Study of charmed baryons at Belle

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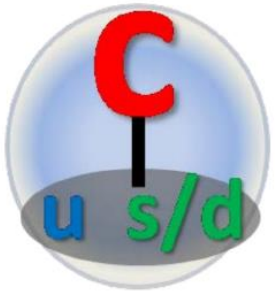
Introduction

- Charmed baryons consist of one heavy c quark and two light (u, d, s) quarks. Large mass difference provides a natural way to classify these states using HQET.



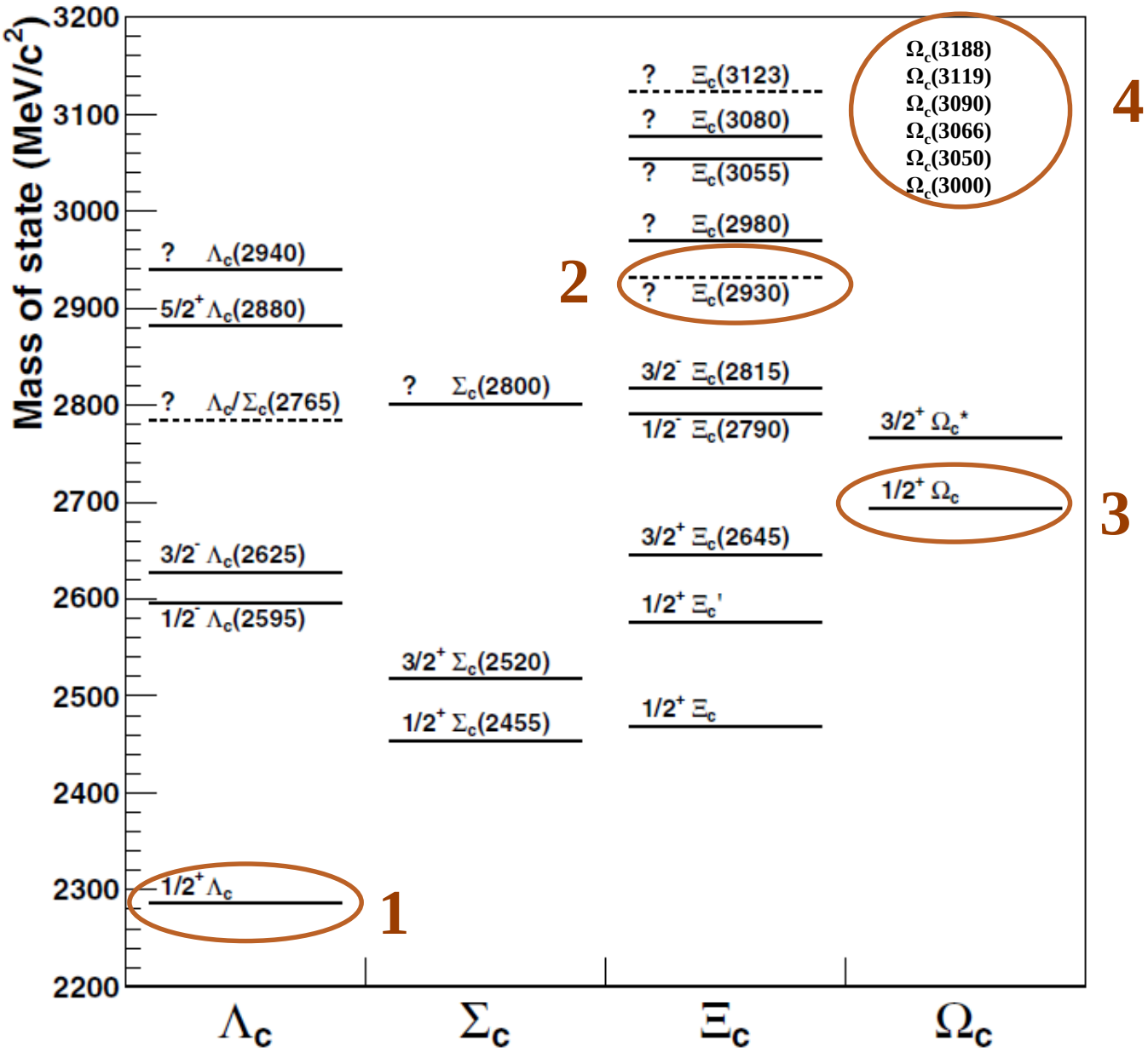
Light di-quark and charm quark

Symbol	I	Content
N (p,n)	$1/2$	udq
Δ	$3/2$	qqq
Λ	0	sud
Σ	1	sqq
Ξ	$1/2$	ssq
Ω	0	sss
Λ_c	0	cud
Σ_c	1	cqq
Ξ_c	$1/2$	csq
Ω_c	0	css
Ξ_{cc}	$1/2$	ccq
Ω_{cc}	0	ccs
Ω_{ccc}	0	ccc

- Naming convention: to take a light baryon and replace one or more of s quarks with c quarks and add a c subscript for every quark replaced.

- Two production mechanisms at B factories:
  - in B decays (known initial J^P),
  - from $e^+e^- \to c\bar{c}$ (efficient continuum background suppression with $p^* > E_{CM}/4$).

Plan of my talk



$\Lambda_c \to \Sigma\pi\pi$ I

Motivation:

- Λ_c is the lightest charmed baryon;
- most Λ_b^0 decays include Λ_c^+;
- recent model-independent measurements of the normalization mode $\Lambda_c^+ \to pK^-\pi^+$ by Belle [1] and BESIII [2] improve the accuracy of the corresponding Λ_c^+ branching ratios;
- Σ-π scattering length can be extracted using $\Lambda_c^+ \to \Sigma\pi\pi \Rightarrow$ study of $\Lambda(1405)$.

Analysis features:

- 711 fb^{-1} of data at $Y(4S)$ resonance;
- three $\Sigma\pi\pi$ decay modes are considered — $\Sigma^+\pi^-\pi^+$, $\Sigma^0\pi^+\pi^0$, $\Sigma^+\pi^0\pi^0$;
- all branching fractions are measured relative to $\Lambda_c^+ \to pK^-\pi^+$;
- $\Lambda^0 \to p\pi^-$;
- $\Sigma^0 \to \Lambda^0\gamma$;
- $\Sigma^+ \to p\pi^0$.

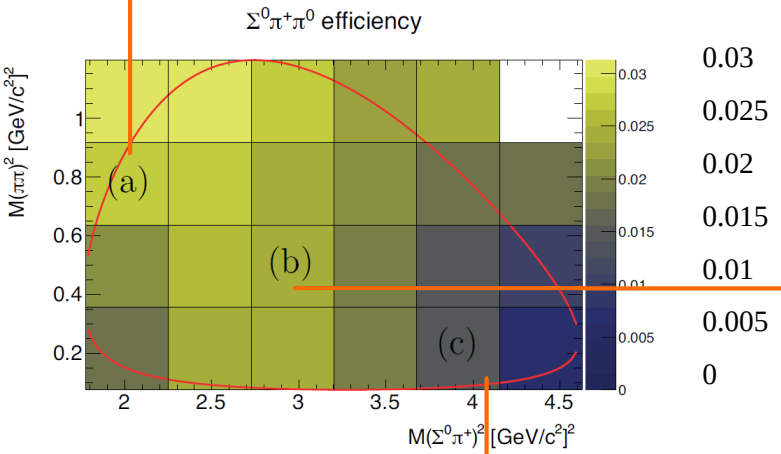
[1] PRL 113 042002 (2014)
[2] PRL 116 052001 (2016)

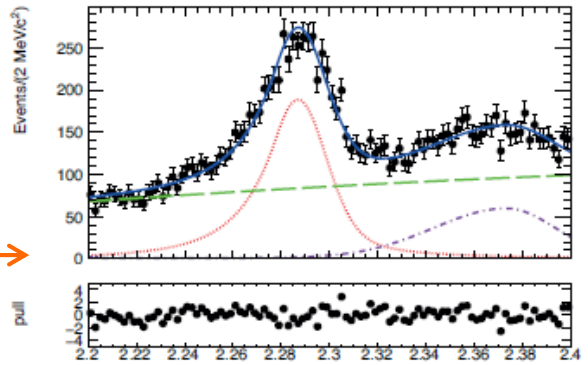
M. Berger, C. Schwanda, K. Suzuki et al., arXiv:1802.0342 (submitted to PRD)

$\Lambda_c \to \Sigma\pi\pi$ II

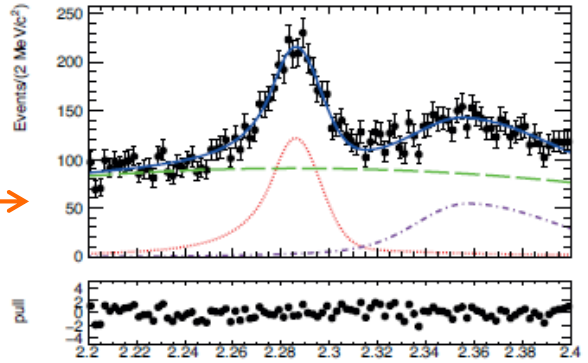
Signal yield extraction:

- model-independent way — binned Dalitz distribution;
- $\Lambda_c^+ \to pK^-\pi^+$ is also analyzed to calculate relative branching fractions;

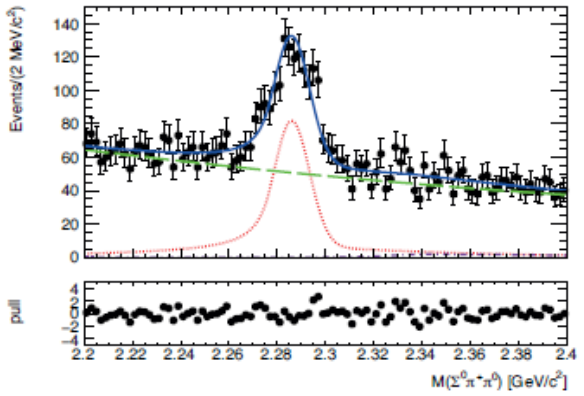




(a)



(b)



(c)

Final state	$\sum_i y_i/\epsilon_i$ $[\times 10^3]$
$\Sigma^+\pi^-\pi^+$	2636 ± 10
$\Sigma^0\pi^+\pi^0$	2272 ± 21
$pK^-\pi^+$	7249 ± 9
$\Sigma^+\pi^0\pi^0$	741 ± 21

signal
combinatorial bkg
$\Lambda^0\pi^+\pi^0 + \gamma$ bkg

$\Lambda_c \to \Sigma\pi\pi$ III

Results:

- branchings are measured relative to that of the decay $\Lambda_c^+ \to pK^-\pi^+$;

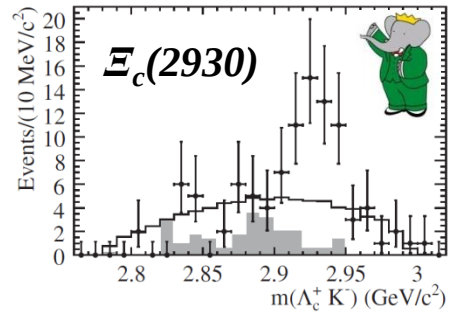
Final state	$\mathcal{B}(\Sigma\pi\pi)/\mathcal{B}(pK\pi)$	$\mathcal{B}(\Sigma\pi\pi)$ [%]	$\mathcal{B}_{WA}(\Sigma\pi\pi)$ [%]
$\Sigma^+\pi^-\pi^+$	$0.706 \pm 0.003 \pm 0.030$	$4.48 \pm 0.02 \pm 0.19 \pm 0.23$	4.57 ± 0.29
$\Sigma^0\pi^+\pi^0$	$0.491 \pm 0.005 \pm 0.023$	$3.12 \pm 0.03 \pm 0.15 \pm 0.16$	2.3 ± 0.9
$\Sigma^+\pi^0\pi^0$	$0.198 \pm 0.006 \pm 0.017$	$1.26 \pm 0.04 \pm 0.11 \pm 0.07$	-
Errors	stat syst	stat syst	$\mathcal{B}(pK\pi)$

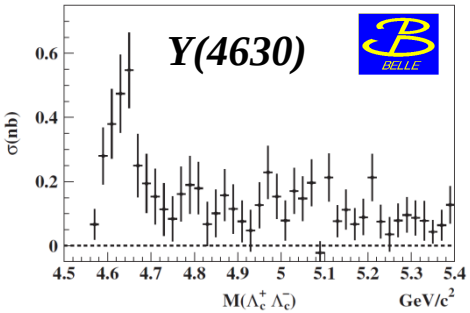
- assuming $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 6.35 \pm 0.33$ %,
- first measurement of $\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$;
- measurement of $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$ is 4 times more precise than the current world average.

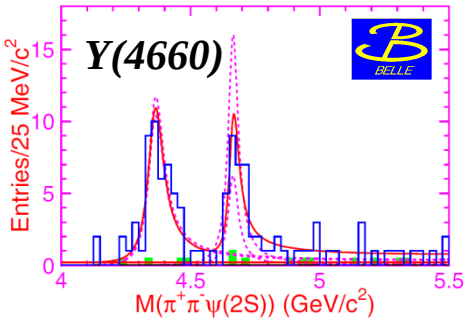
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ I

Motivation:

- charmed-strange baryon $\Xi_c(2930)^0$ reported only in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ by BaBar [1] (no significance given);
- charmonium-like state $Y(4630)$ observed by Belle in $e^+e^- \to \gamma_{ISR} \Lambda_c^+ \bar{\Lambda}_c^-$ [2];
- exotic state $Y(4660)$ (same as $Y(4630)$?) observed by Belle in $e^+e^- \to \gamma_{ISR} \pi^+\pi^- \psi'$ [3]
  - can be modeled as $f_0(980)\psi'$ bound state [4],
  - should have a spin partner Y_η ($f_0(980)\eta_c(2S)$ bound state) with $M \approx 4613 \pm 4$ MeV and $\Gamma \approx 30$ MeV,
  - expected to have large partial width into $\Lambda_c^+ \bar{\Lambda}_c^-$.







Analysis features:

- 711 fb^{-1} of data at $Y(4S)$ resonance;
- $\Lambda_c^+ \to pK^-\pi^+$, pK^0_S, $\Lambda\pi^+$, $pK^0_S\pi^+\pi^-$, $\Lambda\pi^+\pi^+\pi^-$;
- at least one of Λ_c^+ and Λ_c^- are reconstructed via $pK^+\pi^-$ or $pK^-\pi^+$;
- $\Lambda \to p\pi^-$;
- simultaneous 2D fit to ΔM_B vs M_{bc}, where $\Delta M_B = M_B - m_B$, $M_{bc} = \sqrt{(E_{beam}^2 - \Sigma p_i^2)}$.

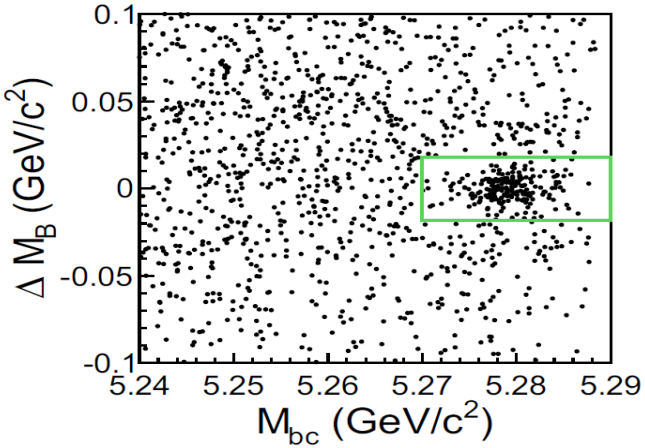
Y. B. Li, C. P. Shen et al. EPJ C78 252 (2018)

[1] PRD 77 031101 (2008)
[2] PRL 101 172001 (2008)
[3] PRL 99 142002 (2007)
[4] PRD 82 094008 (2010)

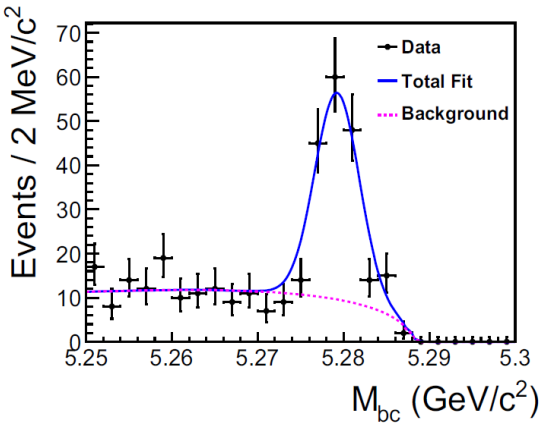
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ II

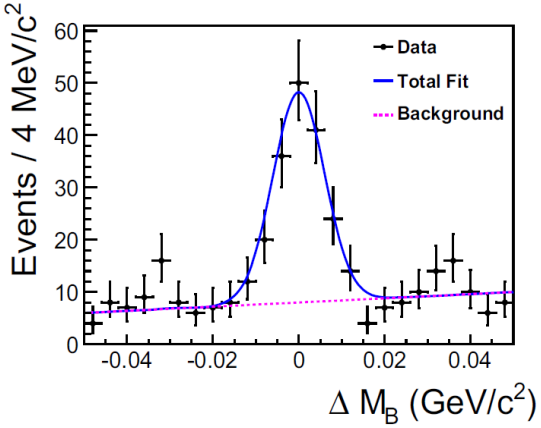
Results:

- 153 ± 14 signal events;
- measurement with improved precision of $\mathcal{B}(B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-) = (4.80 \pm 0.43 \pm 0.60) \times 10^{-4}$;
  previous results by BaBar $(9.0 \pm 4.4 \pm 0.5) \times 10^{-4}$ [1]
  and Belle $(6.2\ ^{+2.5}_{-2.4} \pm 0.3) \times 10^{-4}$ [2].



[1] PRD 77 031101 (2008)
[2] PRL 97 202003 (2006)

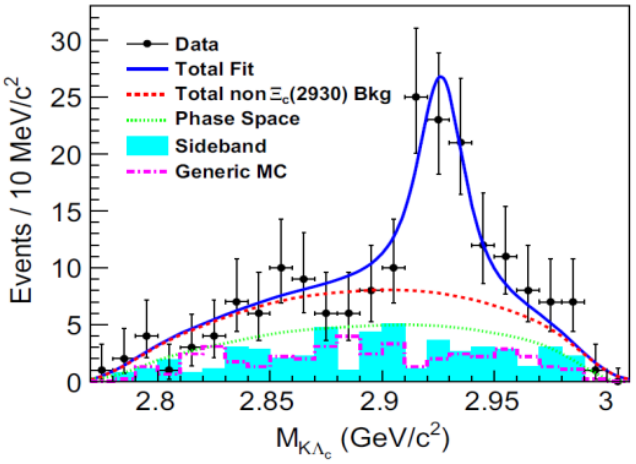




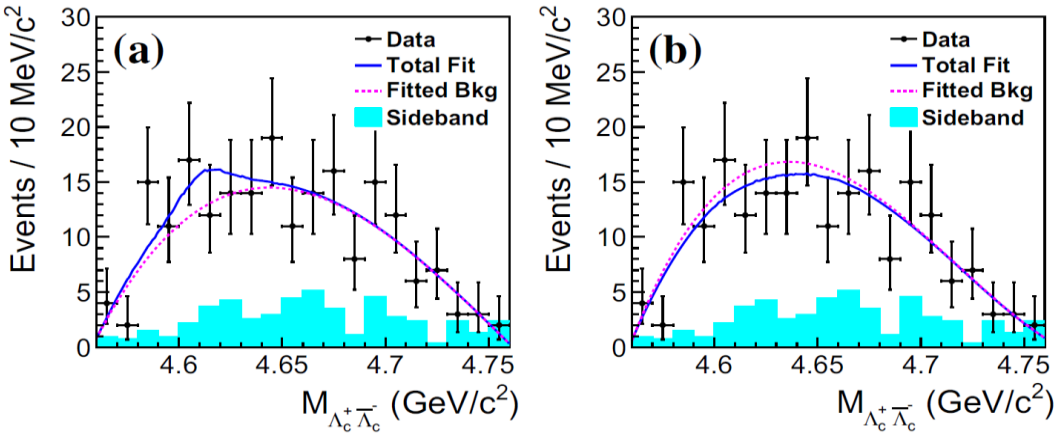
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ III

Results (continued):

- first observation of $\Xi_c(2930)^0$ with significance > 5σ:
  $M = (2928.9 \pm 3.0\ ^{+0.9}_{-12.0})$ MeV,
  $\Gamma = (19.5 \pm 8.4\ ^{+5.9}_{-7.9})$ MeV,
  $\mathcal{B}(B^- \to \Xi_c(2930)^0 \Lambda_c^-)\ \mathcal{B}(\Xi_c(2930)^0 \to K^- \Lambda_c^+) =$
  $= (1.73 \pm 0.45 \pm 0.21) \times 10^{-4}$;



- 90% C. L. upper limits for *Y(4660)* and its theoretically predicted spin partner Y_η:
  (a) $\mathcal{B}(B^- \to K^- Y_\eta)\ \mathcal{B}(Y_\eta \to \Lambda_c^+ \bar{\Lambda}_c^-) < 2.0 \times 10^{-4}$;
  (b) $\mathcal{B}(B^- \to K^- Y(4660))\ \mathcal{B}(Y(4660) \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$,



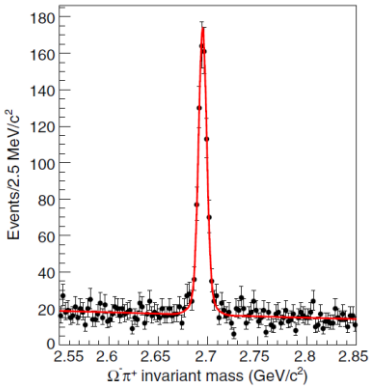
Hadronic decays of Ω_c^0 I

Motivation:

- low Ω_c^0 production cross section $\Rightarrow$ less information on its hadronic decays than for any other weakly decaying charmed baryons (Λ_c^+, Ξ_c^0, and Ξ_c^+) or charmed mesons;
- Ω_c^0 = (css), i.e. two quarks have the same flavor $\Rightarrow$ many decay diagrams producing the same final states $\Rightarrow$ interference $\Rightarrow$ need more information on branchings.

Analysis features:

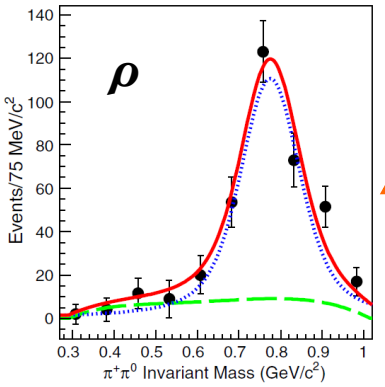
- 980 fb^{-1} of e^+e^- annihilation data;
- eight Ω_c^0 decay modes are considered
  - $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^0$, $\Xi^-K^-\pi^+\pi^+$, $\Xi^0K^-\pi^+$ (previously measured by CLEO [1] and BaBar [2]),
  - $\Xi^-K^0\pi^+$, Ξ^0K^0 , ΛK^0K^0 (previously unreported),
  - $\Sigma^+K^-K^-\pi^+$ (reported by Fermilab E687 [3]);
- all branching fractions are measured relative to $\Omega_c^0 \to \Omega^-\pi^+$;
- $\Lambda \to p\pi^-$;
- $\Xi^- \to \Lambda\pi^-$, ΛK^-;
- $\Omega^- \to \Lambda\pi^-$, ΛK^-;
- $\Xi^0 \to \Lambda\pi^0$;
- $\Sigma^+ \to p\pi^0$.

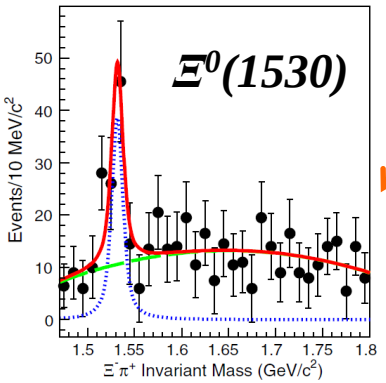


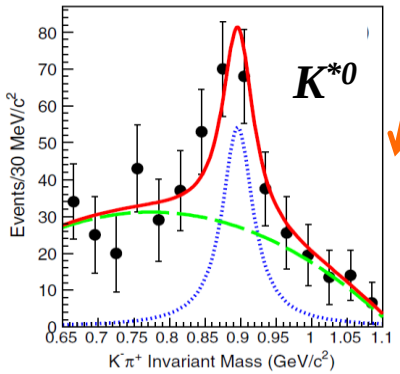
J. Yelton et al. PRD 97 032001 (2018)

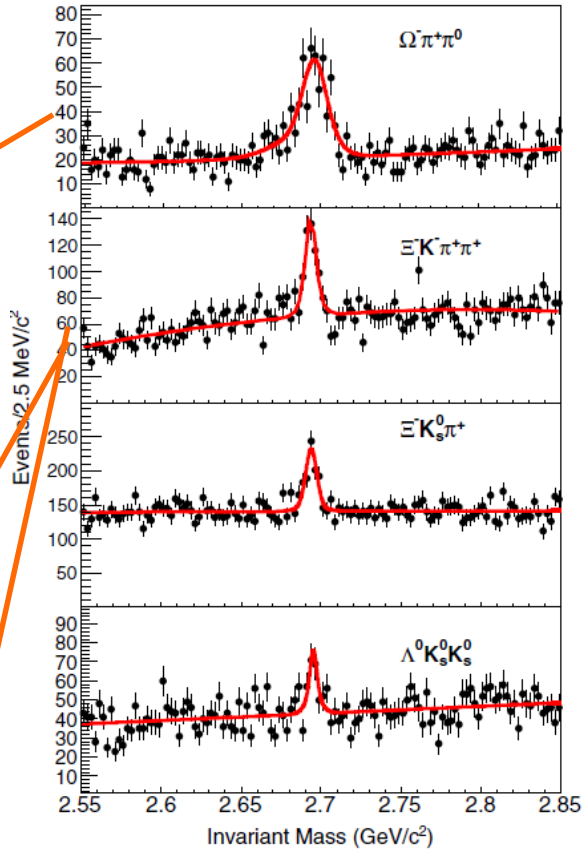
[1] PRL 86 3730 (2001)
[2] PRL 99 062001 (2007)
[3] PLB 338 106 (1994)

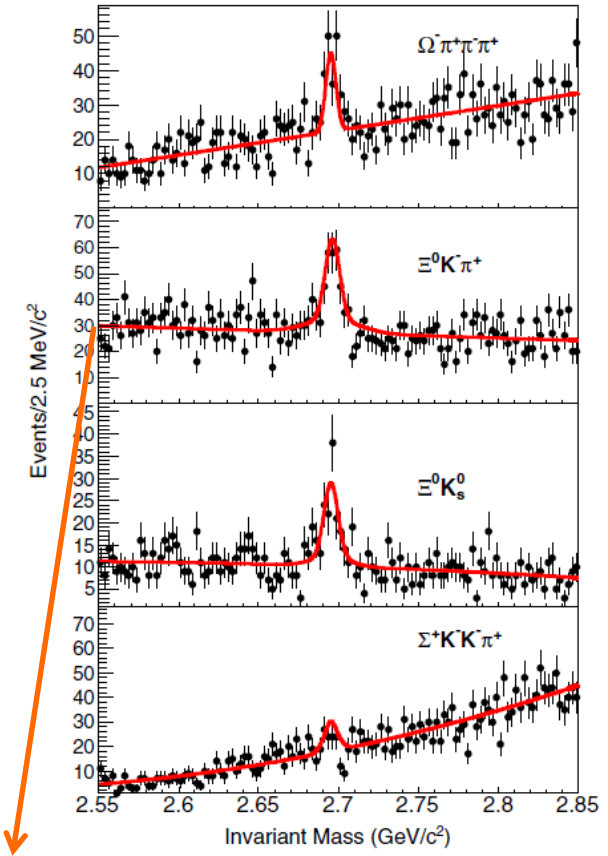
Hadronic decays of Ω_c^0 II

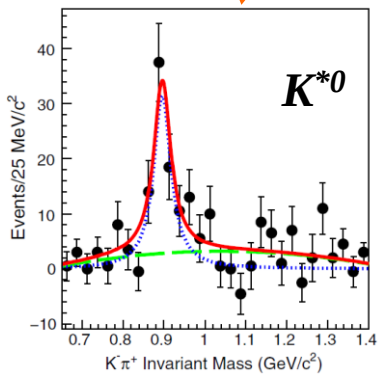












Hadronic decays of Ω_c^0 III

Results:

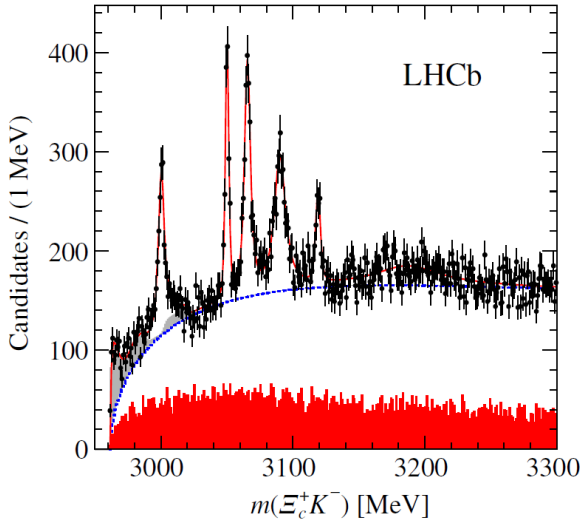
- branching ratios of four Ω_c^0 decay modes measurement with improved precision;
- first measurement of intermediate resonances;
- three decay branching ratios are measured for the first time;
- upper limit is set on $\mathcal{B}(\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+)$ / $\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$, while E687 observed 42.5 ± 8.8 events;
- comment: for other weakly decaying charmed baryons Y_c
  $\mathcal{B}(Y_c \to Y\pi^+\pi^-\pi^+)$ / $\mathcal{B}(Y_c \to Y\pi^+)$ >> **1**, but $\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+\pi^-\pi^+)$ / $\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$ < **1**.

Mode	Branching ratio with respect to $\Omega^-\pi^+$	Substructure	Previous measurement
$\Omega^-\pi^+$	1		
$\Omega^-\pi^+\pi^0$	$2.00 \pm 0.17 \pm 0.11$		$1.27 \pm 0.3 \pm 0.11$
$\Omega^-\rho^+$		>71%	
$\Omega^-\pi^+\pi^-\pi^+$	$0.32 \pm 0.05 \pm 0.02$		$0.28 \pm 0.09 \pm 0.01$
$\Xi^- K^-\pi^+\pi^+$	$0.68 \pm 0.07 \pm 0.03$		$0.46 \pm 0.13 \pm 0.03$
$\Xi^0(1530)K^-\pi^+$		$(33 \pm 9)\%$	
$\Xi^-\bar{K}^{*0}\pi^+$		$(55 \pm 16)\%$	
$\Xi^0 K^-\pi^+$	$1.20 \pm 0.16 \pm 0.08$		$4.0 \pm 2.5 \pm 0.4$
$\Xi^0\bar{K}^{*0}$		$(57 \pm 10)\%$	
$\Xi^-\bar{K}^0\pi^+$	$2.12 \pm 0.24 \pm 0.14$		
$\Xi^0\bar{K}^0$	$1.64 \pm 0.26 \pm 0.12$		
$\Lambda\bar{K}^0\bar{K}^0$	$1.72 \pm 0.32 \pm 0.14$		
$\Sigma^+ K^-K^-\pi^+$	<0.32 (90% CL)		

Excited Ω_c I

Motivation:

- LHCb observed five narrow resonances and one wide enhancement at higher mass in $\Xi_c^+ K^-$ [1];



Analysis features:

- 980 fb^{-1} of e^+e^- annihilation data;
- seven Ξ_c^+ decay modes are considered ($\Xi^-\pi^+\pi^+$, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^-\pi^+$, $\Sigma^+K^-\pi^+$, $\Lambda K_S^0\pi^+$, $\Sigma^0 K_S^0\pi^+$);
- we look for $\Omega_c^{*0} \to \Xi_c^+ K^-$;
- masses and widths are fixed to the values found by LHCb.

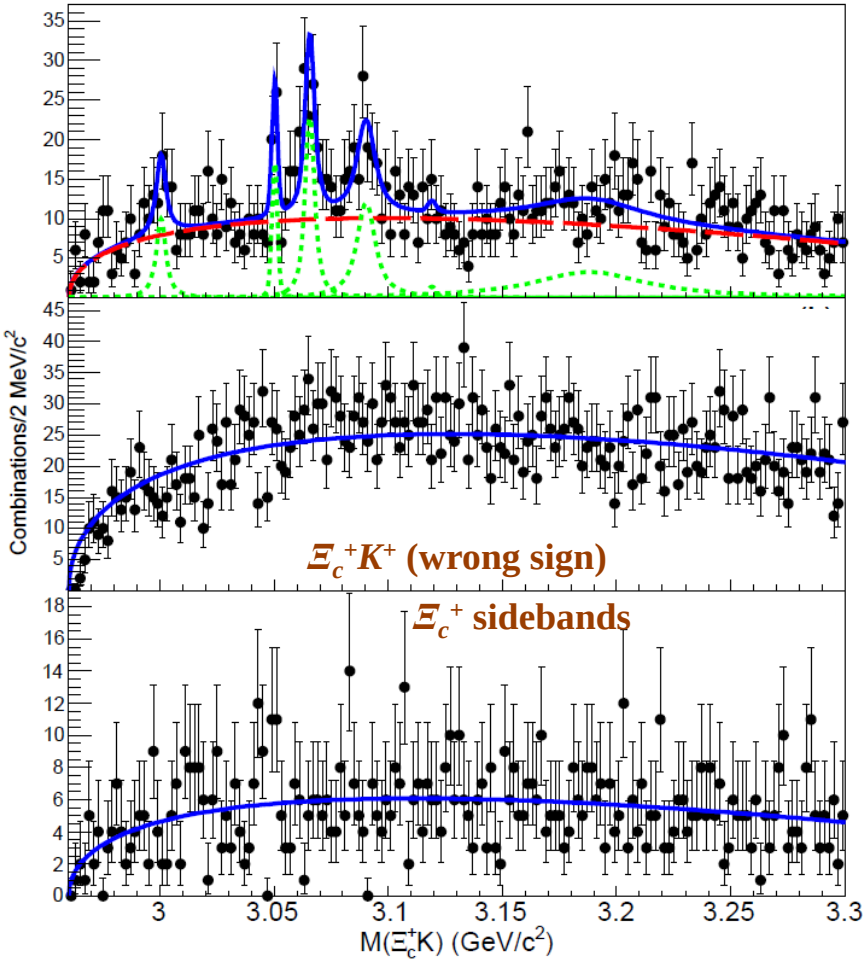
J. Yelton et al. PRD 97 051102R (2018)

[1] PRL 118 182001 (2017)

Excited Ω_c II

Results:

- strong confirmation of $\Omega_c(3066)$ and $\Omega_c(3090)$;
- confirmation with significance < 5σ of $\Omega_c(3000)$ and $\Omega_c(3050)$;
- no confirmation for $\Omega_c(3119)$;
- indication of wide excess at higher mass, consistent with LHCb;
- results fit into the heavy-quark—light-diquark models prediction on the existence of states in the mass range 2.9 – 3.2 GeV.



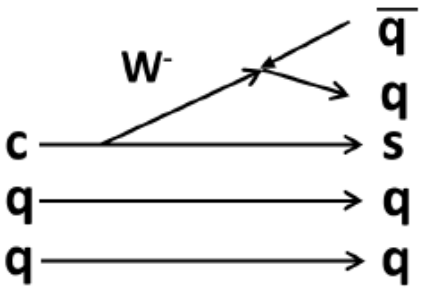
Ω_c Excited State	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle Mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

Summary

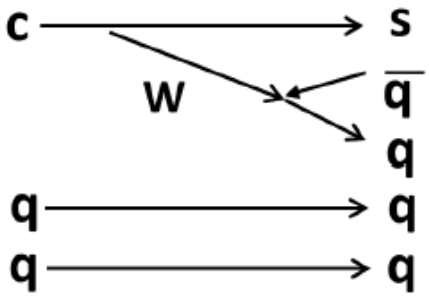
- **$\Lambda_c \to \Sigma\pi\pi$**
  - Branching fractions of decays $\Lambda_c^+ \to \Sigma^+\pi^-\pi^+$ and $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$ are measured relative to that of the decay $\Lambda_c^+ \to pK^-\pi^+$ with improved precision.
  - $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0\pi^0) / \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ is measured for the first time.
- **$B^- \to K^-\Lambda_c^+\Lambda_c^-$**
  - $\mathcal{B}(B^- \to K^-\Lambda_c^+\Lambda_c^-)$ is measured with improved accuracy.
  - $\Xi_c(2930)^0$ is observed for the first time. Its mass, width and product branching fraction is reported.
- **Hadronic decays of Ω_c^0**
  - Branchings of decays $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^0$, $\Xi^-K^-\pi^+\pi^+$, and $\Xi^0K^-\pi^+$ are measured relative to that of the decay $\Omega_c^0 \to \Omega^-\pi^+$ with improved precision.
  - For the first time $\mathcal{B}(\Omega_c \to \Xi^-K^0\pi^+) / \mathcal{B}(\Omega_c \to \Omega^-\pi^+)$, $\mathcal{B}(\Omega_c \to \Xi^0K^0) / \mathcal{B}(\Omega_c \to \Omega^-\pi^+)$, and $\mathcal{B}(\Omega_c \to \Lambda K^0K^0) / \mathcal{B}(\Omega_c \to \Omega^-\pi^+)$ are reported.
  - Upper limit is set on $\mathcal{B}(\Omega_c \to \Sigma^+K^-K^-\pi^+) / \mathcal{B}(\Omega_c \to \Omega^-\pi^+)$.
- **Excited Ω_c**
  - $\Omega_c(3066)$ and $\Omega_c(3090)$ are strongly confirmed.
  - $\Omega_c(3000)$ and $\Omega_c(3050)$ are confirmed with less significance.
  - There is no confirmation for $\Omega_c(3119)$.
  - Indication of wide excess at higher mass, consistent with LHCb, is presented.

Backup

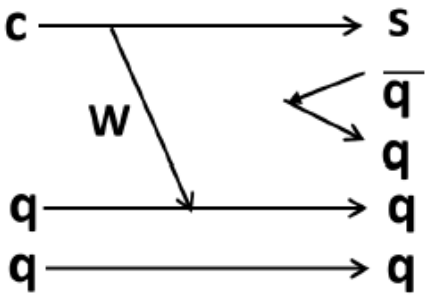
Diagrams



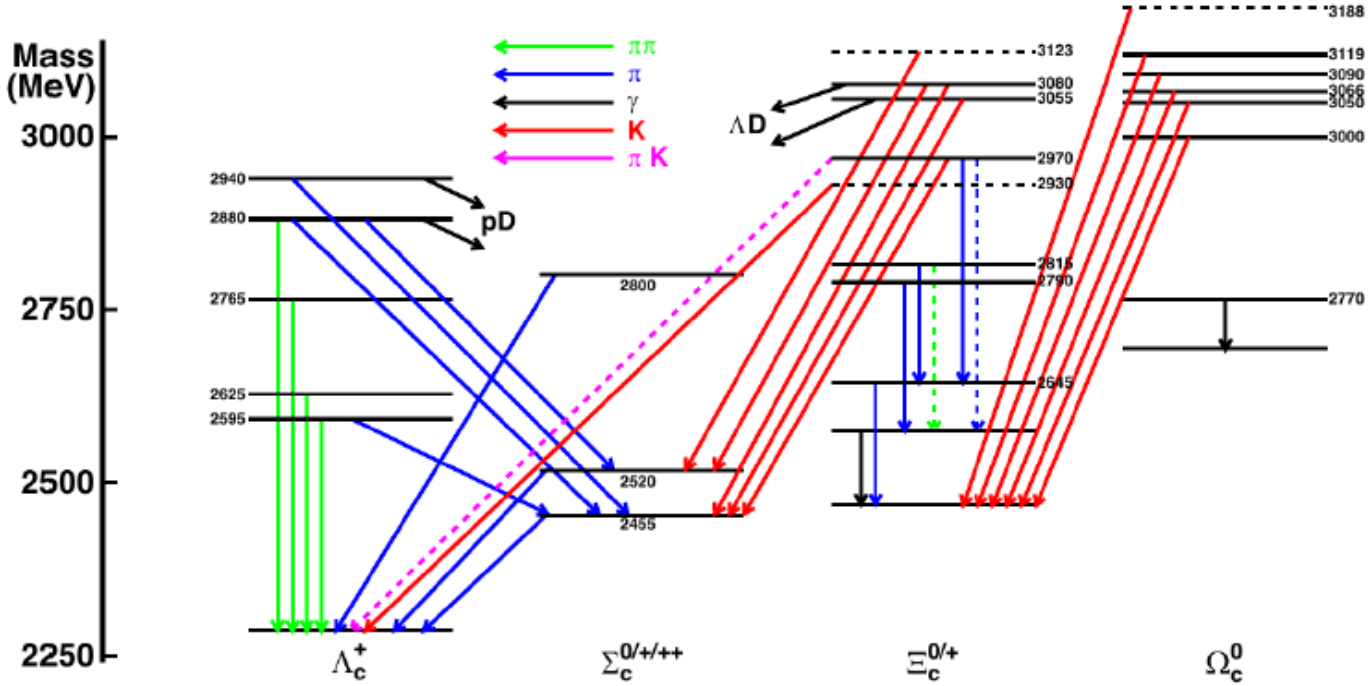
Spectator



Internal W

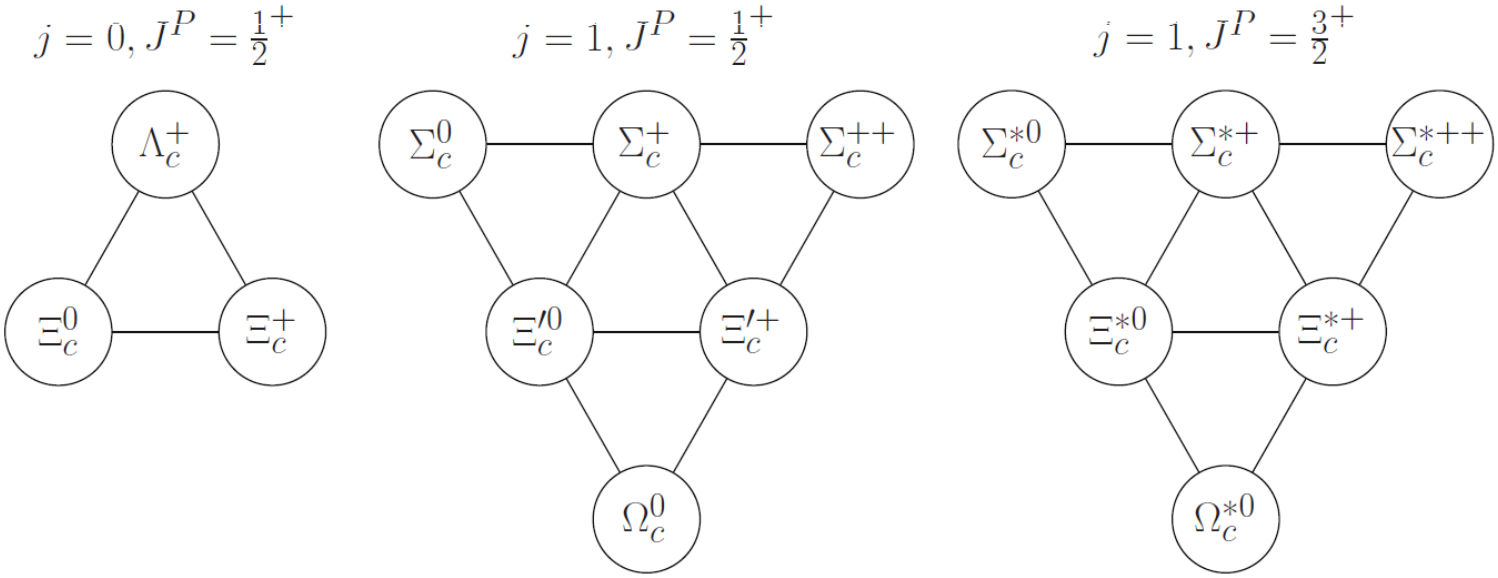


W-exchange

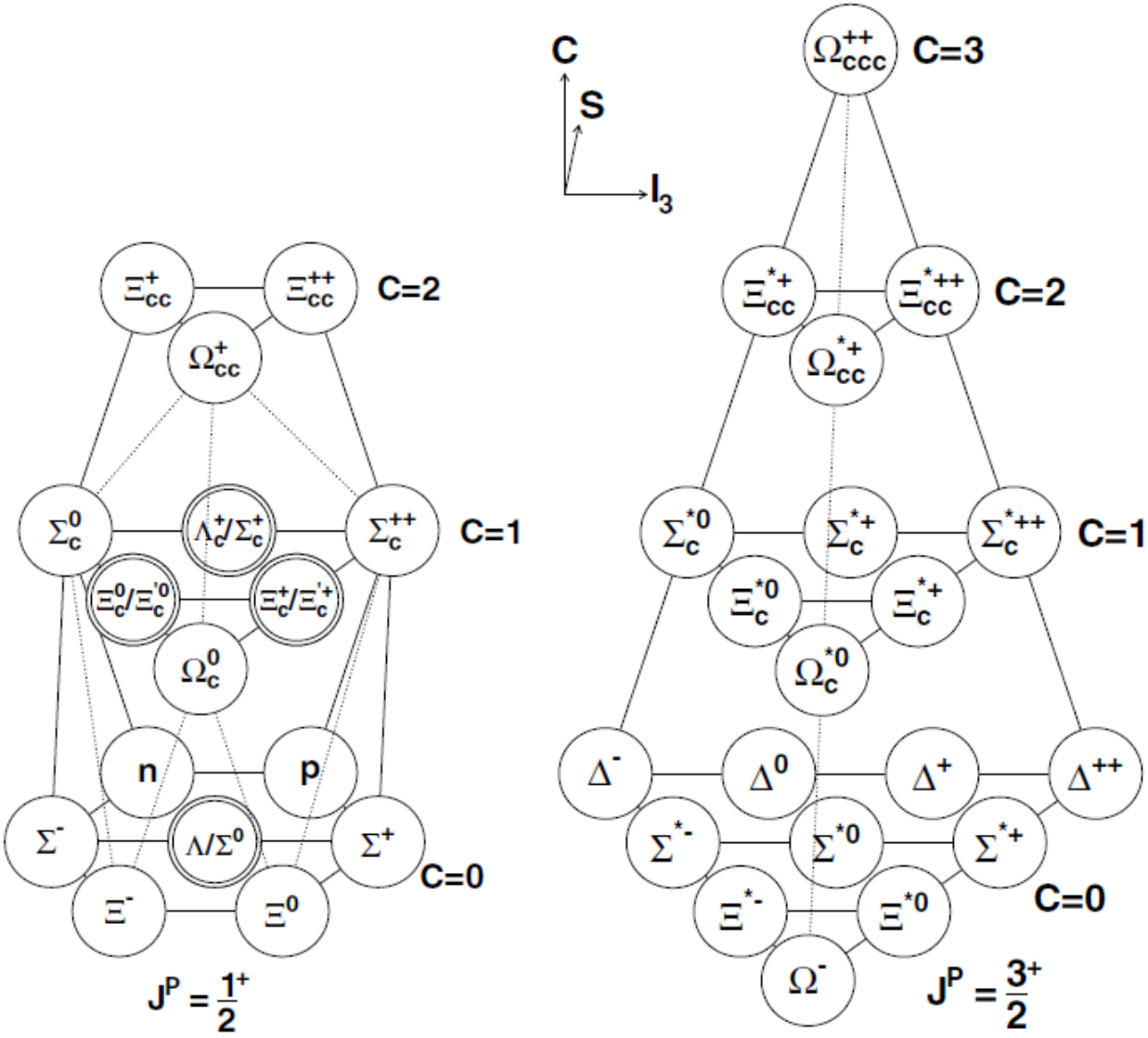


Charmed baryons

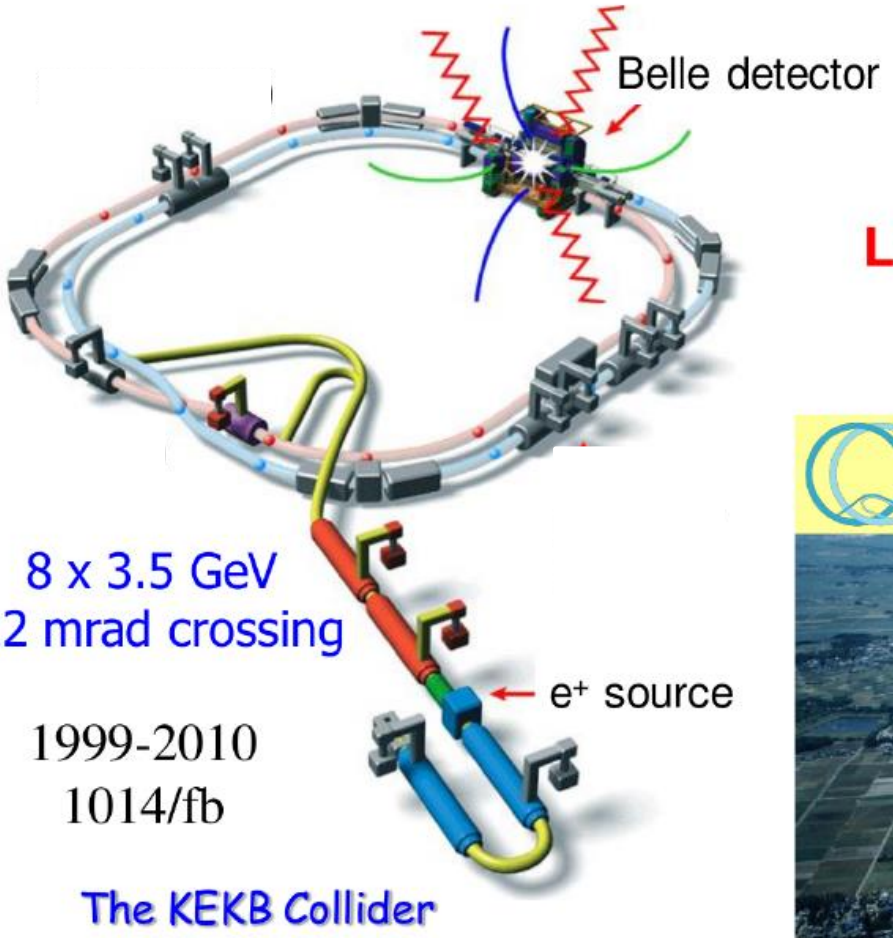
Λ_c – qq with isospin 0 (flavor antisymmetric);
Σ_c – qq with isospin 1 (flavor symmetric);
Ξ_c – sq with isospin 1/2 (either);
Ω_c – ss with isospin 0 (flavor symmetric).



Baryons



Belle experiment



World record:

$L = 2.1 \times 10^{34}/cm^2/sec$

The new generation SuperKEKB has been launched, and Belle II recorded the first collisions on April 26, 2018, JST!

E687 result

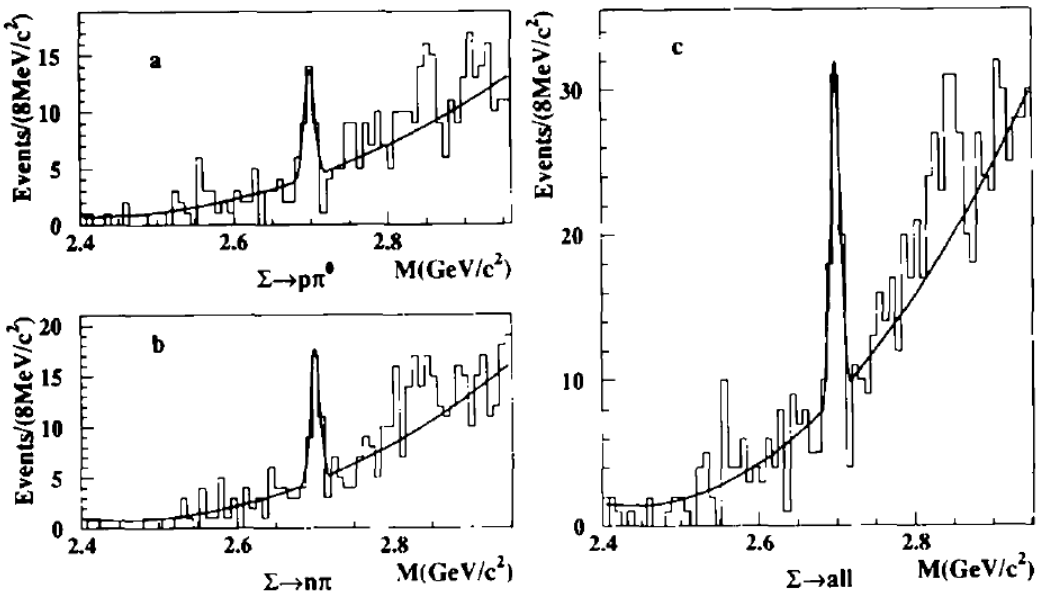


Fig. 1. (a) $\Sigma^- K^- K^- \pi^+$ invariant mass distribution for the $\Sigma^+ \to p\pi^0$ decay mode; (b) $\Sigma^- K^- K^- \pi^+$ invariant mass distribution for the $\Sigma^+ \to n\pi^+$ decay mode; and (c) $\Sigma^+ K^- K^- \pi^+$ invariant mass distribution for both decay modes of the Σ^+.

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