北京航空航天大學
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Recent Belle results on (charmed) baryons and Belle II prospects of baryons

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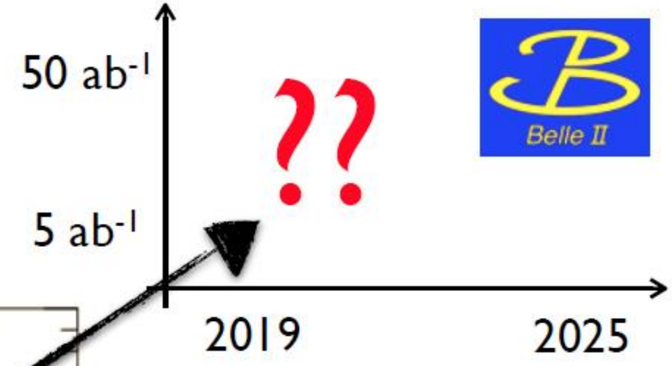
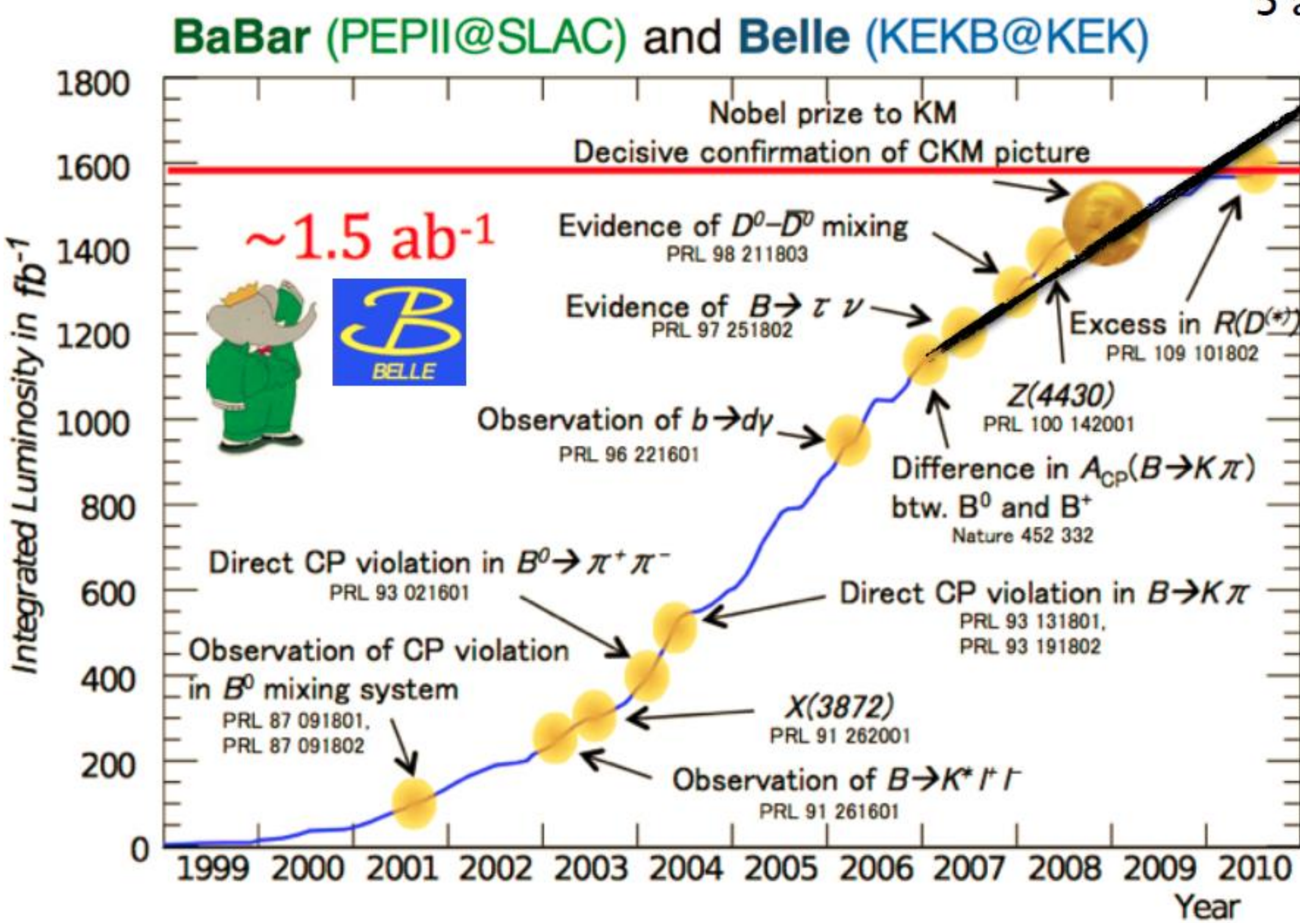
Outline

- Introduction
- Singly (Charmed) Baryon results at Belle
- Belle II status
- Prospects of baryon study at Belle II
- Summary

B-factories in the last decade





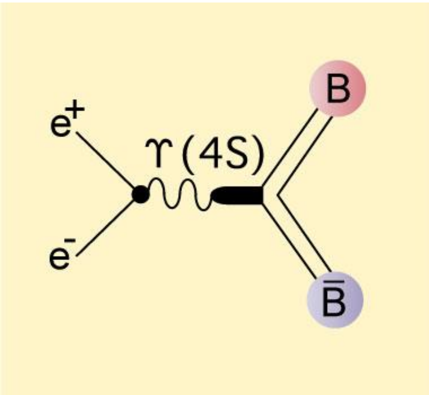
- Belle and BaBar have produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets

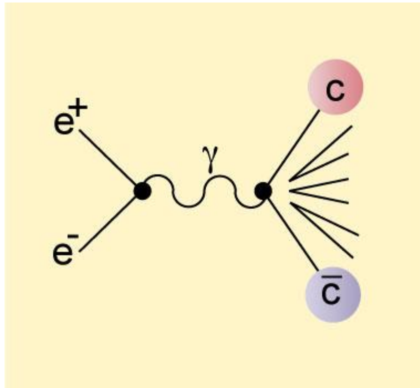
The Physics of B factories
EPJC 74, 3026 (2018)

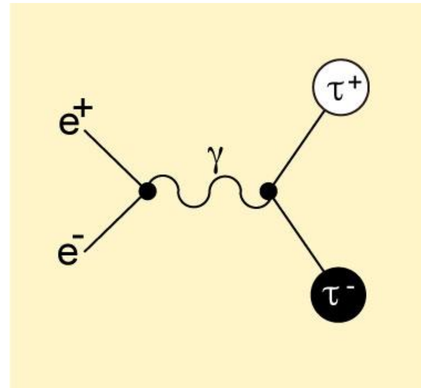
Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

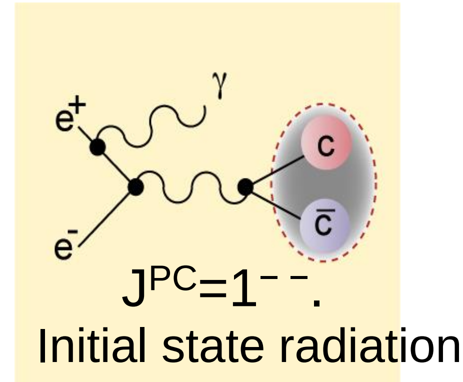
arXiv:1808.10567

The Physics Program



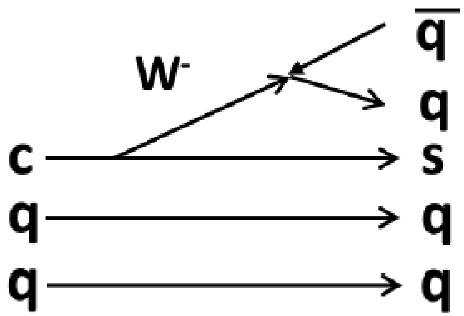




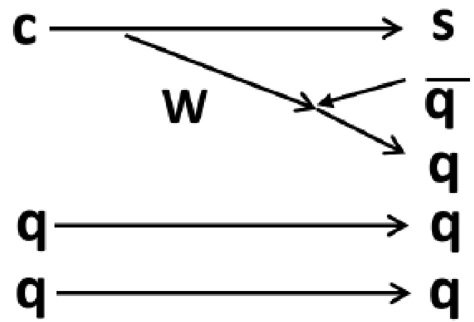


- a (Super) B-factory (~1.1 x 10^9 $B\bar{B}$ pairs per ab^{-1});
- a (Super) charm factory (~1.3 x 10^9 $c\bar{c}$ pairs per ab^{-1});
- a (Super) τ factory (~0.9 x 10^9 $\tau^+\tau^-$ pairs per ab^{-1});
- thanks to the Initial State Radiation, we can effectively scan the range [0.5 – 10] GeV and measure the $e^+e^- \rightarrow$ light hadrons cross-section very precisely;
- finally we can exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, …

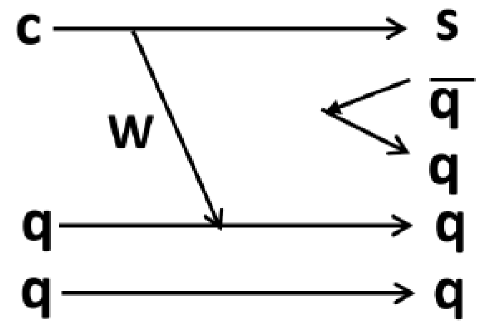
The Charmed Baryon Physics



Spectator



Internal W

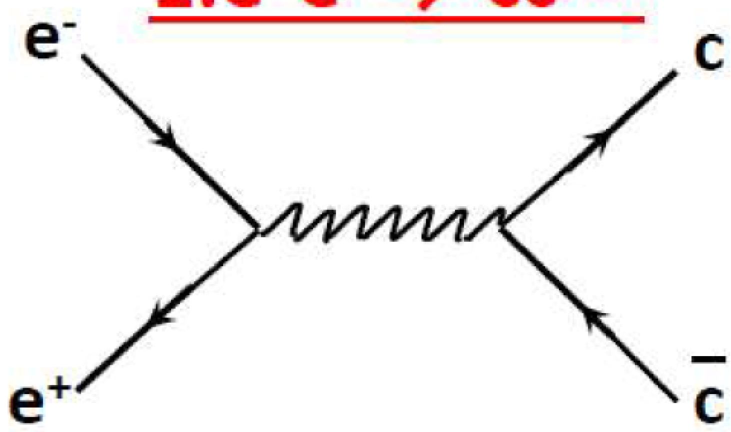


W-exchange

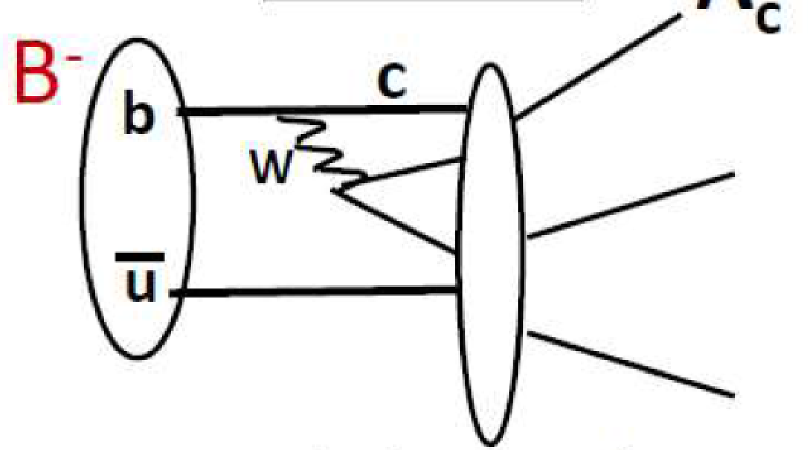
- The weak decay of charmed baryon has not been understood well.
- Three diagrams contribute in the tree level, but their strengths are not known.
- Ground state charm baryon is a good laboratory for studying strange baryons as decay proceed via $c \to s$ transition.
- Belle has collected $\sim 1\ \mathrm{ab}^{-1}\ \mathrm{e}^{+}\mathrm{e}^{-}$ data samples (mainly at $\Upsilon(4S)$).
  - $10^9\ e^+e^- \to c\bar{c}$ samples
  - $7.7 \times 10^8\ B\bar{B}$ samples
- Huge data sample enable to study various charmed baryons.

Baryon production at B-factory

1.$e^+e^- \rightarrow cc^{bar}$



2.B-decay



Baryons produced via fragmentation

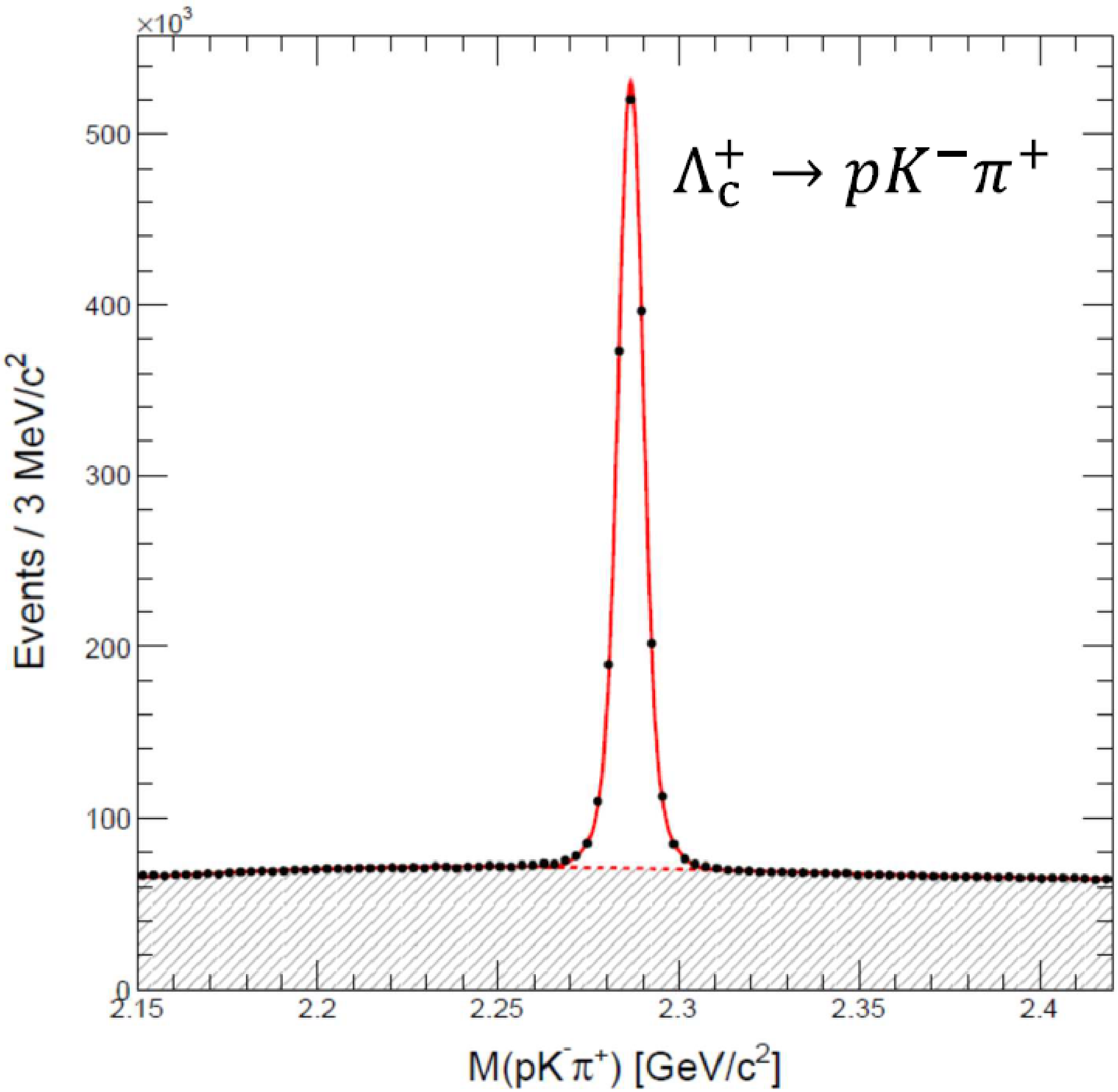
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

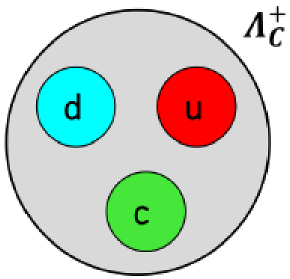
Huge statistics

B is efficiently produced via $\Upsilon(4s)$

Once bottom is produced, it favorably decays into charm.

Huge statistics, good quality





> 1 M events reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

$\Gamma(\Lambda_c \to p^+K^-\pi^+)/\Gamma_{total}$		
$5.84 \pm 0.27 \pm 0.23$	BES3	2016
$6.84 \pm 0.24^{+0.21}_{-0.27}$	Belle	2014

Observation of an excited Ω^- baryon

Ω^- = s s s (S=-3, I=0)

PRL 121, 052003 (2018)

1. Ω^- excited states have proved difficult to find

- Only one excited Ω^- states, $\Omega(2250)$, has been confirmed until now.
- In addition, the evidence for two other states of Ω^- were reported.
- These Ω^- excited states' masses are much higher than the ground state (>600MeV).

2. $\Omega^{*-} \rightarrow \Omega^- + \pi^0$ is highly suppressed since Ω^- is isospin zero

3. Preferred modes

- $\mathbf{\Omega^{*-} \rightarrow \Xi^- + K^0_S}$ ✓
- $\mathbf{\Omega^{*-} \rightarrow \Xi^0 + K^-}$ ✓
- low-lying states
- Analogous to $\Omega_c^0 \rightarrow \Xi_c^+ K^-$

[R. Aaij et al. PRL 118, 182001 (2017)]
[J. Yelton et al. PRD 97, 051102 (2018)]

Data sample	Luminosity(fb^{-1})	Events ($\times 10^8$)
$\Upsilon(1S)$	5.7	1.02
$\Upsilon(2S)$	24.9	1.58
$\Upsilon(3S)$	2.9	-

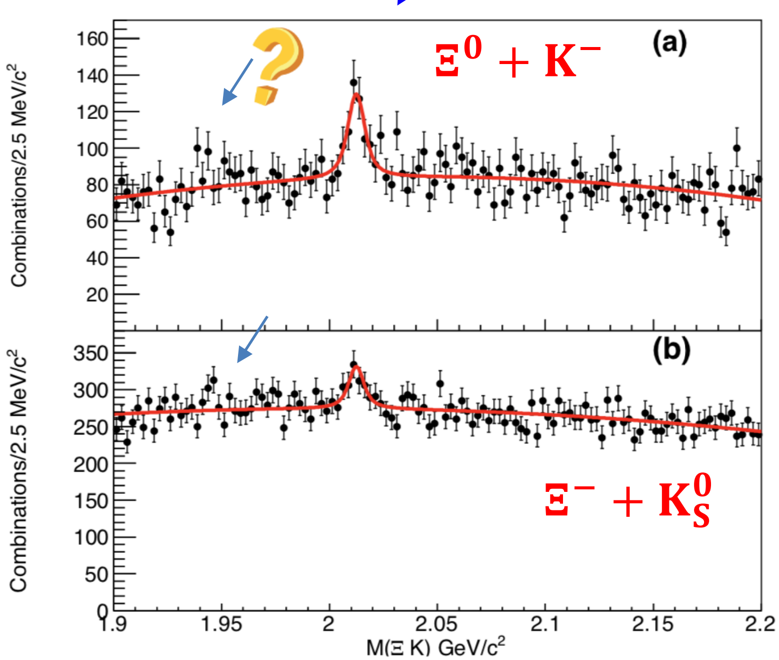
- The decays of these narrow resonances proceed via gluons.
- The production of baryon are enhanced.

Observation of an excited Ω^- baryon

Results & Summary

$$\mathcal{R} = \frac{\mathcal{B}(\Omega^{*-}\to\Xi^0 K^-)}{\mathcal{B}(\Omega^{*-}\to\Xi^- \bar{K}^0)} = 1.2 \pm 0.3$$

Data	Mode	Mass (MeV/c^2)	Yield	Γ(MeV)	χ^2/d.o.f.	n_σ
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$, $\Xi^- K^0_S$ (simultaneous)	2012.4 ± 0.7	242 ± 48, 279 ± 71	$6.4^{+2.5}_{-2.0}$	227/230	8.3
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$	2012.6 ± 0.8	239 ± 53	6.1 ± 2.6	115/114	6.9
$\Upsilon(1S,2S,3S)$	$\Xi^- K^0_S$	2012.0 ± 1.1	286 ± 87	6.8 ± 3.3	101/114	4.4
Other	$\Xi^0 K^-$	2012.4 (Fixed)	209 ± 63	6.4 (Fixed)	102/116	3.4
Other	$\Xi^- K^0_S$	2012.4 (Fixed)	153 ± 89	6.4 (Fixed)	133/116	1.7



PRL 121, 052003 (2018)

- The gap in the spectrum between the ground state and this excited state (~340 MeV) is smaller than other Ω^- excited states, which is more close to the negative-parity orbital excitations of many other baryons.
- The narrow width observed implies that the quantum number $J^P = \frac{3}{2}^-$ is preferable.

Theoretical interpretation for the $\Omega^*(2012)$

It is generally accepted that $\Omega^*(2012)$ is 1P orbital excitation of the ground state Ω baryon with three strange quark, whose quantum numbers are $J^P = \frac{3}{2}^-$.

From PRD 98, 056013 (2018)

Notably, the newly observed $\Omega^*(2012)$ is revealed as a KΞ(1530) hadronic molecule.
[PRD 98, 054009 (2018), PRD 98, 056013 (2018), arXiv:1807.02145, arXiv:1807.06485, arXiv:1807.06485]

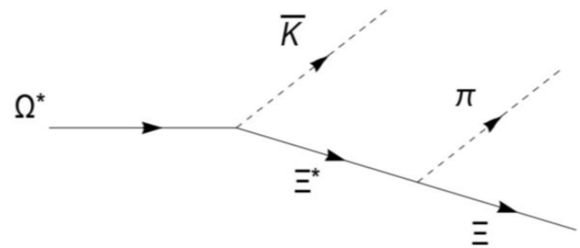


FIG. 1: The three-body decays of $\Omega(2012)$ in the $K\Xi(1530)$ molecular picture.

The $K\Xi\pi$ three-body component is largely dominant.

Mode	$J^P = \frac{3}{2}^-$ $\Omega(2012)$ $(K\Xi(1530))$ Widths (MeV)	Branch Ratio(%)
$K\Xi$	0.4	14.3
$K\pi\Xi$	2.4	85.7
Total	2.8	100.0

The number of expected Ω(2012) events at Belle

$$N^{\text{expected}} = N_{\Omega}^{\text{total}} \times \mathcal{B}^{\text{product}} \times \varepsilon \times \mathcal{B}(\Omega(2012) \to K\Xi/K\Xi\pi)$$

Channel	ε	$\mathcal{B}^{\text{decay}}$	$\mathcal{B}(\Omega(2012) \to K\Xi/K\Xi\pi)$	N^{obs}	N^{expected}
$\Xi^- K_S^0$	15.7%	$\mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{R}(\bar{K}^0 \to K_S^0)$	6.5%	279	-
$\Xi^0 K^-$	4.0%	$\mathcal{B}(\pi^0 \to \gamma\gamma)$	7.8%	242	
$\Xi^- K^- \pi^+$	9.4%	-	28.6%	-	**2091**
$\Xi^- K_S^0 \pi^0$	1.5%	$\mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{B}(\pi^0 \to \gamma\gamma) \times \mathcal{R}(\bar{K}^0 \to K_S^0)$	14.3%	-	**55**
$\Xi^0 K_S^0 \pi^-$	2.3%	$\mathcal{B}(\pi^0 \to \gamma\gamma) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{R}(\bar{K}^0 \to K_S^0)$	28.6%	-	**177**
$\Xi^0 K^- \pi^0$	0.8%	$\mathcal{B}(\pi^0 \to \gamma\gamma) \times \mathcal{B}(\pi^0 \to \gamma\gamma)$	14.3%	-	**82**

- $\mathcal{B}(\Omega(2012) \to K\Xi)$: $\mathcal{B}(\Omega(2012) \to K\Xi\pi)$ = 14.3 : 85.7 in Ref.[arxiv:1807.00997].
- $\mathcal{T}[\Xi^- \bar{K}^0]$: $\mathcal{T}[\Xi^0 K^-]$ = 1 : 1.2 from PRL121, 052003 (2018)
- The isospin analysis shows $\mathcal{T}[\Xi^- K^- \pi^+]: \mathcal{T}[\Xi^- \bar{K}^0 \pi^0]: \mathcal{T}[\Xi^0 \bar{K}^0 \pi^-]: \mathcal{T}[\Xi^0 K^- \pi^0]$ = 2:1:2:1
- In the calculation of $\mathcal{B}^{\text{decay}}$, the common $\mathcal{B}$, e.g., $\mathcal{B}(\Lambda \to p\pi^-)$ is cancelled. $\mathcal{R}(\bar{K}^0 \to K_S^0) = 0.5$
- If theoretical predictions are correct, we will most likely observe $\Omega(2012)$ in mode $\Omega(2012) \to \Xi^- K^- \pi^+$.

Observation of $\Xi^0(1620)$ and evidence for $\Xi^0(1690)$

List of Ξ(S=-2) particles from PDG

[arXiv:1810.06181 [hep-ex]]

Particle	J^P	Overall status	Status as seen in — Ξπ	ΛK	ΣK	Ξ(1530)π	Other channels
Ξ(1318)	1/2+	****					Decays weakly
Ξ(1530)	3/2+	****	****				
Ξ(1620)	½-?	*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	3/2−	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)		***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					
Ξ(2370)		**					
Ξ(2500)		*		*	*		3-body decays

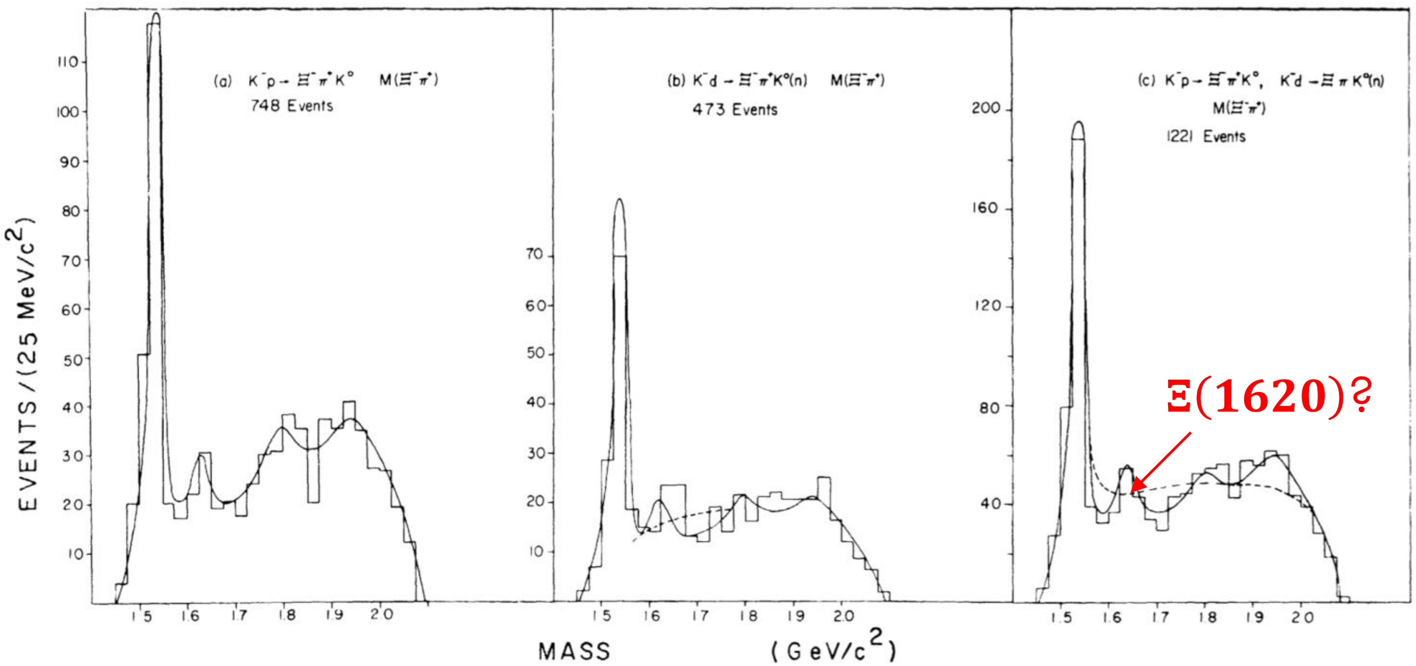
****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

- NOT much is known about Ξ^*
- Not found ½-? With L =1
- **Ξ(1620)** and **Ξ(1690)** are candidates
- Ξπ is possible mode

Status of the $\Xi(1620)$

One star:
Evidence of existence is poor
E. Briefel, PRD 16, 2706 (1977)

But !!
J.K.Hassall says "no evidence"
In NPB189 (1981) 397



The $\Xi^-\pi^+$ effective-mass distributions for the reaction $K^-p \to \Xi^-\pi^+K^0$

Search for $\Xi^0(1620)$ and $\Xi^0(1690)$ at Belle

[arXiv:1810.06181]

Search for $\Xi^0(1620)$ and $\Xi^0(1690)$ at Belle in below channel:

Data set: $\Xi_c^+ \to \Xi^{*0}\pi^+,\ \Xi^{*0} \to \Xi^-\pi^+$ Total 980fb^{-1}

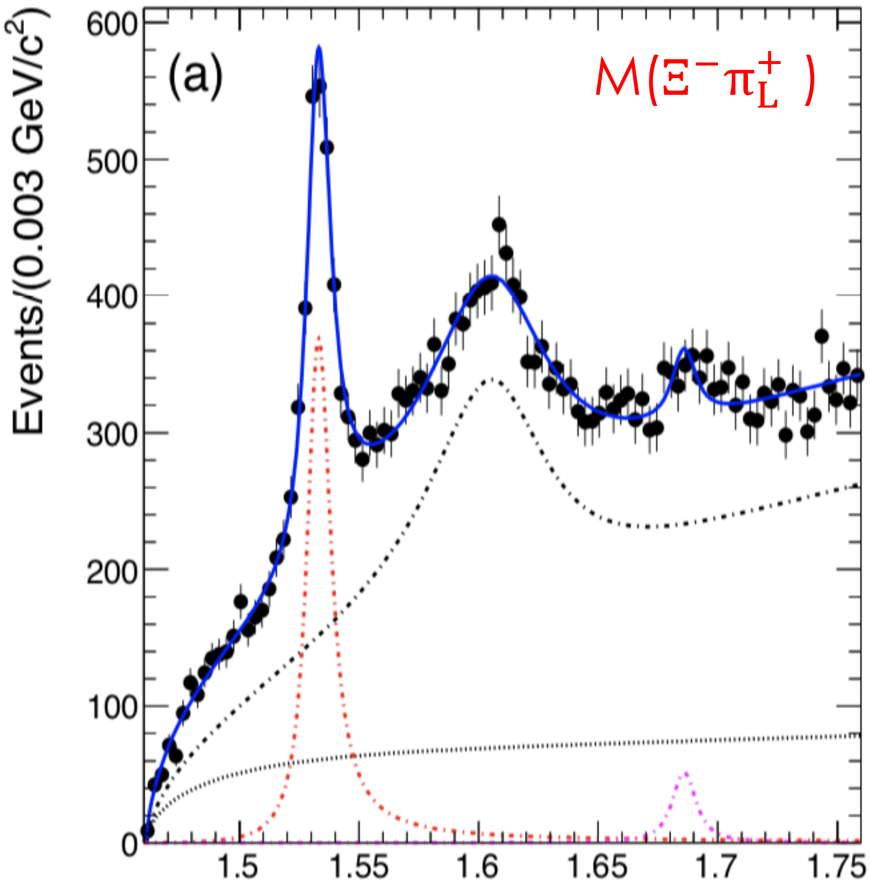
Data sample	Luminosity(fb^{-1})	Data sample	Luminosity(fb^{-1})
$\Upsilon(1S)$	5.74	$\Upsilon(2S)$	24.91
$\Upsilon(3S)$	24.9	e^+e^- at $\sqrt{s}$=10.52GeV	89.5
e^+e^- at $\sqrt{s}$=10.58GeV	711.0	e^+e^- at $\sqrt{s}$=10.867GeV	121.4

Crucial Selection criteria:

- To purify the Ξ_c^+ samples, the scaled momentum $x_p = \frac{p_{CM}}{\sqrt{\frac{1}{4}s - m(\Xi_c^+)^2}} < 0.5$
- The retained Ξ^- candidates are combined with the lower and higher momentum pions, as labeled π_L^+ and π_H^+.
- A vertex fit is applied to the $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ decay, and the $\chi^2 < 50$

Observation of $\Xi^0(1620)$ and evidence for $\Xi^0(1690)$

[arXiv:1810.06181]



In the simultaneous fit

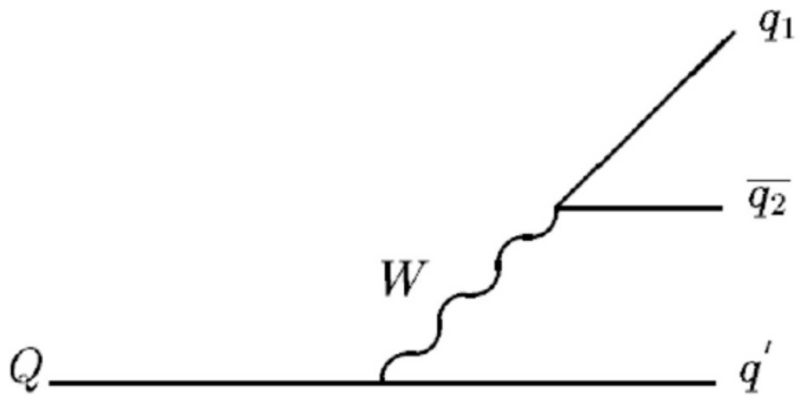
- The $\Xi^0(1530)$ and $\Xi^0(1690)$ signals are modeled with P- and S-wave relativistic BW functions.
- The $\Xi^0(1620)$ signal is modeled with the S-wave relativistic BW function.
- The interference between $\Xi^0(1620)$ and the S-wave non-resonant process is taken into account.
- The combinatorial backgrounds are described by a threshold.

$\Xi^0(1620)$ **state**	
Mass (MeV/c^2)	$1610.4 \pm 6.0^{+5.9}_{-3.5}$
Width (MeV)	$59.9 \pm 4.8^{+2.8}_{-3.0}$

When the S-wave (P-wave) relativistic BW with fixed mass and width is used as the fitting function, the significance for $\Xi^0(1690)$ is 4.6σ (4.0σ).

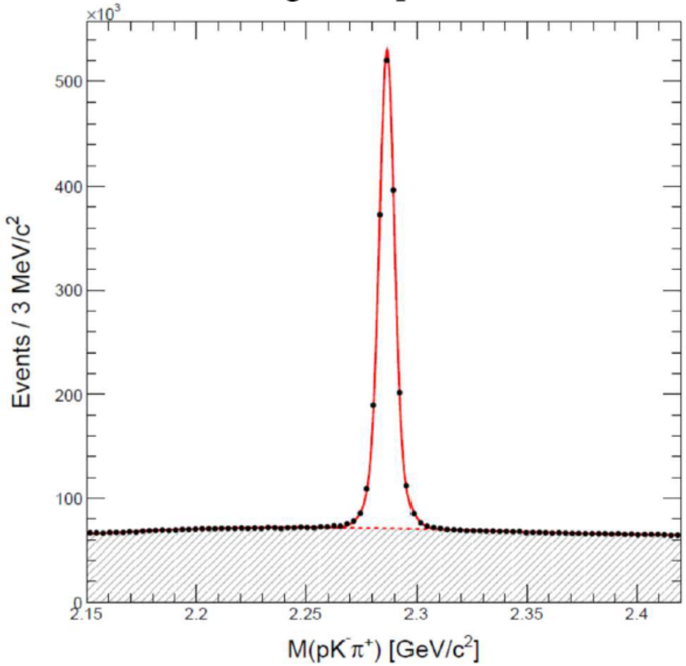
Double-Cabibbo suppressed decay $\Lambda_c^+ \to p K^+ \pi^-$

- Weak decay amplitude of a charm quark
  - c → s: $\cos\theta_c$ ~ 1
    d: $\sin\theta_c$ ~ 0.23 ← Cabibbo suppression
  - At the same time, emitted W decays into a qqbar pair
    $u\bar{d}$: $\cos\theta_c$
    $u\bar{s}$: $\sin\theta_c$
- So, the decay $c \to d(u\bar{s})$ is twice suppressed
  → Doubly Cabibbo-suppressed decay
  - Naively, decay branch is $O(\tan^4\theta_c)$ ~ 0.28% smaller compared to counterpart ($c \to s(\bar{d}u)$)



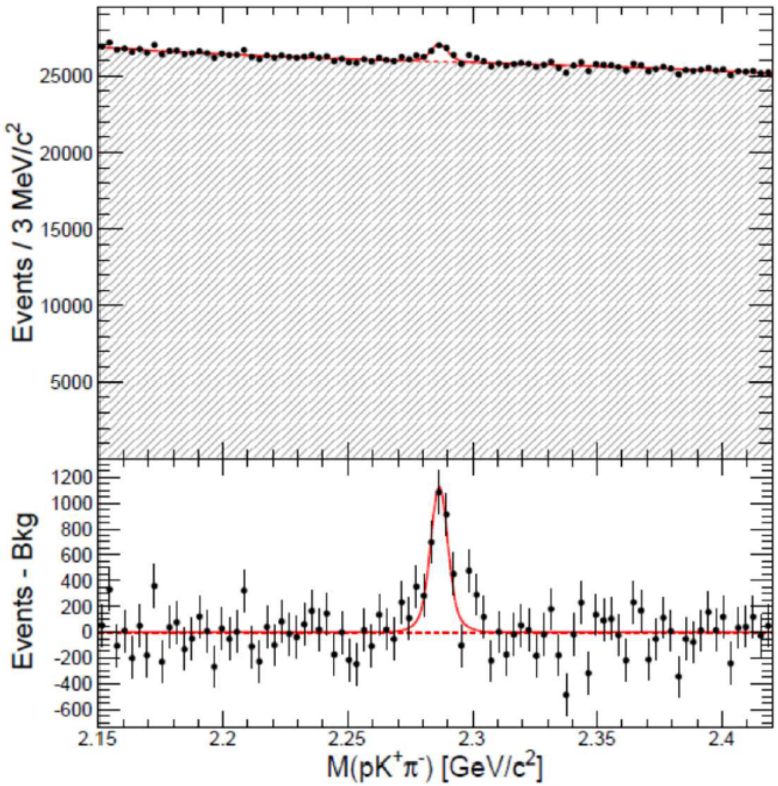
DCS decay $\Lambda_c^+ \to p\,K^+\pi^-$

CF: $\Lambda_c^+ \to pK^-\pi^+$



$(1.452 \pm 0.015) \times 10^6$ events

DCS: $\Lambda_c^+ \to pK^+\pi^-$



3587 ± 380 events

Significant signal observed!

(significance 9.4σ)

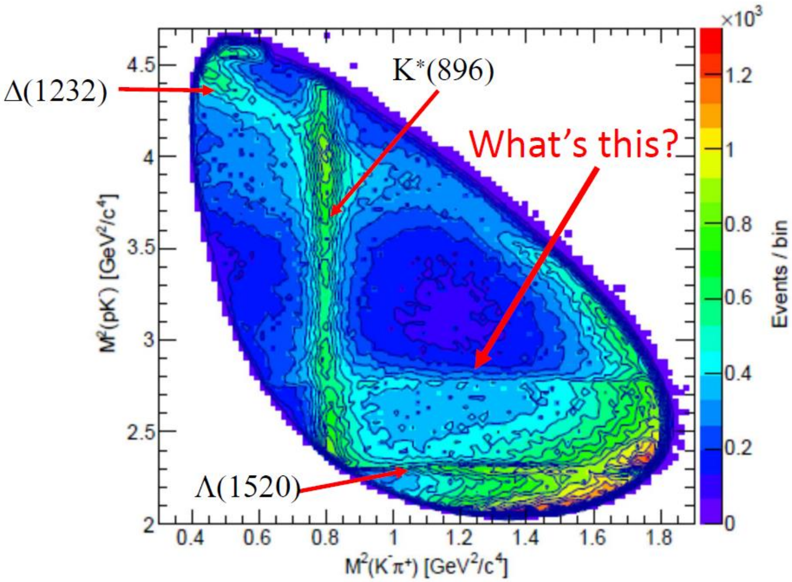
[PRL117, 011801]

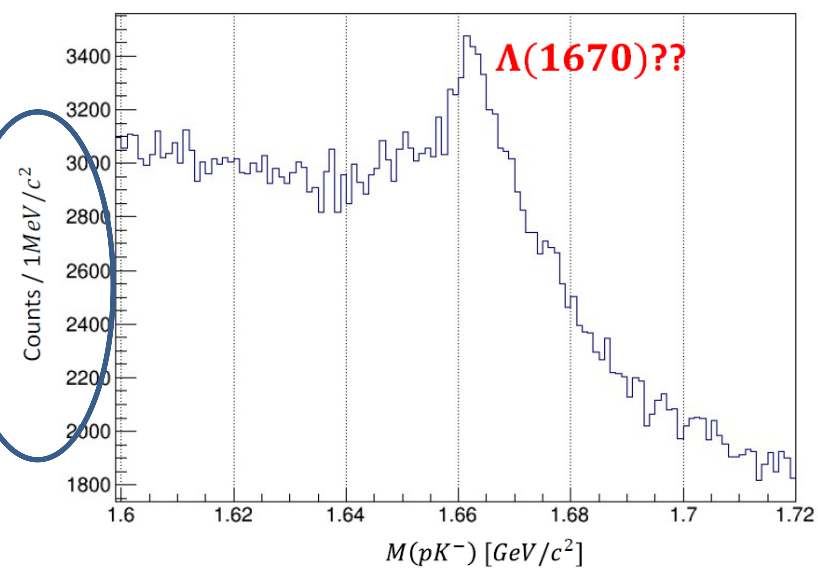
$$BR(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$$

The first observation of DCS decay in Baryon

A new Λ excited states ?

Dalitz plot: $\Lambda_c^+ \to pK^-\pi^+$ [PRL117.011801]





- The peak position is ~1663 MeV, near the Λη threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - Λ(1670): 25-50 MeV
  - Σ(1660): 40-200 MeV
  - Σ(1670): 40-80 MeV
  - Λ(1690): ~60 MeV

- 2 independent groups claim there is a new narrow Λ^* resonance at this energy with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5±0.5 MeV, Γ=1.5±0.5 MeV
- The reason is the same
  - From K^-p → Λη measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
  - Especially the angular distribution → Model independent
- There is no state in quark models
  - It must be an exotic
  - $uds s\bar{s}$ pentaquark??

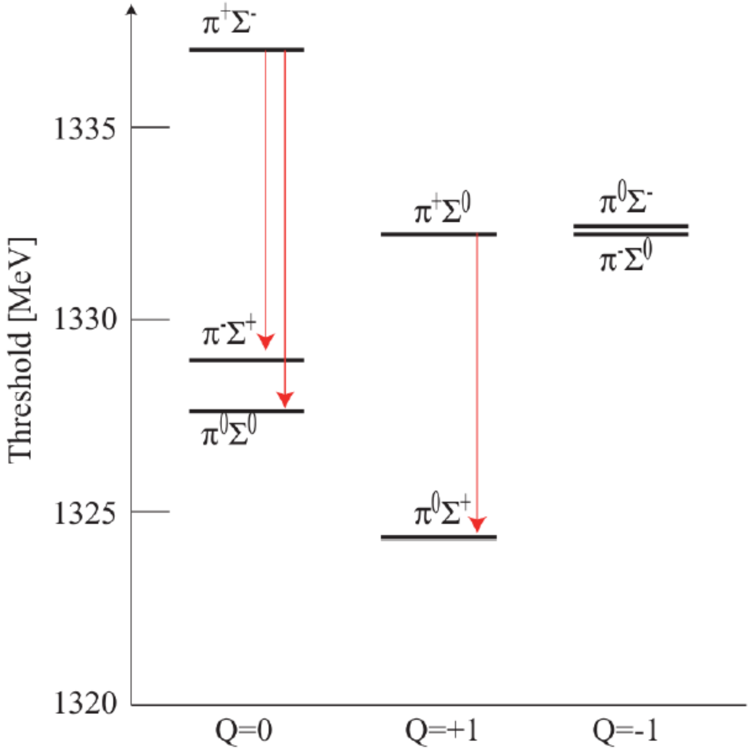
$\Lambda_c \to \Sigma\pi\pi$ decays at Belle

NEW

- Motivation: Measure the $\Sigma\pi$ scattering lengths based on "Cabibbo's method", T. Hyodo and M. Oka, Phys. Rev. C84, 035201 (2011)
- **This talk**: Measure the $\mathcal{B}(\Sigma\pi\pi)$ relative to $pK^-\pi^+$ + int. resonances.

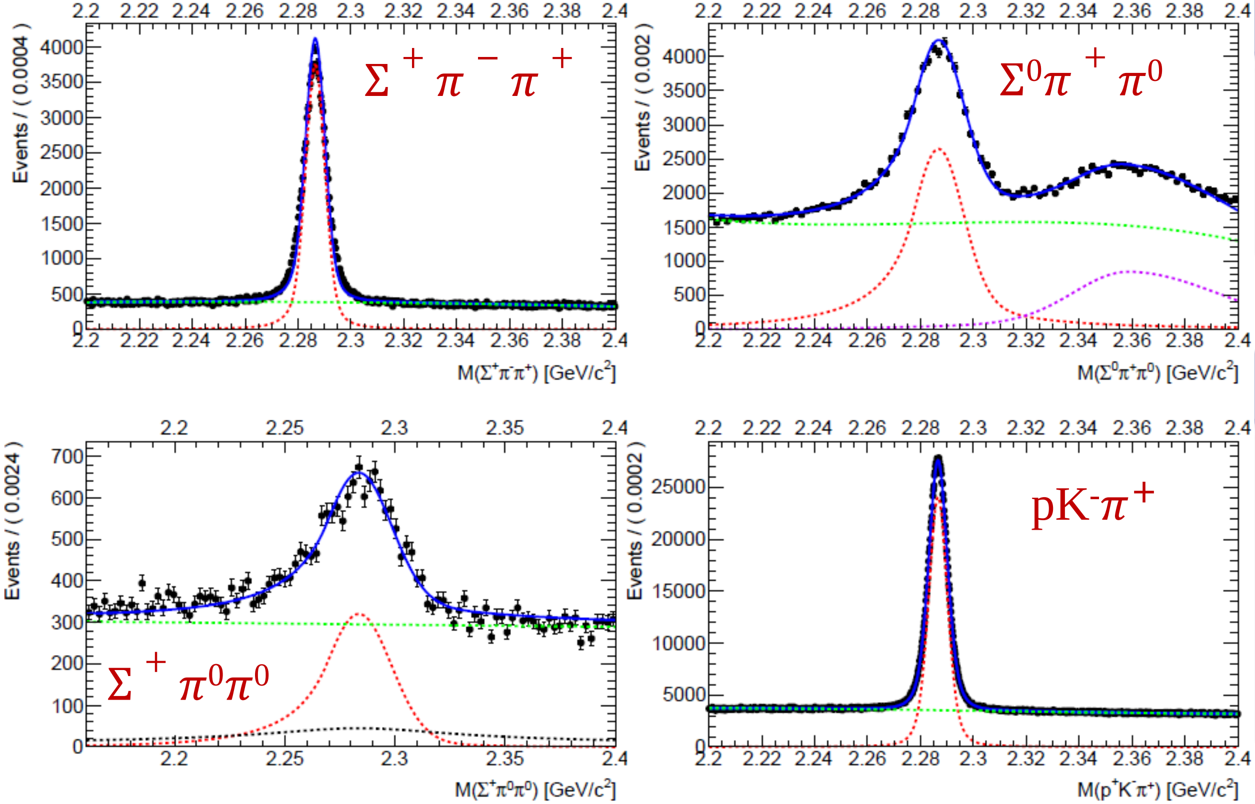
$$\Lambda_c \to \Sigma^+\pi^-\pi^+ (4.57 \pm 0.29\%)^*$$
$$\Lambda_c \to \Sigma^0\pi^+\pi^0 (2.3 \pm 0.9\%)^*$$
$$\Lambda_c \to \Sigma^+\pi^0\pi^0 (\text{unknown})$$

Energy difference of $\Sigma\pi$ under final state charge exchange.



* C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

$\Lambda_c \to \Sigma\pi\pi$ decays at Belle



MC studies

NEW

Shape determination

Consistency tests

Model uncertainty

Λ_c in 711 fb^{-1} at $\Upsilon(4S)$

Final state	Yield
$\Sigma^+\pi^-\pi^+$	$100,208 \pm 369$
$\Sigma^+\pi^0\pi^0$	$5,951 \pm 261$
$\Sigma^0\pi^+\pi^0$	$46,995 \pm 413$
$p^+K^-\pi^+$	$1,182,781 \pm 1,351$

Signal: red, background: green, misreconstructed: black, $\Lambda^0\pi^+\pi^0 + \gamma$: violet

Errors are in order stat., sys. and $(\mathcal{B}(pK\pi))$.

arXiv:1802.03421

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

Observation of Pc states at LHCb

LHCb: PRL115, 072001 (2015)

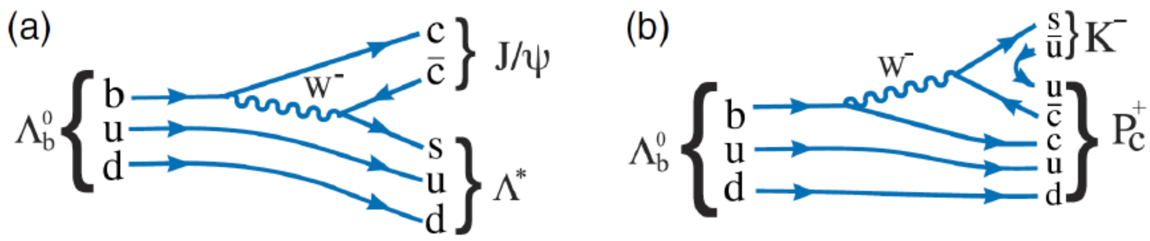
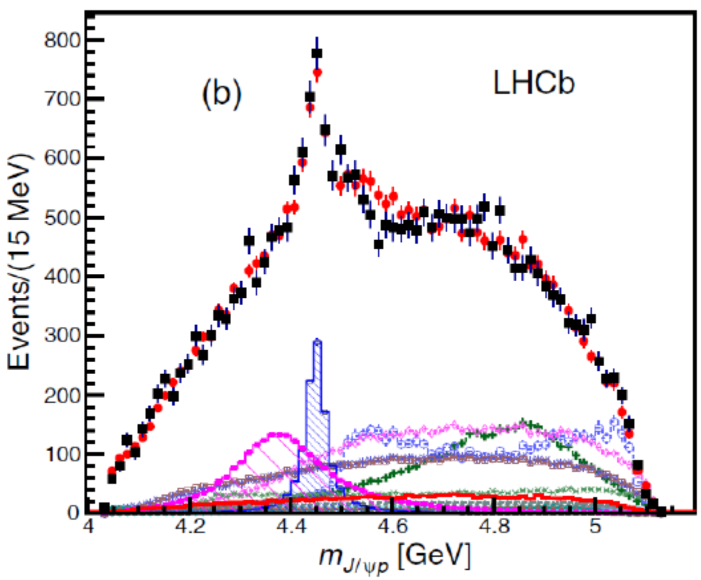
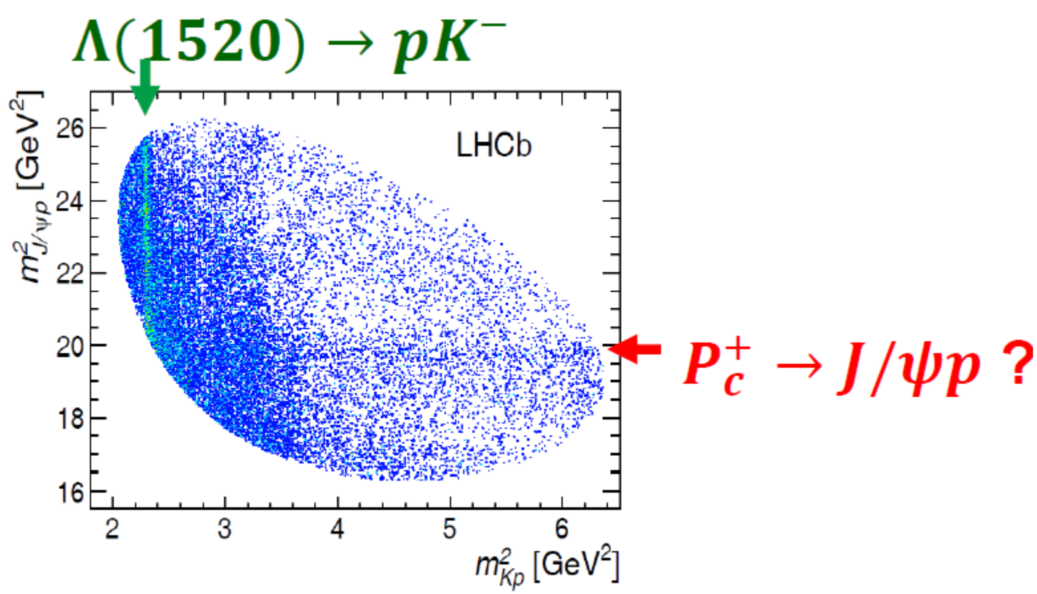


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

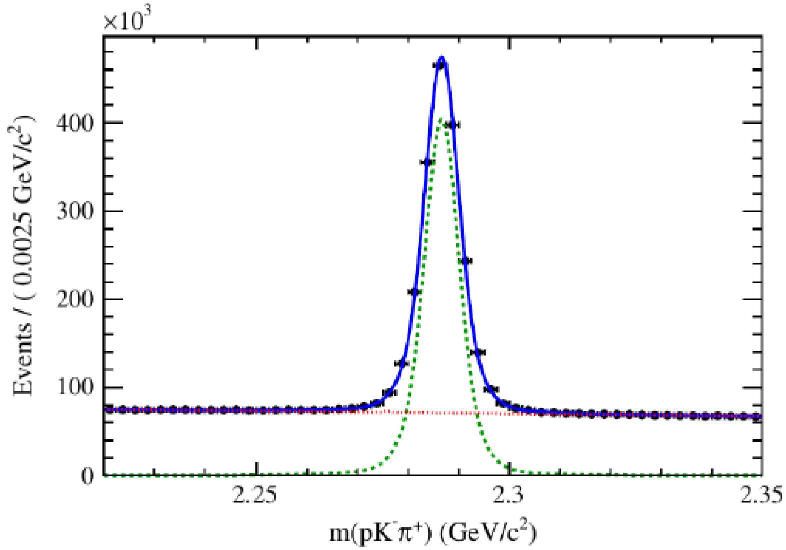


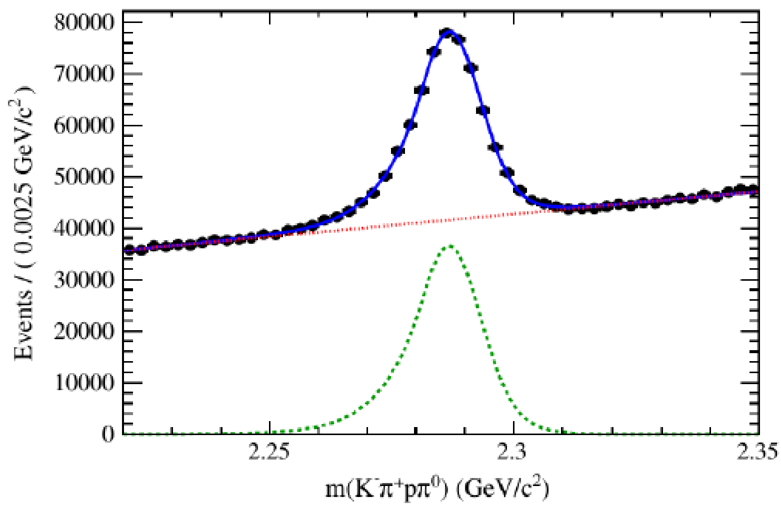


- Analogue search for hidden-strange pentaquark by switching $b \to c(\Lambda_b^0 \to \Lambda_c^+)$, $c \to s(J/\psi \to \phi)$: $\Lambda_c^+ \to \pi^0 P_s^+ \to \pi^0(\phi p)$.

Reference modes

- $\Lambda_c^+ \to \phi p \pi^0$ is Cabibbo-suppressed decay.
- $\Lambda_c^+ \to pK^-\pi^+$ is used for reference, and the Cabibbo-favored decay $\Lambda_c^+ \to K^-\pi^+ p\pi^0$ is measured.





- $\frac{\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p\pi^0)}{\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p)} = (0.685 \pm 0.007 \pm 0.018)$
- Most precise measurement: $\mathcal{B}(\Lambda_c^+ \to K^-\pi^+ p\pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%$
- Previous measurement from BESIII: $(4.53 \pm 0.23 \pm 0.30)\%$

B. Pal *et al.*, Phys.Rev.D96, 051102(R)(2017)

Search for Ps states at Belle

Phys.Rev.D96, 051102(R)(2017)

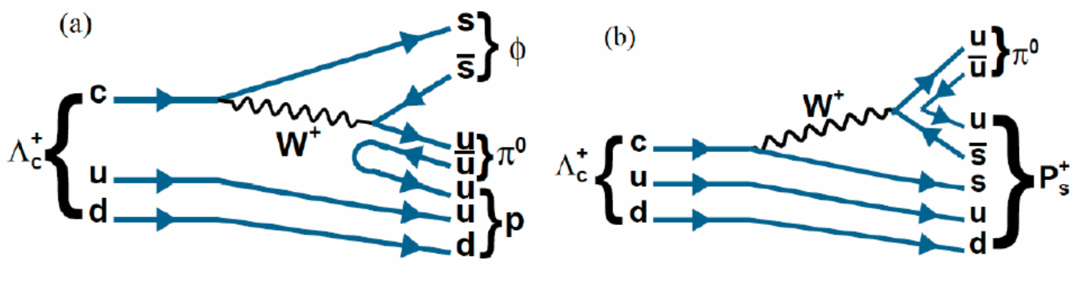
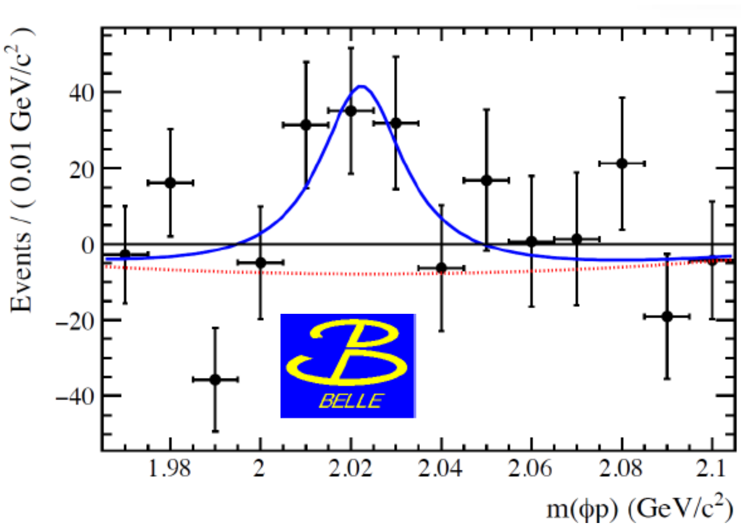


FIG. 1. Feynman diagram for the decay (a) $\Lambda_c^+ \to \phi p \pi^0$ and (b) $\Lambda_c^+ \to P_s^+ \pi^0$.



Perform 2D fit to $M_{K^+K^-p\pi^0}$ vs $M_{K^+K^-}$ plane.

$\Sigma^+ \to p\pi^0$ vetoed

- **No significant Ps signal**
- **Best fit yields a peak at M=(2025±5) MeV/c^2 and Γ=(22±12) MeV**

PRD96, 051102(R) (2017); 915fb^{-1}

Number of candidate $\Lambda_c \to P_s\pi^0 \to \phi p\pi^0$ events: 77.6±28.1

$B(\Lambda_c \to P_s\pi^0) x B(P_s \to \phi p) < 8.3x10^{-5}$ @90% C.L.

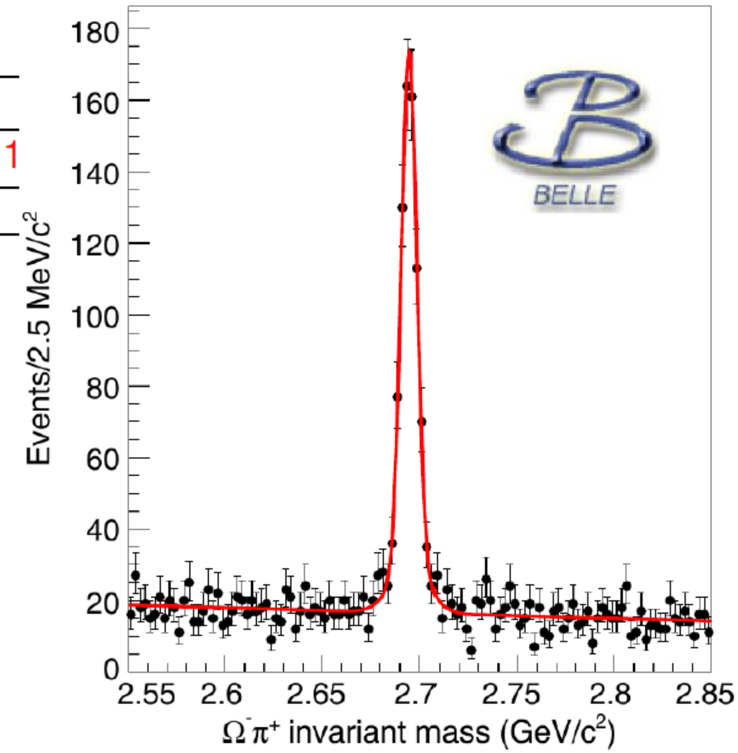
Hadronic decays of Ω_c

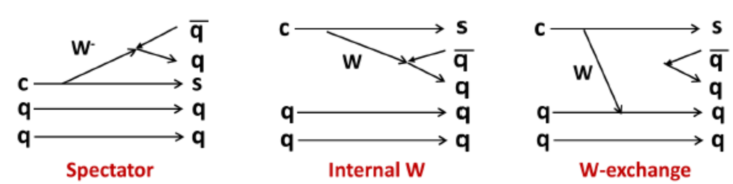
- Among 4 ground state charmed baryons, $\Omega_c(css)$ is not studied well as cross section is small.

State	Λ_c^+	Ξ_c^0	Ξ_c^+	Ω_c
$\tau(ps)$	200 ± 6	112^{+13}_{-10}	442 ± 26	69 ± 1
$\Delta\tau/\tau$ (%)	3	1	6	17

- Only Ω_c has the same flavor light quarks (ss). Constructive interference is thought to be the origin of its short life time.
- Precise measurements will shed light on the dynamics of baryon weak decays.
- Belle performed measurements of 8 decay modes relative to the bench mark mode: $\Omega^-\pi^+$.
  - Most precisements: $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^-\pi^+$, $\Xi^-K^-\pi^+\pi^+$, and $\Xi^0K^-\pi^+$.
  - First measurements: $\Xi^-\bar{K}^0\pi^+$, $\Xi^0\bar{K}^0$ and $\Lambda\bar{K}^0\bar{K}^0$.

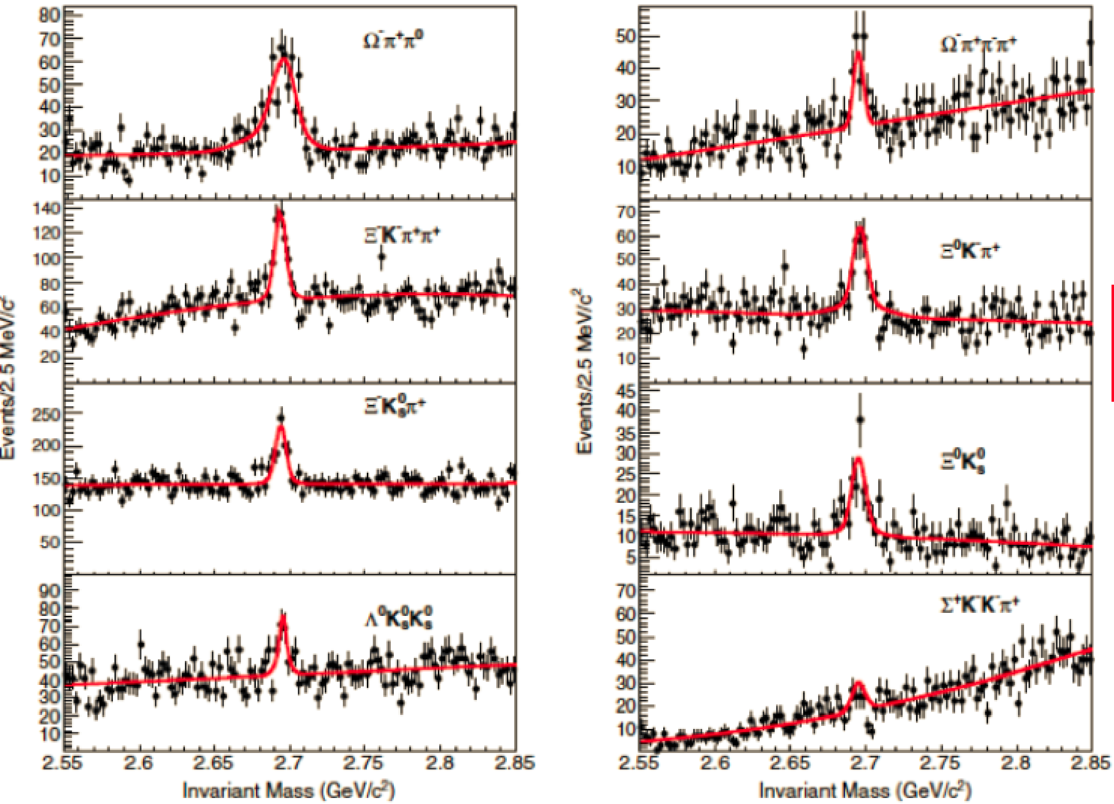
$\Omega_c^0 \to \Omega^-\pi^+$





Ω_c branching fractions

PRD97,032001(2018)



Mode	Signal yield	Order of polynomial	Resolution (MeV/c^2)	Efficiency (%)
$\Omega^-\pi^+$	691 ± 29	1	5.1	10.08
$\Omega^-\pi^+\pi^0$	403 ± 31	2	13.3	2.95
$\Omega^-\pi^+\pi^-\pi^+$	108 ± 16	1	4.4	5.23
$\Xi^-K^-\pi^+\pi^+$	278 ± 27	2	4.3	5.98
$\Xi^0K^-\pi^+$	168 ± 21	1	7.8	2.09
$\Xi^-K^0_S\pi^+$	349 ± 36	1	4.6	4.81
$\Xi^0K^0_S$	98 ± 15	2	7.0	1.73
$\Lambda K^0_SK^0_S$	95 ± 18	1	3.7	3.22
$\Sigma^+K^-K^-\pi^+$	17 ± 8	2	3.8	2.00

Three modes are new measurements.

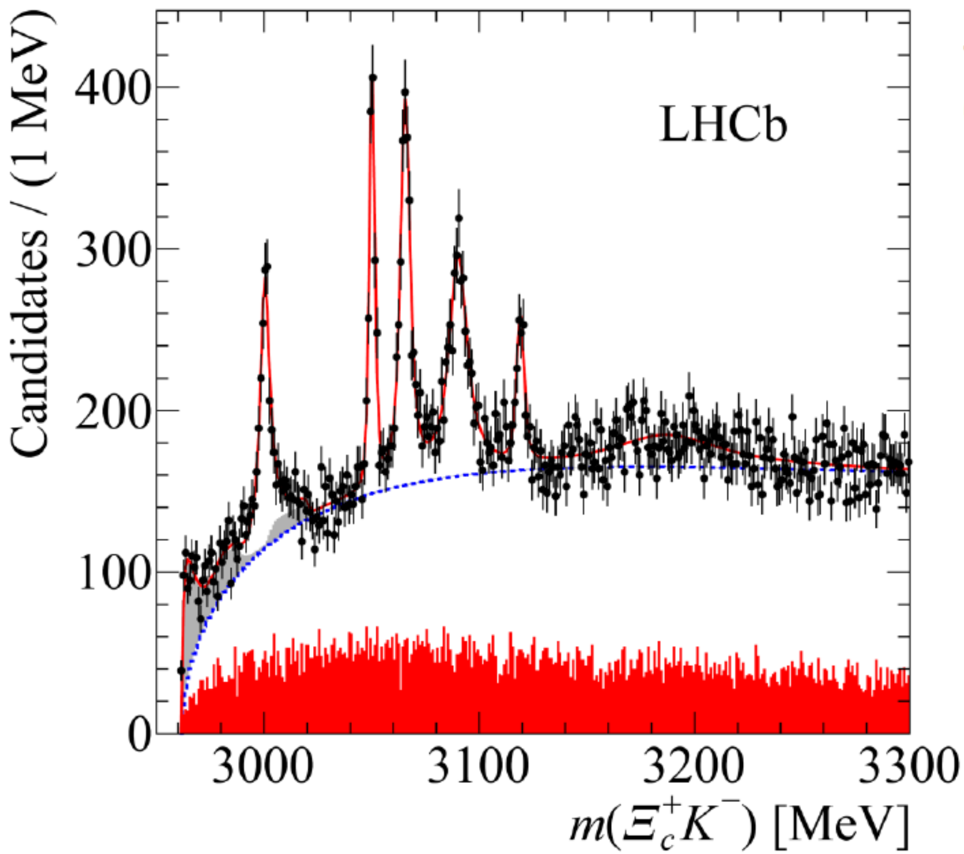
- Precision improved by factor 2 for already measured modes.
- First measurements of intermediate resonances.
  - Dominant contributions.
- Three first observations.

Observation of excited Ωc states at LHCB

Orbitally excited Ω_c cannot decay to $\Omega^-\pi^+$, therefore $\Xi_c^+K^-$ is a good place to look.

Earlier this year, LHCb did exactly that:

PRL118, 182001(2017)



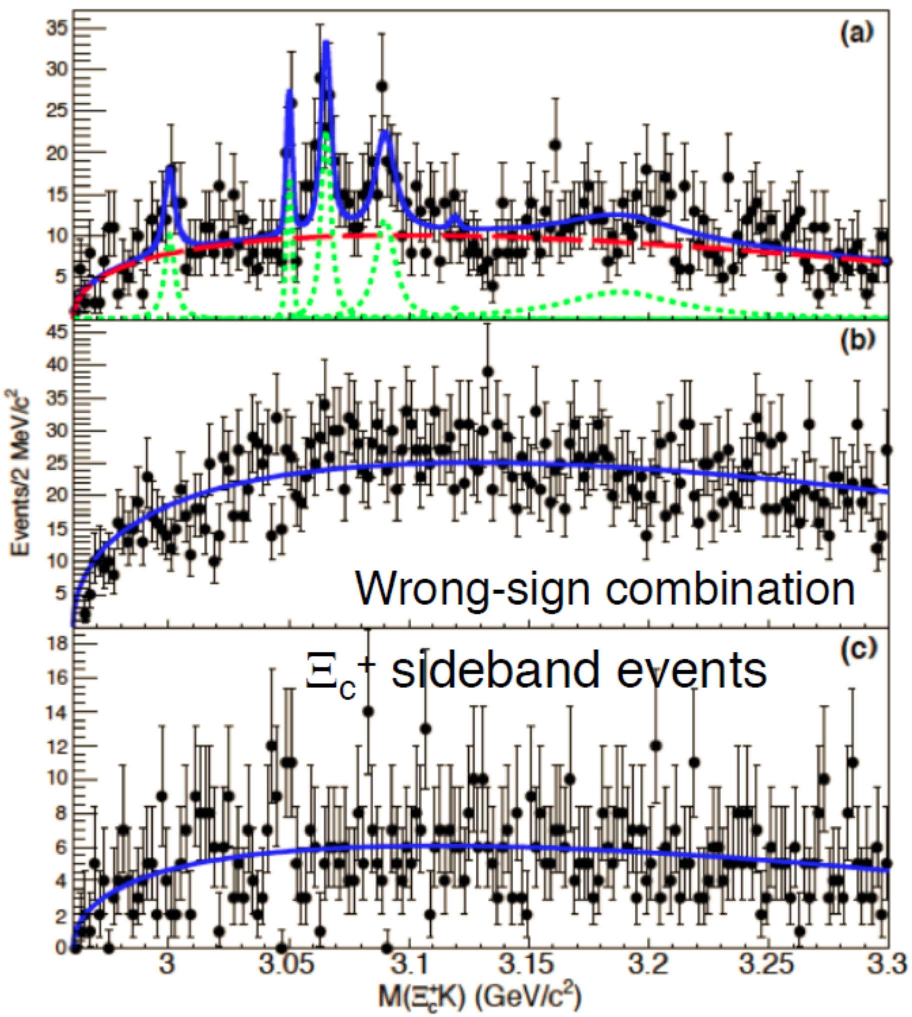
5 Narrow states
(+ possibly one wide one)

BELLE can do the same!

We can identify kaons with good efficiency. Cut at high momentum ($x_p > 0.75$)

Confirmation of excited Ωc states at Belle

PRD97, 051102 (2018)



In $\Xi_c^+K^-$ mass spectrum, peaks at 3000, 3050, 3066 and 3090 MeV, 3119 MeV is not significant.

Four narrow states out of five reported from LHCb confirmed.

Confirmation of excited Ωc states at Belle

PRD97, 051102 (2018)

- The masses and intrinsic widths of all six are fixed to the values given by LHCb
- Strong confirmation of $\Omega_c^0(3066)$ and $\Omega_c^0(3090)$
- confirmation of $\Omega_c^0(3000)$ and $\Omega_c^0(3050)$
- No confirmation of $\Omega_c^0(3119)$ (but no disagreement due to the small statistics)
- confirmation of wide excess at higher mass.

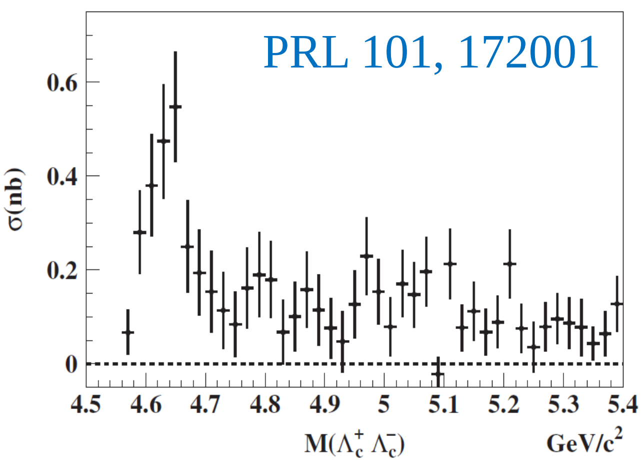
Unit: MeV/c^2

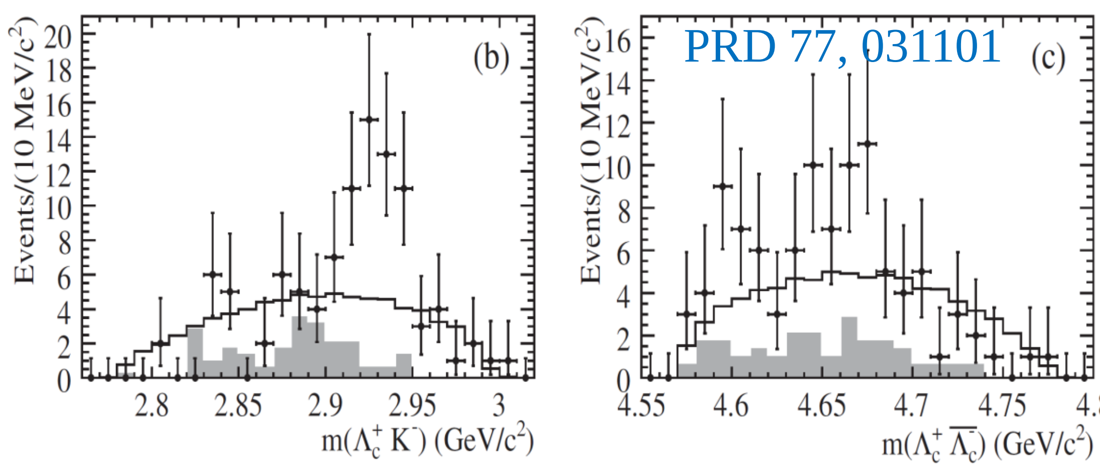
Ω_c Excited State	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188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

- Alternatively, the masses of the five signals are measured by fitting the same distribution without constraining the masses.
- In all cases, the results are consistent with the LHCb values.

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

- Belle reported a structure, called X(4630), in the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass distribution in $e^+e^- \to \gamma_{ISR}\Lambda_c^+\bar{\Lambda}_c^-$ PRL 101, 172001
- BarBar once studied $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$ and found two small peaks in $M_{\Lambda_c^+\bar{\Lambda}_c^-}$ spectrum and a vague structure named $\Xi_c(2930)$ is seen in the distribution of $M_{K\,\Lambda_c}$. Larger data is needed to verify them. PRD 77, 031101
- Also, some theory explained that Y(4660) has a large partial decay width to $\Lambda_c^+\bar{\Lambda}_c^-$ and it's isospin partner Y(4616) is predicted. PRD 82, 094008; PRL102, 242004





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

$\Xi_c(2930)$ *

CHARMED BARYONS
($C = +1$)

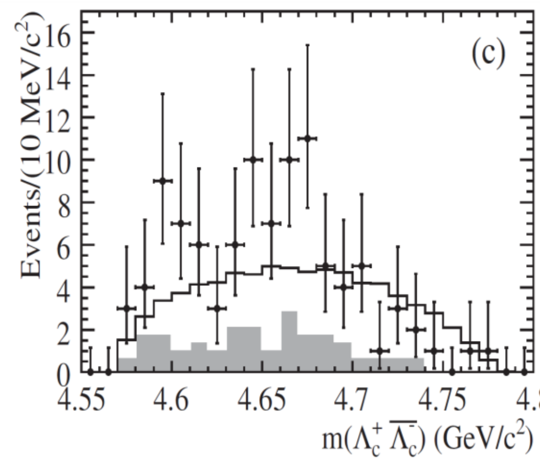
$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$, $\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

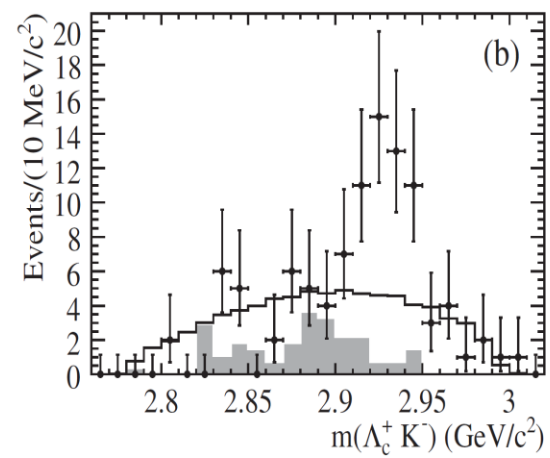
$\Xi_c(2930)$ $I(J^P) = ?(?^?)$

A peak seen in the $\Lambda_c^+ K^-$ mass projection of $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ events.

$\Xi_c(2930)$ MASS	2931 ± 6 MeV
$\Xi_c(2930)$ WIDTH	36 ± 13 MeV

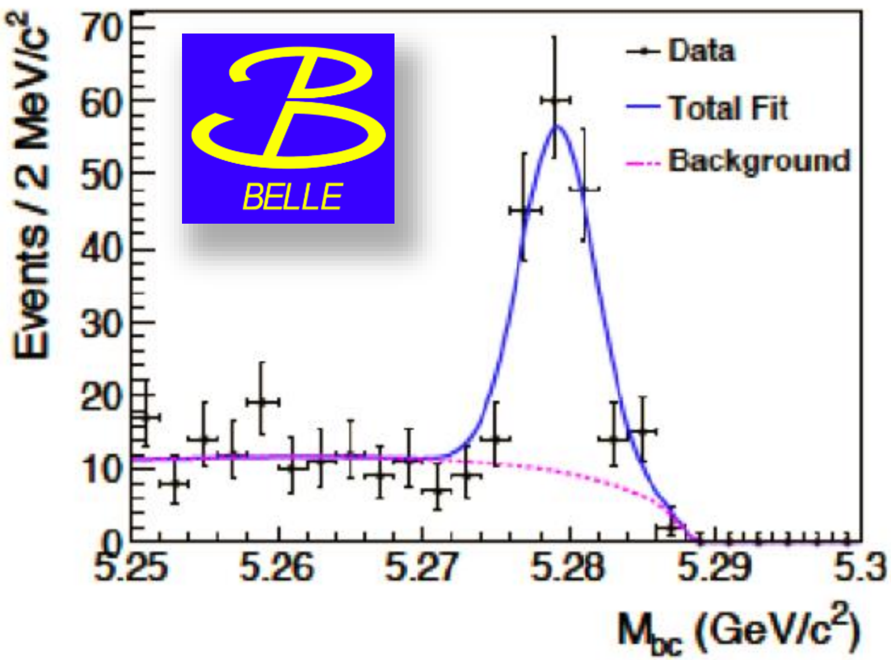
tion for experimental resolution, we obtain $m = 2931 \pm 3(\text{stat}) \pm 5(\text{syst})\ \text{MeV}/c^2$ and $\Gamma = 36 \pm 7(\text{stat}) \pm 11(\text{syst})$ MeV. We do not see any such structure in the m_{ES} sideband region. This description is in good agreement with the data (χ^2 probability of 22%) and could be interpreted as a single Ξ_c^0 resonance with those parameters, though a more complicated explanation (e.g. two narrow resonances in close proximity) cannot be excluded.

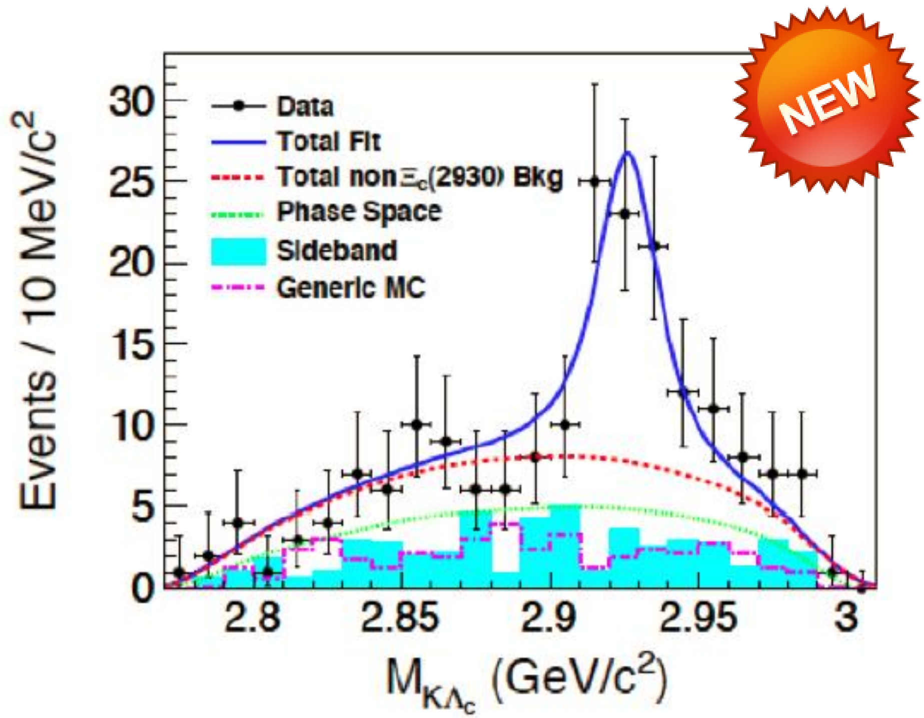




Observation of $\Xi_c(2930)^0$ in $B^+ \to K^+ \Lambda_c^+ \overline{\Lambda}_c^-$ at Belle

Eur. Phys. J. C78, 252 (2018)





153±14 B decay signal events.
$Br(B^+ \to \Lambda_c^+ \Lambda_c^- K^+) = (4.80 \pm 0.43 \pm 0.68) \times 10^{-4}$

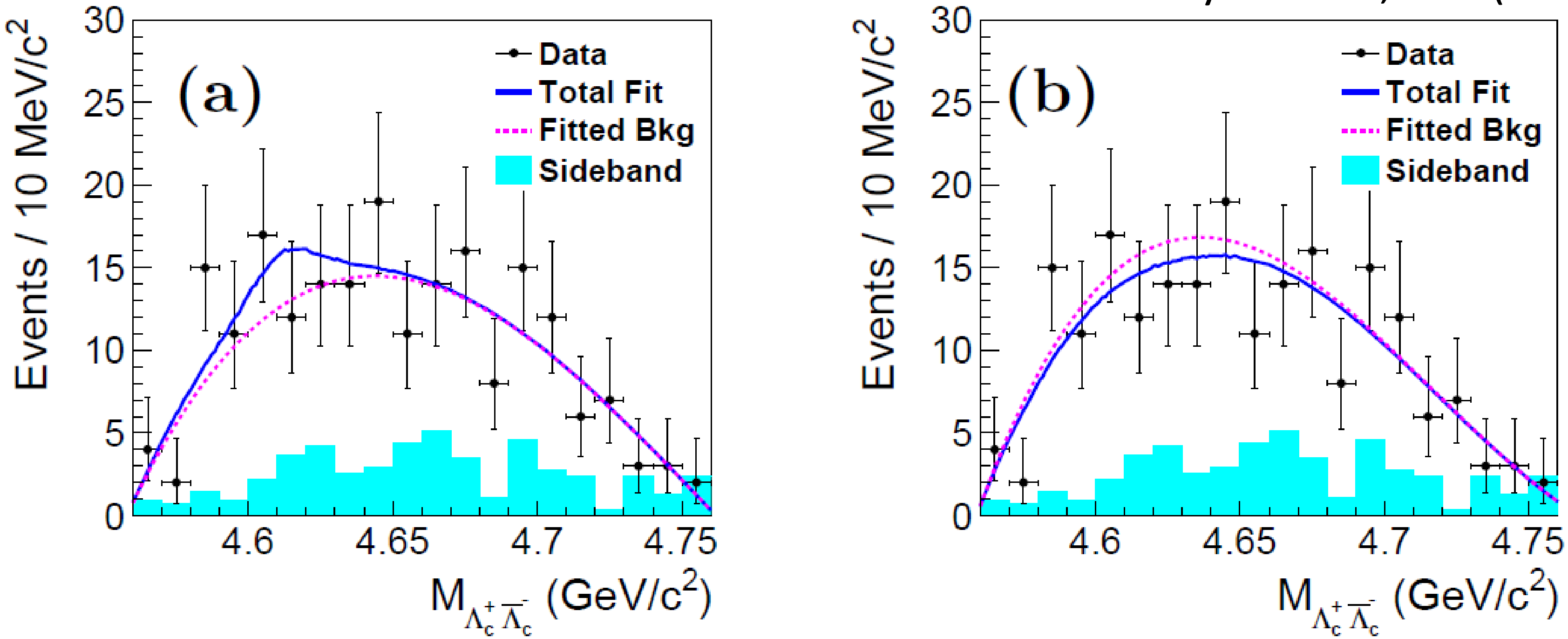
$\Xi_c(2930)^0 \to \Lambda_c^+ K^-$ 61±16 events
5.1σ significance

Clear confirmation for the BaBar claim, PRD77,031101(2008) and much more precise M=2928.9±3.0 +0.8/-12.0 MeV, Γ=19.5±8.4 +5.4/-7.9 MeV

- $\Xi_c(2930)^0 = csd$ is the first charmed-strange baryon established in B decay.

Search for Y(4660) and its spin part in $B^+ \to K^+\Lambda_c^+\overline{\Lambda}_c^-$ at Belle

Eur. Phys. J. C78, 252 (2018)

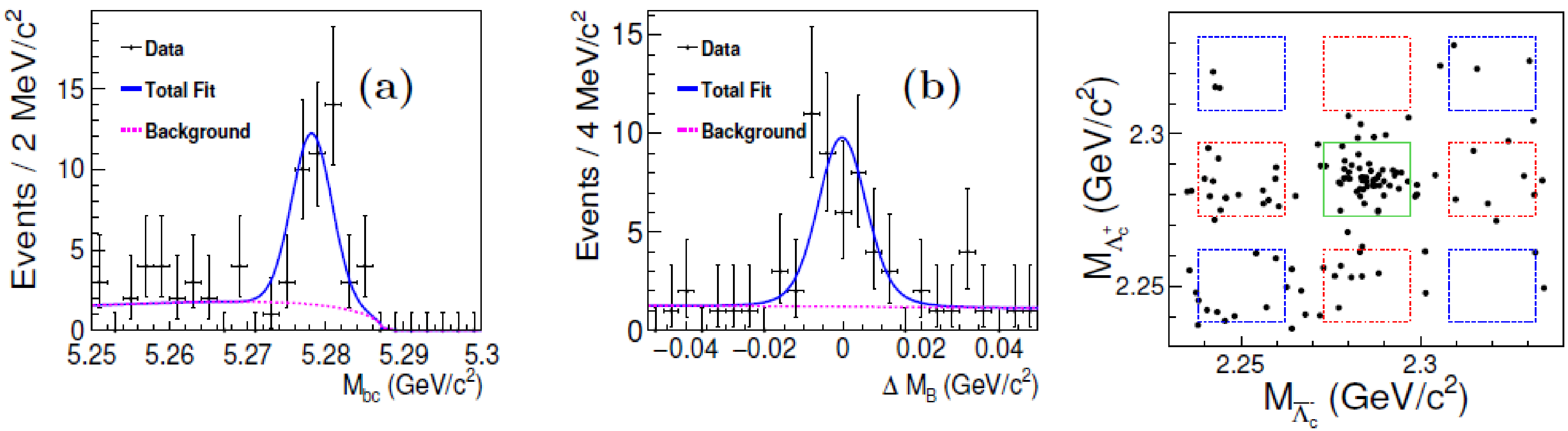


- No Y(4660) and its spin partner Y_η were observed. in the $\Lambda_c^+\overline{\Lambda}_c^-$ invariant mass distribution
- 90% C.L. upper limits of $B^+ \to K^+Y(4660) \to K^+\Lambda_c^+\overline{\Lambda}_c^-$ and $B^+ \to K^+Y_\eta \to K^+\Lambda_c^+\overline{\Lambda}_c^-$ are 1.2×10^{-4} and 2.0×10^{-4}.

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

Eur. Phys. J. C 78, 928 (2018)

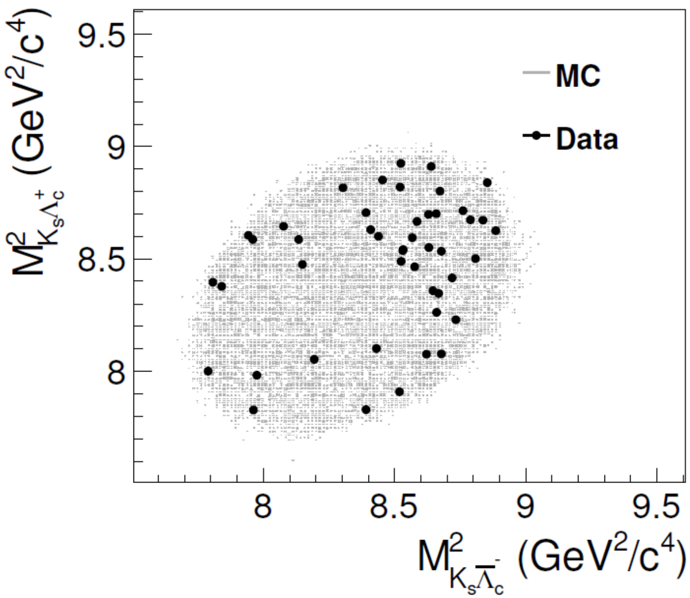
- Based on full $\Upsilon(4S)$ data set (772 M $B\bar{B}$ pairs) at Belle
- Three Λ_c decay channels:
  $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_s(\pi^+\pi^-)$ and $\Lambda_c^+ \to \Lambda(p\pi^-)\pi^+$.
- B candidates extracted via 2D fit to M_{bc} and ΔM_B

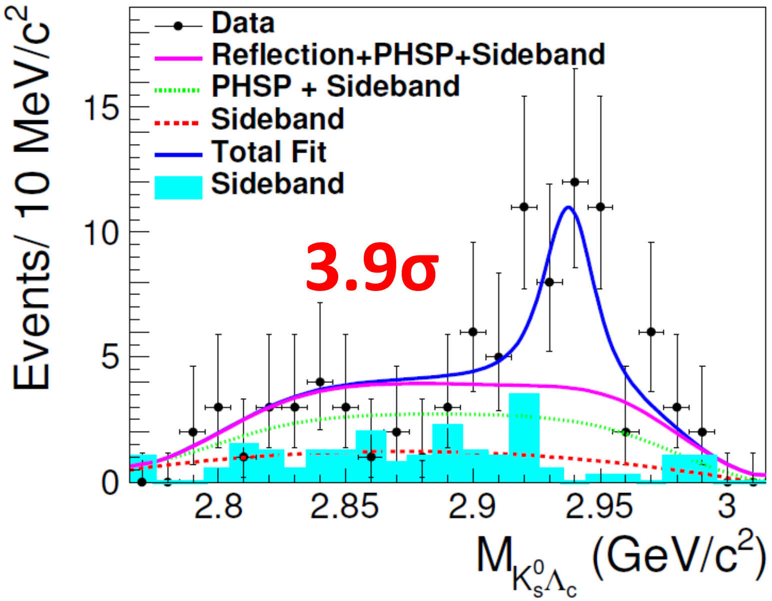


- Quite clear $\Lambda_c^+ \bar{\Lambda}_c^-$ signals and B^0 signals.
  - $N^{\text{sig}} = 34.9 \pm 6.6$ with a statistical signal significance above 8.3σ
  - $\mathcal{B}(\bar{B}^0 \to \bar{K}^0 \Lambda_c^+ \bar{\Lambda}_c^-) = [3.99 \pm 0.76(\text{stat.}) \pm 0.51(\text{syst.})] \times 10^{-4}$

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

- Charged $\Xi_c(2930)$ extracted by fitting $M_{K_S^0 \Lambda_c}$

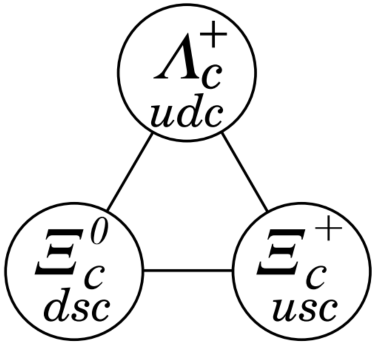




- $N_{\Xi_c^\pm} = 21.2 \pm 4.6$, stat. significance 4.1σ
- $M_{\Xi_c^\pm(2930)} = 2942.3 \pm 4.4 \pm 1.5$ MeV$/c^2$
- $\Gamma_{\Xi_c^\pm(2930)} = 14.8 \pm 8.8 \pm 2.5$ MeV

Measurements of absolute Brs of Ξ_c^0

- Weak decays of charmed hadrons play an unique role in the study of strong interaction； the charmed-baryon sector also offers an unique and excellent laboratory for testing heavy-quark symmetry and light-quark chiral symmetry.
- For the charmed baryons of the SU(3) anti-triplet, only Λ_c absolute Brs were measured by Belle [PRL113,042002(2014), first time] and BESIII [PRL116,052001(2016)]
- Since Ξ_c^0 [PRL62,863(1989)] and Ξ_c^+[PLB122,455 (1983)] were discovered ~30 years ago, no absolute Brs could be measured.



- For Ξ_c^0, the Brs are all measured with ratios to the $\Xi^-\pi^+$, the so called reference mode.

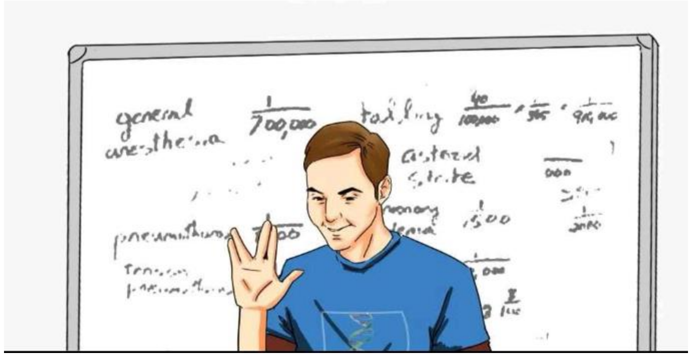
Measurements of absolute Brs of Ξ_c^0

- Theory: $B(\Xi_c^0 \to \Xi^-\pi^+)$~1.3% [PRD48, 4188 (1993)], (2.24±0.34)% [JHEP03, 66(2018)].
- The $B(\Xi_c^0 \to \Lambda K^-\pi^+)$/ $B(\Xi_c^0 \to \Xi^-\pi^+)$ = 1.07 ± 0.12± 0.07 and $B(\Xi_c^0 \to pK^-K^-\pi^+)$/ $B(\Xi_c^0 \to \Xi^-\pi^+)$= 0.33 ± 0.03±0.03 [PLB 605,237]
- $\Xi_c^0 \to pK^-K^-\pi^+$ plays a fundamental role in lots of bottom baryons study at LHCb .
- How to measure Ξ_c^0 absolute Brs ? Model Independent !

$$\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) \equiv \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)}{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)},$$

$$\mathcal{B}(\Xi_c^0 \to \Lambda K^-\pi^+) \equiv \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0 \to \Lambda K^-\pi^+)}{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)}.$$

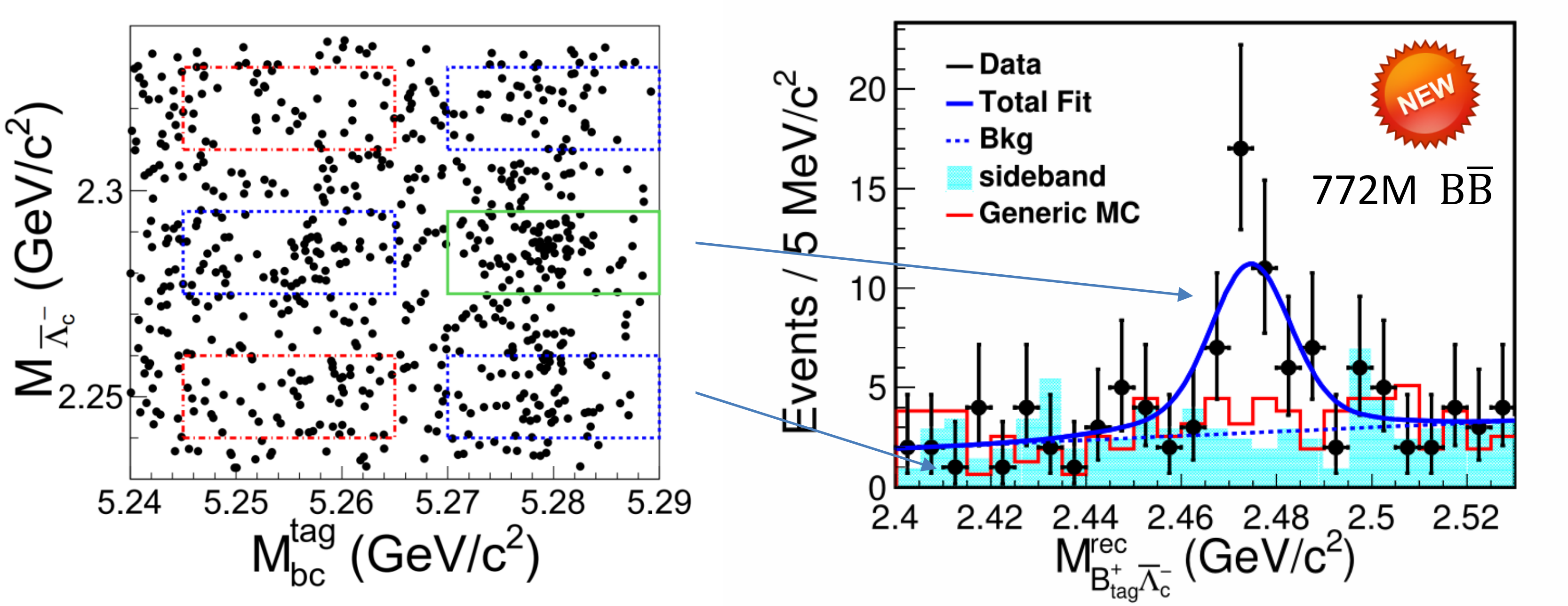
$$\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+) \equiv \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+)}{\mathcal{B}(B^- \to \bar{\Lambda}_c^-\Xi_c^0)}.$$



- For inclusive $B^- \to \bar{\Lambda}_c^-\Xi_c^0$, $\Xi_c^0 \to$anything, never measured before.
- For exclusive $B(B^- \to \bar{\Lambda}_c^-\Xi_c^0)$ $B(\Xi_c^0 \to \Xi^-\pi^+)$; $B(B^- \to \bar{\Lambda}_c^-\Xi_c^0)$ $B(\Xi_c^0 \to \Lambda K^-\pi^+)$, measured by Belle and BaBar with large errors.

Measurements of Br of $B^- \to \overline{\Lambda}_c^- \Xi_c^0$, $\Xi_c^0 \to$anything

- The $\overline{\Lambda}_c^-$ reconstructed via its $\bar{p}K^+\pi^-$ and $\bar{p}K_S^0$ decays arXiv:1811.09738
- A tagged B meson candidate, B_{tag}^+, is reconstructed using a neural network based on the full hadron-reconstruction algorithm



- An unbinned maximum likelihood fit: N(Ξ_c^0)=40.9 ±9.0, 5.5σ(stat.)
- B($B^- \to \overline{\Lambda}_c^- \Xi_c^0$, Ξ_c^0 →anything)= (9.51±2.10±0.88)×10^{-4} for the first time

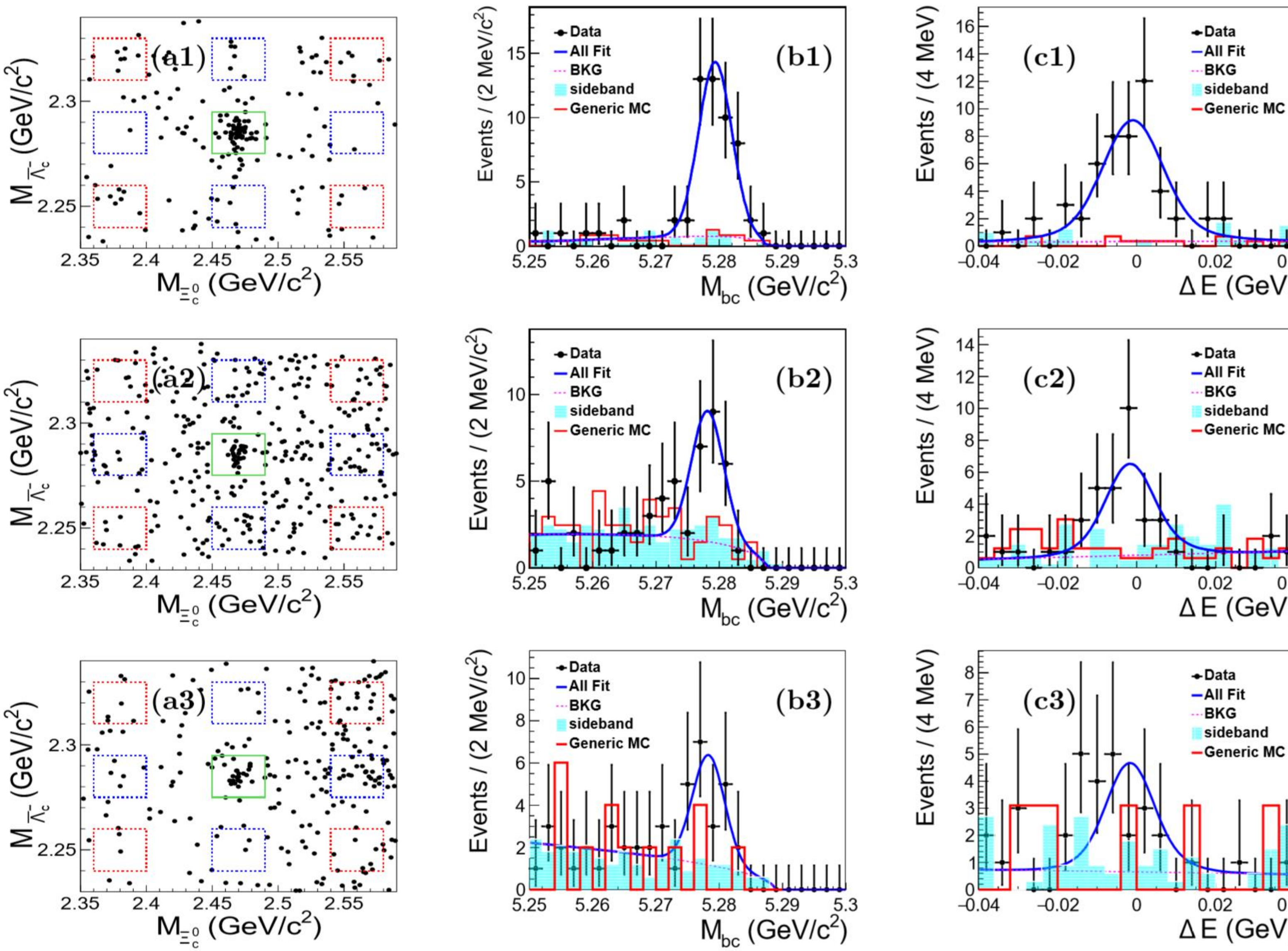
Measurements of Brs of $B^- \to \bar{\Lambda}_c^- \Xi_c^0$, with $\Xi_c^0 \to \Xi^-\pi^+$; $\Xi_c^0 \to \Lambda K^-\pi^+$; $\Xi_c^0 \to pK^-K^-\pi^+$

arXiv:1811.09738

$\Xi^-\pi^+$
44.8 ± 7.3
9.5σ

$\Lambda K^-\pi^+$
24.1 ±5.5
6.8σ

$pK^-K^-\pi^+$
16.6 ± 5.4
4.6σ



Measurements of absolute Brs of Ξ_c^0

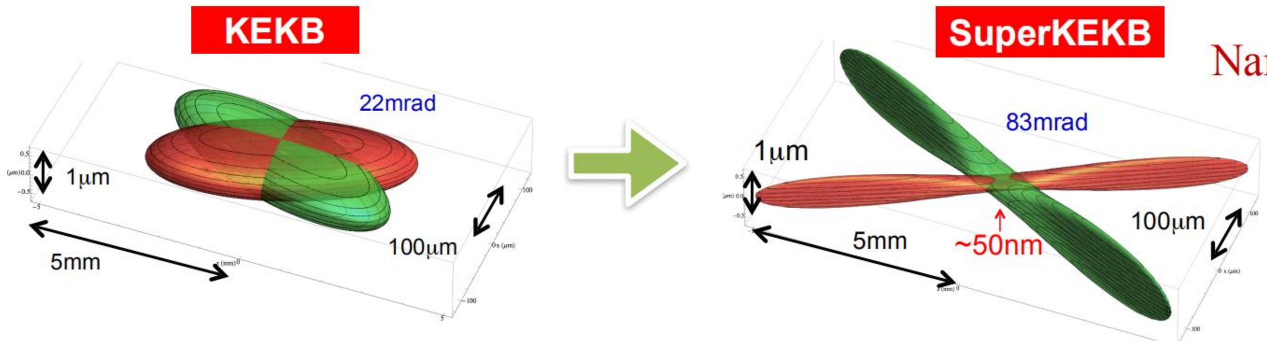
arXiv:1811.09738

Summary of the measured branching fractions and the ratios of Ξ_c^0 decays

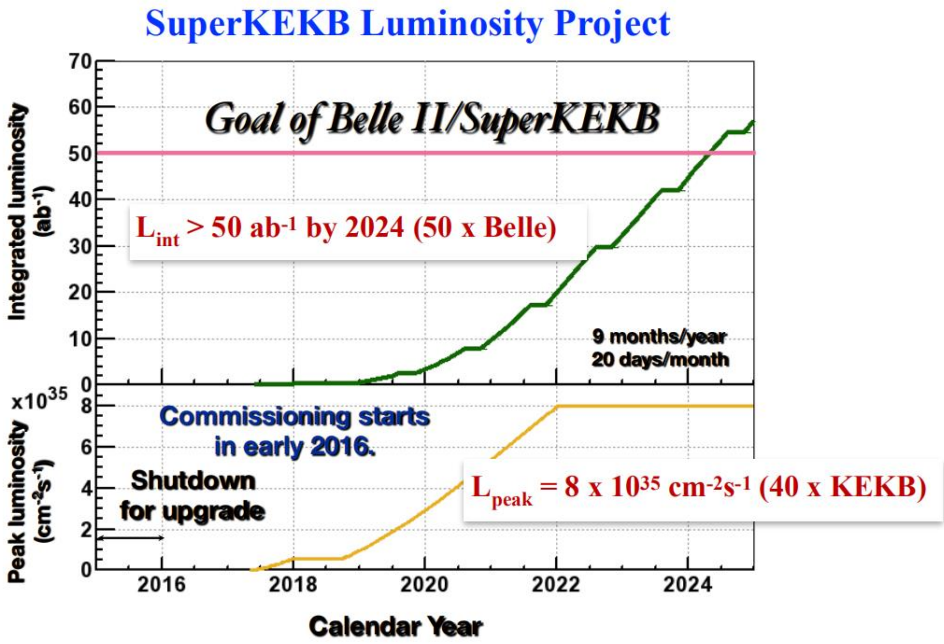
Channel	Br/Ratio	
$B(\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0)$	$(9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$	
$B(\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0)\, B(\Xi_c^0 \to \Xi^- \pi^+)$	$(1.71 \pm 0.28 \pm 0.15) \times 10^{-5}$	$(2.4 \pm 0.9) \times 10^{-5}$
$B(\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0)\, B(\Xi_c^0 \to \Lambda K^- \pi^+)$	$(1.11 \pm 0.26 \pm 0.10) \times 10^{-5}$	$(2.1 \pm 0.9) \times 10^{-5}$
$B(\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0)\, B(\Xi_c^0 \to p K^- K^- \pi^+)$	$(5.47 \pm 1.78 \pm 0.57) \times 10^{-6}$	
$B(\Xi_c^0 \to \Xi^- \pi^+)$	$(1.80 \pm 0.50 \pm 0.14)\%$	
$B(\Xi_c^0 \to \Lambda K^- \pi^+)$	$(1.17 \pm 0.37 \pm 0.09)\%$	PDG
$B(\Xi_c^0 \to p K^- K^- \pi^+)$	$(0.58 \pm 0.23 \pm 0.05)\%$	
$B(\Xi_c^0 \to \Lambda K^- \pi^+)/B(\Xi_c^0 \to \Xi^- \pi^+)$	$0.65 \pm 0.18 \pm 0.04$	1.07 ± 0.14
$B(\Xi_c^0 \to p K^- K^- \pi^+)/B(\Xi_c^0 \to \Xi^- \pi^+)$	$0.32 \pm 0.12 \pm 0.07$	0.34 ± 0.04

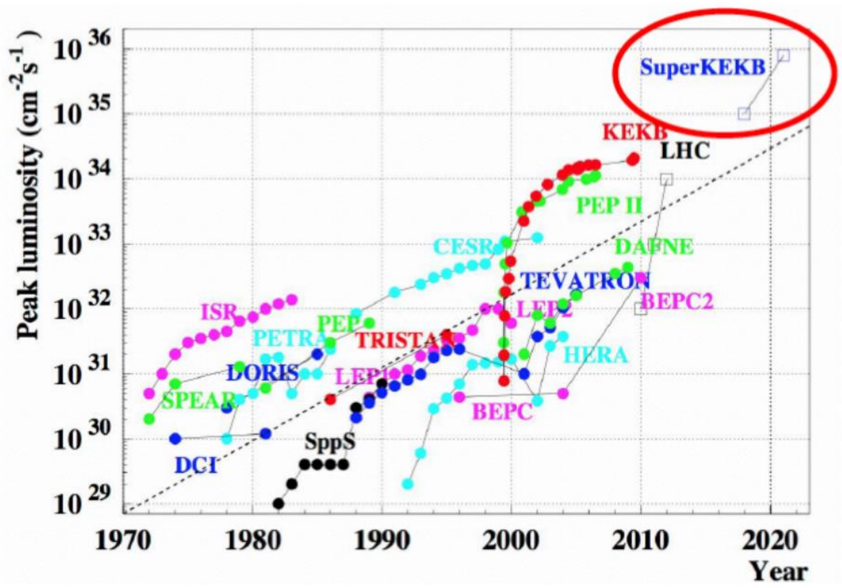
- We have performed an analysis of $\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0$ inclusively and exclusively
- First model-independent measurement of absolute Brs of Ξ_c^0 decays
- The branching fraction $B(\boldsymbol{B}^- \to \bar{\boldsymbol{\Lambda}}_c^- \Xi_c^0)$ is measured for the first time
- The measured $B(\Xi_c^0 \to \Xi^- \pi^+)$ can be used to determine the BR of other Ξ_c^0 decays.

SuperKEKB

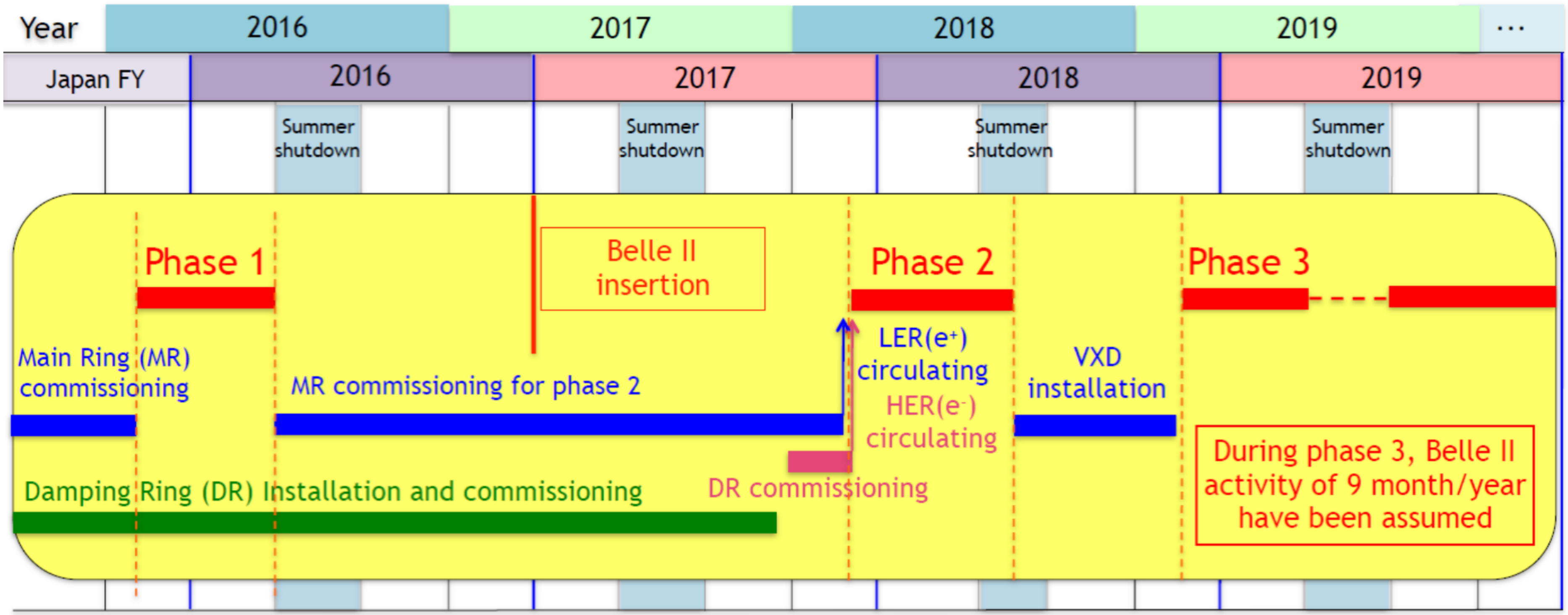


Nano-Beam Scheme



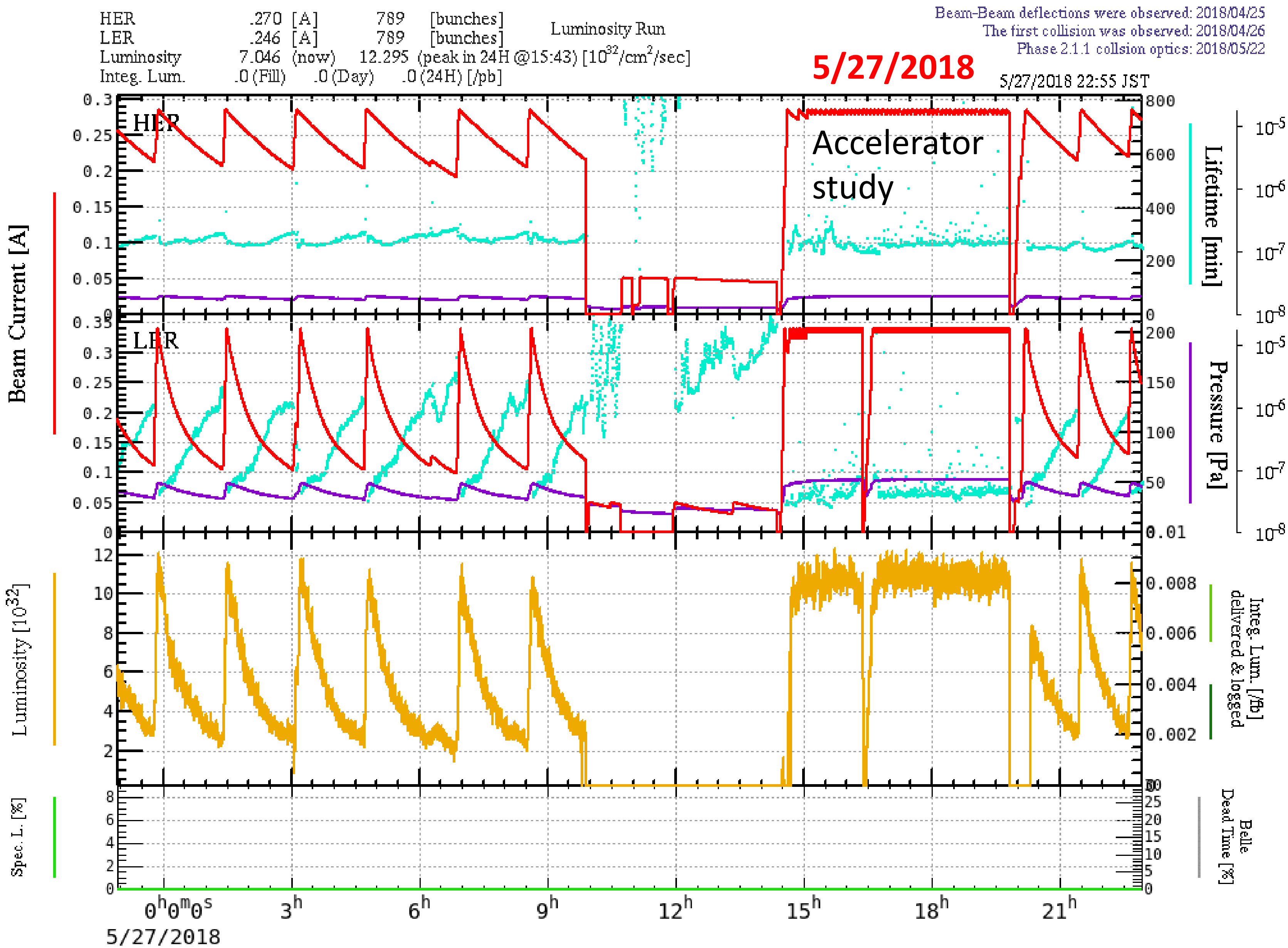


SuperKEKB and Belle II Schedule

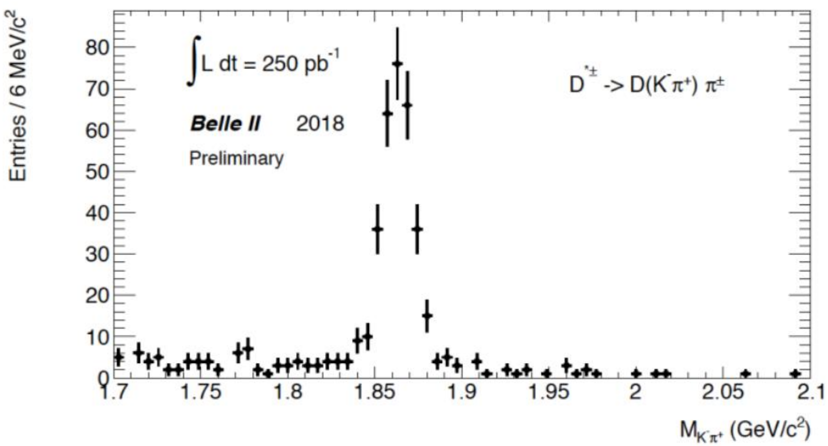


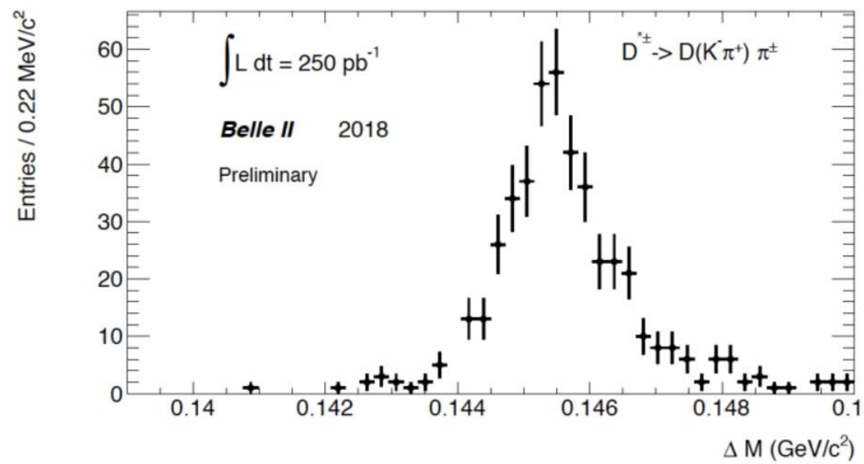
- ✅ Phase1, Feb.-June, 2016
  - Accelerator commissioning, no collision
- ✅ Phase2, Feb.-July 17, 2018
  - Collision w/o vertex detectors
  - Understand background and detector performance
  - Instantaneous luminosity reach ~0.5×10^{34} $cm^{-2}s^{-1}$
  - ~0.5 fb^{-1} data at the Y(4S) resonance was collected

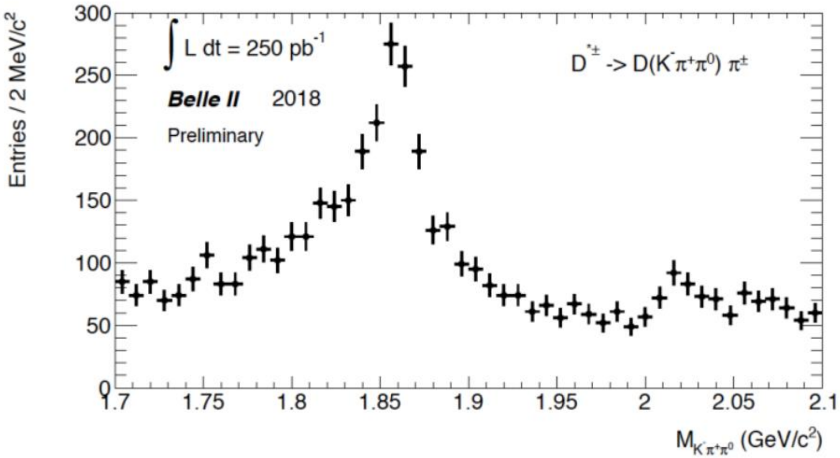
SuperKEKB operation status

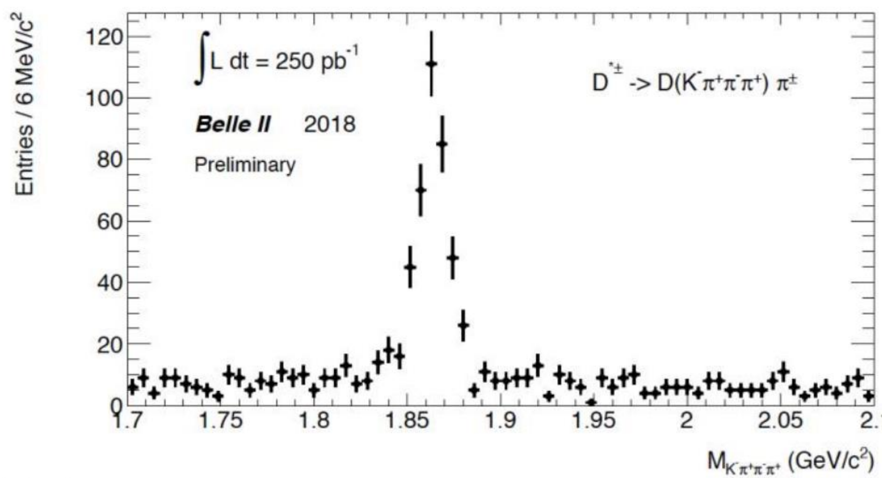


Belle II Performance





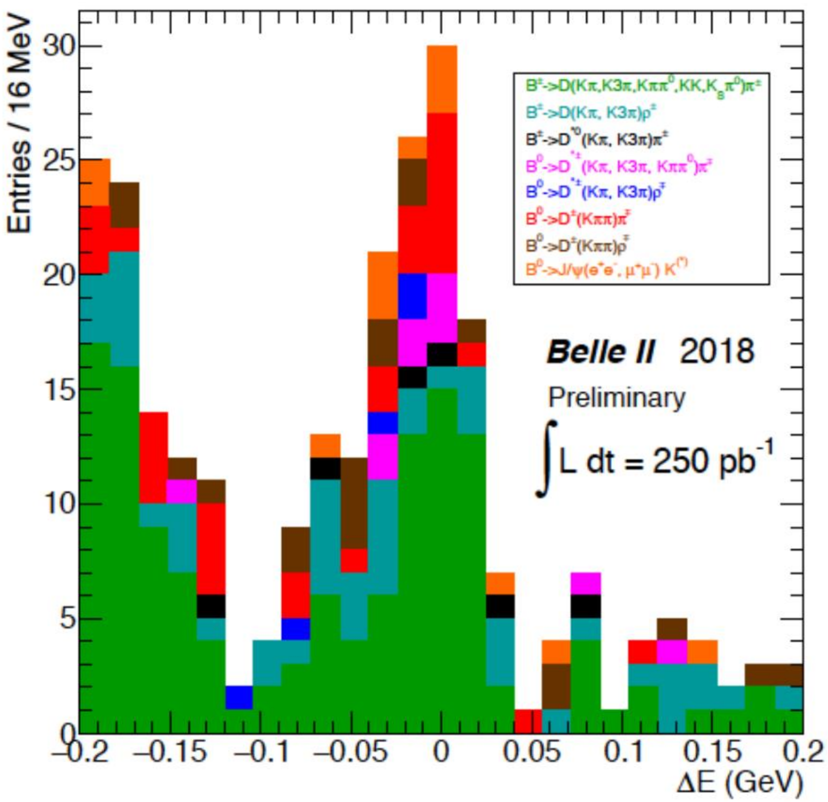


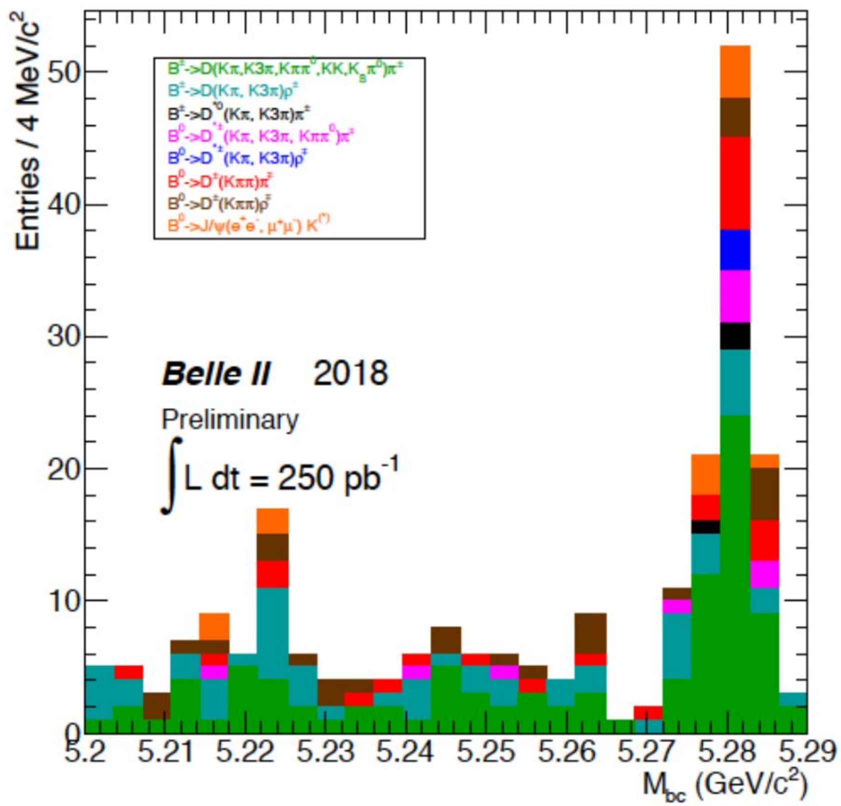


Clear charm signals e+e- → ccbar
Belle II detector is working well!

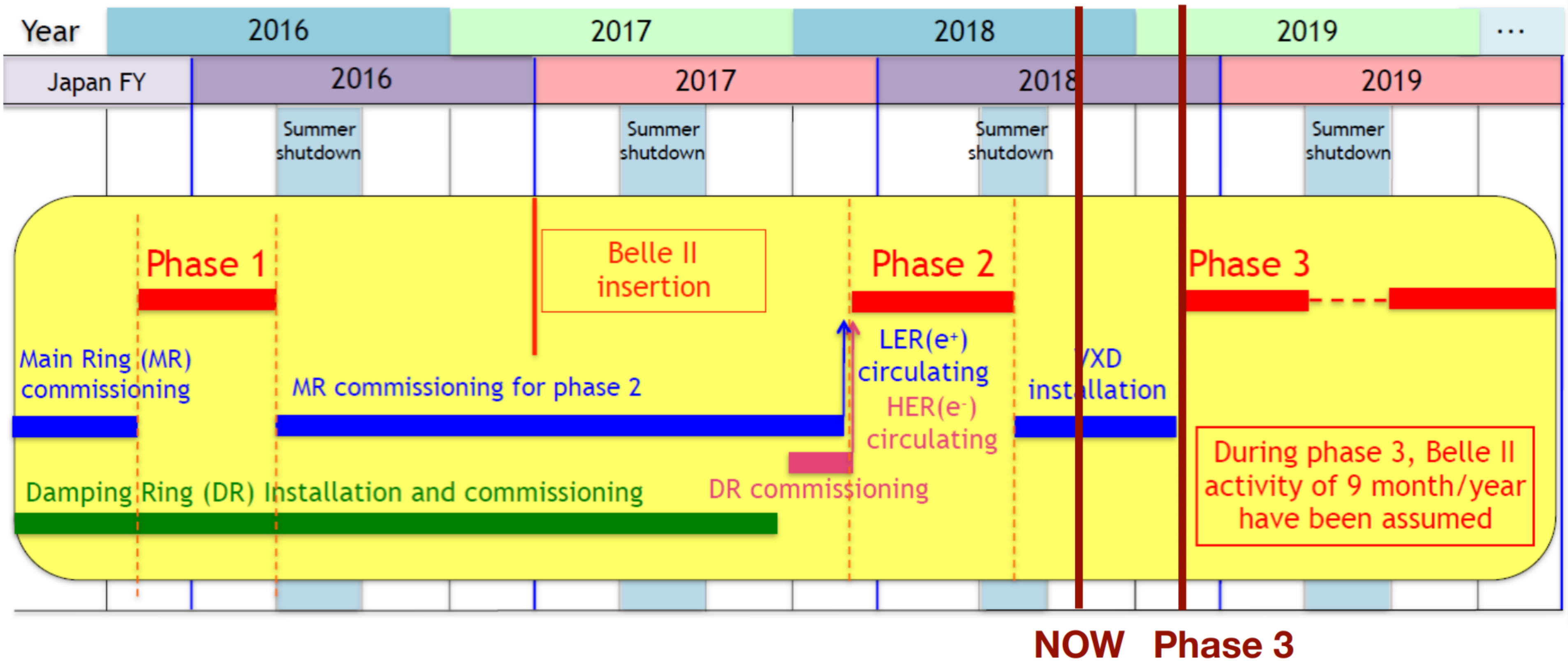
Belle II Performance

We are seeing B signals!





Belle II in future



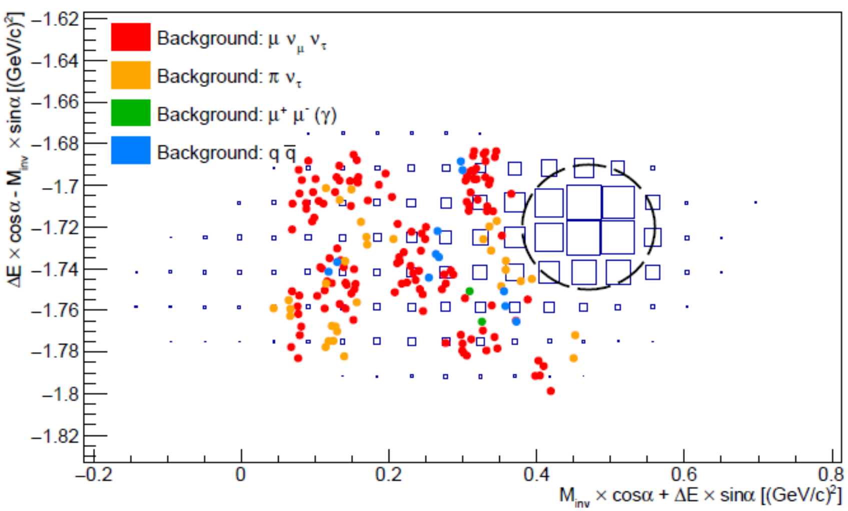
Phase 3

- **Installation of VXD**
- **Start physics run with full detectors in Spring 2019**
- **Operate 9 months per year**

Status of Belle II Physics Book

- Belle II physics book (>630 pages), to be printed by PTEP very soon
  https://confluence.desy.de/display/BI/B2TiP+ReportStatus
- The contents include Belle II detector, simulation, reconstruction. analysis software, B decays, CKM angles, charm, quarkonium(-like), τ, new physics, ….
- Some golden channels are given with Belle II MC simulations, theoretical discussions, sensitivity and systematic estimates

arXiv:1808.10567



MC signal and background estimates for $\tau \to \gamma\mu$

1 ab^{-1}

Mode	Eff.(%)	N_{BG}^{exp}	UL (10^{-8})
$\mu\eta(\to\gamma\gamma)$	8.2	0.63 ± 0.37	3.6
$e\eta(\to\gamma\gamma)$	7.0	0.66 ± 0.38	8.2
$\mu\eta(\to\pi\pi\pi^0)$	6.9	0.23 ± 0.23	8.6
$e\eta(\to\pi\pi\pi^0)$	6.3	0.69 ± 0.40	8.1
$\mu\eta$(comb.)			2.3
$e\eta$(comb.)			4.4
$\mu\eta'(\to\pi\pi\eta)$	8.1	$0.00^{+0.16}_{-0.00}$	10.0
$e\eta'(\to\pi\pi\eta)$	7.3	0.63 ± 0.45	9.4
$\mu\eta'(\to\gamma\rho^0)$	6.2	0.59 ± 0.41	6.6
$e\eta'(\to\gamma\rho^0)$	7.5	0.29 ± 0.29	6.8
$\mu\eta'$(comb.)			3.8
$e\eta'$(comb.)			3.6
$\mu\pi^0$	4.2	0.64 ± 0.32	2.7
$e\pi^0$	4.7	0.89 ± 0.40	2.2

Belle II possibilities

- Many things, but some of them can be done in Belle, too
  - We have not used the full potential of Belle data
- Examples include:
  - Search for more Y_c resonances in unsearched modes; e.g., $\Lambda_c\eta$
  - J^P measurements for Λ_c^*, Ξ_c^*, Ω_c^* ...; Partial wave analysis.
    → We can determine J^P of most of presently known states
    → Comprehensive list of charmed baryons
  - Search for $\Xi*$ and $\Omega*$ resonances in the decay of Λ_c and Ξ_c.
  - Weak decay branches and decay asymmetry parameters
  - Exotic search: pentaquarks, dibaryons, ...
    e.g., ND, $N\overline{D}$(or Θ_c), H, H_c, $\Lambda_c N$, ...

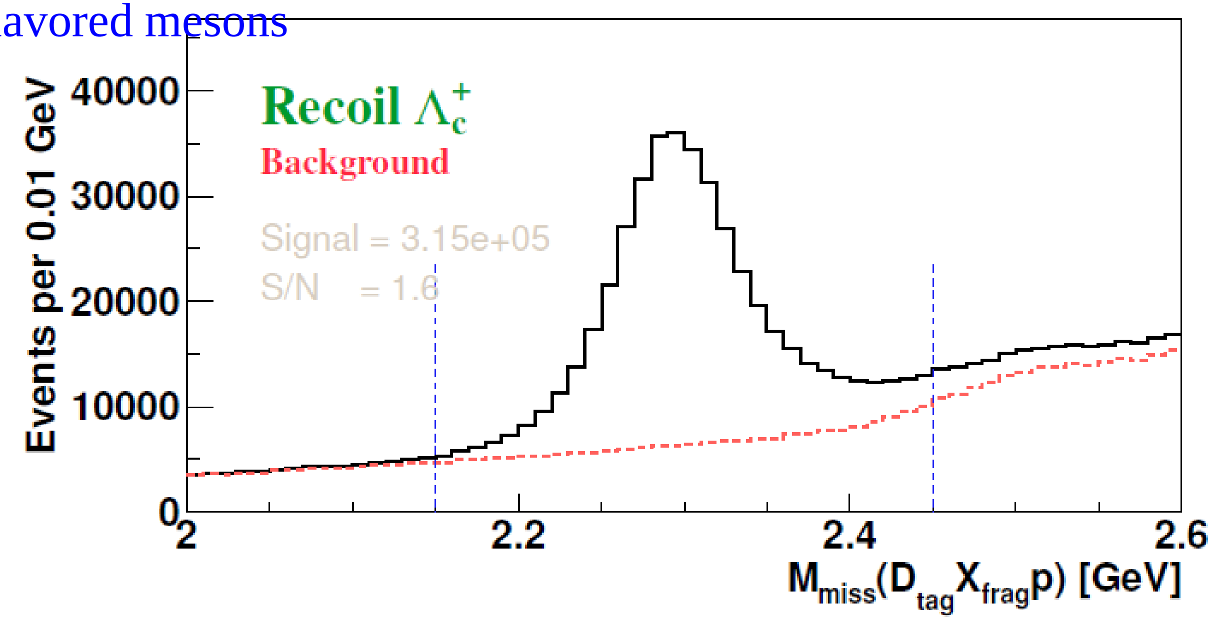
  ....

Inclusive $\Lambda_c^+ \to X$

$e^+e^- \to D_{tag} X_{frag}\, p\, \Lambda_c^+$

X_{frag} : a few unflavored mesons

MC Simulation [5.5 ab^{-1}]



⇒ *Belle II yield in 50 ab^{-1}:* ***2.8 x 10^6 inclusive***

Unique sample:

- *allows measurement of Λ_c absolute branching fractions*
- *allows measurement of semileptonic Λ_c decays*
- *allows searches for Λ_c rare decays with missing energy*

Belle II Collaboration

Belle II中国成员
北京大学
中国科学技术大学
高能所
北京航空航天大学
复旦大学
辽宁师范大学
苏州大学

~800 Colleagues
~100 Institutions
25 Countries/regions

Summary

- Belle data taking is over, but still actively publishing results. Many interesting results are from (charmed)baryon spectroscopy.

  --Observation of an excited Ω^- baryon: $\Omega^*(2012)$

  -- First observation of doubly Cabibbo-suppressed decay in $\Lambda_c^+ \to p\, K^+\pi^-$

  -- Measurements of $\Lambda_c \to \Sigma\pi\pi$

  -- Ω_c and excited Ω_c studies

  -- First observation of $\Xi_c^0(2930)$ and evidence of $\Xi_c^{+-}(2930)$ in B decays

  -- Search for Ps in $\Lambda_c^+ \to p\phi\pi^0$ decay

  -- Measurements of absolute Brs of Ξ_c^0

- Interesting results are expected at Belle II, where 50 times more statistics than Belle.

  --Spin-parity determination of most (charmed)baryons and hyperons.

  --Search for new (charmed)baryon/hyperon resonances

  -- And more …