



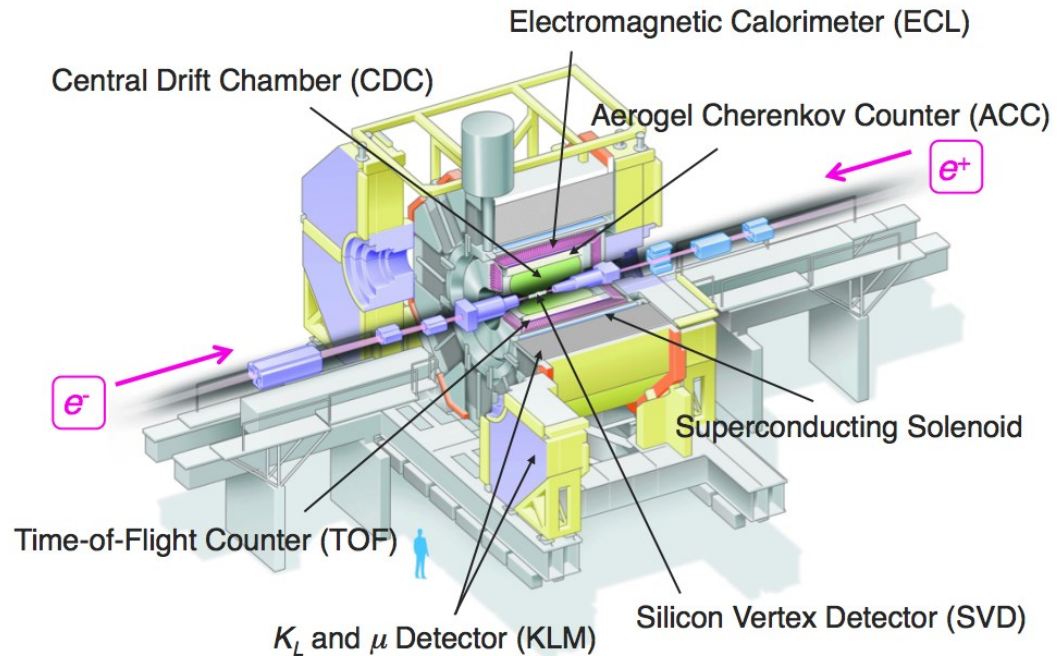
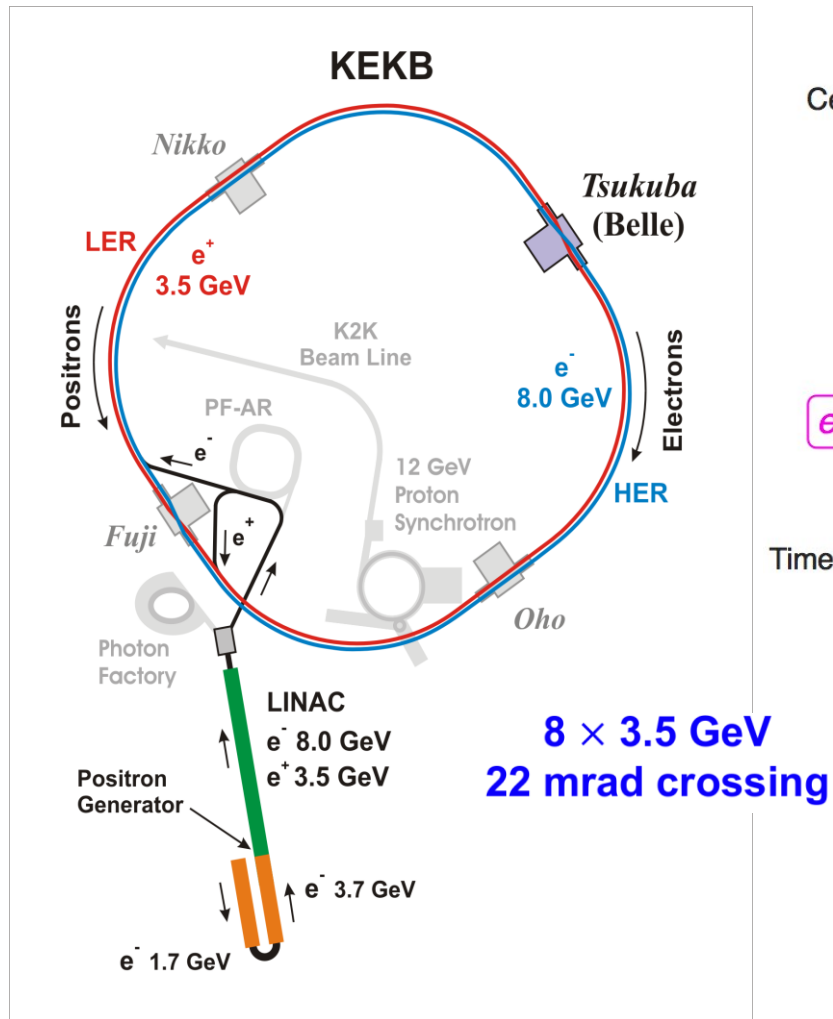
Recent results on charmed baryons from Belle

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On behalf of Belle Collaboration

The 16th edition of the "International Conference on Meson-Nucleon Physics
and the Structure of the Nucleon" (MENU 2023)

October 17, 2023

Belle Experiment and data samples



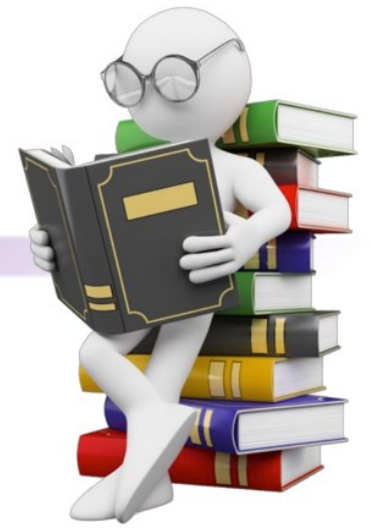
Data taking: 1999 – 2010

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

Total luminosity: 1 ab^{-1}

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

Selected topics



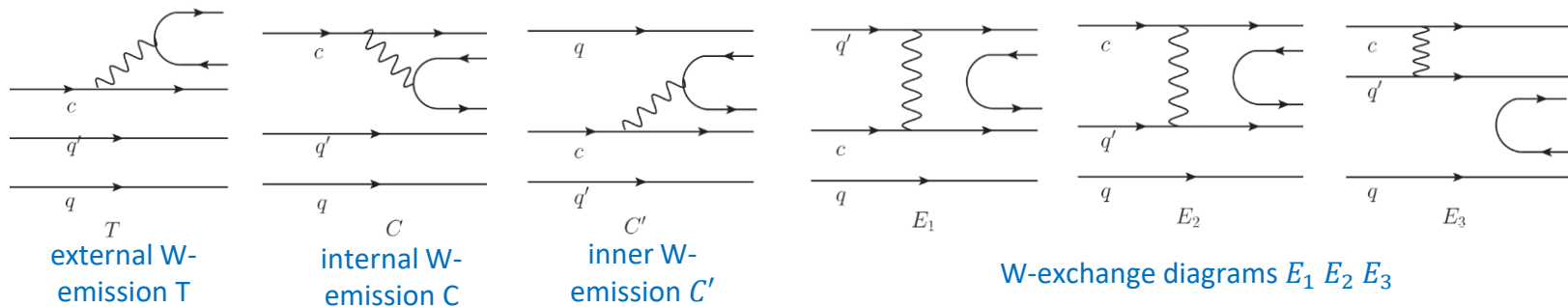
- Measurements of $\Lambda_c^+ \rightarrow \Sigma^+ \pi^0, \Sigma^+ \eta$ and $\Sigma^+ \eta'$
- Branching fractions of $\Lambda_c^+ \rightarrow p K_S^0 K_S^0, p K_S^0 \eta$
- Mass and width of $\Lambda_c(2625)^+$ and branching fractions of
$$\Lambda_c(2625)^+ \rightarrow \Sigma_c^{0,++} \pi$$
- Evidence for $\Omega_c^0 \rightarrow \Xi^- \pi^+$ and search for $\Omega_c^0 \rightarrow \Xi^- (\Omega^-) K^+$

Measurements of $\Lambda_c^+ \rightarrow \Sigma^+ \pi^0, \Sigma^+ \eta$ and $\Sigma^+ \eta'$

PRD 107, 032003 (2023)

■ Motivation

- For the charmed baryon weak decays: $B_c \rightarrow B + M$, 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 $\Lambda_c^+ \rightarrow \Sigma^+ \eta(\eta')$.



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

Branching
fraction

Asymmetry
parameter

Measurements of $\Lambda_c^+ \rightarrow \Sigma^+ \pi^0, \Sigma^+ \eta$ and $\Sigma^+ \eta'$

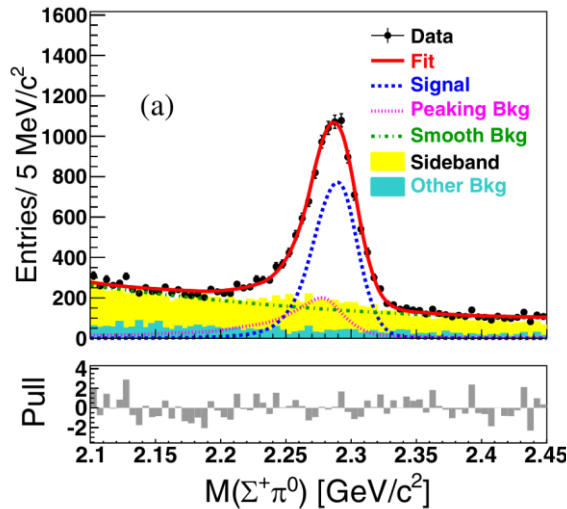
■ Measurements of branching fractions of $\Lambda_c^+ \rightarrow \Sigma^+ \eta$ and $\Lambda_c^+ \rightarrow \Sigma^+ \eta'$

980 fb⁻¹

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

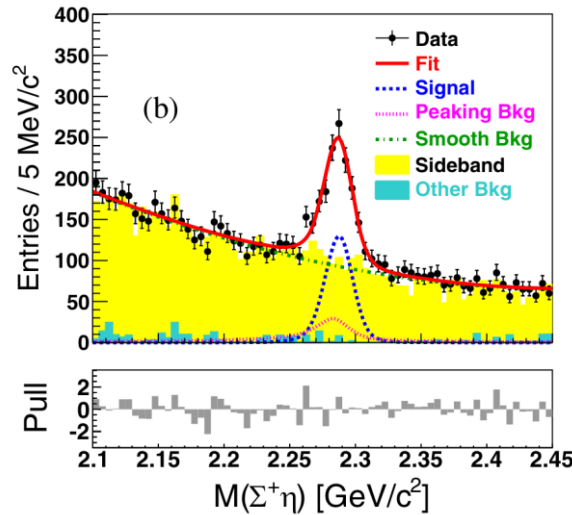
Reference mode:

$\Lambda_c^+ \rightarrow \Sigma^+ \pi^0$



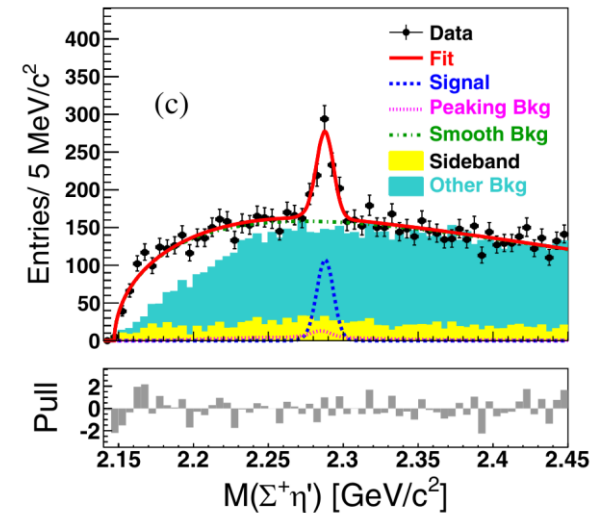
Signal mode:

$\Lambda_c^+ \rightarrow \Sigma^+ \eta$



Signal mode:

$\Lambda_c^+ \rightarrow \Sigma^+ \eta'$



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

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

Most precise result to date.

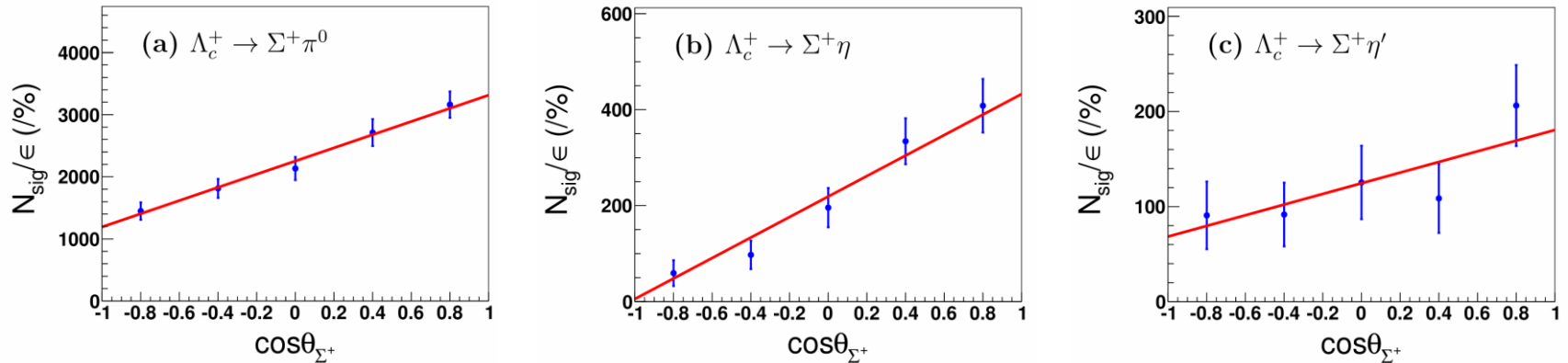
Measurements of $\Lambda_c^+ \rightarrow \Sigma^+ \pi^0, \Sigma^+ \eta$ and $\Sigma^+ \eta'$

■ Measurements of asymmetry parameters of $\Lambda_c^+ \rightarrow \Sigma^+ \pi^0, \Sigma^+ \eta$, and $\Sigma^+ \eta'$

The differential decay rate depends on the asymmetry parameter $\alpha_{\Sigma^+ X}$ as:

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

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.

Branching fractions of $\Lambda_c^+ \rightarrow pK_S^0 K_S^0, pK_S^0 \eta$

■ Motivation

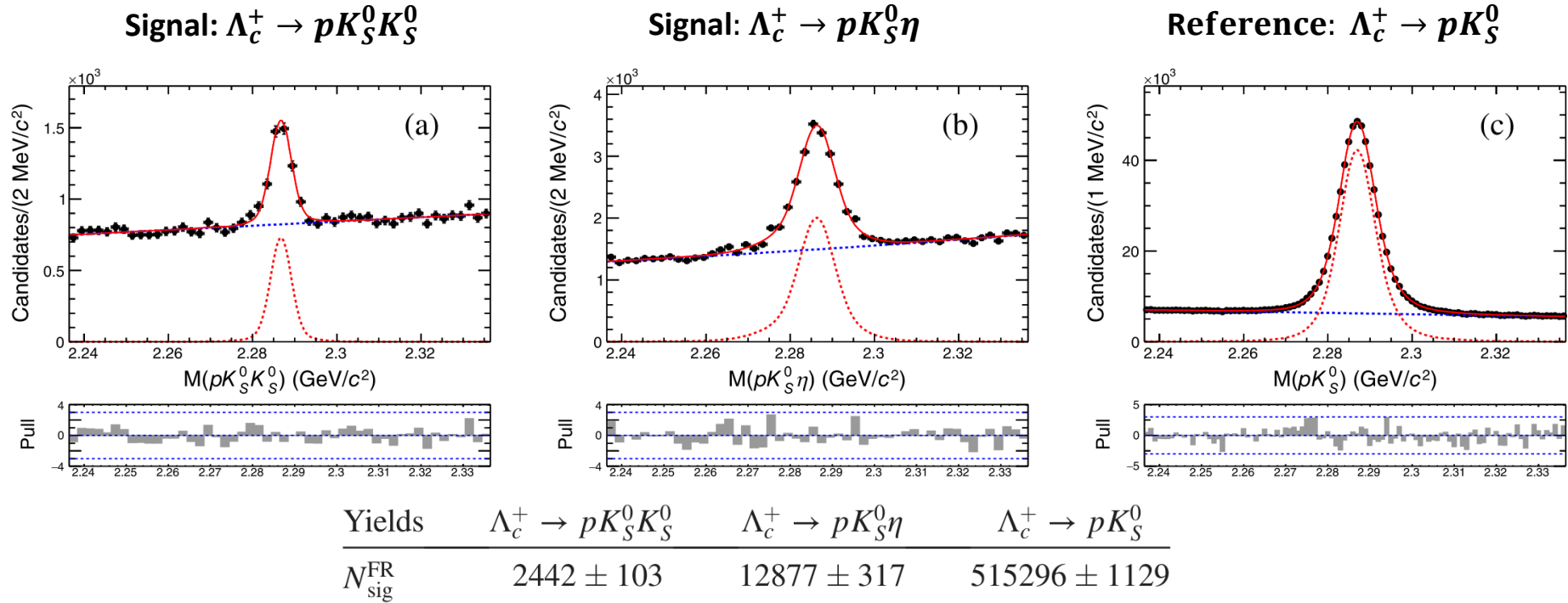
[PRD 107, 032004 \(2023\)](#)

- 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 $\Lambda_c^+ \rightarrow pK_S^0 K_S^0$ 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 $B(\Lambda_c^+ \rightarrow pK_S^0 \eta) = (4.15 \pm 0.90) \times 10^{-3}$ has large uncertainty ($\delta B/B \sim 20\%$) [[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 \(2000\)](#)].

Branching fractions of $\Lambda_c^+ \rightarrow pK_S^0 K_S^0, pK_S^0 \eta$

■ Signal Yield Extraction

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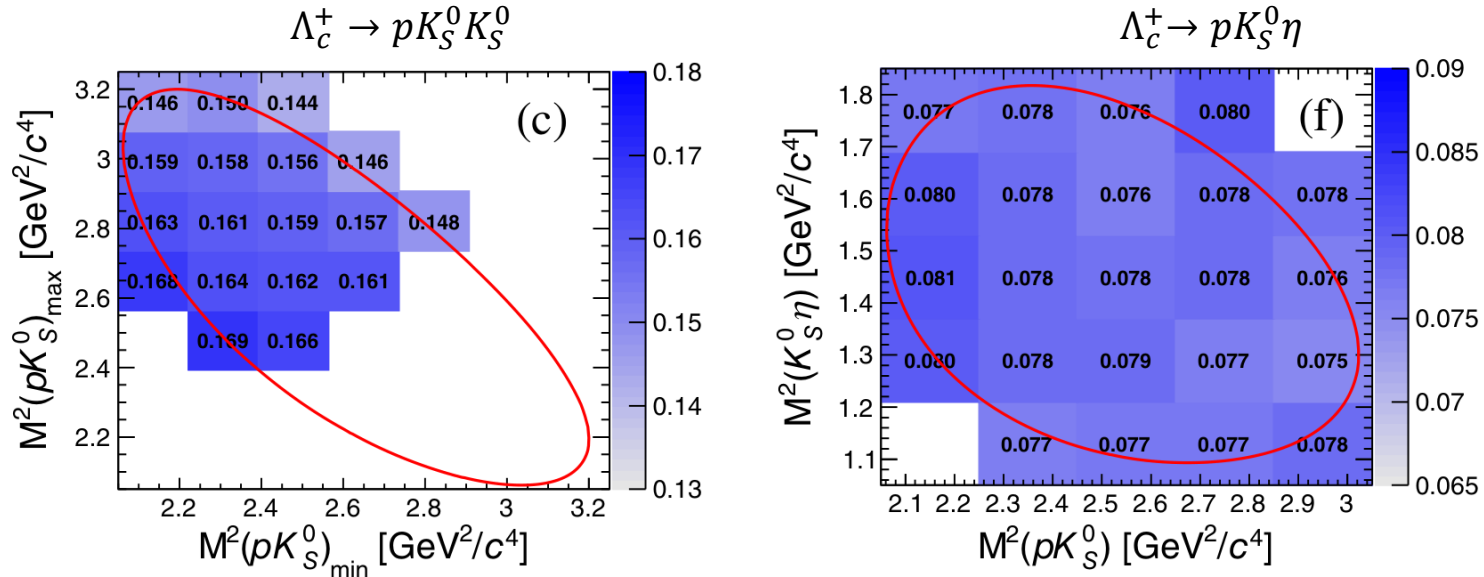


■ Efficiency Plane

- 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.

Branching fractions of $\Lambda_c^+ \rightarrow pK_S^0 K_S^0, pK_S^0 \eta$

■ 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

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0 K_S^0, pK_S^0 \eta)}{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0)} = \frac{y(\Lambda_c^+ \rightarrow pK_S^0 K_S^0, pK_S^0 \eta)}{B_{\text{PDG}} \times y(\Lambda_c^+ \rightarrow pK_S^0)} \quad (y \text{ is the efficiency-corrected yield}).$$

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0 K_S^0)}{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0)} = (1.48 \pm 0.08) \times 10^{-2} \quad \mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0 K_S^0) = (2.35 \pm 0.12 \pm 0.12) \times 10^{-4} \quad \text{:First observation}$$

$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0 \eta)}{\mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0)} = (2.73 \pm 0.06) \times 10^{-1} \quad \mathcal{B}(\Lambda_c^+ \rightarrow pK_S^0 \eta) = (4.35 \pm 0.10 \pm 0.22) \times 10^{-3} \quad \text{:Threefold improvement in precision}$$

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

■ Motivation

[PRD 107, 032008 \(2023\)](#)

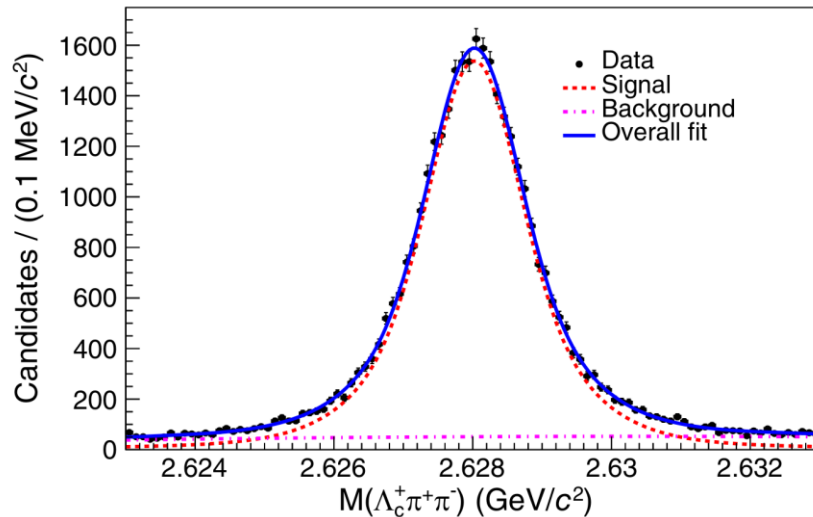
- $\Lambda_c(2625)^+$ ($J^P = 3/2^-$) is the excited state of Λ_c^+ . It dominantly decays to $\Lambda_c^+ \pi^+ \pi^-$ via P-wave decay. The D-wave decay $\Lambda_c(2625)^+ \rightarrow \Sigma_c^{0,++} \pi$ is also allowed, but its contribution is known to be small.
- The limited decay phase space of $\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$ 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 $\Gamma < 0.97 \text{ MeV}/c^2$ at 90% confidence level is based on the CDF measurement in 2011 [[PRD 84,012003 \(2011\)](#)].

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

■ Measurements of mass and width

980 fb⁻¹

Reconstruction mode: $\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$, $\Lambda_c^+ \rightarrow p K^- \pi^+$



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

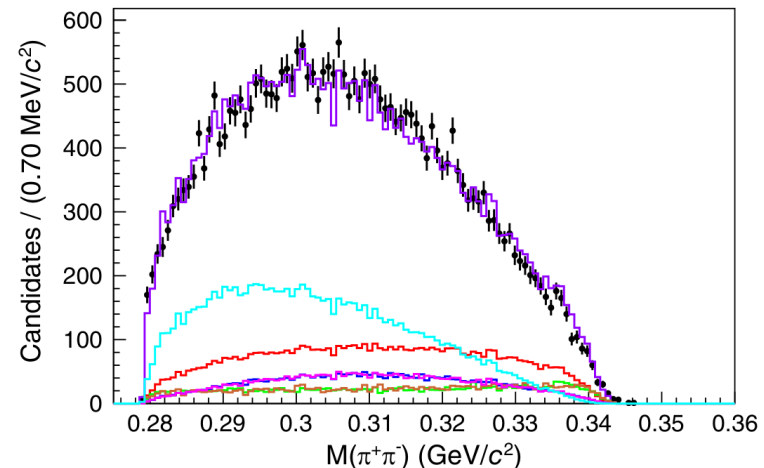
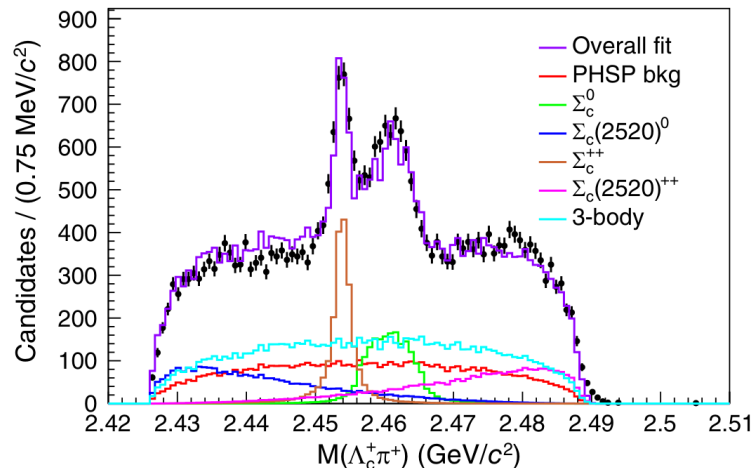
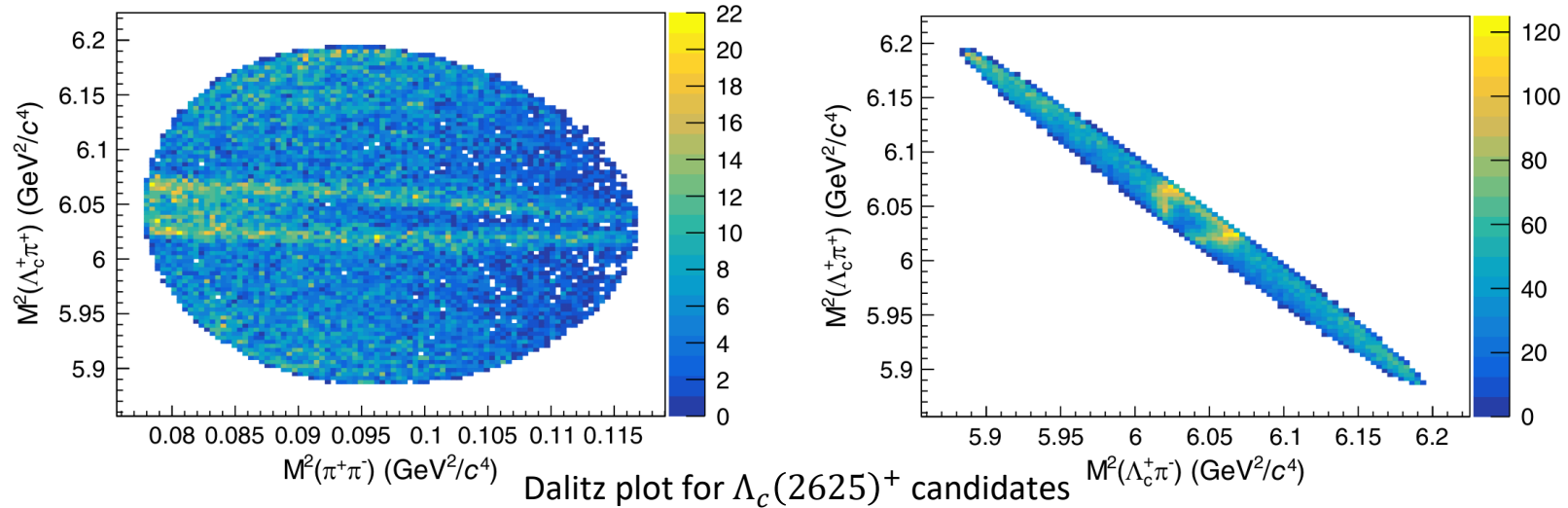
$$\Gamma(\Lambda_c(2625)^+) < 0.52 \text{ MeV}/c^2$$

- ❑ 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.

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

■ Measurements of branching fractions

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



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

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

■ Measurements of branching fractions

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

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

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

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

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

- 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 \(2018\)](#)].

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

[JHEP01 \(2023\) 055](#)

■ Motivation

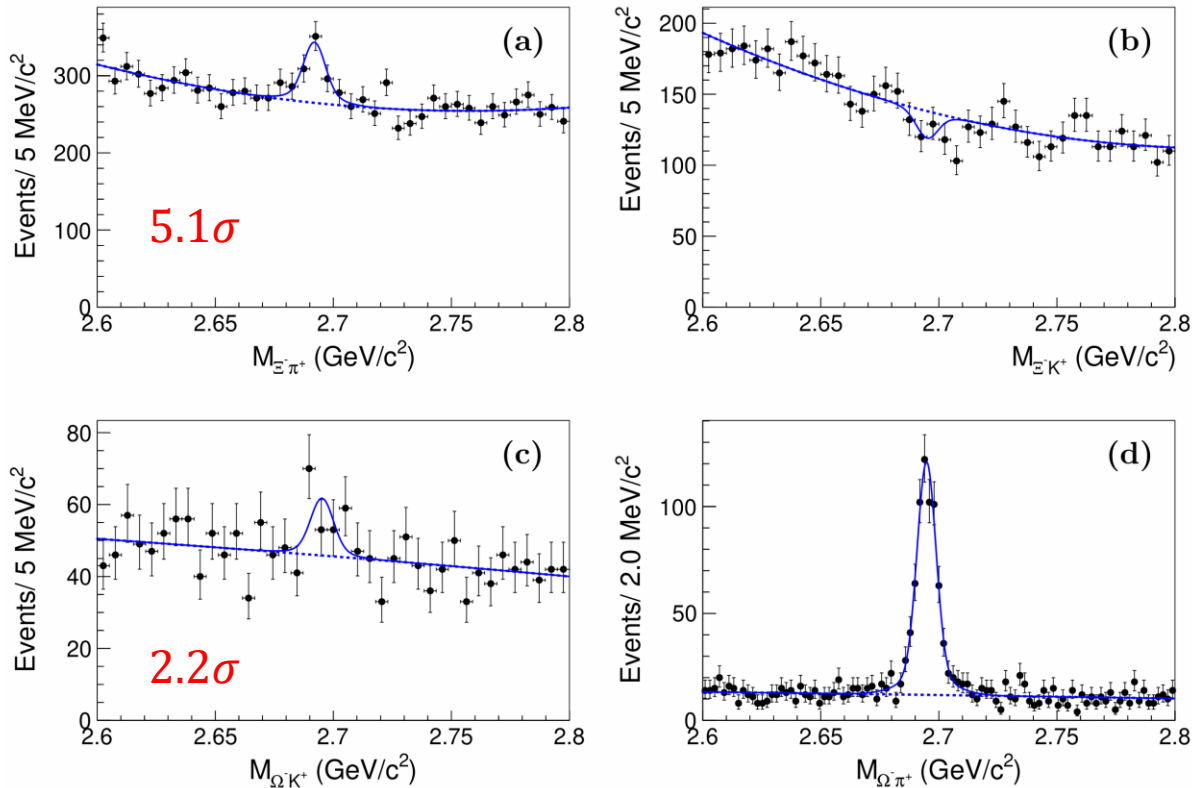
- Ω_c^0 ($J^P = 1/2^+$) is the **heaviest singly-charmed hadron** that decays weakly. The knowledge of the Ω_c^0 state is **limited** compared with Λ_c^+ , $\Xi_c^{0,+}$.
- No measurements of the **absolute BF of the Ω_c^0** are reported, but some measurements of the BF ratios for Ω_c^0 decay modes **with respect to the reference mode $\Omega_c^0 \rightarrow \Omega^- \pi^+$** 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 $\Omega_c^0 \rightarrow \Xi^- \pi^+$, $\Xi^- K^+$ are listed. No prediction is available for $\Omega^- K^+$. **No measurements** of these decays are made.

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

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

■ Branching fraction ratios

980 fb⁻¹



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

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

Measured for
the first time

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 $B(\Lambda_c^+ \rightarrow \Sigma^+ \eta(\eta'))$ with the **best precision** to date and asymmetry parameters of $\Lambda_c^+ \rightarrow \Sigma^+ \eta(\eta')$ **for the first time**.
 - Measurement of $B(\Lambda_c^+ \rightarrow p K_S^0 K_S^0)$ for **the first time** and $B(\Lambda_c^+ \rightarrow p K_S^0 \eta)$ with **threefold improvement** in precision.
 - **Most precise** $\Lambda_c(2625)^+$ mass, width, and branching fraction ratios to date.
 - **Evidence for** $\Omega_c^0 \rightarrow \Xi^- \pi^+$ and measurements of $B(\Omega_c^0 \rightarrow \Xi^- \pi^+, \Xi^- K^+, \Omega^- K^+)$.
- 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!