Recent results on charmed baryons at Belle

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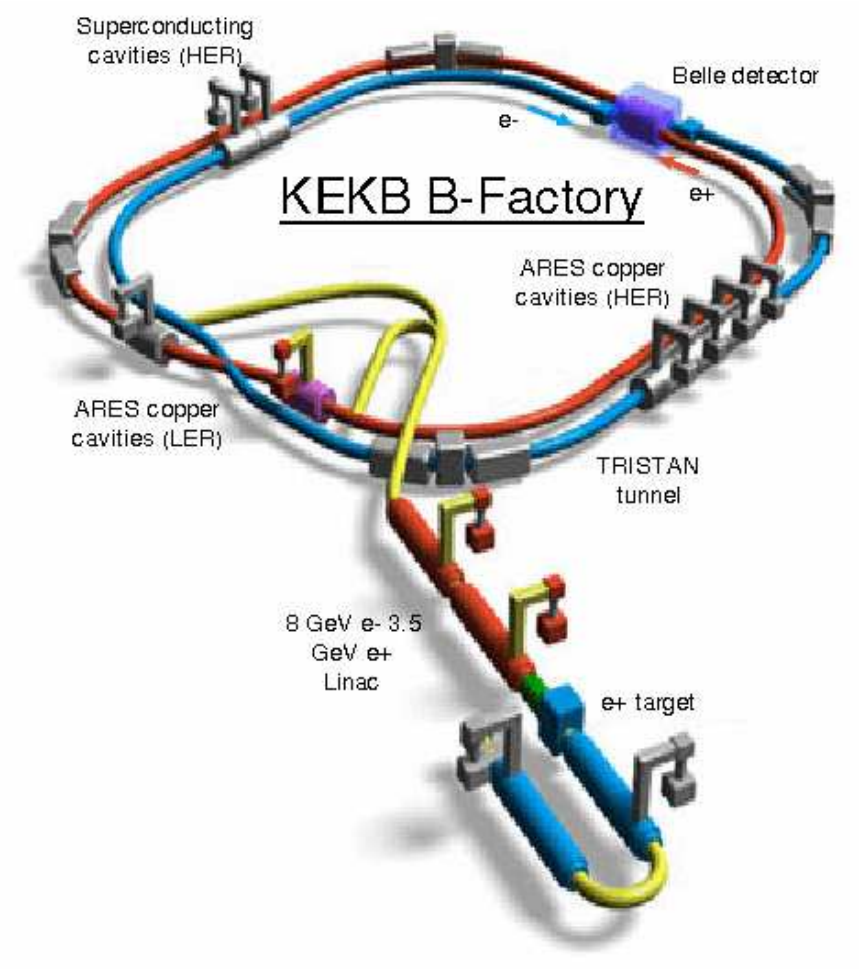
- Introduction
  - KEKB & Belle
  - Charmed baryons
- Recent Belle results:
  - $\Lambda_c \to \Sigma\pi\pi$
  - $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$
  - Hadronic decays of Ω_c
  - Excited $\Omega_c^\star \to \Xi_c^+ K^-$
- Summary

$\Xi_c(2930)^0 \to K^+\Lambda_c^+$
several for the first time
LHCb confirmation

KEKB & Belle

Operation time: Oct 1999 - Jun 2010

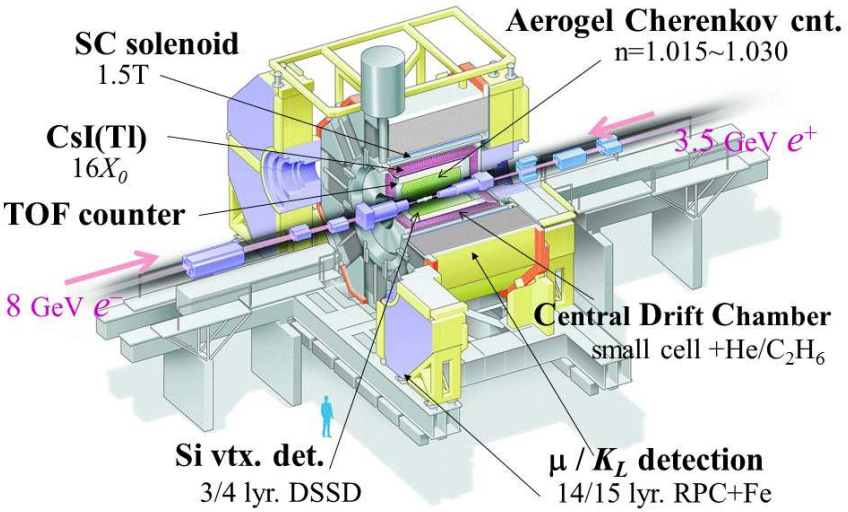


Peak luminosity: $\mathbf{2.1083 \times 10^{34}/cm^2/sec}$

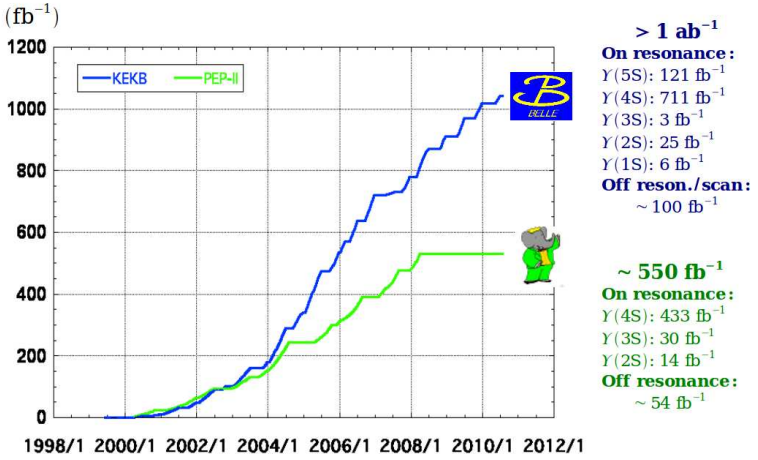
World record! (~ 1 fb^{-1}/day)

(LHC record is close: $\mathbf{2.06 \times 10^{34}/cm^2/sec}$)

Belle Detector



Integrated luminosity of B factories



Charmed baryons

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

- Charmed baryons consist of on **heavy** c quark and two **light** (u, d, s) quarks.

Quark	Mass
u	$2.2^{+0.6}_{-0.4}$ MeV
d	$4.7^{+0.5}_{-0.4}$ MeV
s	$96.0^{+8.0}_{-4.0}$ MeV
c	1.280 ± 0.030 GeV
b	$4.180^{+0.040}_{-0.030}$ GeV

- Charm baryon production mechanisms at B factories:
  - example with Λ_c^+ at Belle analysis [citation of example]

– Continuum: $e^+e^- \to c\,\bar{c}$
  * inclusive Λ_c^+ production, $e^+e^- \to \Lambda_c^+ ...$
    - $\Lambda_c^+ \to pK^+\pi^-$ (DCS) [PRL 117 011801 (2016)]
  * exclusive Λ_c^+ production
    - $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ [PRL 101 172001 (2008)]
    - $e^+e^- \to \Lambda_c^+\bar{p}\pi^+ D^{(*)-}$ [PRL 113 042002 (2014)]
      for $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ absolute width

– B meson: $b \to c\,W^-$
  - $\bar{B}^0 \to \Lambda_c^+\bar{p}$ [PRL 90 121802 (2003)]
  - $\bar{B}_S^0 \to \Lambda_c^+\bar{\Lambda}\pi^-$ [PL B 726 206 (2013)]
  * other flavor B: $b \to (u/c)W^-, W^- \to \bar{c}\,(s/d)$
    - $\bar{B}^0 \to \Xi_c^+\bar{\Lambda}_c^-$ [PR D74 111105R (2006)]

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

Introduction & Motivation:

- Λ_c is the lightest charmed baryon
- $\mathcal{B}(\Lambda_b \to \Lambda_c ...) \sim 10\%$
- Recent improved measurements of $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$:
  - Belle: $(6.84 \pm 0.24^{+0.21}_{-0.27})\%$ [PRL 113 042002 (2014)]
  - BESIII: $(5.84 \pm 0.27 \pm 0.23)\%$ [PRL 116 052001 (2016)]
- $\Lambda_c \to \Sigma\pi\pi$:
  - $\Sigma - \pi$ scattering length
  - $\Lambda(1405) \to \Sigma\pi$

Data sample & Event selection:

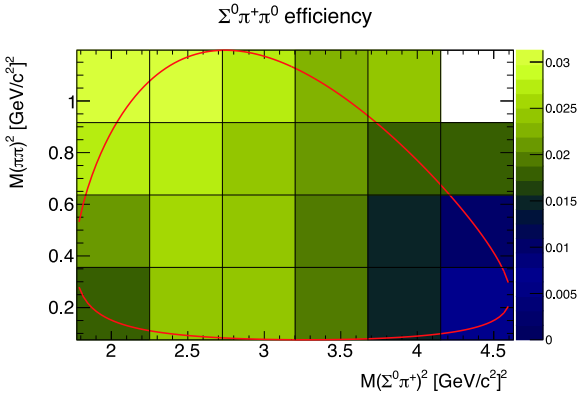
- 711 fb^{-1} at $\Upsilon(4S)$: (not whole Belle data)
  - Λ_c^+ scaled momentum $p/p_{\max} > 0.5$:
    - inclusive Λ_c^+ from continuum, $e^+e^- \to c\bar{c}$
- $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$, $\Sigma^0\pi^+\pi^0$ and $\Sigma^+\pi^0\pi^0$, (but not $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$,
  - $\Sigma^+ \to p\pi^0$ and $\Sigma^0 \to \Lambda\gamma$ as $\Sigma^- \to n\pi^-$ only)
    - $\pi^0 \to \gamma\gamma$ and $\Lambda \to p\pi^-$
- Boosted Decision Tree (BDT) selector based on AdaBoost algorithm:
  - neural network, based on kinematical variables.
- $\Lambda_c^+ \to pK^-\pi^+$ as reference

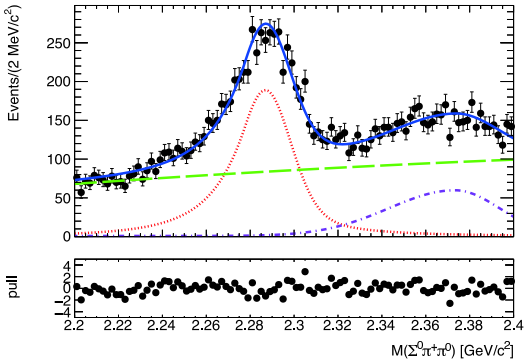
$\Lambda_c \to \Sigma\pi\pi$

Signal yield extraction:

- binned Dalitz distribution:
  - model independent
- $pK^-\pi^+$ — the same way

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





red $\Sigma^0\pi^+\pi^0$ signal
green combinatorial bkgr
blue $\Lambda\pi^+\pi^0 + \gamma$ bkgr

Results & Summary:

[M.Berger et al., arXiv:1802.03421 [hep-ex], submited to PR D]

- branching fractions are measured:

Final state	$\mathcal{B}(\Sigma\pi\pi)/\mathcal{B}(pK\pi)$	$\mathcal{B}(\Sigma\pi\pi)$ [%]	$\mathcal{B}_{WA}(\Sigma\pi\pi)$ [%] [PDG]
$\Sigma^+\pi^-\pi^+$	$0.706 \pm 0.003 \pm 0.030$	$4.48 \pm 0.02 \pm 0.19 \pm 0.23$	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
$\Sigma^+\pi^0\pi^0$	$0.198 \pm 0.006 \pm 0.017$	$1.26 \pm 0.04 \pm 0.11 \pm 0.07$	-

- $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^+\pi^-)$ and $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+\pi^0)$ are improved by four times.
- first time measurement of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0\pi^0)$.

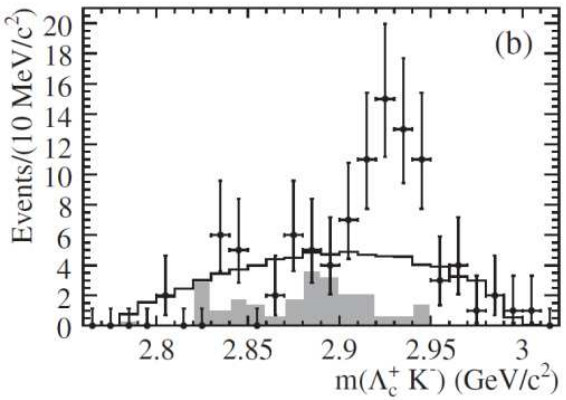
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

Introduction & Motivation:

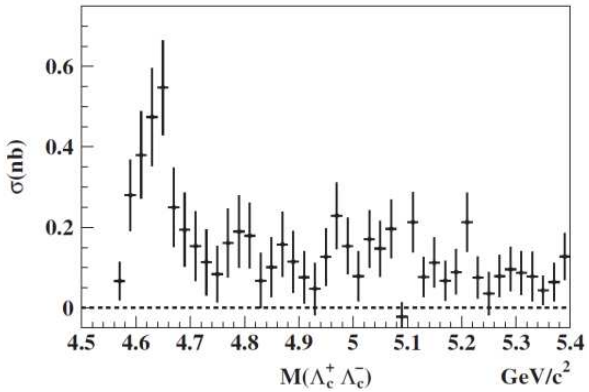
- $\Xi_c(2930)^0$ in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$ by BaBar (but no significance) [PR D 77 031101 (2008)]
- charmonium-like state $Y(4630)$ in $e^+e^- \to \gamma_{ISR}\ \Lambda_c^+ \bar{\Lambda}_c^-$ by Belle [PRL 101 172001 (2008)]
  - now by PDG it is assumed to be the same as
- exotic state $Y(4660)$ in $e^+e^- \to \gamma_{ISR}\ \pi^+\pi^- \psi'$ by Belle [PR D 91 112007 (2015)]

  with $M = (4643 \pm 9)$ MeV & $\Gamma = (72 \pm 11)$ MeV
  - $Y(4660)$ is modeled as $f_0(980)\psi'$ bound state, then
    - predicted to have spin partner Y_η: $f_0(980)\eta_c(2S)$ bound state

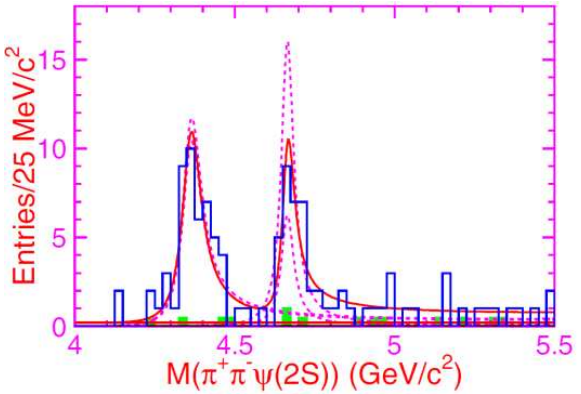
      with large partial decay width to $\Lambda_c^+ \bar{\Lambda}_c^-$ and $M = 4613$ MeV & $\Gamma = 30$ MeV



BaBar: $\Xi_c(2930)^0$



Belle: $Y(4630)$

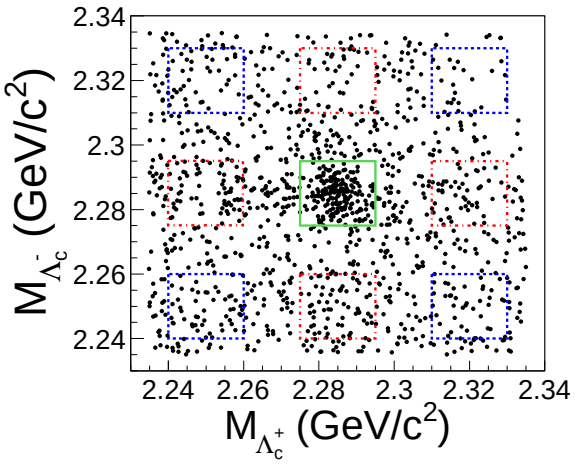


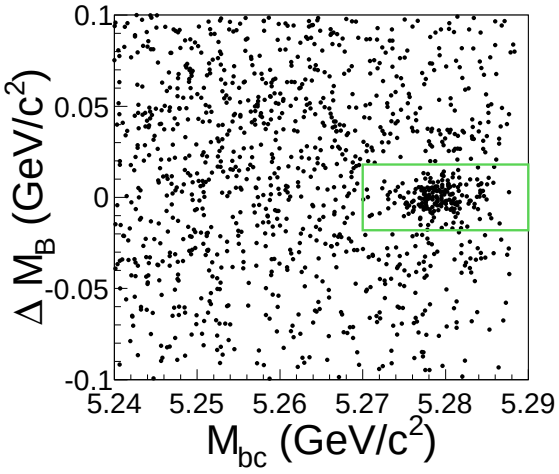
Belle: $Y(4660)$

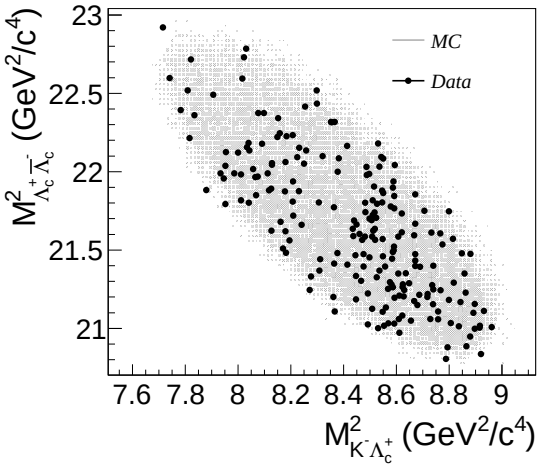
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

Data sample & Event selection:

- 711 fb^{-1} at $\Upsilon(4S)$ (whole $\Upsilon(4S) \to B\bar{B}$ data) $(772 \pm 11) \times 10^6$ $B\bar{B}$ pairs
- $\Lambda_c^+ \to pK^-\pi^+$, pK_S, $\Lambda\pi^+$, $pK_S\pi^+\pi^-$ and $\Lambda\pi^+\pi^+\pi^-$
  - at least one of Λ_c^+ and $\bar{\Lambda}_c^-$ is recostructed via $pK^-\pi^+$ or $\bar{p}K^+\pi^-$
    - $K_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$
- $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$:
  - $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}^{\,2}}$ — beam-constrained mass
  - $\Delta M_B = M - m_{B^-}$ — mass difference (ΔE correlated with $M_{\rm bc}$)







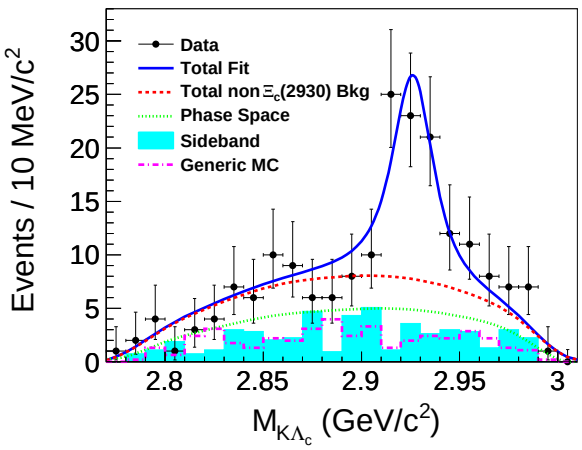
Green box – signal region; red & blue boxes– sidebands regions.

Signal of 153 ± 14 events

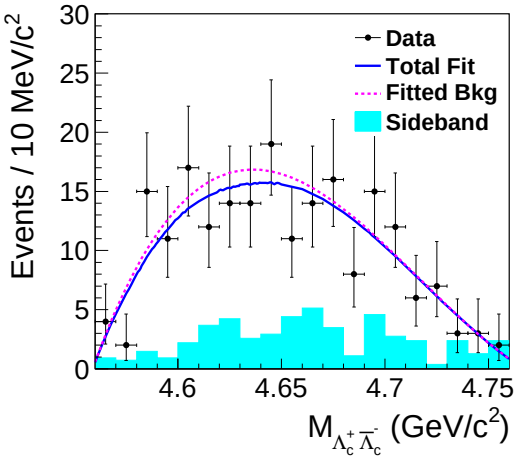
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$

Results & Summary: [Y.B.Li, C.P.Shen et al., EPJ C78 252 (2018)]

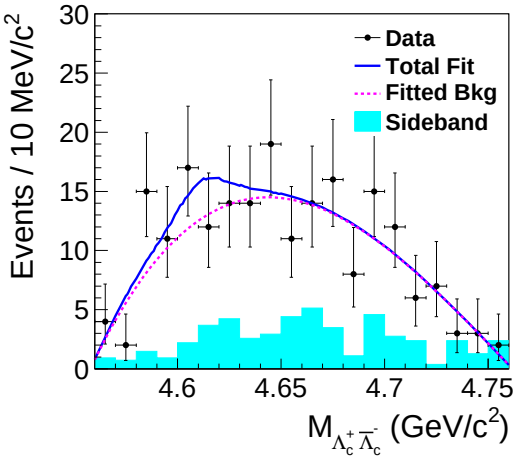
- observation $\Xi_c(2930)^0$ with significance $> 5\sigma$:
  - $M = (2928.9 \pm 3.0^{+0.9}_{-12.0})$ MeV & $\Gamma = (19.5 \pm 8.4^{+5.9}_{-7.9})$ MeV
  - $\mathcal{B}(B^- \to \Xi_c(2930)^0 \bar{\Lambda}_c^-) \times \mathcal{B}(\Xi_c(2930)^0 \to K^- \Lambda_c^+) = (1.73 \pm 0.45 \pm 0.21) \times 10^{-4}$
- no signal $Y(4660)$ nor its spin partner $Y_\eta(4613)$:
  - $\mathcal{B}(B^- \to Y(4660)\bar{\Lambda}_c^-) \times \mathcal{B}(Y(4660) \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$ at 90%CL
  - $\mathcal{B}(B^- \to Y_\eta \bar{\Lambda}_c^-) \times \mathcal{B}(Y_\eta \to \Lambda_c^+ \bar{\Lambda}_c^-) < 2.0 \times 10^{-4}$ at 90%CL



$\Xi_c(2930)^0$



$Y(4660)$



$Y_\eta(4613)$

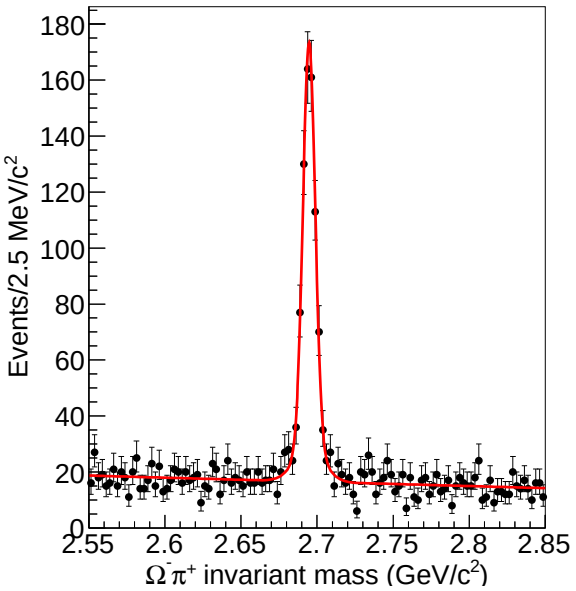
Hadronic decays of Ω_c

Introduction & Motivation:

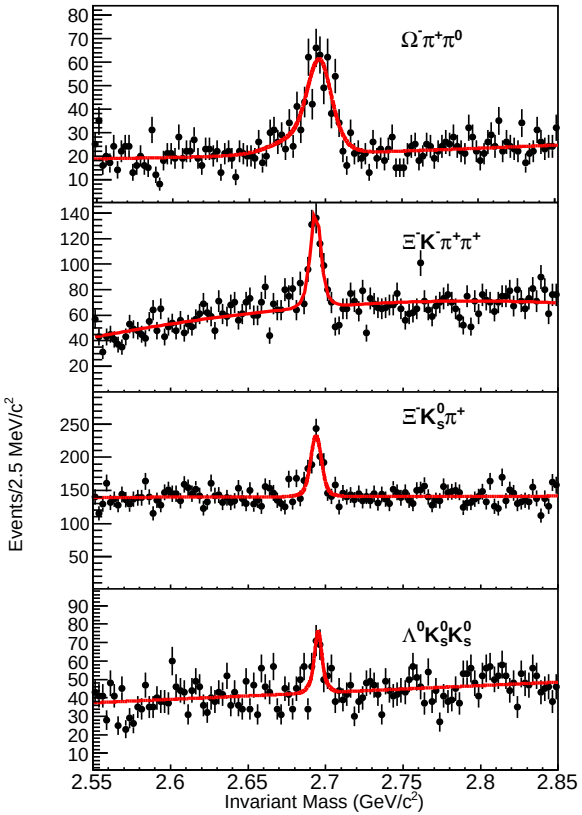
- Ω_c has less information on its hadronic decays, than other charmed baryons
- No measurements on absolute branching fractions, normalizing mode:
  - $\Omega^-\pi^+$
- Previously observed by CLEO and BaBar: [PRL 86 3730 (2001), PRL 99 062001 (2007)]
  - $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^-K^-\pi^+\pi^-$, $\Xi^0K^-\pi^+$
- Previously observed only by E687 (Fermilab): [PL B338 106 (1994)]
  - $\Sigma^+K^-K^-\pi^+$ (more, than $\Omega^-\pi^+$: $\mathbf{42}$ ev. VS $\mathbf{10}$ ev.)
- Previously not observed:
  - $\Xi^-K^0\pi^+$, Ξ^0K^0, ΛK^0K^0

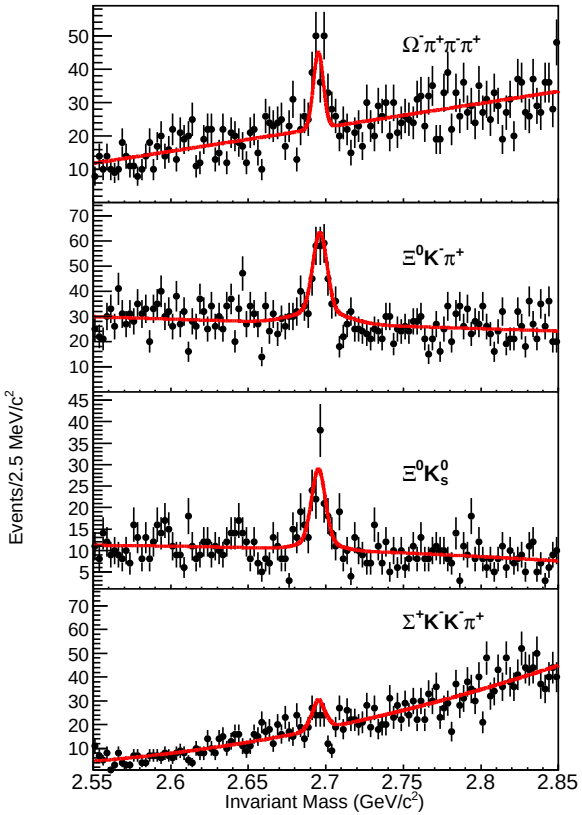
Data sample & Event selection:

- $\mathbf{980}$ fb^{-1} (whole Belle data)
- Ω_c scaled momentum $p/p_{\max} > 0.6$
- $(\Xi/\Omega)^- \to \Lambda(\pi/K)^-$, $\Xi^0 \to \Lambda\pi^0$, $\Sigma^+ \to p\pi^0$
  - $K^0 \to K_S$ of 50% and $K_S \to \pi^0\pi^-$
  - $\pi^0 \to \gamma\gamma$ and $\Lambda \to p\pi^-$



Hadronic decays of Ω_c

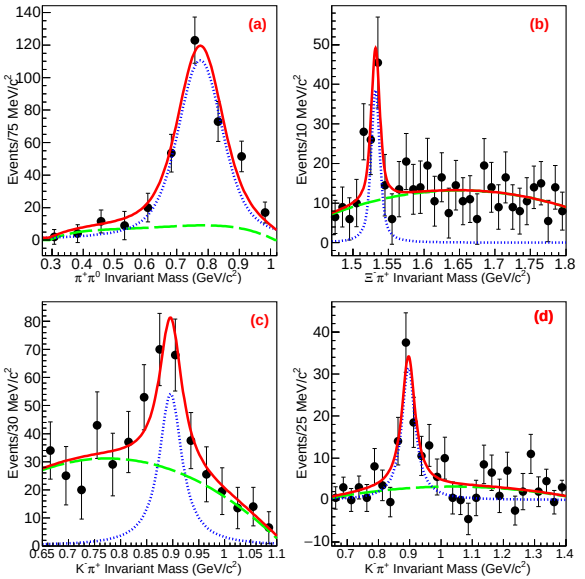




- Substructure:

$\Omega^-(\pi^+\pi^0)$ $\quad$ $(\Xi^-\pi^+)K^-\pi^-$

$\Omega^-\rho^+$ $\quad$ $\Xi^0(1530)K^-\pi^+$



$\Xi^-(K^-\pi^+)\pi^-$ $\quad$ $\Xi^0(K^-\pi^+)$

$\Xi^-\bar{K}^{*0}\pi^+$ $\quad$ $\Xi^0\bar{K}^{*0}$

Hadronic decays of Ω_c

Results & Summary:

[J.Yelton et al., PR D 97 032001 (2018)]

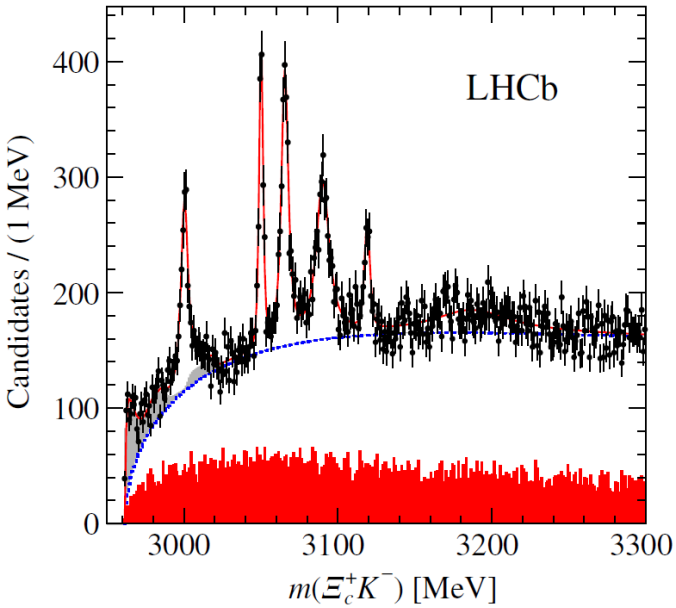
Mode	Branching ratio with respect to $\Omega^-\pi^+$	Substructure	Previous measurement
$\Omega^-\pi^+\pi^0$	$2.00 \pm 0.17 \pm 0.11$		$1.27 \pm 0.3 \pm 0.11$ [BaBar]
$\Omega^-\rho^+$		$> 71\%$	
$\Omega^-\pi^+\pi^-\pi^+$	$0.32 \pm 0.05 \pm 0.02$		$0.28 \pm 0.09 \pm 0.01$ [BaBar]
$\Xi^- K^-\pi^+\pi^+$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

- $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^- K^-\pi^+\pi^-$, $\Xi^0 K^-\pi^+$: improved precision measurements
- $\Xi^- K^0\pi^+$, $\Xi^0 K^0$, $\Lambda K^0 K^0$: first time measurements
- $\Sigma^+K^-K^-\pi^+$: it's surprising
- for other charmed baryons $\mathcal{B}(Y_c \to Y\pi^+\pi^+\pi^-)/\mathcal{B}(Y_c \to Y\pi^+) \gg 1$, but $\mathcal{B}(\Omega_c \to \Omega^-\pi^+\pi^+\pi^-)/\mathcal{B}(\Omega_c \to \Omega^-\pi^+) < 1$

Excited $\Omega_c^\star$

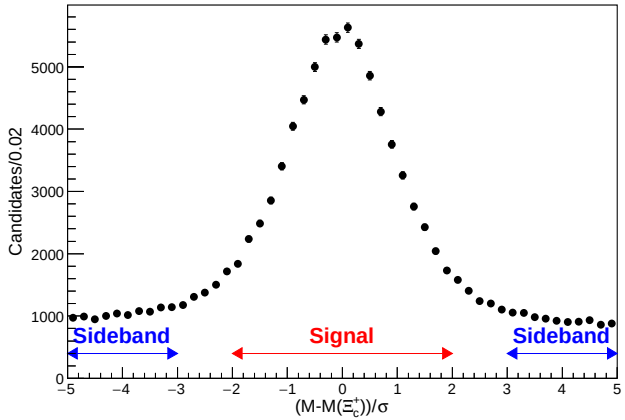
Introduction & Motivation:

- $\Omega_c(2770) \to \Omega_c\gamma$ was the only excited state.
- LHCb discovered at $\Xi_c^+ K^-$: [PRL 118 182001 (2017)]
  - five narrow states $\Omega_c(3000/3050/3066/3090/3119)$;
  - and wide enhancement at 3188 GeV.



Data sample & Event selection:

- 980 fb^{-1} (entire Belle data)
- $\Omega_c^* \to \Xi_c^+ K^-$ scaled momentum $p/p_{\rm max} > 0.75$
- Ξ_c^+ by decays:
  - $\Xi^-\pi^+\pi^+$, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^-\pi^+$, $\Sigma^+K^-\pi^+$, $\Lambda K_S\pi^+$ and $\Sigma^0 K_S\pi^+$.
- Ξ_c^+ by "pull-mass": $(M - m_{\Xi_c^+})/\sigma$

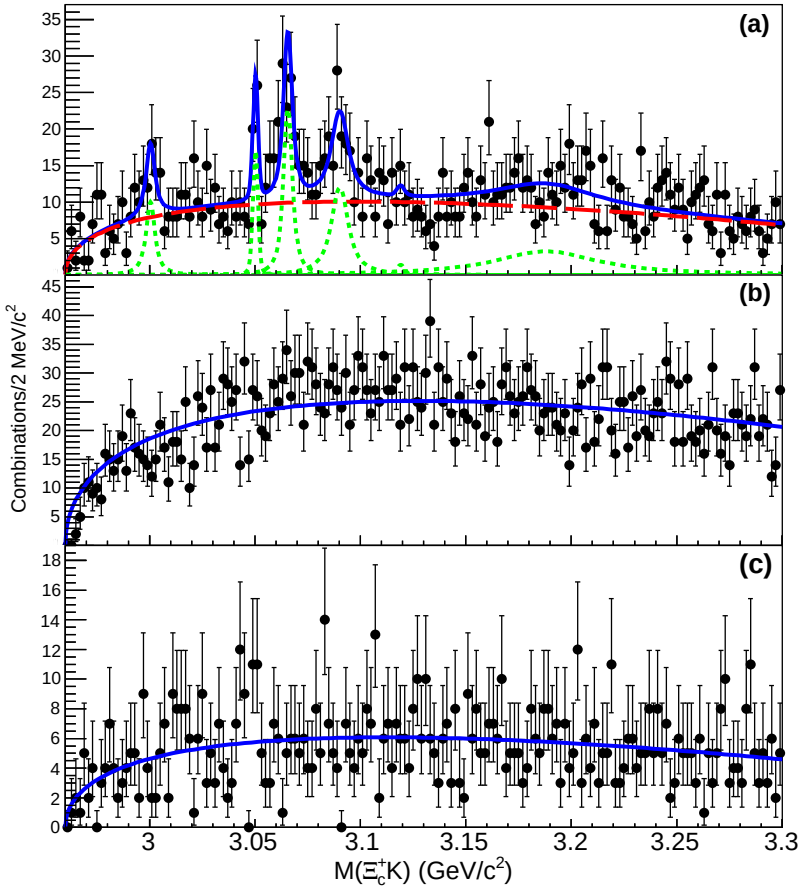


Excited $\Omega_c^\star$

Results: (a) $M(\Xi_c^+ K^-)$
(b) $M(\Xi_c^+ K^+)$, wrong sign
(c) $M(\Xi_c^+ K^-)$ for Ξ_c^+ sideband

Summary: [J.Yelton et al., PR D 97 051102R (2018)]

- confirmation with $< 5\sigma$ of:
  - $\Omega_c(3000)$ and $\Omega_c(3055)$
- strong ($> 5\sigma$) confirmation of:
  - $\Omega_c(3066)$ and $\Omega_c(3090)$
- no confirmation of:
  - $\Omega_c(3119)$ (expected ≈ 17 events)
- indication of:
  - wide enhancement at 3188 GeV.



Yields & Significances are with LHCb fixed M & Γ.

Belle Masses are with LHCb fixed Γ.

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	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

Summary

$\Lambda_c \to \Sigma\pi\pi$: [M.Berger et al., arXiv:1802.03421 [hep-ex], submited to PR D]

- $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^+\pi^-)$ and $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+\pi^0)$ are improved by four times.
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0\pi^0)$ is measured for the first time.

$B^- \to K^-\Lambda_c^+\bar{\Lambda}_c^-$: [Y.B.Li, C.P.Shen et al., EPJ C78 252 (2018)]

- $\mathcal{B}(B^- \to K^-\Lambda_c^+\bar{\Lambda}_c^-)$ is improved.
- $\Xi_c(2930)^0 \to K^-\Lambda_c^+$ is observed, mass and width are measured.

Hadronic decays of Ω_c: [J.Yelton et al., PR D 97 032001 (2018)]

- Improved precision for $\mathcal{B}$ of $\Omega_c \to \Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^-K^-\pi^+\pi^-$, $\Xi^0K^-\pi^+$ decays
- First time measurements of $\mathcal{B}$ of $\Omega_c \to \Xi^-K^0\pi^+$, Ξ^0K^0, ΛK^0K^0 decays.
- Upper limit for $\mathcal{B}(\Omega_c \to \Sigma^+K^-K^-\pi^+)$ decay.
- $\mathcal{B}(\Omega_c \to \Omega^-\pi^+\pi^+\pi^-)/\mathcal{B}(\Omega^-\pi^+) < 1$, unless $\mathcal{B}(Y_c \to Y\pi^+\pi^+\pi^-)/\mathcal{B}(Y\pi^+) \gg 1$

Excited Ω_c^*: [J.Yelton et al., PR D 97 051102R (2018)]

- Confirmation 4 of 5 observed by LHCb narrow states $\Omega_c(3000/3050/3066/3090)$ at $\Xi_c^+K^-$.
- No confirmation $\Omega_c(3119)$ & Indication of wide enhancement at 3188 GeV.

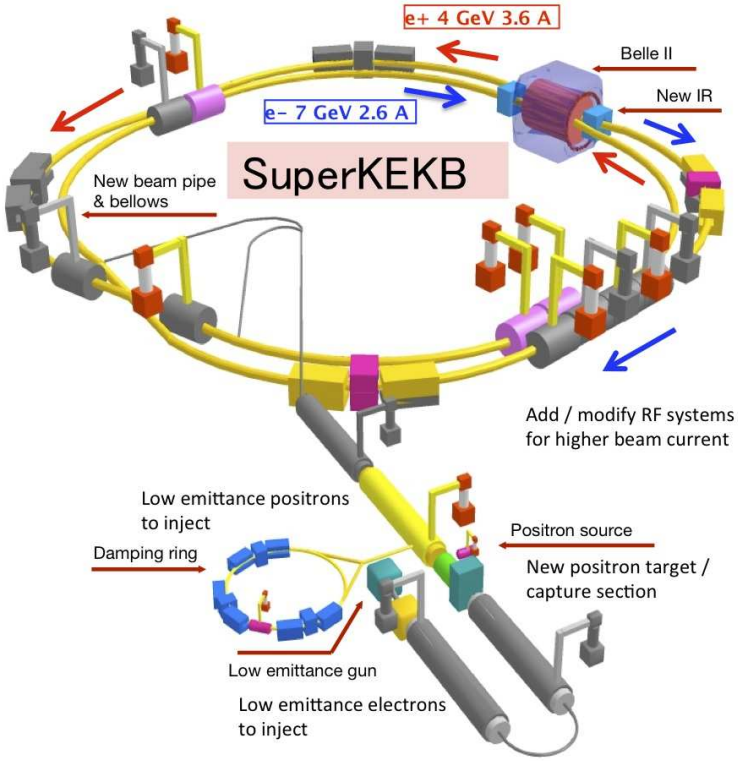
Near future:

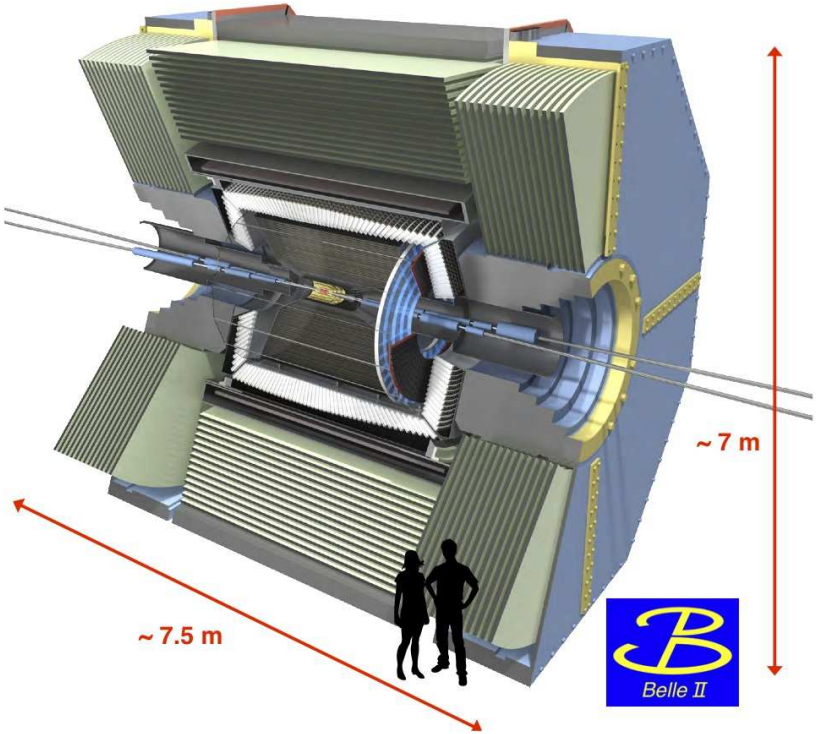
- There are still a lot of interesting to do with charmed baryons at Belle.
- Sure Belle will continue to study charmed baryons by its possibilities.

SuperKEKB & Belle II

Not too far future:

- SuperKEKB & Belle II will make study with new opportunities due to large & good quality data.





SuperKEKB luminosity: $8 \times 10^{35}/\mathrm{cm}^2/\mathrm{sec}$ (40×KEKB) !
Belle II integrated luminosity by 2025: 50 ab^{-1} (50×Belle) !!

Belle II recorded the first SuperKEKB beam collisions on 26 April 2018 and continue to take data !!!