

# 第十八届重味物理与CP破坏研讨会

## Charmed Baryon Results from Belle



Yubo Li

Fudan University

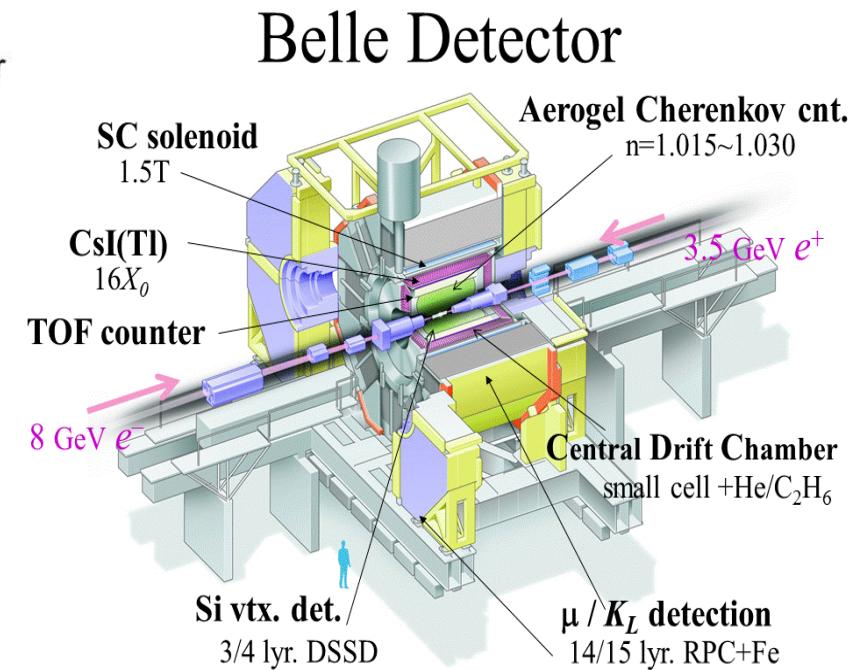
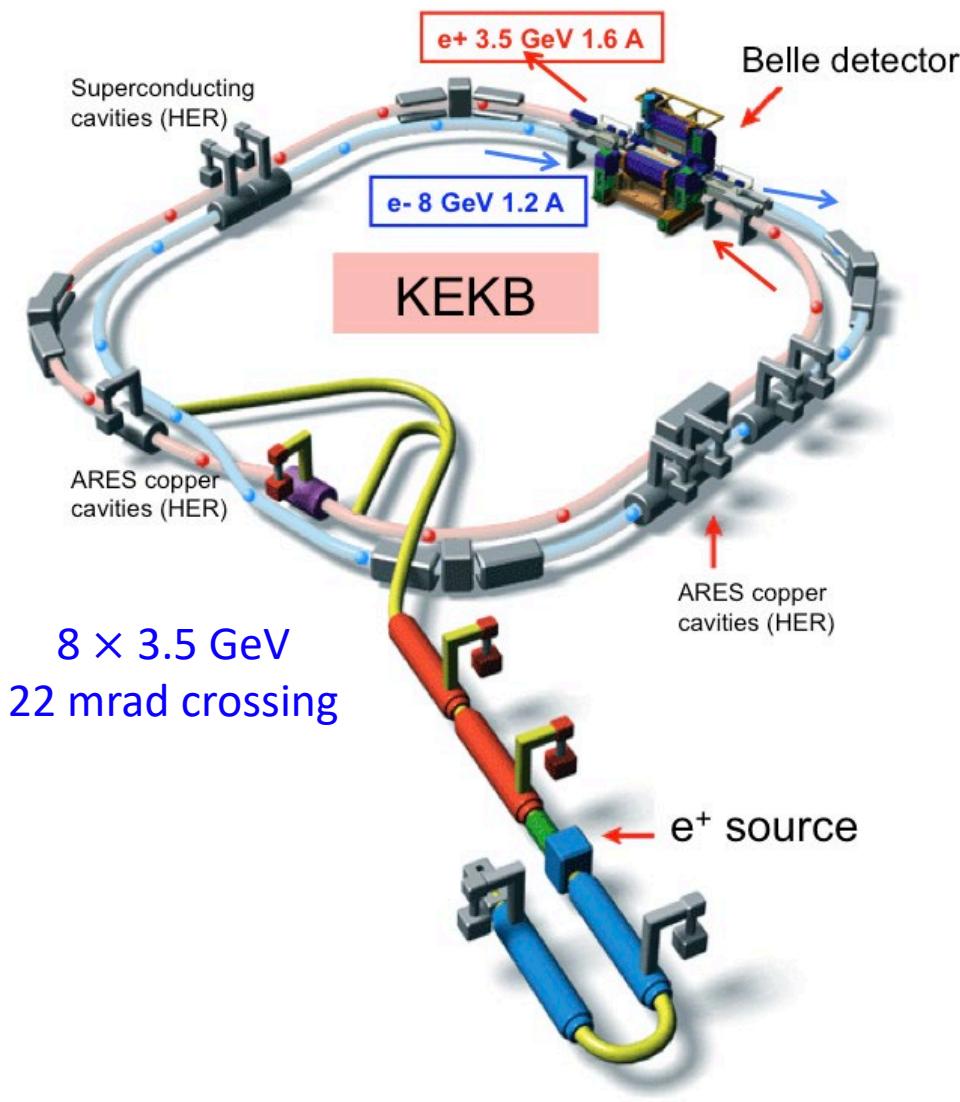
2021年11月12日



# Outline

- **Introduction to Belle experiment**
- $\Xi_c^0 \rightarrow \Xi^0 \phi (\rightarrow K^+ K^-)$
- Evidence for  $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$
- Measurements of  $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l \nu)$  and  $\mathcal{A}_{cp}$  of  $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0},$  and  $\Sigma^+ K^{*-}$
- Masses and Widths of the  $\Sigma_c(2455)^+$  and  $\Sigma_c(2520)^+$
- Summary

# Belle experiment and data samples



Data taking: 1999 – 2010

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

Total luminosity: 980 fb<sup>-1</sup>

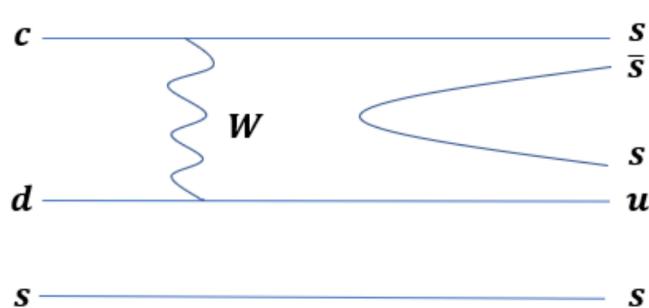
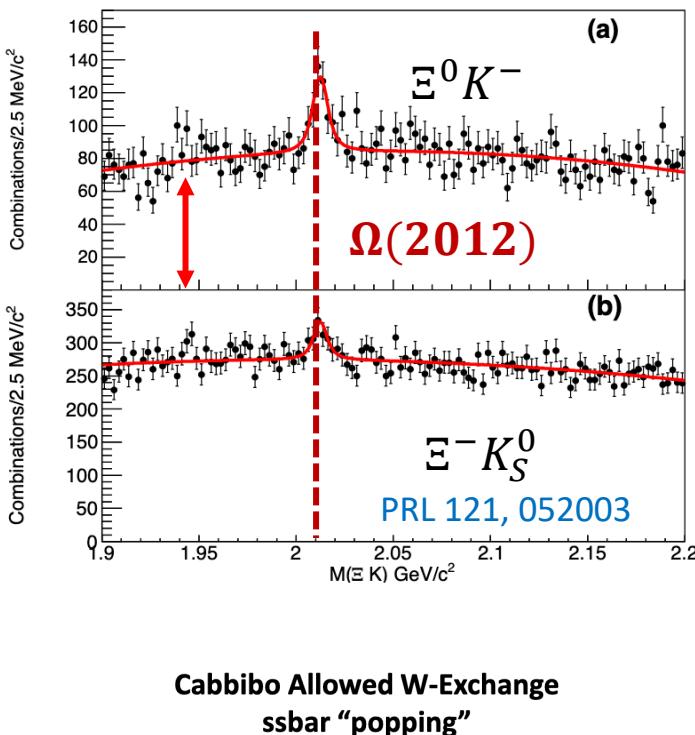
772M B $\bar{B}$  events @ $\Upsilon(4S)$

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$$\Xi_c^0 \rightarrow \Xi^0 \phi(\rightarrow K^+ K^-)$$

PRD.103.112002



- Belle recently discovered  $\Omega(2012)$  excited baryon via  $\Xi K$  decay.
- There should be a partner of  $\Omega(2012)$  near 1.95 GeV

PRD 100, 032006

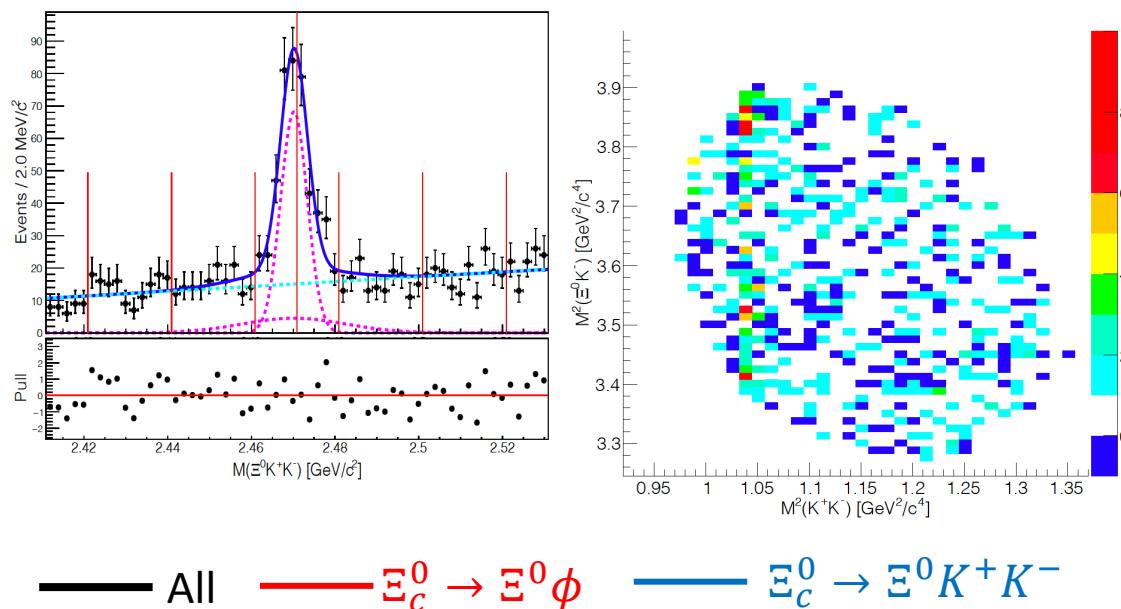
- $\Xi_c^0 \rightarrow \Xi^0 \phi( K^+ K^-)$  with polarized  $\phi \rightarrow K^+ K^-$  could produce peaks in the  $\Xi K$  invariant mass spectra.

PRD 88, 114018

- $\Xi_c^0 \rightarrow \Xi^0 \phi( K^+ K^-)$  can only proceed via W-exchange together with ss production, add to our knowledge of the weak decay of charmed baryons

# $\Xi_c^0 \rightarrow \Xi^0 \phi(\rightarrow K^+ K^-)$

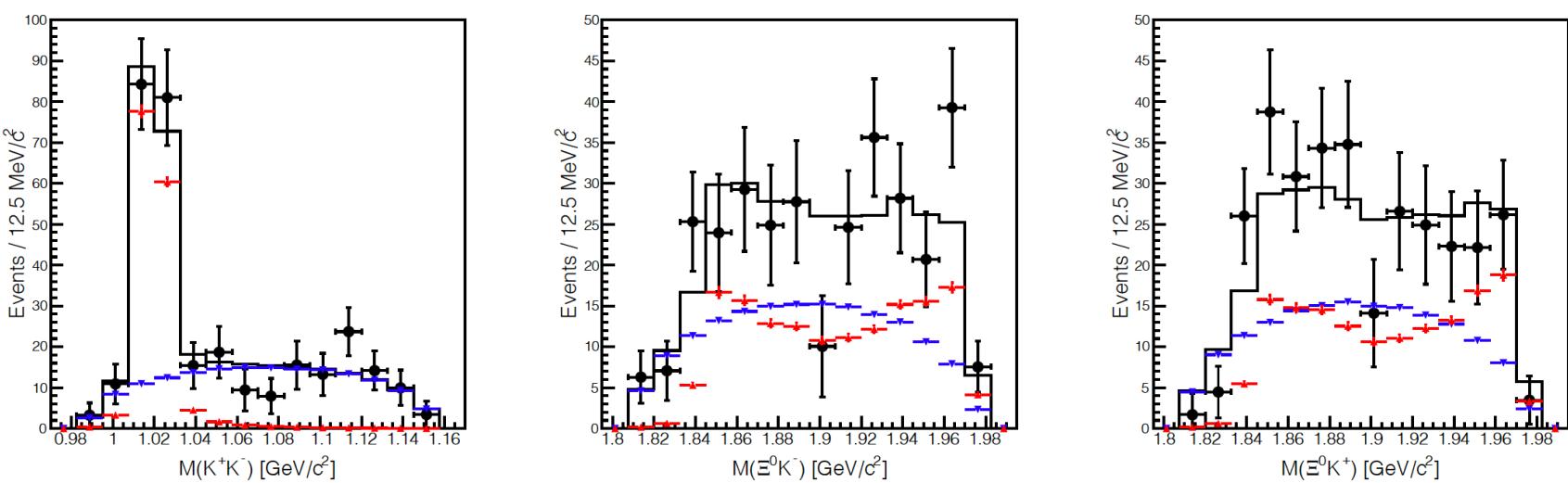
PRD.103.112002



$$\frac{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^0 \phi(\rightarrow K^+ K^-))}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = 0.036 \pm 0.004 \text{ (stat.)} \pm 0.002 \text{ (syst.)}$$

$$\frac{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^0 K^+ K^-)}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = 0.039 \pm 0.004 \text{ (stat.)} \pm 0.002 \text{ (syst.)}$$

$\Xi_c^0 \rightarrow \Xi^0 \phi(\rightarrow K^+ K^-)$  will **not** contribute to event excesses in the  $M_{\Xi K}$  near 1.95 GeV.



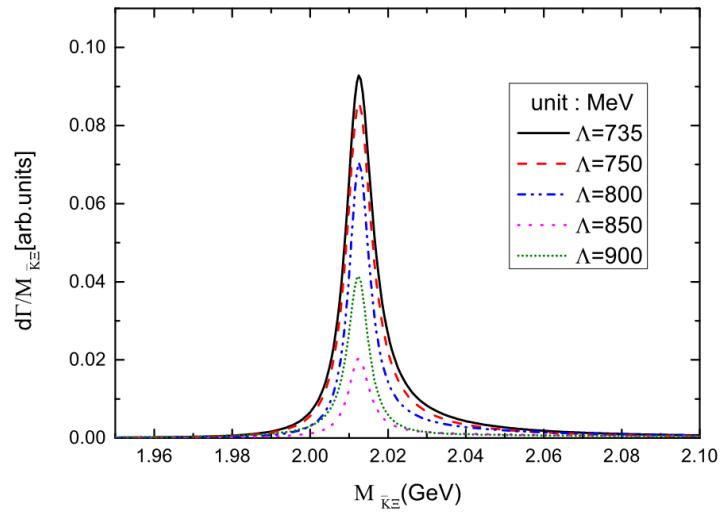
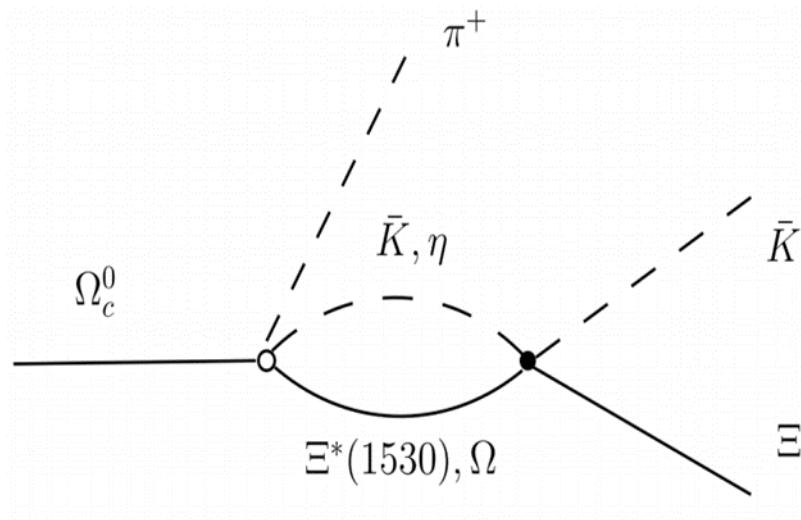
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# Evidence for $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$

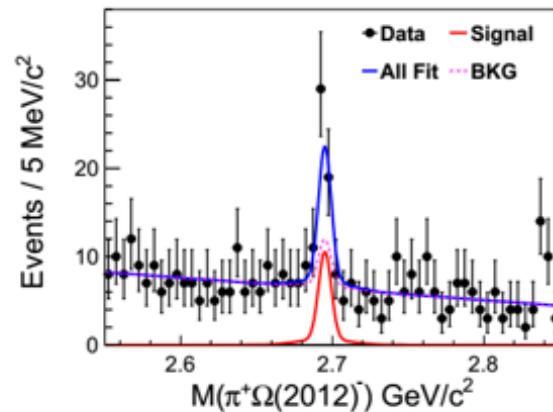
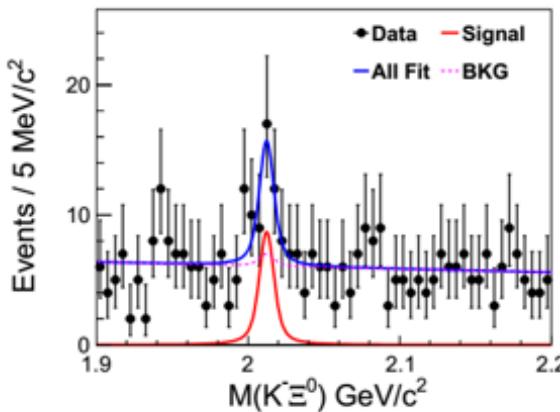
## Motivation:

- Searching for new production model is very important to understand the nature of  $\Omega(2012)^-$ ;
- A theoretical study of the  $\Omega(2012)^-$  in the nonleptonic weak decays of  $\Omega_c^0 \rightarrow \pi^+ \bar{K} \Xi(1530)(\eta\Omega) \rightarrow \pi^+ (\bar{K}\pi\Xi)^-$  and  $(\bar{K}\Xi)^-$  was reported; the authors predicted the **clearly  $\Omega(2012)^-$  peak in the  $(\bar{K}\Xi)^-$  invariant mass spectrum** of the  $\Omega_c^0 \rightarrow \pi^+ (\bar{K}\Xi)^-$ . [PRD 102, 076009 (2020)]



# Evidence for $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$

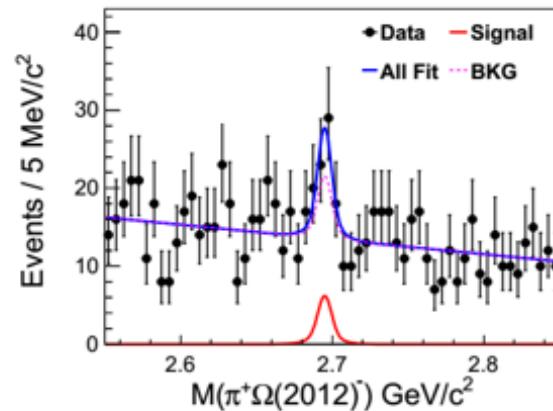
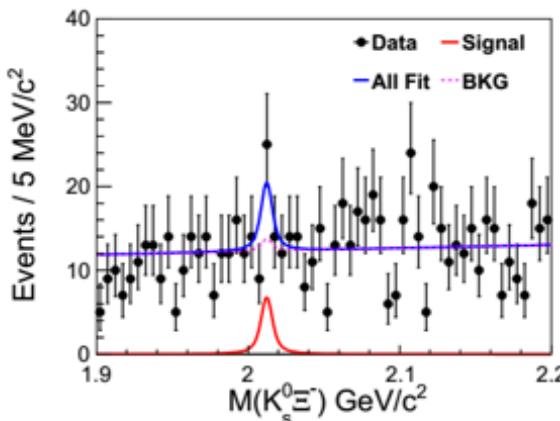
- To extract the  $\Omega(2012)^-$  signal events from  $\Omega_c^0$  decay, a 2D maximum-likelihood fit is performed to  $M(K^-\Xi^0)/M(K_S^0\Xi^-)$  and  $M(\pi^-\Omega(2012))$ .



$$N_{\text{fit}}(K^-\Xi^0) = 28.3 \pm 8.9$$

$$\frac{Br(\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-) Br(\Omega(2012)^- \rightarrow K^-\Xi^0)}{Br(\Omega_c^0 \rightarrow \pi^+ K^-\Xi^0)}$$

$$= (9.6 \pm 3.2(\text{stat.}) \pm 1.8(\text{syst.}))\%$$



$$N_{\text{fit}}(K_S^0\Xi^-) = 17.9 \pm 8.9$$

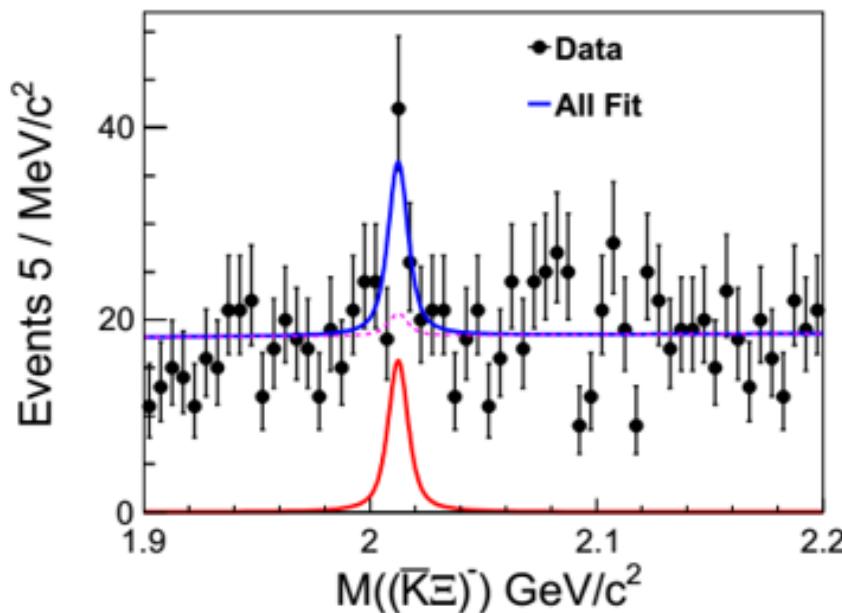
$$\frac{Br(\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-) Br(\Omega(2012)^- \rightarrow \bar{K}^0\Xi^-)}{Br(\Omega_c^0 \rightarrow \pi^+ \bar{K}^0\Xi^-)}$$

$$= (5.5 \pm 2.8(\text{stat.}) \pm 0.7(\text{syst.}))\%$$

- The **statistical significance** of  $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ K^-\Xi^0$  and  $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^- \rightarrow \pi^+ K_S^0\Xi^-$  decays are  $4.0\sigma$  and  $2.3\sigma$ , respectively.

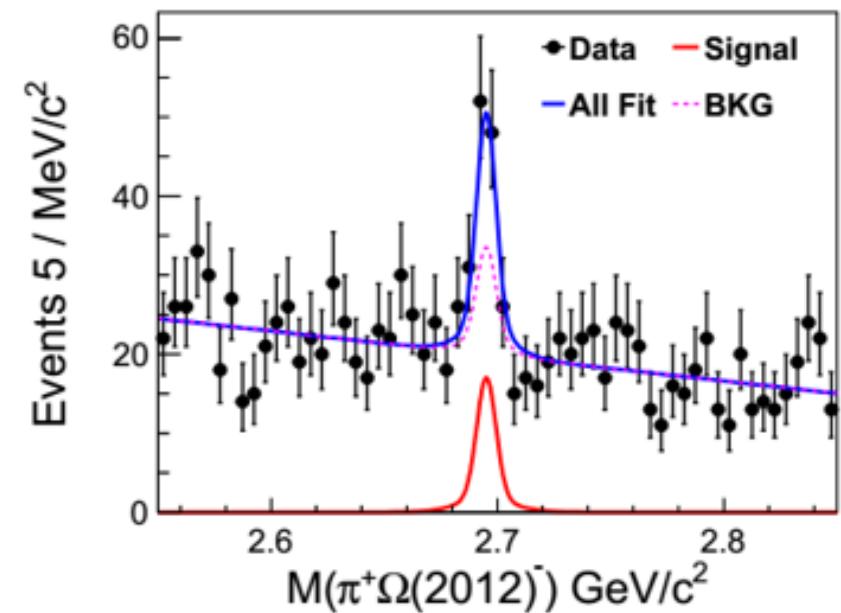
# Evidence for $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$

- A 2D un-binned maximum-likelihood simultaneous fit is performed to  $M((\bar{K}\Xi)^-)$  and  $M(\pi^+ \Omega(2012)^-)$  distributions.



$$N_{\text{fit}} = 46.6 \pm 12.3$$

Signal significance:  $4.2\sigma$   
(including systematic uncertainties)



$$\frac{Br(\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-) \times Br(\Omega(2012)^- \rightarrow (\bar{K}\Xi)^-)}{Br(\Omega_c^0 \rightarrow \pi^+ \Omega^-)}$$

$$= 0.220 \pm 0.059(\text{stat.}) \pm 0.035(\text{syst.})$$

# Outline

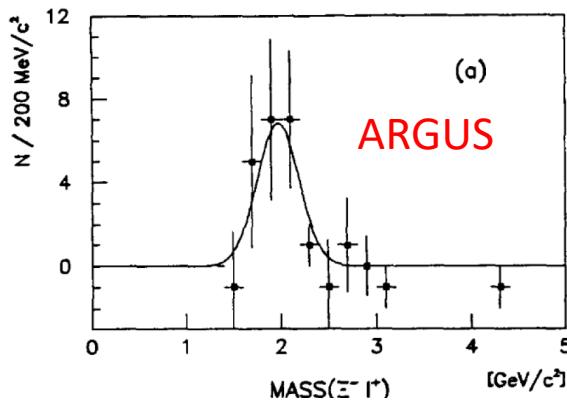
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# $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l \nu)$ and $\mathcal{A}_{cp}$ of $\Xi_c^0 \rightarrow \Xi^- \pi^+$

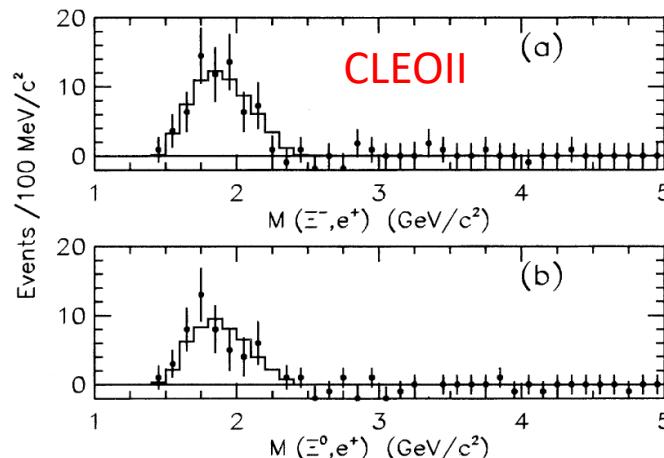
- BESIII measured the  $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda l^+ \nu)$  PRL 115, 221805(2015) & PLB 767, 42 (2017)
- $\mathcal{B}(\Xi_c \rightarrow \Xi^- l^+ \nu)$  was measured by ARGUS and CLEOII

$\Lambda e^+ \nu_e$	$(3.6 \pm 0.4)\%$
$\Lambda \mu^+ \nu_\mu$	$(3.5 \pm 0.5)\%$

- ARGUS: 495.0 pb $^{-1}$  at  $\Upsilon(1S, 2S, 3S)$  and off\_res energy points; **18 events**; PLB 303, 368(1993)  
 $\sigma(e^+ e^- \rightarrow \Xi_c^0 X) \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l^+ \nu_l) = 0.74 \pm 0.24 \pm 0.09$  pb  $l^+ = \mu^+$  or  $e^+$
- CLEOII: 2.1 fb $^{-1}$  at and bellow  $\Upsilon(4S)$  energy point; **54 signal events**; PRL 74 16(1995)  
 $\sigma(e^+ e^- \rightarrow \Xi_c^0 X) \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = 0.63 \pm 0.12 \pm 0.10$  pb  
 $\sigma(e^+ e^- \rightarrow \Xi_c^+ X) \mathcal{B}(\Xi_c^+ \rightarrow \Xi^0 e^+ \nu_e) = 1.55 \pm 0.33 \pm 0.25$  pb

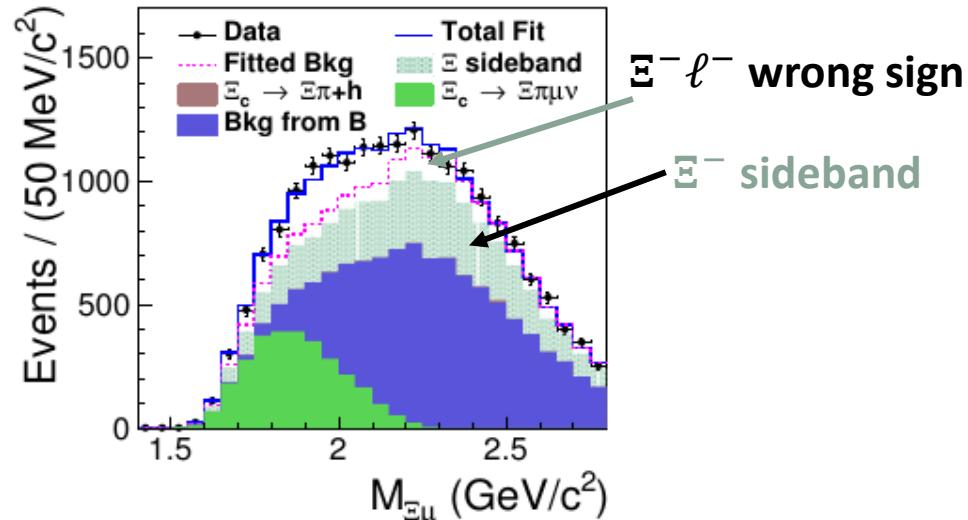
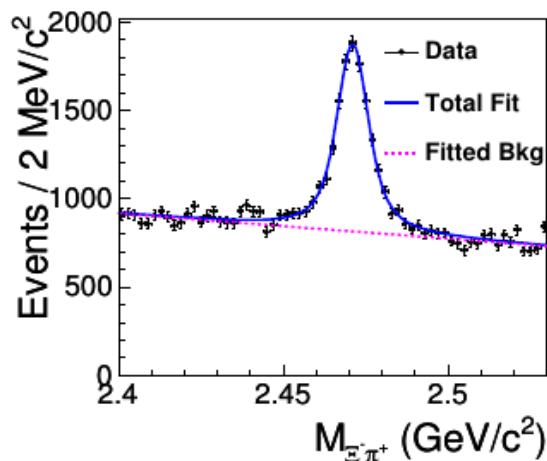
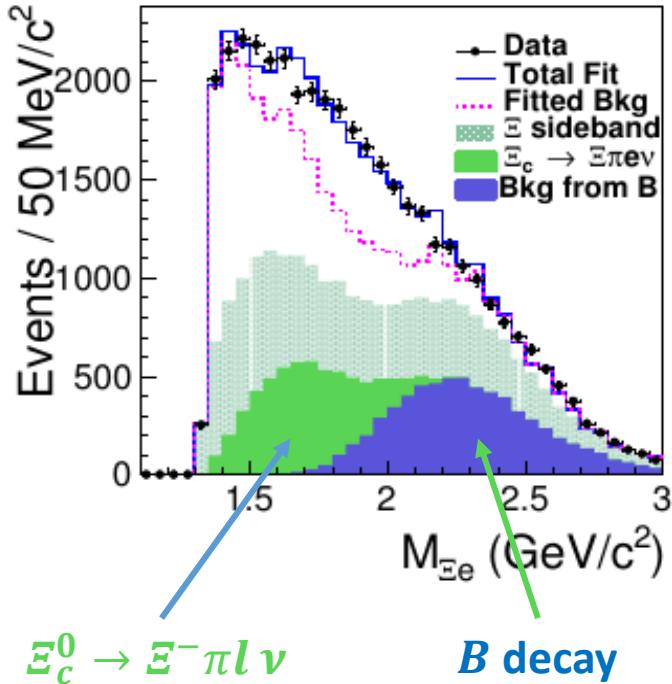


$$\frac{\text{BR}(\Xi_c^0 \rightarrow \Xi^- l^+ X)}{\text{BR}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = 0.96 \pm 0.43 \pm 0.18$$



$$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e) = 0.32 \pm 0.10^{+0.05}_{-0.03}$$

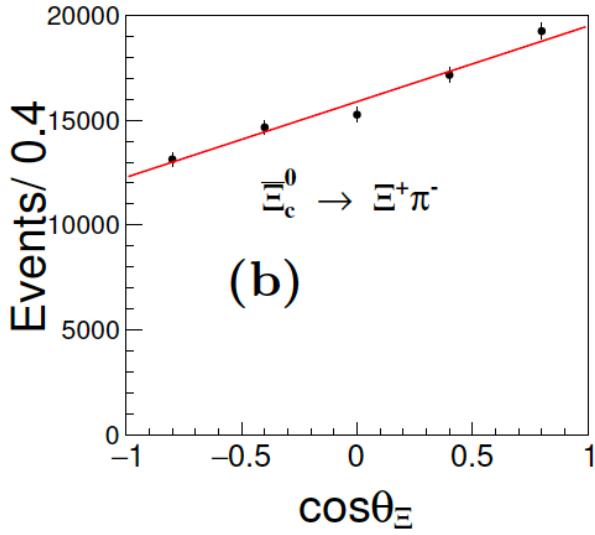
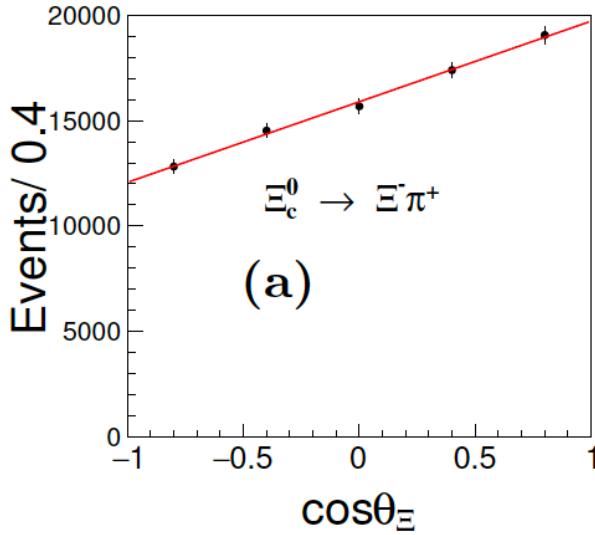
# Measurements of $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l \nu)$



More types of backgrounds are considered such as:

- ✓  $\Xi_c^0 \rightarrow \Xi^- \pi l \nu$
- ✓  $B^- \rightarrow \Xi + \text{hardons}, B^+ \rightarrow D^0 e^+ \nu_e$
- ✓  $\Xi_c^0 \rightarrow \Xi^- n \pi, n = 1, 2, 3 \dots$

# Measurements of $\mathcal{A}_{cp}$ of $\Xi_c^0 \rightarrow \Xi^- \pi^+$



arXiv:2103.06496

$$\frac{dN}{d \cos \theta_\Xi} \propto 1 + \alpha_{\Xi^- \pi^+} \alpha_{\Xi^-} \cos \theta_\Xi$$

$\theta_\Xi$ :

angle between the  $\vec{p}_\Lambda$  and  
 $-\vec{p}_{\Xi_c^0}$  in the  $\Xi^-$  rest frame

	value	theory	old result:
$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)$	$(1.31 \pm 0.39)\%$	$(2.38 \pm 0.44)\%/(3.4 \pm 1.7)\%$ LQCD/QCD sum rule	$(1.9 \pm 1.2)\%$
$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu)$	$(1.27 \pm 0.39)\%$	$(2.29 \pm 0.43)\%$	
$\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu)$	$1.03 \pm 0.09$	$1.040 \pm 0.004$	
$\alpha_{\Xi^- \pi^+}$	$-0.60 \pm 0.045$		$-0.60 \pm 0.4$
$\alpha_{\Xi^+ \pi^-}$	$0.58 \pm 0.045$		
$\mathcal{A}$	$0.015 \pm 0.056$	$\mathcal{A}_{CP} = (\alpha^+ + \alpha^-)/(\alpha^+ - \alpha^-)$	

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# $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}$ , $\Sigma^0 \bar{K}^{*0}$ , and $\Sigma^+ K^{*-}$

- It is difficult for the theoretical study in the non-leptonic decays of charmed baryons due to the failure of the factorization approach.
- Branching fraction measurements help to distinguish different theoretical models.
- The asymmetry parameters of  $\Xi_c^0$  are still not well measured, which is important to test parity violation in charmed-baryon sectors.

Decay branching fractions (%) and asymmetry parameters of the Cabibbo favored  $B_c \rightarrow B_n + V$  decays in QCD and  $SU(3)_F$  approach.

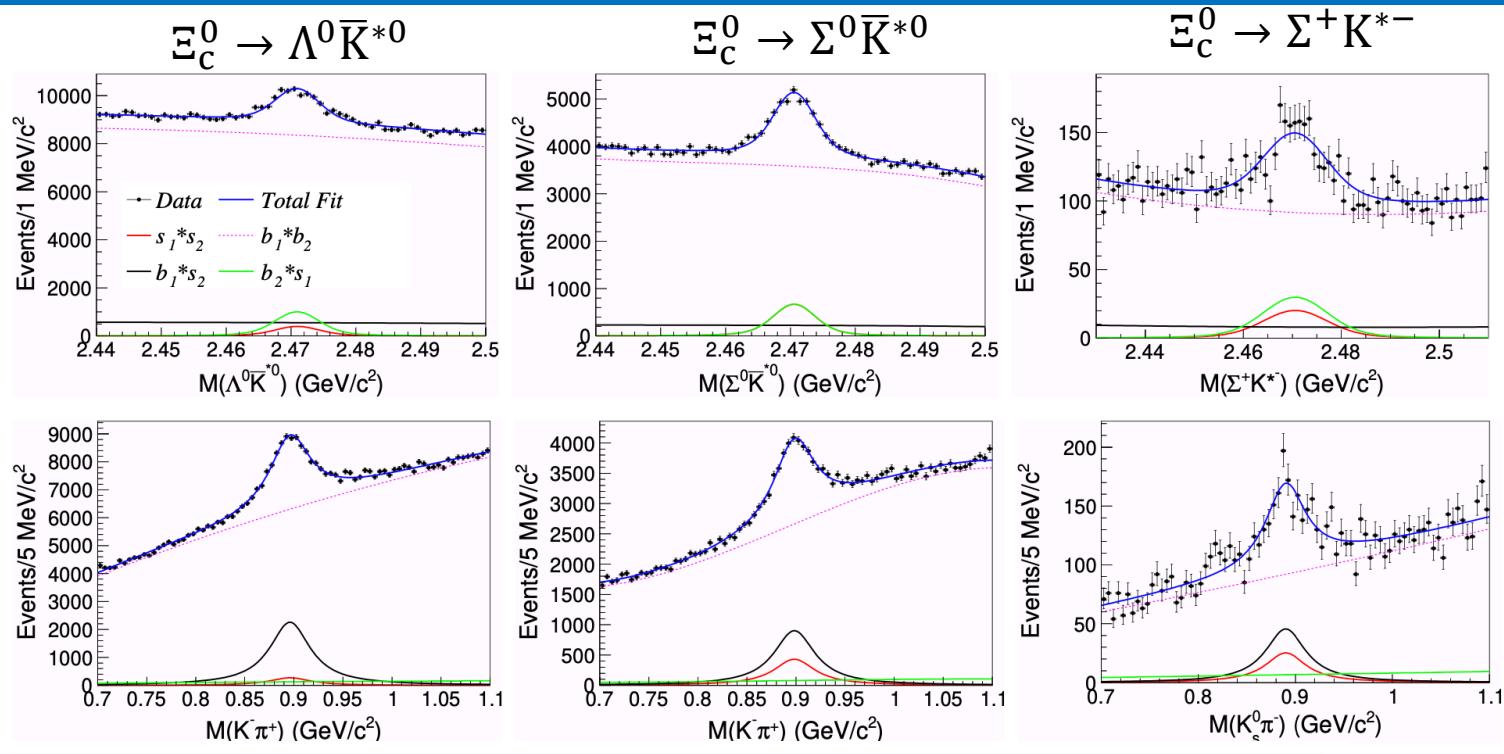
Branching fractions	KK [1]	Zen [2]	HYZ [3]	GLT [4]
$\Xi_c^0 \rightarrow \Lambda^0 \bar{K}^{*0}$	1.55	1.15	$0.46 \pm 0.21$	$1.37 \pm 0.26$
$\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0}$	0.85	0.77	$0.27 \pm 0.22$	$0.42 \pm 0.23$
$\Xi_c^0 \rightarrow \Sigma^+ K^{*-}$	0.54	0.37	$0.93 \pm 0.29$	$0.24 \pm 0.17$

Asymmetry parameters	KK [1]	Zen [2]	GLT [4]
$\Xi_c^0 \rightarrow \Lambda^0 \bar{K}^{*0}$	0.58	+0.49	$-0.67 \pm 0.24$
$\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0}$	-0.87	+0.25	$-0.42 \pm 0.62$
$\Xi_c^0 \rightarrow \Sigma^+ K^{*-}$	-0.60	+0.51	$-0.76^{+0.64}_{-0.24}$

[1] Z. Phys. C 55, 659 (1992) [2] Phys. Rev. D 50, 5787 (1994) [3] Phys. Lett. B 792, 35 (2019)

[4] Phys. Rev. D 101, 053002 (2020)

# $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0}, \text{ and } \Sigma^+ K^{*-}$



$$\mathcal{B}(\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$$

$$0.18 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0}) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$$

$$0.69 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^{*-}) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$$

$$0.34 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0})$$

$$(3.3 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.}) \pm 1.0(\text{ref.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0})$$

$$(12.4 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.}) \pm 3.6(\text{ref.})) \times 10^{-3}$$

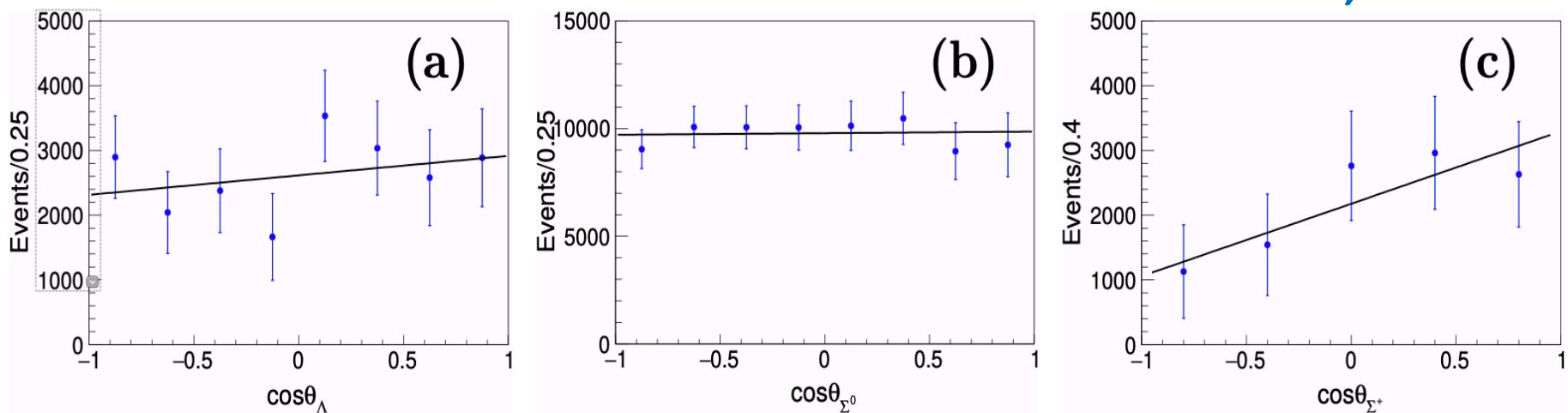
$$\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^{*-})$$

$$(6.1 \pm 1.0(\text{stat.}) \pm 0.4(\text{syst.}) \pm 1.8(\text{ref.})) \times 10^{-3}$$

JHEP 2021, 160

# $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0}$ , and $\Sigma^+ K^{*-}$

JHEP 2021, 160



Note that  $\alpha(\Lambda \rightarrow p\pi^-) = 0.747 \pm 0.010$  and  $\alpha(\Sigma^+ \rightarrow p\pi^0) = -0.980 \pm 0.017$  from PDG.

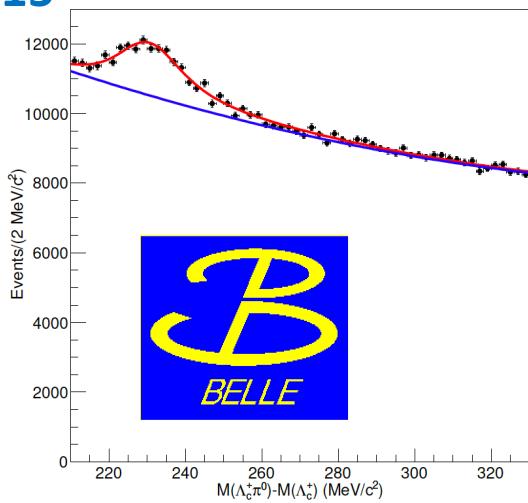
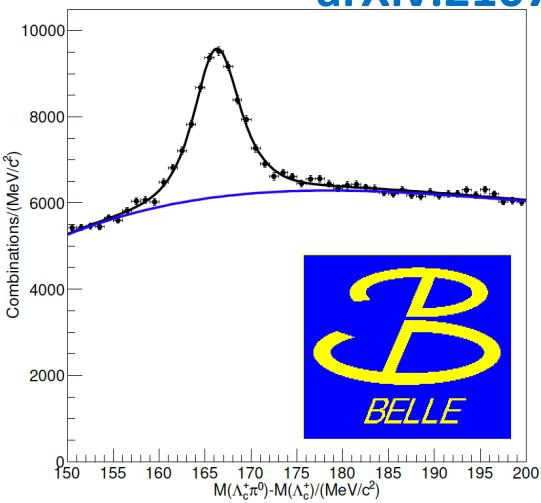
$\alpha(\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0})\alpha(\Lambda \rightarrow p\pi^-)$	$0.115 \pm 0.164(\text{stat.}) \pm 0.038(\text{syst.})$
$\alpha(\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0})\alpha(\Sigma^0 \rightarrow \gamma\Lambda)$	$0.008 \pm 0.072(\text{stat.}) \pm 0.008(\text{syst.})$
$\alpha(\Xi_c^0 \rightarrow \Sigma^+ K^{*-})\alpha(\Sigma^+ \rightarrow p\pi^0)$	$0.514 \pm 0.295(\text{stat.}) \pm 0.012(\text{syst.})$
$\alpha(\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0})$	$0.15 \pm 0.22(\text{stat.}) \pm 0.05(\text{syst.})$
$\alpha(\Xi_c^0 \rightarrow \Sigma^+ K^{*-})$	$-0.52 \pm 0.30(\text{stat.}) \pm 0.02(\text{syst.})$

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# Masses and Widths of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$

arXiv:2107.05615



$$M_{\Sigma_c(2455)^+} - M_{\Lambda_c^+} = 166.17 \pm 0.05^{+0.16}_{-0.07} \text{ MeV}/c^2$$
$$\Gamma_{\Sigma_c(2455)^+} = 2.3 \pm 0.3 \pm 0.3 \text{ MeV}/c^2$$

$$M_{\Sigma_c(2520)^+} - M_{\Lambda_c^+} = 230.9 \pm 0.5^{+0.5}_{-0.1} \text{ MeV}/c^2$$
$$\Gamma_{\Sigma_c(2520)^+} = 17.2^{+2.3}_{-2.1} {}^{+0.31}_{-0.7} \text{ MeV}/c^2.$$

Consistent with theories:

Phys. Lett. B 808, 135619

Phys. Rev. D 92, 074014

Phys. Rev. D 12 2077

- Little experimental information on the singly-charged  $\Sigma_c^+$ , due to lower efficiency, higher backgrounds of  $\pi^0$  transitions
- CLEOII measured the mass, set the limits on width  
Phys. Rev. Lett. 86, 1167  
 $M(\Sigma_c^+) - M(\Lambda_c^+) = (166.4 \pm 0.2 \pm 0.3) \text{ MeV}$   
 $M(\Sigma_c^{*+}) - M(\Lambda_c^+) = (231.0 \pm 1.1 \pm 2.0) \text{ MeV}$
- Useful to check the quark model predictions
- Critical to study the  $\Lambda_c(2593)^+$ , whose pole mass appears to be between the  $\Sigma_c(2455)^+ \pi^0$  and  $\Sigma_c(2455)^{++} \pi^-$

# Summary



- $\Xi_c^0 \rightarrow \Xi^0 \phi (\rightarrow K^+ K^-)$ 
    - Branching fraction measured
    - event excesses in the  $M_{\Xi K}$  near 1.95 GeV not from  $\Xi_c^0 \rightarrow \Xi^0 \phi$
  - Evidence for  $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$ 
    - Branching fraction measured with  $4.2\sigma$  signal
  - Measurements of  $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l \nu)$  and  $\mathcal{A}_{cp}$  of  $\Xi_c^0 \rightarrow \Xi^- \pi^+$ 
    - Error reduce by 1 order
  - $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}$ ,  $\Sigma^0 \bar{K}^{*0}$ , and  $\Sigma^+ K^{*-}$ 
    - First observation
  - Determined masses and widths of the  $\Sigma_c(2455)^+$  and  $\Sigma_c(2520)^+$
- Thank you!**

# Thank you!

# Backup: J<sub>p</sub> of Xic2970

The uncertainty will be dominated by the BF of the ground-state  $\Xi_c$  baryons. Such uncertainties are avoided by calculating the ratio in a different way, with inclusive measurements of  $\Xi_c^0$  and  $\Xi_c^+$  and an assumption of isospin symmetry in their inclusive cross sections. We note that this assumption is confirmed within 15% in the  $\Sigma_c^{(*)}$  case.

TABLE III. Result of the angular analysis of the decay  $\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0 \pi^+$ . Here, n.d.f. denotes the number of degrees of freedom.

Spin hypothesis	1/2	3/2	5/2
$\chi^2/\text{n.d.f.}$	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	$0.13 \pm 0.26$	$0.08 \pm 0.27$
$\rho_{33}$	...	$0.37 \pm 0.26$	$0.12 \pm 0.09$
$\rho_{55}$	...	...	$0.30 \pm 0.28$

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

TABLE IV. Expected angular distribution for spin-parity hypotheses of  $\Xi_c(2970)^+$  with an assumption that the lowest partial wave dominates.

$J^P$	Partial wave	$W(\theta_c)$
1/2 $^+$	$P$	$1 + 3\cos^2 \theta_c$
1/2 $^-$	$D$	$1 + 3\cos^2 \theta_c$
3/2 $^+$	$P$	$1 + 6\sin^2 \theta_c$
3/2 $^-$	$S$	1
5/2 $^+$	$P$	$1 + (1/3)\cos^2 \theta_c$
5/2 $^-$	$D$	$1 + (15/4)\sin^2 \theta_c$

$$R = \frac{N^*}{\mathcal{E}^* \times \frac{N(\Xi_c^+)}{\epsilon^+}} / \frac{N'}{\sum_i \mathcal{E}'_i \times \frac{N(\Xi_c^0)_i}{\epsilon'_i}}.$$

# Backup: Xic to Xi KK

## Values of Helicity Amplitudes for EvtGen HELAMP class

*On-Shell Decay:*

$$q^2 = (\mathbf{p}_{\Xi_c^0} - \mathbf{p}_{\Xi^0})^2 = m_\phi^2$$
$$H_{+\frac{1}{2}0} = -1.091 \quad H_{-\frac{1}{2}0} = 4.123$$
$$H_{+\frac{1}{2}+1} = -2.2305 \quad H_{-\frac{1}{2}-1} = 4.2955$$

```
Decay Xi_c0
0.90 Xi- pi+ PHSP;
0.065 Xi0 phi HELAMP 2.2305 3.14159265359 1.091 3.14159265359 4.123 0.0 4.2955 0.0;
0.035 Xi0 K+ K- PHSP;      H_{+\frac{1}{2}+1}           H_{+\frac{1}{2}0}           H_{-\frac{1}{2}0}           H_{-\frac{1}{2}-1}
Enddecay
```

In Resonant/Mixed MC, the phi is decayed through VSS as expected

Non-Resonant

$\Xi_c^0 \rightarrow \Xi^0 K^+ K^-$

Resonant

$\Xi_c^0 \rightarrow \Xi^0 (\phi \rightarrow K^+ K^-)$

Normalization

$\Xi_c^0 \rightarrow \Xi^- \pi^+$

Mixed

$\Xi_c^0 \rightarrow 0.9 * [\Xi^- \pi^+] +$   
 $\Xi^0 [0.065 * (\phi \rightarrow K^+ K^-) + 0.035 * (K^+ K^-)]$



Truth:

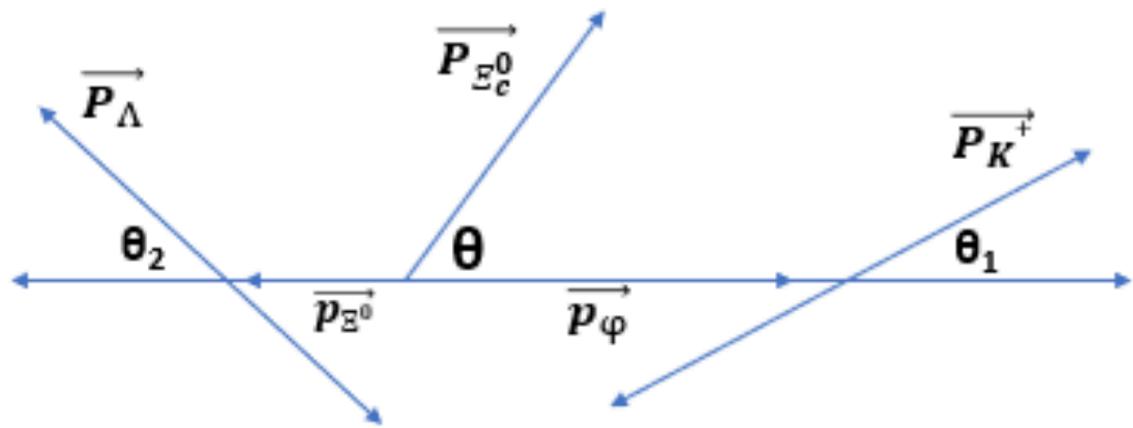
$\Gamma(\Xi^0 \phi) / \Gamma(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.07222...$   
 $\Gamma(\Xi^0 K^+ K^-) / \Gamma(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.03888...$

# Backup: Xic to Xi KK

These topological substructures are due to the helicity angles of the Xic0 polarizing the in the  $\frac{1}{2} \rightarrow \frac{1}{2} + 1$  resonant decay process

Polarization is defined:

$$\vec{P} = \frac{\hat{z} \times \vec{p}}{p}$$



$\Xi_c^0$  decays with polarization  $\overrightarrow{P}_{\Xi_c^0}$   
into a resonant  $\phi \rightarrow K^+ K^-$   
and “spin-conserving”  $\Xi^0 \rightarrow \Lambda \pi^0$

**Weak (Non-Parity Conserving)  $\frac{1}{2} \rightarrow \frac{1}{2} 1$  decay**

Polarization Angles  $\theta$ ,  $\theta_1$ , and  $\theta_2$  describe the full angular distribution of the azimuthally independent (real) final state  $\Xi^0 K^+ K^-$

# Backup: Sigmac mass and width

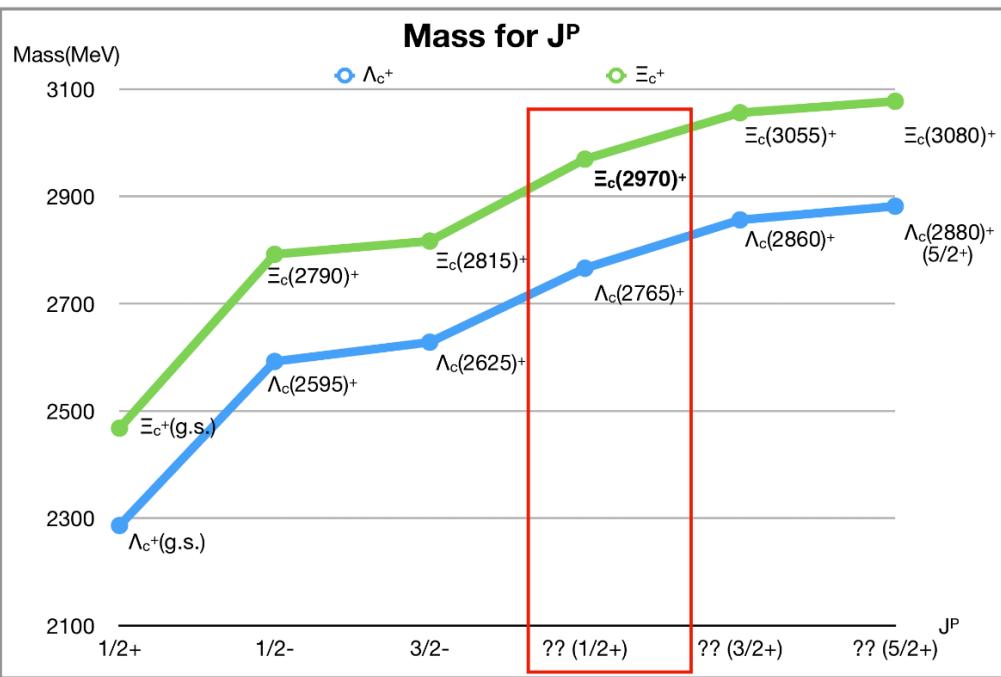
A fit is made to Fig. 2 using a third-order Chebychev polynomial function to represent the background, and a P-wave relativistic Breit-Wigner function convolved with the previously described double-Gaussian resolution function, taking into account the small mass offset. The Breit-Wigner signal function includes a Blatt-Weisskopf barrier factor, with radius parameter of  $R = 3 \text{ GeV}$ .

# Outline

- Introduction to Belle experiment
- Spin and parity determination of  $\Xi_c(2970)^+$
- $\Xi_c^0 \rightarrow \Xi^0 \phi (\rightarrow K^+ K^-)$
- Evidence for  $\Omega_c^0 \rightarrow \pi^+ \Omega(2012)^-$
- Measurements of  $\mathcal{B}(\Xi_c^0 \rightarrow E^- l \nu)$  and  $\mathcal{A}_{cp}$  of  $\Xi_c^0 \rightarrow E^- \pi^+$
- $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0},$  and  $\Sigma^+ K^{*-}$
- Masses and Widths of the  $\Sigma_c(2455)^+$  and  $\Sigma_c(2520)^+$

# $J^p$ of $\Xi_c(2970)^+$

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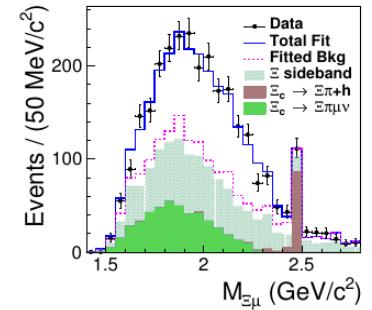
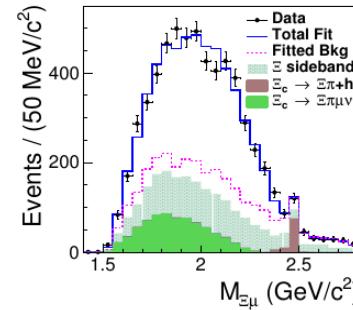
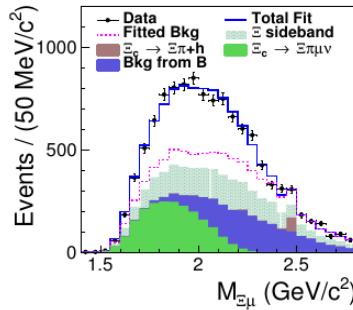
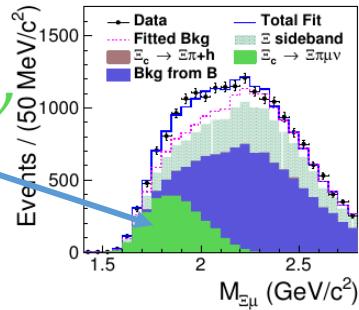
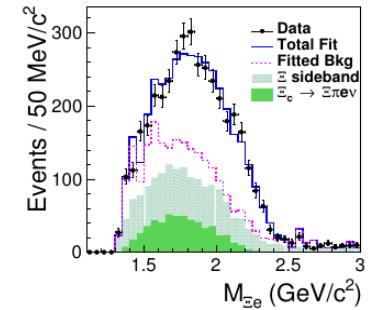
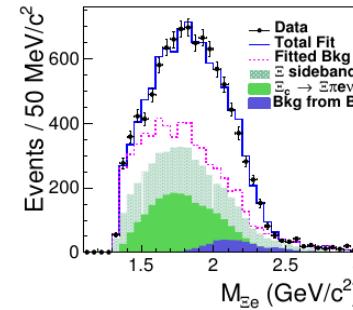
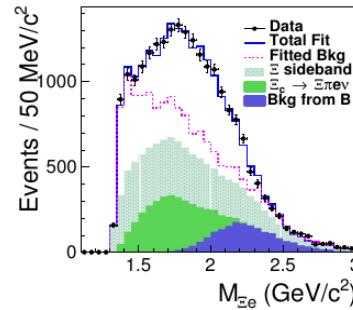
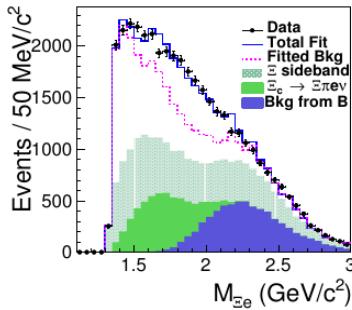


- Similar tendency in mass of the excited states of  $\Lambda_c$  and  $\Xi_c$
- It is conceivable that  $\Xi_c(2970)$  is the counter part of  $\Lambda_c(2675)$ . [PRD 75, 014006 (2007)]

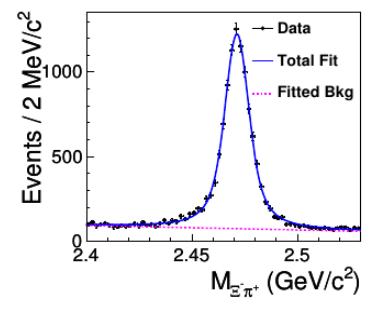
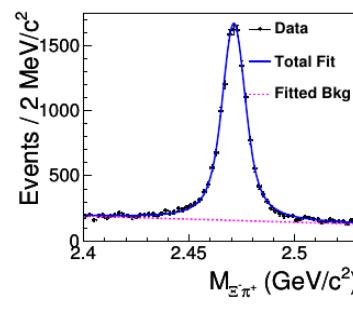
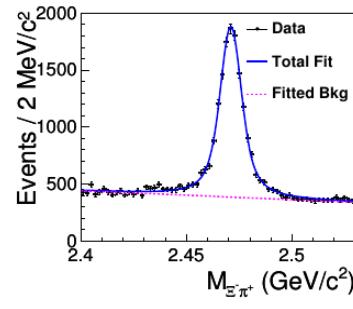
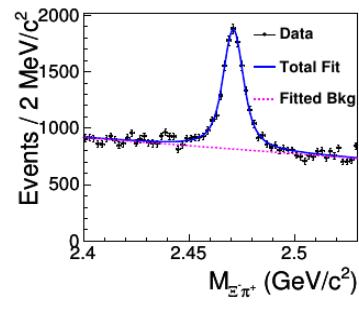
- No experimental determination  $J^p$  for Charmed baryons
- Low excited  $\Xi_c$  states can be uniquely identified as particular states predicted by the quark model
- Identification failed in higher excitation region, due to multiple states within the typical mass accuracy of quark-model predictions.

# Measurements of $\mathcal{B}(\Xi_c^0 \rightarrow E^- l \nu)$

(a):



(c):



$p_{\Xi-X}^*/p_{max}^*$  region: (0.45, 0.55)

(0.55, 0.65)

(0.65, 0.75)

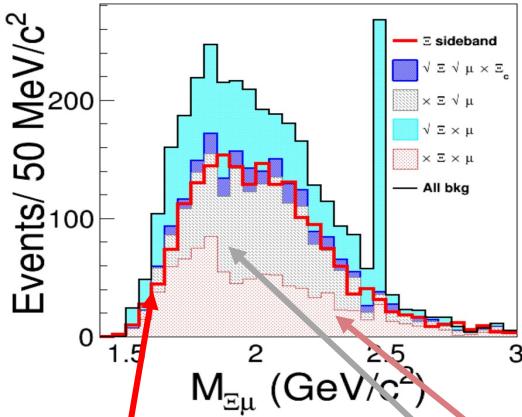
> 0.75

$p_{\Xi\ell(\pi)}^*$  is the momentum of  $\Xi\ell(\pi)$  in center of mass system ,  $p_{max}^* = \sqrt{E_{beam}^2 - M_{\Xi_c^0}^2}$

# Measurements of $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- l \nu)$

## Data-driven method used to describe background shape

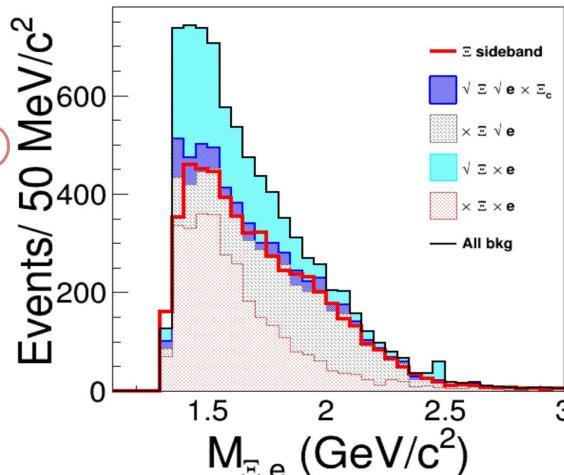
- BKG candidates from generic MC
- Filled histograms are stacked.



- $\Xi^-$  sideband from  $\Xi^- \mu^+$ : ②+③
- $\Xi^- \mu^-$  selection: ①+③+④
- $\Xi^-$  sideband from  $\Xi^- \mu^-$ : ③

	Background component		
	$\Xi$	$\ell$	$\Xi_c^0$
①	✓	✗	✓ or ✗
②	✗	✓	✓ or ✗
③	✗	✗	✗
④	✓	✓	✗

$\Xi^- \ell^-$  is the combination of the same charged  $\Xi^-$  and  $\ell^-$



For data under resonance:  
Backgrounds such as:  
 $B^- \rightarrow \Xi + \text{hardons}$   
 $B^+ \rightarrow D^0 e^+ \nu_e$   
 are **not covered in this method**

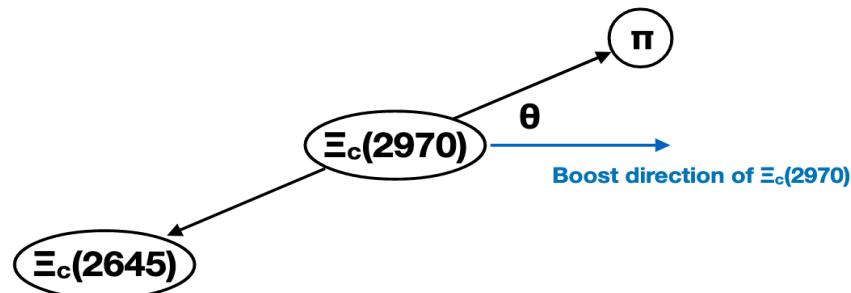
# $J^P$ of $\Xi_c(2970)^+$

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- Parity:

Ratio of partial width

$$\frac{\Gamma(\Xi_c(2970) \rightarrow \Xi_c(2645)\pi)}{\Gamma(\Xi_c(2970) \rightarrow \Xi_c'\pi)}$$



- Expected helicity angle distribution  $W_J(\theta)$  for  $J \rightarrow 3/2+0$ :

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

$$\theta_h$$

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

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

where  $T = \frac{|T(p, \frac{3}{2}, 0)|^2 - |T(p, \frac{1}{2}, 0)|^2}{|T(p, \frac{3}{2}, 0)|^2 + |T(p, \frac{1}{2}, 0)|^2}$  and  $T(p, \lambda_1, \lambda_2)$  is the matrix element of two body decay with helicity of daughter particles to be  $\lambda_1$  and  $\lambda_2$ .

- Spin:

- $\cos \theta_h, \cos \theta_c$

$\theta_h$ : helicity angle of  $\Xi_c(2970)$

$\theta_c$ : helicity angle of  $\Xi_c(2645)$

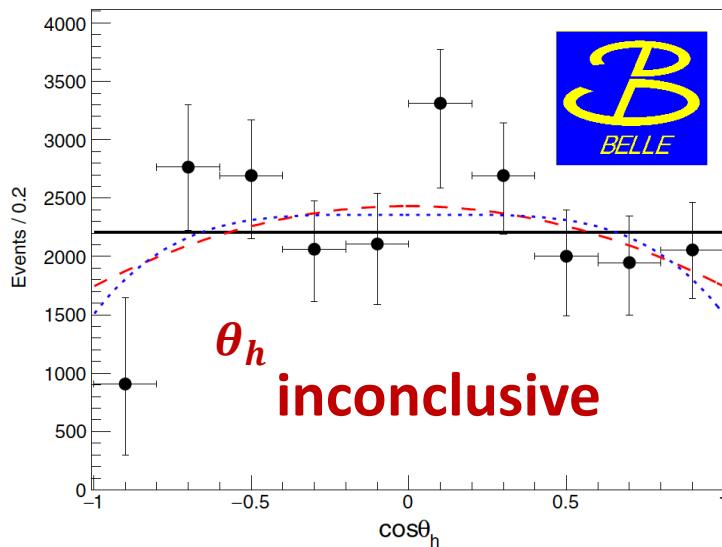
$\Xi_c(2970) \rightarrow \Xi_c(2645)\pi$

$\theta_c$

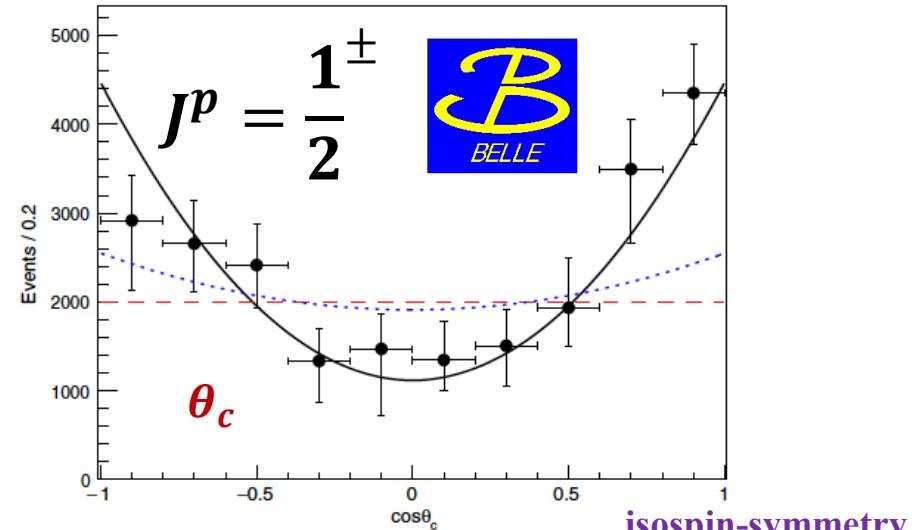
$J^P$	Partial wave	$W(\theta_c)$
$1/2^+$	$P$	$1 + 3\cos^2 \theta_c$
$1/2^-$	$D$	$1 + 3\cos^2 \theta_c$
$3/2^+$	$P$	$1 + 6\sin^2 \theta_c$
$3/2^-$	$S$	1
$5/2^+$	$P$	$1 + (1/3)\cos^2 \theta_c$
$5/2^-$	$D$	$1 + (15/4)\sin^2 \theta_c$

# $J^p$ of $\Xi_c(2970)^+$

—  $J = \frac{1}{2}$     - - -  $J = \frac{3}{2}$     .....  $J = \frac{5}{2}$



—  $J^p = \frac{1}{2}^\pm$     - - -  $J^p = \frac{3}{2}^-$     .....  $J = \frac{5}{2}^-$



$$R = \frac{\Gamma(\Xi_c(2970)^+ \rightarrow \Xi_c(2656)^0 \pi^+)}{\Gamma(\Xi_c(2970) \rightarrow \Xi_c'^0 \pi^+)} = 1.67 \pm 0.29(\text{stat.})^{+0.15}_{-0.09}(\text{syst.}) \pm 0.25$$

$$R = \begin{cases} 1.06 \text{ for } J^p = \frac{1}{2}^+ \text{ with light-quark degrees of freedom } s_l = 0 & \checkmark \\ 0.26 \text{ for } J^p = \frac{1}{2}^+ \text{ with light-quark degrees of freedom } s_l = 1 \\ \ll 1 \text{ for } J^p = \frac{1}{2}^- \text{ since } \Xi_c'^0 \pi^+ \text{ is in S wave while that to } \Xi_c(2656)^0 \pi^+ \text{ in D wave} \end{cases}_{31}$$