Studies of $\Lambda_c(2765)^+$ quantum numbers & other charmed baryons at Belle

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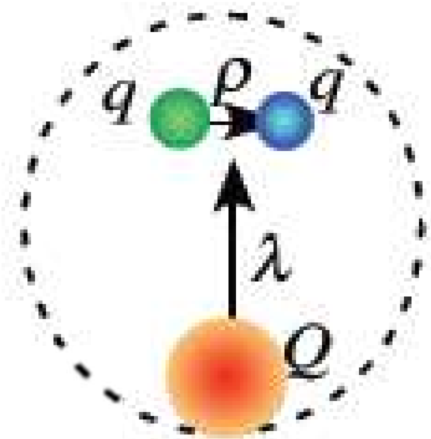
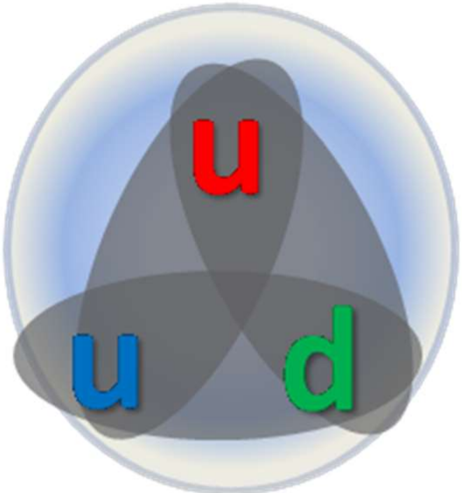
Introduction – Charmed baryons

- Heavy quark in Baryon
  - Bare quark ≒ constituent quark
  - Makes a “static core”, light quarks play around
    → Diquark correlation enhanced?
  - New symmetry – heavy quark symmetry
    → Hyperfine doublet for heavy quark spin.

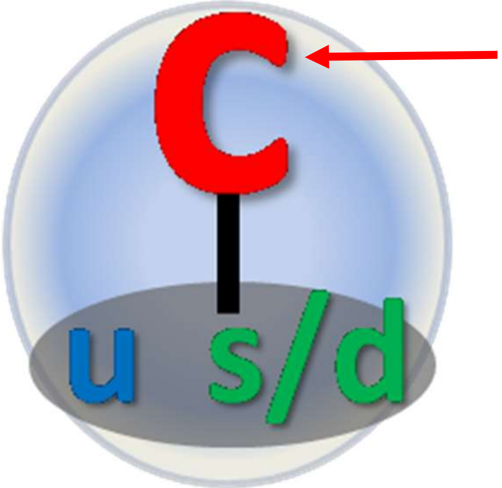


Nucleon



Indistinguishable pairs

Charmed baryon



HQS: spin
Approximately
conserved

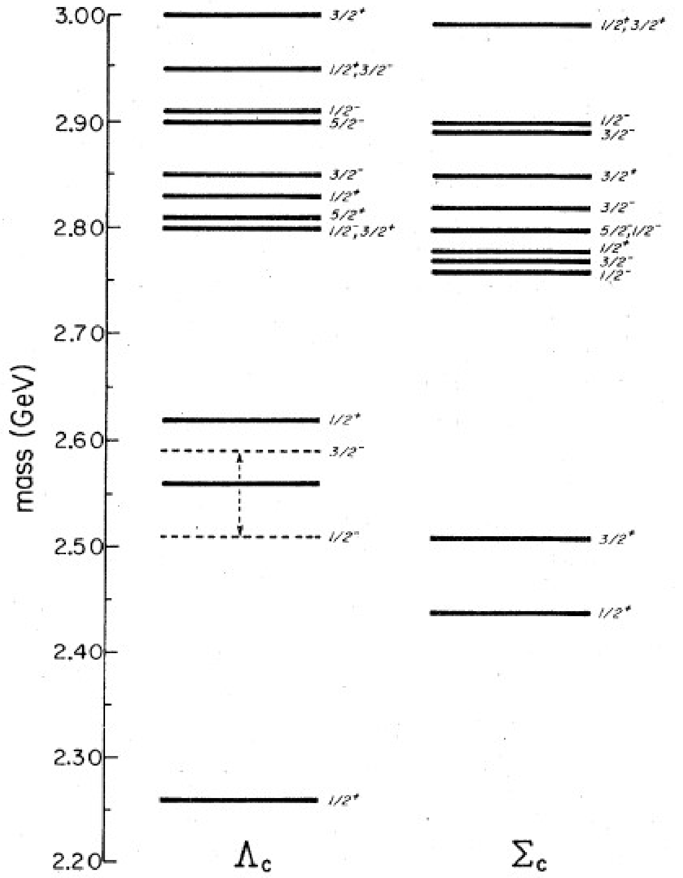
Light di-quark with inert charm?

Known charmed baryons

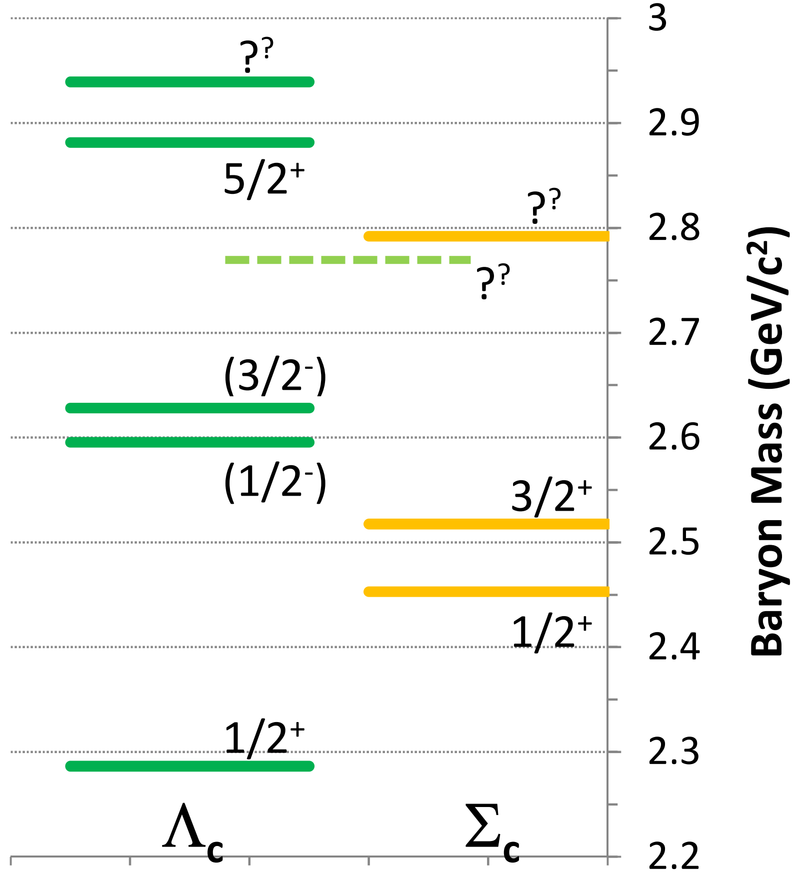
- A few dozens of states are known
- $I(J^P)$ are experimentally determined for very few states
- Quark model predictions are quite good up to $E_x \sim 400$ MeV – assignment of $I(J^P)$

Λ_c/Σ_c Spectrum

Quark model prediction
(L.A. Copley et. al, PRD20 (1979) 768)



Observed
(PDG, 2012 online)



Both missing states & unknown states

Known charmed baryons

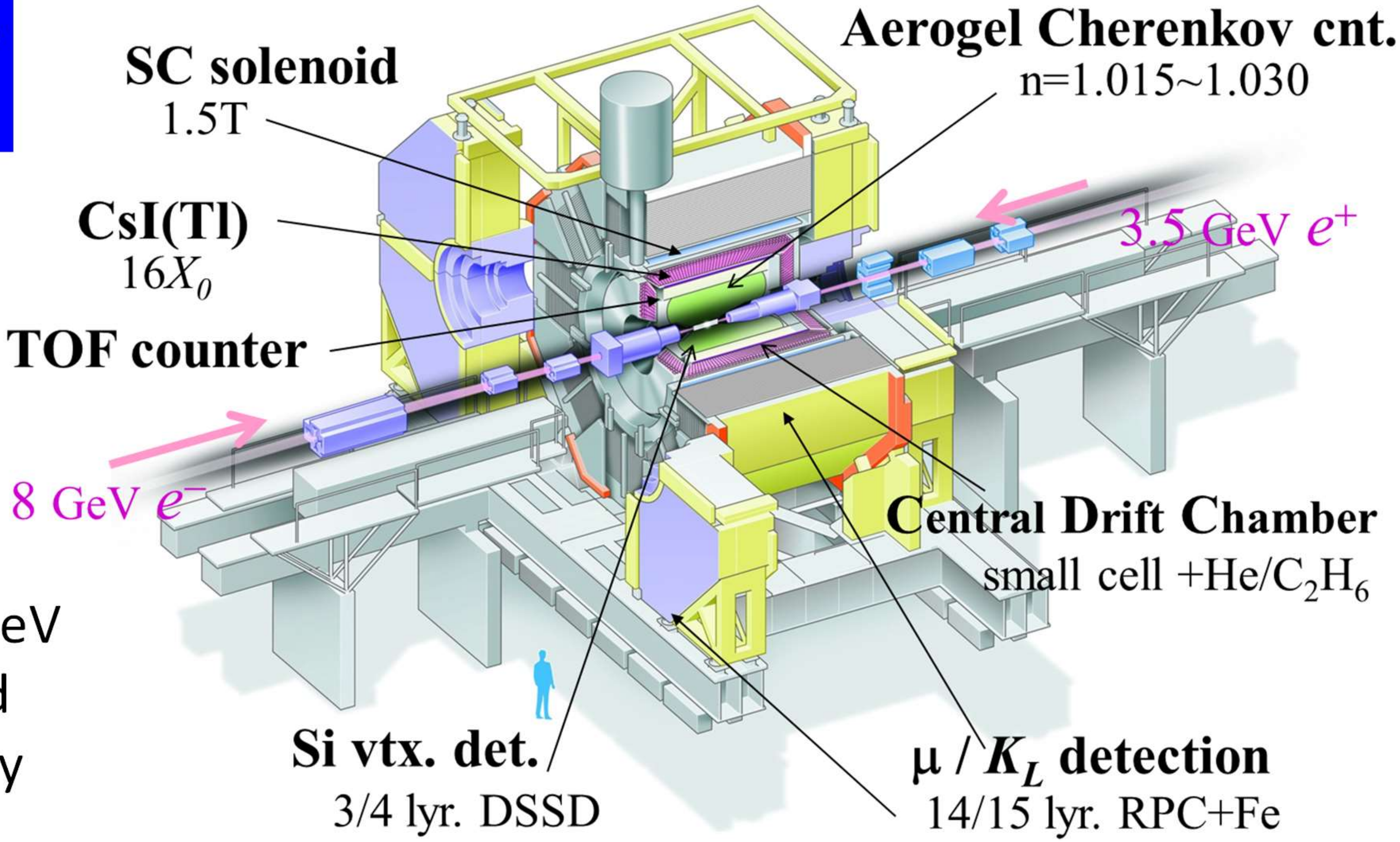
- A few dozens of states are known
- I(J^P) are experimentally determined for very few states
- Quark model predictions are quite good up to $E_x \sim 400$ MeV – assignment of I(J^P)
- There are many predicted states above that
  - Identification needs (at least) experimental determination of I(J^P)

This talk

- Introduces recent activities from the Belle experiment

1. Determination of quantum numbers of $\Lambda_c/\Sigma_c(2765)$
   - Especially isospin
2. Confirmation of $\Xi_c(2930)$ in B decays

Belle experiment



- √s~10.6 GeV
- Integrated Luminosity ~ 1 ab^{-1}

Almost 4π, good momentum resolution (Δp/p～0.1%), EM calorimeter, PID & Si Vertex detector

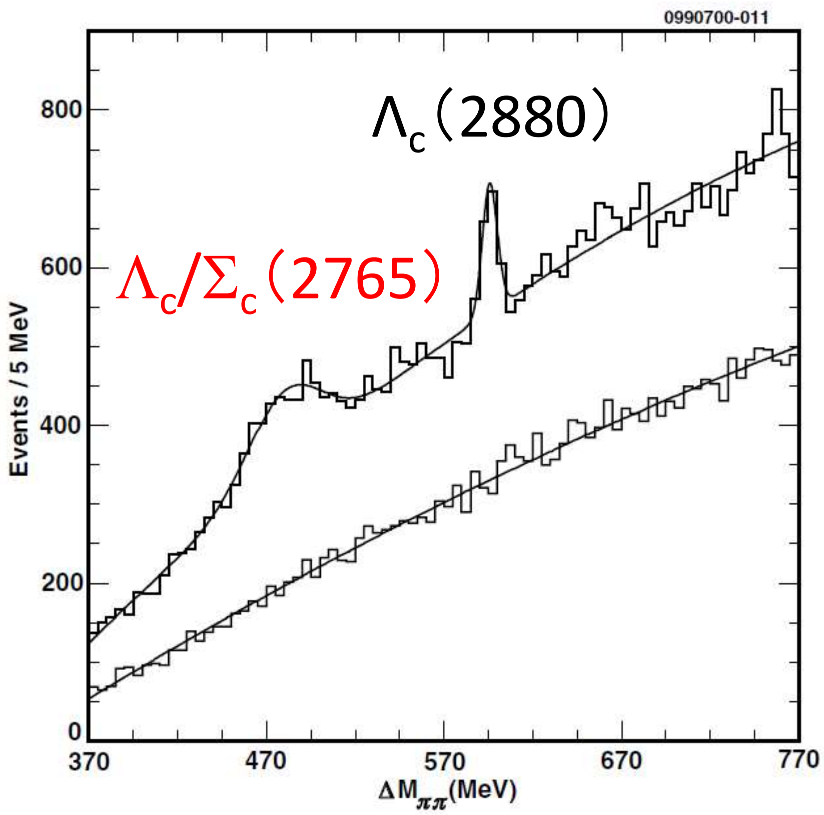
1. $\Lambda_c/\Sigma_c(2765)$

First observation by CLEO

$\Lambda_c(2765)^+$

or $\Sigma_c(2765)$

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



CLEO[PRL86（2001）4479]

- B decay → Λ_c^* → $\Lambda_c\pi\pi$ （$\Sigma_c\pi$、$\Sigma_c^*\pi$ included）
- Width～50 MeV (no uncertainty given)

Known things

- Experimentally – very poor
  - $I(J^P)$ not determined yet
  - No uncertainty on mass from CLEO
- Theoretically – so many
  - 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 $\Lambda_c/\Sigma_c(2765)$

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 $\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \rightarrow \Lambda_c(2765)^{+}\pi^{\pm}\pi^0$

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

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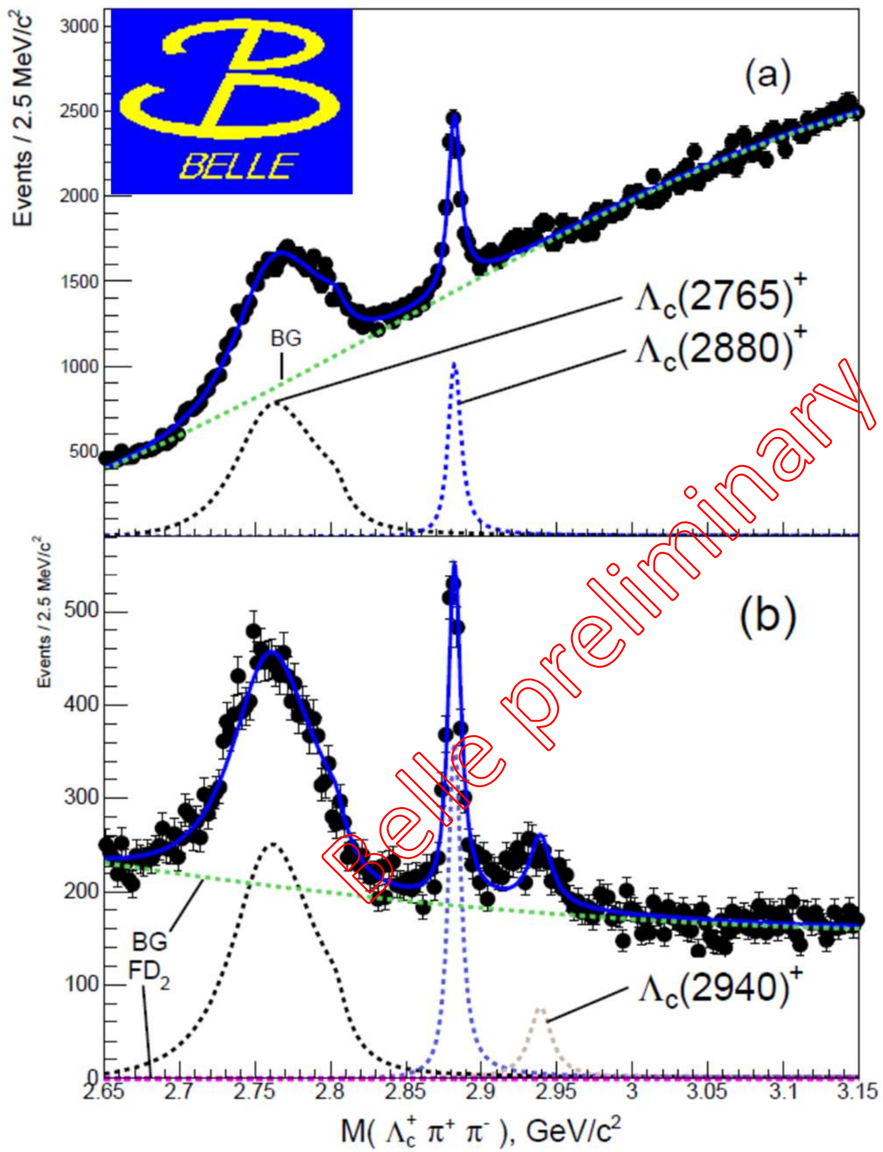
  $\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \rightarrow \Lambda_c(2765)^{+}\pi^{\pm}\pi^0$

Reference mode: $\Lambda_c/\Sigma_c(2765)^+ \rightarrow \Sigma_c\pi$



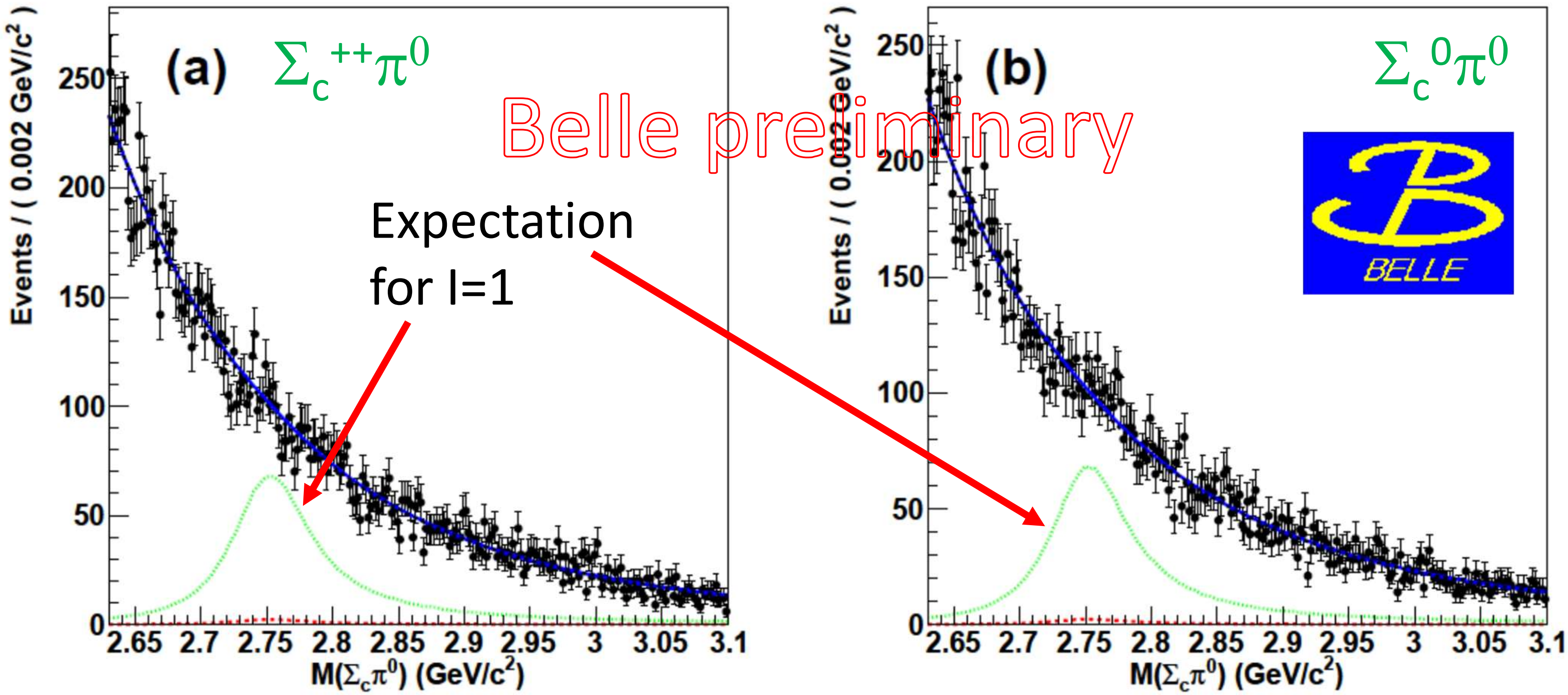
(a) Inclusive $\Lambda_c\pi^+\pi^-$

(b) With Σ_c selection

- Analyzed with full data of Belle (980 fb^{-1})
- Clear peaks are observed
- Fit with Breit-Wigner functions to extract yield.

$\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0$

[Belle-Conf-1905, Submitted to ArXiv]

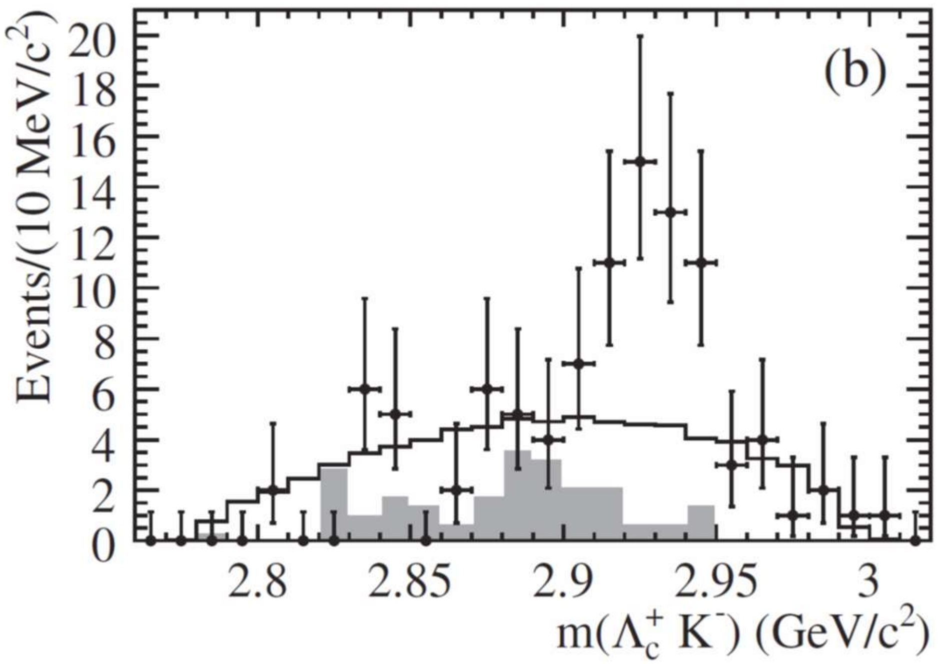


- No peak seen → Isospin is not 1, but 0.
  The name is indeed $\Lambda_c(2765)$

2. $\Xi_c(2930)$

Observed Ξ_c states

- Most are observed in continuum production:
  - Ξ_c, Ξ_c', $\Xi_c^*(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2970)$, $\Xi_c(3055)$, $\Xi_c(3080)$,…
- $\Xi_c(2930)$: First reported by Babar [PRD**77** 031101 (2008)], in B decays, but not reported in other modes.

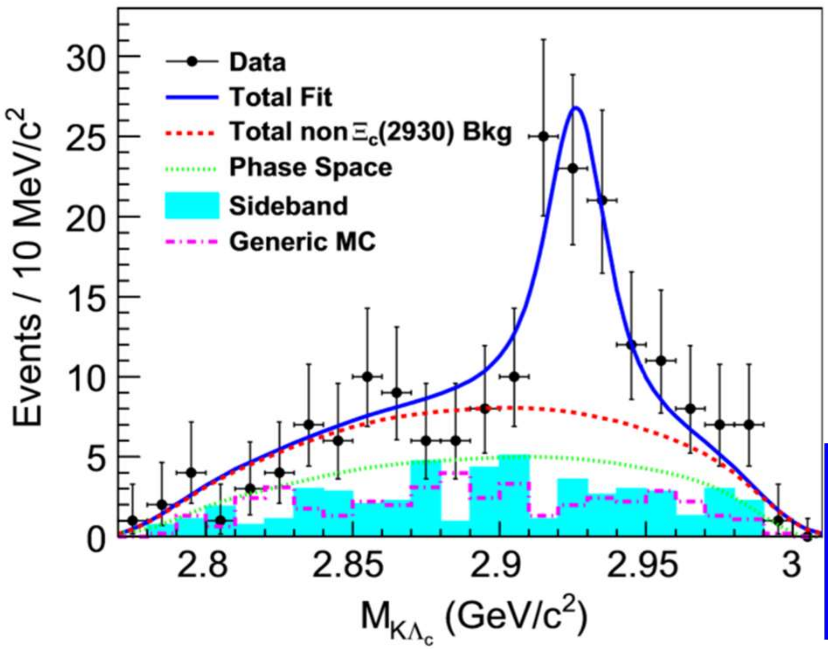


$\Xi_c(2930)^0$ and $\Xi_c(2930)^+$

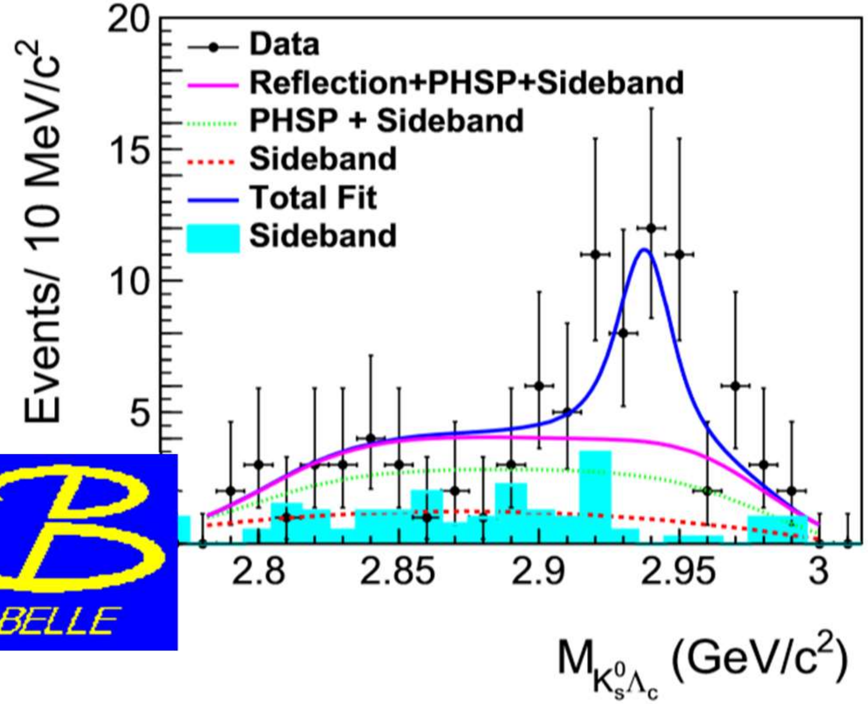
Now confirmed by Belle using $(772\pm11)\times10^6$ $B\bar{B}$ pairs

[EPJC 78, 928 and 78, 252]

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



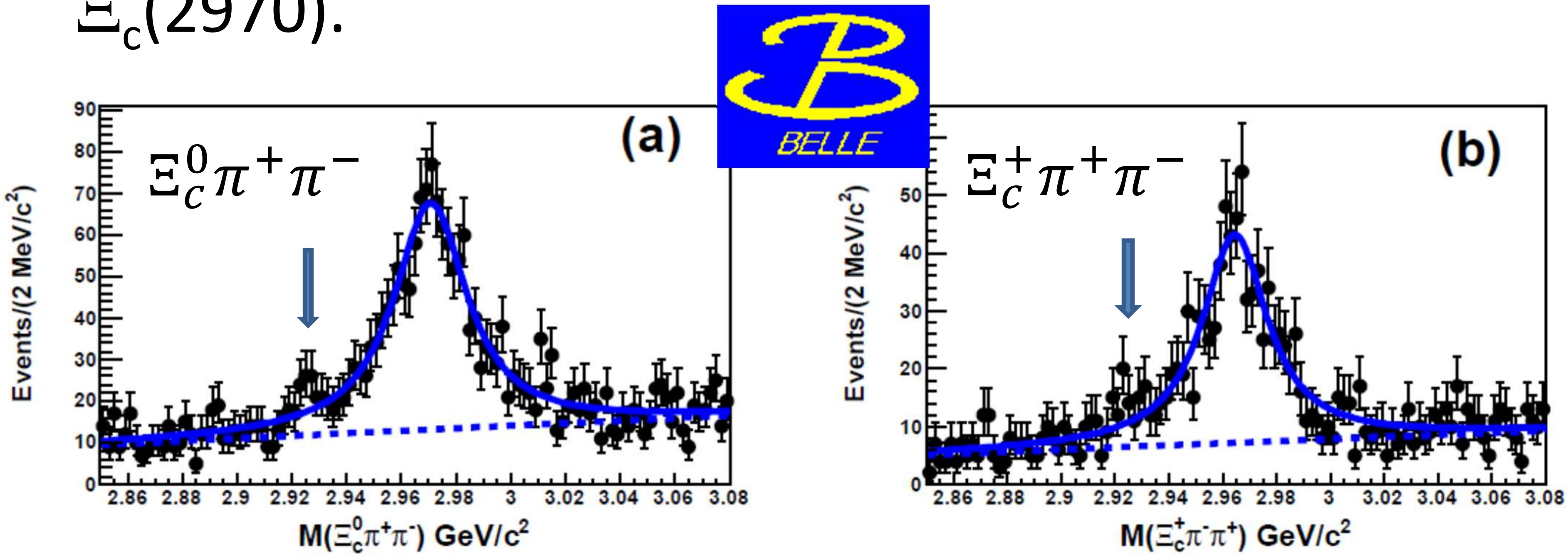
$\Xi_c(2930)^+ \to K_S^0\Lambda_c^+$ in $B^0 \to K_S^0\Lambda_c^+\bar{\Lambda}_c^-$



- $\Xi_c(2930)^0$: 5.1σ significance, $M = 2928.9 \pm 3.0\,^{+0.9}_{-12.0}$ MeV
- $\Xi_c(2930)^+$: > 3.5σ significance, $M = 2942.3 \pm 4.4$ MeV

Can it be seen in other modes?

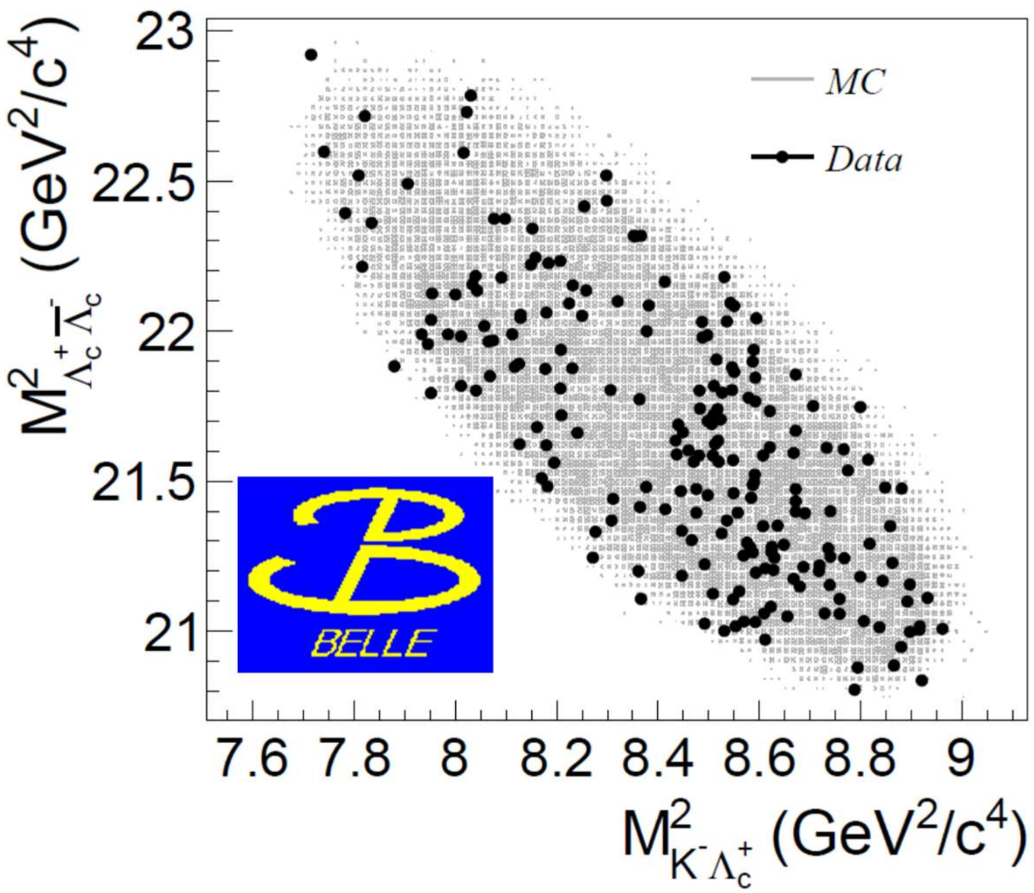
- Not in inclusive $\Lambda_c K$ [Babar: PRD**77**.012002]
- There is a hint in $\Xi_c \pi\pi$ mode [Belle: PRD**94**, 052011], but not conclusive. Anyway much fewer than $\Xi_c(2970)$.



- 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, …)



Summary & Prospect

- Charmed baryons are actively studied in Belle
- Λ_c(2765): Study on I(J^P) quantum numbers are ongoing
  - Isospin (I) is determined to be 0.
  - Spin-parity (J^P) will be coming soon

  → We can discuss the nature of the state
- Ξ_c(2930):
  - The existence is confirmed.
  - Need Belle II statistics to determine Spin-parity
- More results are coming in the future.