# Recent results on charmed baryon at Belle

Suxian Li (Fudan University)
On behalf of Belle Collaboration

Particles and Nuclei International Conference
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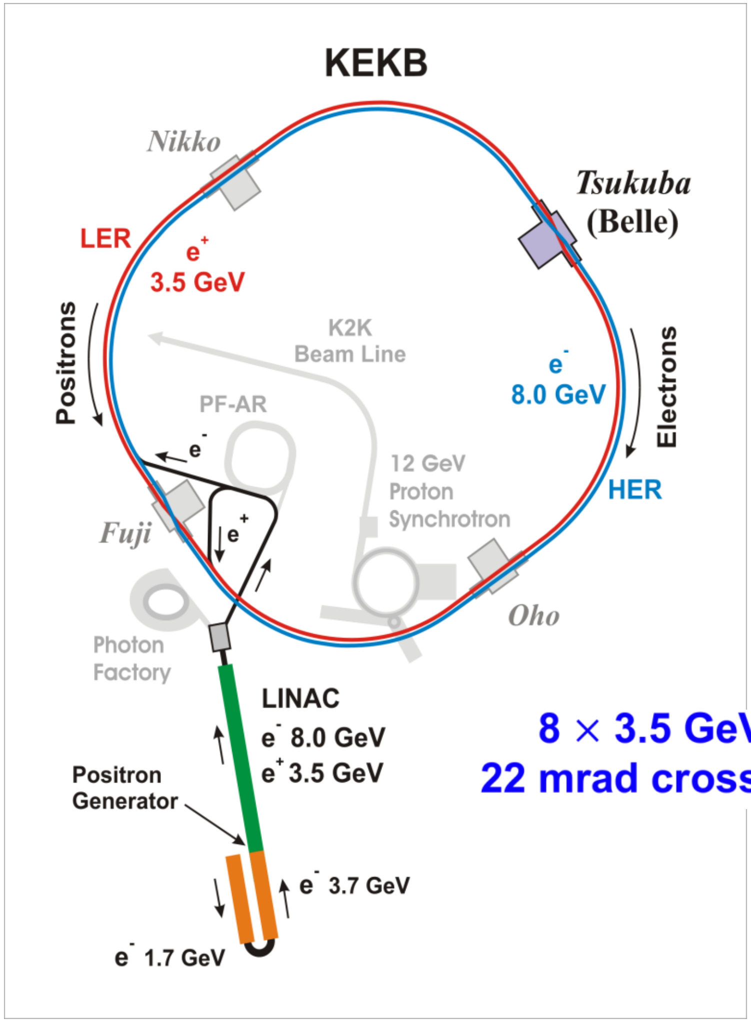
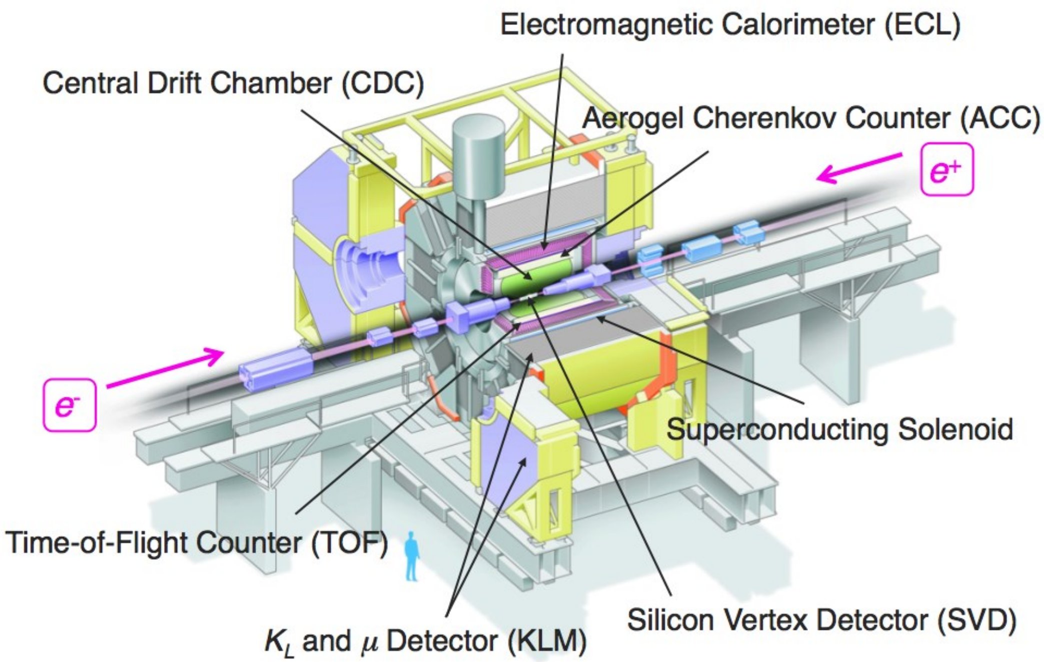
# Belle Experiment and data samples




**8 × 3.5 GeV**
**22 mrad crossing**



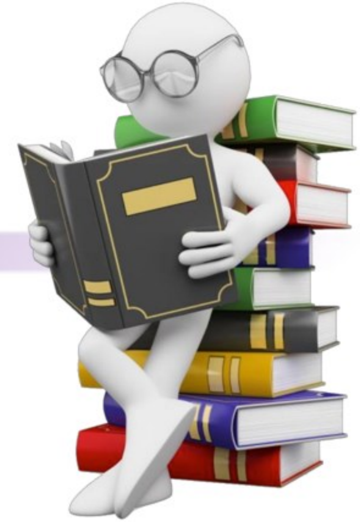

Data taking: 1999 – 2010

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

Total luminosity: 1 $ab^{-1}$

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

# Selected topics



- Masses and widths of $\Sigma_c(2455/2520)^+$
- Branching fraction of $\Lambda_c^+ \to \eta\Lambda\pi^+$
- Radiative decays of $\Xi_c(2970/2815)$
- Evidence for the decay $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{\mathrm{K}}\Xi)^-$
- Spin and parity of $\Xi_c(2970)^+$

# Masses and widths of $\Sigma_c(2455/2520)^+$

PRD (accepted) arXiv:2107.05615

## Motivation:

- Masses and widths of $\Sigma_c^{0/++}$ are well studied via $\Sigma_c^{0/++} \to \Lambda_c^+ \pi^{-/+}$ experimentally.

  [PRD 89, 091102 (2014)]

- Masses of $\Sigma_c^+$ is measured by CLEO II. Only limits are set on intrinsic widths.

  [PRL 86, 1167 (2001)]

- Mass measurements of the isotriplets ($\Sigma_c^0/\Sigma_c^+/\ \Sigma_c^{++}$) allow tests of isospin mass splitting models.
- Most mass models predict: $\mathrm{m}(\Sigma_c^+) < m(\Sigma_c^0/\ \Sigma_c^{++})$.

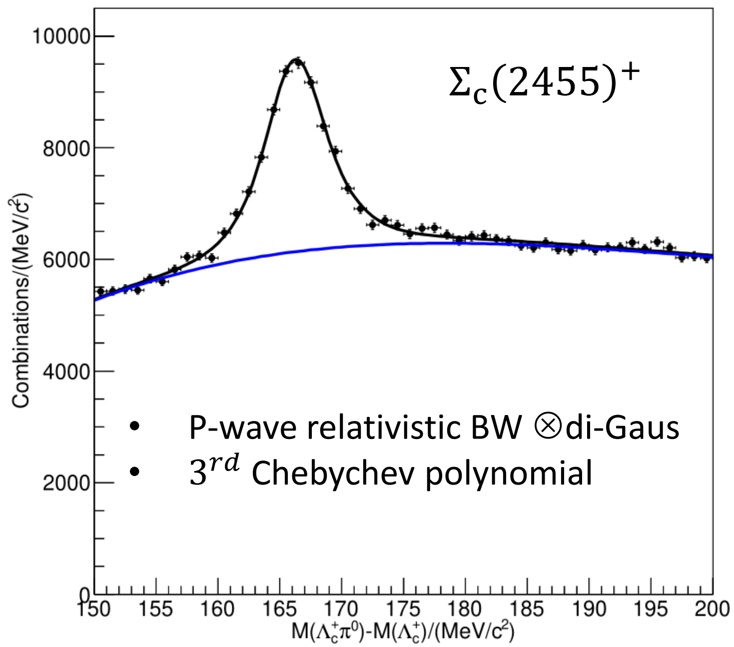
  [L. Chan, PRD 21, 204 (1985); K. Varga, PRD 59, 014012 (1999); B. Silvestre-Brac, JPG 29, 2686 (2003)]

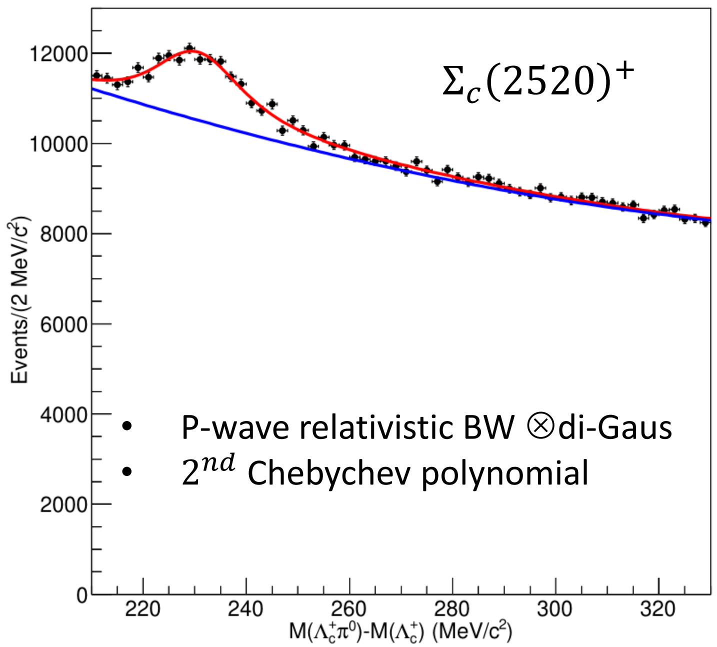
- Natural width models predict: $\Gamma(\Sigma_c^+) > \Gamma\left(\Sigma_c^0/\ \Sigma_c^{++}\right)$.

  [H.-Y. Cheng and C.-K. Chua, PRD 92, 074014 (2015)]

◆ Reconstructed decay: $\Sigma_c(2455/2520)^+ \to \pi^0\Lambda_c^+ \to \pi^0(pK^-\pi^+)$

**980 fb$^{-1}$**




| | $\Sigma_c(2455)^+$ | $\Sigma_c(2520)^+$ |
|---|---|---|
| $\Delta M$ [MeV/$c^2$] | $166.17 \pm 0.05^{+0.16}_{-0.07}$ | $230.9 \pm 0.5^{+0.5}_{-0.1}$ |
| $\Gamma$ [MeV/$c^2$] | $2.3 \pm 0.3 \pm 0.3$ | $17.2^{+2.3+3.1}_{-2.1-0.7}$ |

- First measurement of widths of $\Sigma_c(2455/2520)^+$.
- Much precise measurement of masses of $\Sigma_c(2455/2520)^+$.

# Branching fraction of $\Lambda_c^+ \to \eta\Lambda\pi^+$

PRD 103, 052005 (2021)

## Motivation:

- The $\Lambda_c^+ \to \eta\Lambda\pi^+$ decay is an ideal decay to study the $\Lambda(1670)$ and $a_0(980)$.

  J. J. Xie and L. S. Geng, EPJC 76, 496 (2016).

- Two different models to explain the structure of the $\Lambda(1670)$:
  - $\Lambda(1670)$ is the SU(3) octet partner of the $N(1535)$;

    R. Koniuk and N. Isgur, PRD 21, 1868 (1980)
  - $\Lambda(1670)$ is as a $K\Xi$ bound state.

    E. Oset, A. Ramos, and C. Bennhold, PLB 527, 99 (2002).

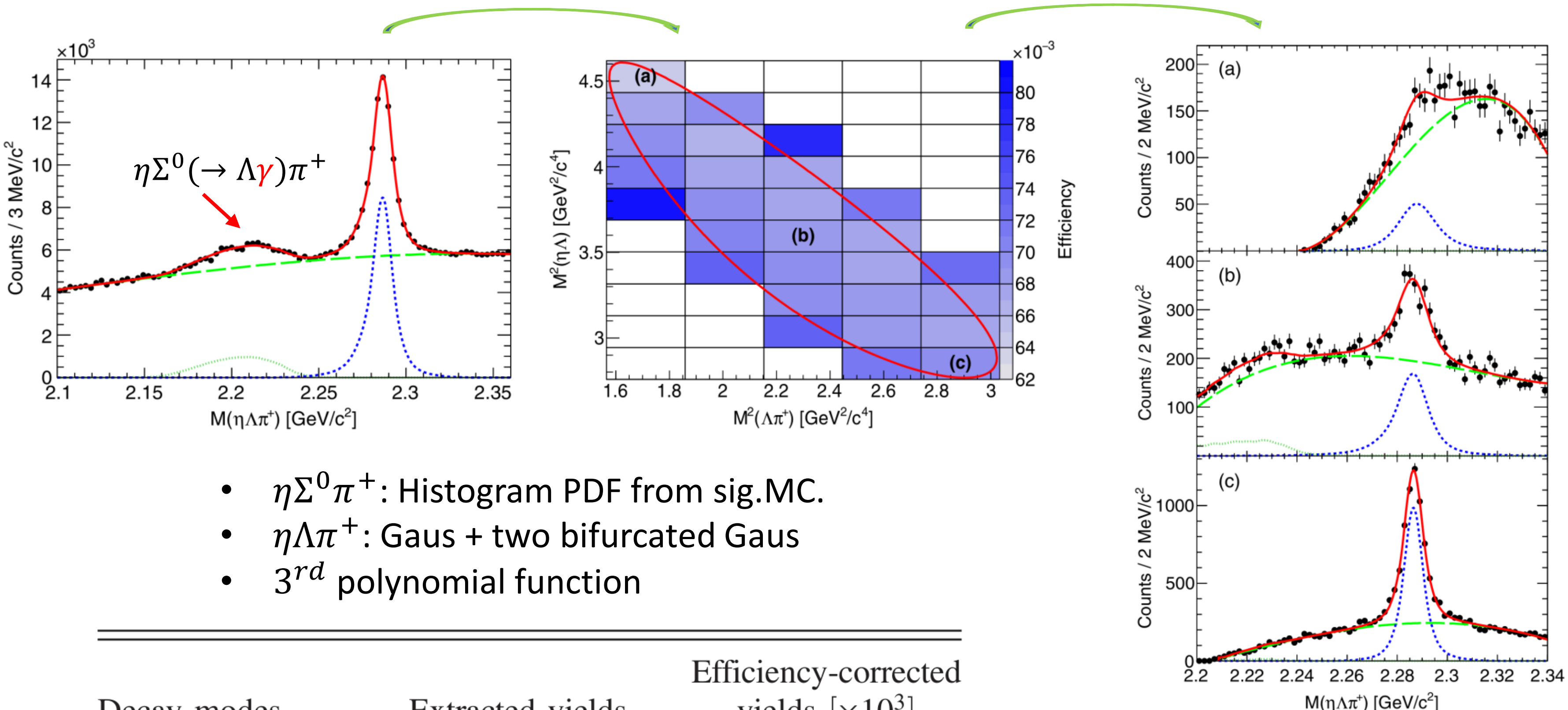
- Few experimental efforts to confirm the structure of the $\Lambda(1670)$.

- In this work, we investigate the $\Lambda(1670)$ in the resonant substructure of the $\Lambda_c^+ \to \eta\Lambda\pi^+$ decay.

$$\frac{\mathcal{B}(\text{Decay Mode})}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y(\text{Decay Mode})}{\mathcal{B}_{\text{PDG}} \times y(\Lambda_c^+ \to pK^-\pi^+)}$$

Efficiency-corrected yields: $y = \frac{Y^{data}}{\epsilon^{MC}}$

**980 $\text{fb}^{-1}$**



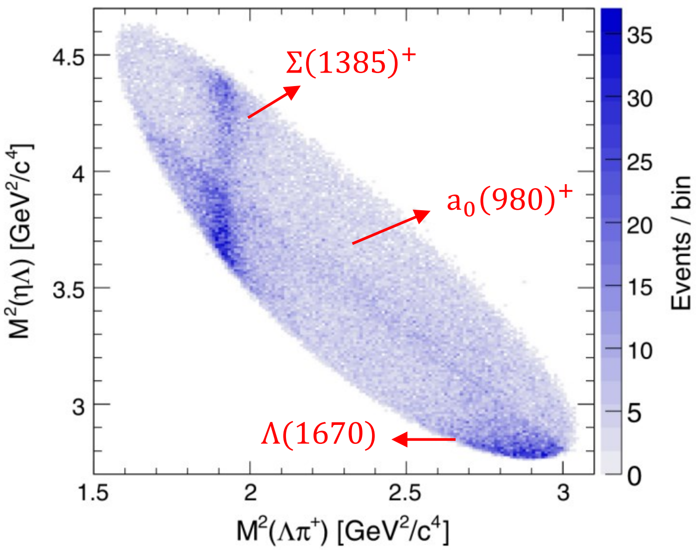

- $\eta\Sigma^0\pi^+$: Histogram PDF from sig.MC.
- $\eta\Lambda\pi^+$: Gaus + two bifurcated Gaus
- $3^{rd}$ polynomial function

Example of fits for three Dalitz bins

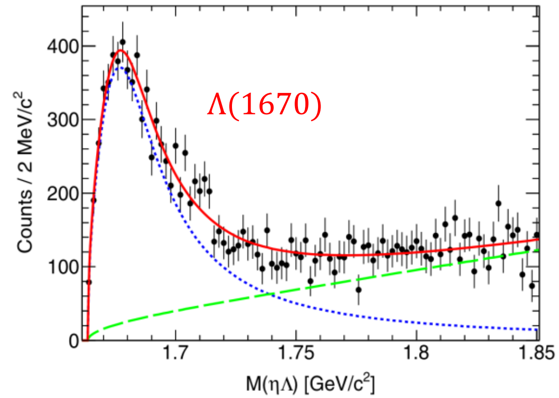
| Decay modes | Extracted yields | Efficiency-corrected yields $[\times 10^3]$ |
|---|---|---|
| $\Lambda_c^+ \to \eta\Lambda\pi^+$ | $51276 \pm 454$ | $741 \pm 7$ |
| $\Lambda_c^+ \to pK^-\pi^+$ | $1544580 \pm 1552$ | $10047 \pm 10$ |
| $\Lambda_c^+ \to \eta\Sigma^0\pi^+$ | $17058 \pm 871$ | $305 \pm 16$ |

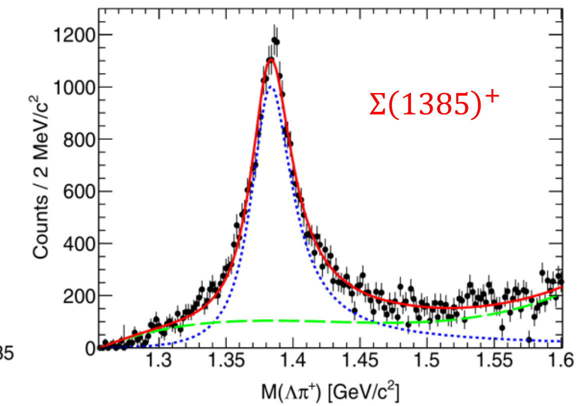
| Decay modes | $\mathcal{B}(\text{Decay mode})/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ | |
|---|---|---|
| $\Lambda_c^+ \to \eta\Lambda\pi^+$ | $0.293 \pm 0.003 \pm 0.014$ | → Much improved precision |
| $\Lambda_c^+ \to \eta\Sigma^0\pi^+$ | $0.120 \pm 0.006 \pm 0.010$ | → First observation |

## $\Lambda_c^+ \to \eta\Lambda\pi^+$




## $Y(\Lambda_c^+)$ versus $M(\eta\Lambda)/M(\Lambda\pi^+)$




- S-wave BW
- $\sqrt{m - m_{\eta\Lambda}}[p_0 + p_1(m - m_{\eta\Lambda})]$

- P-wave BW ⊗ Gaus
- $3^{rd}$ Chebychev

| Decay modes | Extracted yields | Efficiency-corrected yields [$\times 10^3$] |
|---|---|---|
| $\Lambda_c^+ \to \Lambda(1670)\pi^+$ | $9760 \pm 519$ | $140 \pm 7$ |
| $\Lambda_c^+ \to \eta\Sigma(1385)^+$ | $29372 \pm 875$ | $423 \pm 13$ |

| Decay modes | $\mathcal{B}(\text{Decay mode})/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ |
|---|---|
| $\Lambda_c^+ \to \Lambda(1670)\pi^+$; $\Lambda(1670) \to \eta\Lambda$ | $(5.54 \pm 0.29 \pm 0.73) \times 10^{-2}$ |
| $\Lambda_c^+ \to \eta\Sigma(1385)^+$ | $0.192 \pm 0.006 \pm 0.016$ |

| Resonances | Mass [MeV/$c^2$] | Width [MeV] |
|---|---|---|
| $\Lambda(1670)$ | $1674.3 \pm 0.8 \pm 4.9$ | $36.1 \pm 2.4 \pm 4.8$ |
| $\Sigma(1385)^+$ | $1384.8 \pm 0.3 \pm 1.4$ | $38.1 \pm 1.5 \pm 2.1$ |

### First observation:

- $\Lambda_c^+ \to \eta\Sigma^0\pi^+$ and $\Lambda_c^+ \to \Lambda(1670)\pi^+$

### Much improved precision:

- $B(\Lambda_c^+ \to \eta\Lambda\pi^+)$ and $B(\Lambda_c^+ \to \eta\Sigma(1385)^+)$
- Masses and widths of $\Lambda(1670)$ and $\Sigma(1385)^+$

# Radiative decays of $\Xi_c(2790/2815)$

PRD 102, 071103 (2020)

## Motivation:

- A recent study reported measurement of the masses and widths of the $\Xi_c(2790)^{+/0}$ and $\Xi_c(2815)^{+/0}$ states. PRD 94, 052011 (2016)

- They can also decay via the $\pi^0$ decays that are harder to see, and the $\Xi_c(2815)$ has been seen in $\Xi_c'\pi$. PRD 94, 052011 (2016)

- But what about the radiative decays?

$$\boldsymbol{\Xi_c(2790)^{+/0} \to \Xi_c^{+/0}\gamma}$$
$$\boldsymbol{\Xi_c(2815)^{+/0} \to \Xi_c^{+/0}\gamma}$$

- The theoretical predictions show: (K-L. Wang, Y-X. Yao, X-H. Zhong, and Q. Zhao, PRD 96, 116016 (2017))
  - Neutral states ($\Gamma$ ~200 keV) – **would be seen**
  - Charged states ($\Gamma$ < 10 keV) – **would not be seen**

# Basic technique

[1.] Reconstruct the ground states $\Xi_c^{0/+}$

- $\Xi_c^0$: with ten decay modes.
- $\Xi_c^+$: with seven decay modes.

[2.] Reconstruct the excited $\Xi_c$ from $\boldsymbol{\Xi_c^{+/0}\gamma}$

$$E_\gamma > 0.55\ \text{GeV}$$

[3.] Fit the $M(\Xi_c^{+/0}\gamma)$ in the region of the $\Xi_c(2790)$ and $\Xi_c(2815)$.

[4.] Divide by the yield in the known decay modes:

$$\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to (\Xi_c^+\gamma)\pi^-\ ;$$
$$\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to (\Xi_c^0\pi^+)\pi^-$$

PRD 94, 052011 (2016)

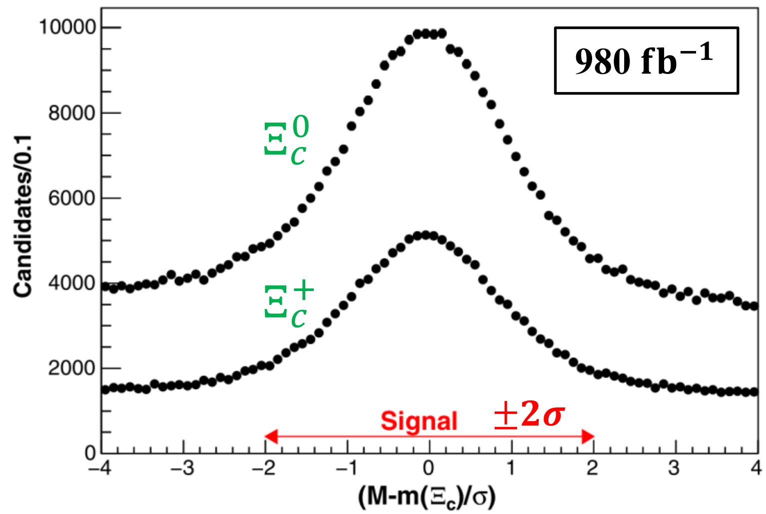



FIG. 1. Pull mass distribution for the $\Xi_c^0$ (upper data points), and $\Xi_c^+$ (lower data points) candidates.

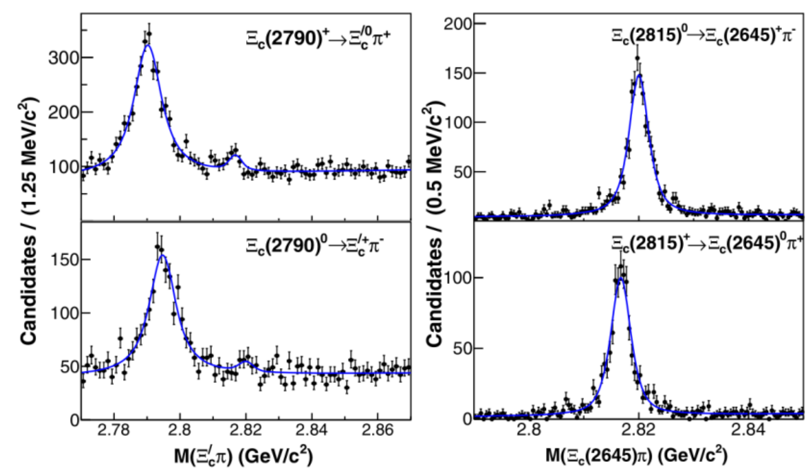
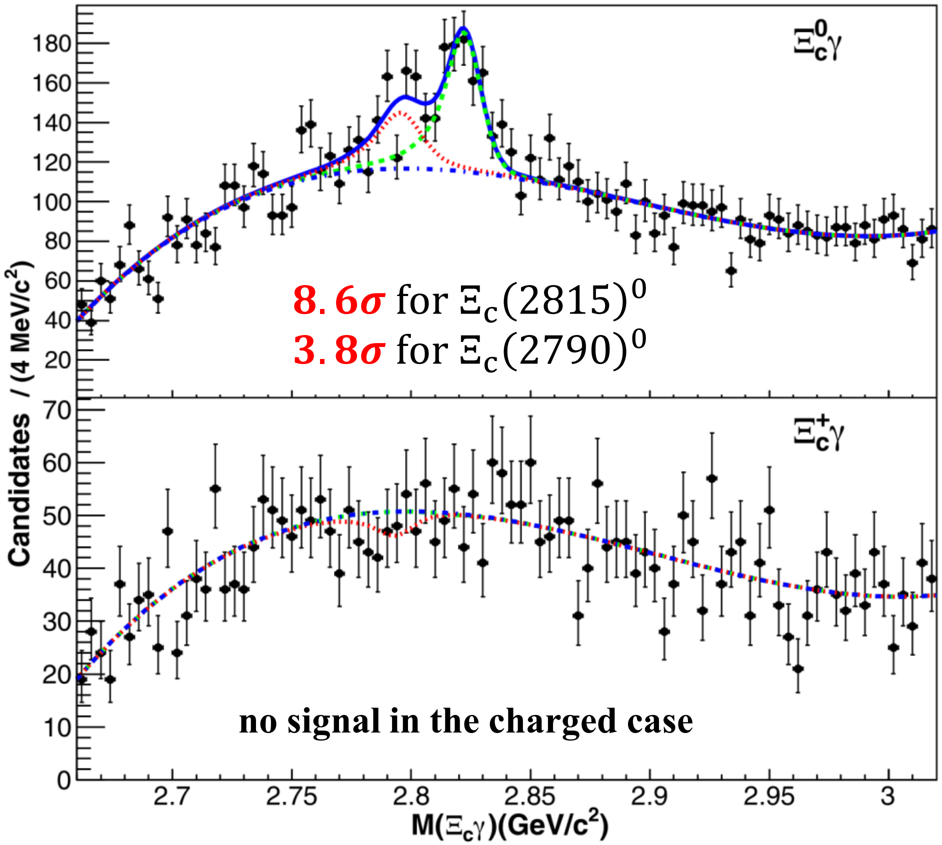



FIG. 3. The signals used as normalization modes in the analysis.

# Result:

980 $fb^{-1}$




$$\frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$$

$$\frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$$

$$\frac{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^-\pi^+]} < 0.09 \text{ at 90\% C.L.}$$

$$\frac{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+]} < 0.06 \text{ at 90\% C.L.}$$

- **First observation** of the radiative decays of excited $\Xi_c$ .
- Give the ratios of branching fractions.
- Confirm the theoretical prediction. (K-L. Wang, Y-X. Yao, X-H. Zhong, and Q. Zhao, PRD 96, 116016 (2017))

# $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{\mathrm{K}}\Xi)^-$

PRD (accepted) arXiv:2106.00892

## Motivation:

- a new excited $\Omega^-$ resonance was seen, with $M = (2012 \pm 0.7 \pm 0.6)\ \mathrm{MeV}/c^2$ and $\Gamma = \left(6.4^{+2.5}_{-2.0} \pm 1.6\right)\ \mathrm{MeV}/c^2$.

  [PRL 121, 052003 (2018)]

- $\Omega(2012)^-$ is interpreted as a $\bar{K}\Xi(1530)$ hadronic molecule.

  [Y. H. Lin and B. S. Zou, PRD 98, 056013 (2018); M. P. Valderrama, PRD 98, 054009 (2018); R. Pavao and E. Oset, EPJC 78, 857 (2018)]

- No $\Omega(2012)^-$ signal is observed via $\Omega(2012)^- \to \left(\bar{K}\Xi(1530)\right)^- \to \left(\bar{K}\pi\Xi\right)^-$ by Belle

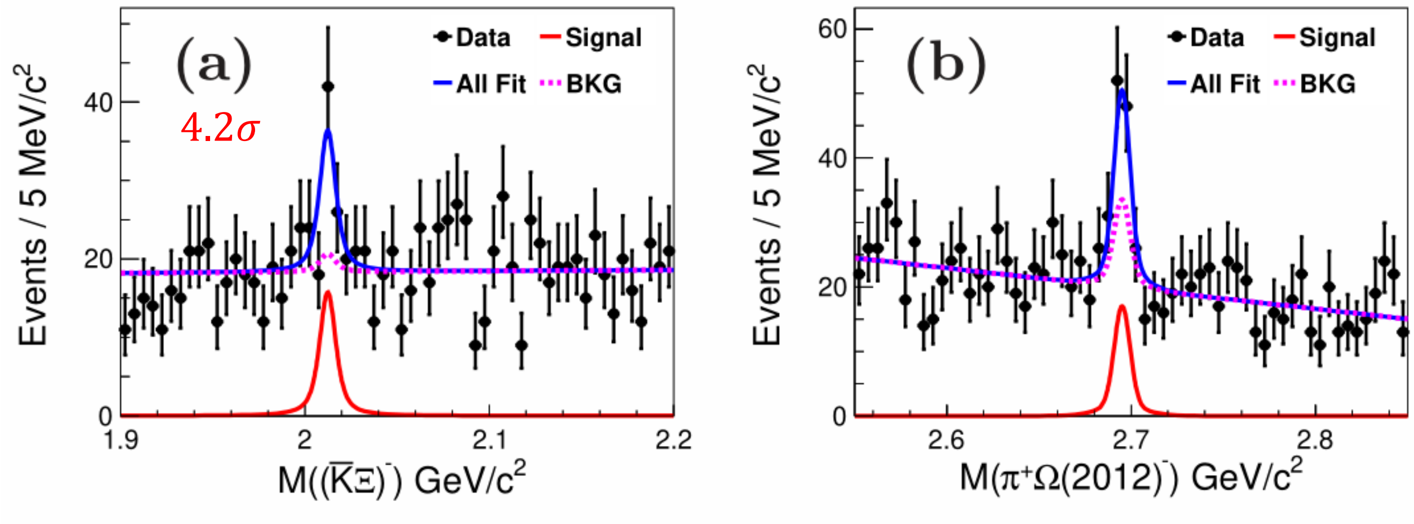
  [PRD 100, 032006 (2019)]

- Clearly $\Omega(2012)^-$ peak in the $M[(\bar{\mathrm{K}}\Xi)^-]$ of the $\Omega_c^0 \to \pi^+(\bar{\mathrm{K}}\Xi)^-$ is predicted.

  [C. H. Zeng, J. X. Lu, E. Wang, J. J. Xie, and L. S. Geng, PRD 102, 076009 (2020)]

## 2D simultaneous fit to $M(\bar{K}\Xi)$ and $M(\pi\Omega(2012))$

**980 fb$^{-1}$**




- $\frac{B(\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+ (\bar{K}\Xi)^-)}{B(\Omega_c^0 \to \pi^+ \Omega^-)} = 0.220 \pm 0.059 \pm 0.035$
- $\frac{B(\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+ K^- \Xi^0)}{B(\Omega_c^0 \to \pi^+ K^- \Xi^0)} = (9.6 \pm 3.2 \pm 1.8)\%$
- $\frac{B(\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+ K_S^0 \Xi^-)}{B(\Omega_c^0 \to \pi^+ K_S^0 \Xi^-)} = (5.5 \pm 2.8 \pm 0.7)\%$

# Spin and parity of $\Xi_c(2970)^+$

## Motivation:

PRD **103, L111101** (2021)

### $\Xi_c$(2970) States

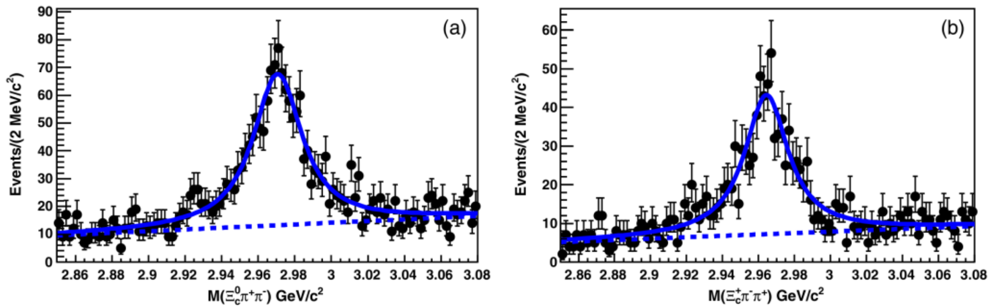



FIG. 6. The (a) $\Xi_c^0\pi\pi$ and (b) $\Xi_c^+\pi\pi$ invariant mass distributions with a cut on $\Xi_c(2645)$ invariant mass of the intermediate state and a scaled momentum cut of $x_p > 0.7$. Both show clear $\Xi_c(2980)$ signals. The fits are described in the text. The dashed lines represent the combinatorial background contributions.

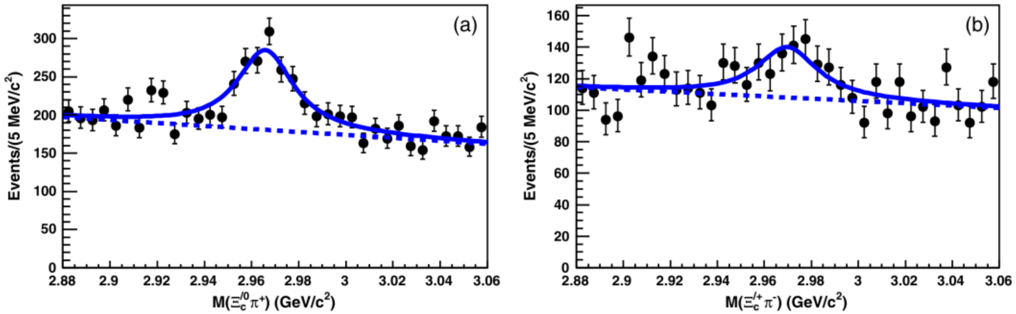



FIG. 9. The (a) $\Xi_c'^0\pi^+$ and (b) $\Xi_c'^+\pi^-$ invariant mass distributions. The fits are described in the text. The dashed lines represent the combinatorial background contributions.

- **Mass and width were measured precisely via:**

  $\Xi_c(2970) \rightarrow \Xi_c(2645)\pi \rightarrow \Xi_c\pi\pi$

- **The $\Xi_c(2970)$ is also observed from the decay:**

  $\Xi_c(2970) \rightarrow \Xi_c'\pi \rightarrow \Xi_c\gamma\pi$

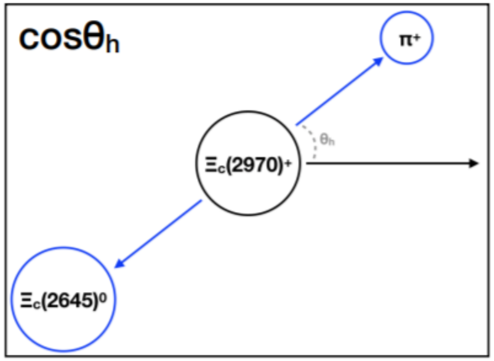
PRD 94, 052011 (2016)

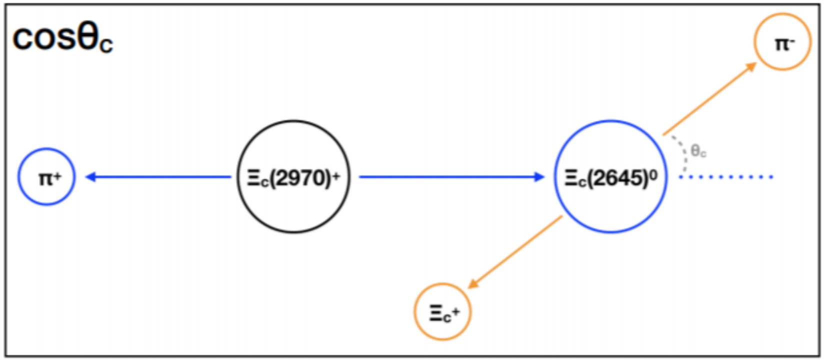
- **Spin and parity of the $\Xi_c$(2970) is not determined yet.**
- **There is not even a presumed spin-parity.**

# Principle of Determination

- **Spin**
- For the decay $\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0\pi_1^+ \rightarrow \Xi_c^+\pi_1^-\pi_2^+$,
- Two decay angular distribution are studied.
  - $\cos\theta_h$ : Helicity angle of $\Xi_c(2970)^+$
  - $\cos\theta_c$ : Helicity angle of $\Xi_c(2645)^0$

$\theta_h$ : angle bet.
direction of $\Xi_c(2970)^+$ in beam CM frame and direction of $\pi^+$ in $\Xi_c(2970)$'s rest frame.
$\theta_c$ : angle bet.
direction of $\Xi_c(2645)^0$ in $\Xi_c(2970)$'s rest frame and direction of $\pi^-$ in $\Xi_c(2645)$'s rest frame.



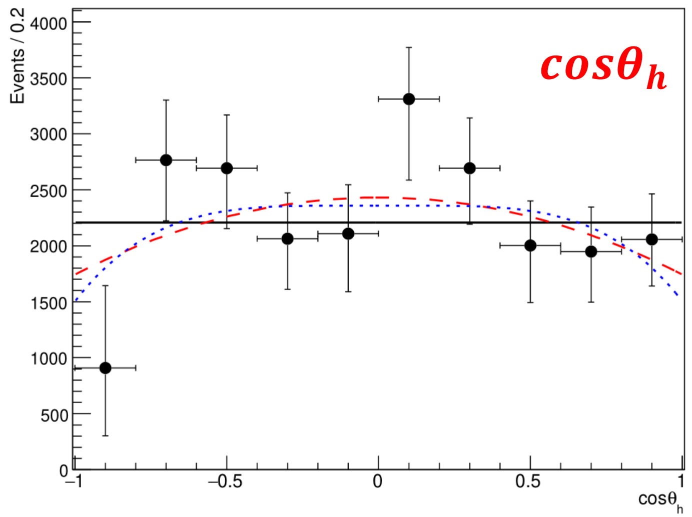

- **Parity**
  - Ratio of branching fractions is studied.
    - Compared with the prediction from Heavy Quark Spin Symmetry (HQSS)

$$R = \frac{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0\pi^+)}$$

# Determination of the Spin

**Full Belle data sample**

- Divide the data into 10 equal bins for $cos\theta_h$ and $cos\theta_c$.
- Fit $M(\Xi_c\pi\pi)$ in each bin.
- Fit the angular distributions with the expected decay angular distributions $W_{1/2}$, $W_{3/2}$, $W_{5/2}$




$$W_{\frac{1}{2}} = constant$$

$$W_{\frac{3}{2}} = \rho_{33}\left\{1 + T\left(\frac{3}{2}\cos^2\theta_h - \frac{1}{2}\right)\right\} + \rho_{11}\left\{1 + T\left(-\frac{3}{2}\cos^2\theta_h + \frac{1}{2}\right)\right\}$$

$$W_{\frac{5}{2}} = \frac{3}{32}[\rho_{55}5\{(-\cos^4\theta_h - 2\cos^2\theta_h + 3) + T(-5\cos^4\theta_h + 6\cos^2\theta_h - 1)\} + \rho_{33}\{(15\cos^4\theta_h - 10\cos^2\theta_h + 11) + T(75\cos^4\theta_h - 66\cos^2\theta_h + 7))\} + \rho_{11}2\{(-5\cos^4\theta_h + 10\cos^2\theta_h + 3) + T(-25\cos^4\theta_h + 18\cos^2\theta_h - 1)\}]$$

| Spin hypothesis | 1/2 | 3/2 | 5/2 |
|---|---|---|---|
| $\chi^2$/n.d.f. | 9.3/9 | 7.7/7 | 7.5/6 |
| Probability | 41% | 36% | 28% |
| T | – | $-0.5 \pm 1.1$ | $0.7 \pm 1.6$ |
| $\rho_{11}$ | 0.5 | $0.13 \pm 0.26$ | $0.08 \pm 0.27$ |
| $\rho_{33}$ | – | $0.37 \pm 0.26$ | $0.12 \pm 0.09$ |
| $\rho_{55}$ | – | – | $0.30 \pm 0.28$ |

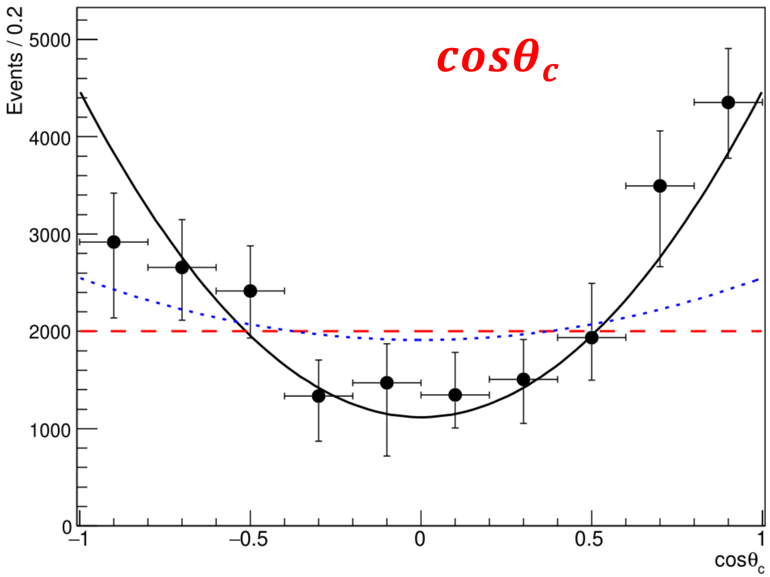
- Best fit is the spin 1/2 hypothesis
- Exclusion level of the spin 3/2 (5/2) hypothesis is as small as $0.8\sigma$ $(0.5\sigma)$.
- Therefore, the result is inconclusive.

# Determination of the Spin

**Full Belle data sample**

- To draw a more decisive conclusion, we fit angular distributions of $cos\theta_c$ with the expected angular distribution

$$W(\theta_c) = 3/2[\rho^*_{33}\sin^2\theta_c + \rho^*_{11}(1/3+\cos^2\theta_c)]\ ,\ \rho^*_{33}+\rho^*_{11} = 1/2$$




| $J^P$ | $1/2^{\pm}$ | $3/2^{-}$ | $5/2^{+}$ |
|---|---|---|---|
| $\chi^2$/n.d.f. | 6.4/9 | 32.2/9 | 22.3/9 |
| Exclusion level (s.d.) | - | 5.5 | 4.8 |

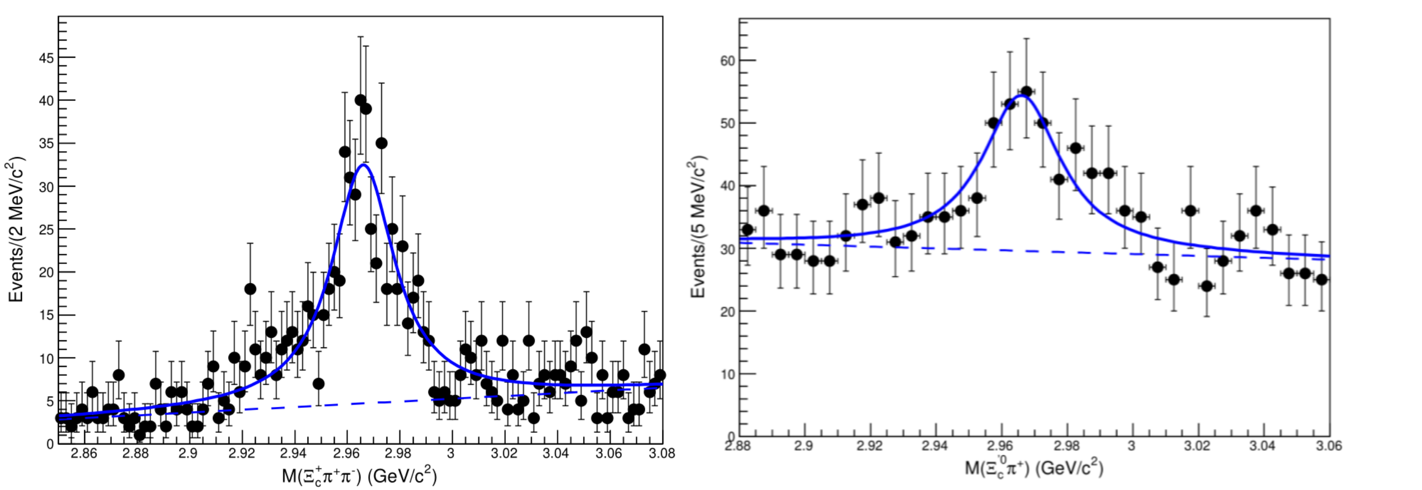
- This result is most consistent with the spin ½ hypothesis.
- The $1/2^{\pm}$ scenario is preferred over $3/2^{-}$ ($5/2^{+}$) by $5.5\sigma$ ($4.8\sigma$).
- Excludes the $\Xi_c^*$ spin of 1/2 in which the distribution should be flat.

# Determination of the Parity

- The branching ratio R is sensitive to the parity.

$$R = \frac{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+)}$$

- Fit the $M(\Xi_c^+\pi^-\pi^+)$ and $M(\Xi_c'^0\pi^+)$ for two mode.




- Branching ratio $R = 1.67 \pm 0.29^{+0.15}_{-0.09} \pm 0.17(\mathrm{IS})$, where IS is Isospin symmetry.

Heavy-quark spin symmetry (HQSS) prediction

| Parity | + | + | − | − |
|---|---|---|---|---|
| Brown-muck spin $s_\ell$ | 0 | 1 | 0 | 1 |
| R | 1.06 | 0.26 | 0 | $\ll$1 |

Our result favors a positive-parity assignment with $sl = 0$

# Summary

- Although Belle has stopped data taking for ~10 years, we are still producing exciting results.
- We report first measurement of $\Gamma(\Sigma_c(2455/2520)^+)$ and more precise $M(\Sigma_c(2455/2520)^+)$.
- We report BF measurement of $\Lambda_c^+ \to \eta\Lambda\pi^+$ and first observation of $\Lambda(1670)$
- We report first observation of radiative decays of excited $\Xi_c(2970/2815)$ and give the BR
- We report evidence for the decay $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\overline{K}\Xi)^-$
- We report the spin and parity of $\Xi_c(2970)^+$
- Belle II will provide greater sensitivity and precise measurements in charmed baryon physics with 50 $ab^{-1}$.

***Thanks for your attentions!***

# Backup