Constraint on spin and parity of $\Xi_c(2970)$ at Belle

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チャームバリオン内のダイクォーク構造の探求

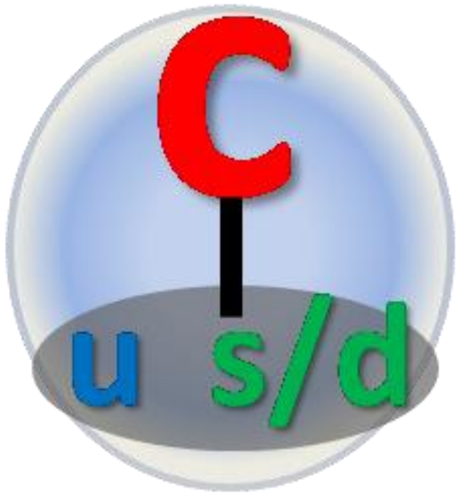
Physics of single charmed baryons

- Charm quark is heavy: (1500 MeV/c^2) > u,d,s quarks (300-500 MeV/c^2)
- spin-spin interaction $\propto 1/m_1 m_2$
- Di-quark correlation in light quarks? (more simple! New d.o.f!).

Nucleon

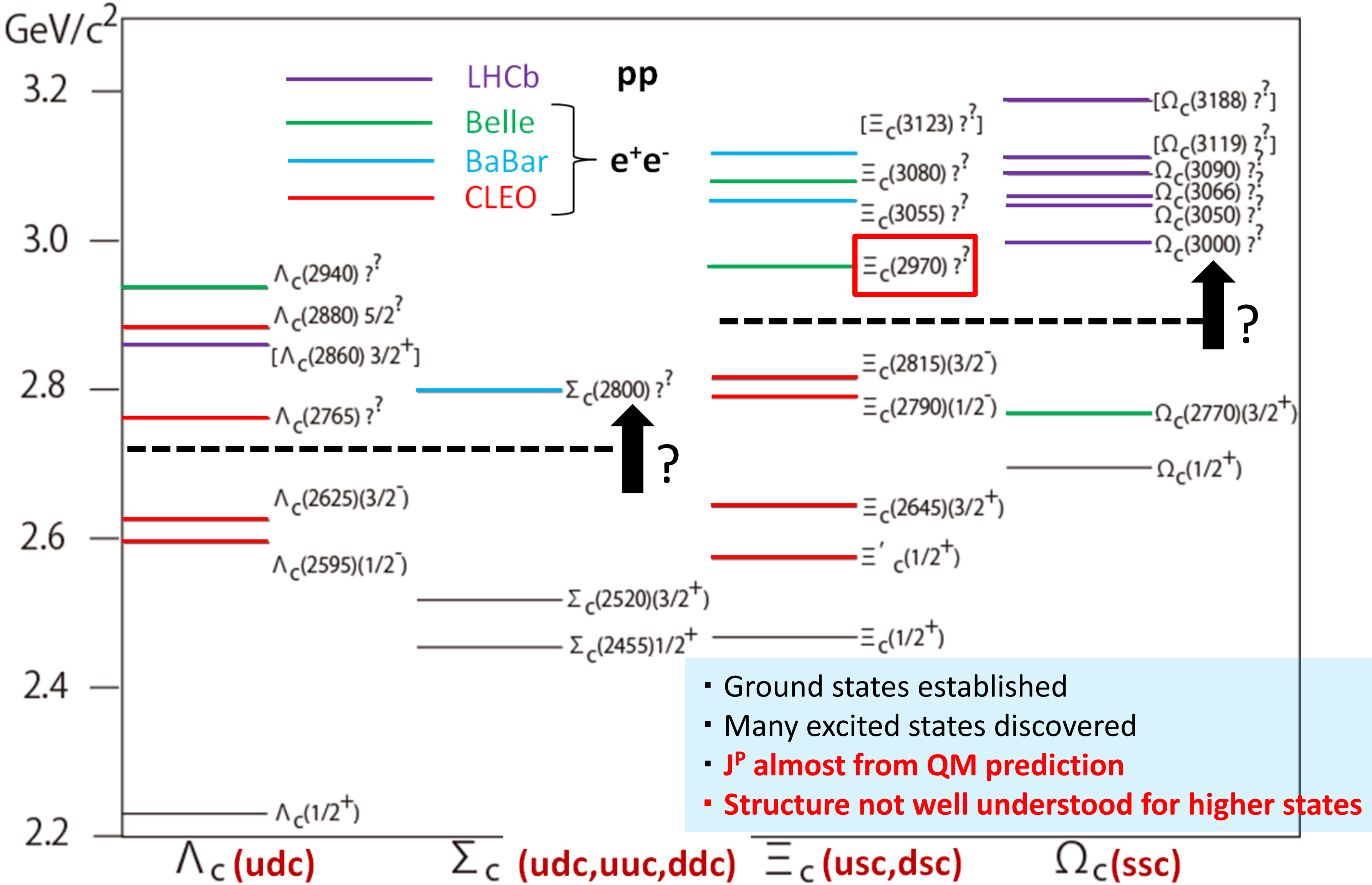
Every pair can not be distinguished.

Charmed baryon



Light di-quark and charm quark?

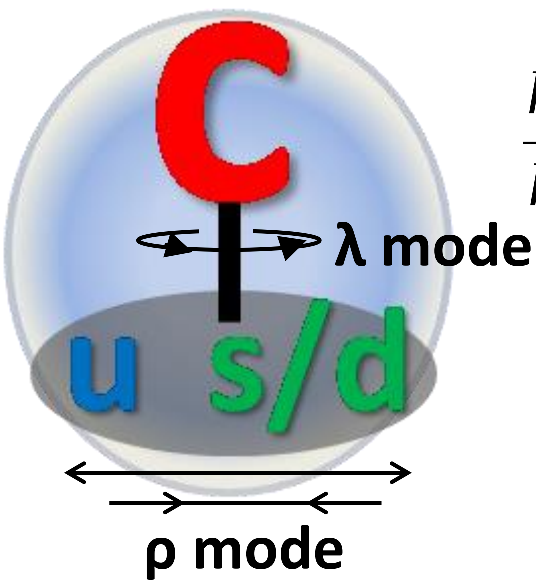
Observed charmed baryons



- Ground states established
- Many excited states discovered
- **J^P almost from QM prediction**
- **Structure not well understood for higher states**

Excitation modes in the charmed baryons

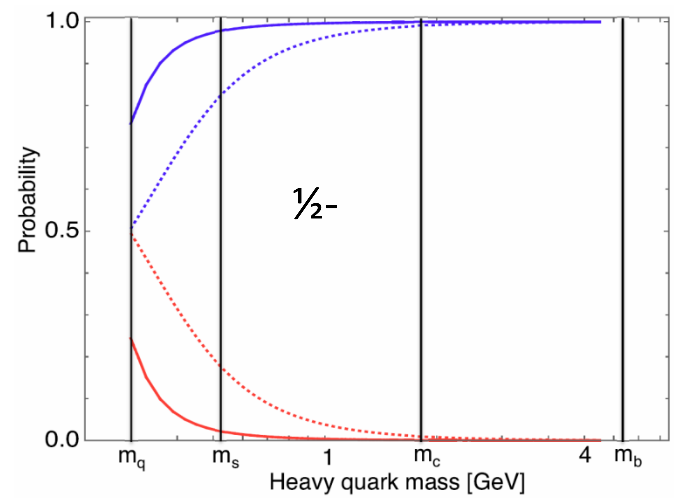
- There are two kind of excitation modes.
  - λ mode: excitation between c quark and u-d di-quark.
  - ρ mode: excitation in the di-quarks.



$$\frac{h\omega_\rho}{h\omega_\lambda} = \sqrt{\frac{3m_Q}{2m_q + m_Q}} \sim= \sqrt{3}$$

The fraction of λ mode for the 1st excited state.

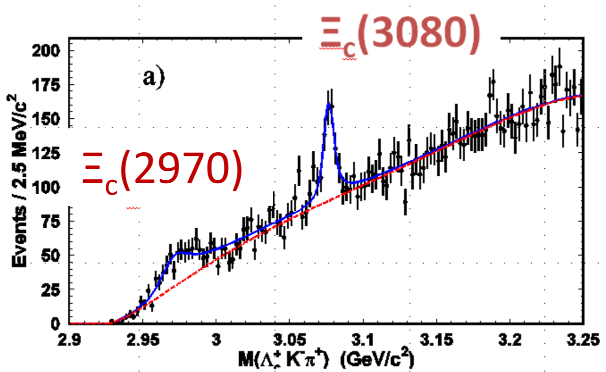
T. Yoshida et al. PRD 92, 114029 (2015)



- λ mode excited states are already observed
  $\Lambda_c(2593) = 1/2^-$ $\Lambda_c(2625) = 3/2^-$ $\Xi_c(2790) = 1/2^-$, $\Xi_c(2815) = 3/2^-$
- There should be other state with negative parity corresponding to ρ mode

$\Xi_c(2970)^+$

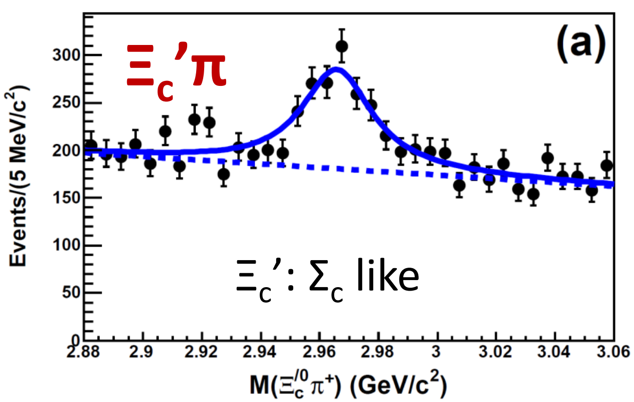
First observation by Belle in $\Lambda_c^+K^-\pi^+$ (in 2006)



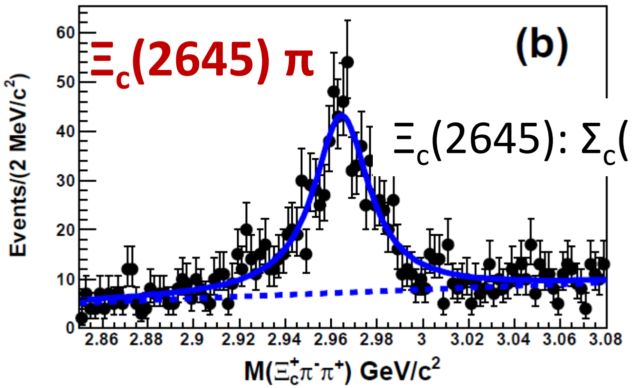
Mass = 2969.4 ± 0.8 MeV
Width = $20.9^{+2.4}_{-3.5}$ MeV

Phys. Rev. Lett. 97, 162001

Another two decay modes are also observed



Phys. Rev. D 94, 052011

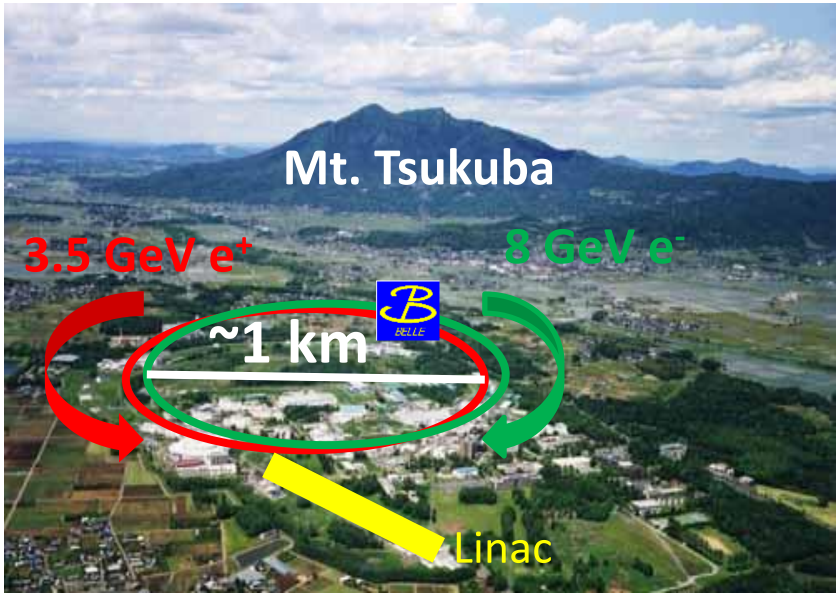


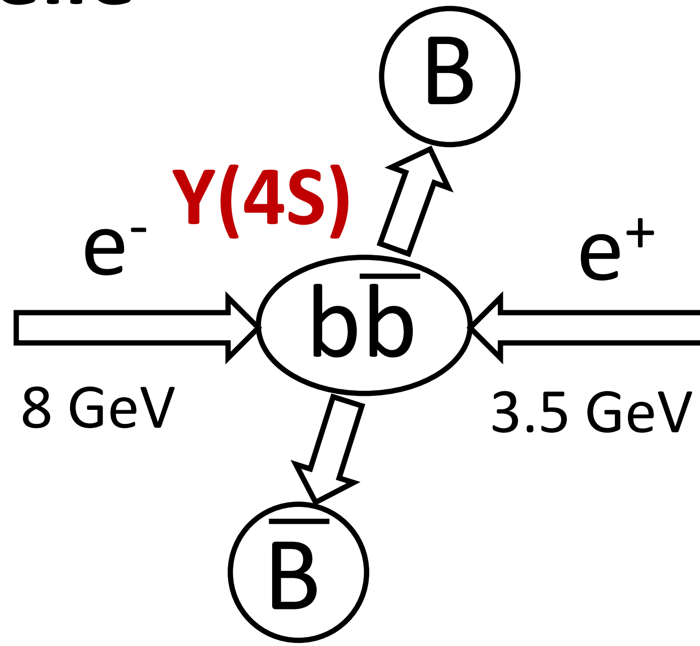
$\Xi_c(2645)$: $\Sigma_c(1385)$ like

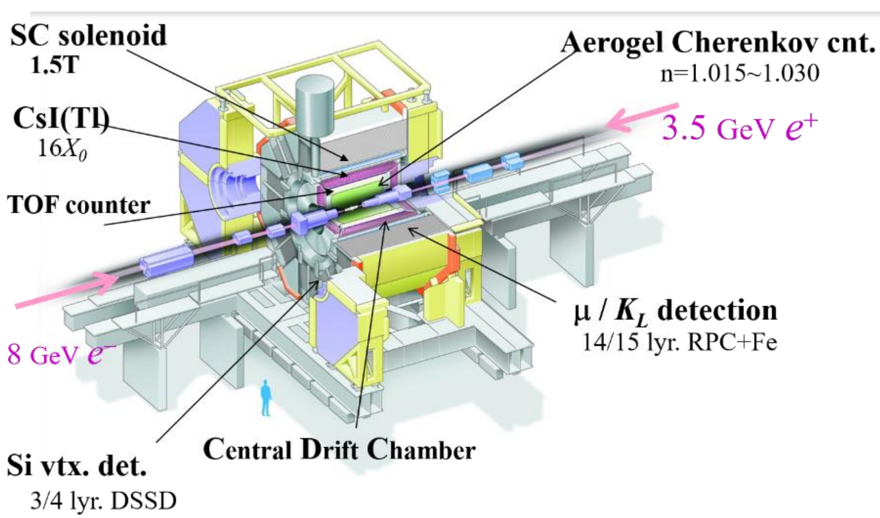
Today's talk:

- Experimental determination of JP for $\Xi_c(2970)$
- Collaborative work with T. Moon (SNU) and K. Tanida (JAEA)

KEKB/Belle







- Asymmetric energy e^+e^- collider
  to test KM theory in B-meson decays.

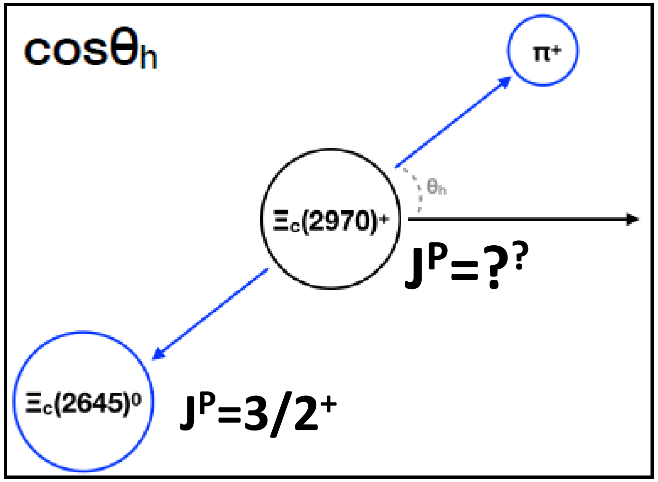
- $1ab^{-1}$ data sample
  ~= 1×10^9 cc^{bar} events.
  $O(10^6)$ $\Lambda_c^+ \rightarrow pK^-\pi^+$ reconstructed.

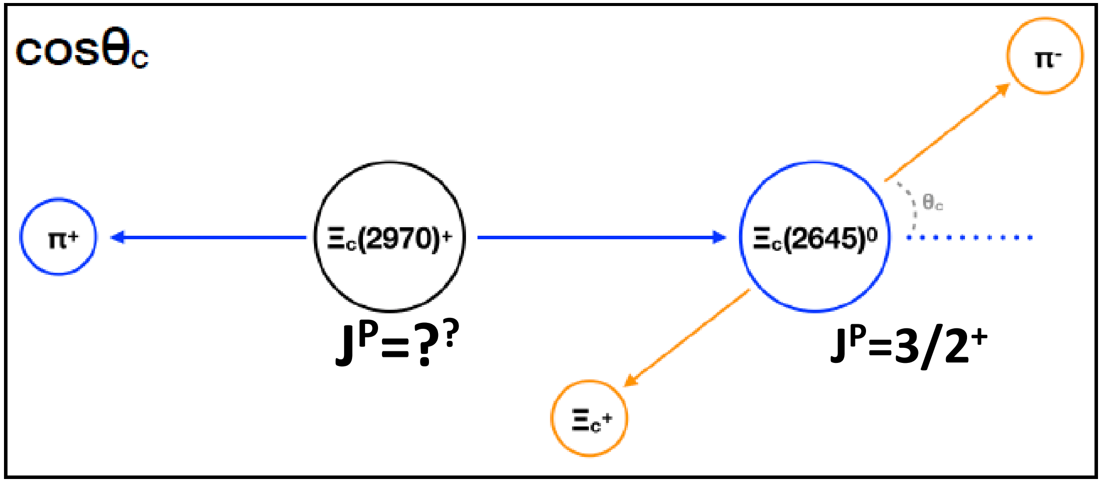
- Belle: General purpose detector.

- Hadron spectroscopy also possible.

Spin measurement

- Use the decay chain $\Xi_c(2645)\ \pi$, $\Xi_c(2645) \rightarrow \Xi_c^+\pi^-$
- Measure two angular distributions

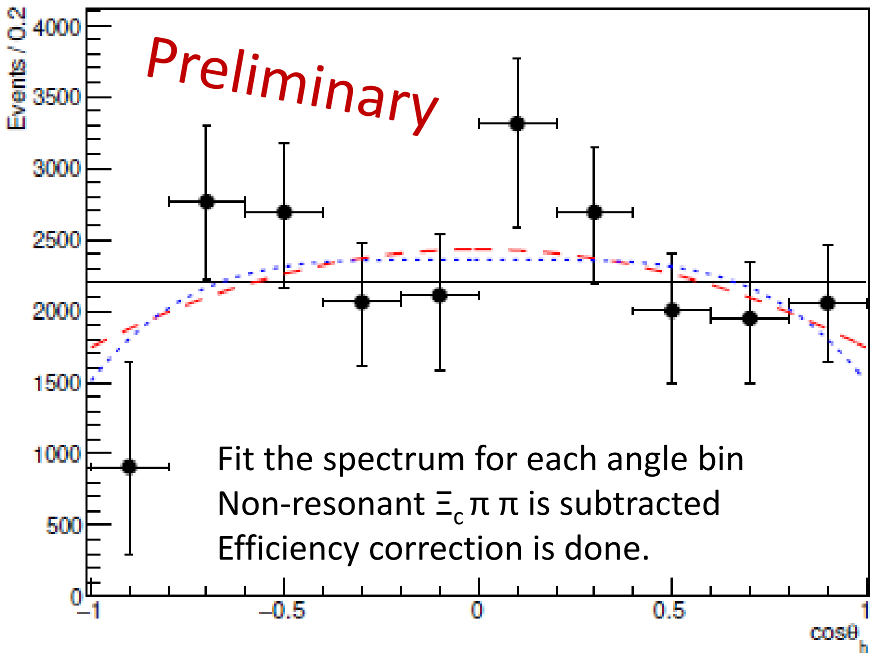




Θ_h:Helicity angle of the $\Xi_c(2970)^+$

Θ_c: Helicity angle of $\Xi_c(2645)_0$

cos(Θ_h) distribution



$$W_{1/2} = \text{constant} \quad (1)$$

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

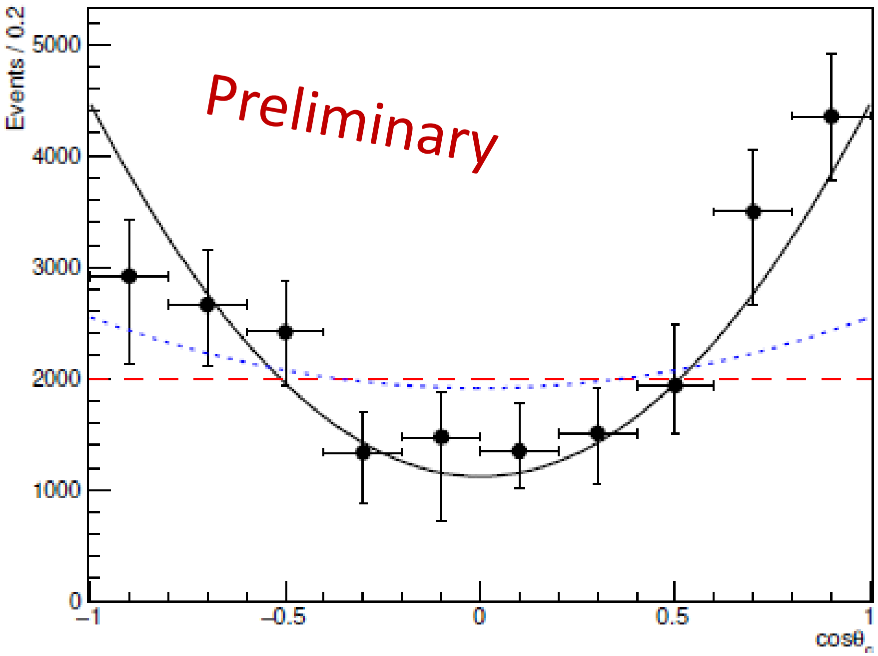
$$\begin{aligned} W_{5/2} = \frac{3}{32}[&\rho_{55}5\{(-\cos^4\theta_h - 2\cos^2\theta_h + 3) \\ &+T(-5\cos^4\theta_h + 6\cos^2\theta_h - 1)\} \\ &+\rho_{33}\{(15\cos^4\theta_h - 10\cos^2\theta_h + 11) \\ &+T(75\cos^4\theta_h - 66\cos^2\theta_h + 7))\} \\ &+\rho_{11}2\{(-5\cos^4\theta_h + 10\cos^2\theta_h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

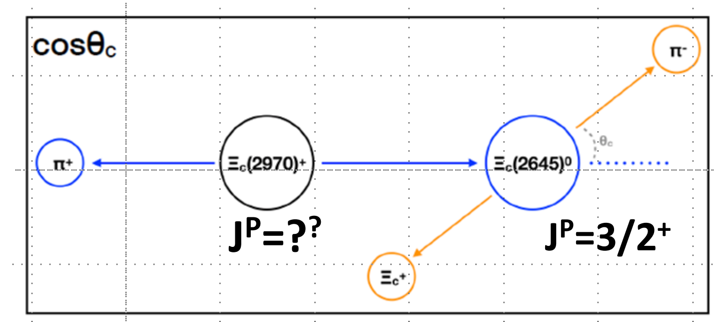
$$T = \frac{|T(p,\frac{3}{2},0)|^2 - |T(p,\frac{1}{2},0)|^2}{|T(p,\frac{3}{2},0)|^2 + |T(p,\frac{1}{2},0)|^2}$$

Spin hypothesis	1/2	3/2	5/2
χ^2/n.d.f.	9.3/9	7.7/7	7.5/6
Prob.	41%	36%	28%
T	-	-0.5 ± 1.1	0.7 ± 1.6
ρ_{11}	0.5	0.13 ± 0.26	0.08 ± 0.27
ρ_{33}	-	0.37 ± 0.26	0.12 ± 0.09
ρ_{55}	-	-	0.30 ± 0.28

- Fit quality is almost independent of spin assumption.
- Note flat distribution can be made in any spin hypothesis
  (all the ρ_{ii} to be the same = no polarization)
- **Conlusion from Θ_h analysis:**
  Spin=1/2 or other spin with small polarization

cos(Θ_c) distribution





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

$\rho_{11}=0.46\pm0.04$, $\rho_{33}=0.04\pm0.04$ $\chi^2/ndf = 5.6/8$

Helicity 1/2 is dominated.

- The helicity of $\Xi_c(2645)$ is delegated from $\Xi_c(2970)$.
  Dominance of helicity 1/2 can be naturally explained with $\Xi_c(2970)$ spin to be 1/2.

- Fit assuming lowest partial wave dominates with other JP is also tried. $3/2^-$ and $5/2^+$ are excluded by 5.1 (4.0)σ (others have upward).

- Spin = 1/2 is strongly favored.

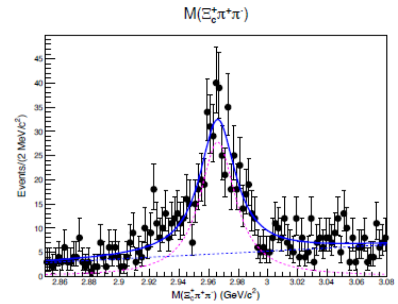
- Exclude $\Xi_c(2645)$ spin to be 1/2

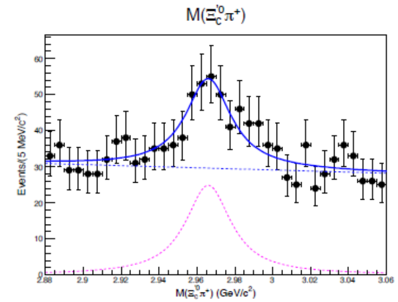
J^P	Partial Wave	$W(\theta_c)$
$1/2^+$	P	$1+3\cos^2\theta_c$
$1/2^-$	D	$1+3\cos^2\theta_c$
$3/2^+$	P	$1+6\sin^2\theta_c$
$3/2^-$	S	1
$5/2^+$	P	$1+(1/3)\cos^2\theta_c$
$5/2^-$	D	$1+(15/4)\sin^2\theta_c$

Parity determination

Measure the ratio of branching fractions

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





The value *R* can be calculated by assuming the heavy quark spin symmetry.

Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

Difficulty: Charges of ground state Ξ_c are different in two decay modes.

$\Xi_c(2645)^0 \pi$, $\Xi_c(2645) \to \Xi_c^+ \pi^-$

$\Xi_c^{\prime 0} \pi^+$, $\Xi_c^{\prime 0} \to \Xi_c^0 \gamma$

$$R = \frac{N^*}{\mathcal{E}^* \times \mathcal{B}^+} \Big/ \frac{N'}{\sum_i \mathcal{E}'_i \times \mathcal{B}^0_i}$$

N*, N': Yield of $\Xi_c(2970)$ in each decay mode

ε*, ε': Efficiency of $\Xi_c(2970)$

$B^{+/0}$: Branching fractions of ground state Ξ_c for decay modes we used to reconstruct them

- The branching fractions ($B^{+/0}$) can not be canceled.
- The uncertainty of R is dominated by those for branching fractions (more than 80%...)

R measurement assuming isospin symmetry

The branching fractions of ground state Ξ_c can be obtained in the following equation:

$$\mathcal{B}_i^{+(0)} = \frac{N(\Xi_c^{+(0)})_i}{\mathcal{L} \times \sigma_{\Xi_c} \times \epsilon_i^{+(0)}}$$

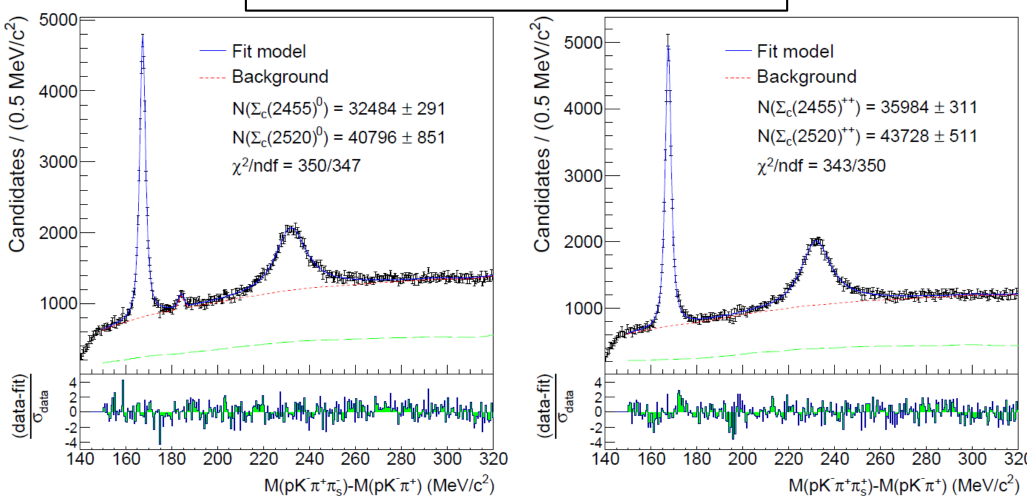
$N(\Xi_c^{+(0)})$: Yield of inclusive $\Xi_c^{+/0}$

$\sigma_{\Xi c}$: Cross section of the ground state Ξ_c

- By assuming $\sigma_{\Xi c}$ are the same between Ξ_c^0 and Ξ_c^+ based on isospin symmetry, R can be written in the following equation.

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

Example in Σ_c^0 and Σ_c^{++}



Phys. Rev. D 89, 091102(R)

~10% difference for $\Sigma_c(2455)$

~7% difference for $\Sigma_c(2520)$

Result

$$R = 1.67 \pm 0.29(\text{stat.})^{+0.15}_{-0.09}(\text{syst.}) \pm 0.25\,(\text{IS})$$

Preliminary

Parity	$+$	$+$	$-$	$-$
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

$J^P = 1/2^+$ with Brown-much spin to be zero is favored

Summary

- $J^P=1/2^+$ is favored for $\Xi_c(2970)$
- First experimental constraint on J^P for Ξ_c family
- This is a family of Roper state:
  The excitation energy of ~530 MeV is consistent with other $1/2^+$ state.
- Paper draft for PRL is under review within Belle

Backup