Recent Results on Charmed Baryons at Belle

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Outline

- **Introduction**

- **Observation of $\Xi_c(2930)^0$ and evidence of $\Xi_c(2930)^+$**

- **First measurements of Ξ_c absolute branching fractions**

- **First measurements of $B^- \to \overline{\Lambda}_c^- \Xi_c^{*0}$ branching fractions**

- **Determination of $\Lambda_c/\Sigma_c(2765)^+$ isospin**

- **Summary & prospect**

Thank Yubo Li (李郁博) , Peking Univ. and Chengping Shen (沈成平), Fudan Univ. for their good works.

Introduction to charmed baryon studies(I)

- The singly charmed baryon is composed of a charm quark and two light quarks.

- Charmed baryon spectroscopy provides an excellent ground for studying the dynamics of light quarks in the environment of a heavy quark.

- Charmed baryon spectroscopy also offers an excellent laboratory for testing heavy-quark symmetry of c and b quarks or chiral symmetry of light quarks, both of which have important implications for the low-energy dynamics of heavy baryons interacting with Goldstone bosons.

- Weak decays of charmed hadrons play a unique role in the study of strong interactions, as the charm mass scale is near the boundary between perturbative and non-perturbative QCD.

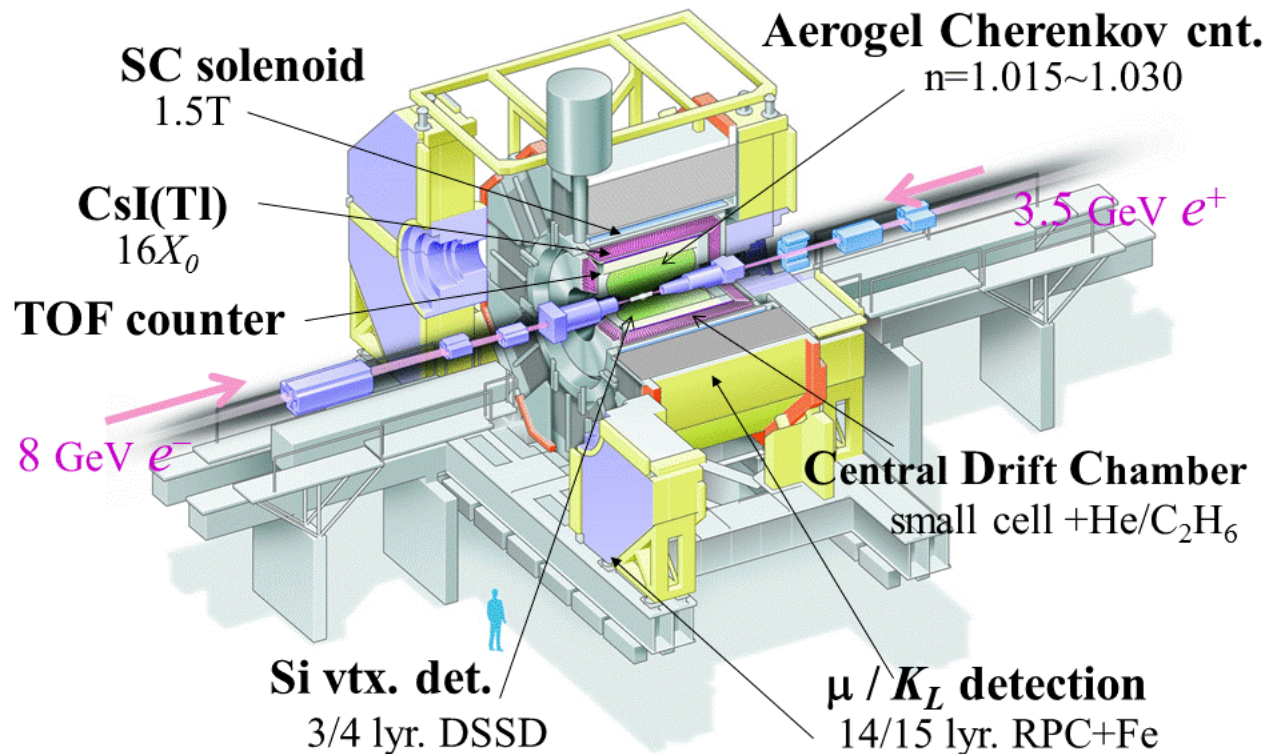- Decays of charmed baryons provide complementary information to that of charmed-meson decays.
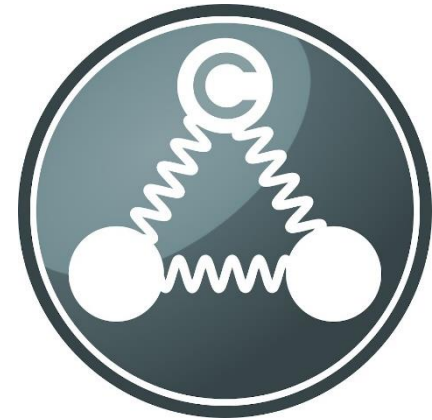
Introduction to charmed baryon studies(II)

- Although many charmed baryons have been discovered, there are still some unobserved.
  - Observation of them will provide more information to understand the physics in the charmed baryon sector.

- Although many efforts have been made to identify the quantum numbers of discovered charmed baryons, but most of them have not yet been determined experimentally.
  - Determination of them helps to figure out the nature of the charmed baryons.

- Decays of charmed mesons (D^0, D^+, and D_s^+) are all well measured, but except for Λ_c^+ , absolute branching fractions (BFs) of charmed baryons have not yet been measured.
  - Measurement of the absolute BFs is crucial to validate relevant theoretical models as well as to constrain the model parameters.

Introduction to Belle experiment

Belle Detector

SC solenoid
1.5T

CsI(Tl)
$16X_0$

TOF counter

$8 \text{ GeV } e^-$

Si vtx. det.
3/4 lyr. DSSD

Aerogel Cherenkov cnt.
n=1.015~1.030

$3.5 \text{ GeV } e^+$

Central Drift Chamber
small cell +He/C_2H_6

μ / K_L **detection**
14/15 lyr. RPC+Fe

Data taking: 1999—2010

On/off/Scan Y(nS) peaks

Total luminosity: 980 fb^{-1}

772M $B\overline{B}$ events @ Y(4S)

Observation of $\Xi_c(2930)^0$ and Evidence of $\Xi_c(2930)^+$

- **Observation of $\Xi_c(2930)^0$**
  in $K^-\Lambda_c^+$ of $B^- \to K^-\Lambda_c^+\overline{\Lambda}_c^-$

  [EPJC 78, 252]

- **Evidence of $\Xi_c(2930)^+$**
 **in $\overline{K}^0\Lambda_c^+$ of $\overline{B}^0 \to \overline{K}^0\Lambda_c^+\overline{\Lambda}_c^-$**

  [EPJC 78, 928]

- BarBar studied $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$, and found a vague structure named $\Xi_c(2930)$ in $M_{K^+\Lambda_c^+}$ spectrum and two small peaks in $M_{\Lambda_c^+\bar{\Lambda}_c^-}$ spectrum. [PRD 77, 031101].
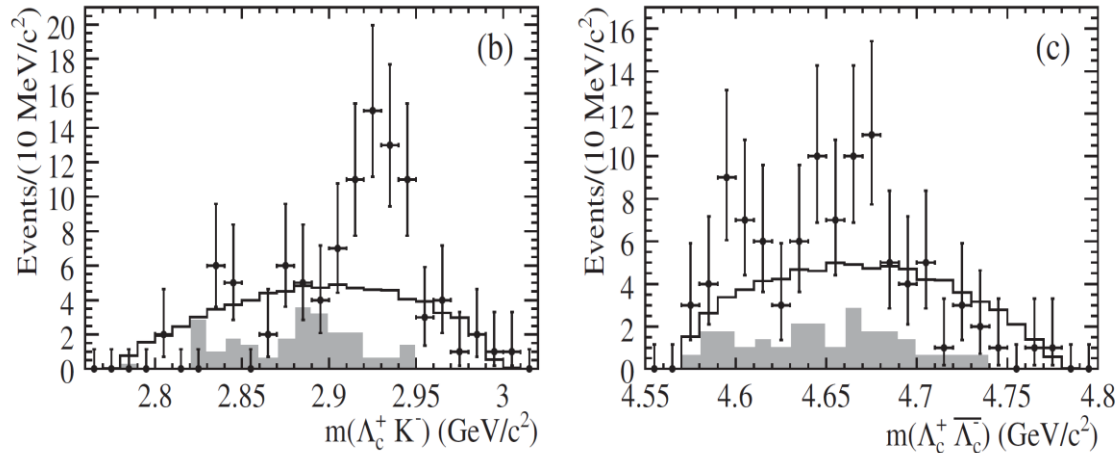
- $\Xi_c(2930)$ a mass of $[2931 \pm 3(\text{stat.}) \pm 5(\text{syst.})]$ MeV/c^2 and a width of $[36 \pm 7(\text{stat.}) \pm 11(\text{syst.})]$ MeV. $\Xi_c(2930)$ *

  Neither the results of the fit to their spectrum
  nor the significance of the signal were given

- Belle has previously studied $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ with **386M $B\bar{B}$ events** but the distributions of the intermediate $K^- \Lambda_c^+$ systems have not been presented. [PRL 97, 202003]

- **A good chance to use the full Belle data sample of 772M $B\bar{B}$ events to test the existence of $\Xi_c(2930)$**

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Motivation (II)

- Belle reported a structure named $\mathbf{Y(4630)}$ in $\mathbf{M(\Lambda_c^+ \bar{\Lambda}_c^-)}$ spectrum of $\mathbf{e^+ e^- \rightarrow \gamma_{ISR} \Lambda_c^+ \bar{\Lambda}_c^-}$ [PRL 101, 172001]
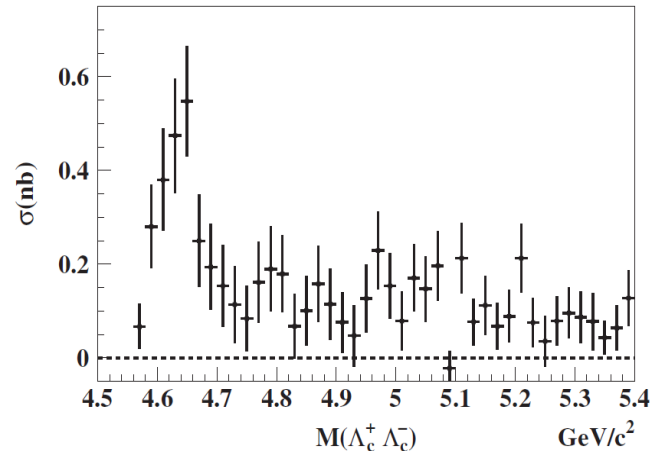
- As its mass is very close to that of the $\mathbf{Y(4660)}$ observed by Belle in $\mathbf{M(\pi^+ \pi^- \psi')}$ spectrum of $\mathbf{e^+ e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- \psi'}$, many theoretical explanations assume they are the same.
- Also, some theory explained that $\mathbf{Y(4660)}$ has a large partial decay width to $\Lambda_c^+ \bar{\Lambda}_c^-$ and it's spin partner $\mathbf{Y_\eta}$ is predicted. [PRD 82, 094008; PRL102, 242004]
- So the $\mathbf{B \rightarrow K \Lambda_c^+ \bar{\Lambda}_c^-}$ decay mode can be used to **search for Y(4660) and Y_η** by studing $\mathbf{M(\Lambda_c^+ \bar{\Lambda}_c^-)}$ spectrum.

Observation of $\Xi_c(2930)^0$ in $K^-\Lambda_c^+$ of $B^- \to K^-\Lambda_c^+\overline{\Lambda}_c^-$

$M_{K\Lambda_c}$ (GeV/c²)

5.1σ
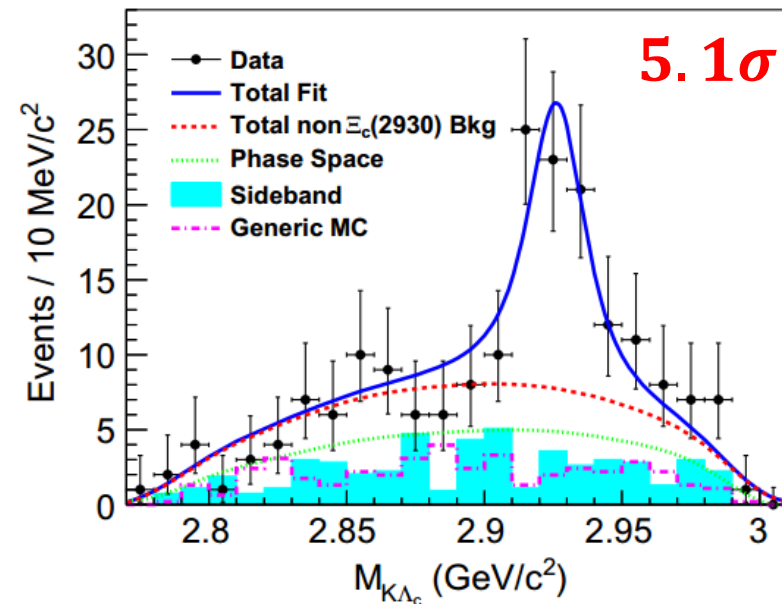
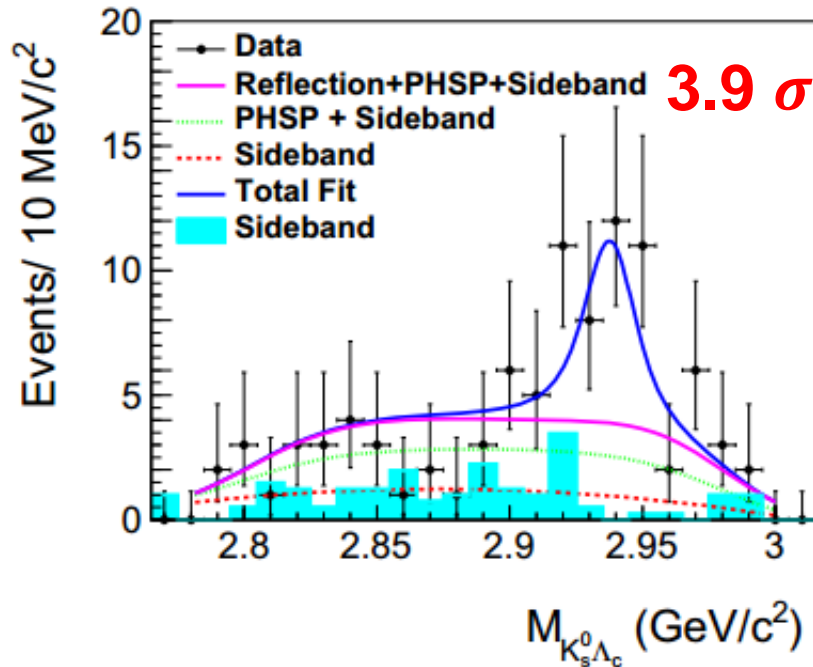- First strange-charmed baryon established in B decays

- Clear confirmation of the Babar claim

$N_{\Xi_c} = 61 \pm 16$

$M_{\Xi_c(2930)} = (2928.9 \pm 3.0^{+0.9}_{-12.0})$ MeV/c²

$\Gamma_{\Xi_c(2930)} = (19.5 \pm 8.4^{+5.9}_{-7.9})$ MeV.

$\mathcal{B}(B^- \to \Xi_c(2930)\overline{\Lambda}_c^-)\mathcal{B}(\Xi_c(2930) \to K^-\Lambda_c^+) = (1.73 \pm 0.45 \pm 0.21) \times 10^{-4}.$

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Evidence of $\Xi_c(2930)^+$ in $\bar{K}^0 \Lambda_c^+$ of $\bar{B}^0 \to \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-$

3.9 σ

The mass and width difference between neutral and charged $\Xi_c(2930)$

$$\Delta m = [-13.4 \pm 5.3(\text{stat.})^{+1.7}_{-12.1}(\text{syst.})] \text{ MeV}/c^2$$

$$\Delta \Gamma = [4.7 \pm 12.2(\text{stat.})^{+6.4}_{-8.3}(\text{syst.})] \text{ MeV}$$

After this measurement, $* \to **$
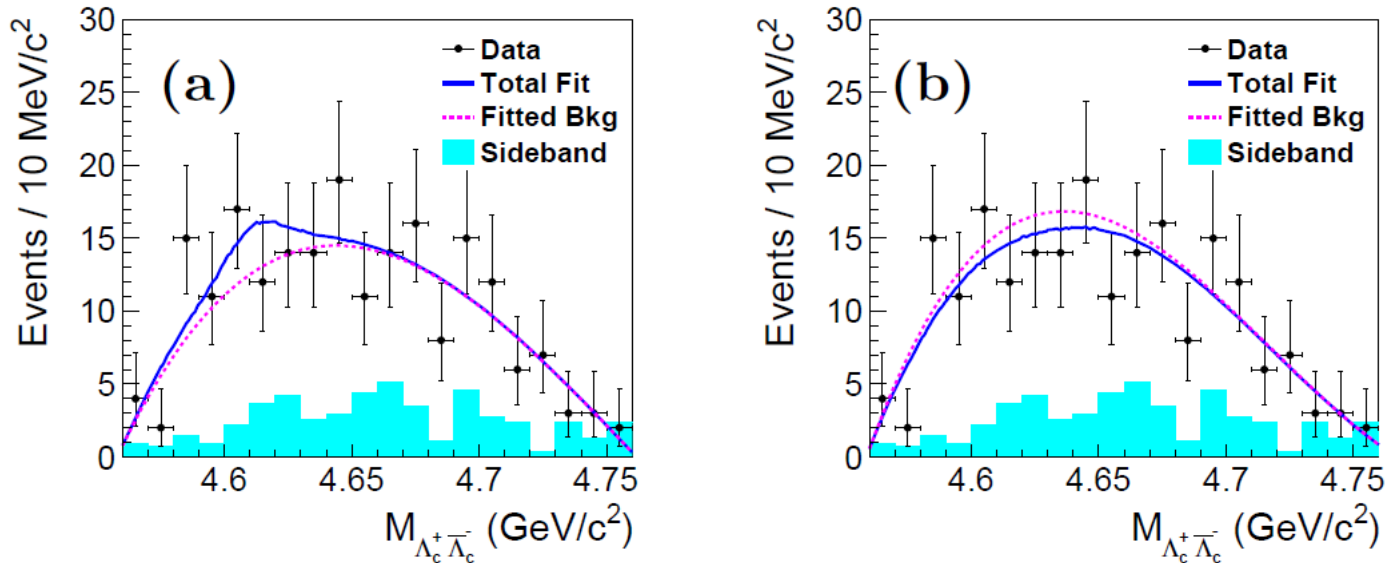
$\boxed{\Xi_c(2930)}$

$I(J^P) = ?(?^?)$ Status: $**$

$$N_{\Xi_c(2930)^+} = 21.2 \pm 4.6$$

$$M_{\Xi_c(2930)^+} = [2942.3 \pm 4.4(\text{stat.}) \pm 1.5(\text{syst.})] \text{ MeV}/c^2$$

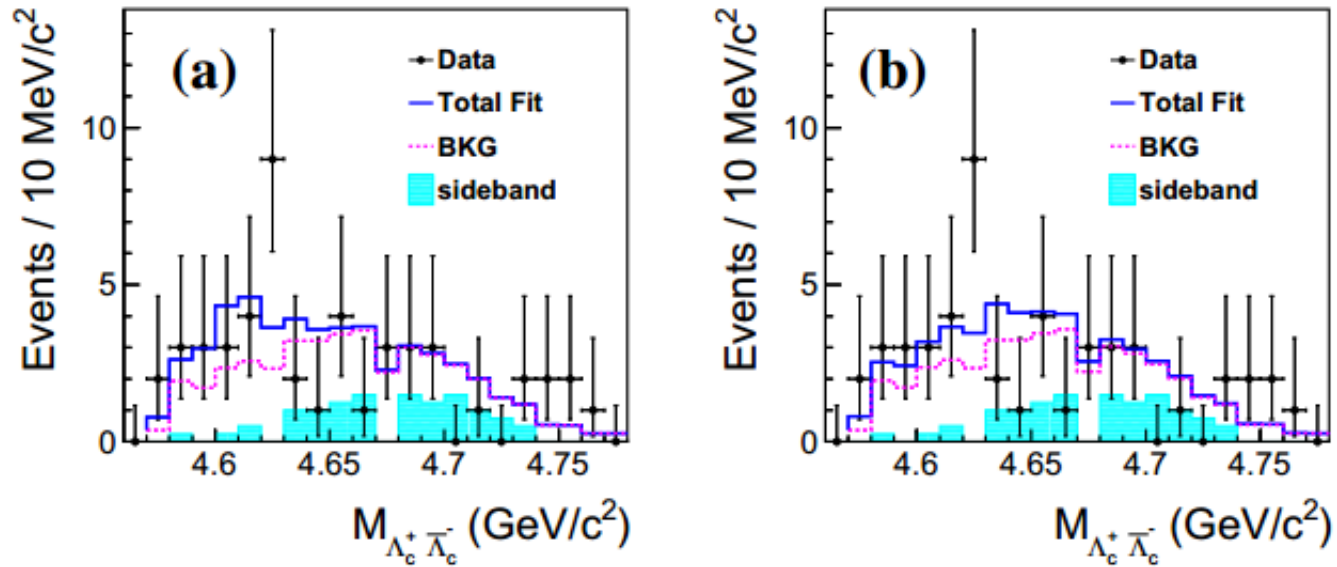$$\Gamma_{\Xi_c(2930)^+} = [14.8 \pm 8.8(\text{stat.}) \pm 2.5(\text{syst.})] \text{ MeV}.$$

$$\mathcal{B}(\bar{B}^0 \to \Xi_c(2930)^+ \bar{\Lambda}_c^-)\mathcal{B}(\Xi_c(2930)^+ \to \bar{K}^0 \Lambda_c^+) = [2.37 \pm 0.51(\text{stat.}) \pm 0.31(\text{syst.})] \times 10^{-4}$$

- No **$Y(4660)$** and **Y_η** signals were observed in the **$\Lambda_c^+ \bar{\Lambda}_c^-$** invariant mass distribution of $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$.
- 90% C.L. upper limits of $B^- \to K^- Y(4660) \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ and $B^- \to K^- Y_\eta \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ are 1.2×10^{-4} and 2.0×10^{-4}.

Search for $Y(4660)$ and Y_η in $\Lambda_c^+\overline{\Lambda}_c^-$ of $\overline{B}^0 \to \overline{K}^0\Lambda_c^+\overline{\Lambda}_c^-$

- No $Y(4660)$ and Y_η signals were observed in the $\Lambda_c^+\overline{\Lambda}_c^-$ invariant mass distribution of $\overline{B}^0 \to \overline{K}^0\Lambda_c^+\overline{\Lambda}_c^-$.

- 90% C.L. upper limits of $\overline{B}^0 \to \overline{K}^0 Y(4660) \to \overline{K}^0\Lambda_c^+\overline{\Lambda}_c^-$ and $\overline{B}^0 \to \overline{K}^0 Y_\eta \to \overline{K}^0\Lambda_c^+\overline{\Lambda}_c^-$ are 2.2×10^{-4} and 2.3×10^{-4}.

First Measurements of Absolute Branching Fractions of the Ξ_c^0 and Ξ_c^+ Baryons

$B^- \to \overline{\Lambda}_c^- \Xi_c^0$:
- $\Xi_c^0 \to \Xi^- \pi^+$
- $\Xi_c^0 \to \Lambda K^- \pi^+$
- $\Xi_c^0 \to p K^- K^- \pi^+$

[PRL 122, 082001]

$\overline{B}^0 \to \overline{\Lambda}_c^- \Xi_c^+$:
- $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
- $\Xi_c^+ \to p K^- \pi^+$

[PRD 100, 031101 (R)]

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Motivation (I)

- In SU(3) anti-triplet charmed baryons, only Λ_c^+ absolute BFs were measured by Belle [PRL 113, 042002] and BESIII [PRL 116,052001]

- Though Ξ_c^0 [PRL 62,863(1989)] and Ξ_c^+ [PLB 122,455(1983)] have been discovered for ~30 years, no absolute BFs were measured

- For Ξ_c^0, the BFs are all measured relative to $\Xi^- \pi^+$
- For Ξ_c^+, the BFs are all measured relative to $\Xi^- \pi^+ \pi^+$

- Once the absolute BFs of $\Xi_c^0 \rightarrow \Xi^- \pi^+$ and $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ are measured, the absolute values of all the BFs measured relative to them can be calculated

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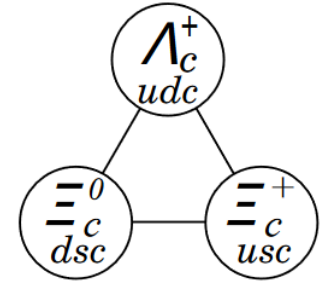
- $\Xi_c^0 \rightarrow pK^-K^-\pi^+$ and $\Xi_c^+ \rightarrow pK^-\pi^+$ are the fundamental decay modes to reconstruct Ξ_c^0 and Ξ_c^+ at **LHCb**

  ➢ Their absolute BFs are important input for the studies of **bottom baryons** and **double charmed baryons** at **LHCb**

- In theory:

  $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+) \approx 1.12\%$ or 0.74% [PRD48,4188]

  $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = (1.47 \pm 0.84)\%$ [PRD97,073006]

  $\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = (2.2 \pm 0.8)\%$ [EPJC78,224; CPC42,051001]

  ➢ Experimental information is crucial to **validate theoretical models** and **constrain model parameters**

- The decay $B \rightarrow \overline{\Lambda}_c^- \Xi_c$, proceeds via the transition $b \rightarrow c\bar{c}s$, **BF** $\sim 10^{-3}$ in theoretical calculation

  ➢ A good chance to analyze $B \rightarrow \overline{\Lambda}_c^- \Xi_c$ at Belle

Method

- Measured by Ξ_c exclusive decays
- Fully reconstruct the signals
- Extract signal yields from ΔE and M_{bc}

$$\Delta E = \Sigma_i E_i - E_{\text{beam}}$$
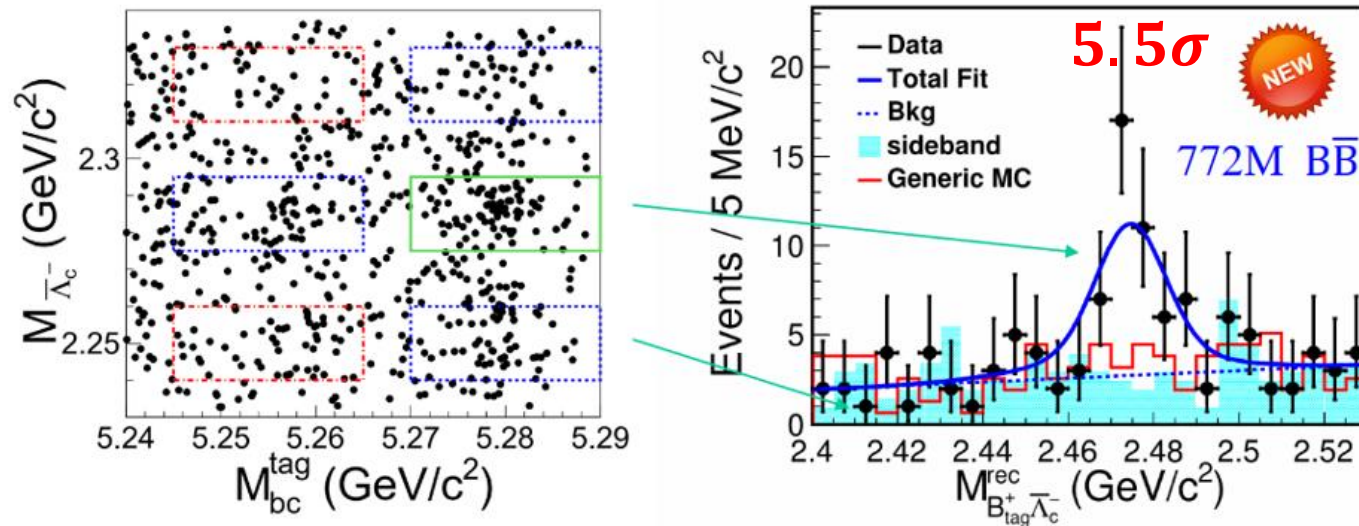
$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - (\Sigma_i \vec{p}_i)^2}$$

$$\mathcal{B}(\Xi_c \to xxx) = \frac{\mathcal{B}(B \to \overline{\Lambda}_c^- \Xi_c)\mathcal{B}(\Xi_c \to xxx)}{\mathcal{B}(B \to \overline{\Lambda}_c^- \Xi_c)}$$

Data sample of 772M $B\overline{B}$ events @ Y(4S)

- Measured by Ξ_c inclusive decays
- Tag a B and reconstruct a $\overline{\Lambda}_c^-$
- Using a missing-mass technique
- Extract signal yields from $M_{B_{\text{tag}}^0 \overline{\Lambda}_c^-}^{\text{rec}}$ spectra

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- B^+ tagged with **FR** algorithm
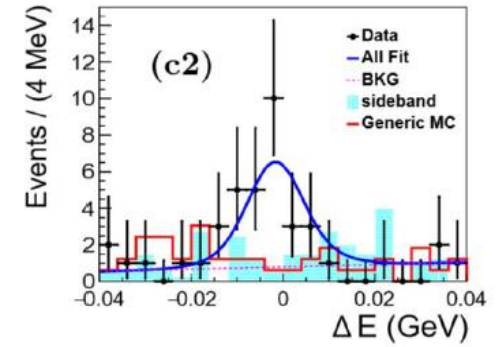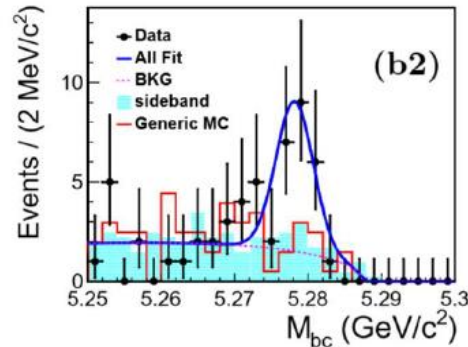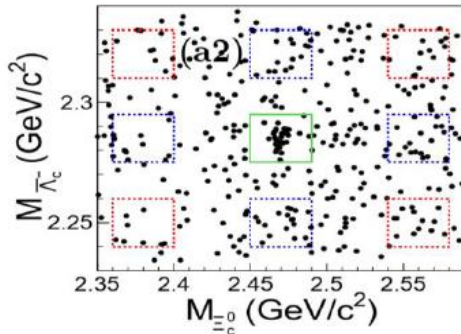- $\overline{\Lambda}_c^-$ reconstructed via $\overline{p}K^+\pi^-$ and $\overline{p}K_s^0$

- Fitted result: $N\left(\Xi_c^0\right) = 40.9 \pm 9.0$

- $\mathcal{B}\left(B^- \to \overline{\Lambda}_c^- \Xi_c^0\right) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$

- First measurement of $\mathcal{B}\left(B^- \to \overline{\Lambda}_c^- \Xi_c^0\right)$

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Ξ_c^0 exclusive yields

$\Xi^-\pi^+$
44.8 ± 7.3
9.5σ

$\Lambda K^-\pi^+$
24.1 ± 5.5
6.8σ

$pK^-K^-\pi^+$
16.6 ± 5.4
4.6σ
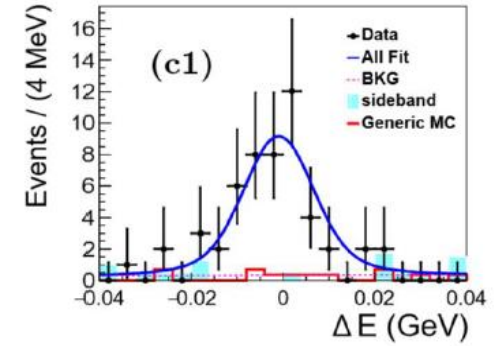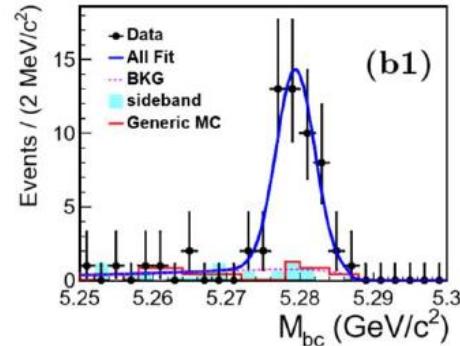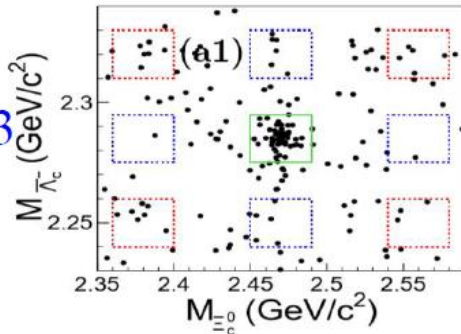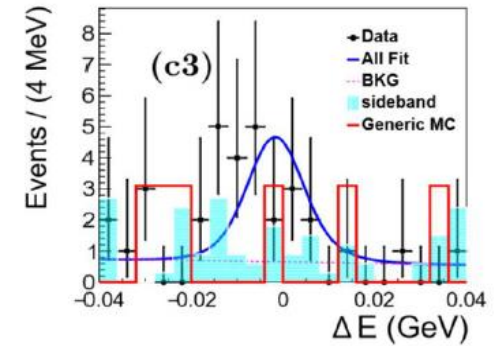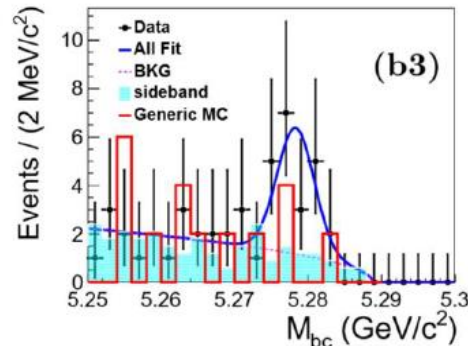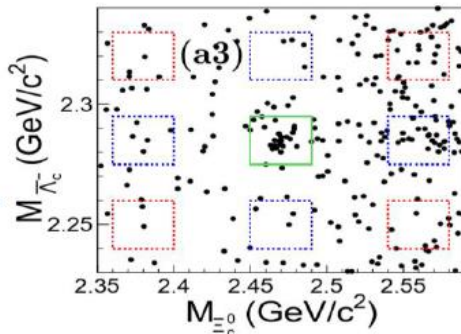
Ξ_c^0 exclusive BFs

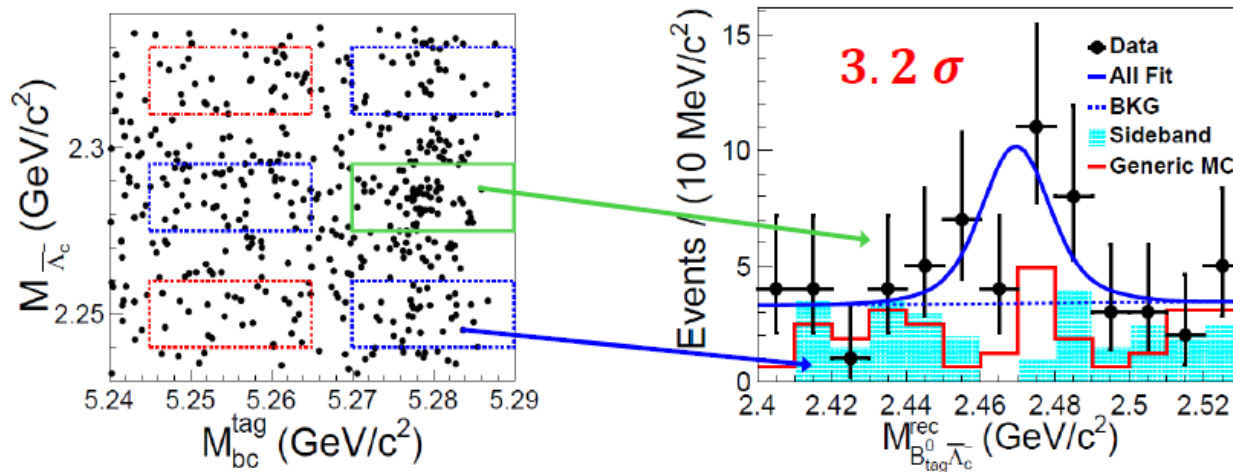| BF	Result	Theory	PDG
$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^0)$	$(9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$	$\sim 10^{-3}$	
$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^0)\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$(1.71 \pm 0.28 \pm 0.15) \times 10^{-5}$		$(2.4 \pm 0.9) \times 10^{-5}$
$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^0)\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)$	$(1.11 \pm 0.26 \pm 0.10) \times 10^{-5}$		$(2.1 \pm 0.9) \times 10^{-5}$
$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^0)\mathcal{B}(\Xi_c^0 \to pK^- K^- \pi^+)$	$(5.47 \pm 1.78 \pm 0.57) \times 10^{-6}$		
$\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$(1.80 \pm 0.50 \pm 0.14)\%$	1.12% or 0.74%	
$\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)$	$(1.17 \pm 0.37 \pm 0.09)\%$		
$\mathcal{B}(\Xi_c^0 \to pK^- K^- \pi^+)$	$(0.58 \pm 0.23 \pm 0.05)\%$		
$\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.65 \pm 0.18 \pm 0.04$		1.07 ± 0.14
$\mathcal{B}(\Xi_c^0 \to pK^- K^- \pi^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.32 \pm 0.12 \pm 0.07$		0.34 ± 0.04

PRL 122, 082001

- **First** measurements of absolute BFs of Ξ_c^0
- $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ can be used to determine the absolute values of other Ξ_c^0 decay BRs

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Measurement of $\mathcal{B}\left(\overline{B}^0 \rightarrow \overline{\Lambda}_c^- \Xi_c^+\right)$

- B^0 Tagged with **FR** algorithm
- $\overline{\Lambda}_c^-$ reconstructed via $\overline{p}K^+\pi^-$

- Fitted result: $N(\Xi_c^+) = 18.8 \pm 6.8$
- $\mathcal{B}\left(\overline{B}^0 \rightarrow \overline{\Lambda}_c^- \Xi_c^+\right) = (1.16 \pm 0.42 \pm 0.15) \times 10^{-4}$
- First model-independent measurement of $\mathcal{B}\left(\overline{B}^0 \rightarrow \overline{\Lambda}_c^- \Xi_c^+\right)$

$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
N = 24.2 ± 5.4

6.9σ

$\Xi_c^+ \to pK^- \pi^+ N$
= 24.0 ± 6.9

4.5σ

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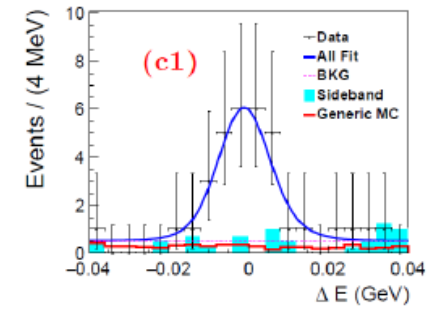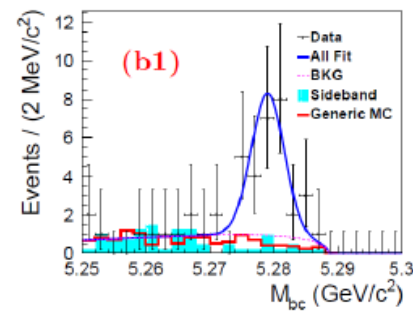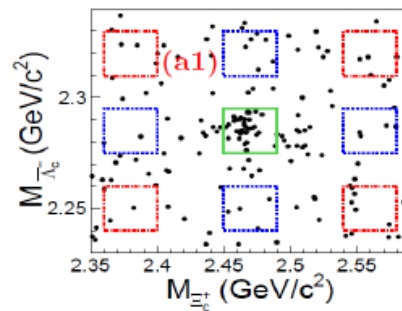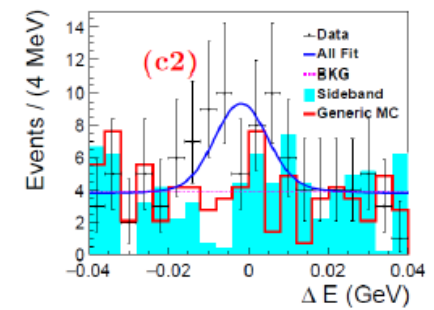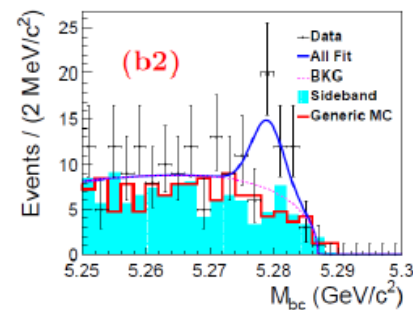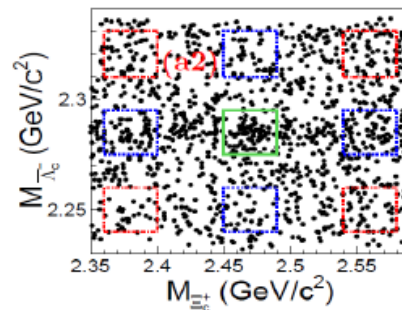
Ξ_c^+ exclusive BFs

BF	Result	Theory	PDG
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+)$	$(1.16 \pm 0.42 \pm 0.15) \times 10^{-3}$	$\sim 10^{-3}$	
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+))\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$(3.32 \pm 0.74 \pm 0.33) \times 10^{-5}$		$(1.8 \pm 1.8) \times 10^{-5}$
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+)\mathcal{B}(\Xi_c^+ \to pK^- \pi^+)$	$(5.27 \pm 1.51 \pm 0.69) \times 10^{-5}$		
$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$(2.86 \pm 1.21 \pm 0.38)\%$	$(1.47 \pm 0.84)\%$	
$\mathcal{B}(\Xi_c^+ \to pK^- \pi^+)$	$(0.45 \pm 0.21 \pm 0.07)\%$	$(2.2 \pm 0.8)\%$	
$\mathcal{B}(\Xi_c^+ \to pK^- \pi^+)/\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$0.16 \pm 0.06 \pm 0.02$		0.21 ± 0.04

PRD 100, 031101(R)

- **First** measurements of absolute BFs of Ξ_c^+
- $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ can be used to determine the absolute values of other Ξ_c^+ decay BFs
- $\mathcal{B}(\Xi_c^+ \to pK^- \pi^+)$ is smaller theoretical prediction
  - ➤ Indicating a large U-spin symmetry breaking？

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Summary

- We studied $B \to \overline{\Lambda}_c^- \Xi_c^{0,+}$ with $\Xi_c^{0,+}$ decay exclusively and inclusively

- The absolute BFs of $\Xi_c^{0,+}$ are measured for the first time

Ξ_c^0	
$\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$(1.80 \pm 0.50 \pm 0.14)\%$
$\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)$	$(1.17 \pm 0.37 \pm 0.09)\%$
$\mathcal{B}(\Xi_c^0 \to p K^- K^- \pi^+)$	$(0.58 \pm 0.23 \pm 0.05)\%$

Ξ_c^+	
$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$(2.86 \pm 1.21 \pm 0.38)\%$
$\mathcal{B}(\Xi_c^+ \to p K^- \pi^+)$	$(0.45 \pm 0.21 \pm 0.07)\%$

- The absolute BFs of $B \to \overline{\Lambda}_c^- \Xi_c^{0/+}$ are measured for the first time as well

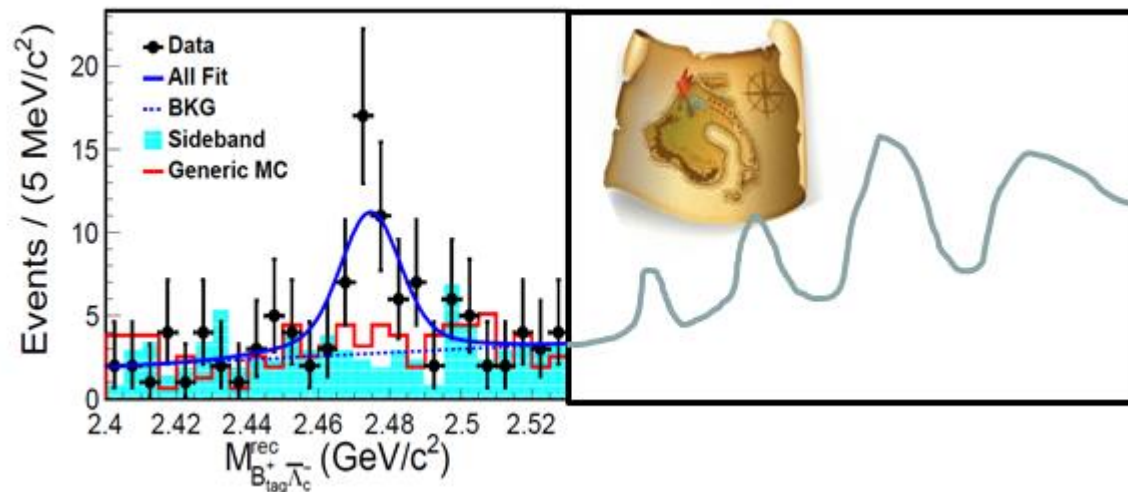|	
$\mathcal{B}(B^- \to \overline{\Lambda}_c^- \Xi_c^0)$	$(9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$

$\mathcal{B}(\overline{B}^0 \to \overline{\Lambda}_c^- \Xi_c^+)$	$(1.16 \pm 0.42 \pm 0.15) \times 10^{-3}$

First measurements of $B^- \to \overline{\Lambda}_c^- \Xi_c^{*0}$ branching fractions

- $B^- \to \overline{\Lambda}_c^- \Xi_c'^0$
- $B^- \to \overline{\Lambda}_c^- \Xi_c(2645)^0$
- $B^- \to \overline{\Lambda}_c^- \Xi_c^0(2970)^0$

(Paper draft is in the final polishment stage)

Motivation

- In the previous part of this talk, the absolute BFs of $B \to \overline{\Lambda}_c^- \Xi_c^{0/+}$ as well as the absolute BFs of $\Xi_c^{0,+}$ are measured

- In those works, only the $\Xi_c^{0/+}$ region of $\overline{\Lambda}_c^-$ recoil mass is focused on.

- A natural question is: can we observe the excited Ξ_c states in the higher region of $\overline{\Lambda}_c^-$ recoil mass.

- In this part, we present the first measurements of branching fractions of the decays $B^- \to \overline{\Lambda}_c^- \Xi_c'^0$, $B^- \to \overline{\Lambda}_c^- \Xi_c(2645)^0$, and $B^- \to \overline{\Lambda}_c^- \Xi_c^0(2970)^0$, using a missing-mass technique.

- We measure the branching fractions via the **inclusive Ξ_c^{*0}** decays, and do not see significant signals in the **exclusive Ξ_c^{*0}** decays

Result of $\mathcal{B}(\bar{B}^- \to \bar{\Lambda}_c^- \Xi_c^{*0})$
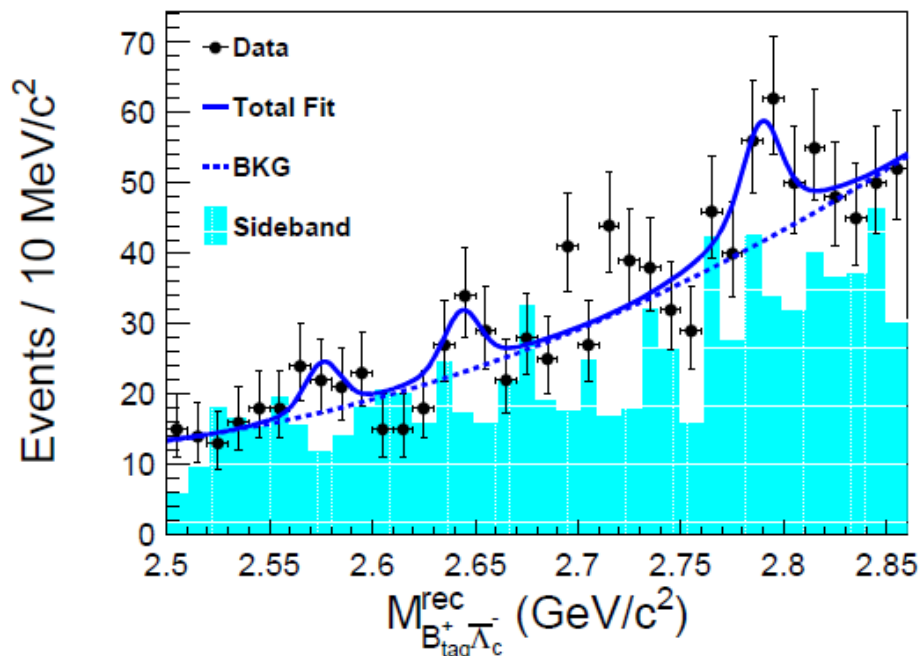
The empty space between the fitted background level and the normalized sidebands histogram is the contribution from other multi-body $B^- \to \bar{\Lambda}_c^- + anything$ decays.

Since in the fit to the data the statistical significances of $\Xi_c^{'0}$ and $\Xi_c(2645)^0$ are less than 3σ, upper limits at 90% credibility level (C.L.) on the numbers of $\Xi_c^{'0}$ and $\Xi_c(2645)^0$ are determined.

	N_{sig}	$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^{*0})$ [Upper Limit]	Significance (σ)
$\Xi_c^{'0}$	18 ± 10	$(3.4 \pm 2.0 \pm 0.4) \times 10^{-4}$ $[6.5 \times 10^{-4}]$	1.7
$\Xi_c(2645)^0$	24 ± 13	$(4.4 \pm 2.4 \pm 0.5) \times 10^{-4}$ $[7.9 \times 10^{-4}]$	1.9
$\Xi_c(2790)^0$	60 ± 22	$(1.1 \pm 0.4 \pm 0.2) \times 10^{-3}$	3.1

Experimental Determination of the Isospin of $\Lambda_c/\Sigma_c(2765)^+$

- **Search for its isospin partners in $\Sigma_c(2455)^{++/0} \, \pi^0$**

[arXiv:1908.06235]

Introduction (I)

- A few dozens of **charmed baryons** have been discovered, but in most cases their **quantum numbers** have not yet been determined experimentally [PRD 98, 030001]

- In particular, for higher excited states with excitation energies greater than **400 MeV**, unique identification is not possible, because quark models predict several states within their typical mass uncertainties of **~50 MeV/c^2** [PRD 34, 2809; IJMPA 23, 2817; PRD 92, 114029]

- **$\Lambda_c/\Sigma_c(2765)^+$** is the **lightest** charmed baryon for which there is no assumed quark-model identification.
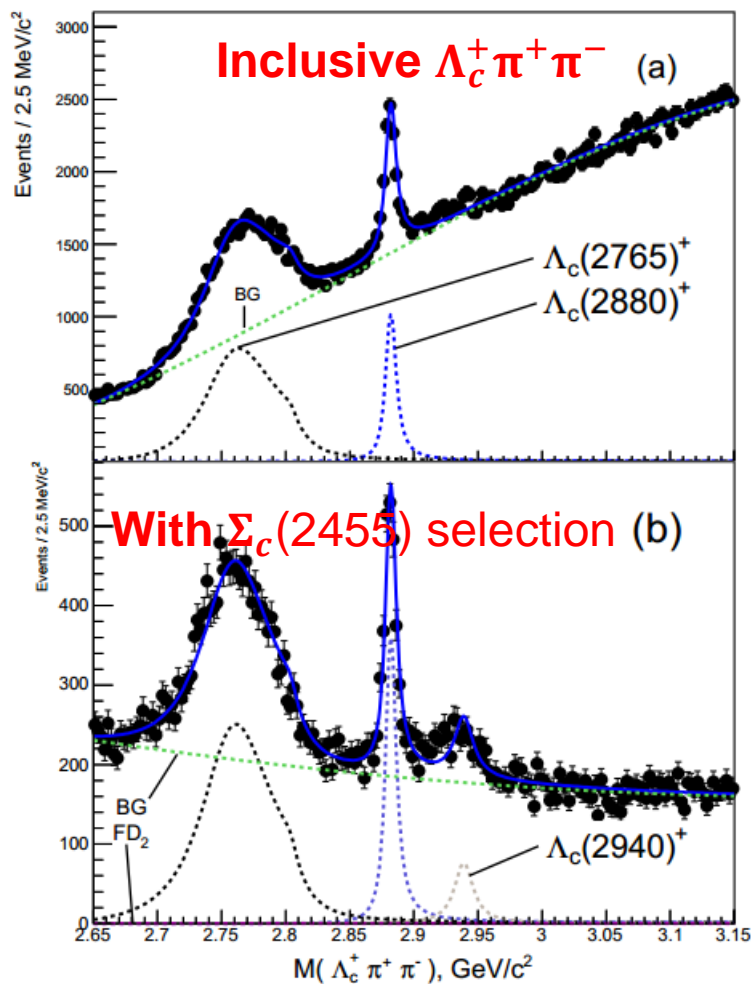
$\Lambda_c(2765)^+$
or $\Sigma_c(2765)$

$I(J^P) = ?(?^?)$ Status: $*$
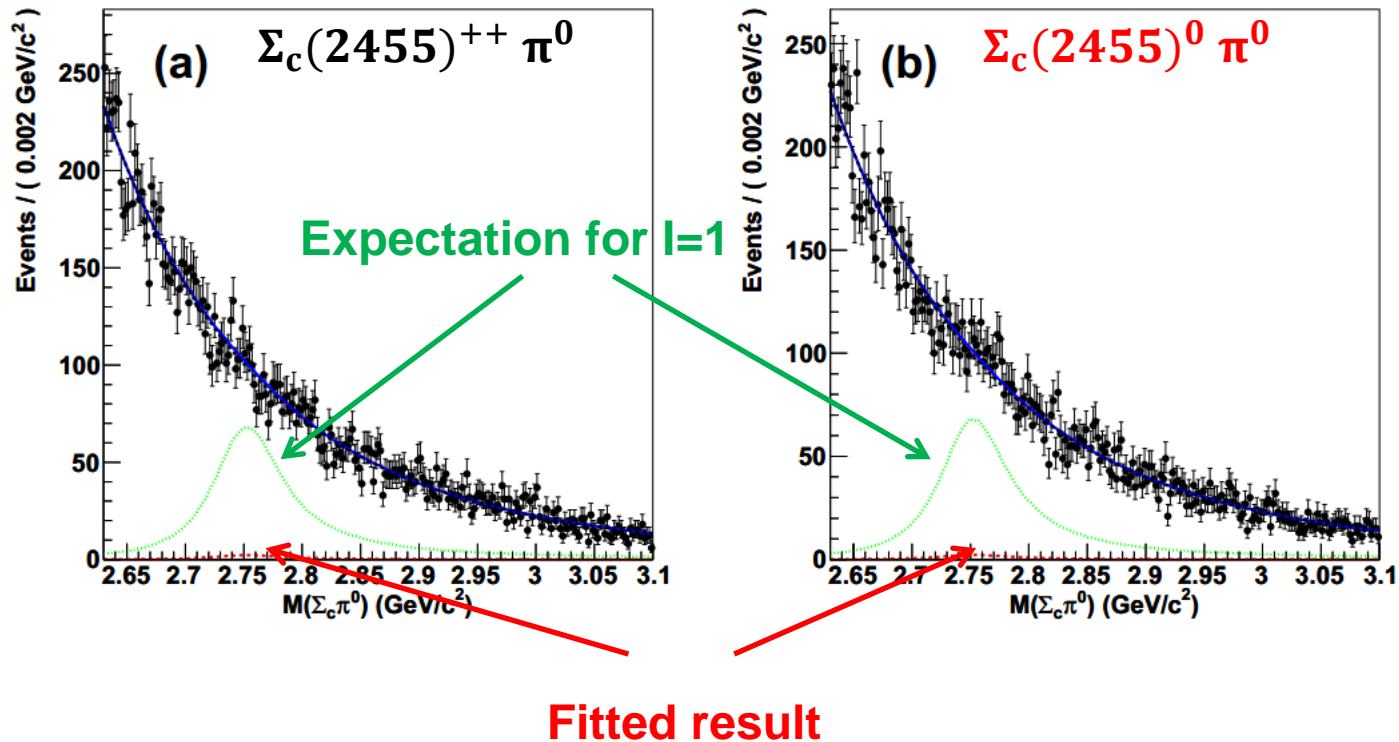
Introduction (II)

- $\Lambda_c/\Sigma_c(2765)^+$ is first observed by **CLEO** in $\Lambda_c^+\pi^+\pi^-$ [PRL 86, 4779] and later confirmed by **Belle** in $\Sigma_c(2455)^{++/0}\pi^{-/+}$ [PRL 98, 262001]

- Quark models: **six** states in this mass region

  $I(J^P) = 0(1/2^+), 0(1/2^-), 1(1/2^-), 1(1/2^-), 1(3/2^-), 1(3/2^-),$

  ➢ Including other models, any combination of **I=0 or 1**, **J=1/2 or 3/2**, and **P=+ or –** seems possible

- Experimental determination of $I(J^P)$ is necessary to identify the nature of $\Lambda_c/\Sigma_c(2765)^+$

- In this part, we present a determination of the isospin of $\Lambda_c/\Sigma_c(2765)^+$ by searching for its possible isospin partners $\Sigma_c(2765)^{++/0}$ in the $\Sigma_c(2455)^{++/0}\pi^0 \rightarrow \Lambda_c^+\pi^{+/-}\pi^0$ modes

- Determination of **spin-parity (J^P)** will be coming soon.

Reference mode: $\Sigma_c(2455)^{++/0}\pi^{-/+}$

- Analyzed with full Belle datasets of $980\ \mathbf{fb^{-1}}$

- Clear peaks of $\Lambda_c/\Sigma_c(2765)^+$ are observed

- Fit with **Breit-Wigner** functions to extract signal yields.

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Result of Searching for $\Sigma_c(2455)^{++/0}\,\pi^0$

(a) $\Sigma_c(2455)^{++}\,\pi^0$

(b) $\Sigma_c(2455)^0\,\pi^0$

Expectation for I=1

Fitted result

- No significant $\Sigma_c(2455)^{++/0}\,\pi^0$ signals are seen, contrary to the expectation for **I=1**
- Isospin of $\Lambda_c/\Sigma_c(2765)^+$ is **not 1 but 0**; the name should be $\Lambda_c(2765)^+$

Summary & prospect

- Although Belle stopped data taking about ten years ago, it is still producing many excited results on charmed baryons

  - Observation of $\Xi_c(2930)^0$ and evidence of $\Xi_c(2930)^+$

  - First measurements of Ξ_c absolute branching fractions

  - First measurements of $B^- \rightarrow \overline{\Lambda}_c^- \Xi_c^{*0}$ branching fractions

  - Determination of $\Lambda_c / \Sigma_c(2765)^+$ isospin

- Belle II has already started data taking, and will accumulate **50 ab^{-1}** datasets by 2027, which will provide greater sensitivity and precise measurements in the spectroscopy and decays of charmed baryons

  Belle II physics book (arXiv:1808.10567)
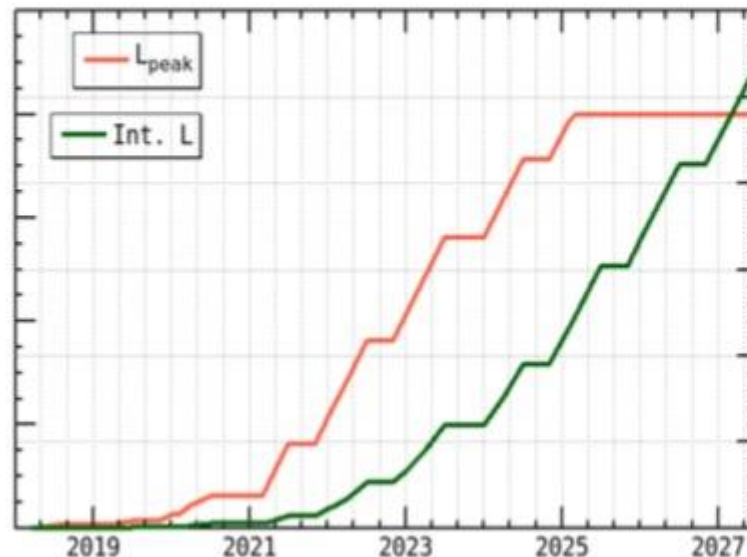 https://arxiv.org/abs/1808.10567

Backup

Longer Term Plan

Use this until we officially revise
(The plot used in my opening talk is temporal, and has been removed)


Full PXD installation
- Make it ready as early as possible, and install it as late as possible.
- Timing for long shutdown must be decided taking account of
  - Situation of the installed detector
  - Physics need (scenario)
  - Impact for funding

TOP MCP-PMT can be installed at any summer shutdown (after 2021, most likely in 2021

We will revise the long-term plan in February, after learning more in the autumn run (2019c).

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Introduction

- Charm energy scale, $\alpha_s \sim 1$:
  - ☐ boundary of (non-)perturbative
  - ☐ platform for strong interaction study

- **Charmed baryons** offer more information:
  - ➤ W-exchange diagrams can contribute without the helicity suppression
  - ➤ Internal W emission is significant.
  - ➤ Parity violation is readily observable because the decay of the daughter hyperon also violates parity.
  - ➤ Testing heavy quark symmetry and light quark chiral symmetry

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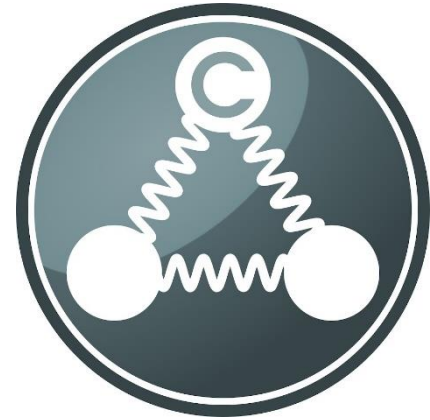
Introduction

- Charmed Baryons are difficult to produce
  - ➤ no resonant production mechanisms
  - ➤ continuum production with small cross-sections
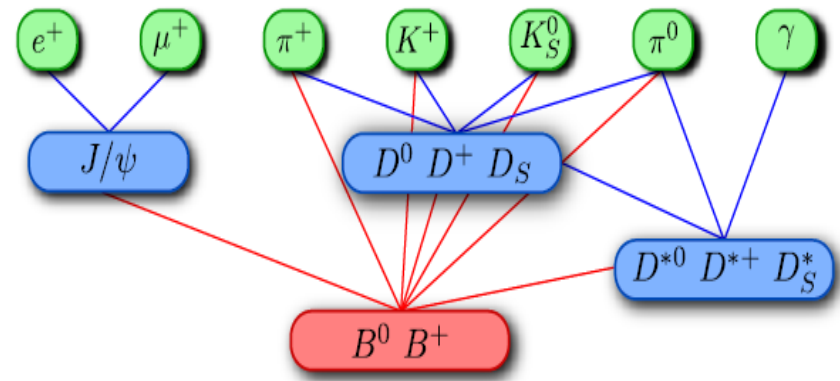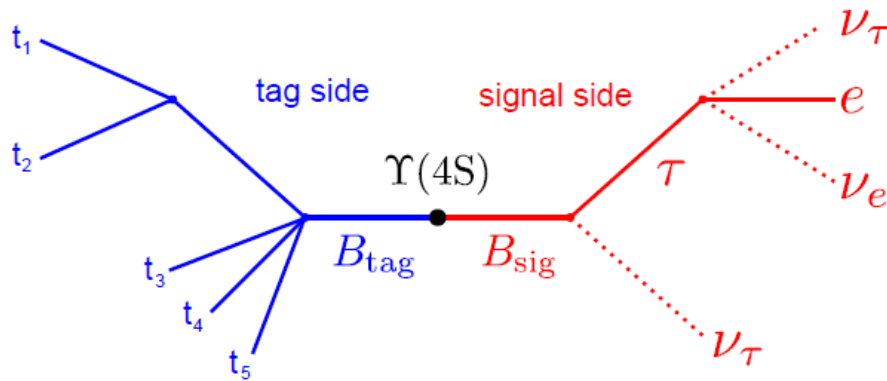- Products in the decays of heavy mesons
  Or high energy colliders

B meson tagging

- B mesons come from $\Upsilon(4S) \to B\bar{B}$
- If we reconstruct a B_{tag} , the recoil is B_{sig}
- 1042 B decay channels, 71 neural networks
- Overall efficiencies:

<center>

0.36% for B^+   **0.24% for B^0**

</center>

Full Reconstruction (FR) algorithm

Back Up

- **HadonB(J) skim;**

  1. |dr|<0.5 and |dz|<2cm; Pt>0.1GeV for all charged tracks;

  2. Pt for all charged particle >0.1GeV/c;

- **For particle identification:**

  1. $\frac{\mathcal{L}(\pi)}{\mathcal{L}(\pi)+\mathcal{L}(K)} > 0.6$ for π;

  2. $\frac{\mathcal{L}(K)}{\mathcal{L}(K)+\mathcal{L}(\pi)} > 0.6$ for K;

  3. $\frac{\mathcal{L}(p)}{\mathcal{L}(p)+\mathcal{L}(\pi)} > 0.6$ and $\frac{\mathcal{L}(p)}{\mathcal{L}(p)+\mathcal{L}(K)} > 0.6$ for (anti-)proton;
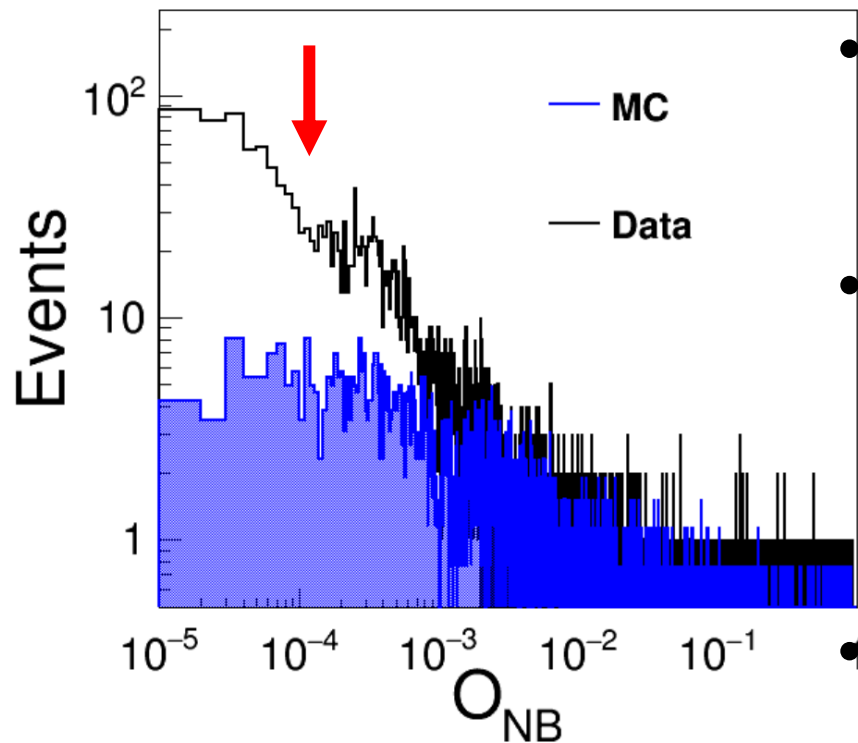
- Apply vertex and mass fit for $\Lambda_c^+(\Xi_c^0)$ candidates, vote events with $\chi^2/ndf > 15$

- K_S candidates are selected by nisKsFinder and Applied vertex and mass fit, vote events with $\chi^2/ndf > 50$

- Λ candidates from Vee2 bank, Applied vertex and mass fit, vote events with $\chi^2/ndf > 50$
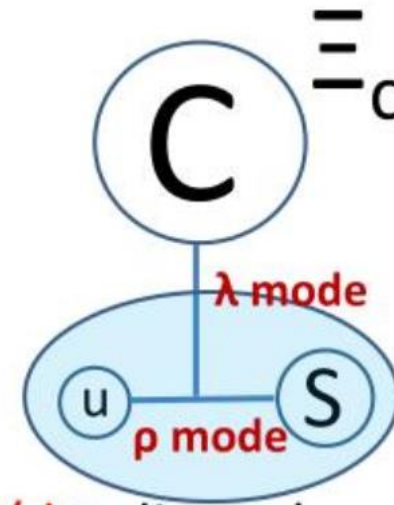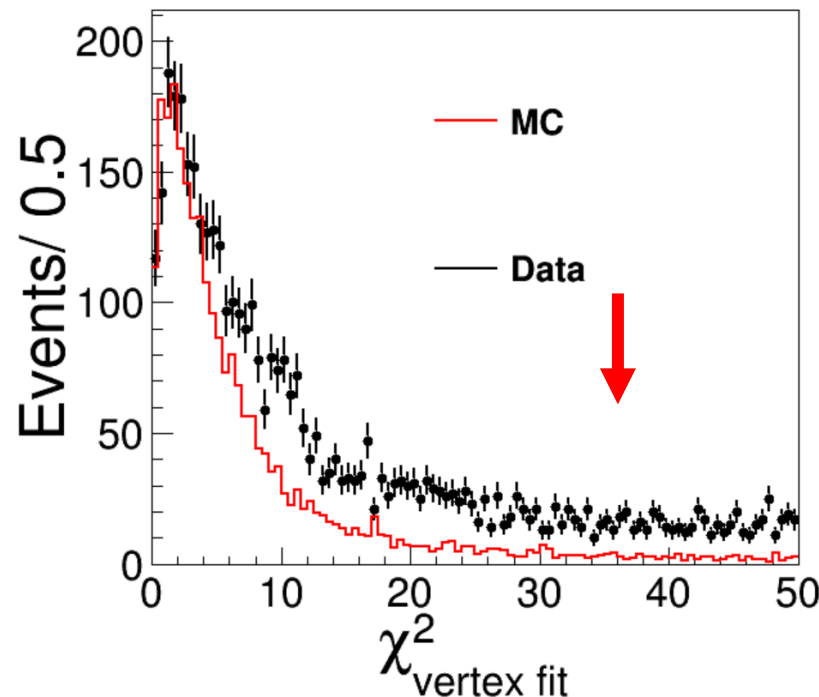
Full Reconstruction

Neural network(NN) based full reconstruction used to tag $B^{\pm}$.

- tag $B^{\pm}$ cont_NBRank are required to be 1

- NN output with continuum suppression are required:
  $$\log(O_{NB}) > -4$$

- $\Lambda_c^{\pm}$ have opposite charge with tag $B^{\pm}$.

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$\Lambda_c^+ \to p\,K^-\pi^+$ mode

$\chi^2_{mass\ vertex}$ distribution of mass and vertex fit to Λ_c^+. MC histogram is normalized to the data according to the first 5 bins.

Red arrows indicate the cut we applied:

$$\chi^2_{mass\ vertex} < 15$$

How to determine $I(J^P)$?

- Spin (J): angular distribution of the decay $\Lambda_c/\Sigma_c(2765) \rightarrow \Sigma_c^{(*)}\pi$ & angular correlation of two pions in $\Lambda_c/\Sigma_c(2765) \rightarrow \Sigma_c^*\pi_1 \rightarrow \Lambda_c\pi_1\pi_2$

- Parity (P): Use branching ratio (used for $\Lambda_c(2880)$)

$$R = \frac{\Gamma(\Lambda_c^* \rightarrow \Sigma_c^*\pi)}{\Gamma(\Lambda_c^* \rightarrow \Sigma_c\pi)}$$

- Isospin (I): Search for possible isospin partners ($\Sigma_c(2765)^{++/0}$) by

$$\Sigma_c(2455)^{++/0}\,\pi^0 \rightarrow \Lambda_c^+\pi^{+/-}\pi^0 \text{ modes}$$

Can it be seen in other modes?

- Not in inclusive $\Lambda_c K$ [Babar: PRD**77**.012002]

- There is a hint in $\Xi_c \pi \pi$ mode [Belle: PRD**94**, 052011], but not conclusive. Anyway much fewer than $\Xi_c(2970)$.
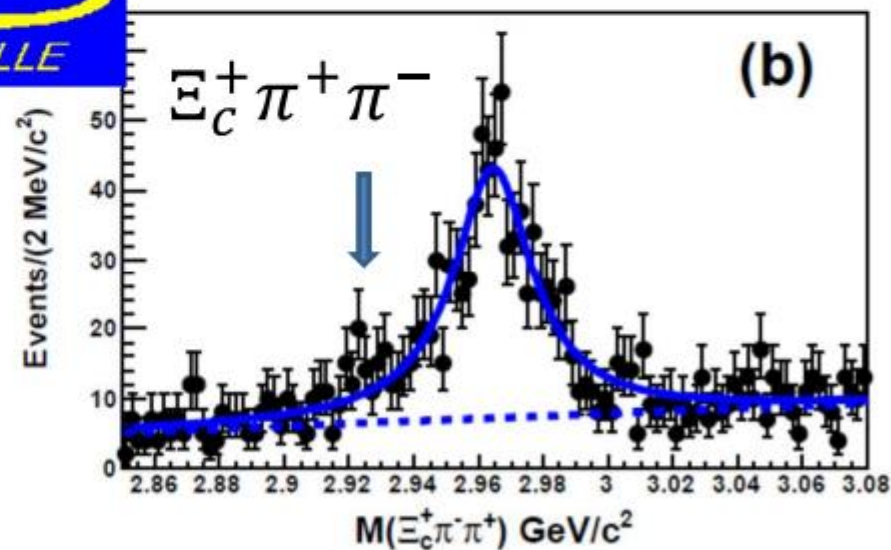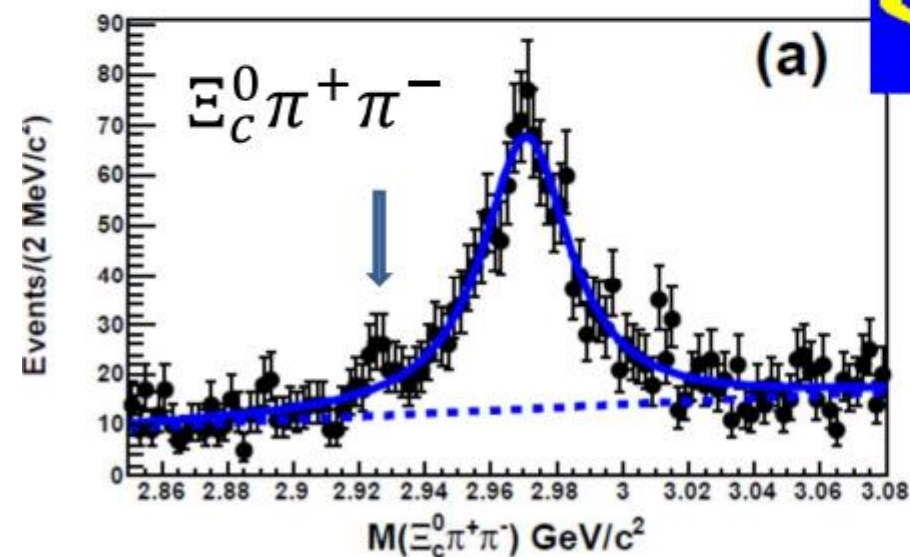
- May have a different structure from others

Spin-parity?

- Spin could be determined from angular distribution, i.e., line density in the Dalitz plot, if we have enough statistics...

- We have to wait for Belle II

- Parity needs even more (polarization, ...)