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Recent Belle results on (charmed) baryons and Belle II prospects of baryons

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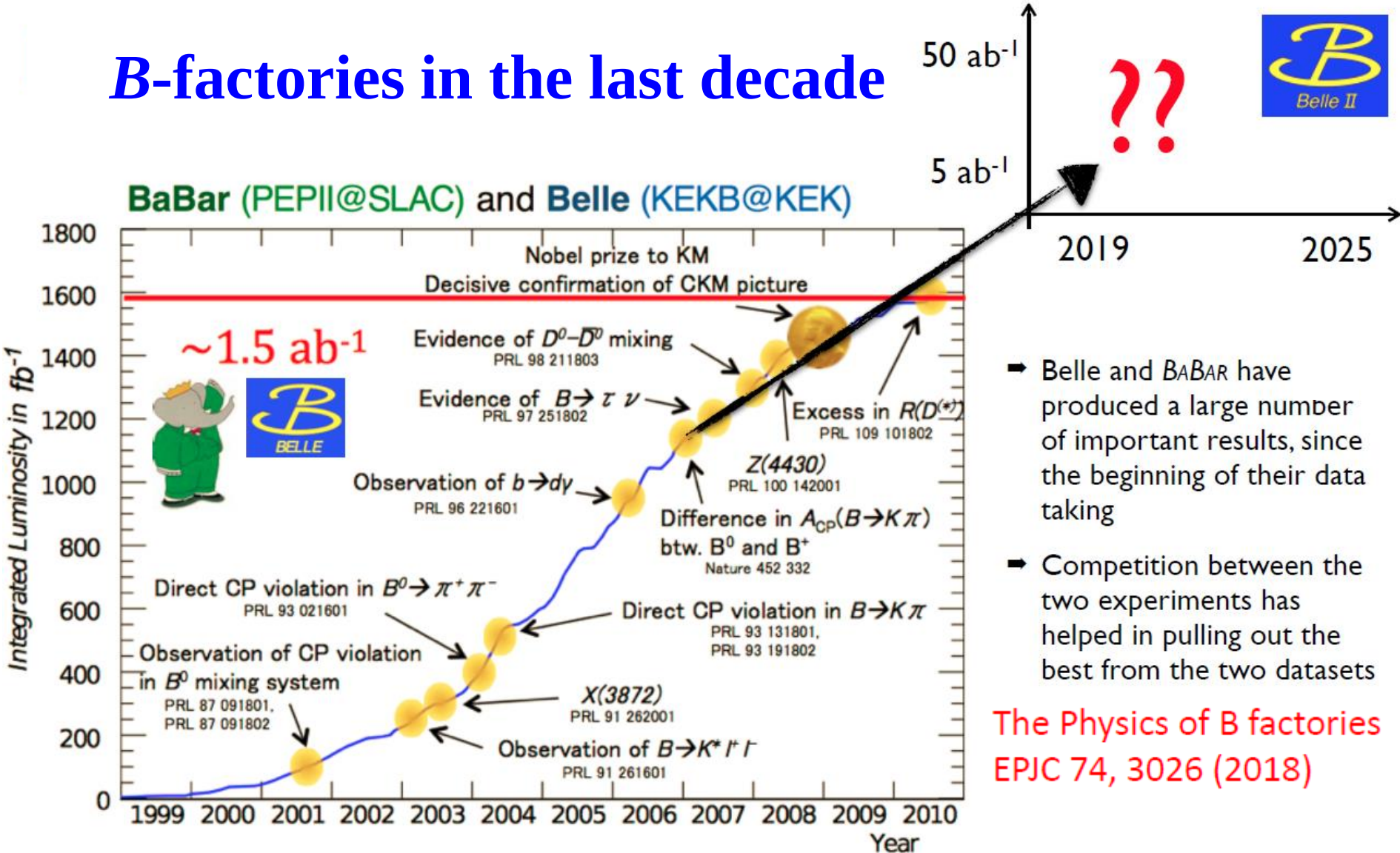
The 5th XYZ meeting
Zhengzhou University, Oct. 20-23, 2018

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

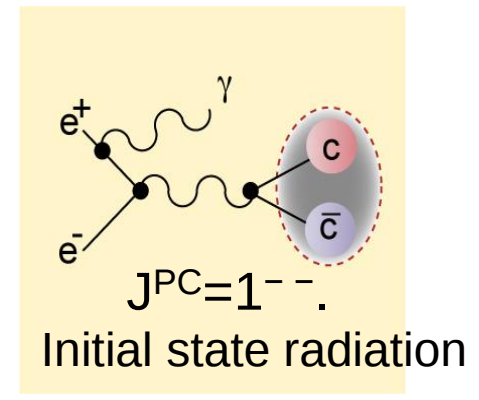
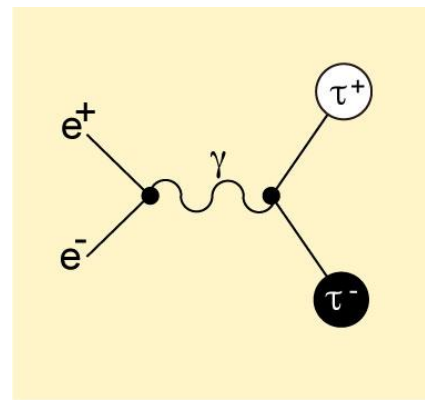
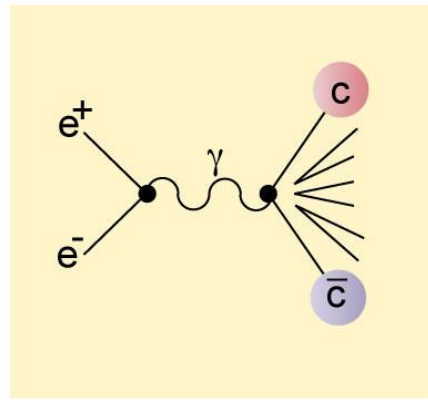
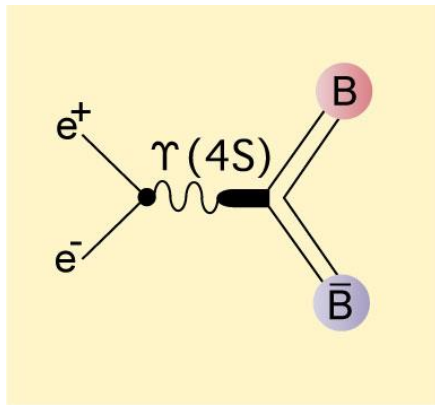


- ➔ Belle and BABAR have produced a large number of important results, since the beginning of their data taking
- ➔ Competition between the two experiments has helped in pulling out the best from the two datasets

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

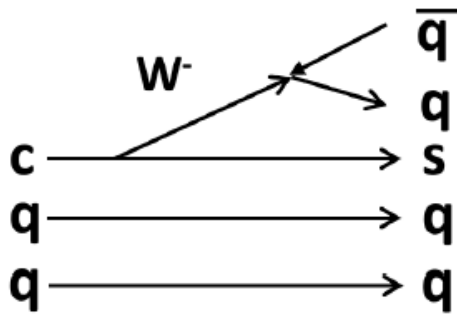
Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

The Physics Program

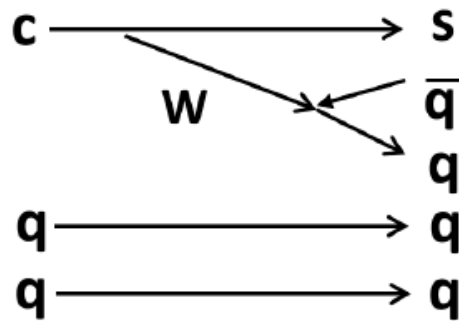


- a (Super) B-factory ($\sim 1.1 \times 10^9 B\bar{B}$ pairs per ab^{-1});
- a (Super) charm factory ($\sim 1.3 \times 10^9 c\bar{c}$ pairs per ab^{-1});
- a (Super) τ factory ($\sim 0.9 \times 10^9 \tau^+\tau^-$ pairs per ab^{-1});
- thanks to the Initial State Radiation, we can effectively scan the 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, ...

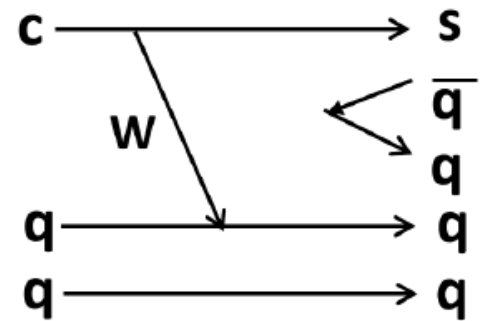
The Charmed Baryon Physics



Spectator



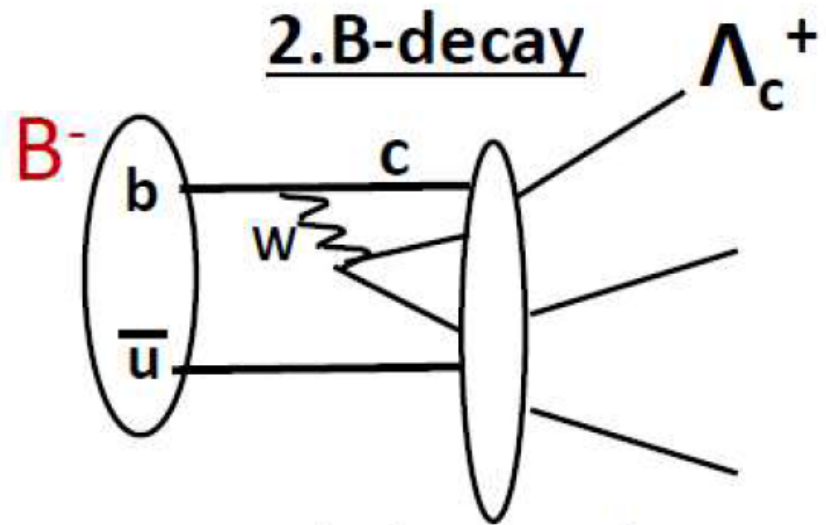
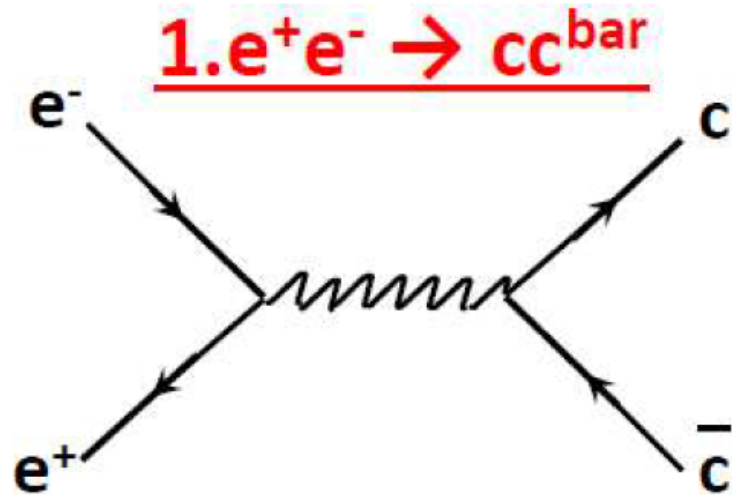
Internal W



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 $c \rightarrow s$ transition.
- Belle has collected $\sim 1 \text{ ab}^{-1} e^+e^-$ data samples (mainly at $\Upsilon(4S)$).
 - $10^9 e^+e^- \rightarrow c\bar{c}$ samples
 - $7.7 \times 10^8 B\bar{B}$ samples
- Huge data sample enable to study various charmed baryons.

Baryon production at B-factory



Baryons produced via fragmentation

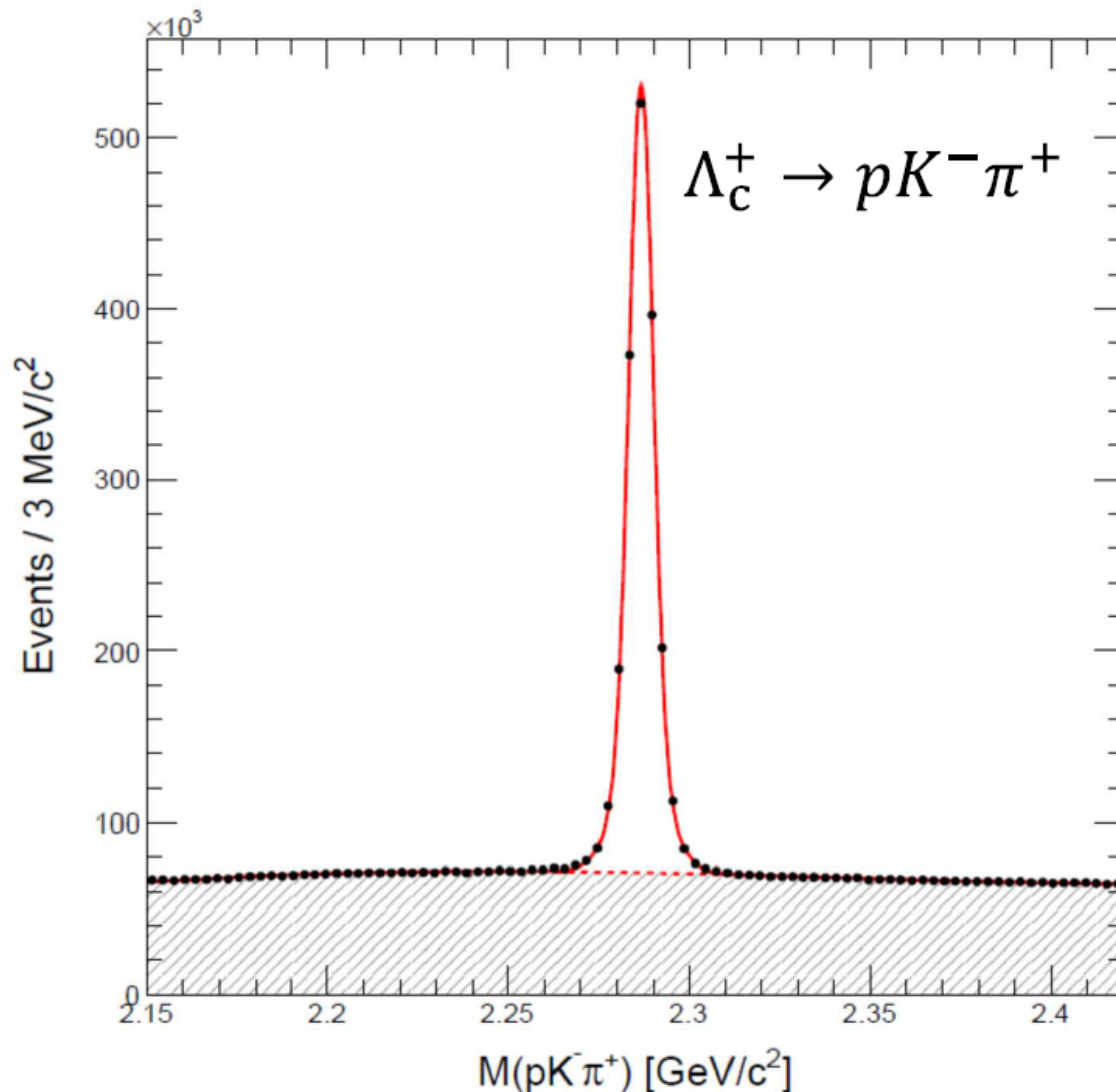
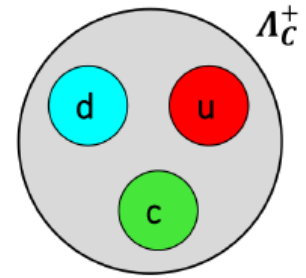
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

B is efficiently produced via $Y(4s)$

Once bottom is produced, it favorably decays into charm.

Huge statistics

Huge statistics, good quality



> 1 M events
reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

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

Observation of an excited Ω^- baryon

$$\Omega^- = s s s (S=-3, I=0)$$

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 ($>600\text{MeV}$).

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

3. Preferred modes

- $\Omega^{*-} \rightarrow \Xi^- + K_S^0$ ✓
- $\Omega^{*-} \rightarrow \Xi^0 + K^-$ ✓
- 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
$\Upsilon(1S)$	24.9	1.58
$\Upsilon(3S)$	2.9	-

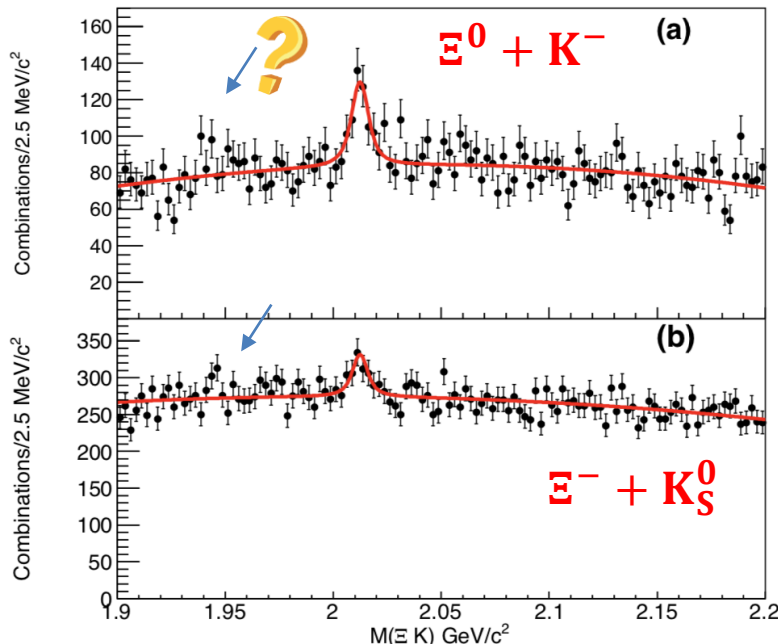
- The decays of these narrow resonances proceed via gluons.
- The production of baryon are enhanced.

Observation of an excited Ω^- baryon

Results & Summary

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

Data	Mode	Mass (MeV/c ²)	Yield	Γ (MeV)	$\chi^2/\text{d.o.f.}$	n_σ
$\Upsilon(1S, 2S, 3S)$	$\Xi^0 K^-$, $\Xi^- K_S^0$ (simultaneous)	2012.4 ± 0.7	242 ± 48 , 279 ± 71	$6.4_{-2.0}^{+2.5}$	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
$\Upsilon(1S, 2S, 3S)$	$\Xi^- K_S^0$	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	$\Xi^- K_S^0$	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 $K\Xi(1530)$ hadronic molecule.

[PRD 98, 054009 (2018), PRD 98, 056013 (2018), arXiv:1807.02145, arXiv:1807.06485, arXiv:1807.06485]

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

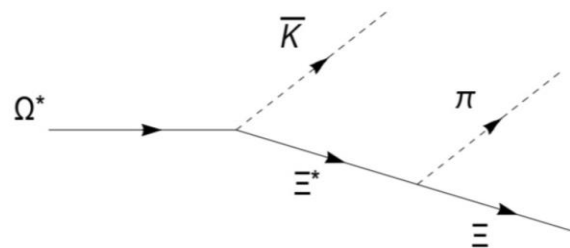


FIG. 1: The three-body decays of $\Omega(2012)$ in the $K\Xi(1530)$ molecular picture.

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 $\Omega(2012)$ events at Belle

$$N^{\text{expected}} = N_{\Omega}^{\text{total}} \times \mathcal{B}^{\text{product}} \times \varepsilon \times \mathcal{B}(\Omega(2012) \rightarrow \mathbf{KE/KE}\pi)$$

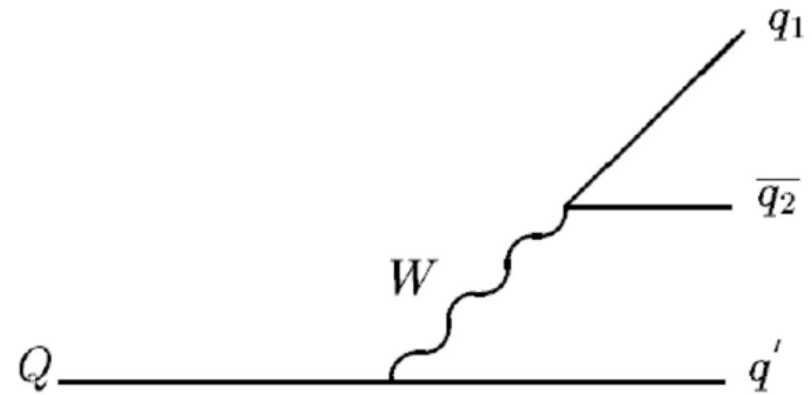
Channel	ε	$\mathcal{B}^{\text{decay}}$	$\mathcal{B}(\Omega(2012) \rightarrow \mathbf{KE/KE}\pi)$	Nobs	N^{expected}
$E^- K_S^0$	15.7%	$\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) \times \mathcal{R}(\bar{K}^0 \rightarrow K_S^0)$	6.5%	279	-
$E^0 K^-$	4.0%	$\mathcal{B}(\pi^0 \rightarrow \gamma\gamma)$	7.8%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

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

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

- Weak decay amplitude of a charm quark
 - $c \rightarrow s: \cos\theta_c \sim 1$
 $d: \sin\theta_c \sim 0.23 \leftarrow$ Cabibbo suppression
 - At the same time, emitted W decays into a $q\bar{q}$ pair
 - $u\bar{d}: \cos\theta_c$
 - $u\bar{s}: \sin\theta_c$

- So, the decay $c \rightarrow d(u\bar{s})$ is twice suppressed

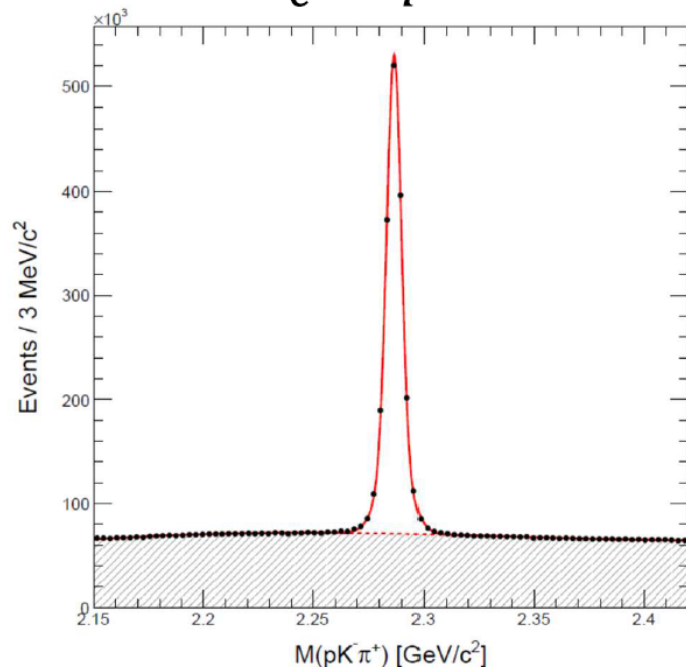


→ Doubly Cabibbo-suppressed decay

- Naively, decay branch is $O(\tan^4\theta_c) \sim 0.28\%$ smaller compared to counterpart ($c \rightarrow s(\bar{d}u)$)

DCS decay $\Lambda_c^+ \rightarrow p K^+ \pi^-$

CF: $\Lambda_c^+ \rightarrow p K^- \pi^+$

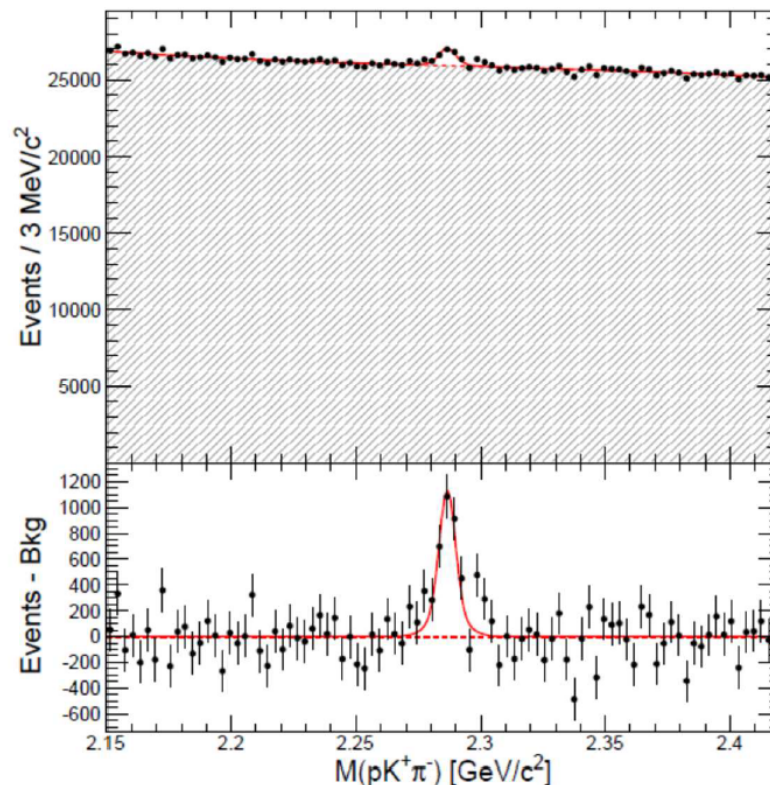


$(1.452 \pm 0.015) \times 10^6$ events

Significant signal observed!

(significance 9.4σ)

DCS: $\Lambda_c^+ \rightarrow p K^+ \pi^-$



3587 ± 380 events

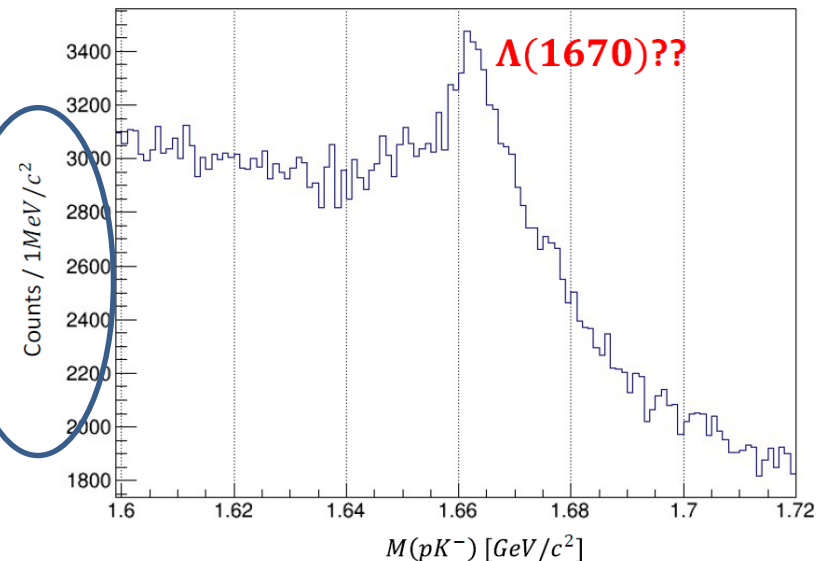
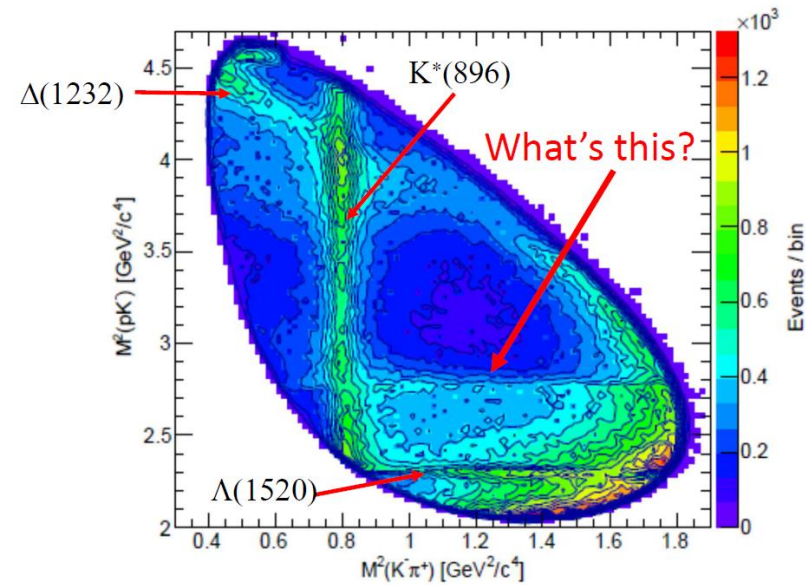
[PRL117, 011801]

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

The first observation of DCS decay in Baryon

A new Λ excited states ?

Dalitz plot: $\Lambda_c^+ \rightarrow p K^- \pi^+$ [PRL117.011801]



- The peak position is ~ 1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~ 10 MeV, significantly narrower than Λ , Σ resonances in this region
 - $\Lambda(1670)$: 25-50 MeV
 - $\Sigma(1660)$: 40-200 MeV
 - $\Sigma(1670)$: 40-80 MeV
 - $\Lambda(1690)$: ~ 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, $\Gamma=10+22-4$ MeV
 - Liu & Xie [PRC85.038201, PRC86.055202]
 $J^P=3/2^-$ (D_{03}), $M=1668.5 \pm 0.5$ MeV, $\Gamma=1.5 \pm 0.5$ MeV
- The reason is the same
 - From $Kp \rightarrow \Lambda\eta$ measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
 - Especially the angular distribution $\rightarrow$ **Model independent**
- There is no state in quark models
 - It must be an exotic
 - $udss\bar{s}$ pentaquark??

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



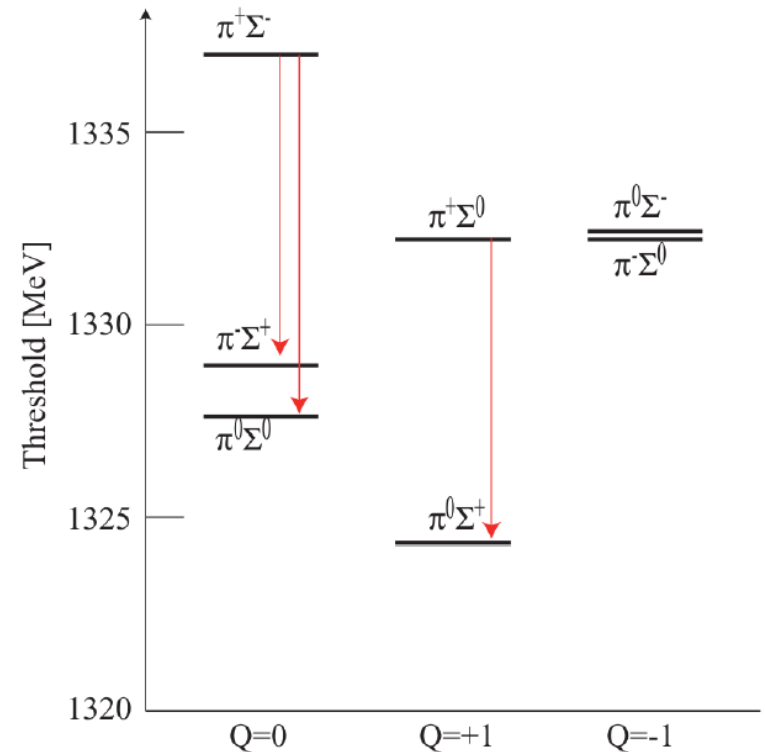
- Motivation: Measure the $\Sigma\pi$ scattering lengths based on "Cabibbo's method", T. Hyodo and M. Oka, Phys. Rev. C84, 035201 (2011)
- **This talk:** Measure the $\mathcal{B}(\Sigma\pi\pi)$ relative to $pK^-\pi^+$ + int. resonances.

$$\Lambda_c \rightarrow \Sigma^+\pi^-\pi^+(4.57 \pm 0.29\%)*$$

$$\Lambda_c \rightarrow \Sigma^0\pi^+\pi^0(2.3 \pm 0.9\%)*$$

$$\Lambda_c \rightarrow \Sigma^+\pi^0\pi^0(\text{unknown})$$

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



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

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

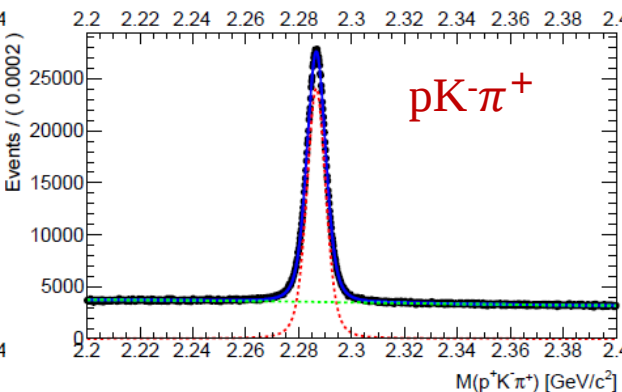
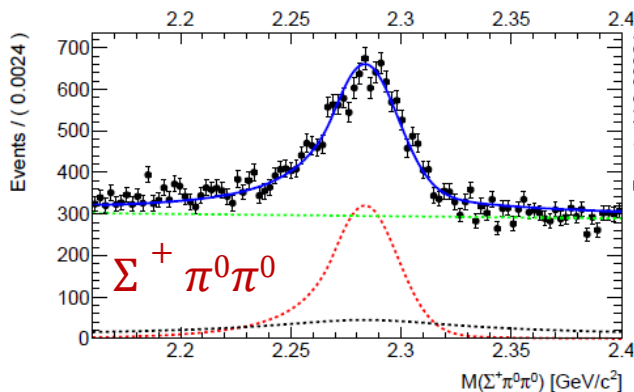
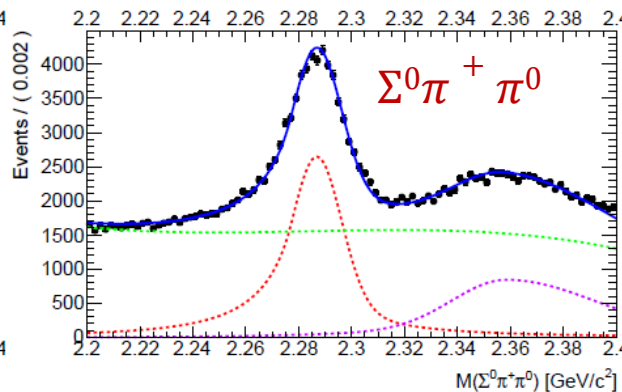
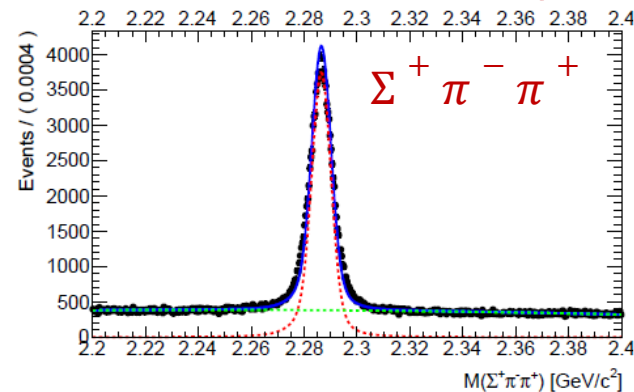
NEW

MC studies

Shape determination
Consistency tests
Model uncertainty

Λ_c in 711 fb^{-1} at $Y(4S)$

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](https://arxiv.org/abs/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)

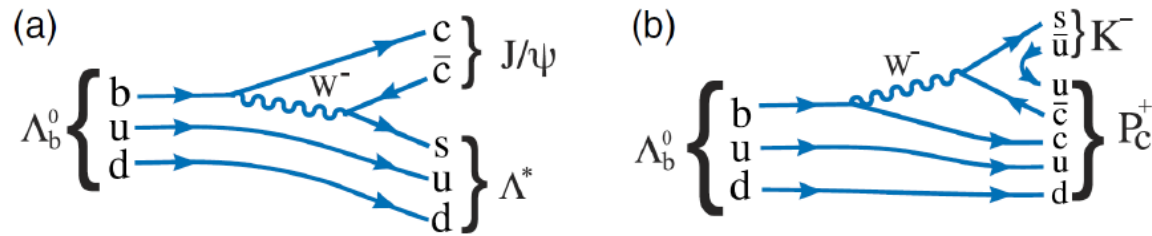
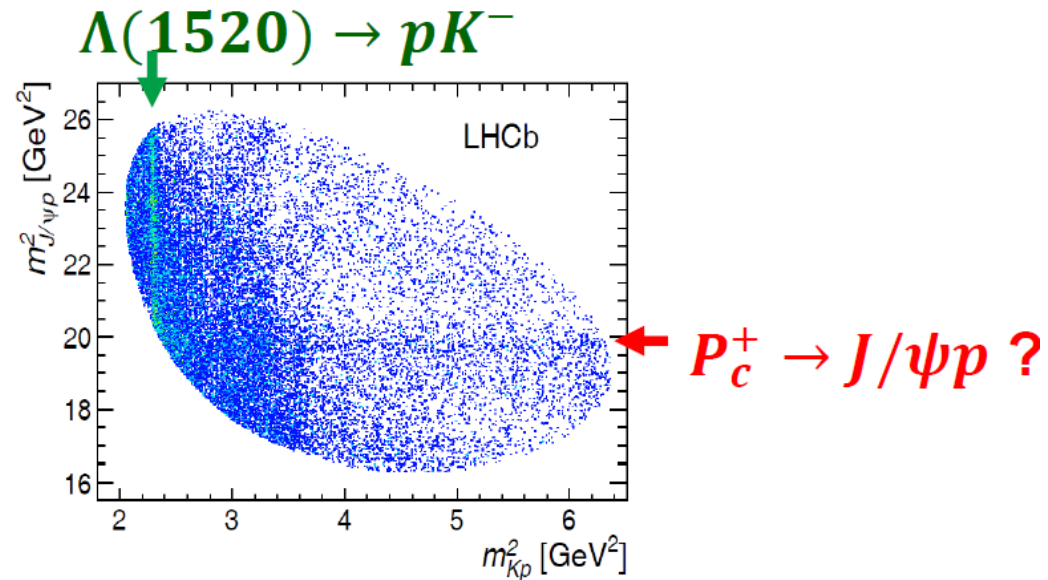
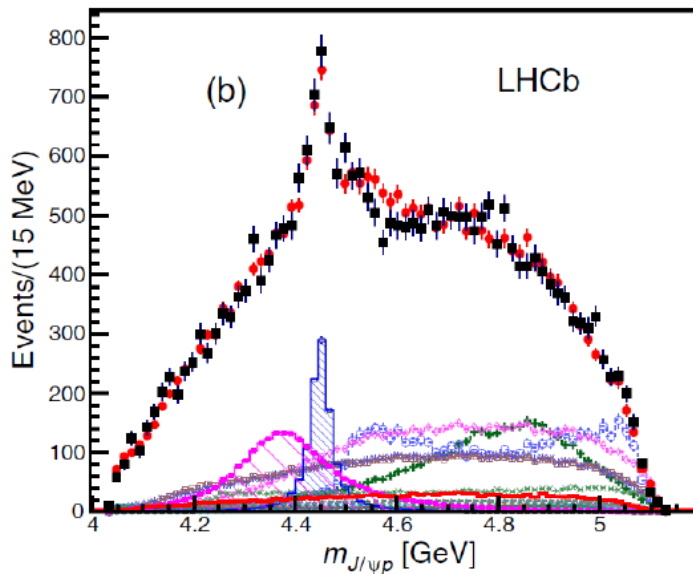


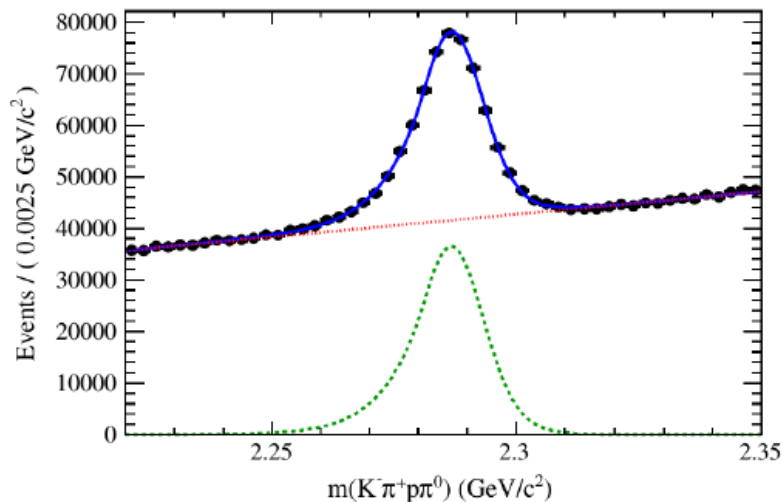
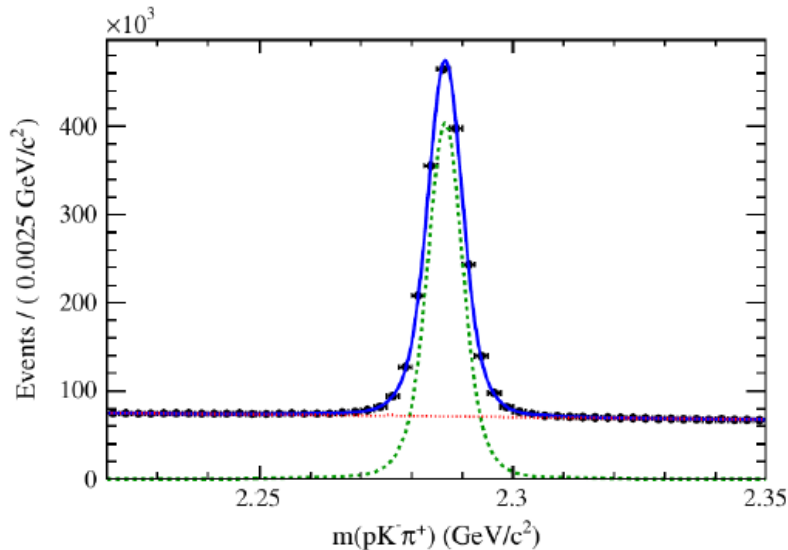
FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \rightarrow P_c^+ K^-$ decay.



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

Reference modes

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



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

Search for Ps states at Belle

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

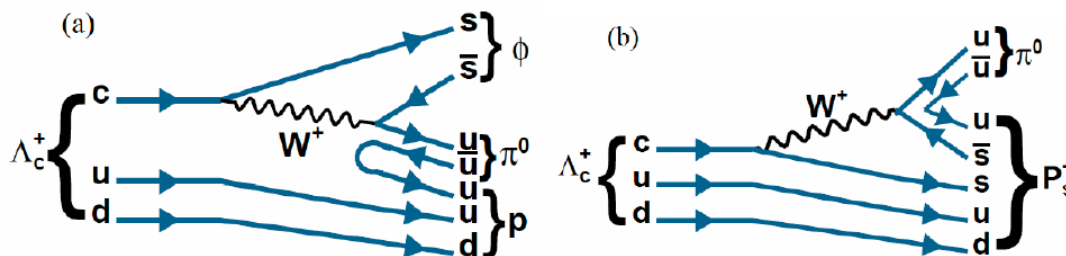
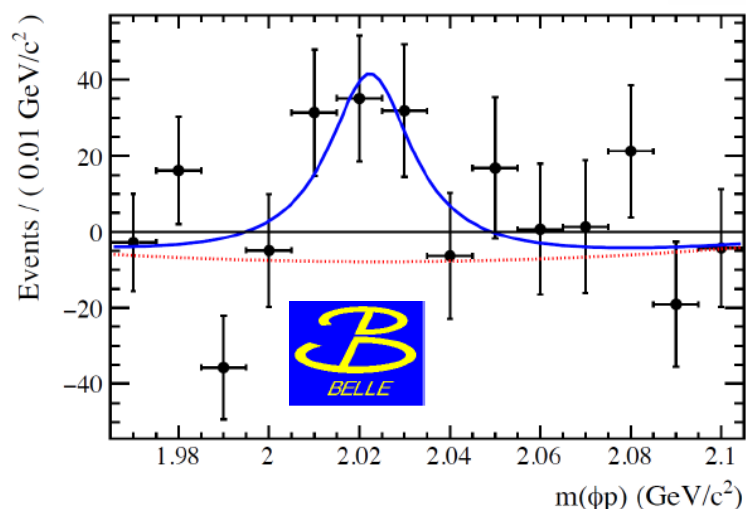


FIG. 1. Feynman diagram for the decay (a) $\Lambda_c^+ \rightarrow \phi p \pi^0$ and (b) $\Lambda_c^+ \rightarrow P_s^+ \pi^0$.



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

- **No significant Ps signal**
- Best fit yields a peak at $M=(2025 \pm 5) \text{ MeV}/c^2$ and $\Gamma=(22 \pm 12) \text{ MeV}$

[PRD96, 051102\(R\) \(2017\); 915fb⁻¹](#)

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

$B(\Lambda_c \rightarrow P_s \pi^0) \times B(P_s \rightarrow \phi p) < 8.3 \times 10^{-5} \text{ @90\% C.L.}$

Hadronic decays of Ω_c

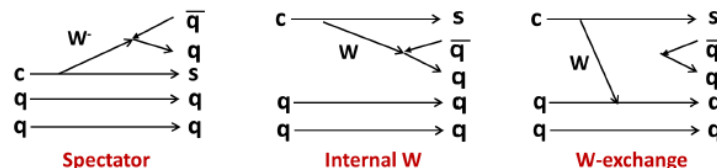
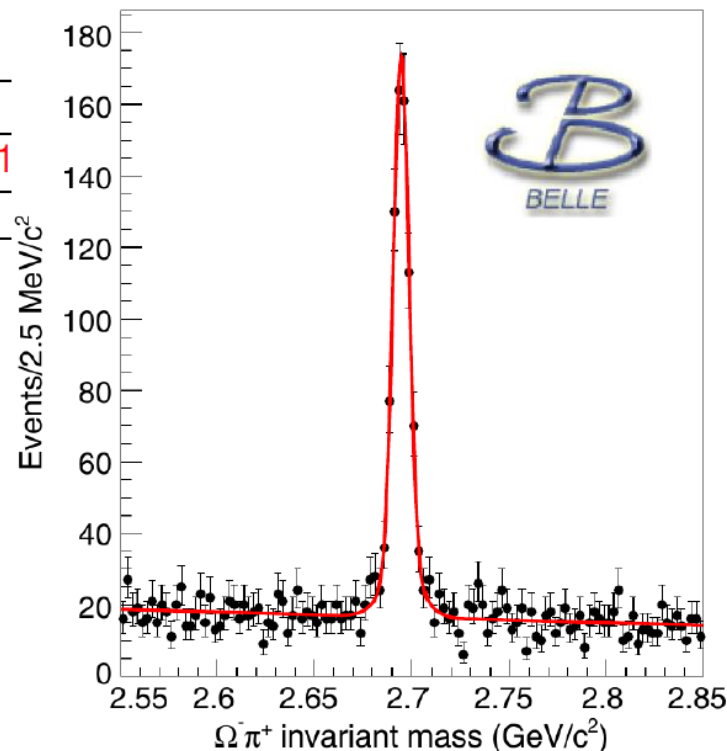
- Among 4 ground state charmed baryons, $\Omega_c(css)$ is not studied well as cross section is small.

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: $\Omega^- \pi^+$.

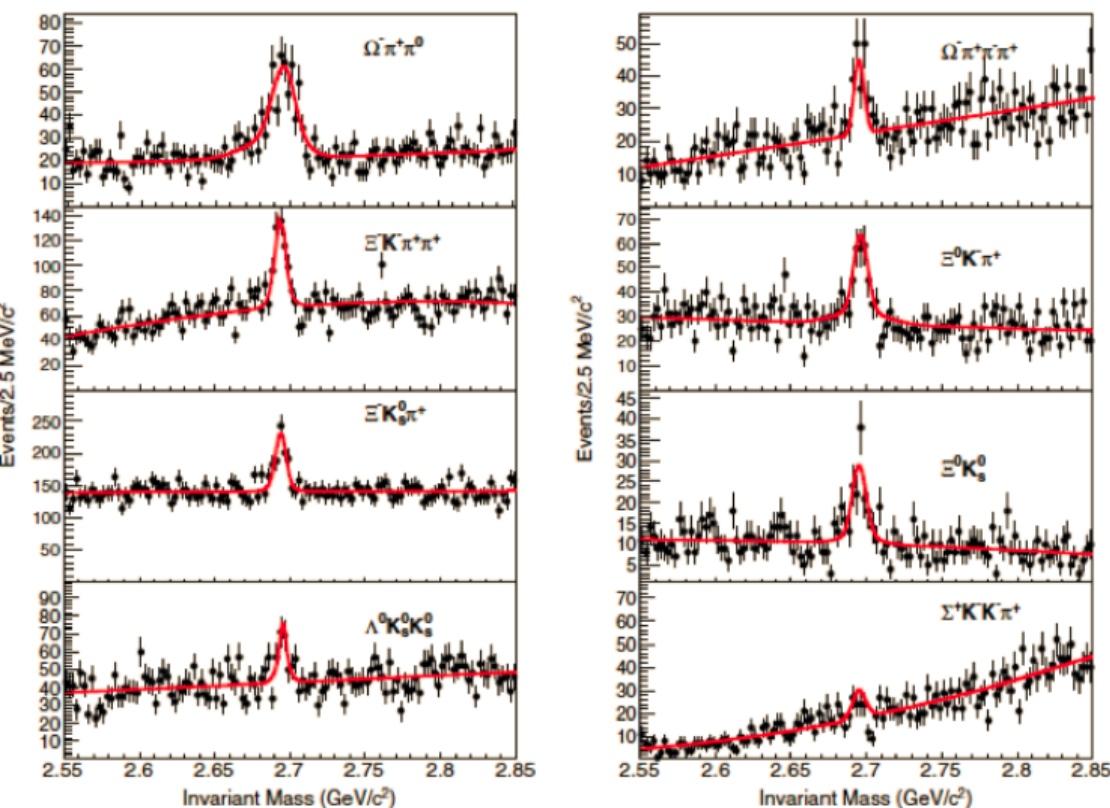
- Most precise measurements: $\Omega^- \pi^+ \pi^0$, $\Omega^- \pi^+ \pi^- \pi^+$, $\Xi^- K^- \pi^+ \pi^+$, and $\Xi^0 K^- \pi^+$.
- First measurements:** $\Xi^- \bar{K}^0 \pi^+$, $\Xi^0 \bar{K}^0$ and $\Lambda \bar{K}^0 \bar{K}^0$.

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



Ω_c branching fractions

PRD97,032001(2018)



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

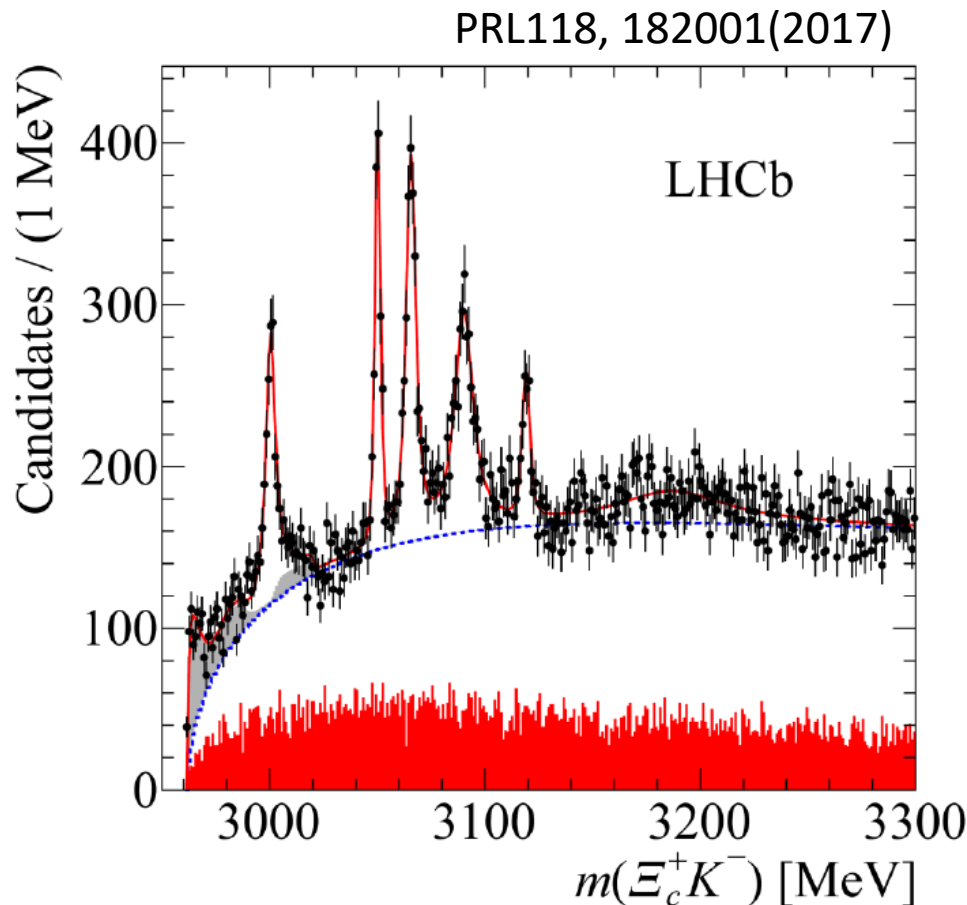
Three modes are new measurements.

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

Observation of excited Ω_c 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:



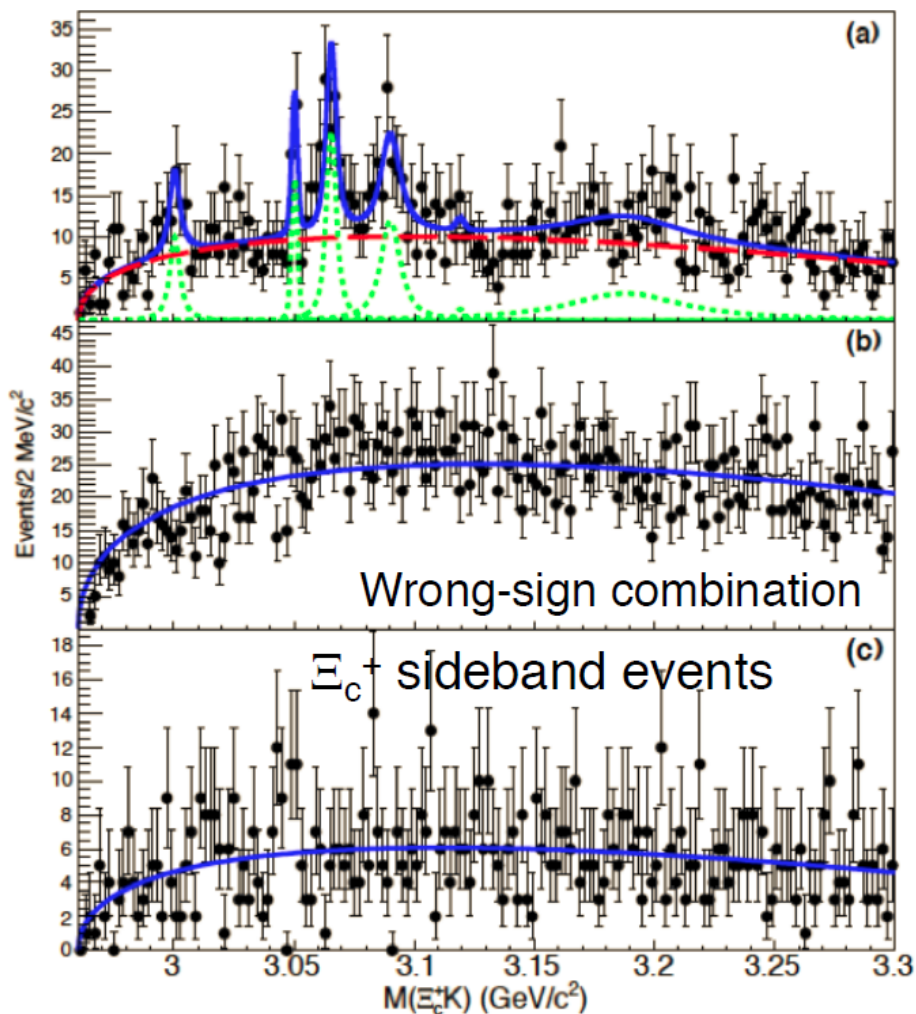
5 Narrow states
(+ possibly one wide one)

BELLE can do the same!

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

Confirmation of excited Ω_c 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 Ω_c 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/c²

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

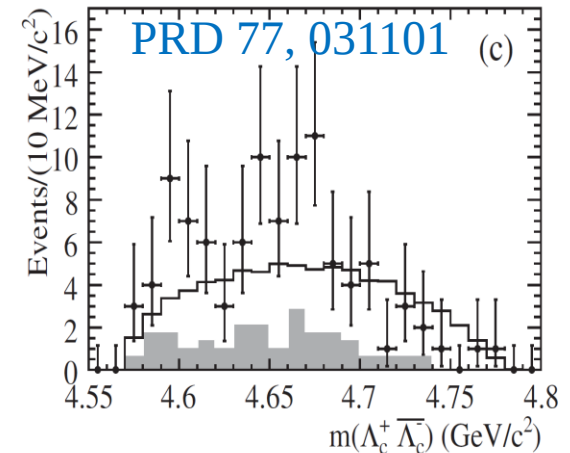
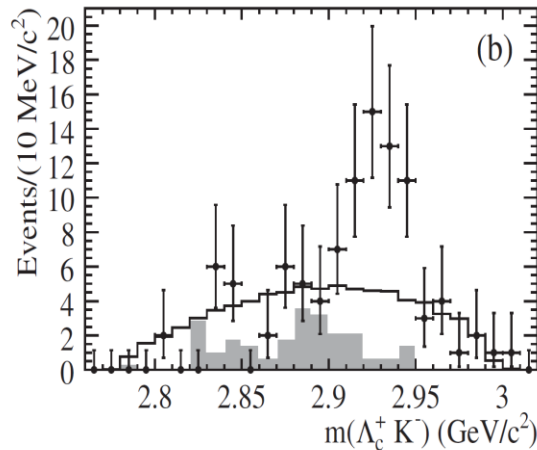
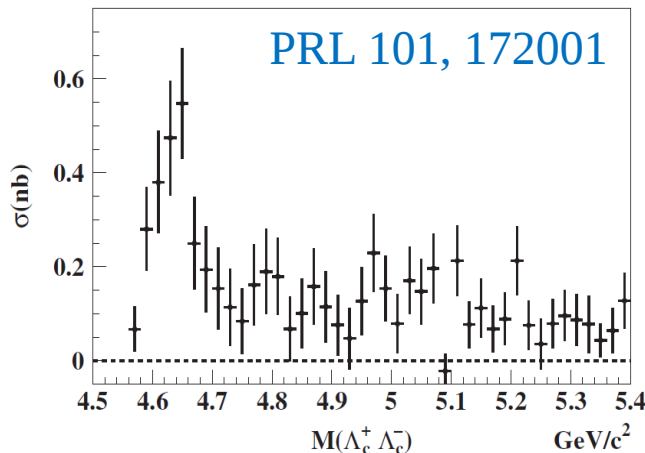
- Alternatively, the masses of the five signals are measured by fitting the same distribution without constraining the masses.
- In all cases, the results are consistent with the LHCb values.

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

- Belle reported a structure, called X(4630), in the $\Lambda_c^+ \bar{\Lambda}_c^-$ invariant mass distribution in $e^+ e^- \rightarrow \gamma_{ISR} \Lambda_c^+ \bar{\Lambda}_c^-$ [PRL 101, 172001](#)
- BarBar once studied $B^+ \rightarrow K^+ \Lambda_c^+ \bar{\Lambda}_c^-$ 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](#); [PRL 102, 242004](#)



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

$\Xi_c(2930)$

*

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 $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ events.

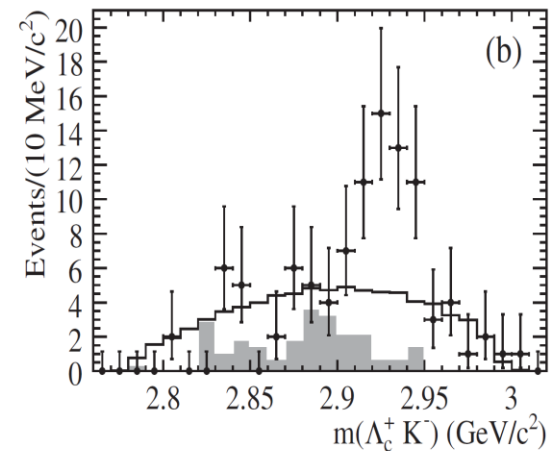
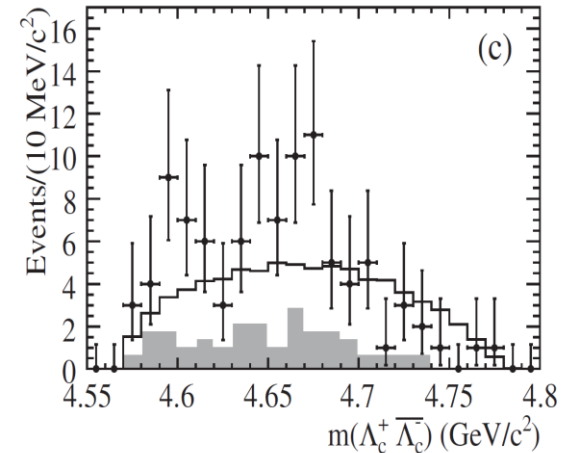
$\Xi_c(2930)$ MASS

2931 ± 6 MeV

$\Xi_c(2930)$ WIDTH

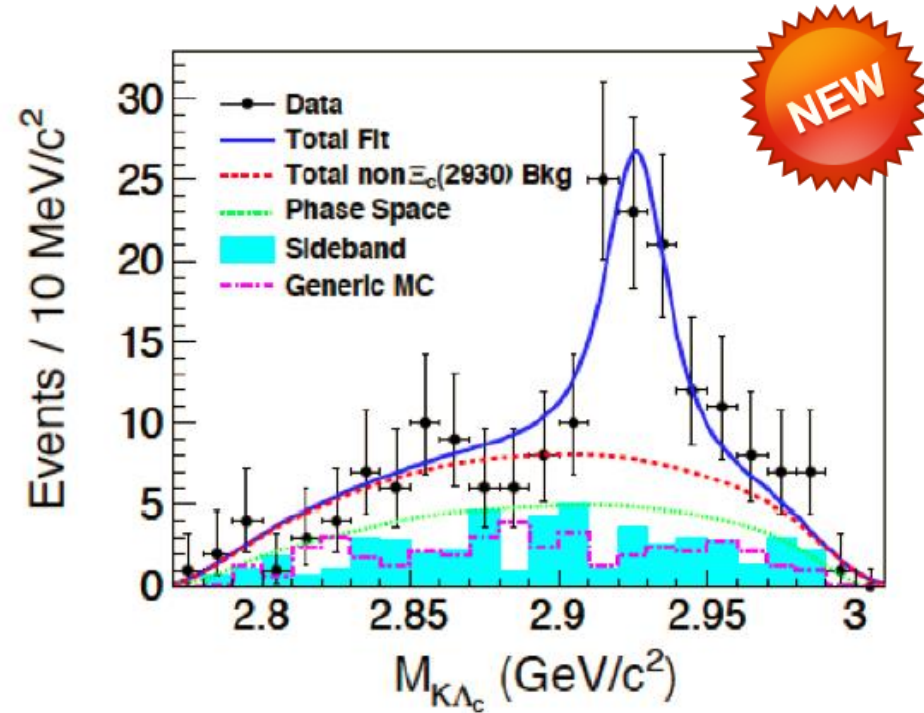
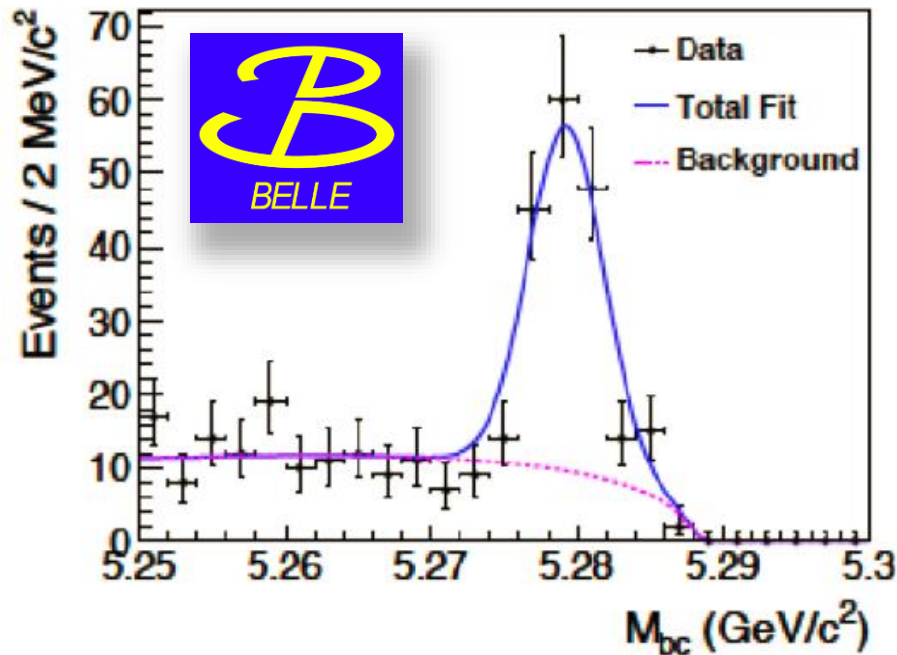
36 ± 13 MeV

tion for experimental resolution, we obtain $m = 2931 \pm 3(\text{stat}) \pm 5(\text{syst})$ 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 $B^+ \rightarrow K^+ \Lambda_c^+ \bar{\Lambda}_c^-$ at Belle

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



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

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

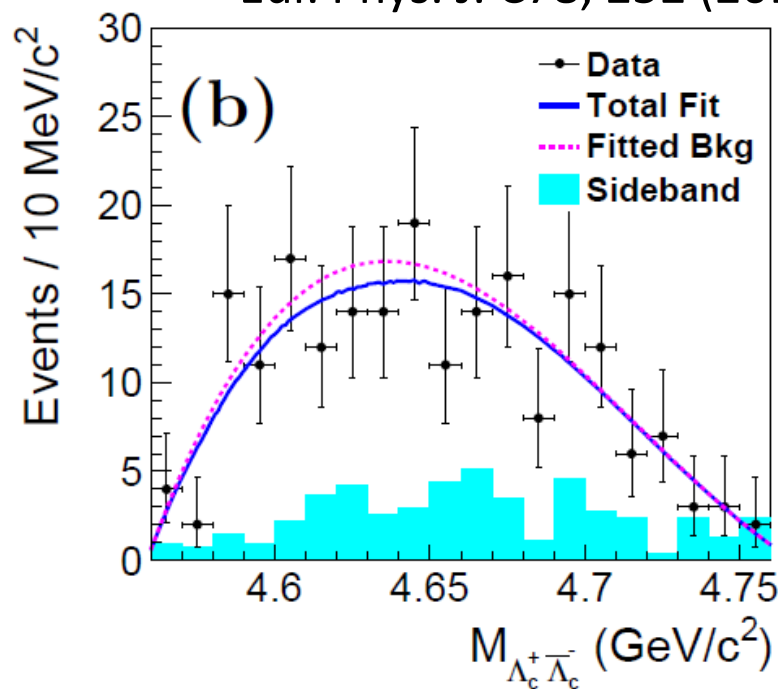
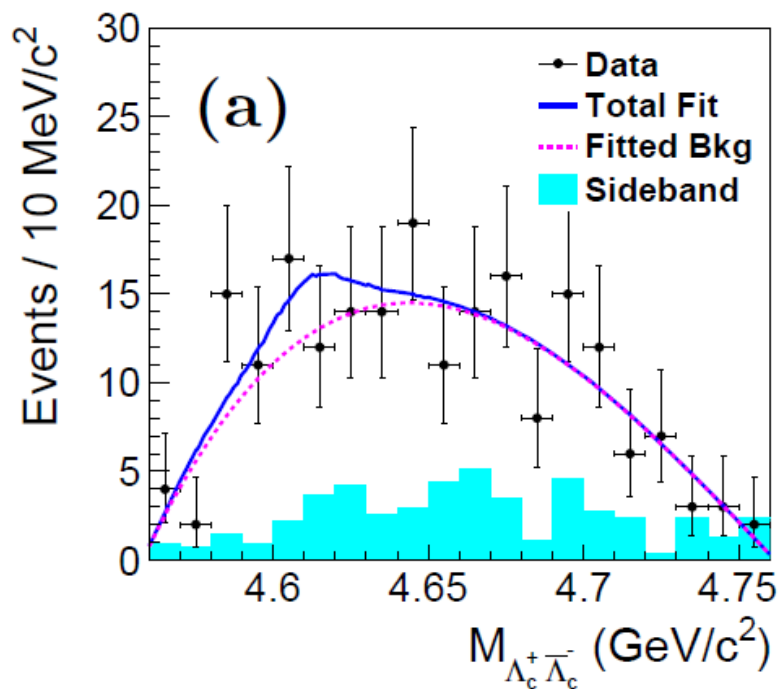
Clear confirmation for the BaBar claim, PRD77,031101(2008) and much more precise $M = 2928.9 \pm 3.0 +0.8/-12.0$ MeV, $\Gamma = 19.5 \pm 8.4 +5.4/-7.9$ MeV

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



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

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

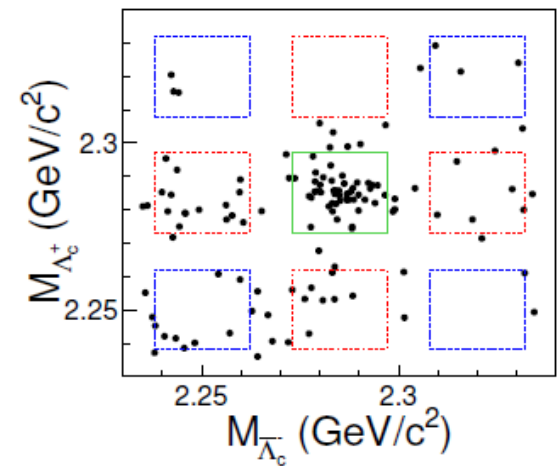
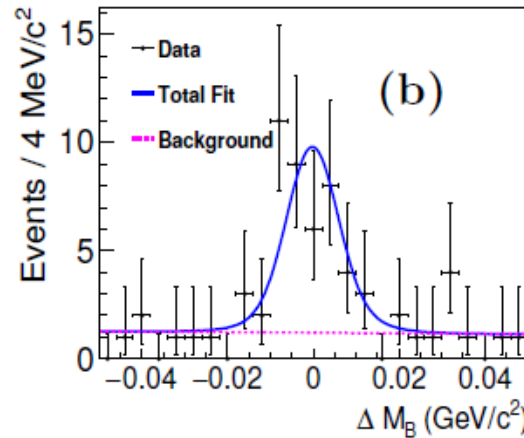
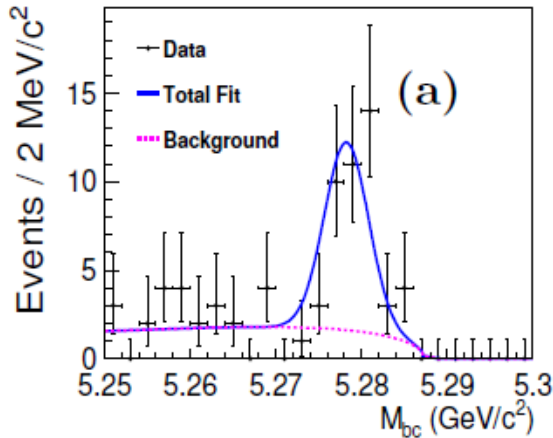


- No $Y(4660)$ and its spin partner Y_η were observed. in the $\Lambda_c^+ \bar{\Lambda}_c^-$ invariant mass distribution
- 90% C.L. upper limits of $B^+ \rightarrow K^+ Y(4660) \rightarrow K^+ \Lambda_c^+ \bar{\Lambda}_c^-$ and $B^+ \rightarrow K^+ Y_\eta \rightarrow K^+ \Lambda_c^+ \bar{\Lambda}_c^-$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

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

[arXiv:1806.09182](https://arxiv.org/abs/1806.09182)

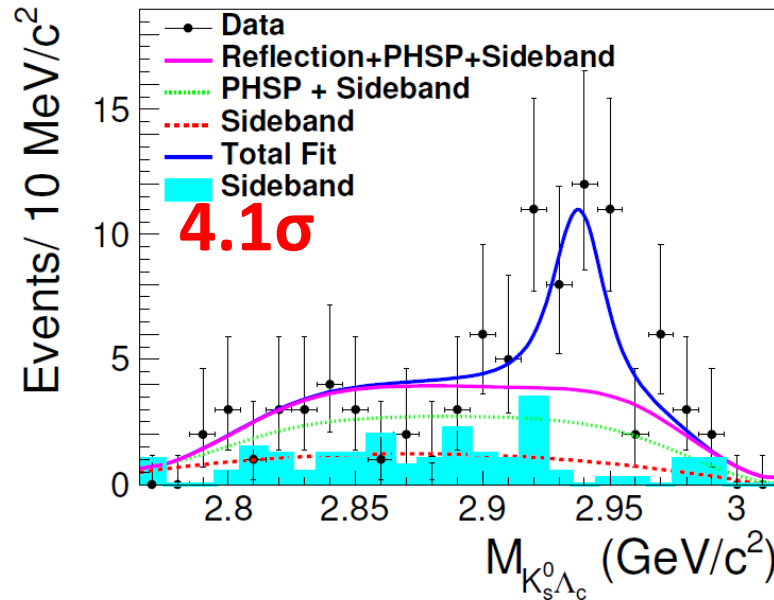
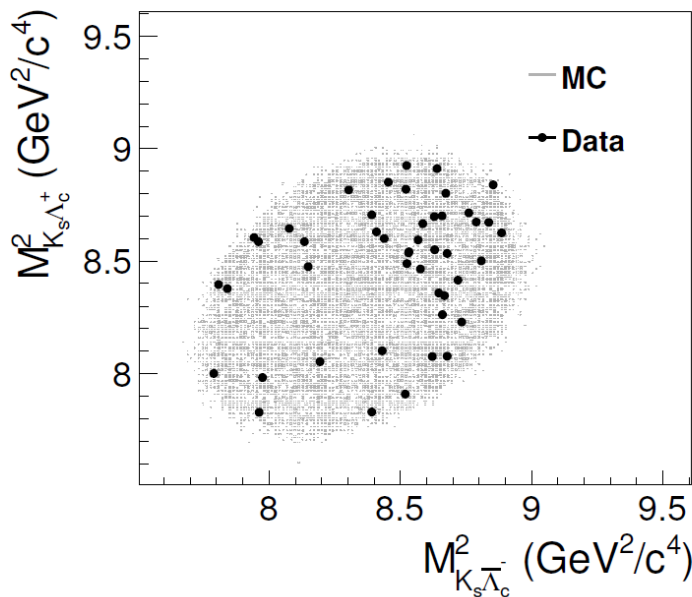
- Based on full $\Upsilon(4S)$ data set (772 M $B\bar{B}$ pairs) at Belle
- Three Λ_c decay channels:
 $\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow pK_s(\pi^+\pi^-)$ and $\Lambda_c^+ \rightarrow \Lambda(p\pi^-)\pi^+$.
- B candidates extracted via 2D fit to M_{bc} and ΔM_B



- 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
 - $\mathcal{B}(B^0 \rightarrow K^0 \Lambda_c^+ \bar{\Lambda}_c^-) = (3.84 \pm 0.73 \pm 0.48) \times 10^{-4}$

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

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



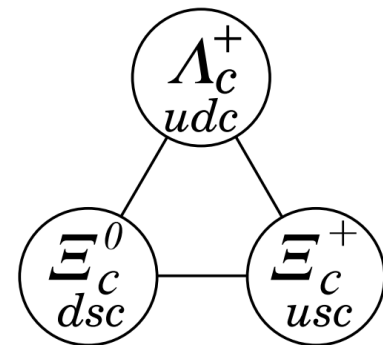
- $N_{\Xi_c^\pm} = 21.2 \pm 4.6$, stat. significance 4.1σ
- $M_{\Xi_c^\pm(2930)} = 2942.3 \pm 4.4 \pm 1.6 \text{ MeV}/c^2$
- $\Gamma_{\Xi_c^\pm(2930)} = 14.8 \pm 8.8 \pm 7.1 \text{ MeV}$



Measurements of absolute Brs of Ξ_c^0



- Weak decays of charmed hadrons play a unique role in the study of strong interaction; the charmed-baryon sector also offers a 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: $B(\Xi_c^0 \rightarrow \Xi^- \pi^+) \sim 1.3\%$ [PRD48, 4188 (1993)],
(2.24 ± 0.34)% [JHEP03, 66(2018)].
- The $B(\Xi_c^0 \rightarrow \Lambda K^- \pi^+) / B(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 1.07 \pm 0.12 \pm 0.07$ and
 $B(\Xi_c^0 \rightarrow p K^- K^- \pi^+) / B(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.33 \pm 0.03 \pm 0.03$ [PLB 605,237]
- $\Xi_c^0 \rightarrow p K^- K^- \pi^+$ plays a fundamental role in lots of bottom baryons study at LHCb .
- How to measure Ξ_c^0 absolute Brs ? Model Independent !

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

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

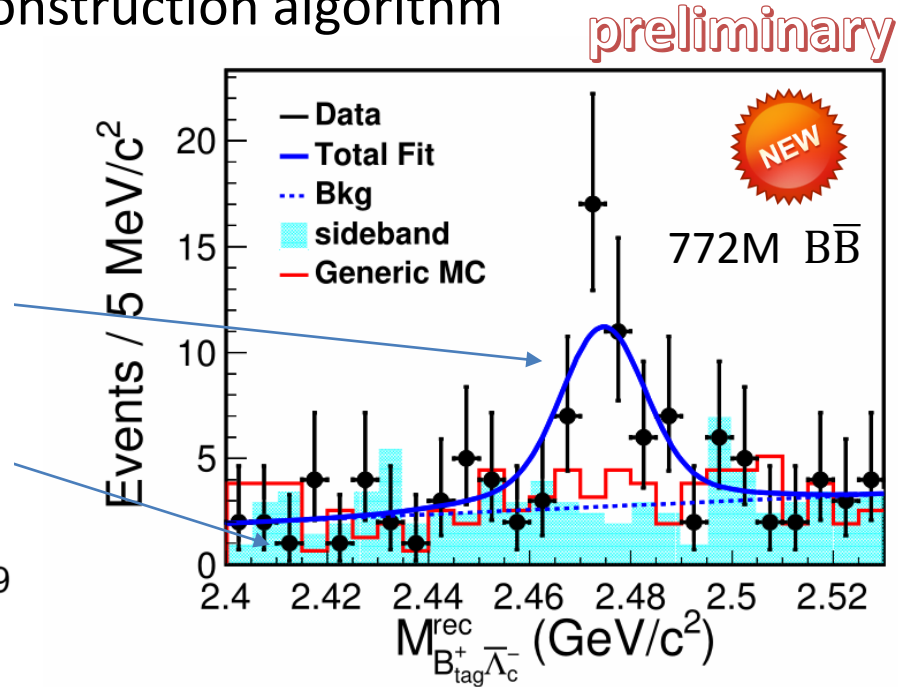
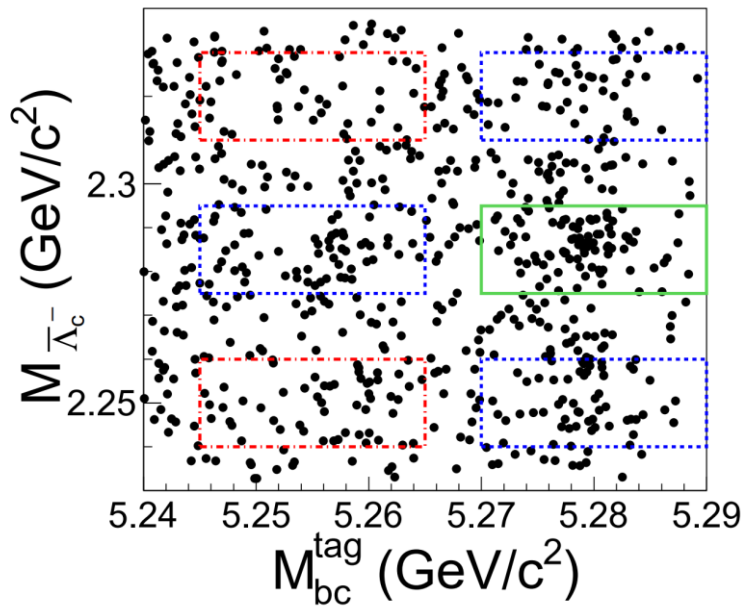
$$B(\Xi_c^0 \rightarrow p K^- K^- \pi^+) \equiv \frac{B(B^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0) B(\Xi_c^0 \rightarrow p K^- K^- \pi^+)}{B(B^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0)}.$$



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

Measurements of Br of $B^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0$, $\Xi_c^0 \rightarrow \text{anything}$

- The $\bar{\Lambda}_c^-$ reconstructed via its $\bar{p}K^+\pi^-$ and $\bar{p}K_s^0$ decays
- 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: $N(\Xi_c^0) = 40.9 \pm 9.0$, $5.5\sigma(\text{stat.})$
- $B(B^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0, \Xi_c^0 \rightarrow \text{anything}) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$ for the first time

Measurements of Brs of $B^- \rightarrow \bar{\Lambda}_c^- \Xi_c^0$, with

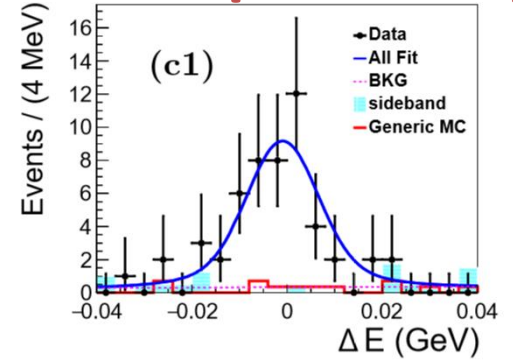
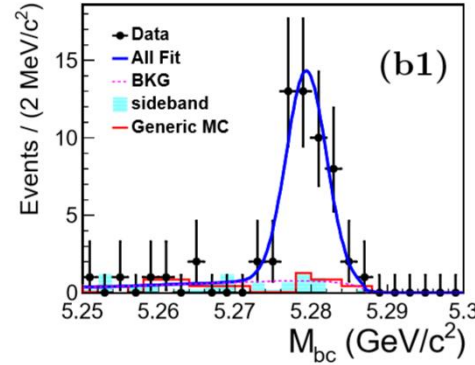
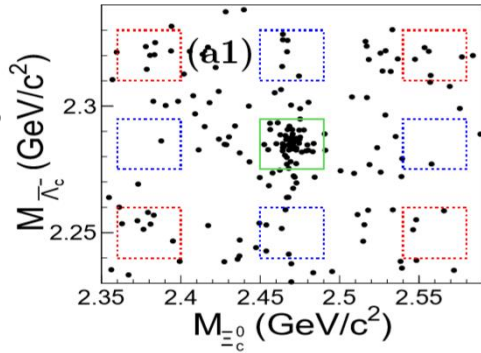
$$\Xi_c^0 \rightarrow \Xi^- \pi^+; \Xi_c^0 \rightarrow \Lambda K^- \pi^+; \Xi_c^0 \rightarrow p K^- K^- \pi^+$$

preliminary

$$\Xi^- \pi^+$$

$$44.8 \pm 7.3$$

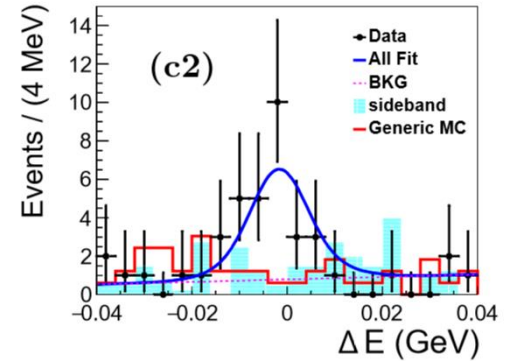
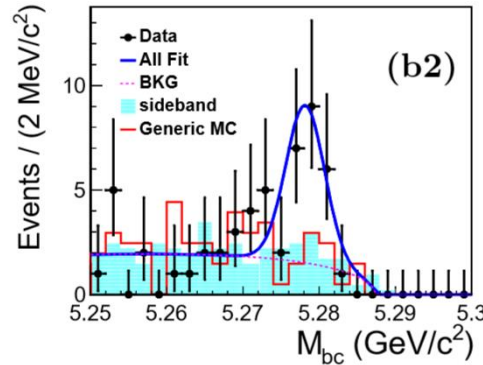
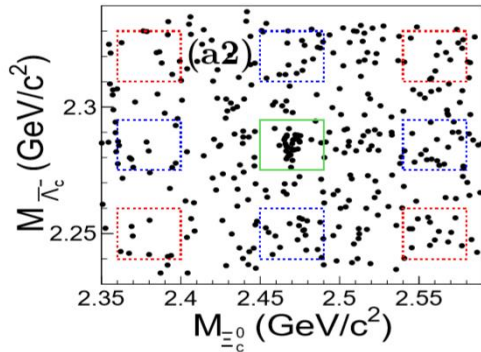
$$9.5\sigma$$



$$\Lambda K^- \pi^+$$

$$24.1 \pm 5.5$$

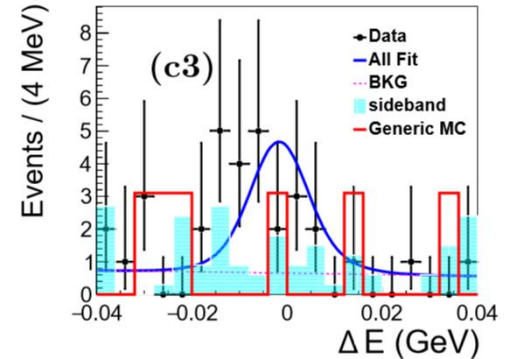
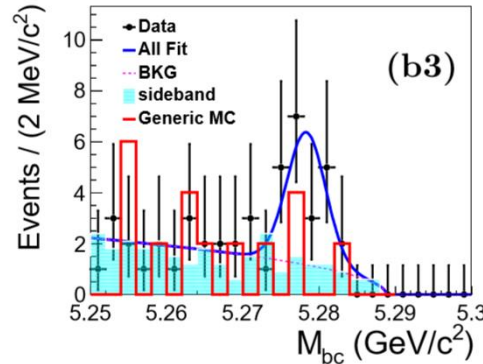
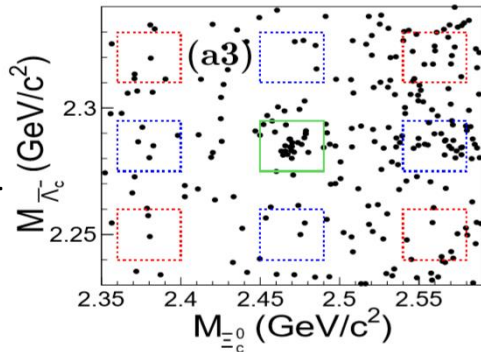
$$6.8\sigma$$



$$p K^- K^- \pi^+$$

$$16.6 \pm 5.4$$

$$4.6\sigma$$



Measurements of absolute Brs of Ξ_c^0

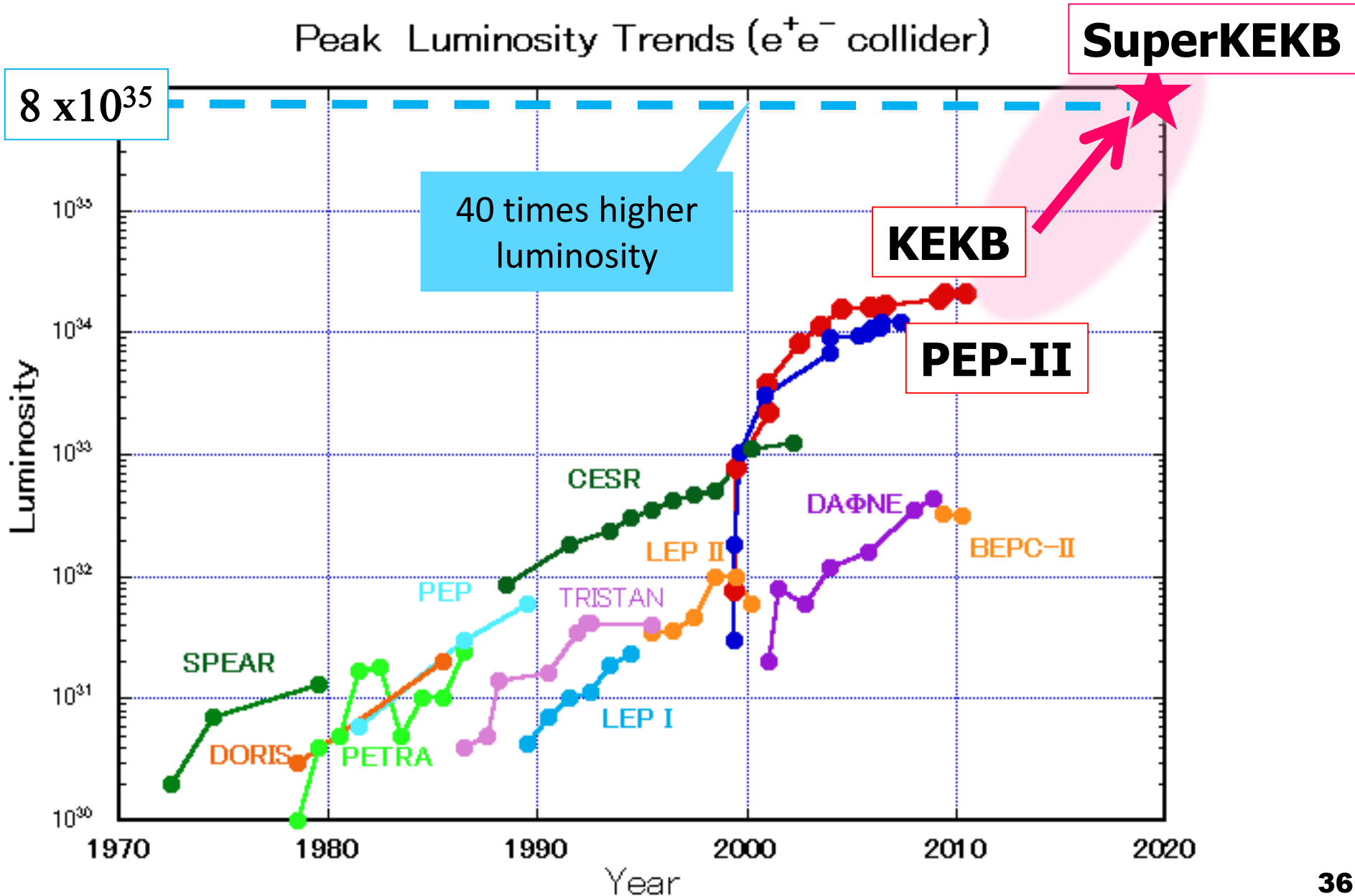
Summary of the measured branching fractions and the ratios of Ξ_c^0 decays

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

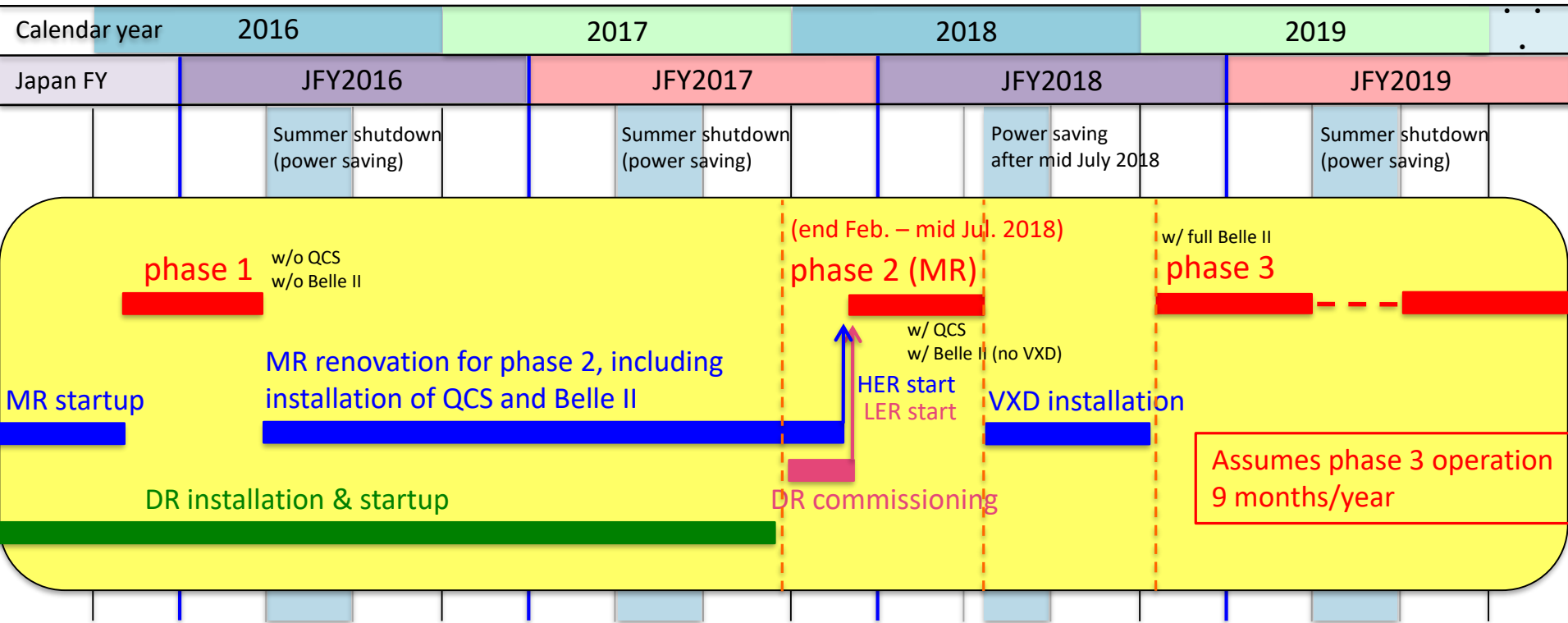
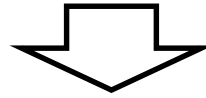
↑
PDG
↓

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

Need $O(100x)$ more data → Next generation B-factories

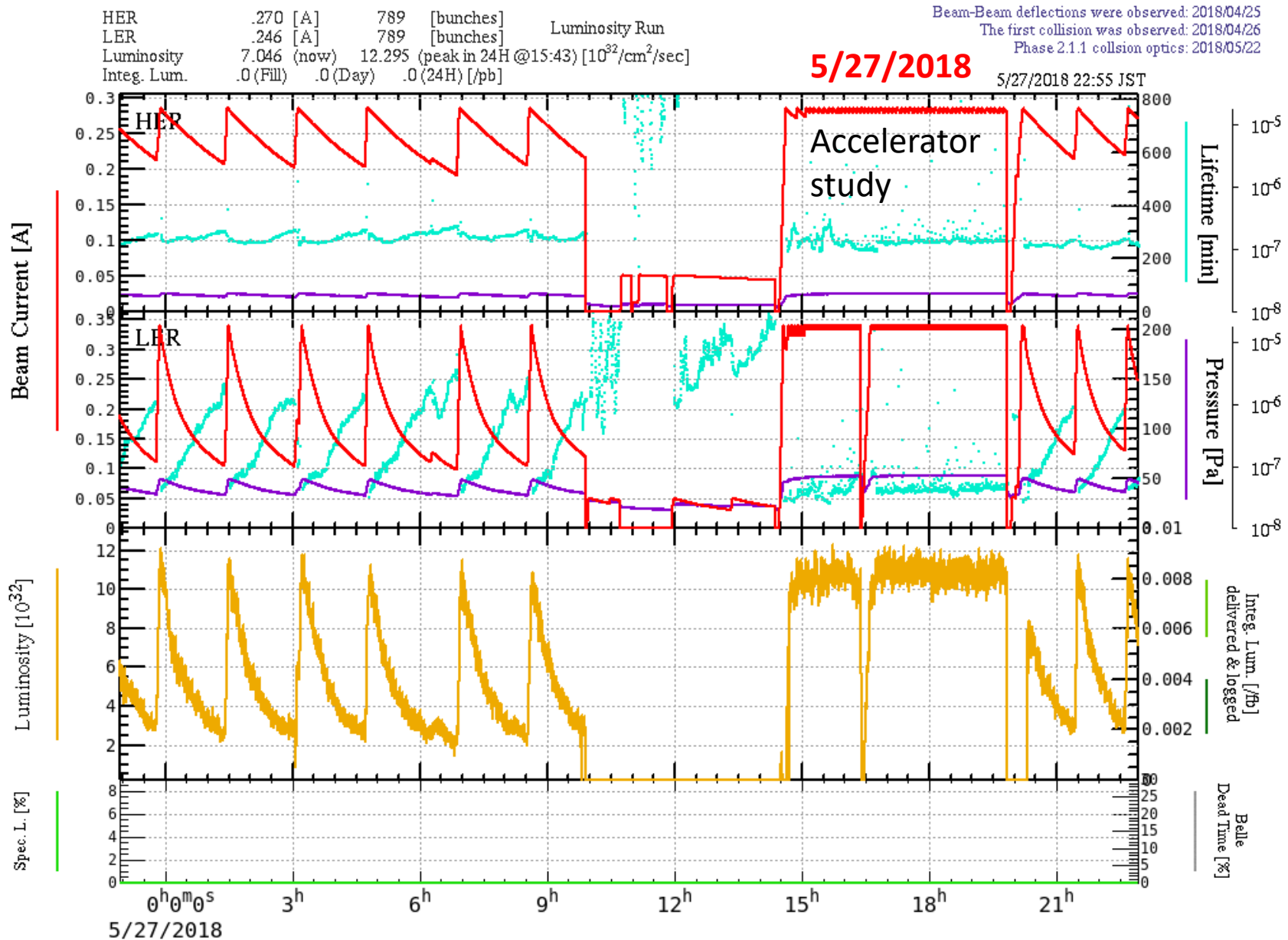


SuperKEKB/Belle II schedule Oct. 2017



- **Phase I:** commissioning of the main ring; installation of outer detectors; vacuum scrubbing and beam bkg. studies
- **Phase 2:** start of the collisions, detector commissioning without vertex detector; first physics runs on Y(4S) and Y(6S) ($\sim 20 \pm 20 \text{ fb}^{-1}$) [now- July 2018]
- **Phase 3:** full detector operation in the end of 2018

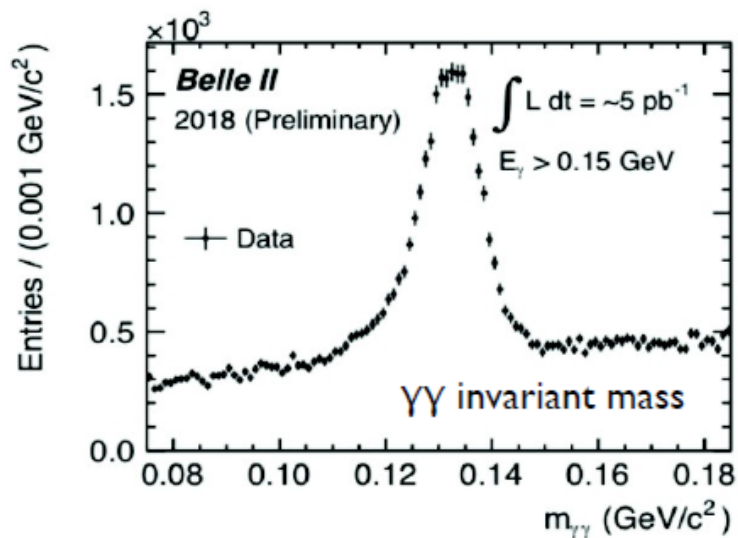
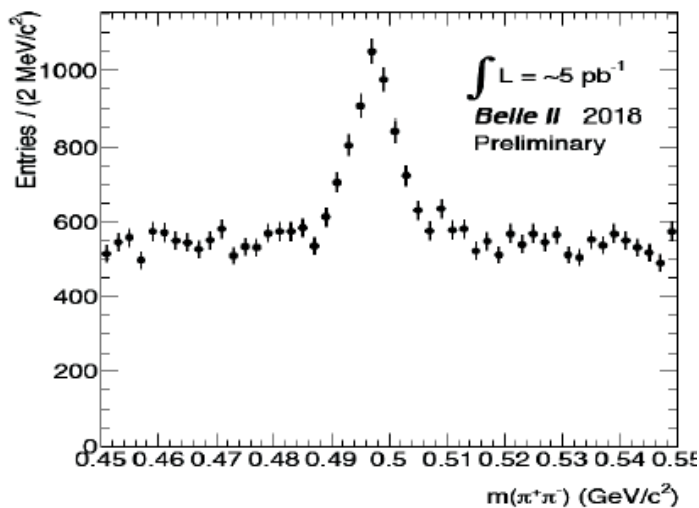
SuperKEKB operation status



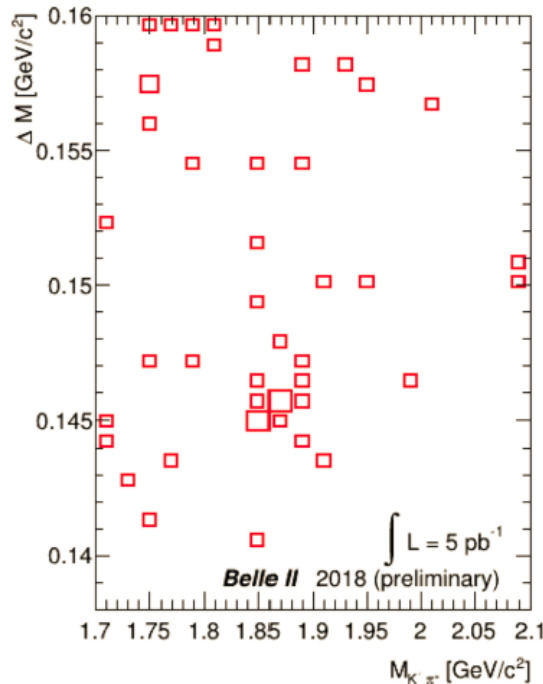
First Preliminary Study with Data (5 pb⁻¹)

first bumps observed!

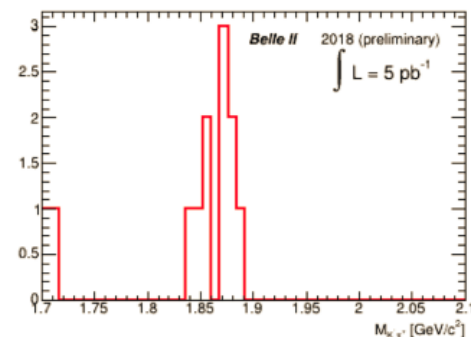
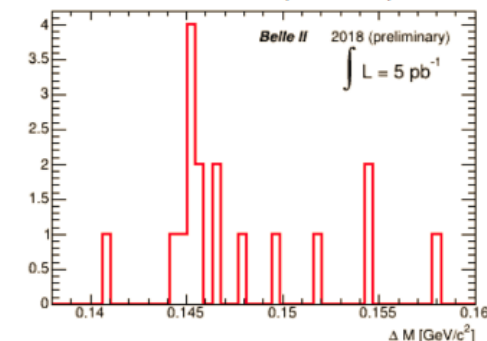
$\pi\pi\pi$ invariant mass



$D^* \rightarrow D^0(\rightarrow K^- \pi^+) \pi$



$1.845 < M(K\pi) < 1.885$
(GeV/c²)



$0.144 < \Delta M < 0.146$
(GeV/c²)



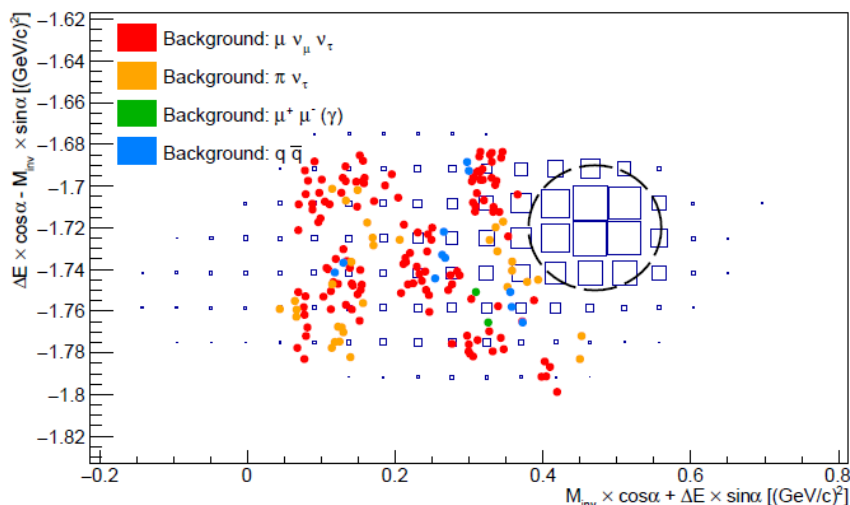
calibrations at a very early stage,
no PID cuts applied

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

1 ab⁻¹

arXiv:1808.10567



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

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

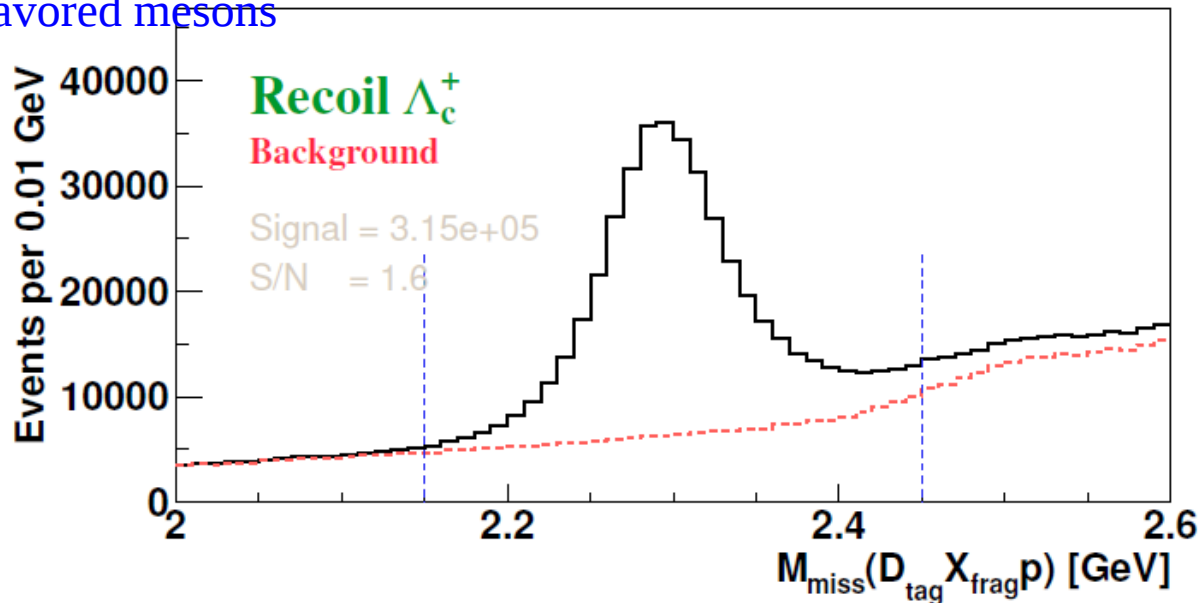
- Many things, but some of them can be done in Belle, too
 - We have not used the full potential of Belle data
- Examples include:
 - Search for more Y_c resonances in unsearched modes; e.g., $\Lambda_c \eta$
 - J^P measurements for Λ_c^* , Ξ_c^* , Ω_c^* ...; Partial wave analysis.
 - We can determine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

Inclusive $\Lambda_c^+ \rightarrow X$

$$e^+e^- \rightarrow D_{\text{tag}} X_{\text{frag}} p \Lambda_c^+$$

MC Simulation [5.5 ab^{-1}]

X_{frag} : a few unflavored mesons



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

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 $\Lambda_c^+ \rightarrow p K^+ \pi^-$
- Measurements of $\Lambda_c \rightarrow \Sigma \pi \pi$
- 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 $\Lambda_c^+ \rightarrow p \phi \pi^0$ 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 ...



thank you!