Recent Belle results on baryons and charmed baryons

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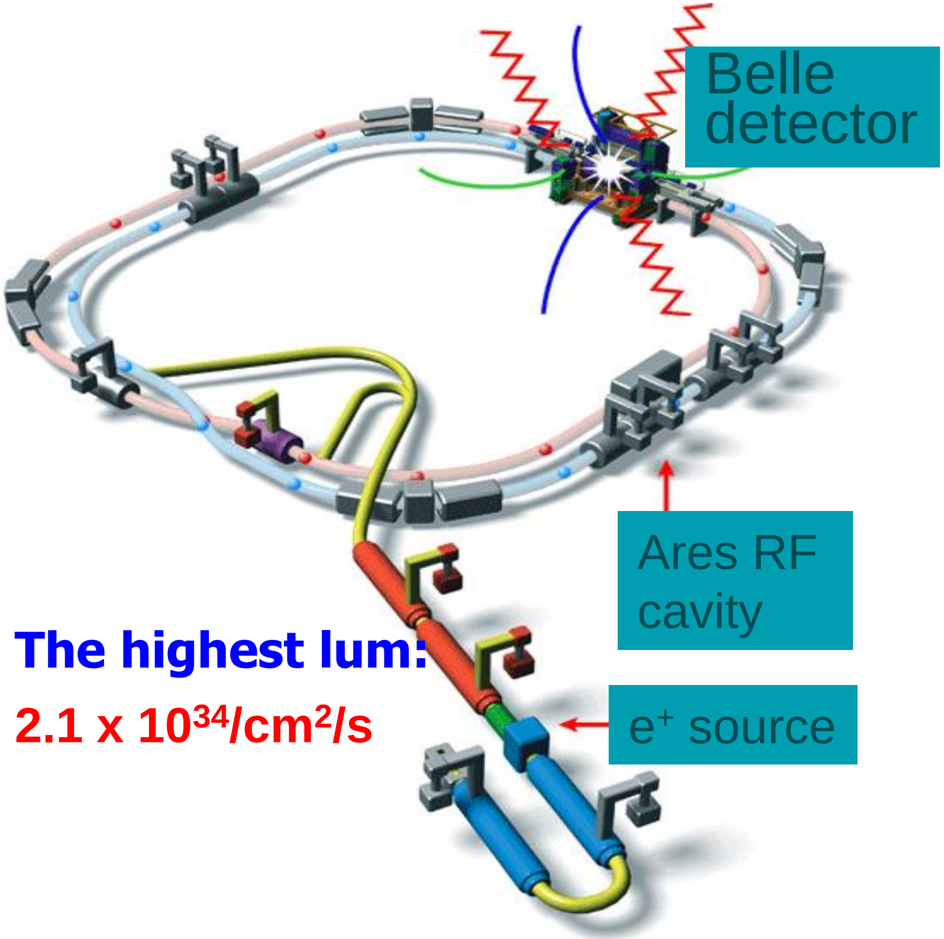
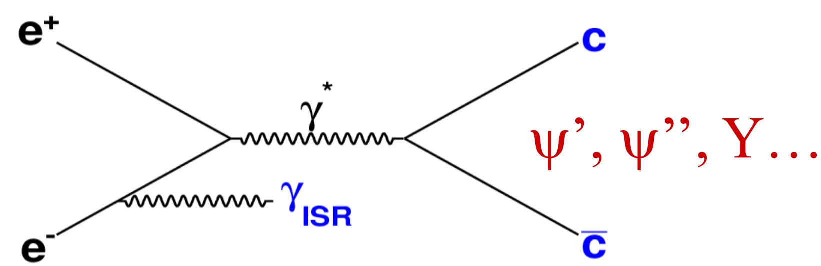
Belle experiment



The highest lum:

2.1 x 10^{34}/cm^2/s

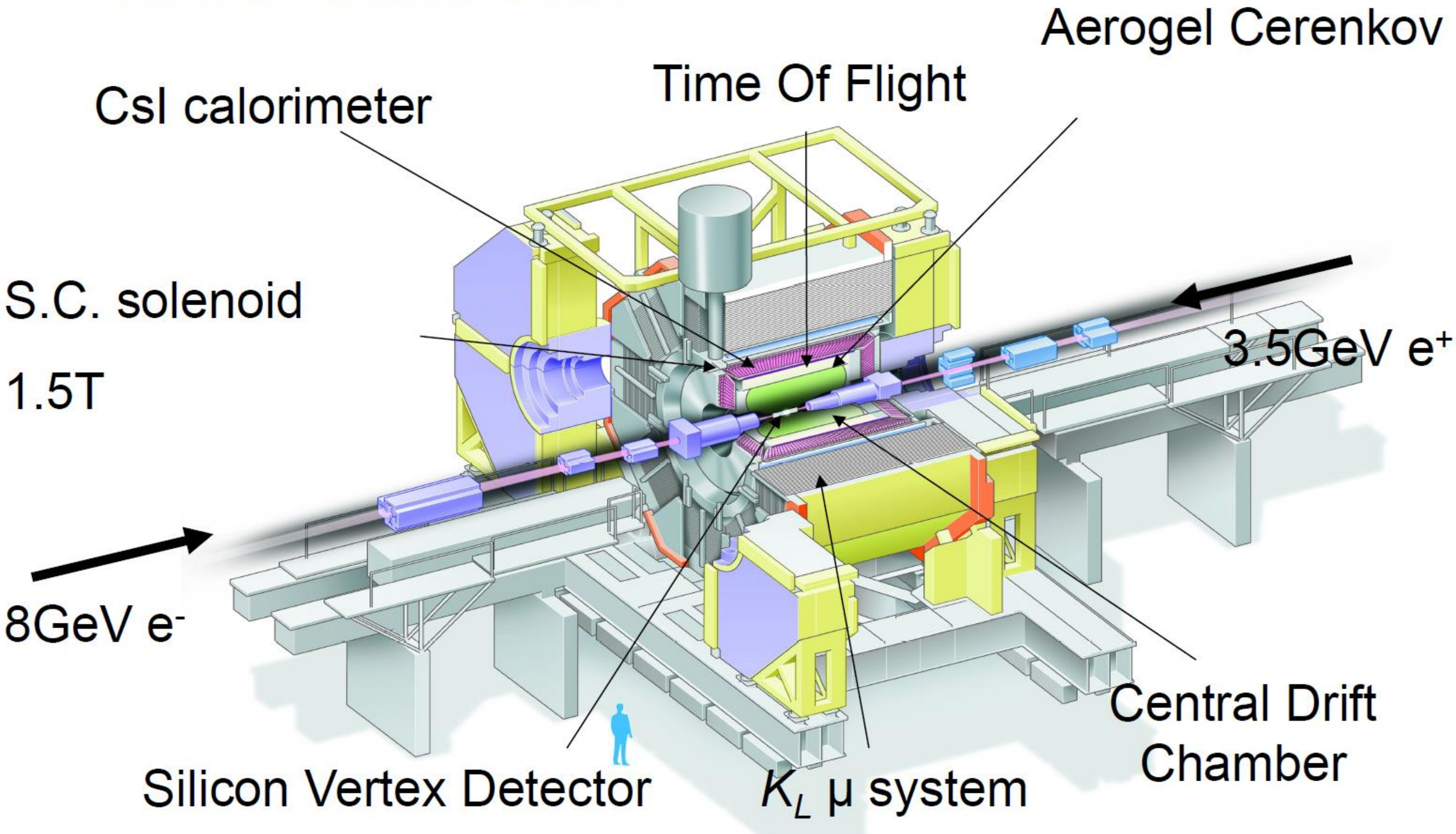
KEKB Collider



CMS energy
10.58 GeV

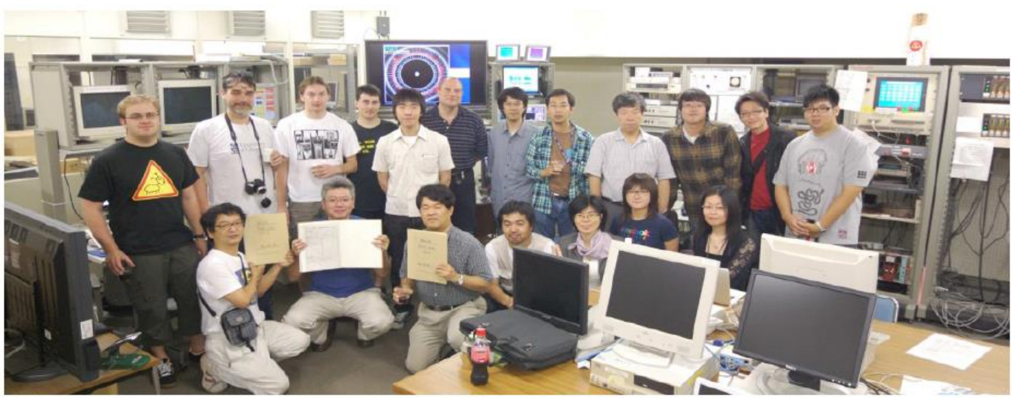
Effective CMS
3-5 GeV

Belle detector



High resolution, general purpose 4π *spectrometer with particle-id*

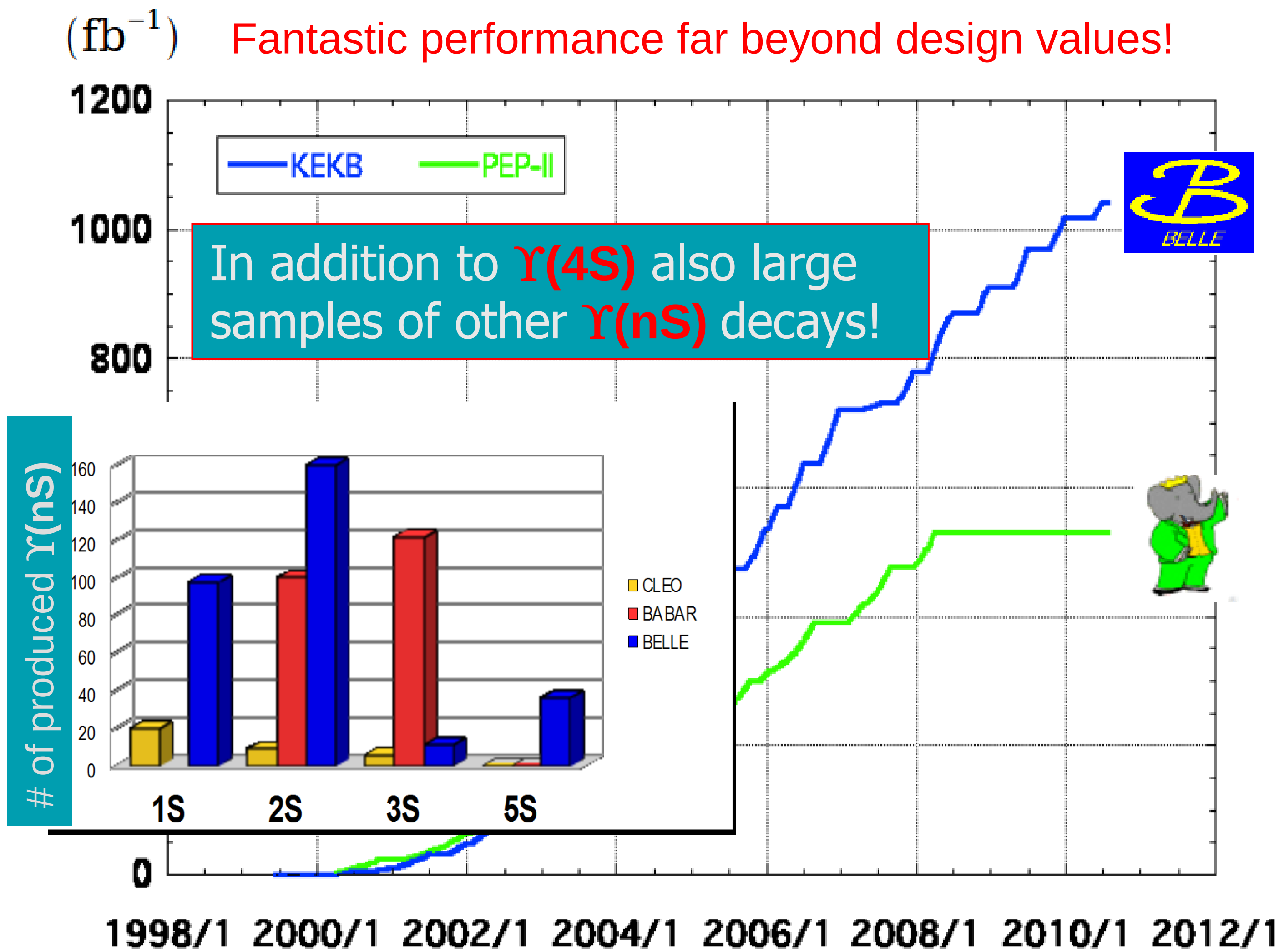
The last beam abort of KEKB on June 30, 2010



First physics run on June 2, 1999
Last physics run on June 30, 2010
$L_{peak} = 2.1x10^{34}/cm^2/s$
$L > 1ab^{-1}$

Integrated luminosity of B factories

Fantastic performance far beyond design values!



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

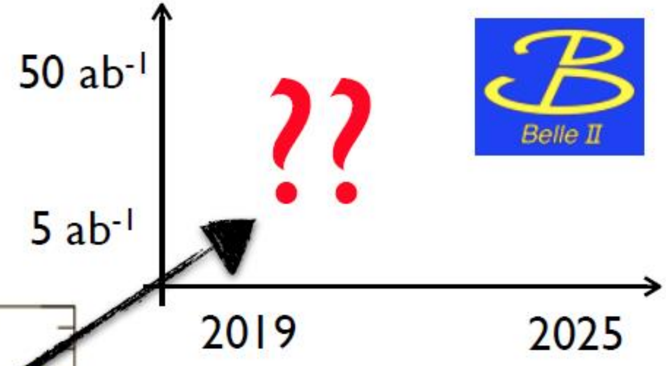
$\Upsilon(3S)$: 30 fb^{-1}

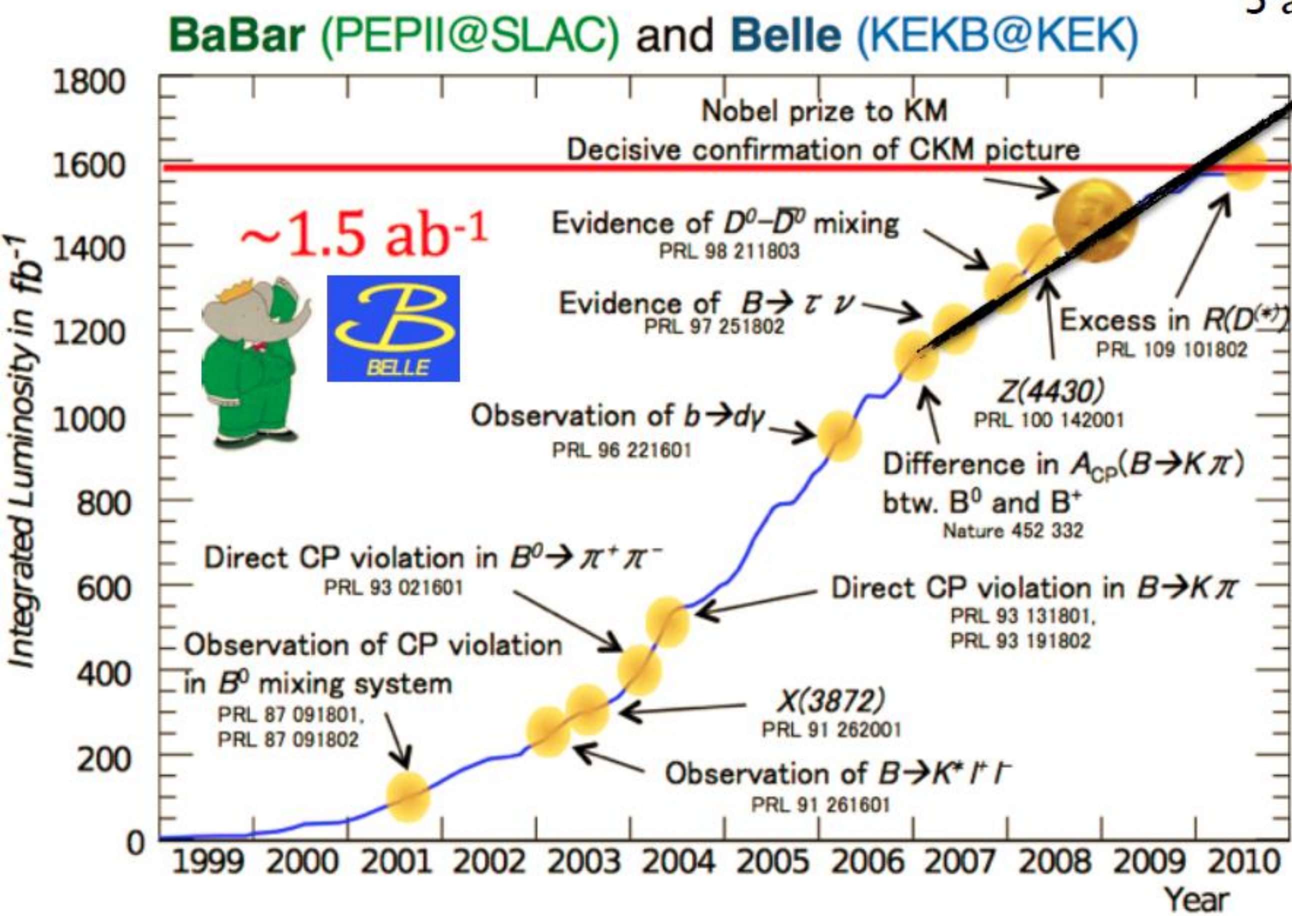
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

B-factories in the last decade





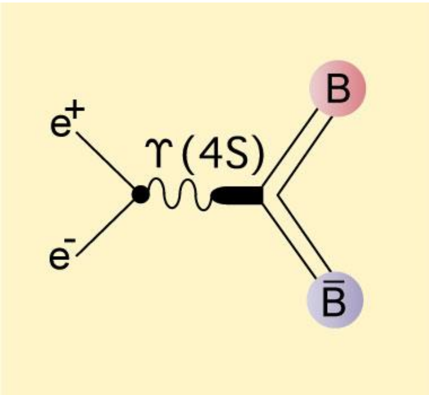
- Belle and BaBar have produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets

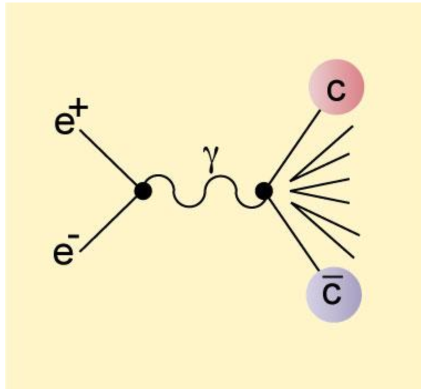
The Physics of B factories
EPJC 74, 3026 (2018)

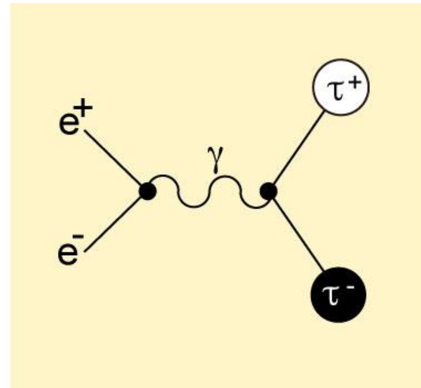
Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

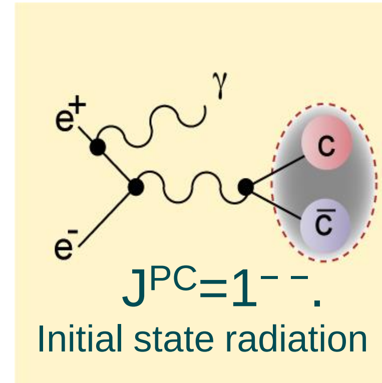
arXiv:1808.10567

The Physics Program







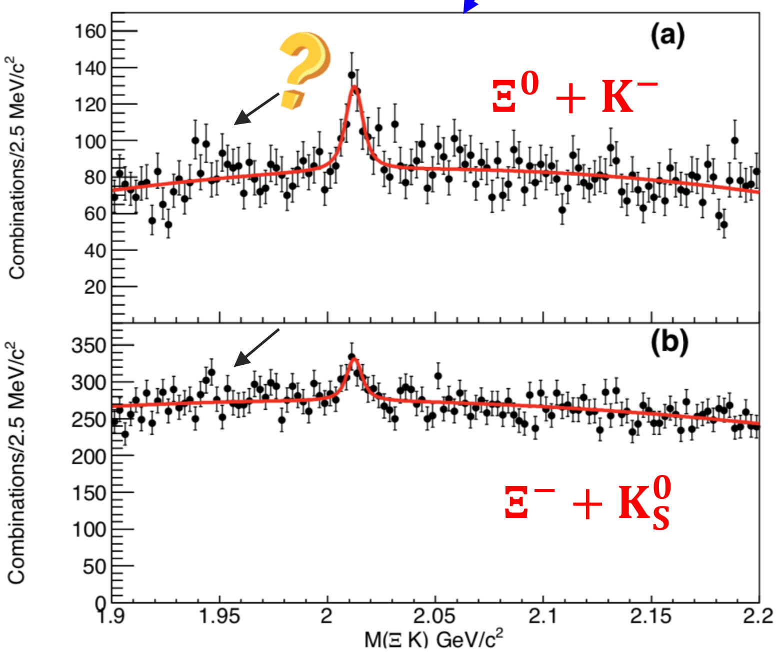


- a (Super) B-factory (~1.1 x 10^9 $B\bar{B}$ pairs per ab^{-1});
- a (Super) charm factory (~1.3 x 10^9 $c\bar{c}$ pairs per ab^{-1});
- a (Super) τ factory (~0.9 x 10^9 $\tau^+\tau^-$ pairs per ab^{-1});
- thanks to the Initial State Radiation, we can effectively scan the range [0.5 – 10] GeV and measure 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, …

Observation of an excited Ω^- baryon

$$\mathcal{R} = \frac{\mathcal{B}(\Omega^{*-}\to\Xi^0 K^-)}{\mathcal{B}(\Omega^{*-}\to\Xi^-\bar{K}^0)} = 1.2\pm0.3$$

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 in other Ω^- excited states, which is closer 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 the three strange quarks, whose quantum numbers are $J^P = \frac{3}{2}^-$.

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, ...]

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

From PRD 98, 056013 (2018)

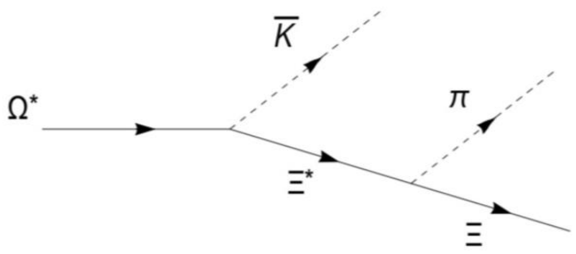
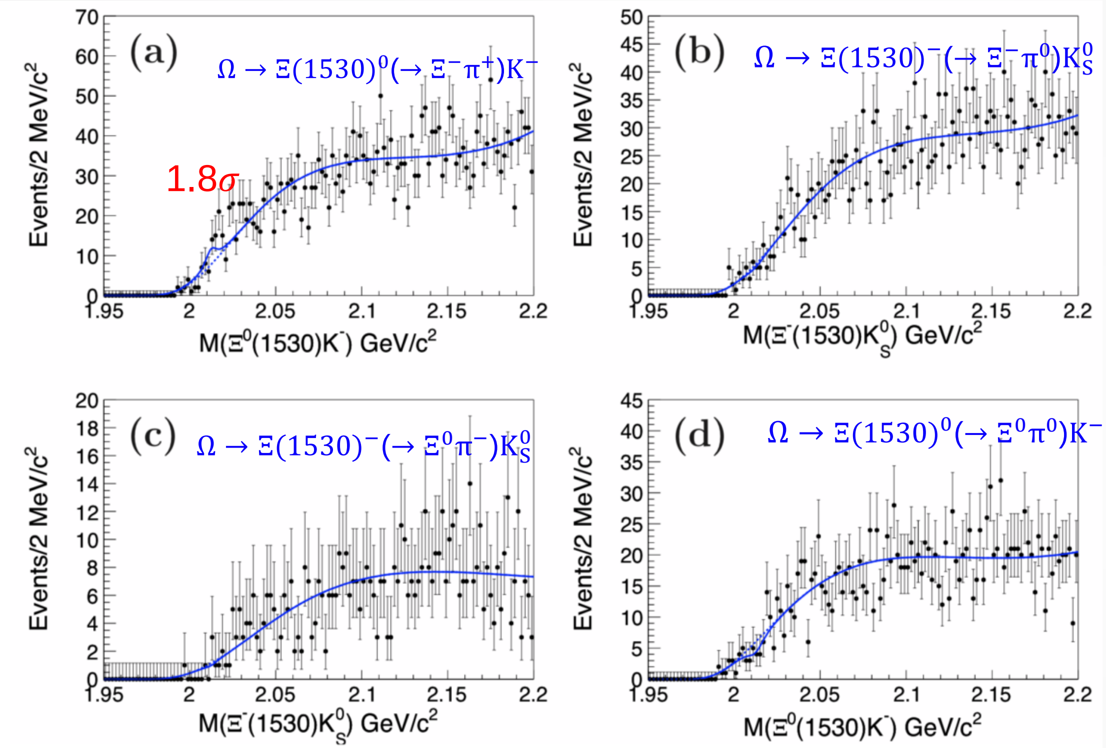


FIG. 1: The three-body decays of Ω(2012) in the $K\Xi(1530)$ molecular picture.

Mode	$J^P = \frac{3}{2}^-$ Ω(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

Search for $\Omega(2012) \to K\Xi(1530) \to K\pi\Xi$

We use the same data samples to search for $\Omega(2012) \to K\Xi(1530) \to K\pi\Xi$ in the decay of the narrow resonances $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$.



Mode	N^{Fit}	N^{UL}
$\Omega \to \Xi(1530)^0(\to \Xi^-\pi^+)K^-$	22.5±12.9	41.0
$\Omega \to \Xi(1530)^-(\to \Xi^-\pi^0)K^0_S$	-3.5±11.6	16.6
$\Omega \to \Xi(1530)^-(\to \Xi^0\pi^-)K^0_S$	-1.0±3.6	7.2
$\Omega \to \Xi(1530)^0(\to \Xi^0\pi^0)K^-$	-12.0±9.8	13.2

No clear $\Omega(2012)$ signals are observed.
We give the upper limits on the ratios of the branching fractions at 90% C.L. as below.

$$R^{\Xi^-\pi^+K^-}_{\Xi^-\bar{K}^0} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^0(\to \Xi^-\pi^+)K^-)}{\mathcal{B}(\Omega \to \Xi^-\bar{K}^0)} < 9.3\%$$

$$R^{\Xi^-\pi^0\bar{K}^0}_{\Xi^-\bar{K}^0} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^-(\to \Xi^-\pi^0)\bar{K}^0)}{\mathcal{B}(\Omega \to \Xi^-\bar{K}^0)} < 81.1\%$$

$$R^{\Xi^0\pi^-\bar{K}^0}_{\Xi^0K^-} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^-(\to \Xi^0\pi^-)\bar{K}^0)}{\mathcal{B}(\Omega \to \Xi^0K^-)} < 21.3\%$$

$$R^{\Xi^0\pi^0K^-}_{\Xi^0K^-} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^0(\to \Xi^0\pi^0)K^-)}{\mathcal{B}(\Omega \to \Xi^0K^-)} < 30.4\%$$

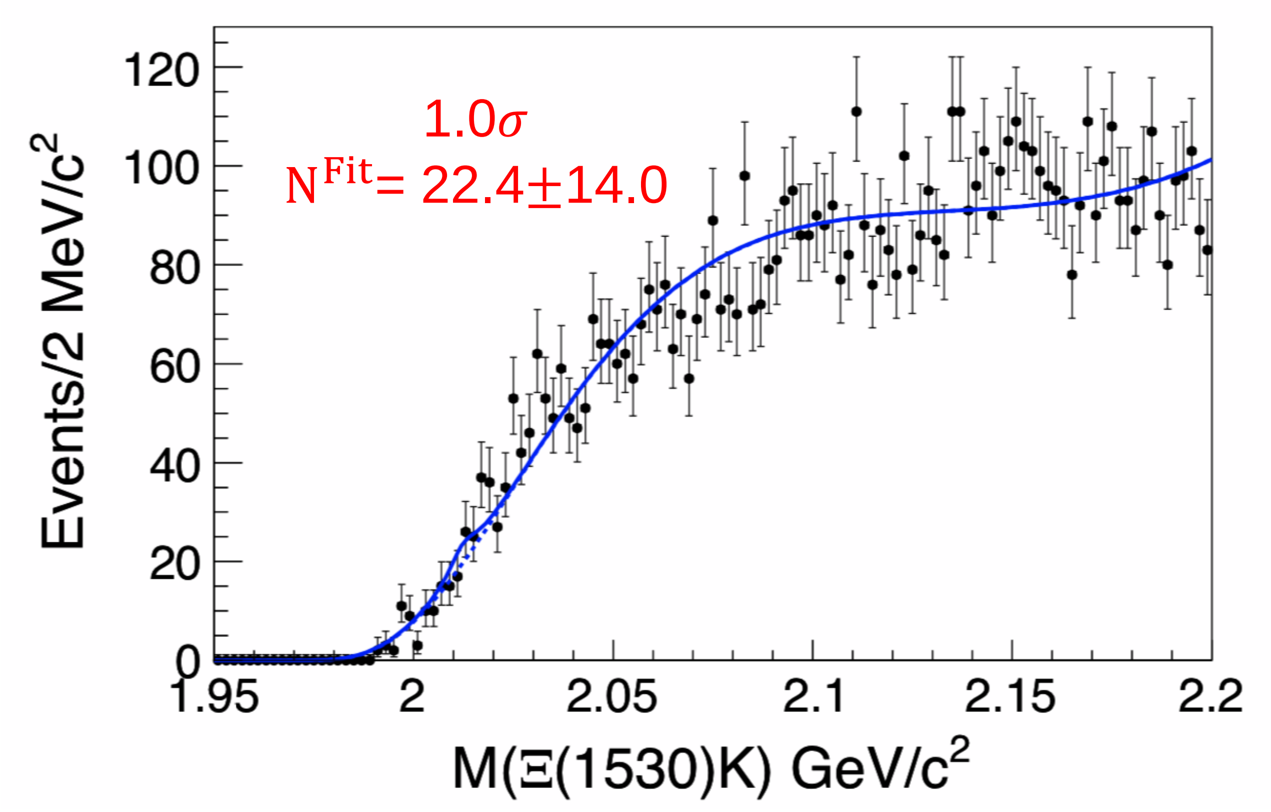
$$R^{\Xi^-\pi^+K^-}_{\Xi^0K^-} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^0(\to \Xi^-\pi^+)K^-)}{\mathcal{B}(\Omega \to \Xi^0K^-)} < 7.8\%$$

$$R^{\Xi^0\pi^-\bar{K}^0}_{\Xi^-\bar{K}^0} = \frac{\mathcal{B}(\Omega \to \Xi(1530)^-(\to \Xi^-\pi^0)\bar{K}^0)}{\mathcal{B}(\Omega \to \Xi^-\bar{K}^0)} < 25.6\%$$

S.Jia, *C.P.Shen et al (Belle)
PRD 100, 032006 (2019)

Search for $\Omega(2012) \rightarrow K\Xi(1530) \rightarrow K\pi\Xi$

A simultaneous fit to all three-body decay modes is performed.



$$R_{\Xi K}^{\Xi\pi K} = \frac{\mathcal{B}(\Omega\rightarrow\Xi(1530)(\rightarrow\Xi\pi)K)}{\mathcal{B}(\Omega\rightarrow\Xi K)} = (6.0\pm3.7(\text{stat.})\pm1.3(\text{syst.}))\%$$

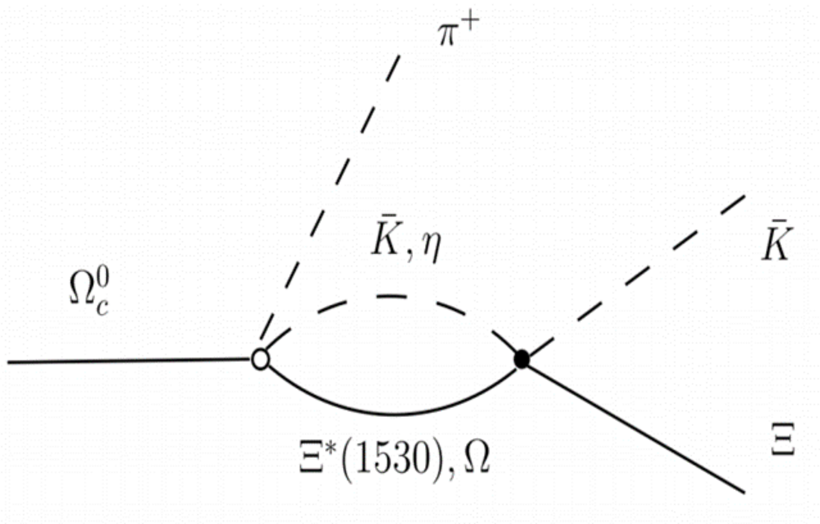
$$R_{\Xi K}^{\Xi\pi K} = \frac{\mathcal{B}(\Omega\rightarrow\Xi(1530)(\rightarrow\Xi\pi)K)}{\mathcal{B}(\Omega\rightarrow\Xi K)} < 11.9\% \text{ at } 90\% \text{ C.L.}$$

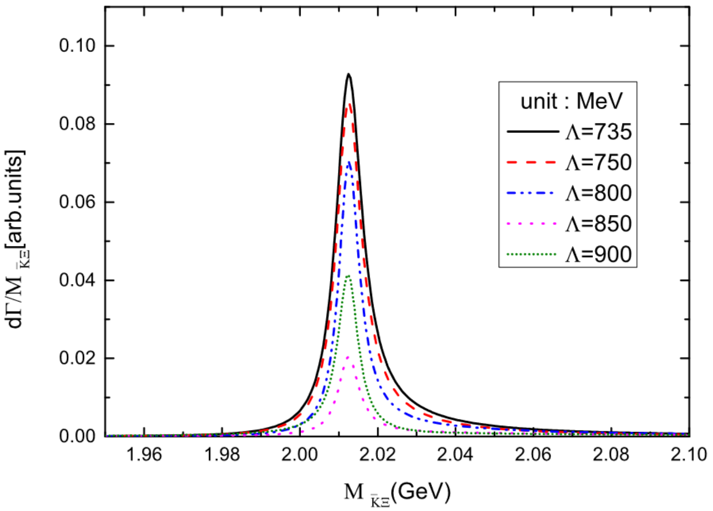
Evidence for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

Motivation:

- Searching for new production model is very important to understand the nature of $\Omega(2012)^-$;
- A theoretical study of the $\Omega(2012)^-$ in the nonleptonic weak decays of $\Omega_c^0 \to \pi^+\bar{K}\,\Xi(1530)(\eta\Omega) \to \pi^+(\bar{K}\pi\Xi)^-$ and $(\bar{K}\Xi)^-$was reported; the authors predicted the clearly $\Omega(2012)^-$peak in the $(\bar{K}\Xi)^-$ invariant mass spectrum of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$.

[PRD 102, 076009 (2020)]

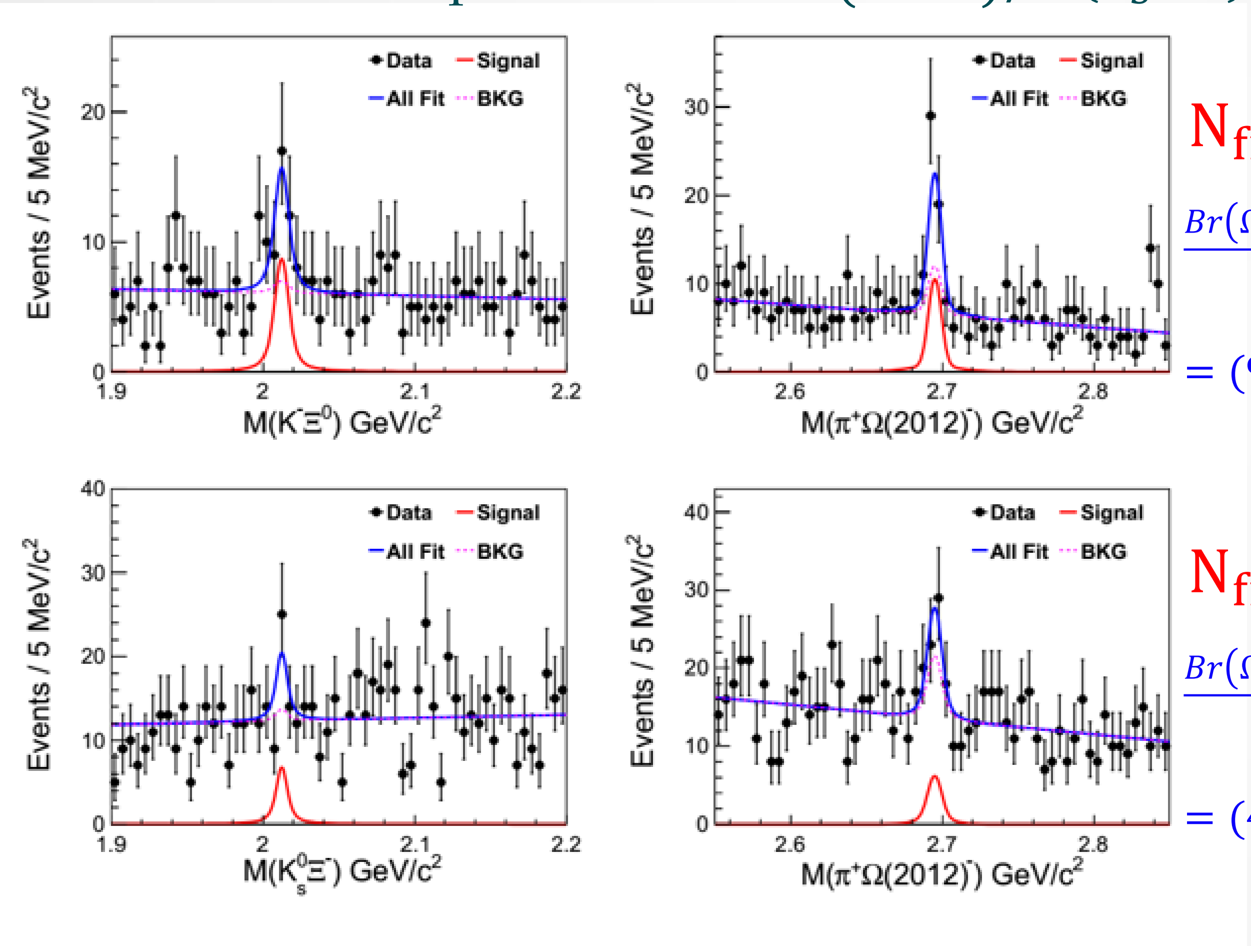




Evidence for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

Phys. Rev. D 104, 052005 (2021)

- To extract the $\Omega(2012)^-$ signal events from Ω_c^0 decay, a 2D maximum-likelihood fit is performed to $M(\mathrm{K}^-\Xi^0)/M(K_S^0\Xi^-)$ and $M(\pi^-\Omega(2012))$.



$$N_{\mathrm{fit}}(\mathrm{K}^-\Xi^0) = 28.3 \pm 8.9$$

$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-)Br(\Omega(2012)^- \to K^-\Xi^0)}{Br(\Omega_c^0 \to \pi^+K^-\Xi^0)}$$

$$= (9.64 \pm 3.04(\mathrm{stat.}) \pm 1.89(\mathrm{syst.}))\%$$

$$N_{\mathrm{fit}}(\mathrm{K}_S^0\Xi^-) = 17.9 \pm 8.9$$

$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-)Br(\Omega(2012)^- \to \bar{K}^0\Xi^-)}{Br(\Omega_c^0 \to \pi^+\bar{K}^0\Xi^-)}$$

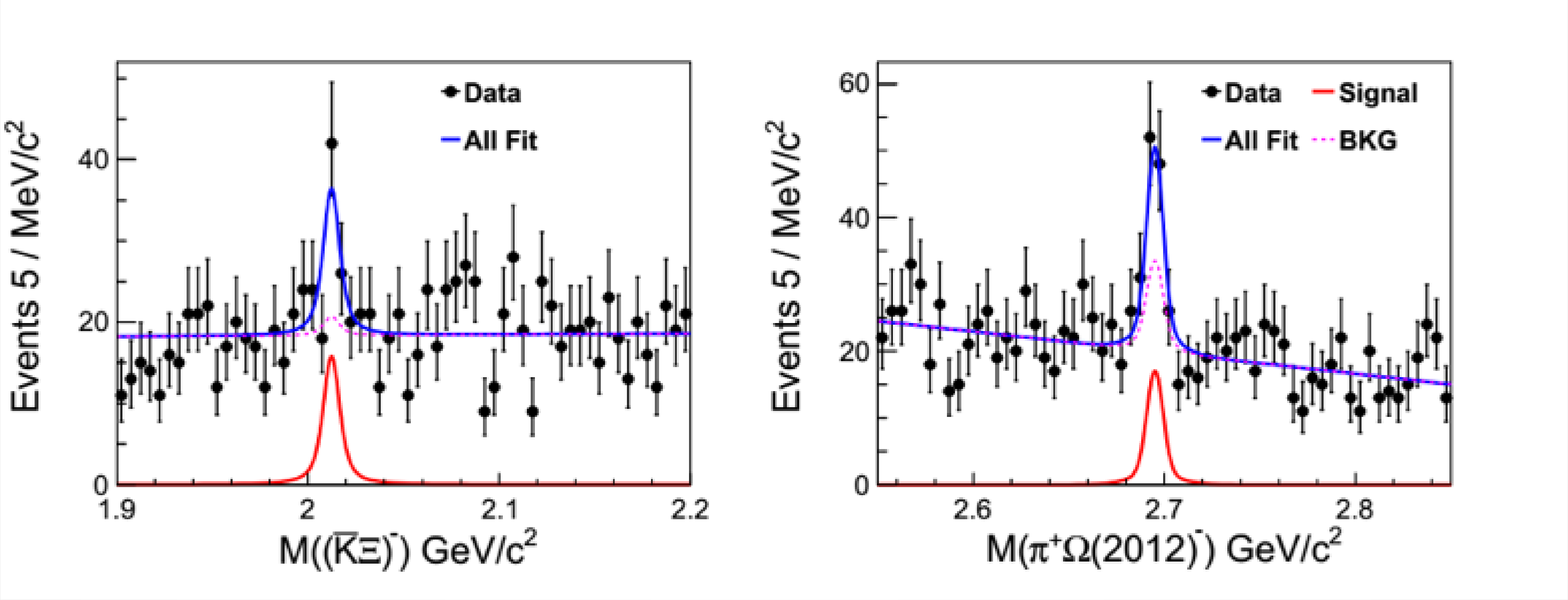
$$= (4.62 \pm 2.30(\mathrm{stat.}) \pm 0.75(\mathrm{syst.}))\%$$

- The statistical significances of $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K^-\Xi^0$ and $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K_S^0\Xi^-$ decays are 4.0σ and 2.3σ, respectively.

Evidence for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

Phys. Rev. D 104, 052005 (2021)

- A 2D un-binned maximum-likelihood simultaneous fit is performed to $M((\bar{K}\Xi)^-)$ and $M(\pi^+\Omega(2012)^-)$ distributions.



$N_{fit} = 46.6 \pm 12.3$

Signal significance: 4.2σ

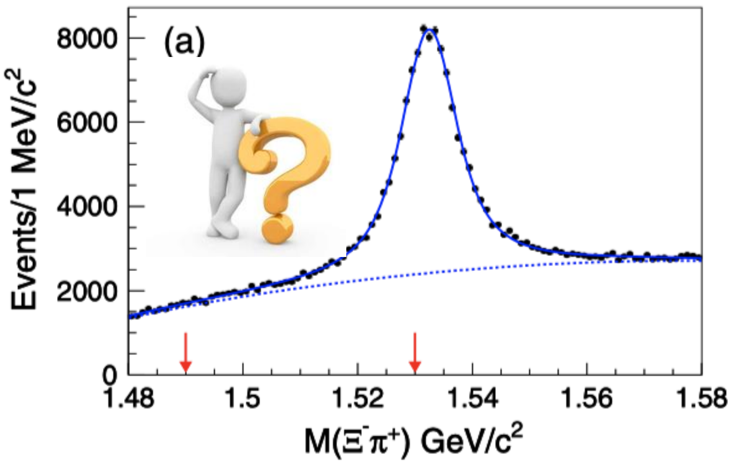
(including systematic uncertainties)

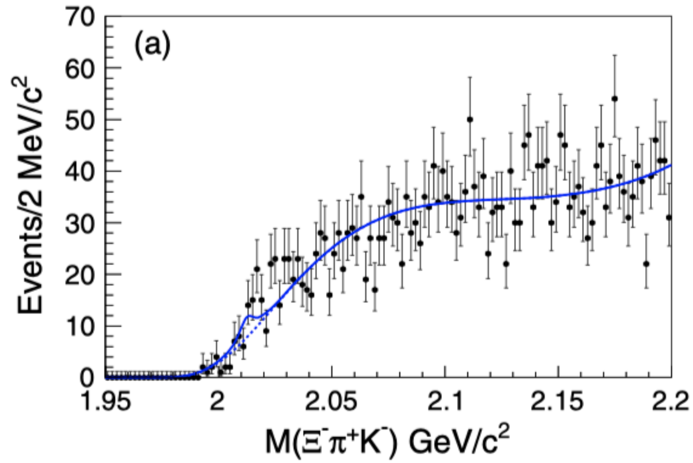
$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times Br(\Omega(2012)^- \to (\bar{K}\Xi)^-)}{Br(\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-)} = (6.50 \pm 1.22(\text{stat.}) \pm 0.94(\text{syst.}))\%$$

Revisit Ω(2012) → KΞ(1530) → KπΞ at Belle

The previous results [PRD 100, 032006 (2019)]:

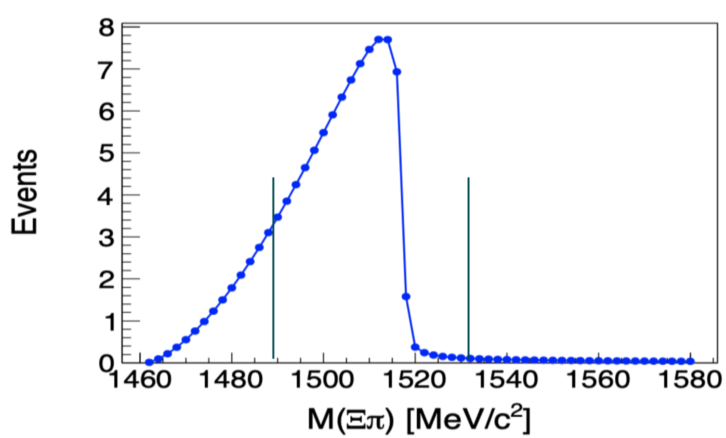
$$\mathcal{R}^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)(\to \Xi\pi)K)}{\mathcal{B}(\Omega(2012) \to \Xi K)} < 11.9\% \text{ at } 90\% \text{ C.L.}$$

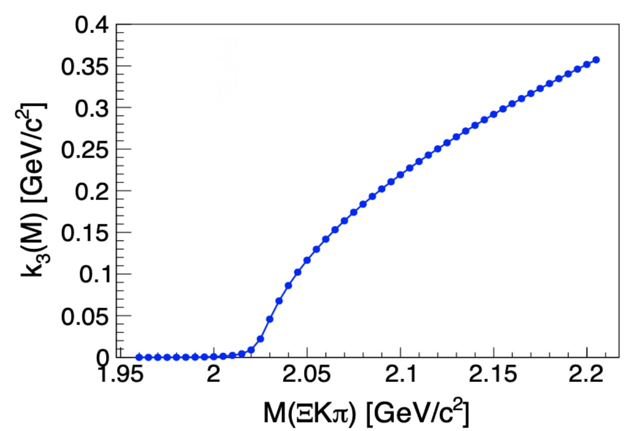




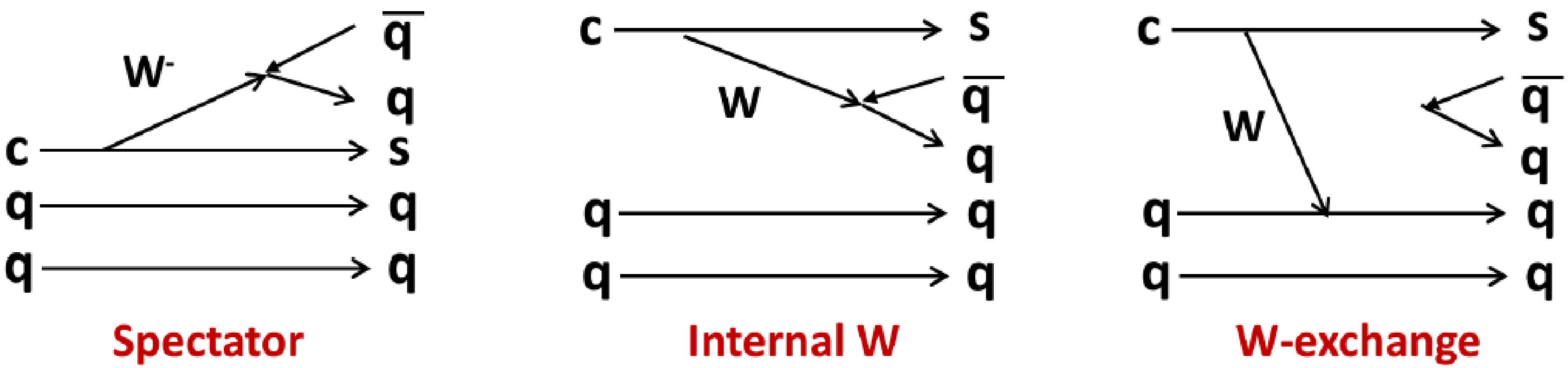
However, we realized that (1) the requirement of M(Ξπ) includes large non-Ξ(1530) decay backgrounds; (2) not consider a three-body phase space in M(KπΞ), which increases sharply due to the unstable Ξ(1530) constituent.

The expected M(Ξπ) lineshape and three-body phase space are shown below according to Ref. [PRD 81, 094028 (2010)].



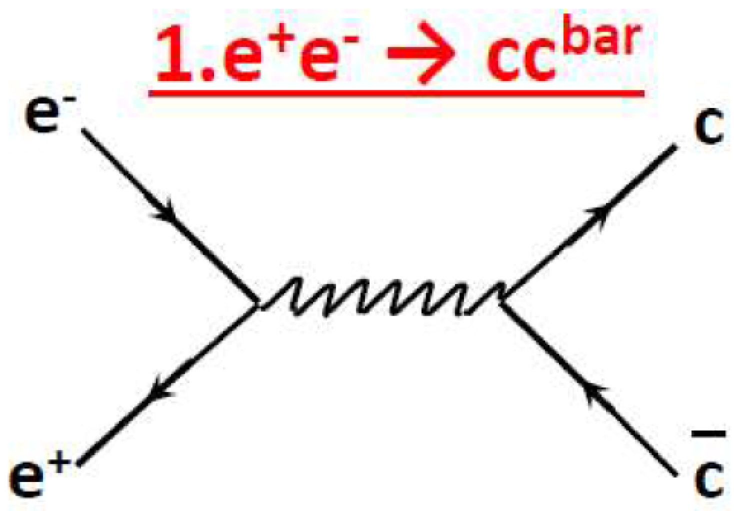


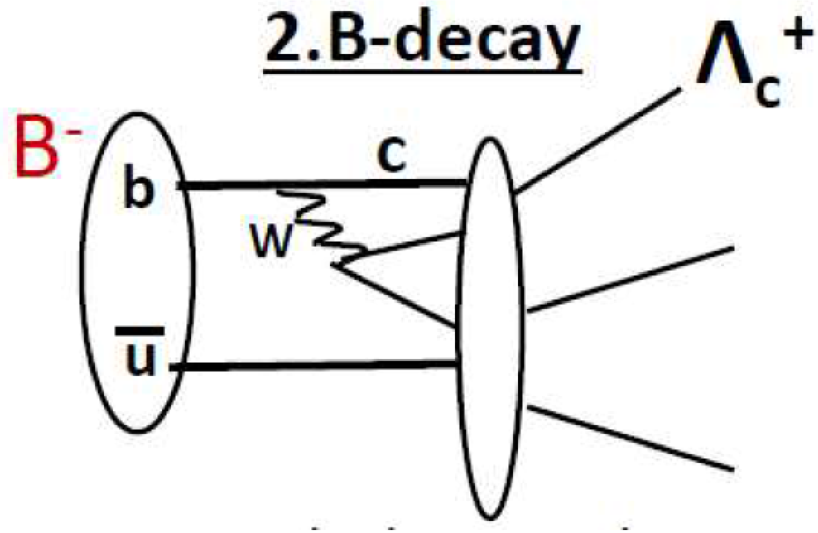
The Charmed Baryon Physics



- 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





Baryons produced via fragmentation

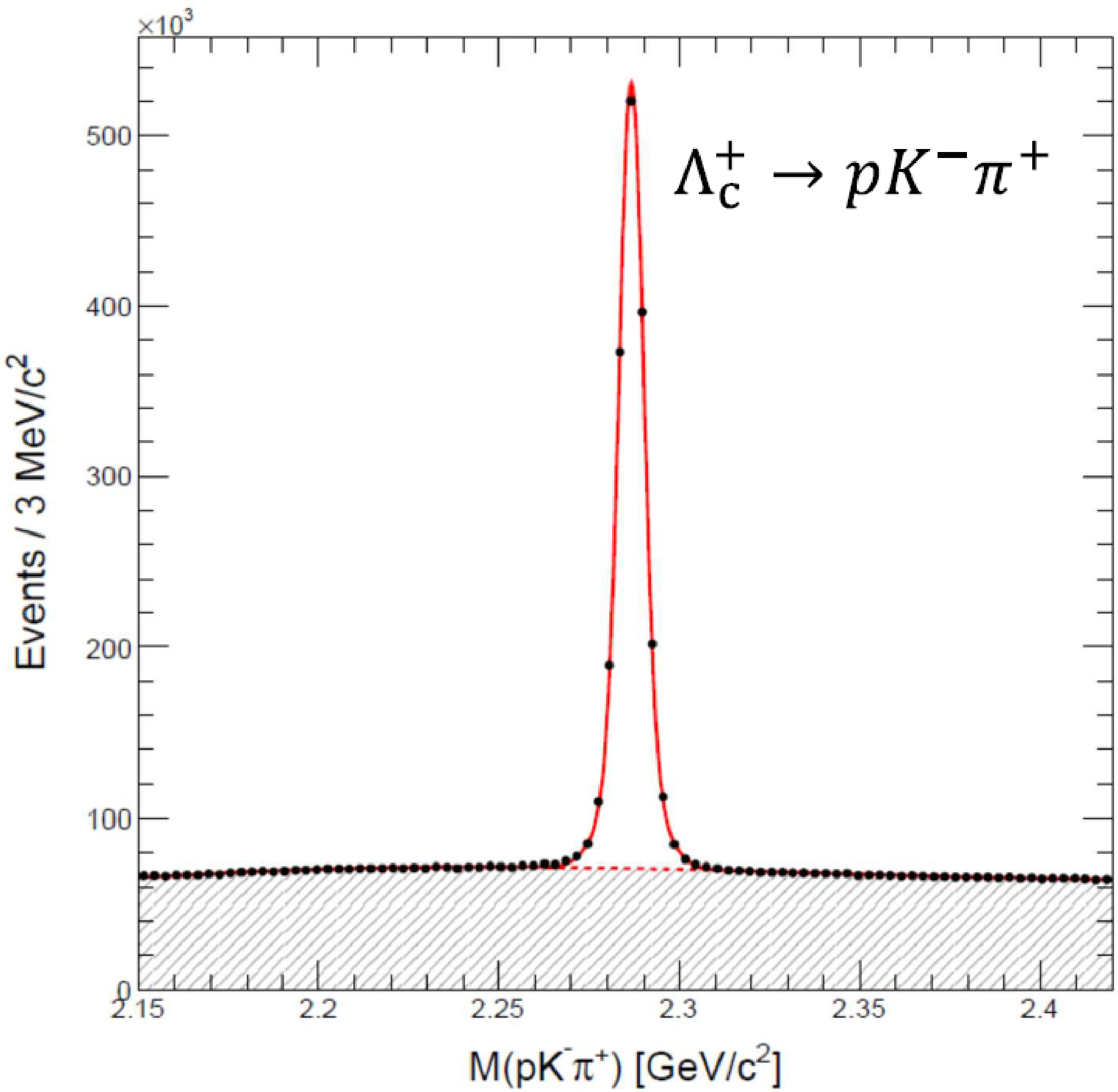
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

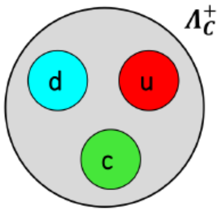
Huge statistics

B is efficiently produced via Υ(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

$B(\Lambda_c^+ \to pK^-\pi^+)$:
$(5.84 \pm 0.27 \pm 0.23)\%$
BESIII 2016

$(6.84 \pm 0.24^{+0.21}_{-0.27})\%$
Belle 2014

Measurements of Branching Fractions of $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\eta$ decays at Belle

Motivation:

- **The weak decay of charmed baryons is very useful for testing many contradictory theoretical models and methods**. However, the cognition and exploration of charmed baryon goes pretty slowly.
- The precision of measurement of the decay branching fraction remains poor for many Cabibbo-favored (CF) decays and even worse for some decays dominated by Cabibbo-suppressed even though many different experiments like Belle and BESIII have hard work on improving the measurement results of charmed baryons.
- In theory, the singly Cabibbo-suppressed (SCS) decays $\boldsymbol{\Lambda_c^+ \to p\pi^0}$ and $\boldsymbol{\Lambda_c^+ \to p\eta}$ proceed dominantly through internal W-emission and W-exchange. The measurement of these two decay branching fractions may **be interesting to study the underlying dynamic of charmed baryon decays.**
- In experiment, BESIII report the branching fractions of these two SCS decays, which are $\boldsymbol{B(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4}}$ at 90% confidence level and $\boldsymbol{B(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.30) \times 10^{-3}}$.
- In this analysis, we utilize the much higher statistic sample of Λ_c^+ collected by Belle detector to improve the measurement precision.

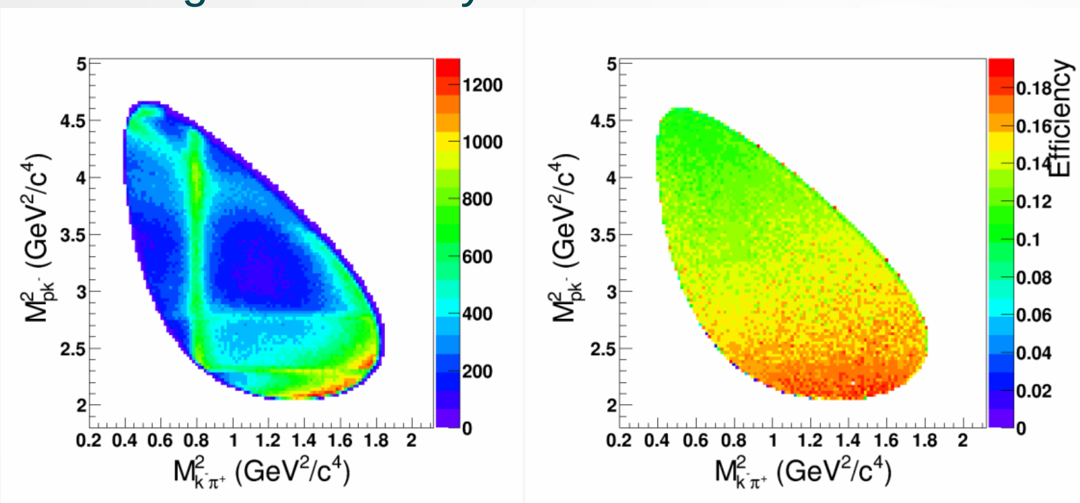
Measurement of $\Lambda_c^+ \to pK^-\pi^+$ decay

PRD103, 072004 (2021)

A method of branching ratio with respect to CF decay $\Lambda_c^+ \to pK^-\pi^+$ (reference mode) is applied to measure the branching fractions of two SCS decays.

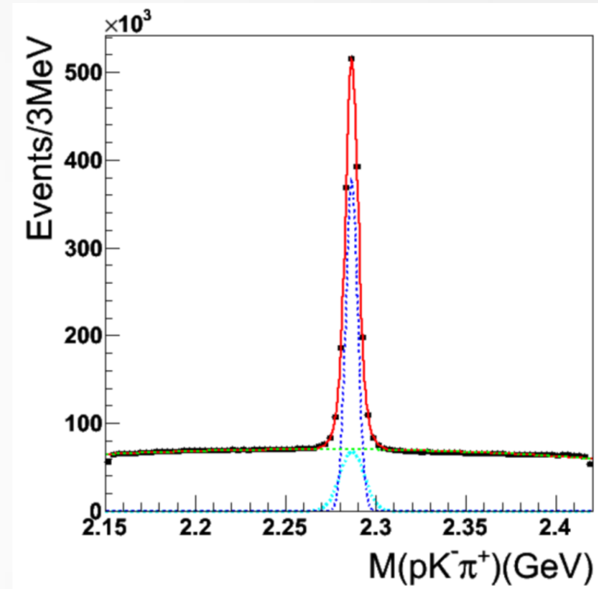
$$\frac{B(SCS)}{B(CF)} = \frac{N^{obs}(SCS)}{\epsilon^{MC}(SCS)} \times \frac{\epsilon^{MC}(CF)}{N^{obs}(CF)}$$

Signal efficiency estimation: Dalitz method.



Left: Dalitz plot from data; Right: Dalitz plot of efficiency from signal MC.

$$\varepsilon = \sum s_i / \sum_j (s_j/\varepsilon_j) = (14.06 \pm 0.01)\ \%.$$



Fit to M($pK^-\pi^+$) from data.

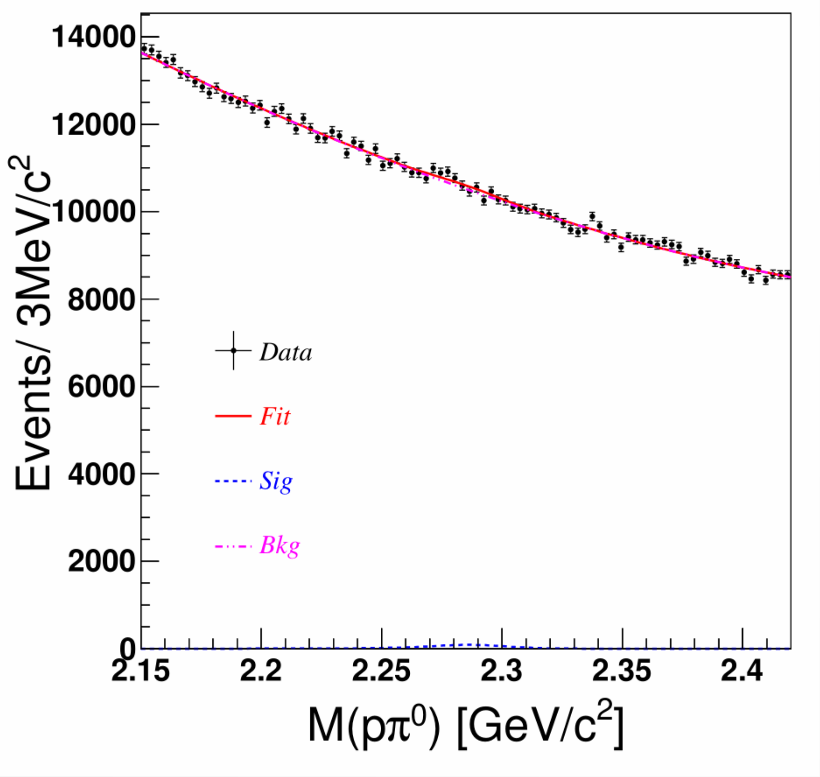
double Gaussian + second-order polynomial

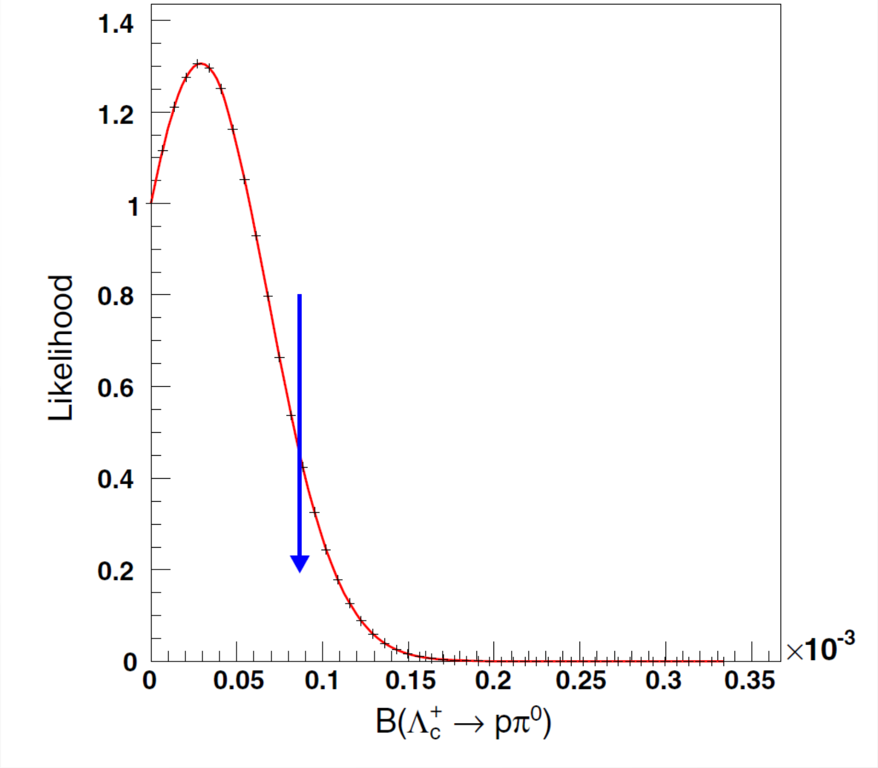
Yield: **1476200 ± 1560**
χ^2/ndf=1.06

Measurement of $\Lambda_c^+ \to p\pi^0$ $(\to \gamma\gamma)$ decay

PRD103, 072004 (2021)

- The efficiency estimated from signal MC sample is $(8.891 \pm 0.030)\%$.
- There is no obvious signal excess in M($p\pi^0$) from data. We set an upper limit on branching fraction of $B(\Lambda_c^+ \to p\pi^0) < 8 \times 10^{-5}$ at 90% C.L., reducing the value to more than half of the current best upper limit of 2.7×10^{-4}.



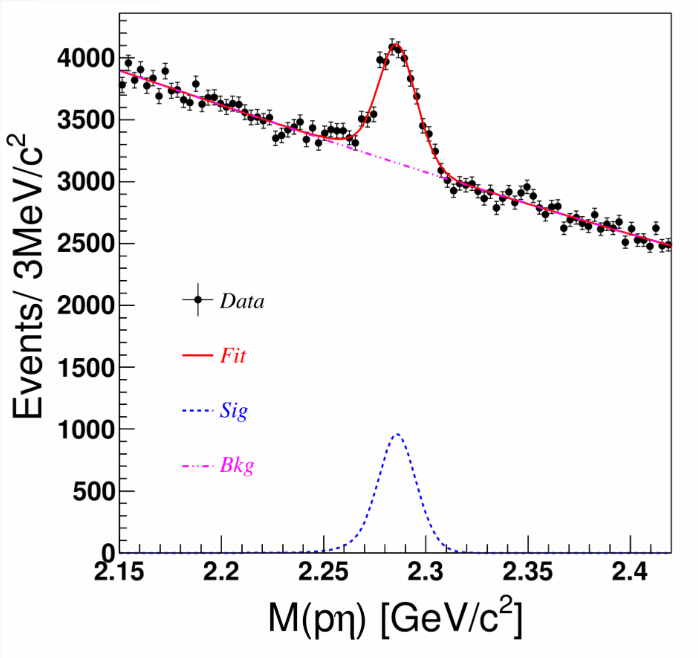


Left: fit to the invariant mass distribution of $p\pi^0$ with a fixed signal yield of **1269**. Right: The likelihood distribution changing with the branching fraction with the systematic uncertainty involved.

Measurement of $\Lambda_c^+ \to p\eta(\to \gamma\gamma)$decay

PRD103, 072004 (2021)

- The efficiency estimated from signal MC sample is $(\mathbf{8.279 \pm 0.030})\%$.



Gaussian + CB for signal. Second-order polynomial for background.

Yield: **7734 ± 263**
χ^2/ndf=1.23

- A significant $\boldsymbol{\Lambda_c^+}$ signal is observed in M($\boldsymbol{p\eta}$) distribution from data. The branching fraction is $\boldsymbol{B(\Lambda_c^+ \to p\eta) = (1.42 \pm 0.05 \pm 0.11) \times 10^{-3}}$, which is consistent with the latest BESIII measured result of $(1.24 \pm 0.30) \times 10^{-3}$ with much improved precision.
- The measured $\boldsymbol{B(\Lambda_c^+ \to p\eta)}$ is at least an order of magnitude larger than $\boldsymbol{B\left(\Lambda_c^+ \to p\pi^0\right)}$, which is consistent with the theoretical prediction of an internal W-emission mechanism involving an s quark in $\boldsymbol{\Lambda_c^+ \to p\eta}$.

Precise Measurement of $\Lambda_c^+ \to p\omega$

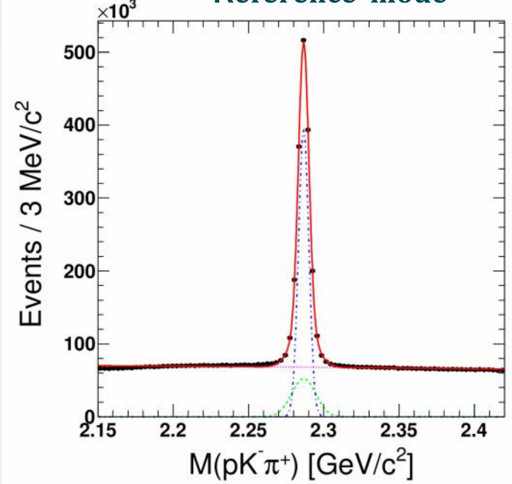
PRD 104, 072008 (2021)

- A method to measure the branching fractions of $\Lambda_c^+ \to p\omega(\to \pi^+\pi^-\pi^0)$ decays is:

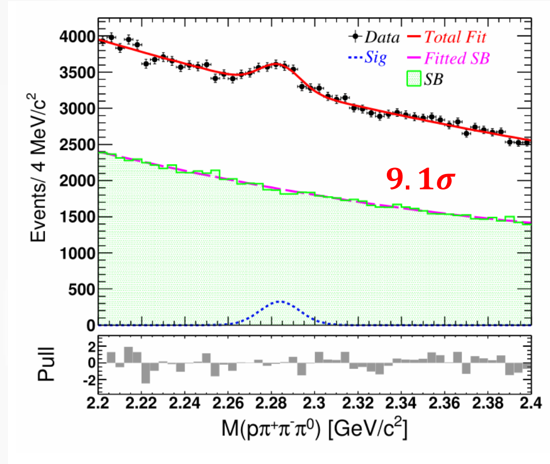
$$\frac{B(\text{Decay mode})}{B(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y\,(\text{Decay mode})}{B_{\text{PDG}} \times y(\Lambda_c^+ \to pK^-\pi^+)}$$

(y is the efficiency-corrected yield).

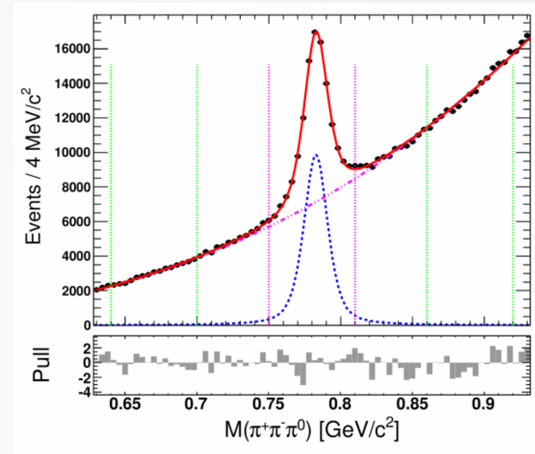
Reference mode



Signal mode



$\omega \to \pi^+\pi^-\pi^0$



Simultaneous fit for events in the ω signal region and the normalized ω sideband regions.

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (8.27 \pm 0.75 \pm 0.62 \pm 0.42) \times 10^{-4}.$$

NEW

Most precise result to data

- This result is **consistent with** the LHCb result $(9.4 \pm 3.9) \times 10^{-4}$.
- This result **agrees with** the of theoretical predictions within uncertainties based on the SU(3)F flavor symmetry.

First Observation of $\Lambda_c^+ \to p\eta'$

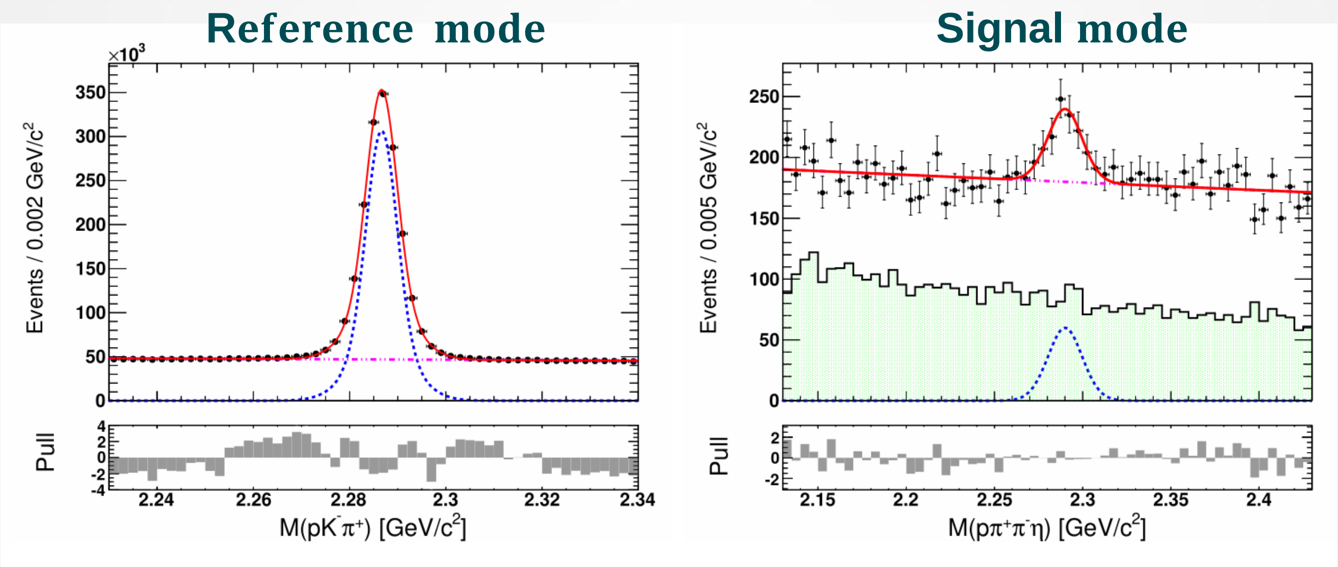
NEW

- A method to measure the branching fractions of $\Lambda_c^+ \to p\eta'(\to \pi^+\pi^-\eta)$ decays is:

$$\frac{B(\text{Decay mode})}{B(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y\,(\text{Decay mode})}{B_{\text{PDG}} \times y(\Lambda_c^+ \to pK^-\pi^+)}$$

(y is the efficiency-corrected yield).

preliminary



$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (4.73 \pm 0.82 \pm 0.43 \pm 0.24) \times 10^{-4}$$

First observation of Λ_c^+ in $\Lambda_c^+ \to p\eta'$

- Our result is **consistent with** the most theoretical calculations based on $SU(3)_F$ symmetry.

Measurements of absolute Brs of Ξ_c^0

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

Y.B.Li, C.P.Shen et al (Belle) PRL122, 082001 (2019)

BF	Result	Theory	PDG
$\mathcal{B}(B^-\to \bar{\Lambda}_c^-\Xi_c^0)$	$(9.51\pm2.10\pm0.88)\times10^{-4}$	$\sim10^{-3}$	
$\mathcal{B}(B^-\to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)$	$(1.71\pm0.28\pm0.15)\times10^{-5}$		$(2.4\pm0.9)\times10^{-5}$
$\mathcal{B}(B^-\to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0\to\Lambda K^-\pi^+)$	$(1.11\pm0.26\pm0.10)\times10^{-5}$		$(2.1\pm0.9)\times10^{-5}$
$\mathcal{B}(B^-\to \bar{\Lambda}_c^-\Xi_c^0)\mathcal{B}(\Xi_c^0\to pK^-K^-\pi^+)$	$(5.47\pm1.78\pm0.57)\times10^{-6}$		
$\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)$	$(1.80\pm0.50\pm0.14)\%$	1.12% or 0.74%	
$\mathcal{B}(\Xi_c^0\to\Lambda K^-\pi^+)$	$(1.17\pm0.37\pm0.09)\%$		
$\mathcal{B}(\Xi_c^0\to pK^-K^-\pi^+)$	$(0.58\pm0.23\pm0.05)\%$		
$\mathcal{B}(\Xi_c^0\to\Lambda K^-\pi^+)/\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)$	$0.65\pm0.18\pm0.04$		1.07 ± 0.14
$\mathcal{B}(\Xi_c^0\to pK^-K^-\pi^+)/\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)$	$0.32\pm0.12\pm0.07$		0.34 ± 0.04

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

Measurement of Ξ_c^+ absolute BRs

Y. B. Li. C. P. Shen et al (Belle) PRD 100, 031101 (2019)

BF	Result	Theory	PDG
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+)$	$(1.16 \pm 0.42 \pm 0.15) \times 10^{-3}$	$\sim 10^{-3}$	
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+))\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$(3.32 \pm 0.74 \pm 0.33) \times 10^{-5}$		$(1.8 \pm 1.8) \times 10^{-5}$
$\mathcal{B}(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+)\mathcal{B}(\Xi_c^+ \to p K^- \pi^+)$	$(5.27 \pm 1.51 \pm 0.69) \times 10^{-5}$		
$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$(2.86 \pm 1.21 \pm 0.38)\%$	$(1.47 \pm 0.84)\%$	
$\mathcal{B}(\Xi_c^+ \to p K^- \pi^+)$	$(0.45 \pm 0.21 \pm 0.07)\%$	$(2.2 \pm 0.8)\%$	
$\mathcal{B}(\Xi_c^+ \to p K^- \pi^+)/\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$	$0.16 \pm 0.06 \pm 0.02$		0.21 ± 0.04

- First model –independent $\mathcal{B}\left(\bar{B}^0 \to \bar{\Lambda}_c^- \Xi_c^+\right)$ measurement
- $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ can be used to determine the BR of other Ξ_c^+ decay

Measurements of Brs and asymmetry parameters of $\Xi_c^0 \to \Lambda\bar{K}^{*0}$, $\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+K^{*-}$

JHEP 06 (2021) 160

- There are some difficulties for the theoretical study in the non-leptonic decays of charmed baryons due to the failure of the factorization approach.
- Branching fraction measurements help to distinguish different theoretical models.
- The asymmetry parameters of Ξ_c^0 are still not well measured, which is important to test parity violation in charmed-baryon sectors.

Decay branching fractions (%) and asymmetry parameters of the Cabibbo favored $B_c \to B_n + V$ decays in QCD and $SU(3)_F$ approach.

Branching fractions	KK [1]	Zen [2]	HYZ [3]	GLT [4]
$\Xi_c^0 \to \Lambda^0\bar{K}^{*0}$	1.55	1.15	0.46±0.21	1.37±0.26
$\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$	0.85	0.77	0.27±0.22	0.42±0.23
$\Xi_c^0 \to \Sigma^+K^{*-}$	0.54	0.37	0.93±0.29	0.24±0.17

Asymmetry parameters	KK [1]	Zen [2]	GLT [4]
$\Xi_c^0 \to \Lambda^0\bar{K}^{*0}$	0.58	+0.49	-0.67±0.24
$\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$	-0.87	+0.25	-0.42±0.62
$\Xi_c^0 \to \Sigma^+K^{*-}$	-0.60	+0.51	$-0.76^{+0.64}_{-0.24}$

[1] Z. Phys. C 55, 659 (1992) [2] Phys. Rev. D 50, 5787 (1994) [3] Phys. Lett. B 792, 35 (2019)
[4] Phys. Rev. D 101, 053002 (2020)

Measurements of Brs $\Xi_c^0 \to \Lambda\bar{K}^{*0}$, $\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+K^{*-}$

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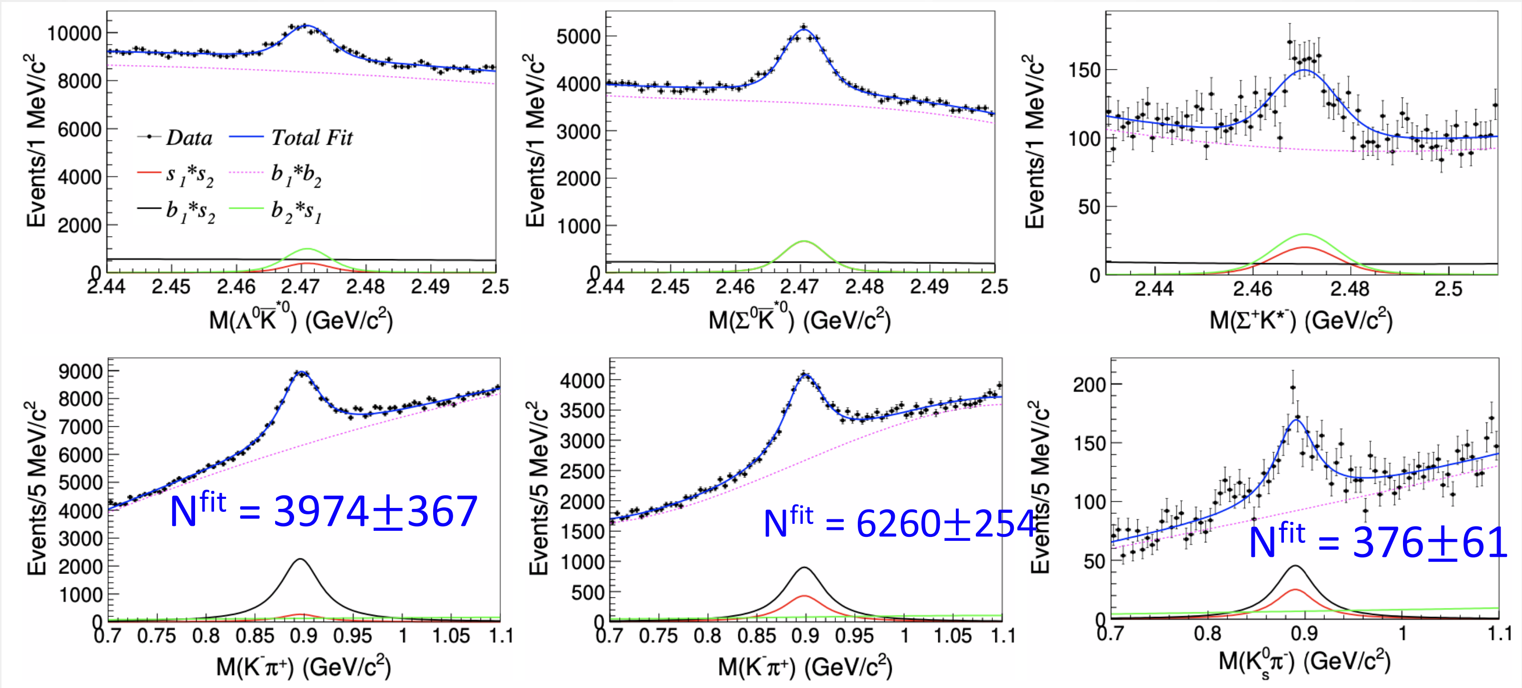
$\Xi_c^0 \to \Lambda^0\bar{K}^{*0}$ $\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$ $\Xi_c^0 \to \Sigma^+K^{*-}$



$\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.18 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.69 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+K^{*-})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.34 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^{*0})$	$(3.3 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.}) \pm 1.0(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})$	$(12.4 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.}) \pm 3.6(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+K^{*-})$	$(6.1 \pm 1.0(\text{stat.}) \pm 0.4(\text{syst.}) \pm 1.8(\text{ref.})) \times 10^{-3}$

By using the reference mode $\Xi_c^0 \to \Xi^-\pi^+$, we calculate the absolute branching fractions with signal yields between reference and signal channels after efficiency corrections.

Asymmetry parameter extractions

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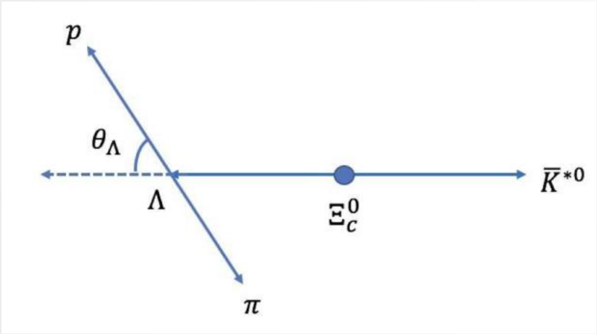
For $\Xi_c^0 \to \Lambda^0 \overline{K}^{*0}$, $\Xi_c^0 \to \Sigma^0 \overline{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+ K^{*-}$, the differential decay rates [PRD 101, 053002 (2020)] are given by:

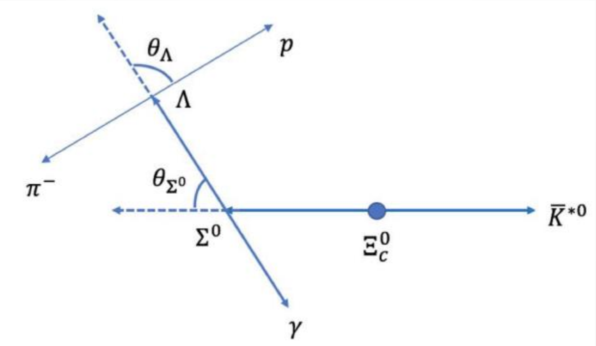
$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha(\Xi_c^0 \to \Lambda \overline{K}^{*0})\alpha(\Lambda \to p\pi^-)\cos\theta_\Lambda,$$

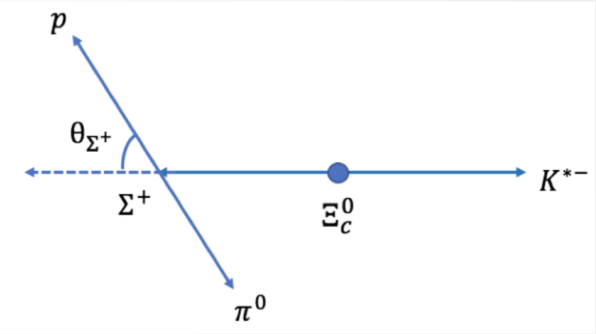
$$\frac{dN}{d\cos\theta_{\Sigma^0}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^0 \overline{K}^{*0})\alpha(\Sigma^0 \to \Lambda\gamma)\cos\theta_{\Sigma^0}, \text{ and}$$

$$\frac{dN}{d\cos\theta_{\Sigma^+}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^+ K^{*-})\alpha(\Sigma^+ \to p\pi^0)\cos\theta_{\Sigma^+}.$$

Definitions of θ_Λ, θ_{Σ^0}, and θ_{Σ^+}:







- This measurement is insensitive to production polarization of Ξ_c^0 in B-factory [PRD 63, 111102 (2001)].
- The asymmetry parameter $\alpha(\Sigma^0 \to \Lambda\gamma)$ is expected to be zero due to the case of parity conservation for an electromagnetic decay of $\Sigma^0 \to \Lambda\gamma$.

Asymmetry parameters

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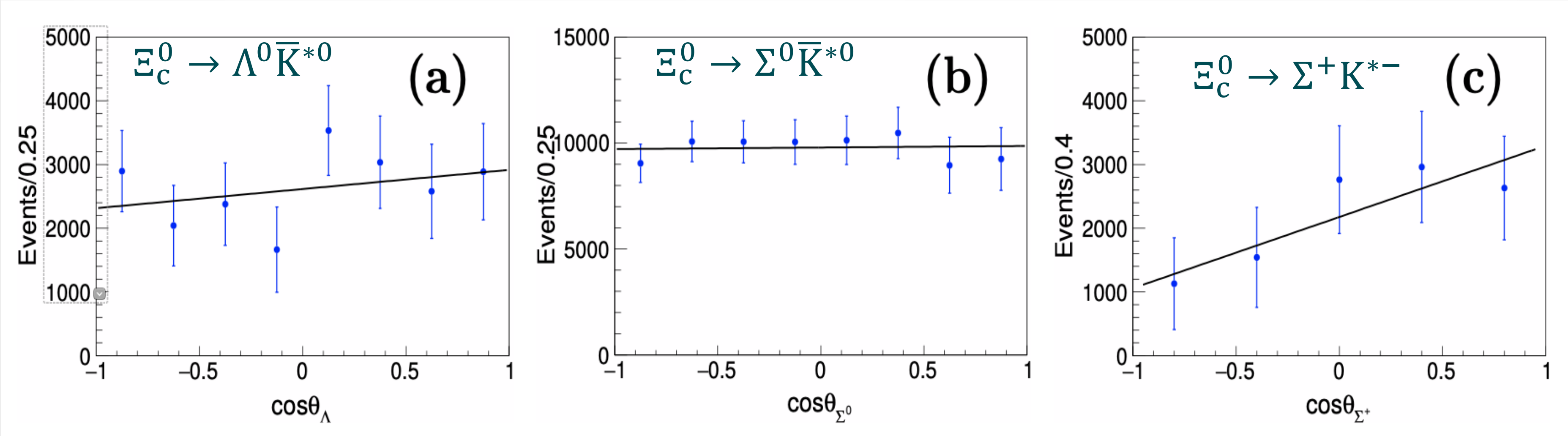


Note that $\alpha(\Lambda \to p\pi^-) = 0.747 \pm 0.010$ and $\alpha(\Sigma^+ \to p\pi^0) = -0.980 \pm 0.017$ from PDG.

$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})\alpha(\Lambda \to p\pi^-)$	$0.115 \pm 0.164(\text{stat.}) \pm 0.038(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})\alpha(\Sigma^0 \to \gamma\Lambda)$	$0.008 \pm 0.072(\text{stat.}) \pm 0.008(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})\alpha(\Sigma^+ \to p\pi^0)$	$0.514 \pm 0.295(\text{stat.}) \pm 0.012(\text{syst.})$
$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})$	$0.15 \pm 0.22(\text{stat.}) \pm 0.05(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})$	$-0.52 \pm 0.30(\text{stat.}) \pm 0.02(\text{syst.})$

Measurements of $Br(\Xi_c^0 \to \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-)$

- The Cabibbo-favored (CF) two-body hadronic weak decays $\Xi_c^0 \to B_f$(light baryons) + P(pseudoscalar mesons) have been analyzed based on the dynamical model calculations and $SU(3)_F$ flavor symmetry methods.

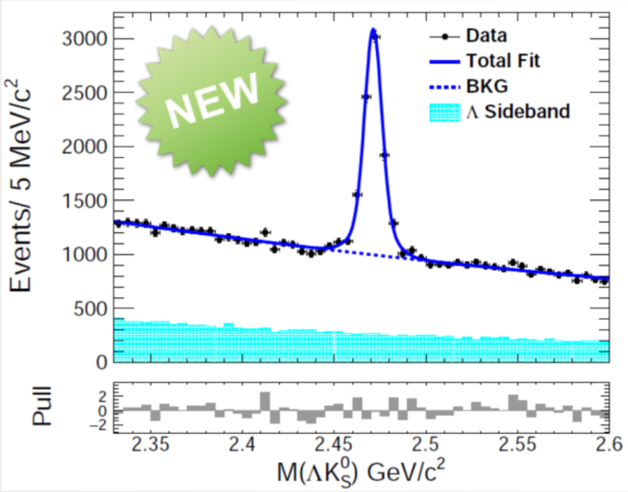
- The predicted branching fractions for the CF decays $\Xi_c^0 \to \Lambda\bar{K}^0/\Sigma^0\bar{K}^0/\Sigma^+K^-$ based on different models are listed in the below Table.

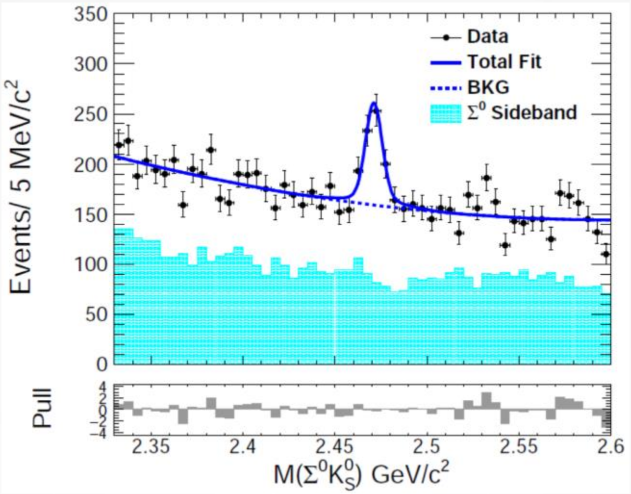
Mode	dynamical model [PRD 101, 014011 (2020)]	SU(3) I [PLB 794, 19 (2019)]	SU(3) II [3] [JHEP 02 165 (2020)]
$\Xi_c^0 \to \Lambda\bar{K}^0$	13.3×10^{-3}	$(10.5 \pm 0.6) \times 10^{-3}$	$(8.3 \pm 5.3) \times 10^{-3}$
$\Xi_c^0 \to \Sigma^0\bar{K}^0$	0.4×10^{-3}	$(0.8 \pm 0.8) \times 10^{-3}$	$(7.9 \pm 4.8) \times 10^{-3}$
$\Xi_c^0 \to \Sigma^+K^-$	7.8×10^{-3}	$(5.9 \pm 1.1) \times 10^{-3}$	$(22.0 \pm 5.7) \times 10^{-3}$

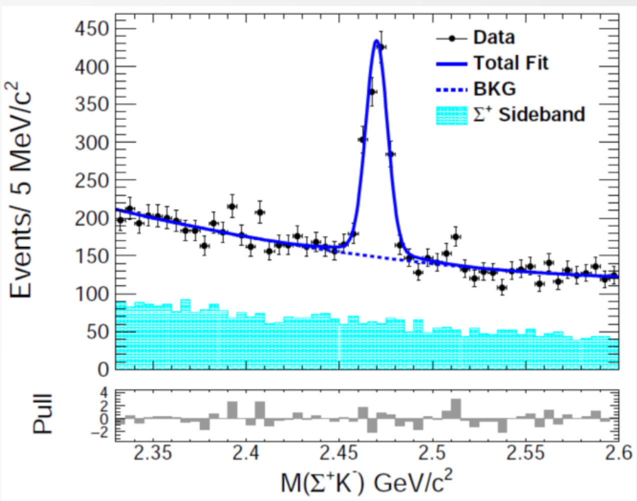
- In this analysis, we present the measurements of branching fractions of $\Xi_c^0 \to \Lambda K_S^0$, $\Xi_c^0 \to \Sigma^0 K_S^0$, and $\Xi_c^0 \to \Sigma^+ K^-$ using all Belle data.

Measurements of $Br(\Xi_c^0 \to \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-)$

arXiv:2111.08981







Relative branching fractions:

$$\frac{Br(\Xi_c^0 \to \Lambda K_S^0)}{Br(\Xi_c^0 \to \Xi^- \pi^+)} = 0.229 \pm 0.008 \pm 0.012$$

$$\frac{Br(\Xi_c^0 \to \Sigma^0 K_S^0)}{Br(\Xi_c^0 \to \Xi^- \pi^+)} = 0.038 \pm 0.006 \pm 0.004$$

$$\frac{Br(\Xi_c^0 \to \Sigma^+ K^-)}{Br(\Xi_c^0 \to \Xi^- \pi^+)} = 0.123 \pm 0.007 \pm 0.010$$

Absolute branching fractions:

$$Br(\Xi_c^0 \to \Lambda K_S^0) = (4.12 \pm 0.14 \pm 0.21 \pm 1.19) \times 10^{-3}$$

$$Br(\Xi_c^0 \to \Sigma^0 K_S^0) = (0.69 \pm 0.10 \pm 0.08 \pm 0.20) \times 10^{-3}$$

$$Br(\Xi_c^0 \to \Sigma^+ K^-) = (2.21 \pm 0.13 \pm 0.19 \pm 0.64) \times 10^{-3}$$

- The measured ratios of the branching fractions among the three decay modes are consistent with the theoretical predictions based on $SU(3)$ flavor symmetry approaches within the theoretical errors, but contradict those predicted by dynamical model calculations.

Measurement of $\mathcal{B}(\Omega_c^0 \to \Omega^- l^+ \nu)$ and $\mathcal{B}(\Xi_c^0 \to \Xi^- l\, \nu)$

Semileptonic decays of charmed baryons:

- ➢ Ideal test of QCD in transition region of (non-)perturbative.
- ➢ The cleanest processes among charm decays
- ➢ Verify lepton flavor universality (LFU).

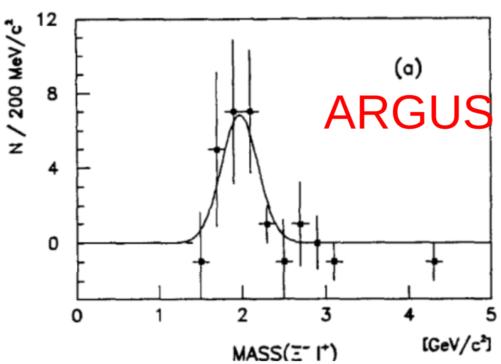
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, e^+\nu_e) = (3.6 \pm 0.4)\%$ PRL 115, 221805(2015)

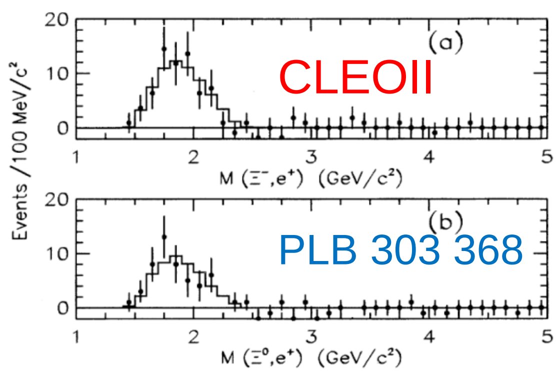
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, \mu^+\nu_e) = (3.5 \pm 0.4)\%$ PLB 767, 42 (2017)

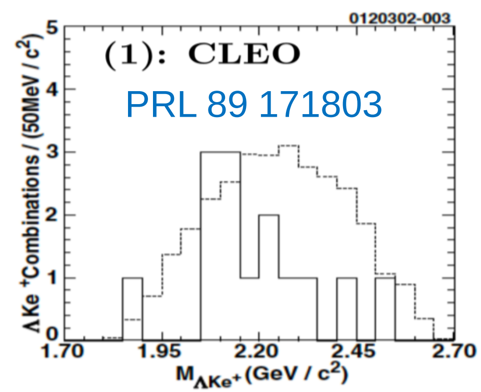
Experimentally:

- ●BESIII measured the $\mathcal{B}(\Lambda_c^+ \to \Lambda l^+ \nu)$
- ●ARGUS and CLEOII measured $\mathcal{B}(\Xi_c \to \Xi\, l^+ \nu)$
- ●CLEO measured $\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)$

} **large uncertainty**





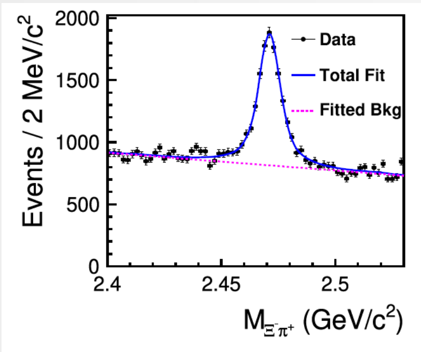


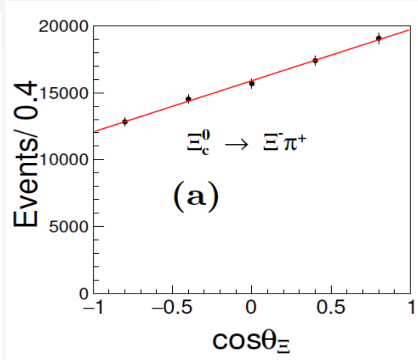
$$\frac{\mathcal{B}(\Xi_c \to \Xi^- \ell^+ \nu)}{\mathcal{B}(\Xi_c \to \Xi^- \pi^+)} = 0.96 \pm 0.47 \qquad 3.1 \pm 1.1 = \frac{\mathcal{B}(\Xi_c \to \Xi^- e^+ \nu)}{\mathcal{B}(\Xi_c \to \Xi^- \pi^+)}$$

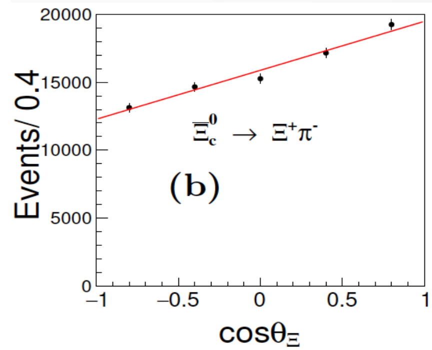
$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 2.4 \pm 1.2$$

Measurement of $\mathcal{B}(\Omega_c^0 \to \Omega^- l^+ \nu)$ and $\mathcal{B}(\Xi_c^0 \to \Xi^- l\, \nu)$

$\mathcal{A}_{cp}$ of $\Xi_c^0 \to \Xi^- \pi^+$: search for CP violation in charmed baryons section







refine the simulation of reference channel

$$\frac{dN}{d\cos\theta_\Xi} \propto 1 + \alpha_{\Xi^-\pi^+}\alpha_{\Xi^-} \cos\theta_\Xi$$

θ_Ξ: helicity angle

$\alpha_{\Xi^- \pi^+} = -0.60 \pm 0.045$

$\alpha_{\Xi^+ \pi^-} = 0.58 \pm 0.045$

Previous:

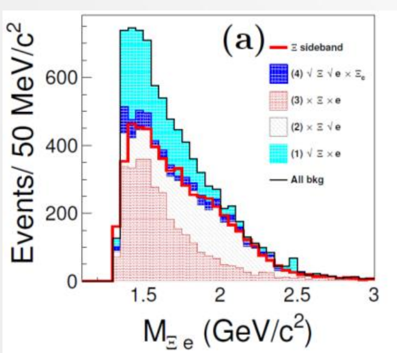
-0.60 ± 0.4

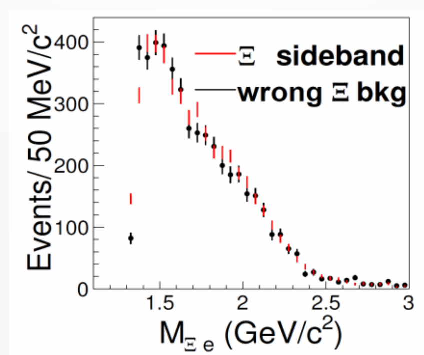
$$\mathcal{A}_{CP} = (\alpha_{\Xi^-\pi^+} + \alpha_{\bar{\Xi}^+\pi^-})/(\alpha_{\Xi^-\pi^+} - \alpha_{\bar{\Xi}^+\pi^-})$$

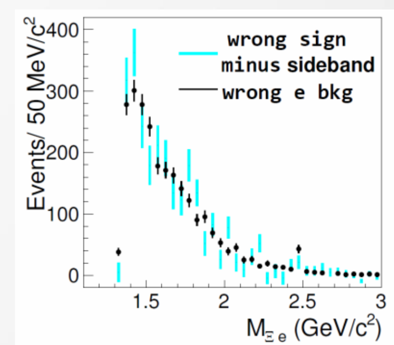
$\mathcal{A}_{cp} = 0.015 \pm 0.056$

PRL 127, 121803 (2021)

$\Xi_c \to \Xi\, l^+\nu$: **data-driven method** for bkg extraction





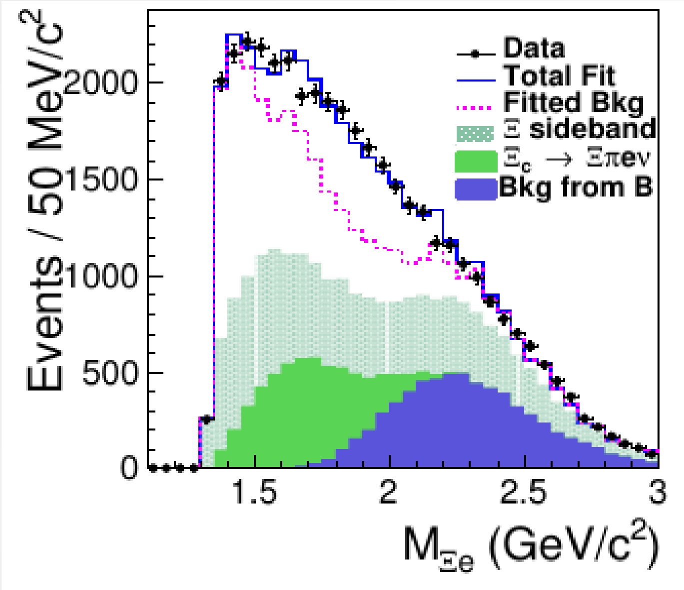


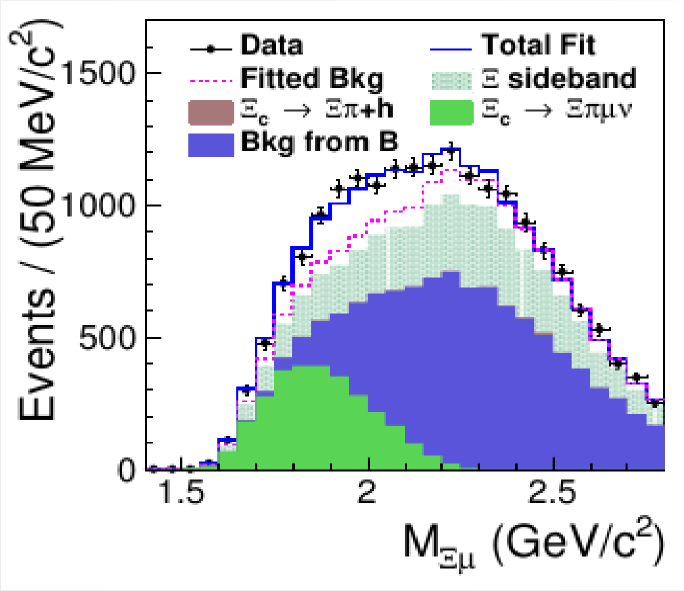
All simulated BKG

Ξ^- **sideband** *v. s.* wrong Ξ^- bkg

$\Xi^- e^-$**- sideband** *v. s.* **wrong e$^+$** bkg

Measurement of $\mathcal{B}(\Xi_c^0 \to \Xi^- l\, \nu)$





PRL 127, 121803 (2021)

Fit component:

- Signal : True signal histogram
- BKG1: Ξ^- sideband
- BKG2: $\Xi^-\ell^-$ - Ξ^- sideband
- BKG3: $\Xi_c^0 \to \Xi^-\pi^+\ell\nu$ histogram
- BKG5: $\Xi_c^0 \to \Xi^-\pi + h$ histogram
- BKG4: Bkg histogram from B decay

$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+\nu_e) = (1.31 \pm 0.39)\%$

Previous: $(2.34 \pm 1.59)\%$

$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+\nu_\mu) = (1.27 \pm 0.39)\%$

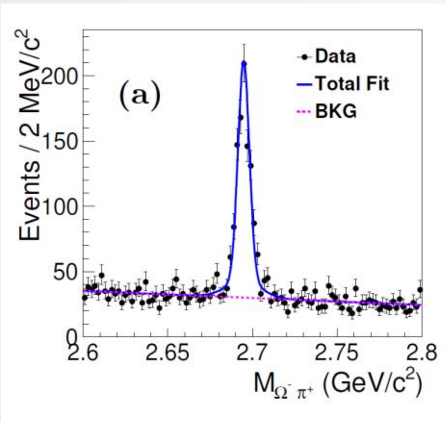
Consistent with LFU

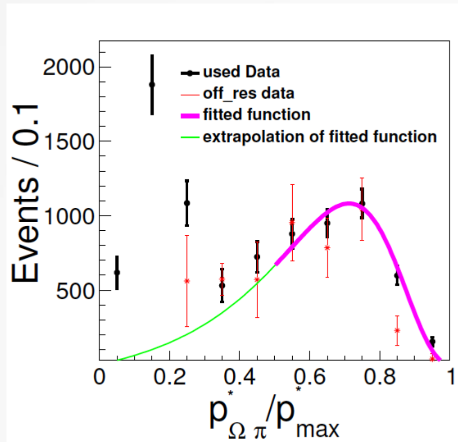
Measurement of $\mathcal{B}(\Omega_c^0 \to \Omega^- l^+ \nu)$

NEW

preliminary

$\Omega_c^0 \to \Omega^- \pi^+$: Fragmentation Function extraction





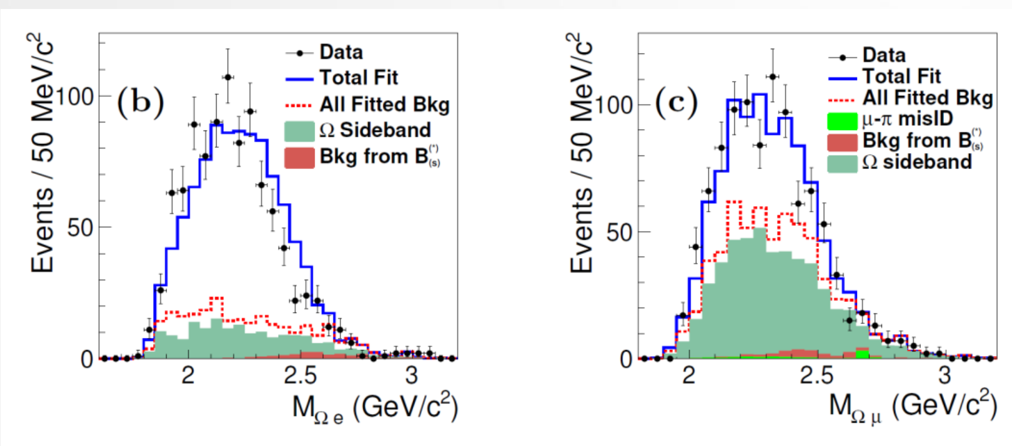
Peterson's fragmentation function

$$\frac{dN}{dx_p} \approx \frac{1}{x_p} \cdot \frac{1}{\left(1 - \frac{1}{x_p} - \frac{\epsilon_p}{1-x_p}\right)^2}$$

- data with $p^*_{\Omega\ell(\pi)}/p^*_{\max}$>0.5 used in fit
- $\epsilon_p = 0.1160 \ \pm 0.014$

$\Omega_c^0 \to \Omega^- \mu^+ \nu$: signal extraction

Similar Data-driven method used in $\Xi_c^0 \to \Xi^- l\, \nu$



$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.98 \pm 0.15$$

Previous: 2.4 ± 1.2

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.94 \pm 0.21$$

Consistent with LFU

Ξ_c worklist:

1. Measurement of absolute decay branching fractions

$\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.52)\%$ PRL 122 082001

$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.27)\%$ PRD 100 031101

μ? { $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.8 \pm 1.2)\%$ PDG

$\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e) = (1.8^{+0.7}_{-0.8})\%$ PDG, ratios to $\Xi^- 2\pi^+$ }

} Need updated

2. Find more decay modes:

PRD 101, 053002

CF (%)

$\Xi_c^+ \to \Sigma^+ \bar{K}^{*0}$	1.40 ± 0.69[a]
$\Xi_c^+ \to \Xi^0 \rho^+$	14.48 ± 2.44[a]
$\Xi_c^0 \to \Lambda^0 \bar{K}^{*0}$	1.37 ± 0.26
$\Xi_c^0 \to \Sigma^0 \bar{K}^{*0}$	0.42 ± 0.23
$\Xi_c^0 \to \Sigma^+ K^{*-}$	0.24 ± 0.17
$\Xi_c^0 \to \Xi^0 \rho^0$	0.88 ± 0.22
$\Xi_c^0 \to \Xi^0 \omega$	2.78 ± 0.45
$\Xi_c^0 \to \Xi^0 \phi$	0.14 ± 0.13
$\Xi_c^0 \to \Xi^- \rho^+$	8.98 ± 0.55

SCS (10^{-3})

$\Xi_c^+ \to \Lambda^0 \rho^+$	1.52 ± 0.57
$\Xi_c^+ \to p \bar{K}^{*0}$	4.71 ± 1.22[a]
$\Xi_c^+ \to \Sigma^0 \rho^+$	11.45 ± 1.52
$\Xi_c^+ \to \Sigma^+ \rho^0$	2.85 ± 0.81
$\Xi_c^+ \to \Sigma^+ \omega$	4.11 ± 0.77
$\Xi_c^+ \to \Sigma^+ \phi$	1.82 ± 0.40[a]
$\Xi_c^+ \to \Xi^0 K^{*+}$	4.28 ± 1.64
$\Xi_c^0 \to \Lambda^0 \rho^0$	0.13 ± 0.11
$\Xi_c^0 \to \Lambda^0 \omega$	1.51 ± 0.20
$\Xi_c^0 \to \Lambda^0 \phi$	0.44 ± 0.08[a]
$\Xi_c^0 \to p K^{*-}$	0.19 ± 0.14
$\Xi_c^0 \to n \bar{K}^{*0}$	2.52 ± 0.79
$\Xi_c^0 \to \Sigma^0 \rho^0$	0.11 ± 0.10
$\Xi_c^0 \to \Sigma^0 \omega$	0.70 ± 0.13
$\Xi_c^0 \to \Sigma^0 \phi$	0.30 ± 0.07
$\Xi_c^0 \to \Sigma^+ \rho^-$	0.19 ± 0.13
$\Xi_c^0 \to \Sigma^- \rho^+$	5.56 ± 0.34
$\Xi_c^0 \to \Xi^0 K^{*0}$	0.79 ± 0.23
$\Xi_c^0 \to \Xi^- K^{*+}$	3.36 ± 0.23

DCS (10^{-4})

$\Xi_c^+ \to \Lambda^0 K^{*+}$	$0.34^{+0.37}_{-0.34}$
$\Xi_c^+ \to p \rho^0$	0.22 ± 0.17
$\Xi_c^+ \to p \omega$	1.66 ± 0.70
$\Xi_c^+ \to p \phi$	2.29 ± 0.39
$\Xi_c^+ \to n \rho^+$	0.43 ± 0.33
$\Xi_c^+ \to \Sigma^0 K^{*+}$	3.08 ± 0.20
$\Xi_c^+ \to \Sigma^+ K^{*0}$	0.40 ± 0.08
$\Xi_c^0 \to \Lambda^0 K^{*0}$	0.28 ± 0.13
$\Xi_c^0 \to p \rho^-$	0.15 ± 0.11
$\Xi_c^0 \to n \rho^0$	0.07 ± 0.06
$\Xi_c^0 \to n \omega$	0.56 ± 0.24
$\Xi_c^0 \to n \phi$	0.77 ± 0.13
$\Xi_c^0 \to \Sigma^0 K^{*0}$	0.07 ± 0.01
$\Xi_c^0 \to \Sigma^- K^{*+}$	2.08 ± 0.14

Semileptonic (PLB792, 214)

$10^3 \mathcal{B}(\Xi_c^+ \to \Sigma^0 e^+ \nu_e)$	3.1 ± 0.4
$10^4 \mathcal{B}(\Xi_c^+ \to \Lambda e^+ \nu_e)$	10.3 ± 1.5
$10^4 \mathcal{B}(\Xi_c^0 \to \Sigma^- e^+ \nu_e)$	15.7 ± 2.2

3. Decay parameter measurement:

Ξ_c^0 DECAY PARAMETERS

α FOR $\Xi_c^0 \to \Xi^- \pi^+$ -0.6 ± 0.4

The only measurement with large error

4. Form factors

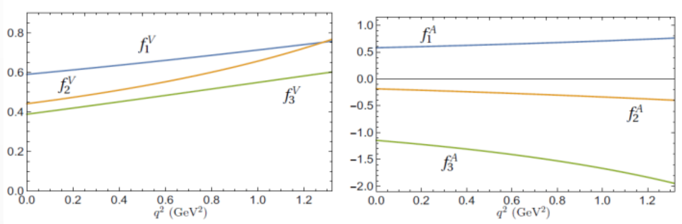


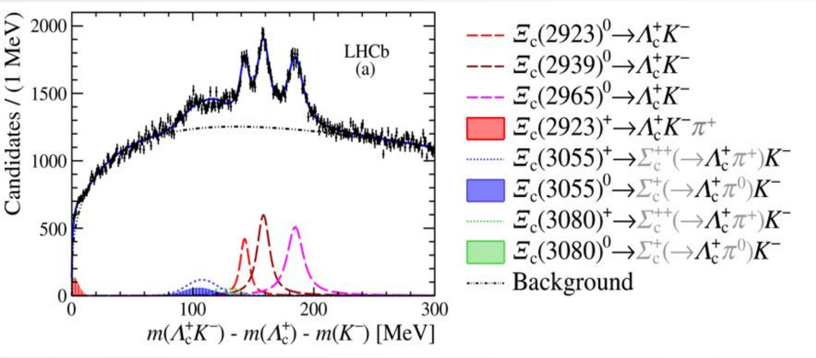
FIG. 1: Form factors of the weak $\Xi_c \to \Xi$ transitions.

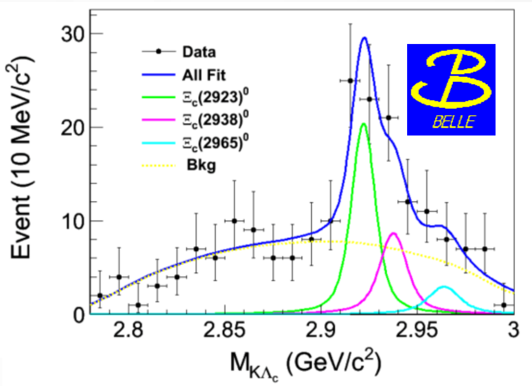
EPJC 79 695

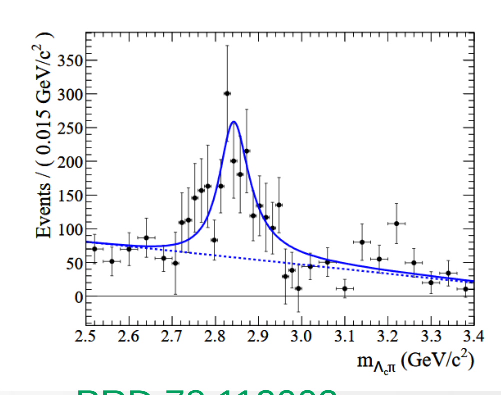
Plentiful physics parameters need to be measured !

Charmed baryon spectra at BelleII

- LHCb recently reconstructed $K^+\Lambda_c^-$ and found $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$
- $\Xi_c(2930)^0$ is the sum of them ?







PRD.78.112003

Phys. Rev. Lett. 124, 222001

- We use LHCb's results as input, refit our plot and find the fit result is good
  - More data needed to extract signal yield with low uncertainty
  - Notice $\Xi_c(2923)^+ \to \Lambda_c^+ K^- \pi^+$, can we find more decay channel?
  - How about $\Sigma_c(2800)$? Is $\Sigma_c(2800)$ the overlap of several Σ_c?
  - ....

Summary

- Although Belle has stopped data taking for >10 years ago, we are still producing exciting results [China group has made great contributions].
- Belle II started data taking on 25 March 2019 with its full detector.
- The Belle II experiment at SuperKEKB aims to find New Physics beyond the SM with ultimate precision measurement (a few %, typically) of heavy flavor decays.
- SuperKEKB has achieved Lpeak =2.4 x $10^{34}cm^{-2}s^{-1}$ (world highest luminosity)
- Belle II is performing as expected, and obtained early physics results.
- SuperKEKB/Belle II aims at accumulate $50ab^{-1}$ by ~2030, by further improving the luminosity performance.

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感谢您的批评指正

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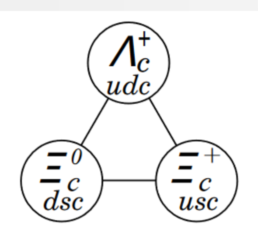
BackUp : Semileptonic decays

Semileptonic decays of charmed baryons:

- be calculated with QCD factorization approach
- The cleanest processes among charm decays
- Decay rate depend on CKM matrix element $|V_{cq}|$ and strong interaction (form factor)
- Verify lepton universality.

$$\mathcal{A}(\mathbf{B_c} \to \mathbf{B_n}\ell^+\nu_\ell) = \frac{G_F}{\sqrt{2}} V_{cq} \langle \mathbf{B_n} | J_\mu^{(V-A)} | \mathbf{B_c} \rangle \bar{u}_\nu \gamma^\mu \frac{(1-\gamma_5)}{2} v_\ell$$



$$\mathrm{B_c} = (\Xi_c^0, -\Xi_c^+, \Lambda_c),$$

$$\mathrm{B}_n = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

$$J_\mu^{(V-A)} = \bar{q}\gamma_\mu(1-\gamma_5)/2c$$

$\bar{u}_\nu$ and v_ℓ: Dirac bispinors $q = s, d$

G_F: Fermi constant

BackUp: $\Xi_c \to \Xi\ (\Lambda) l\ \nu$

$\Xi_c \to \Xi\ (\Lambda) l\ \nu$ have been well studied theoretically.

- Total branching fraction($\mathcal{B}$),
- forward-backward asymmetries($\mathcal{A}_{FB}$),
- differential decay rates($d\Gamma/dq^2$)

are observable values that uncover the underline dynamics of QCD.

Theories such as:

SU(3) symmetry arXiv:1901.05610 PRD, 97, 073006 (2018) PLB, 792, 214 (2019); Quasipotential approach relativistic quark model EPJC, 79, 695 (2019); light-front quark modelCPC, 42,093101(2018); light-cone QCD sum rules EPJC, 79, 695 (2019)

calculated:

$\mathcal{B}(\Xi_c^0 \to \Xi^- l^+ \nu_e) = 1.35{\sim}7.26\%$ $\quad$ $\mathcal{B}(\Xi_c^+ \to \Xi^0 l^+ \nu_e) = 3.3{\sim}28.6\%$

$\mathcal{B}(\Xi_c^+ \to \Lambda l^+ \nu_e) = 0.082{\sim}0.17\%$

Also EPJC, 79, 695 (2019) predict: $\frac{6\Gamma(\Xi_c \to \Lambda e \nu_e)}{|V_{cd}|^2} = \frac{\Gamma(\Xi_c \to \Xi e \nu_e)}{|V_{cs}|^2}$

BackUp: Excited states:

By John Yelton

https://hflav-eos.web.cern.ch/hflav-eos/charm/baryons/Excited_Apr19/baryons_April19.html

Charmed Baryon Excited State	Mode	Mass (MeV/c^2)	Natural Width (MeV/c^2)	J^P	Status and Comments
$\Lambda_c(2595)^+$	$\Lambda_c^+\pi^+\pi^-$, $\Sigma_c\pi$	2592.25 ± 0.28	$2.59 \pm 0.30 \pm 0.47$	$1/2^-$	well established, most precise mmeasurement by CDF [1]
$\Lambda_c(2625)^+$	$\Lambda_c^+\pi^+\pi^-$	2628.11 ± 0.19	< 1.9	$3/2^-$	well established, most precise measurements by CDF [1]
$\Lambda_c(2765)^+$	$\Lambda_c^+\pi^+\pi^-$, $\Sigma_c\pi$	2766.6 ± 2.4	50	??	discovered by CLEO, seen by Belle, but parameters not measured [2]
$\Lambda_c(2880)^+$	$\Lambda_c^+\pi^+\pi^-$, $\Sigma_c\pi$, $\Sigma_c(2520)\pi$, D^0p	2881.53 ± 0.35	5.8 ± 1.1	$5/2^+$ (experimental evidence)	well established and seen in more than one mode [2] [4]
$\Lambda_c(2940)^+$	D^0p, $\Sigma_c\pi$	$2939.3^{+1.4}_{-1.5}$	17^{+8}_{-6}	??	Seen by both BaBar [4] and BelleMizuk
$\Sigma_c(2455)^{++}$	$\Lambda_c^+\pi^+$	167.510 ± 0.17	$1.89\pm^{+0.09}_{-0.18}$	$1/2^+$	well established, most precise measurements by Belle [5]
$\Sigma_c(2455)^+$	$\Lambda_c^+\pi^+$	166.4 ± 0.4	< 4.6 @ 90% CL	$1/2^+$	well established, but parameters not measured precisely
$\Sigma_c(2455)^0$	$\Lambda_c^+\pi^+$	167.29 ± 0.17	$1.83^{+0.11}_{-0.19}$	$1/2^+$	well established, most precise measurements by Belle [5]
$\Sigma_c(2520)^{++}$	$\Lambda_c^+\pi^+$	$231.95^{+0.17}_{-0.12}$	$14.78 \pm +0.30_{-0.40}$	$3/2^+$	well etablished, most precise measurements by Belle [5]
$\Sigma_c(2520)^+$	$\Lambda_c^+\pi^+$	231.0 ± 2.3	< 17 @ 90% CL	$3/2^+$	fairly well established, awaits precise measurement
$\Sigma_c(2520)^0$	$\Lambda_c^+\pi^+$	$232.02^{+0.15}_{-0.14}$	$15.3^{+0.4}_{-0.5}$	$3/2^+$	well established, most precise measurements by Belle [5]
$\Sigma_c(2800)^{++}$	$\Lambda_c^+\pi^+$	514^{+4}_{-6}	75^{+18+12}_{-13-11}	tentatively identified	observed by Belle [6] - should be confirmed
$\Sigma_c(2800)^+$	$\Lambda_c^+\pi^0$	505^{+15}_{-5}	62^{+37+52}_{-23-38}	as members of the predicted	
$\Sigma_c(2800)^0$	$\Lambda_c^+\pi^-$	519^{+5}_{-7}	72^{+22}_{-15}	Σ_{c2} $3/2^-$ isospin triplet?	same states as that below?
	$\Lambda_c^+\pi^-$	$560 \pm 8 \pm 10$	86^{+33}_{-22}		seen by Babar [7] in resonant substructure of B decays - needs confirmation
$\Xi_c'^+$	$\Xi_c^+\gamma$	110.5 ± 0.4		$1/2^+$	well established
$\Xi_c'^0$	$\Xi_c^0\gamma$	108.3 ± 0.4		$1/2^+$	well established
$\Xi_c(2645)^+$	$\Xi_c^0\pi^+$	178.5 ± 0.1	2.1 ± 0.2	$3/2^+$	well established, widths recently measured by Belle [8]
$\Xi_c(2645)^0$	$\Xi_c^+\pi^-$	174.7 ± 0.1	2.4 ± 0.2	$3/2^+$	
$\Xi_c(2790)^+$	$\Xi_c'^0\pi^+$	320.7 ± 0.5	9 ± 1	$1/2^-$	well established, widths recently measured by Belle [8]
$\Xi_c(2790)^0$	$\Xi_c'^+\pi^-$	323.8 ± 0.5	10 ± 1	$1/2^-$	
$\Xi_c(2815)^+$	$\Xi_c(2645)^0\pi^+$	348.8 ± 0.1	2.43 ± 0.23	$3/2^-$	well established, widths recently measured by Belle [8]
$\Xi_c(2815)^0$	$\Xi_c(2645)^+\pi^-$	349.4 ± 0.1	2.54 ± 0.23	$3/2^-$	
$\Xi_c(2930)^+$	$\Lambda_c^+K_S^0$	$2942.3 \pm 4.4 \pm 1.5$	$14.8 \pm 8.8 \pm 2.5$	??	"evidence" recently reported by Belle [9]
$\Xi_c(2930)^0$	$\Lambda_c^+K^-$	$2928.9 \pm 3.0^{+0.9}_{-12.0}$	$19.5 \pm 8.4^{+5.9}_{-7.9}$	??	originally reported by BaBar [11], confirmed by Belle [10]
$\Xi_c(2970)^+$	$\Lambda_c^+K^-\pi^+$, $\Sigma_c^{++}K^-$, $\Xi_c(2645)^0\pi^+$	2967.2 ± 0.8	21 ± 3	??	well established, but parameters in different modes and experiments differ
$\Xi_c(2970)^0$	$\Xi_c(2645)^+\pi^-$	2970.4 ± 0.8	28 ± 3	??	well established, but parameters in different modes and experiments differ
$\Xi_c(3055)^+$	$\Sigma_c^{++}K^-$,ΛD	3055.7 ± 0.4	8.0 ± 1.9	??	seen by Belle and BaBar [12] [14]
$\Xi_c(3055)^0$	ΛD	3059.0 ± 0.8	6.2 ± 2.4	??	newly observed by Belle [14]
$\Xi_c(3080)^+$	$\Lambda_c^+K^-\pi^+$, $\Sigma_c^{++}K^-$, $\Sigma_c(2520)^{++}K^-$, ΛD	3077.8 ± 0.3	3.6 ± 0.7	??	seen by Belle and BaBar [12] [15]
$\Xi_c(3080)^0$	$\Lambda_c^+K_S^0\pi^-$, $\Sigma_c^0K_S^0$, $\Sigma_c(2520)^0K_S^0$	3079.9 ± 1.0	5.6 ± 2.2	??	seen by Belle and BaBar [12] [14] [15]
$\Omega_c(2770)^0$	$\Omega_c^0\gamma$	2765.9 ± 2.0	0	$3/2^+$	seen by BaBar [16] and Belle [17]
$\Omega_c(3000)^0$	$\Xi_c^+K^-$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	??	LHCb [18]
$\Omega_c(3050)^0$	$\Xi_c^+K^-$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	< 1.2, 95%CL	??	LHCb [18]
$\Omega_c(3066)^0$	$\Xi_c^+K^-$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	??	LHCb [18]
$\Omega_c(3090)^0$	$\Xi_c^+K^-$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	??	LHCb [18]
$\Omega_c(3119)^0$	$\Xi_c^+K^-$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	??	LHCb [18]
$\Omega_c(3118)^0$	$\Xi_c^+K^-$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	??	Reported by LHCb [18], not clear if it is several resonances

BackUp: Current charmed baryon status

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$ was $\Xi_c(2980)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

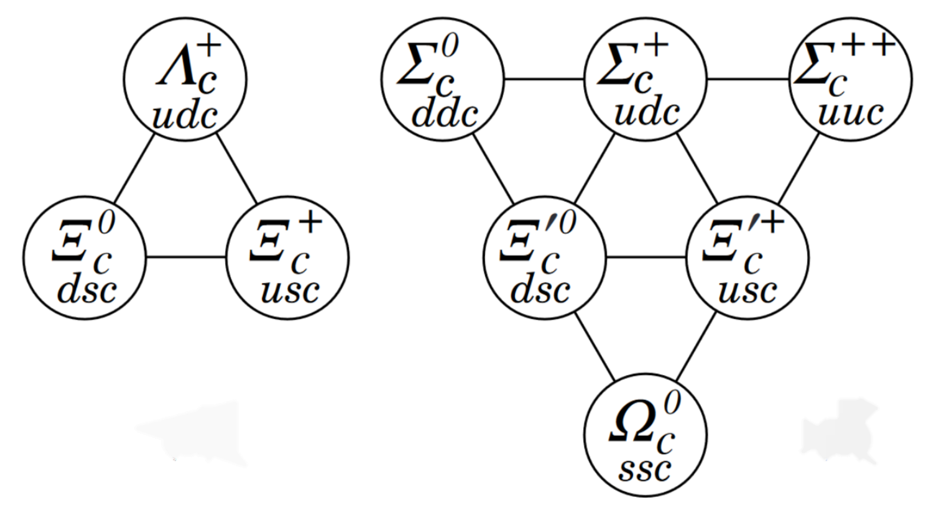
****:Existence is certain, properties fairly explored.

***:Existence is very likely or certain, further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

**:Evidence of existence is only fair.

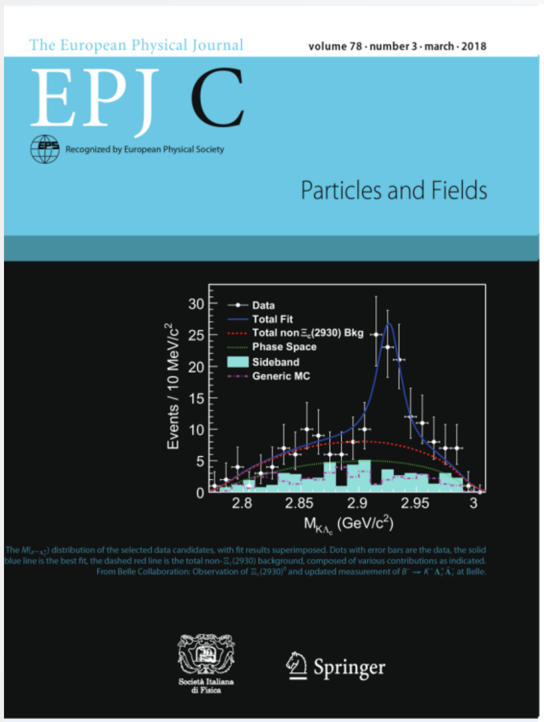
*:Evidence of existence is poor.

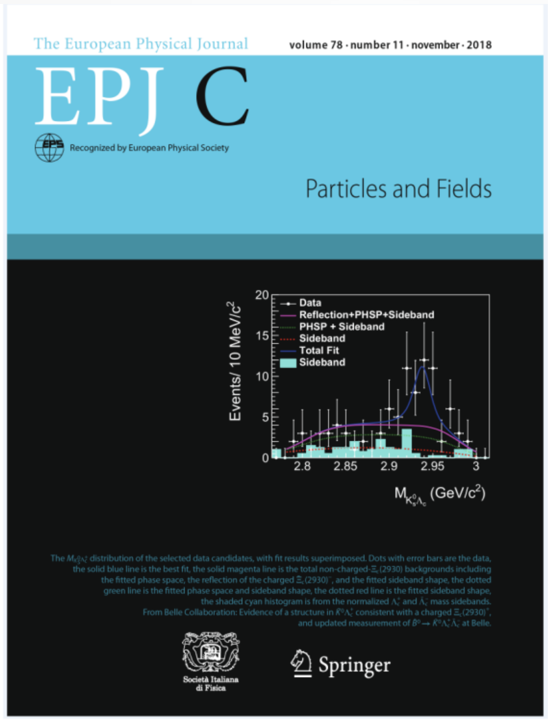
Only Λ_c^+, Ξ_c^0 and $\Sigma_c(2455)$ in ** status**



发现了新粲重子激发态$\Xi_c(2930)$

- 相继发现带电的和中性的$\Xi_c(2930)$，具有奇特性质：唯一在B介子衰变过程中发现，但未在正负电子直接对撞过程中观测到的Ξ_c激发态，引起广泛关注。





两篇论文均被选为EPJC封面论文。

理论解释：
普通的Ξ_c激发态
$\Lambda_c\bar{K}$分子态
。。。。

Y.B.Li, *C.P.Shen *et al* (Belle) EPJC 78, 928 (2018)；
Y.B.Li, *C.P.Shen *et al* (Belle) EPJC 78, 252 (2018)