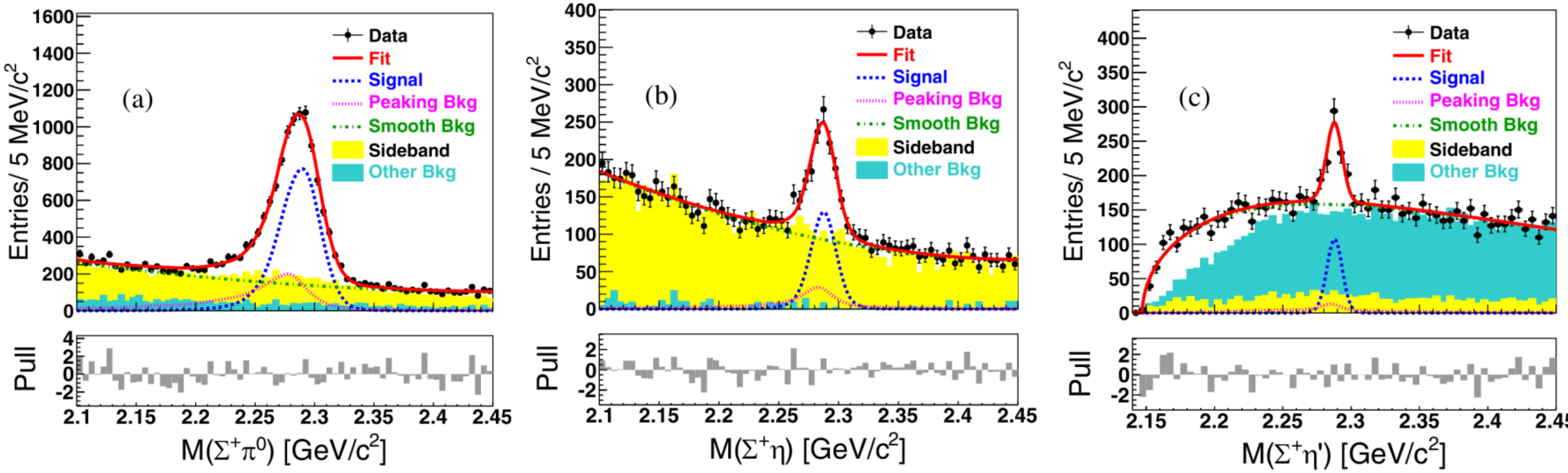
■ **Measurements of branching fractions of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$** **980 fb^{-1}**

Method: $\frac{B(\Lambda_c^+ \to \Sigma^+\eta/\Sigma^+\eta')}{B(\Lambda_c^+ \to \Sigma^+\pi^0)} = \frac{y(\Lambda_c^+ \to \Sigma^+\eta/\Sigma^+\eta')}{B_{\mathrm{PDG}} \times y(\Lambda_c^+ \to \Sigma^+\pi^0)}$ (y is the efficiency-corrected yield).

Reference mode: $\Lambda_c^+ \to \Sigma^+\pi^0$

Signal mode: $\Lambda_c^+ \to \Sigma^+\eta$

Signal mode: $\Lambda_c^+ \to \Sigma^+\eta'$



$$\frac{B(\Lambda_c^+\to\Sigma^+\eta)}{B(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.25 \pm 0.03 \pm 0.01; \quad B(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3}$$

$$\frac{B(\Lambda_c^+\to\Sigma^+\eta')}{B(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.33 \pm 0.06 \pm 0.02; \quad B(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3}$$

Most precise result to date.

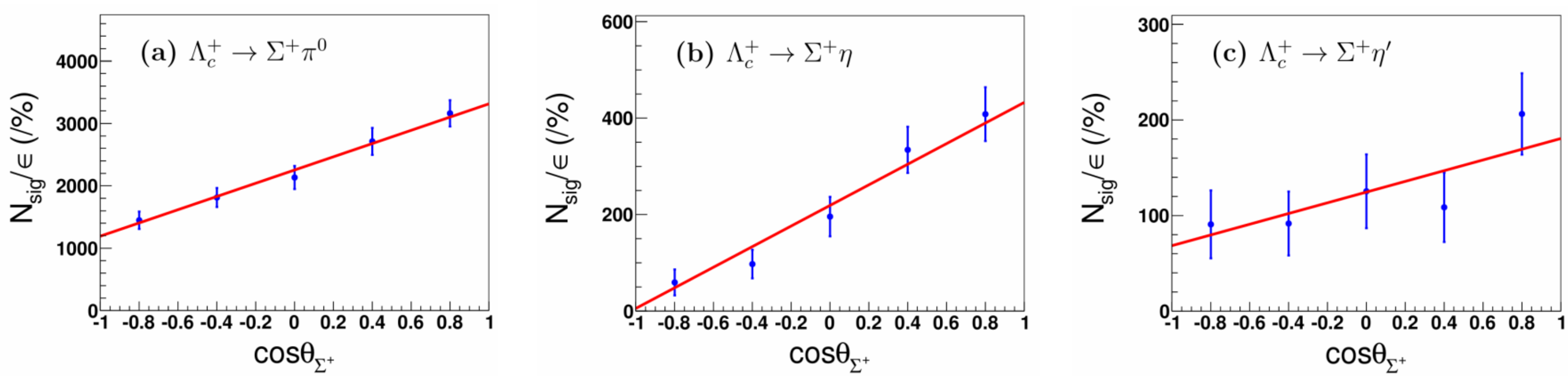
1. Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$ and $\Sigma^+\eta'$

- **Measurements of asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$, $\Sigma^+\eta$, and $\Sigma^+\eta'$**

The differential decay rate depends on the asymmetry parameter α_{Σ^+X} as:

$$\frac{dN}{dcos\theta_{\Sigma^+}} \propto 1 + \alpha_{\Sigma^+X}\alpha_{p\pi^0}cos\theta_{\Sigma^+}$$

θ_{Σ^+} is the angle between the proton momentum vector and the opposite of the Λ_c^+ momentum vector in the Σ^+ rest frame; $\alpha_{p\pi^0} = -0.982 \pm 0.014$ from world average value.



- $\alpha_{\Sigma^+\pi^0} = -0.48 \pm 0.02 \pm 0.02$
  - agrees with the world average value: -0.55 ± 0.11.
  - with much improved precision.
  - The consistency with $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$ indicates no isospin symmetry broken.
- $\alpha_{\Sigma^+\eta} = -0.99 \pm 0.03 \pm 0.05$ and $\alpha_{\Sigma^+\eta'} = -0.46 \pm 0.06 \pm 0.03$
  - measured for the first time.

2. Branching fractions of $\Lambda_c^+ \to pK_S^0 K_S^0, pK_S^0 \eta$

Motivation

PRD 107, 032004 (2023)

- Precise measurements of branching fractions of charmed baryon weak decays are useful for studying the dynamics of charmed baryons and testing the predictions of theoretical models.

- No result of branching fraction for $\Lambda_c^+ \to pK_S^0 K_S^0$ is reported. According to theoretically results based on SU(3)F symmetry [EPJC 79 (2019) 946], we estimate $\sim O(10^3)$ signal yield at Belle.

- Measured branching fraction $B(\Lambda_c^+ \to pK_S^0 \eta) = (4.15 \pm 0.90) \times 10^{-3}$ has large uncertainty (δB/B~20%) [PDG]. We target at an improved precision of BF.

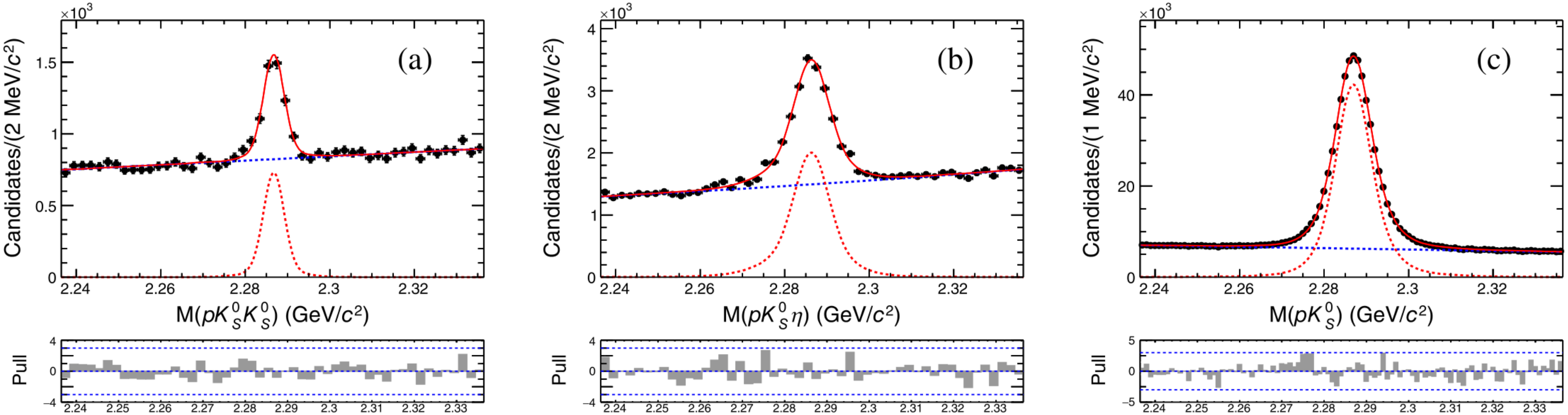
- Check Dalitz-plot for the intermediate resonances existence.:
  - e.g. N*(1535), which is puzzling because it can decay with strange-hadron-involved in final state, like ηN and $K\Lambda$, but it does not contain any $s\bar{s}$ component according to the naïve constituent quark model [PPNP. 45, S241 (2000)].

2. Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

Signal Yield Extraction

980 fb^{-1}

Signal: $\Lambda_c^+ \to pK_S^0K_S^0$ Signal: $\Lambda_c^+ \to pK_S^0\eta$ Reference: $\Lambda_c^+ \to pK_S^0$



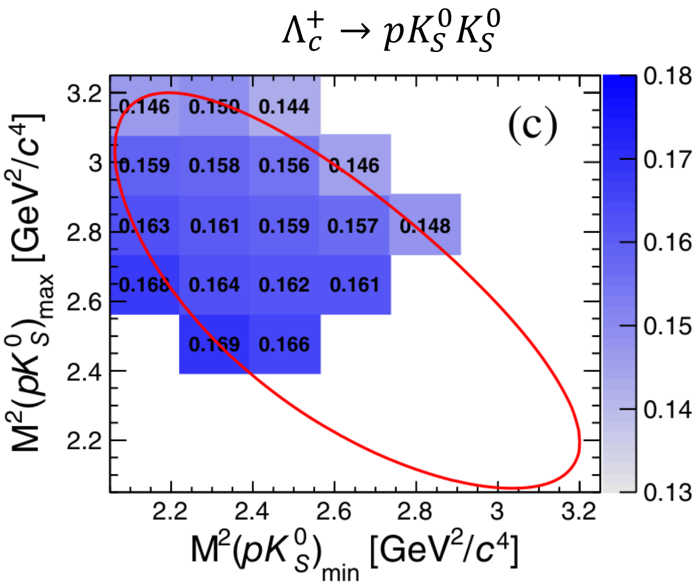
Yields	$\Lambda_c^+ \to pK_S^0K_S^0$	$\Lambda_c^+ \to pK_S^0\eta$	$\Lambda_c^+ \to pK_S^0$
$N_{\rm sig}^{\rm FR}$	2442 ± 103	12877 ± 317	515296 ± 1129

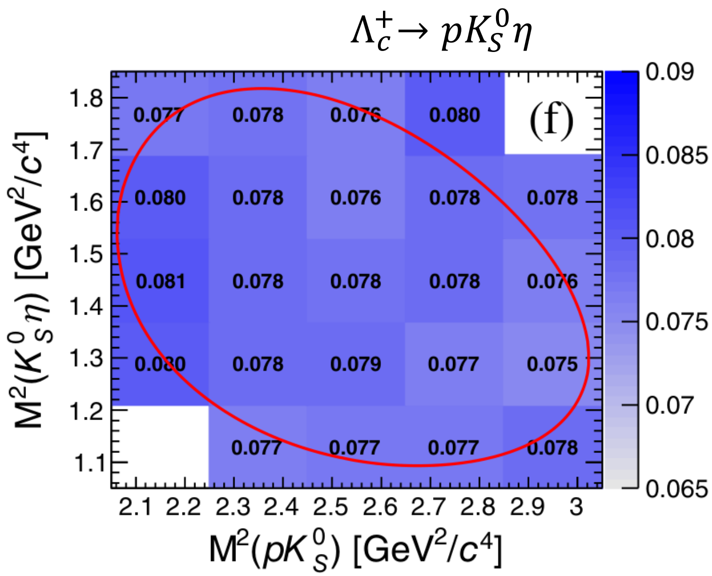
Efficiency Plane

- For reference mode, directly use the efficiency from MC.
- For signal modes, possible intermediate structures affect on final averaged efficiencies. Therefore, we use the Dalitz-plot-based efficiency planes.

2. Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

Efficiency Plane





Plots (c, f) show the average signal efficiency in bins across the Dalitz plane. The red curves show the edges of kinematic phase-space region of the decays.

Branching fraction

$$\frac{B(\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta)}{B(\Lambda_c^+ \to pK_S^0)} = \frac{y(\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta)}{B_{\text{PDG}} \times y(\Lambda_c^+ \to pK_S^0)}$$

(y is the efficiency-corrected yield).

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK_S^0K_S^0)}{\mathcal{B}(\Lambda_c^+ \to pK_S^0)} = (1.48 \pm 0.08) \times 10^{-2}$$

$$\mathcal{B}(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.12) \times 10^{-4}$$:First observation

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta)}{\mathcal{B}(\Lambda_c^+ \to pK_S^0)} = (2.73 \pm 0.06) \times 10^{-1}$$

$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.22) \times 10^{-3}$$:Threefold improvement in precision

3. Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

Motivation

PRD 107, 032008 (2023)

- $\Lambda_c(2625)^+ (\mathrm{J^P} = 3/2^-)$ is the excited state of Λ_c^+. It dominantly decays to $\Lambda_c^+\pi^+\pi^-$ via P-wave decay. The D-wave decay $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$ is also allowed, but its contribution is known to be small.

- The limited decay phase space of $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$ makes it difficult to extract the $\Sigma_c^{0,++}$ yields by fitting the $M(\Lambda_c^+\pi^\pm)$, due to the presence of reflection peaks formed by the combination of the Λ_c^+ and the other final-state pion. This can be solved by using a full Dalitz fit [PRD 98, 114007 (2018)].

- The mass of the $\Lambda_c(2625)^+$, relative to the Λ_c^+ mass, is already relatively well known [PRD 84,012003 (2011)], but the large Belle data sample allows for a more precise measurement.

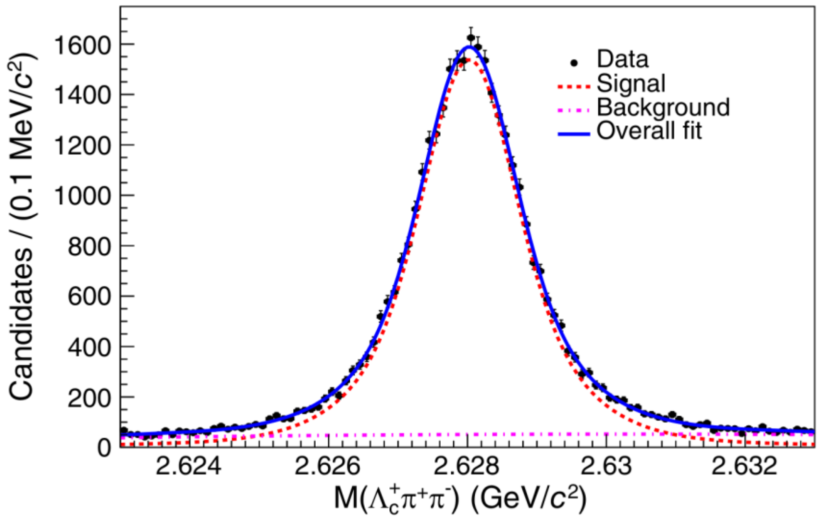
- No intrinsic width of the $\Lambda_c(2625)^+$ has yet been measured, and the current upper limit $\Gamma < 0.97\ \mathrm{MeV}/c^2$ at 90% confidence level is based on the CDF measurement in 2011 [PRD 84,012003 (2011)].

3. Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

Measurements of mass and width

980 fb^{-1}

Reconstruction mode: $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-, \Lambda_c^+ \to pK^-\pi^+$



$$M(\Lambda_c(2625)^+) - M(\Lambda_c^+)$$
$$= 341.518 \pm 0.006 \pm 0.049\ \mathrm{MeV}/c^2$$

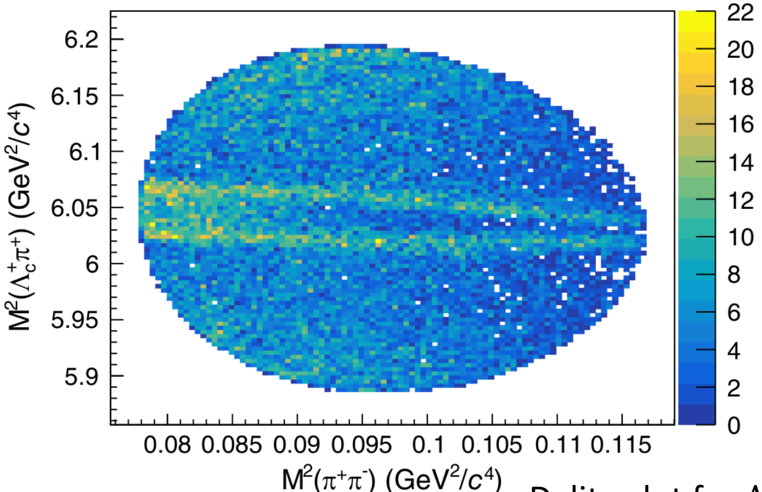
$$\Gamma(\Lambda_c(2625)^+) < 0.52\ \mathrm{MeV}/c^2$$

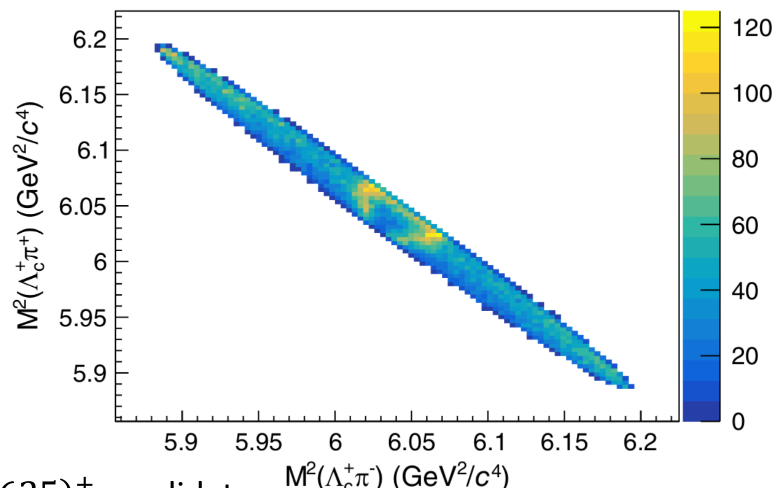
- The measured mass is consistent with the previous CDF measurement but with approximately half the uncertainty.
- The upper limit on width is around a factor of 2 more stringent than the previous limit. An improved limit on the width of the $\Lambda_c(2625)^+$ will help to constrain various theoretical predictions.

3. Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

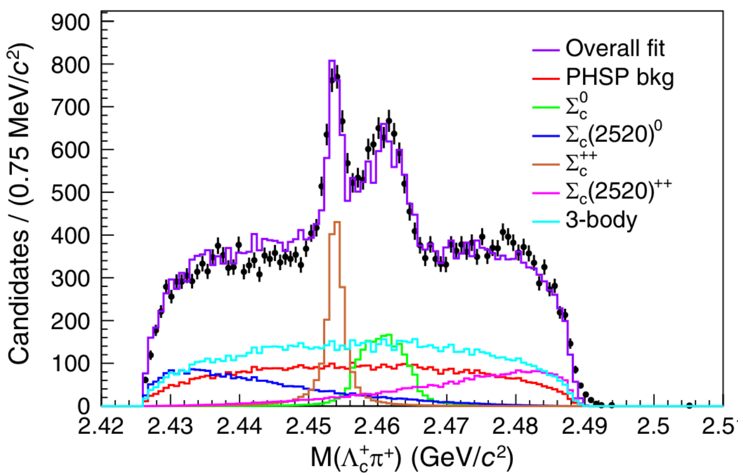
Measurements of branching fractions

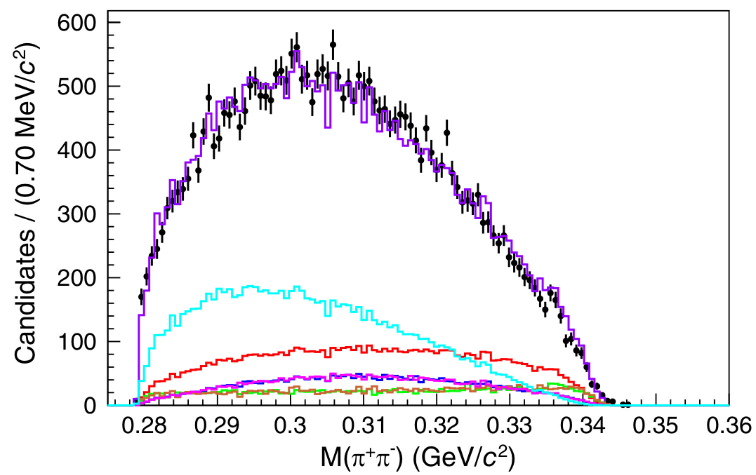
Full Dalitz plot fitted with AmpTools is performed [PRD 98, 114007 (2018)].





Dalitz plot for $\Lambda_c(2625)^+$ candidates





Dalitz plot fit result plotted as projections. Solid lines show the overall fitted distribution and its individual components as indicated in the legend.

3. Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

Measurements of branching fractions

The branching ratio of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$ relative to the reference mode $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$ is calculated using:

$$\frac{B(\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi)}{B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = \frac{N_{sig}(\Sigma_c^{0,++}) - N_{bkg}(\Sigma_c^{0,++})}{N_{sig}(\Lambda_c(2625)^+)}$$

$N_{bkg}(\Sigma_c^{0,++})$ is obtained from sidebands of $\mathrm{M}(\Lambda_c^+\pi^+\pi^-)$. We obtain:

$$\frac{B(\Lambda_c(2625)^+ \to \Sigma_c^{0}\pi)}{B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.19 \pm 0.23 \pm 0.40)\%$$

$$\frac{B(\Lambda_c(2625)^+ \to \Sigma_c^{++}\pi)}{B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.13 \pm 0.26 \pm 0.32)\%$$

- The measured branching fraction ratios are the most precise to date.
- Our measurements align with the prediction that assuming $\Lambda_c(2625)^+$ is a λ mode excitation [PRD 98, 114007 (2018)].

4. Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-(\Omega^-)K^+$

JHEP01 (2023) 055

Motivation

- Ω_c^0 ($J^P = 1/2^+$) is the heaviest singly-charmed hadron that decays weakly. The knowledge of the Ω_c^0 state is limited compared with $\Lambda_c^+, \Xi_c^{0,+}$.

- No measurements of the absolute BF of the Ω_c^0 are reported, but some measurements of the BF ratios for Ω_c^0 decay modes with respect to the reference mode $\Omega_c^0 \to \Omega^-\pi^+$ have been made. [PTEP 2020,083C01]

- Various theoretical methods have been developed to describe the Ω_c^0 decays, e.g. quark model [CPC 42,093101 (2018)], pole model and current algebra (CA) [PRD 101, 094033 (2020)]. However, the range of these predictions is rather wide.

- The predictions of BF for $\Omega_c^0 \to \Xi^-\pi^+, \Xi^-K^+$ are listed. No prediction is available for Ω^-K^+. No measurements of these decays are made.

Decay mode	quark model	pole model and CA
$\Omega_c^0 \to \Xi^-\pi^+$	1.96×10^{-3}	1.04×10^{-1}
$\Omega_c^0 \to \Xi^-K^+$	1.74×10^{-4}	1.06×10^{-2}

4. Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-(\Omega^-)K^+$

Branching fraction ratios

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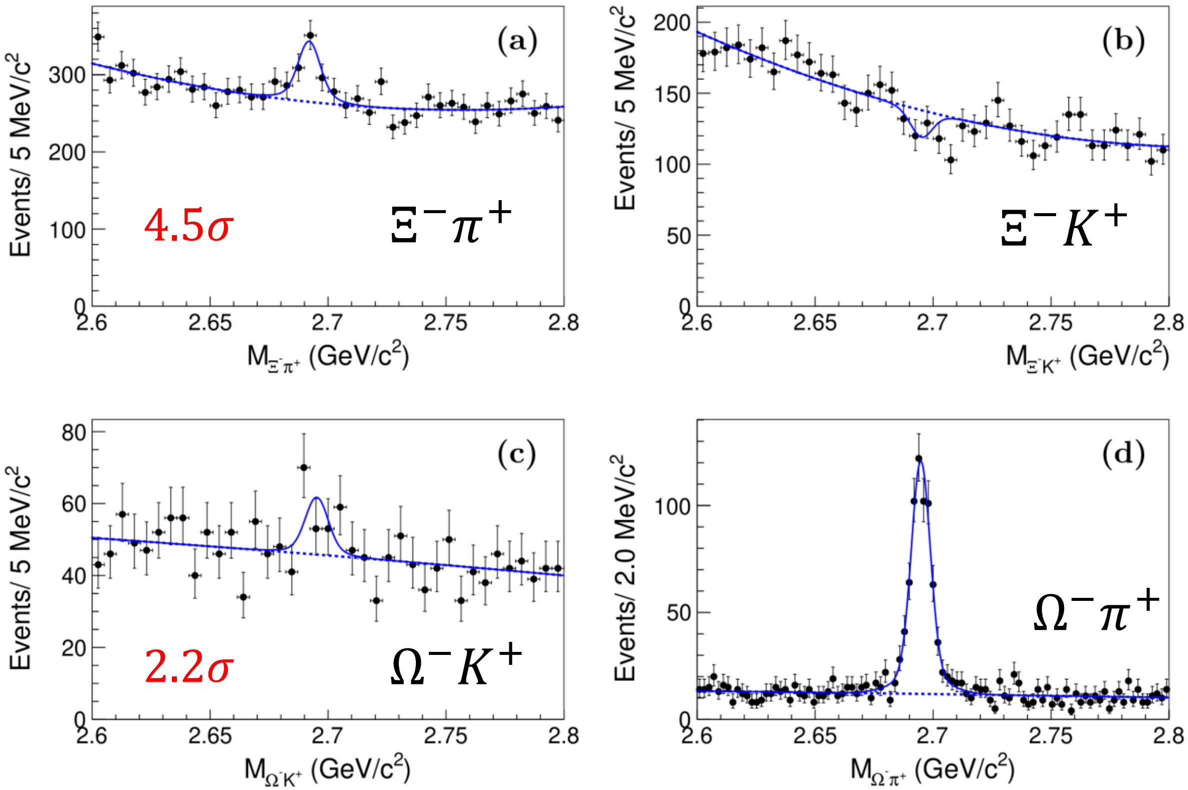

$$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)} = [25.3 \pm 5.2(\text{stat.}) \pm 3.0(\text{syst.})]\,\%$$

Measured for the first time

$$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^-K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)} < 0.070 \qquad \frac{\mathcal{B}(\Omega_c^0 \to \Omega^-K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)} < 0.29$$

Summary

- Although Belle has stopped data taking for ~10 years, we are still producing excited results, especially for charmed baryons. In this talk, we report:
  - Measurement of $\mathrm{B}(\Lambda_c^+ \to \Sigma^+\eta(\eta'))$ with the best precision to date and asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\eta(\eta')$ for the first time.
  - Measurement of $\mathrm{B}(\Lambda_c^+ \to pK_S^0K_S^0)$ for the first time and $\mathrm{B}(\Lambda_c^+ \to pK_S^0\eta)$ with threefold improvement in precision.
  - Most precise $\Lambda_c(2625)^+$ mass, width, and branching fraction ratios to date.
  - Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and measurements of $\mathrm{B}(\Omega_c^0 \to \Xi^-\pi^+, \Xi^-K^+, \Omega^-K^+)$.
- These experimental results will be useful to future constrain the parameter space of the theoretical models and can be applied to other heavy quark systems.
- In the future, Belle II will provide greater sensitivity and precise measurements in charmed baryon physics with 50 ab^{-1}.

Thanks for your attentions!