第十一届中国物理学会高能物理分会

Charmed Baryon Results from Belle

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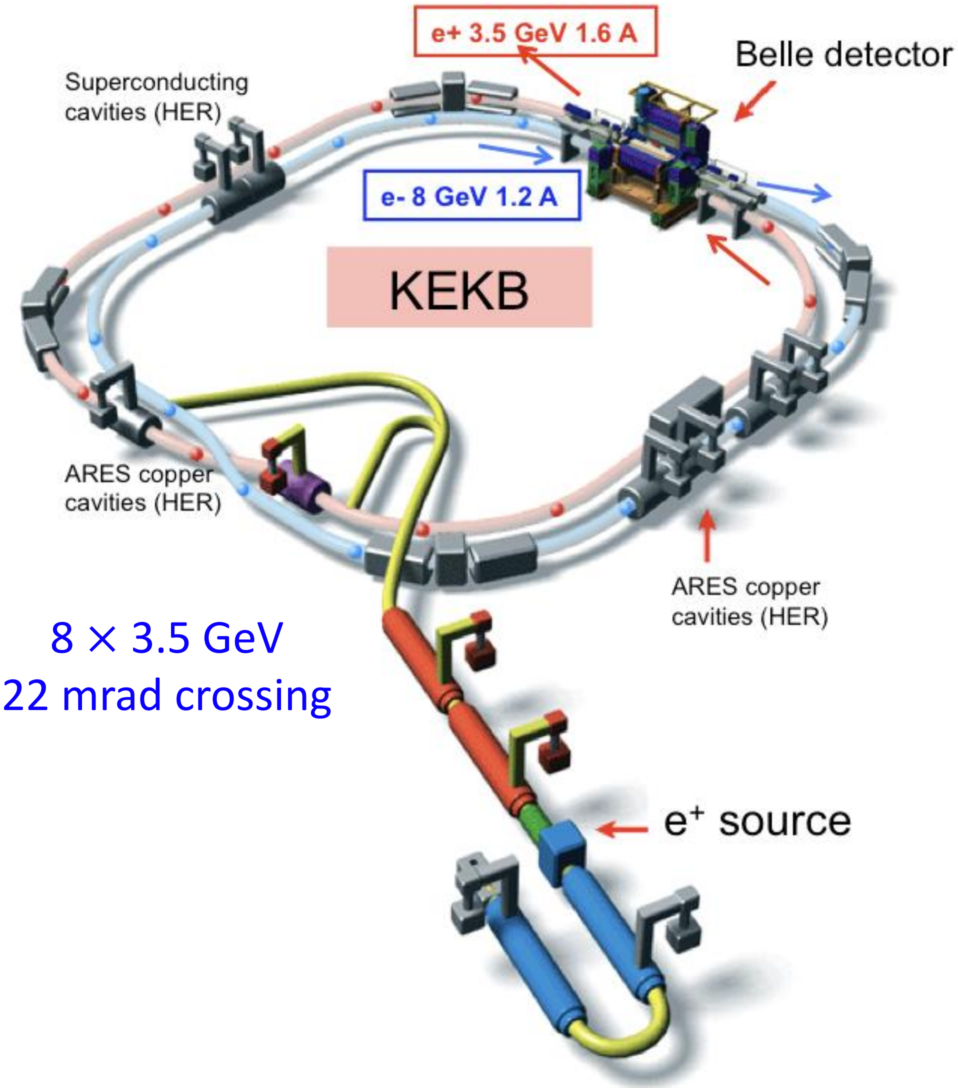
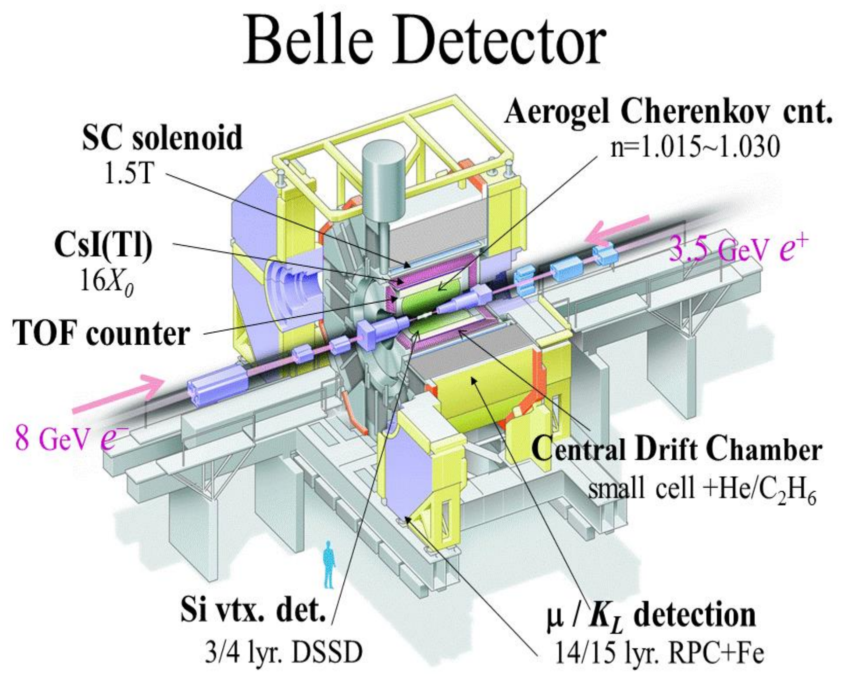
20212年08月10日

Belle experiment and data samples



8 × 3.5 GeV
22 mrad crossing



Data taking: 1999 – 2010

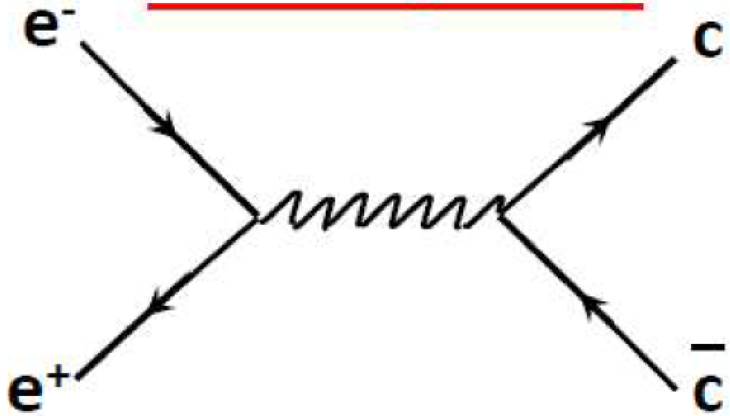
On/off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 980 fb^{-1}

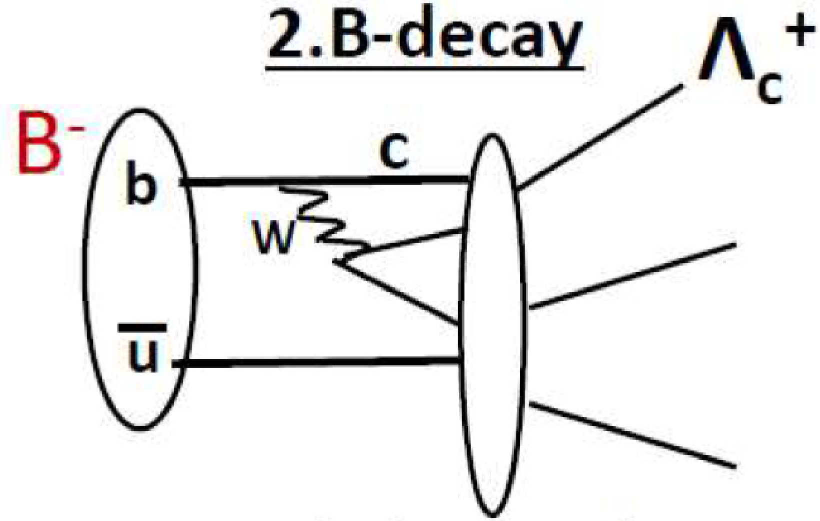
772M $B\bar{B}$ events @$\Upsilon(4S)$

Baryon production at B-factory

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



2. B-decay



Baryons produced via fragmentation

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

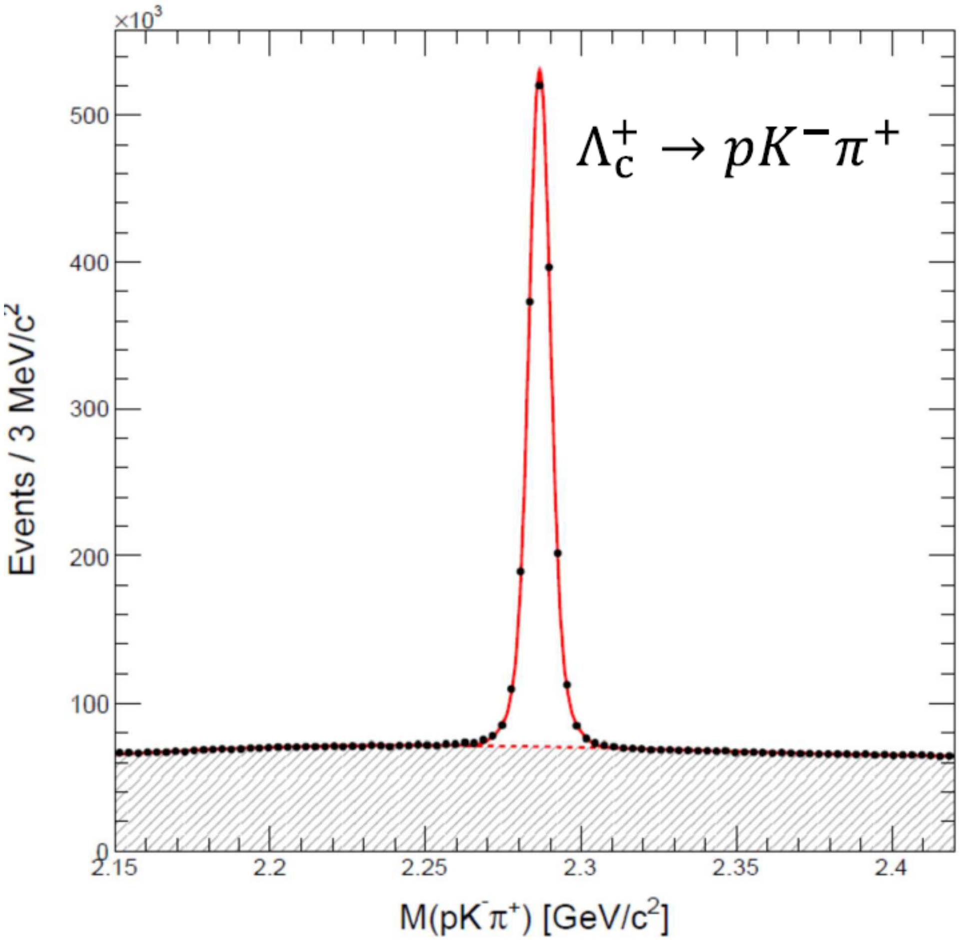
Huge statistics

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

Once bottom is produced, it favorably decays into charm.

Baryon production at B-factory

Huge statistics, good quality



> 1 M events reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

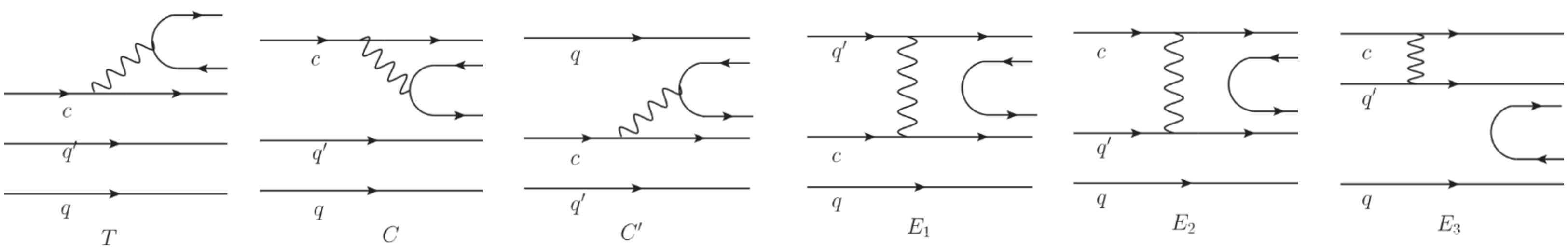
$B(\Lambda_c^+ \to pK^-\pi^+)$:
$(5.84 \pm 0.27 \pm 0.23)\%$
BESIII 2016
PRL 116 052001

$(6.84 \pm 0.24^{+0.21}_{-0.27})\%$
Belle 2014
PRL 113 042002

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Lambda_c^+ \to \Sigma^+\eta, \Lambda_c^+ \to \Sigma^+\eta'$

Motivation

- For the charmed baryon weak decays: $B_c \to B + M$ (M is pseudoscalar or vector meson), the topological diagrams are as follows. Among them, T and C are factorizable, while C′ and E_{1-3} give nonfactorizable contributions.



external W-emission T | internal W-emission C | inner W-emission C' | W-exchange diagrams E_1 E_2 E_3

- Naively, it is expected that the rates of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$ are comparable or the former is larger than the latter. However, the branching fraction of $\Lambda_c^+ \to \Sigma^+\eta'$ measured by BESIII was found to be larger than the $\Lambda_c^+ \to \Sigma^+\eta$ mode.

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 3.5 \pm 2.1 \pm 0.4.$$

Decay	Körner CCQM	Xu Pole	Cheng CA	Cheng Pole	Ivanov CCQM	Żenczykowski Pole	Sharma CA	Zou CA	Geng SU(3)	Experiment	
$\Lambda_c^+ \to \Sigma^+\eta$	0.16				0.11	0.90	0.57	0.74	0.32 ± 0.13	0.44 ± 0.20	Branchin fraction
$\Lambda_c^+ \to \Sigma^+\eta'$	1.28				0.12	0.11	0.10		1.44 ± 0.56	1.5 ± 0.6	
$\Lambda_c^+ \to \Sigma^+\eta$	0.33				0.55	0	-0.91	-0.95	-0.40 ± 0.47		Asymmetry parameter
$\Lambda_c^+ \to \Sigma^+\eta'$	-0.45				-0.05	-0.91	0.78		$1.00^{+0.00}_{-0.17}$		

- Compare the asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ could test the isospin symmetry.

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Lambda_c^+ \to \Sigma^+\eta, \Lambda_c^+ \to \Sigma^+\eta'$

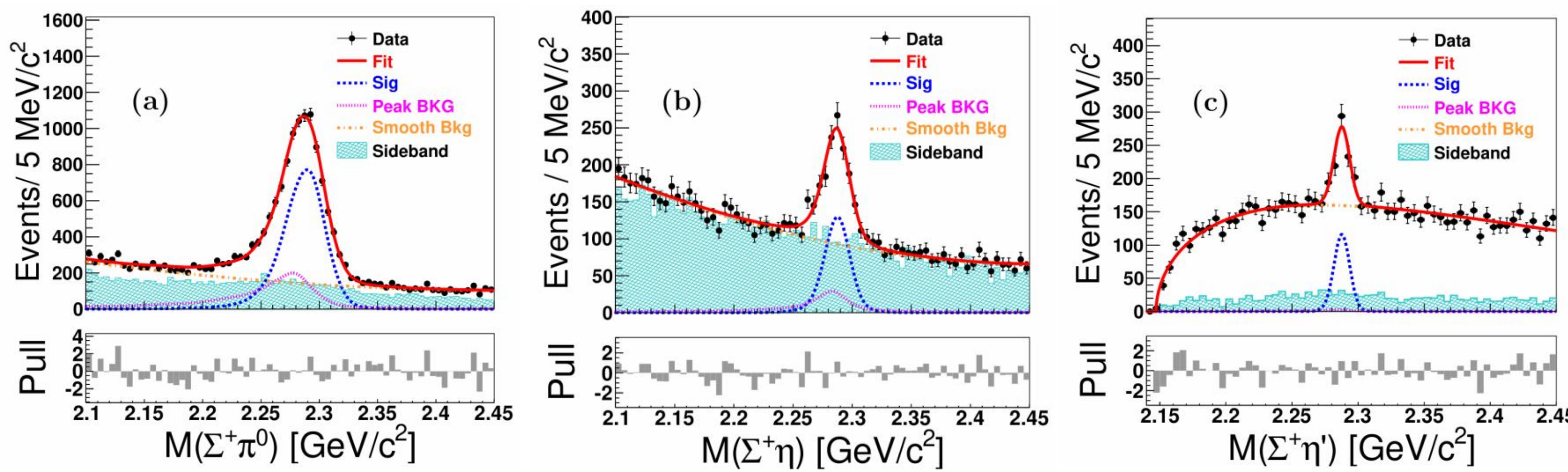
preliminary

- **Measurements of branching fractions of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$**

NEW

Method: $\frac{B(\Lambda_c^+ \to \Sigma^+\eta/\Sigma^+\eta')}{B(\Lambda_c^+ \to \Sigma^+\pi^0)} = \frac{y(\Lambda_c^+ \to \Sigma^+\eta/\Sigma^+\eta')}{B_{\mathrm{PDG}} \times y(\Lambda_c^+ \to \Sigma^+\pi^0)}$ (y is the efficiency-corrected yield).

Reference mode: $\Lambda_c^+ \to \Sigma^+\pi^0$ **Signal mode:** $\Lambda_c^+ \to \Sigma^+\eta$ **Signal mode:** $\Lambda_c^+ \to \Sigma^+\eta'$



$$\frac{B(\Lambda_c^+ \to \Sigma^+\eta)}{B(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.25 \pm 0.03 \pm 0.01; \quad B(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3}$$

$$\frac{B(\Lambda_c^+ \to \Sigma^+\eta')}{B(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.33 \pm 0.06 \pm 0.02; \quad B(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3}$$

Most precise result to date.

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Lambda_c^+ \to \Sigma^+\eta, \Lambda_c^+ \to \Sigma^+\eta'$

preliminary

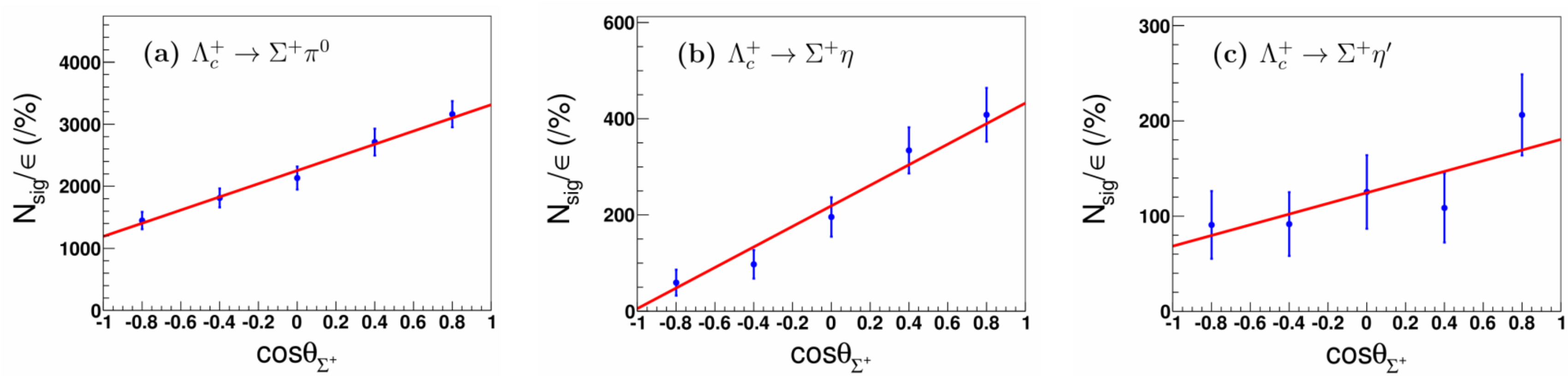
NEW

■ Measurements of asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$, $\Sigma^+\eta$, and $\Sigma^+\eta'$

The differential decay rate depends on the asymmetry parameter α_{Σ^+X} as:

$$\frac{dN}{dcos\theta_{\Sigma^+}} \propto 1 + \alpha_{\Sigma^+X}\alpha_{p\pi^0}cos\theta_{\Sigma^+}$$

θ_{Σ^+} is the angle between the proton momentum vector and the opposite of the Λ_c^+ momentum vector in the Σ^+ rest frame; $\alpha_{p\pi^0} = -0.982 \pm 0.014$ from world average value.

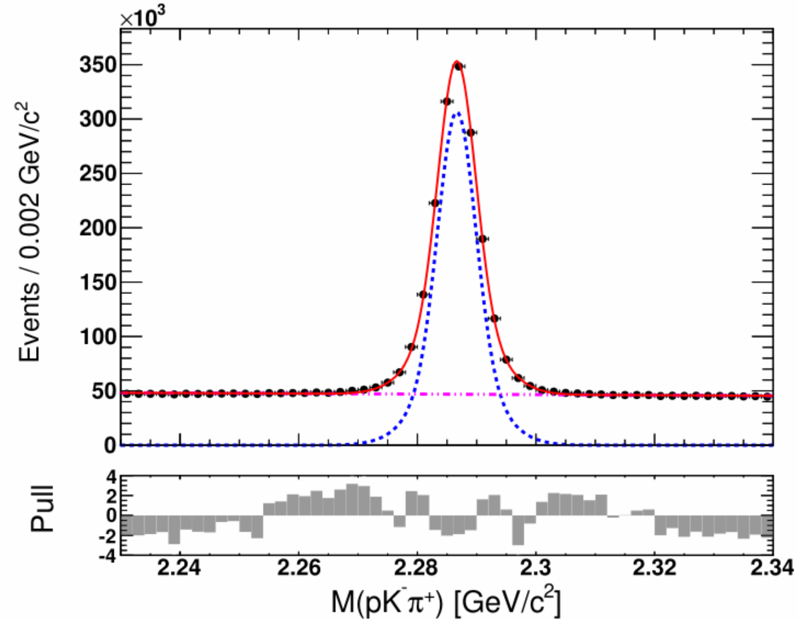


- $\alpha_{\Sigma^+\pi^0} = -0.48 \pm 0.02 \pm 0.02$
  - ➢ agrees with the world average value: -0.55 ± 0.11.
  - ➢ with much improved precision.
  - ➢ The consistency with $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$ indicates no isospin symmetry broken.
- $\alpha_{\Sigma^+\eta} = -0.99 \pm 0.03 \pm 0.05$ and $\alpha_{\Sigma^+\eta'} = -0.46 \pm 0.06 \pm 0.03$
  - ➢ measured for the first time.

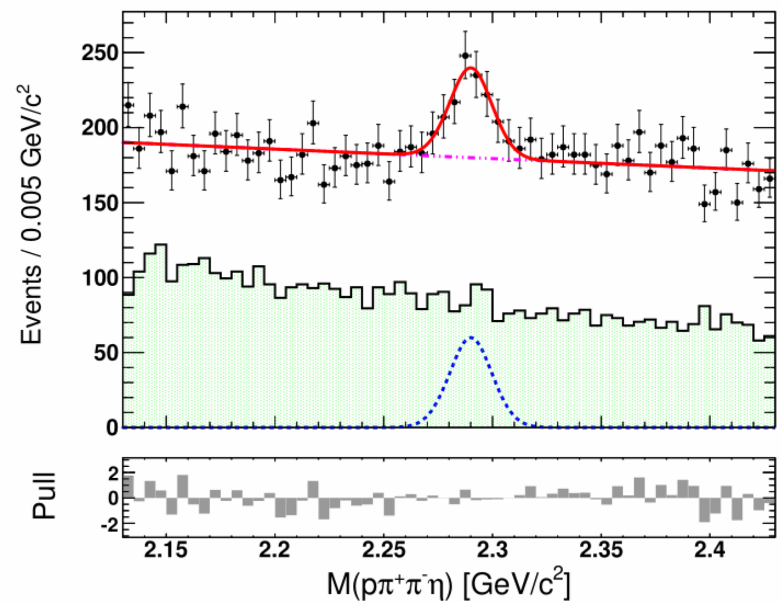
First Observation of $\Lambda_c^+ \to p\eta'$

JHEP03(2022)090

Reference mode



Signal mode



$$\mathrm{B}(\Lambda_c^+ \to p\eta')=(4.73\pm0.82\pm0.47\pm0.24)\times10^{-4}$$

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.

First search for the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

Motivation:

- Weak radiative decays of charmed hadrons are dominated by the long-range nonperturbative processes that can enhance the branching fractions up to 10^{-4}, whereas short-range interactions are predicted to yield rates at the level of 10^{-8}[1,2]
- At the Cabibbo-favored level, there are two decay modes for the weak radiative decays of anti-triplet charmed baryons induced from $cd \to us\gamma$, i.e., $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays.
- The theoretical estimates of branching fractions cover ranges of $(4.5 - 29.1) \times 10^{-5}$ and $(3.0 - 19.5) \times 10^{-5}$ for $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays, respectively [3-6].

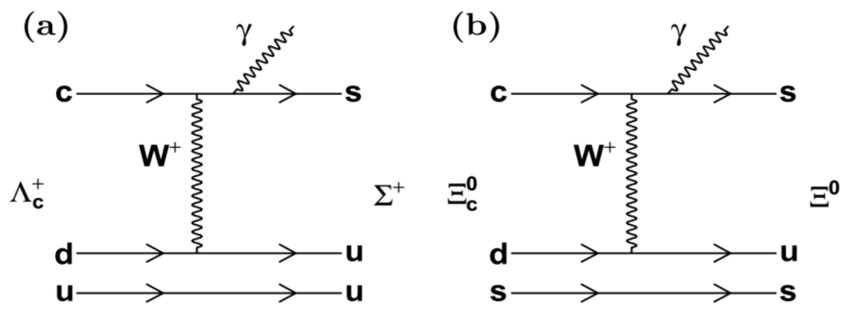


FIG. 1: The W-exchange diagrams accompanied by a photon emission from the external s quark for (a) $\Lambda_c^+ \to \Sigma^+\gamma$ and (b) $\Xi_c^0 \to \Xi^0\gamma$ decays as examples.

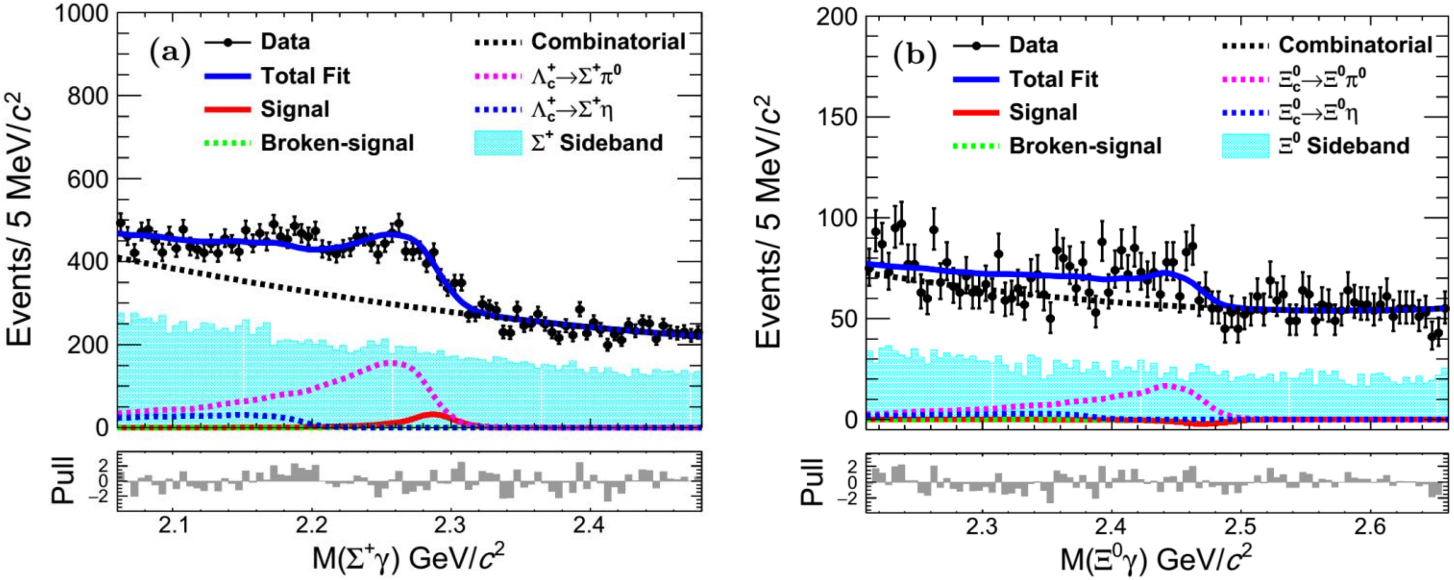
- In this analysis, we perform the first search the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ using 980 fb^{-1} data collected by Belle.

[1]PRD 52, 6383 (1995); [2] PLB 382, 415 (1996); [3] PRD 28, 2176 (1983); [4] PRD 47, 2858 (1993); [5] PRD 51, 1199 (1995); [6] arXiv:2109.01216.

First search for the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

arXiv:2206.12517

- There are no evident $\Lambda_c^+ \to \Sigma^+\gamma$ or $\Xi_c^0 \to \Xi^0\gamma$ signals. The signal significance of $\Lambda_c^+ \to \Sigma^+\gamma$ decay is only 2.2σ, after considering the systematic uncertainty.



- Taking $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$ as normalization channels, the upper limits at 90% confidence level (C.L.) on the ratios of branching fractions are

$$\frac{\mathrm{Br}(\Lambda_c^+ \to \Sigma^+\gamma)}{\mathrm{Br}(\Lambda_c^+ \to pK^-\pi^+)} < 3.99 \times 10^{-3} \qquad \frac{\mathrm{Br}(\Xi_c^0 \to \Xi^0\gamma)}{\mathrm{Br}(\Xi_c^0 \to \Xi^-\pi^+)} < 1.15 \times 10^{-2}$$

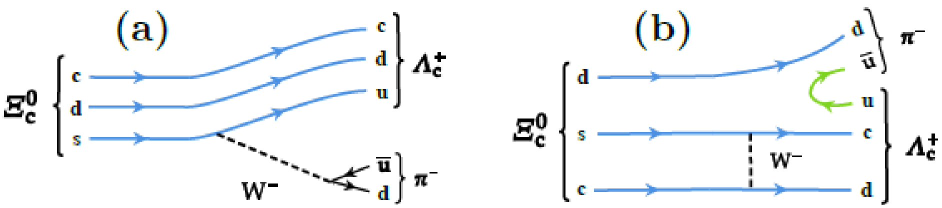
- The upper limits at 90% C.L. on the absolute branching fractions are determined to be

$$\mathrm{Br}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.55 \times 10^{-4} \qquad \mathrm{Br}\left(\Xi_c^0 \to \Xi^0\gamma\right) < 1.73 \times 10^{-4}$$

Measurements of $Br(\Xi_c^0 \to \Lambda_c^+ \pi^-)$

NEW

- There is a special class of weak decay, the heavy-flavor-conserving nonleptonic decays, in charmed baryons containing both an *s* and a *c* quark, that proceeds via the decay of the s quark, i.e. $\Xi_c^0 \to \Lambda_c^+ \pi^-$. The decay width of $\Xi_c^0 \to \Lambda_c^+ \pi^-$ is based on the size of the *s* quark decay amplitude of $s \to u(\bar{u}d)$ and the weak scattering amplitude $cs \ \to dc$.



The Feynman diagrams of the (a) $s \to u(\bar{u}d)$ and (b) $cs \ \to dc$ modes of $\Xi_c^0 \to \Lambda_c^+ \pi^-$.

- The branching fraction of $\Xi_c^0 \to \Lambda_c^+ \pi^-$ have been predicted based on the heavy quark expansion, and the heavy quark symmetry(HQS).

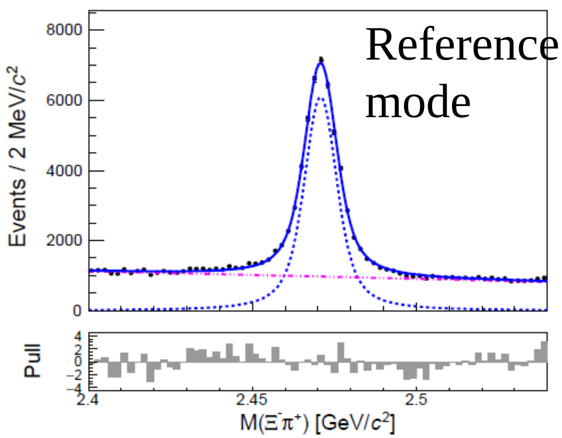
Mode	[Phys. Rev. D 46, 5060 (1992)]	[Phys. Rev. D 100, 114030 (2019)]	[Phys. Lett. B 757, 330 (2016)]	[Phys. Lett. B 750, 653 (2015)]
$\Xi_c^0 \to \Lambda_c^+ \pi^-$	0.39×10^{-3}	$> (0.25 \pm 0.15) \times 10^{-3}$	$(1.34 \pm 0.53) \times 10^{-3}$	$< 0.39\times 10^{-3}$

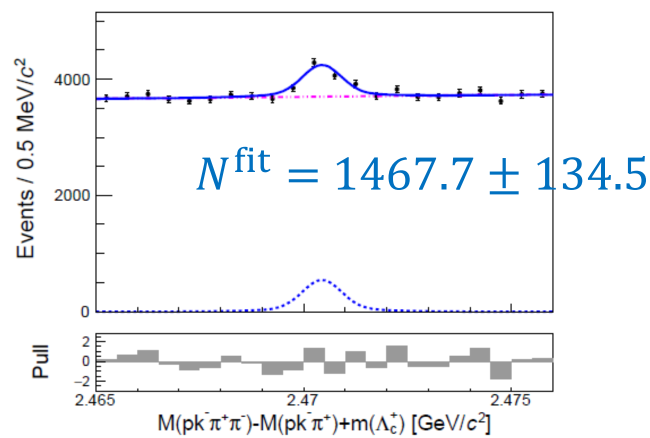
Measurements of $Br(\Xi_c^0 \to \Lambda_c^+ \pi^-)$

NEW

- We present the measurement of branching fractions of $\Xi_c^0 \to \Lambda_c^+ \pi^-$ using all Belle data.

arXiv:2206.08527





$$\frac{Br(\Xi_c^0 \to \Lambda_c^+ \pi^-)}{Br(\Xi_c^0 \to \Xi^- \pi^+)} = (3.8 \pm 0.4\ (\text{stat.}) \pm 0.03\ (\text{syst.}) \pm 2.0\ (\text{ref.})) \times 10^{-3}$$

$$Br(\Xi_c^0 \to \Lambda_c^+ \pi^-) = (6.8 \pm 0.6 \pm 0.6 \pm 2.0\ ) \times 10^{-3}$$

- The result is consistent with previous measurement by LHCb experiment and recent theoretical calculation, and larger than the previous theoretical predictions.

Evidence of a new Λ_c^+ excited state ?

- 粲重子谱学：研究重味夸克有效理论(HQET)等理论的重要平台
- 高质量激发态：难以用现有理论理解其性质
- Λ_c^+激发态大部分可以衰变到$\Lambda_c^+\pi\pi$ 末态 (或存在 Σ_c中间态)

$\Lambda_c(2595)^+$ Decay Modes	
Γ_1	$\Lambda_c^+\pi^+\pi^-$

$\Lambda_c(2625)^+$ Decay Modes	
Γ_1	$\Lambda_c^+\pi^+\pi^-$

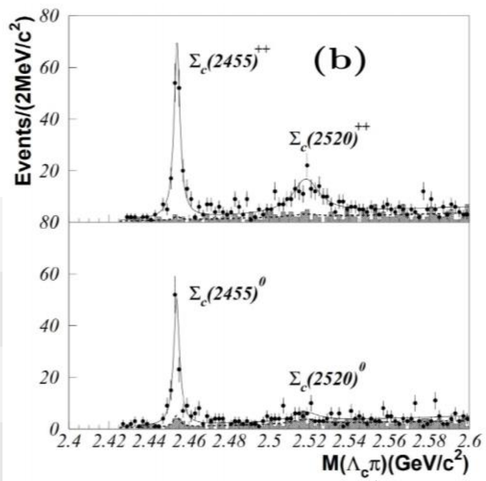
- $\overline{B}^0 \to \Lambda_c\pi\pi\overline{p}$ 是一个理想的衰变道
  - ➢本底水平低，成分明晰
  - ➢分支比在10^{-4} 量级
  - ➢Belle 有772×10^6 $B\overline{B}$样本：产率充裕

$\Lambda_c(2880)^+$ Decay Modes	
Γ_1	$\Lambda_c^+\pi^+\pi^-$

$\Lambda_c(2940)^+$ Decay Modes	
Γ_1	pD^0
Γ_2	$\Sigma_c(2455)^{0,++}\pi^\pm$

B^0 Decay Modes

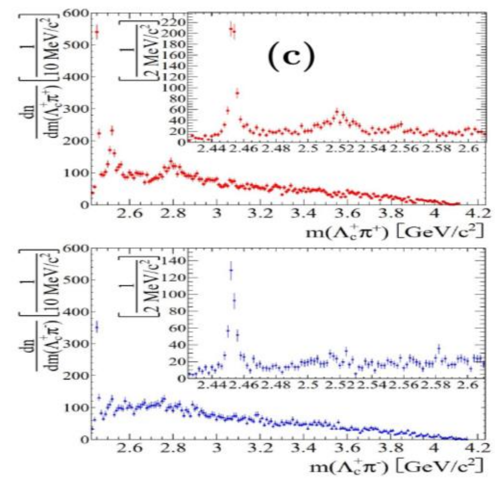
Γ_{500}	$\overline{\Lambda}_c^{\,-}p\pi^+\pi^-$ (nonresonant)	$(5.5\pm1.0)\times10^{-4}$
Γ_{501}	$\overline{\Sigma}_c(2520)^{--}p\pi^+$	$(1.02\pm0.18)\times10^{-4}$
Γ_{502}	$\overline{\Sigma}_c(2520)^0 p\pi^-$	$< 3.1\times10^{-5}$
Γ_{503}	$\overline{\Sigma}_c(2455)^0 p\pi^-$	$(1.08\pm0.16)\times10^{-4}$



Belle: 357 fb^{-1}

(一半数据量)

PRD 75, 011101 (2007)

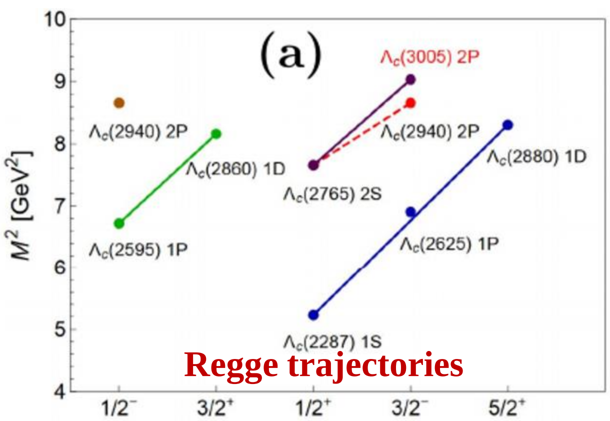


Babar: 426 fb^{-1}

PRD 87, 092004 (2013)

Evidence of a new Λ_c^+ excited state ?

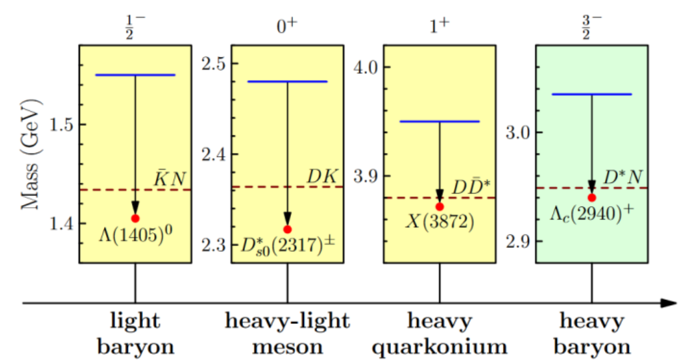
- $\Lambda_c(2940) \to \Sigma_c(2455)\pi$: 是目前最高的$\Lambda_c$激发态
- LHCb测量支持$J^P = \frac{3}{2}^-$，但不排除其他可能值 JHEP 05, 030 (2017).
- $\Lambda_c(2940)$质量低于传统夸克模型预期



Int J Theor Phys 59, 1129 (2020)

State	J^P	Present	[9]	[10]	[11]	[16]	[20]	[21]	PDG [1]
$2P$	$\frac{1}{2}^-$	2.978	3.017	2.983	2.989	2.890		2.980	
$2P$	$\frac{3}{2}^-$	2.970	3.034	3.005	3.000	2.917		3.004	$2.9396^{+0.0014}_{-0.0015}$

[9]. Phys. Lett. B 659, 612 (2008).
[10]. Phys. Rev. D 84, 014025 (2011).
[11]. Phys. Rev. D 91, 054034 (2015).
[16]. Phys. Rev. D 92, 114029 (2015).
[21]. Eur. Phys. J. C 77, 154 (2017).



理论解释：

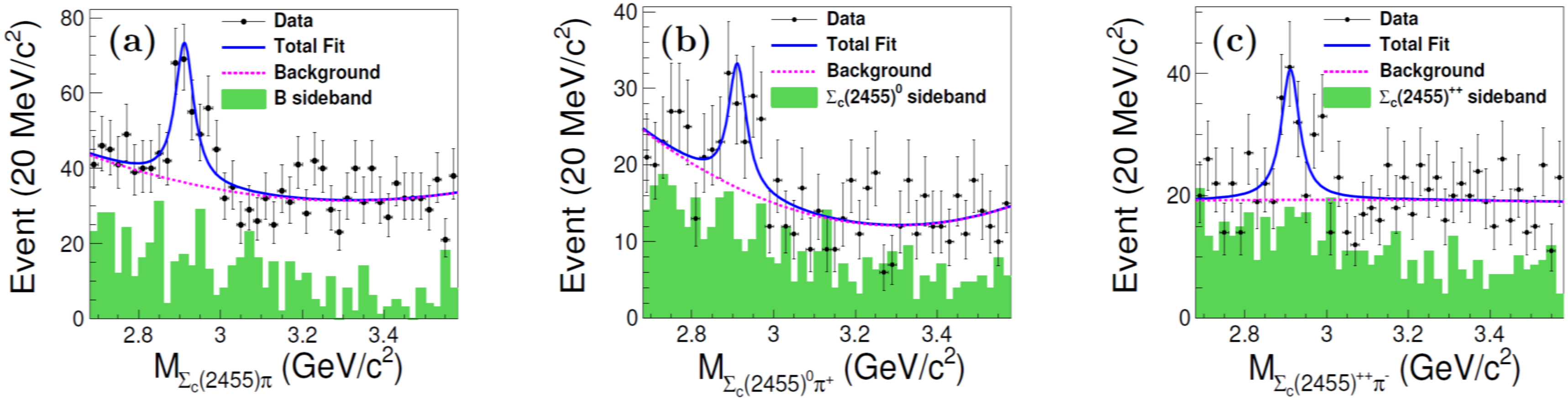
- $\Lambda_c(2940)$的 $J^P = \frac{1}{2}^-$， 属于另外一条Regge trajectories
  - 寻找$\Lambda_c(3005)$
- 类似$\Lambda(1405), D_s(2317), X(3872)$， $\Lambda_c(2940)$中含有D^*N贡献
  - $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$质量反转，大于$\Lambda_c\left(\frac{3}{2}^-, 2P\right)$

$\bar{B}^0 \to \Lambda_c^* \bar{p}$, $\Lambda_c^* \to \Sigma_c\pi$:
寻找新的Λ_c激发态，
并且可以限制其J^P值

Evidence of a new Λ_c^+ excited state ?

Λ_c激发态的寻找：

arXiv:2206.08822



- 在$\Sigma_c(2455)\pi$不变质量谱上，观测到一个结构，质量宽度测得：

$$m = (2913.8 \pm 5.6 + 3.7)\ \mathrm{MeV/c^2}$$
$$\Gamma = (51.8 \pm 20.0 \pm 18.8)\ \mathrm{MeV}$$

- 统计显著性6.1σ，考虑各种系统误差后，最保守的显著性4.2σ
- 其J^P倾向于$\frac{1}{2}^-$,即：此结构符合$\Lambda_c\left(\frac{1}{2}^-, 2P\right)$,命名为$\Lambda_c(2910)$
- 对2P态：$\Lambda_c(2910)$ 和$\Lambda_c(2940)$需要进一步实验测量和理论解释

- The Ω^-, with three strange quarks, is the strangest baryon.
- Its excited states have proved difficult to find.
- It is surprising that the mass gap between the ground state and its excitations is so large.

Ω BARYONS ($S = -3$, $I = 0$)

$\Omega^- = s\,s\,s$

Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

The $\Omega(2012)$ was observed in $\Upsilon(1S, 2S, 3S)$ decays by Belle in 2018.

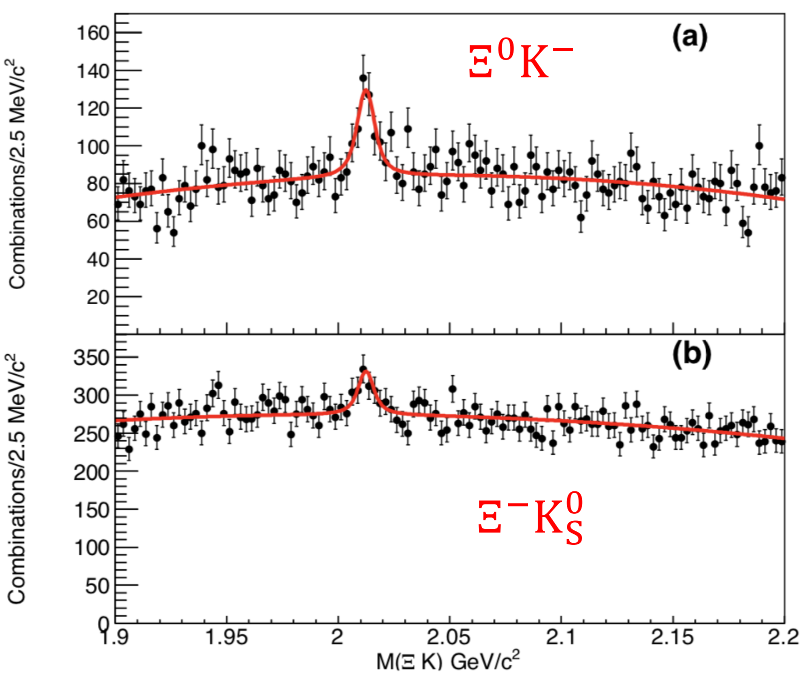
The observations/evidences for these states were reported four decades ago.

Observation of the $\Omega(2012)^-$

Results & Summary

[PRL 121, 052003 (2018)]

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



$$\mathcal{R} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi^0 K^-)}{\mathcal{B}(\Omega(2012)^- \to \Xi^- \bar{K}^0)} = 1.2 \pm 0.3$$

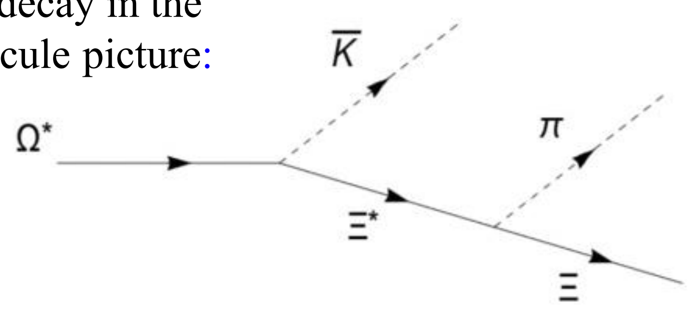
- The $\Omega(2012)^-$ was found for the first time at Belle in decays of the narrow resonances $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$.
- The rather narrow width of the $\Omega(2012)^-$ implies that the $J^P = \frac{3}{2}^-$ identification is more likely.

Theoretical interpretations for the $\Omega(2012)^-$

The $\Omega(2012)^-$ has been interpreted as a standard baryon or a $\Xi(1530)\bar{K}$ molecule.

Interpretations	References	Comments
Standard baryon	PRD 98, 034004 (2018), EPJC 78, 894 (2018), PRD 98, 114023 (2018), PRD 101, 016002 (2020), PRD 105, 094006 (2022), PRC 103, 025202 (2021), PRD 98, 014031 (2018), PLB 792, 315 (2019), arXiv: 2203.04458 (2022), arXiv: 2201.10427 (2022)	The $\Omega(2012)^-$ decays dominantly to $\Xi\bar{K}$.
$\Xi(1530)\bar{K}$ molecule	PRD 98, 054009 (2018), EPJC 78, 857 (2018), PRD 98, 076012 (2018), JPG 48, 025001 (2021), PRD 98, 056013 (2018), PRD 101, 094016 (2020), EPJC 80, 361 (2020), PRD 102, 074025 (2020), arXiv: 2204.13396 (2022),	The $\Omega(2012)^-$ decays equally to $\Xi\bar{K}$ and $\Xi(1530)\bar{K}$. Or the $\Xi(1530)\bar{K}$ decay mode is dominant.

The three-body decay in the $\Xi(1530)\bar{K}$ molecule picture:



Measurement of the branching fraction for $\Omega(2012)^- \to \Xi(1530)\bar{K}$ is crucial to distinguish the nature of the $\Omega(2012)$!

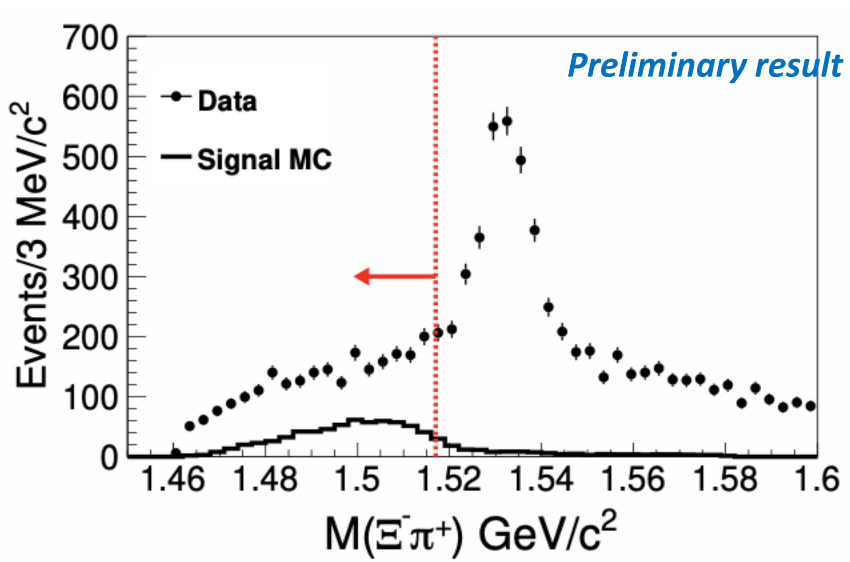
Revisit $\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

arXiv:2207.03090

NEW

In contrast to the previous study [PRD 100, 032006 (2019)]:

1. $M(\Xi\pi) < 1.517$ GeV
2. parameterize the $\Omega(2012)^-$ signal shape with a Flatté-like function with a three-body phase space included



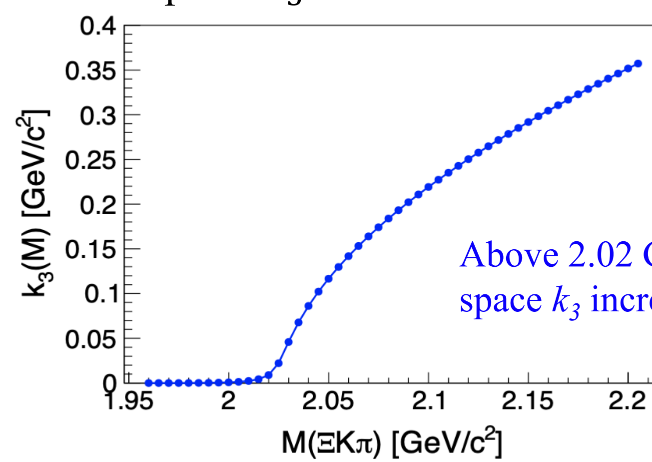
- The black solid histogram shows the expected lineshape of the $\Xi(1530)$.
- The number of signal-MC events is scaled to three times the yield of $\Omega(2012)^- \to \Xi^-\pi^+K^-$ in data to make it more visible.

The Flatté-like function [PRD 81, 094028 (2010)]

$$T_n(M) = \frac{g_n k_n(M_n)}{|M_n - m_{\Omega(2012)} + \frac{1}{2}\sum_{j=2,3} g_j[\kappa_j(M_j) + i k_j(M_j)]|^2}$$

- g_n is the effective coupling of to the n–body final state
- k_n and κ_n parameterize the real and imaginary parts of the $\Omega(2012)^-$self-energy

The shape of k_3:

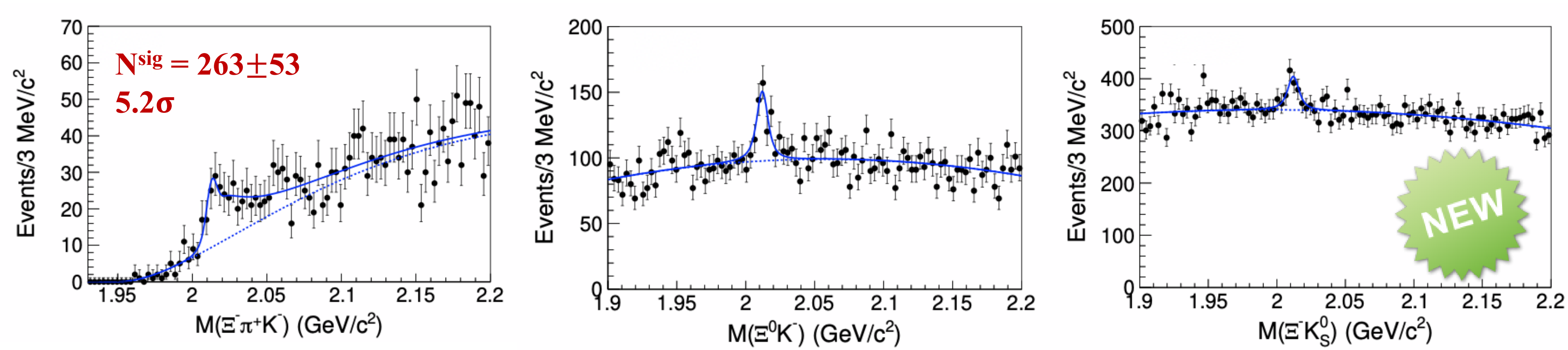


Above 2.02 GeV, the phase space k_3 increases sharply.

Observation of $\Omega(2012)^- \to \Xi(1530)\bar{K}$ and measurement of the couplings of $\Omega(2012)^- \to \Xi(1530)\bar{K}$ and $\Xi\bar{K}$

We fit simultaneously to the binned $\Xi^-\pi^+K^-$, Ξ^0K^-, and $\Xi^-K^0_S$ mass distributions from Υ(1S,2S,3S) data samples.

arXiv:2207.03090



The mass and effective couplings :

$\Omega(2012)^-$ mass	(2012.5±0.7±0.5) MeV
The coupling to $\Xi\bar{K}$	$(1.7\pm0.3\pm0.3)\times10^{-2}$
The coupling to $\Xi(1530)\bar{K}$	$(41.1\pm35.8\pm6.0)\times10^{-2}$

The ratio of the branching fraction for the three-body to two-body decays:

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K})}{\mathcal{B}(\Omega(2012)^- \to \Xi\bar{K})}$$

0.97±0.24(stat.)±0.07(syst.)

Our result is consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$.

Summary

- Although Belle has stopped data taking for >10 years ago, we are still producing exciting results [China group has made great contributions].
- Various results in Charmed Baryon sector
  - Semileptonic, hadronic, radiative decay
  - Branching fraction, asymmetry parameter.
  - Intermediate states in the decay
  - ……
- Belle II is performing as expected and obtained early physics results.

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

Measurements 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).

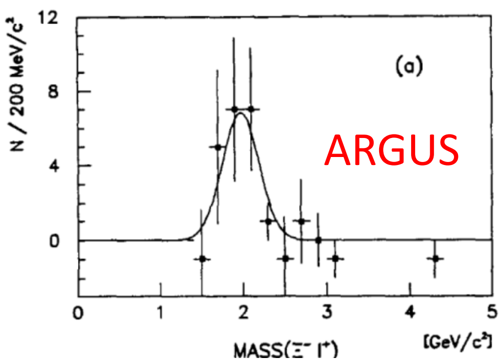
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, e^+ \nu_e) = (3.6 \pm 0.4)\%$ PRL 115, 221805(2015)

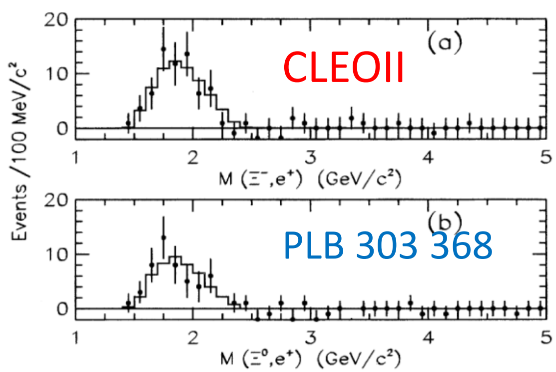
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, \mu^+ \nu_e) = (3.5 \pm 0.4)\%$ PLB 767, 42 (2017)

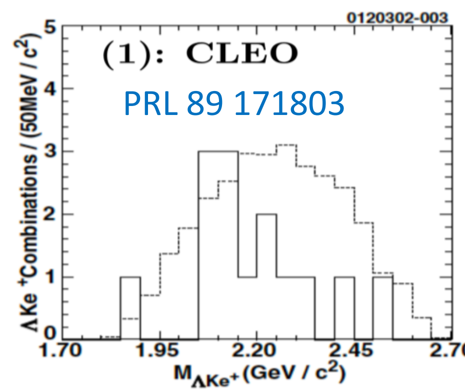
Experimentally:

- 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







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

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

For Belle measurements, please see Yubo Li's report at 16:20 on July 29.

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	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

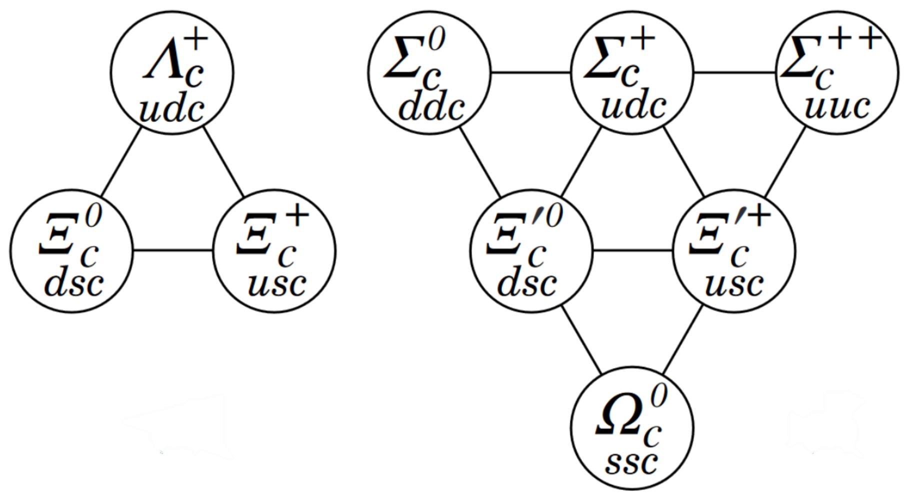
****:Existence is certain, properties fairly explored.

***: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**



k_3 and κ_3 are

PRD 81, 094028 (2010)

$$k_3(M) = \frac{g_l}{2\pi\mu_p}\int_0^{\sqrt{2\mu_p q(M)}} p^2 dp \times \frac{(q(M)-\frac{p^2}{2\mu_p})^{(2l+1)/2}}{(M_R - q(M) + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(q(M)-\frac{p^2}{2\mu_p})^{2l+1}},$$

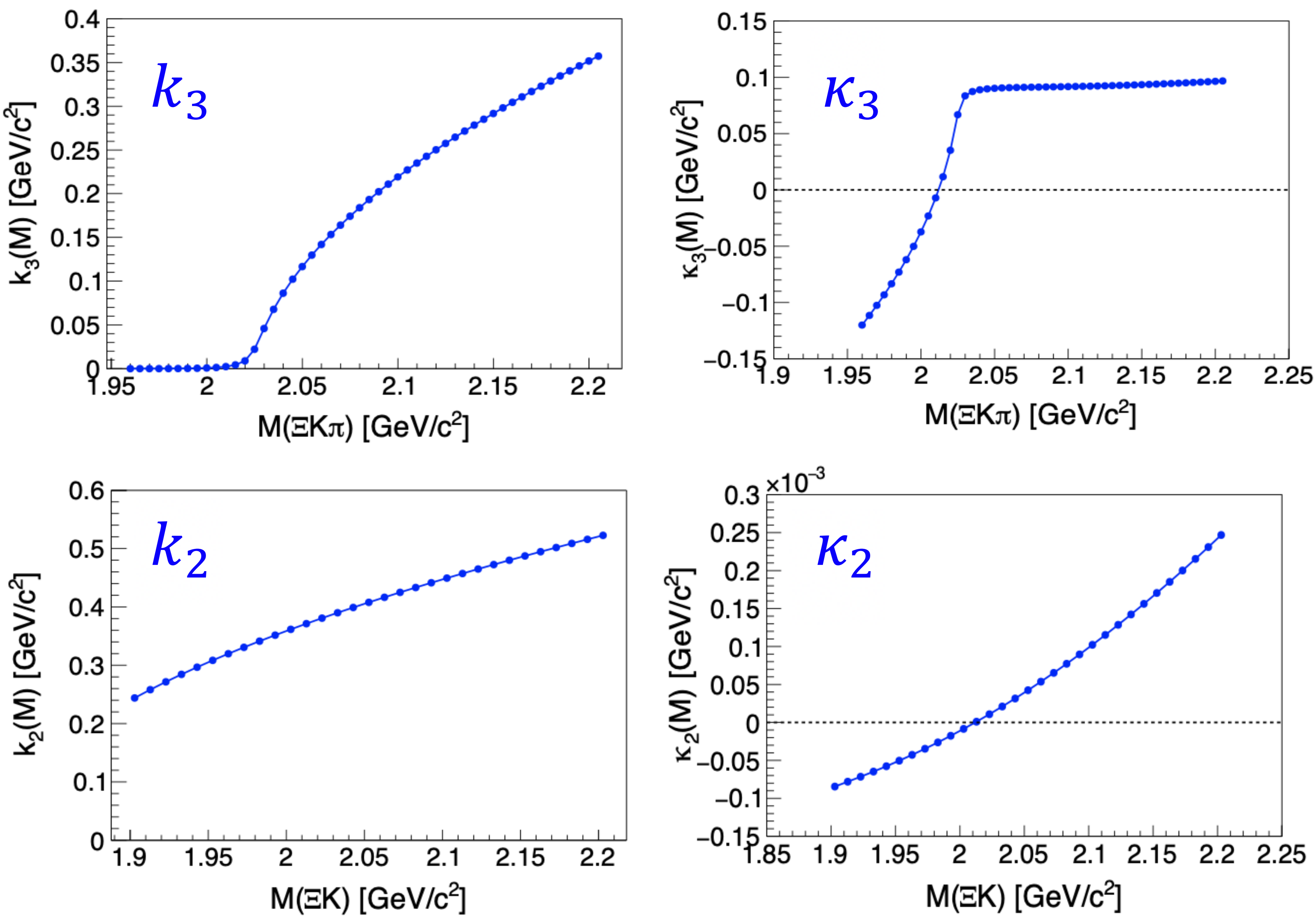
$$\kappa_3(M) = \kappa(q(M)) + \kappa'(q(M)) - \kappa(q(m)) - \kappa'(q(m)),$$

$$\kappa(M) = \frac{1}{\pi\mu_p}\int_0^{\infty} p^2 dp \times \frac{M_R - q(M) + \frac{p^2}{2\mu_p}}{(M_R - q(M) + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(q(M)-\frac{p^2}{2\mu_p})^{2l+1}},$$

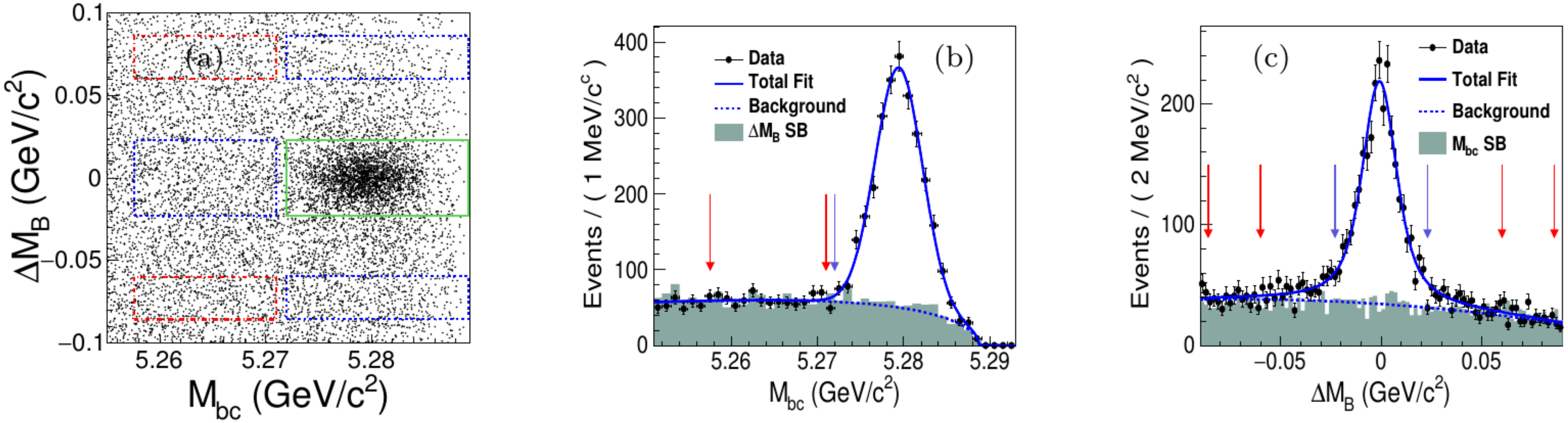
$$\kappa'(M) = -\frac{g_l}{2\pi\mu_p}\int_{\sqrt{2\mu_p q(M)}}^{\infty} p^2 dp \times \frac{(\frac{p^2}{2\mu_p} - q(M))^{(2l+1)/2}}{(M_R - q(M) + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(q(M)-\frac{p^2}{2\mu_p})^{2l+1}}.$$

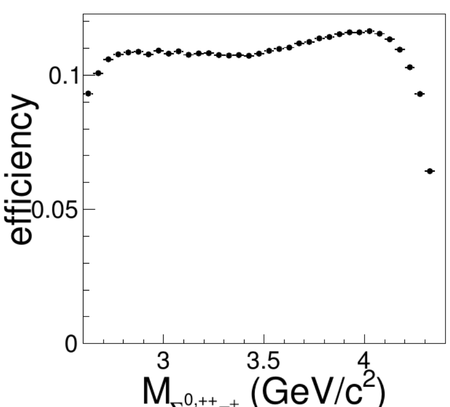
Here, $q(M) = M(\Xi\pi\overline{K}) - m_\Xi - m_\pi - m_K$, $q(m) = m_{\Omega(2012)^-} - m_\Xi - m_\pi - m_K$, $\mu_p = \frac{m_K(m_\pi + m_\Xi)}{m_\Xi + m_\pi + m_K}$ is the reduced mass of the $\Xi\overline{K}$ system, $M_R = m_{\Xi(1530)} - m_\Xi - m_\pi$ is the mass of the unstable constituent, the coupling g_l is $\Gamma_R/E_R^{l+1/2}$ (Γ_R is the width of $\Xi(1530)$), the orbital angular momentum of $\overline{K}$ in the $\Xi(1530)\overline{K}$ system is $l = 1$, and p is the $\overline{K}$ momentum in the $\Xi(1530)\overline{K}$ center-of-mass system.

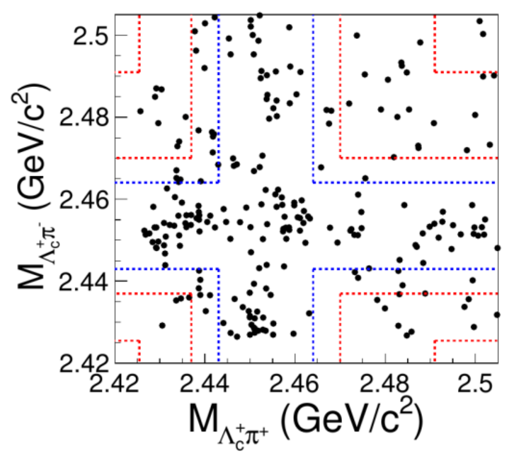
The functions k_2 and κ_2 are identical to k_3 and κ_3 with $\Xi(1530)$ replaced with Ξ, followed by $\Xi \to \Lambda\pi$.



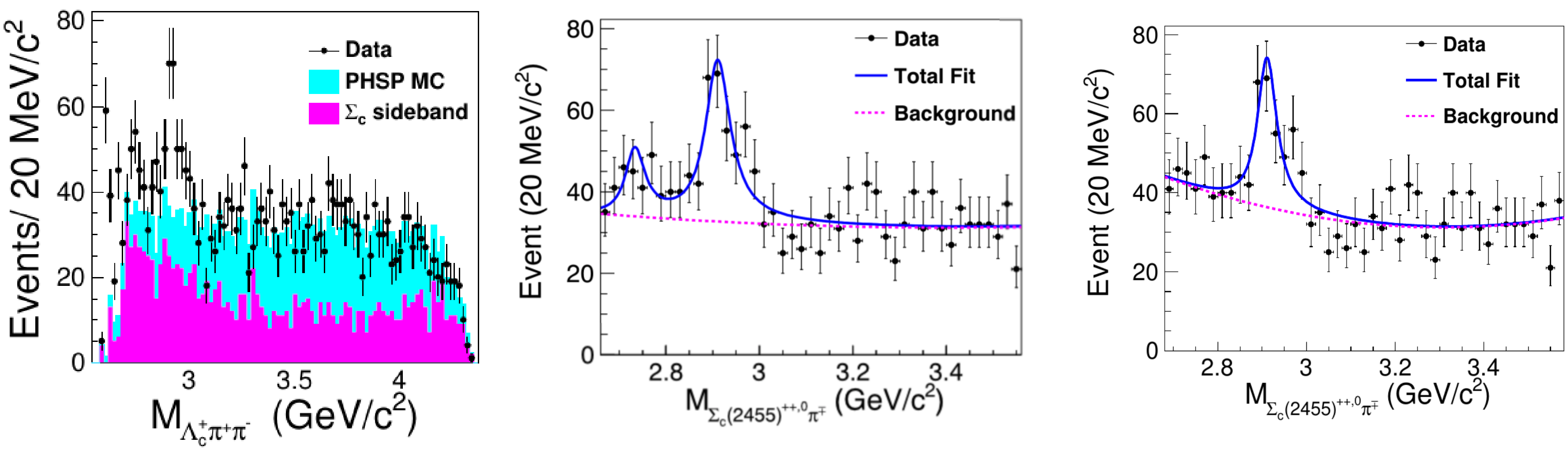
k_3
k_3(M) [GeV/c^2]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.95
2
2.05
2.1
2.15
2.2
M(ΞKπ) [GeV/c^2]
κ_3
κ_3(M) [GeV/c^2]
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
1.9
1.95
2
2.05
2.1
2.15
2.2
2.25
M(ΞKπ) [GeV/c^2]
k_2
k_2(M) [GeV/c^2]
0.6
0.5
0.4
0.3
0.2
0.1
0
1.9
1.95
2
2.05
2.1
2.15
2.2
M(ΞK) [GeV/c^2]
κ_2
×10^{-3}
κ_2(M) [GeV/c^2]
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
1.85
1.9
1.95
2
2.05
2.1
2.15
2.2
2.25
M(ΞK) [GeV/c^2]


(a)
ΔM_B (GeV/c^2)
M_{bc} (GeV/c^2)
(b)
Data
Total Fit
Background
ΔM_B SB
Events / (1 MeV/c^c)
M_{bc} (GeV/c^2)
(c)
Data
Total Fit
Background
M_{bc} SB
Events / (2 MeV/c^2)
ΔM_B (GeV/c^2)

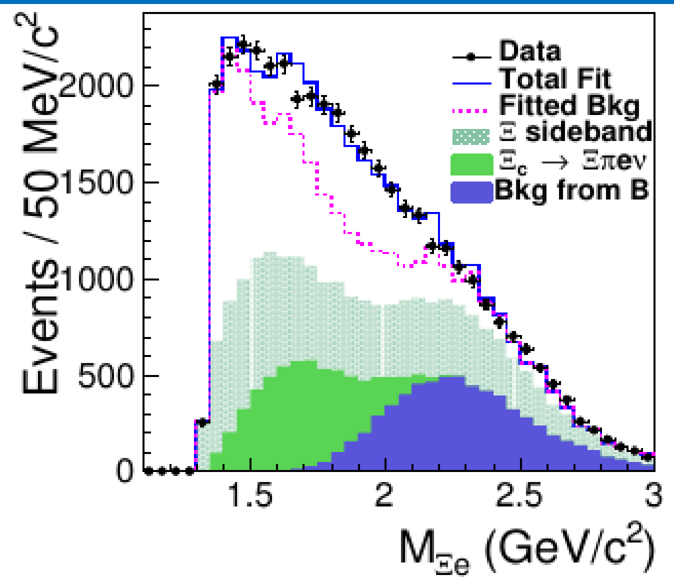

efficiency
$M_{\Sigma_c^{0,++}\pi^\pm}$ (GeV/c^2)

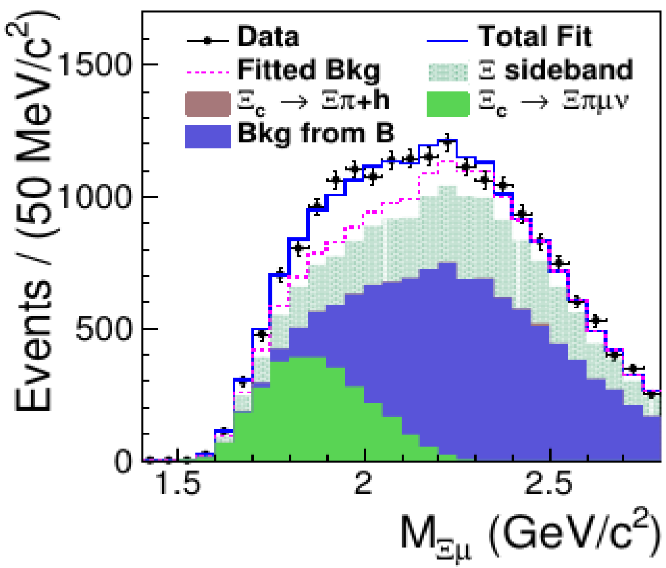

$M_{\Lambda_c^+\pi^-}$ (GeV/c^2)
$M_{\Lambda_c^+\pi^+}$ (GeV/c^2)

(c): $\Sigma_c(2455)^{++\text{ or }0}$



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

data-driven method for bkg extraction

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

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

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

Consistent with LFU

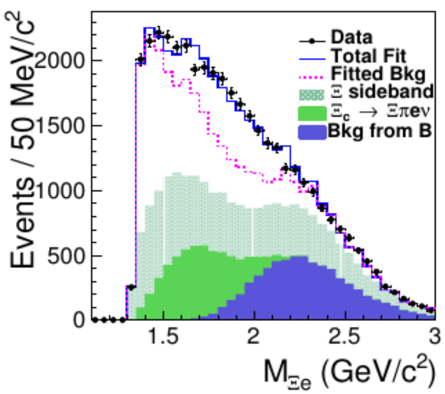
$\mathcal{B}(\Xi_c^0 \to \Xi^- l\, \nu)$ and $\mathcal{A}_{cp}$ of $\Xi_c^0 \to \Xi^- \pi^+$

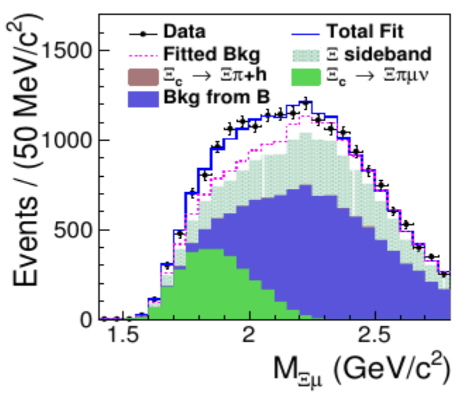
Semileptonic decays of charmed baryons:

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

BELLE

[PRL. 127. 121803 (2021)]





Data-driven method for bkg extraction

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

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

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

Consistent with LFU

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

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

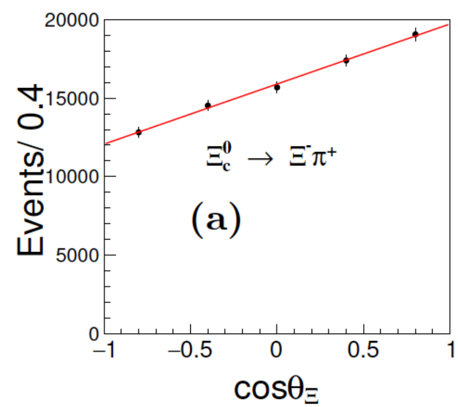
$$\mathcal{A}_{CP} = (\alpha_{\Xi^-\pi^+} + \alpha_{\bar{\Xi}^+\pi^-})/(\alpha_{\Xi^-\pi^+} - \alpha_{\bar{\Xi}^+\pi^-})$$

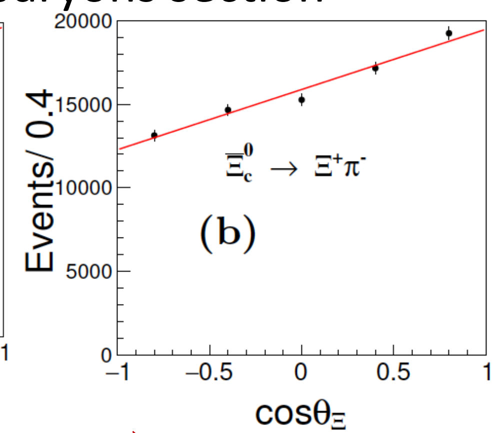
$\alpha_{\Xi^-\pi^+} = -0.60 \pm 0.045$

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

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

Previous: -0.60 ± 0.4



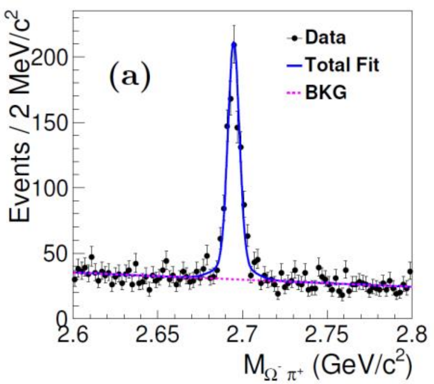


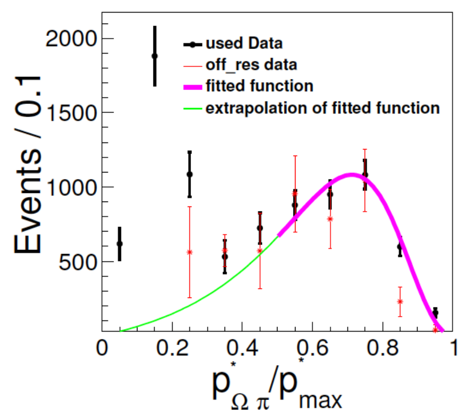
θ_Ξ: angle between the $\vec{p}_\Lambda$ and $-\vec{p}_{\Xi_c^0}$ in the Ξ^- rest frame

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

Y. B. Li, *C.P.Shen et al., Phys. Rev. D 105, L091101 (2022)

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





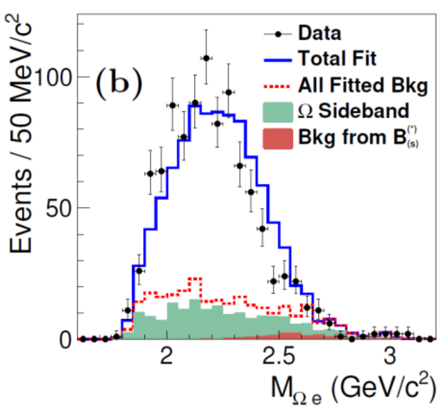
Peterson's fragmentation function

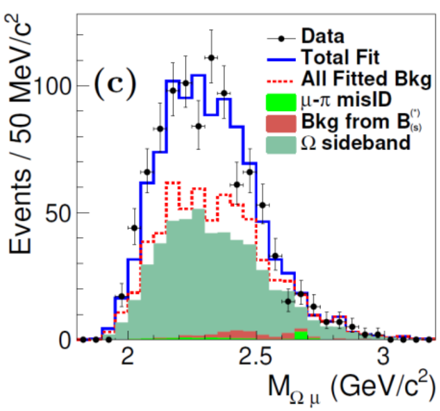
$$\frac{dN}{dx_p} \approx \frac{1}{x_p} \cdot \frac{1}{\left(1 - \frac{1}{x_p} - \frac{\epsilon_p}{1-x_p}\right)^2}$$

- 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 $\Xi_c^0 \to \Xi^- l\, \nu$





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

Previous: 2.4 ± 1.2

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

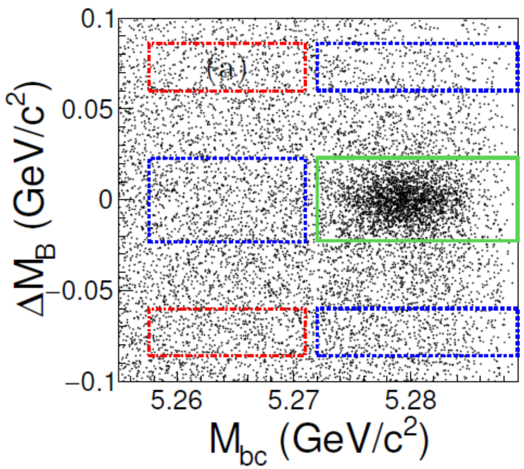
Consistent with LFU

Evidence of a new Λ_c^+ excited state ?

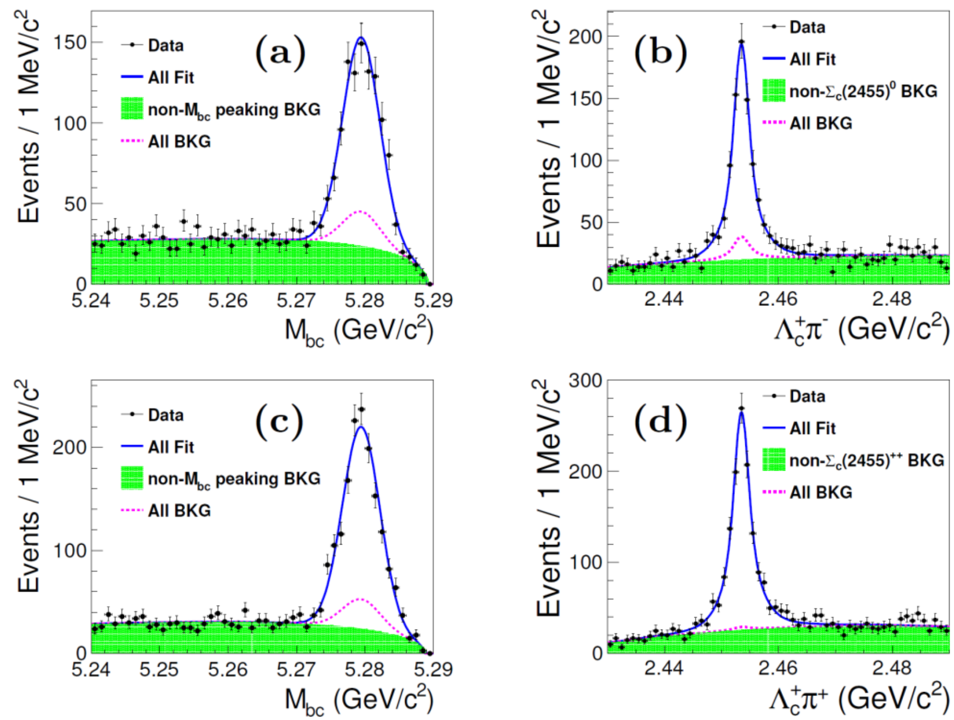
$\mathcal{B}(\overline{\mathrm{B}}^0 \to \Sigma_c(2455)\pi\bar{p})$的测量：

arXiv:2206.08822

Λ_c^+通过$pK^-\pi^+, pK_s$和$\Lambda\pi^+$重建



$\Delta M_B \equiv M_{signalB} - m_B$

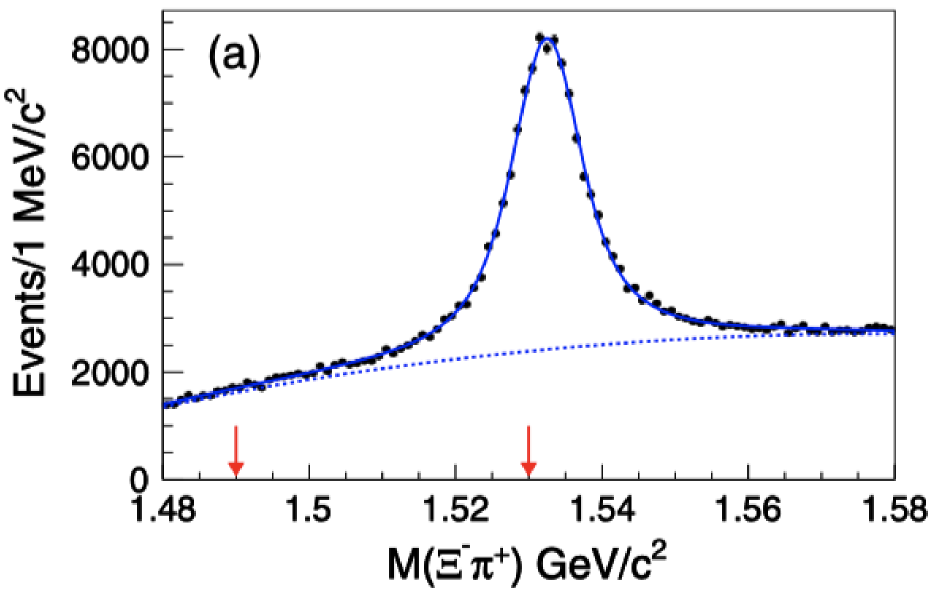


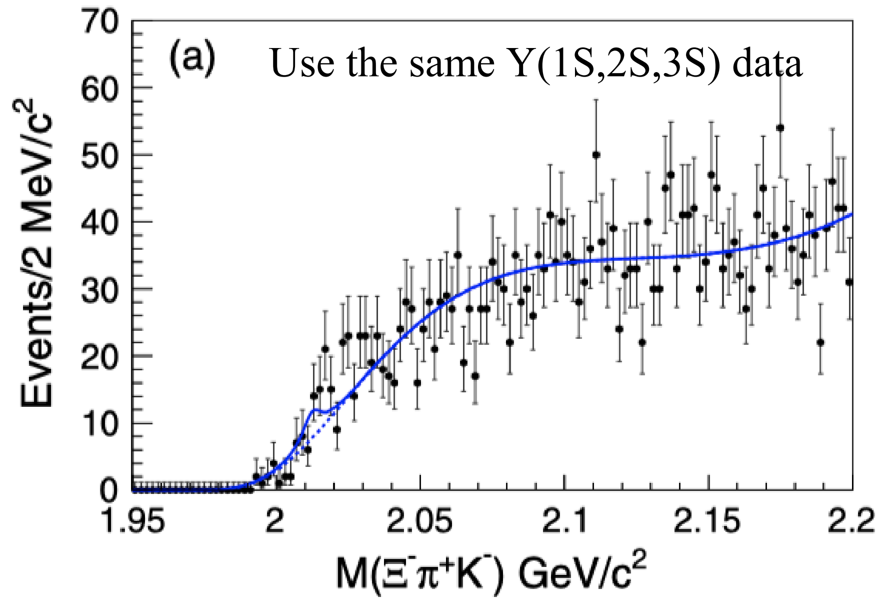
- 观测道明显的$\overline{\mathrm{B}}^0 \to \Sigma_c(2455)\pi\bar{p}$信号
- 测得衰变分支比与此前测量一致，精度提升较大

B 衰变末态	产额	分支比(10^{-4})	PDG (10^{-4})
$\boldsymbol{\Sigma_c(2455)^0\pi\bar{p}}$	767 ± 44	$1.09 \pm 0.06 \pm 0.07$	1.08 ± 0.16
$\boldsymbol{\Sigma_c(2455)^{++}\pi\bar{p}}$	1213 ± 73	$1.84 \pm 0.11 \pm 0.12$	1.88 ± 0.24

Search for $\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

The previous analysis [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 $M(\Xi\pi)$ includes large non-$\Xi(1530)$ decay backgrounds;

(2) do NOT consider a three-body phase space in $M(\Xi\pi\bar{K})$, which increases sharply due to the unstable $\Xi(1530)$ constituent.