第21届
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THE 21ST NATIONAL SYMPOSIUM ON HEAVY FLAVOR PHYSICS AND CP VIOLATION

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Recent results on baryons and charmed baryons from Belle and Belle II

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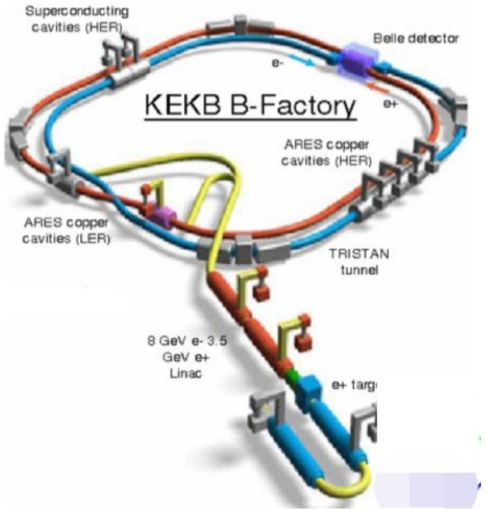
Belle and Belle II Experiments

- Asymmetric e^+e^- colliders
- Collisions mainly at 10.58 GeV , i.e at $\Upsilon(4S)$ resonance

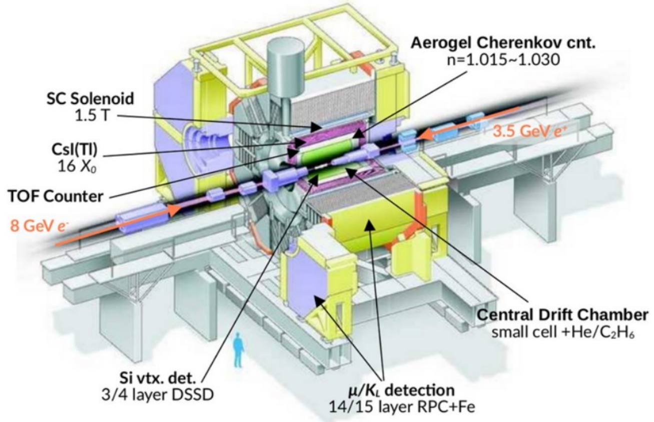
KEKB

1999-2010

- e^+ (3.5 GeV) e^-(8 GeV)
- L_{peak}: $2.1 \times 10^{34}\ cm^{-2}s^{-1}$ [achieved]



BELLE @ KEKB



SuperKEKB

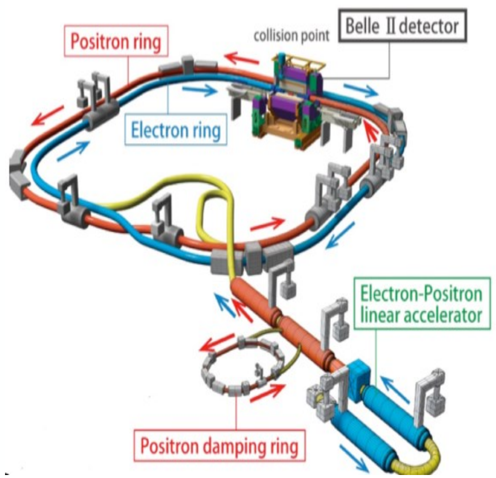
2019-current

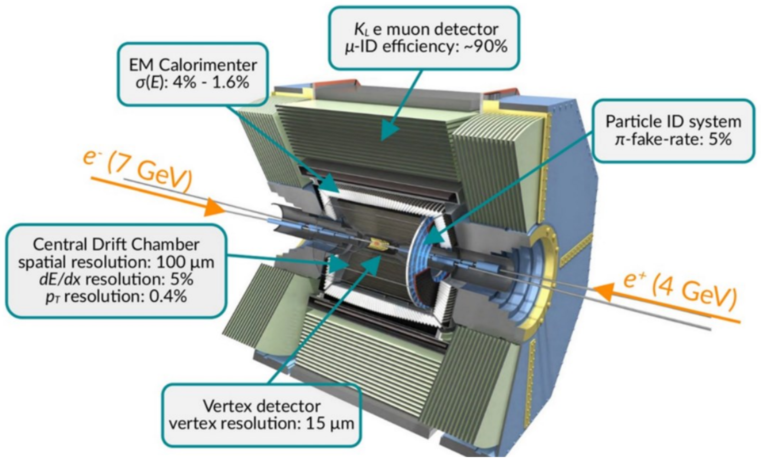
- e^+ (4 GeV) e^-(7 GeV)

Target:	**Achieved:**
$\int Ldt = 50\ ab^{-1}$	$\int Ldt > 530\ fb^{-1}$
$L_{peak} = 6 \times 10^{35}\ cm^{-2}s^{-1}$	$L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$

Current world record

Belle II @ SuperKEKB



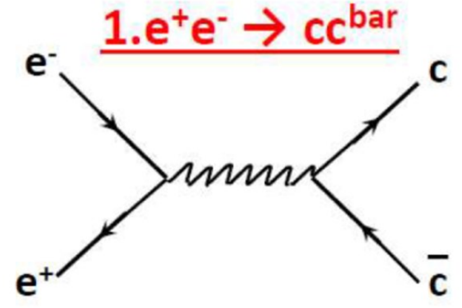


Charm physics at Belle (II)

Two primary mechanisms for charm production at Belle/Belle II:

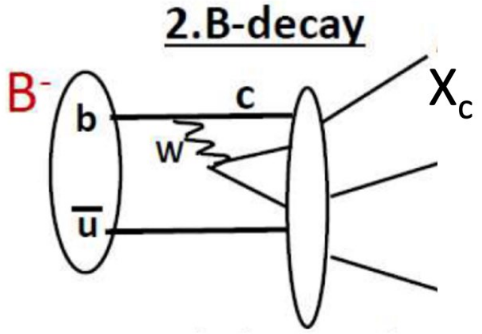
1. $e^+e^- \to c\bar{c} \to X_c$

- Absolute measurements not possible without reference
- Used for most analyses due to its simplicity compared to $B\bar{B}$ processes



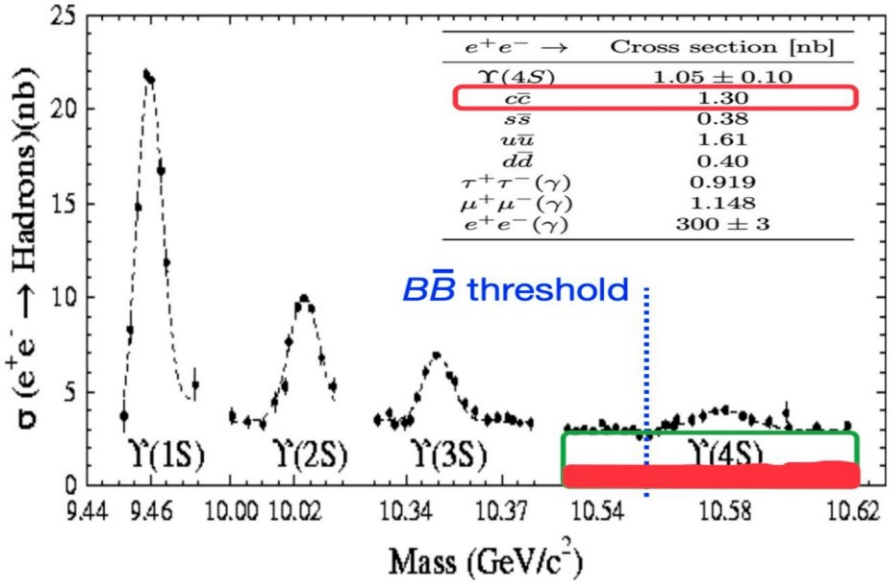
2. $e^+e^- \to \Upsilon(4S) \to B\bar{B} \to X_c$

- Precise $B\bar{B}$ cross section allows for absolute measurements



Full topics for charm physics:

- $D^0 - \overline{D^0}$ mixing
- Amplitude analysis
- Lifetime
- CP violation
- Rare decay
- Charmed baryon



Selected Topics

- Charmed Baryon Spectroscopy:
  - Search for excited charmed baryons in $\Lambda_c^+\eta$ system
- Hadronic decay of charmed baryons:
  - $\Xi_c^0 \to \Xi^0 h^0 (h^0 = \pi^0, \eta, \eta')$
  - $\Lambda_c^+ \to \Sigma^+ \eta^{(\prime)}, \ldots$
- Semileptonic decays of charmed baryons:
  - $\Xi_c^0 \to \Xi^0 l^+ l^-$
- First observation of $\Omega(2012) \to \Xi(1530)\bar{K}$

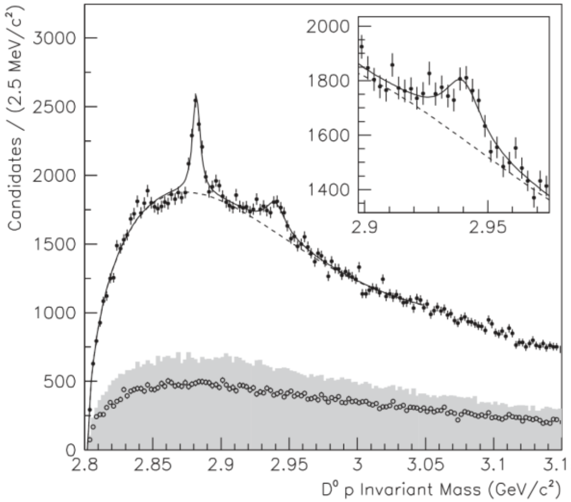
Search for excited charmed baryons in $\Lambda_c^+\eta$ system

Excited Λ_c^+ states predicted by quark model.

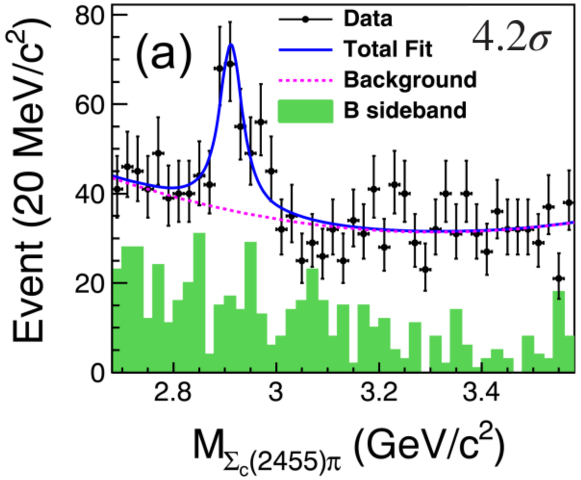
	Λ_c	
J^P	Theory (MeV)	Experiment (MeV)
$\frac{1}{2}^+$	2285	2285
	2857	
	3123	
$\frac{3}{2}^+$	2920	
	3175	
	3191	
$\frac{5}{2}^+$	2922	2881
	3202	
	3230	
$\frac{1}{2}^-$	2628	2595
	2890	
	2933	
$\frac{3}{2}^-$	2630	2628
	2917	
	2956	
$\frac{5}{2}^-$	2960	
	3444	
	3491	

Only a few states found in experiment!!

PRL. 98, 012001 (2007)



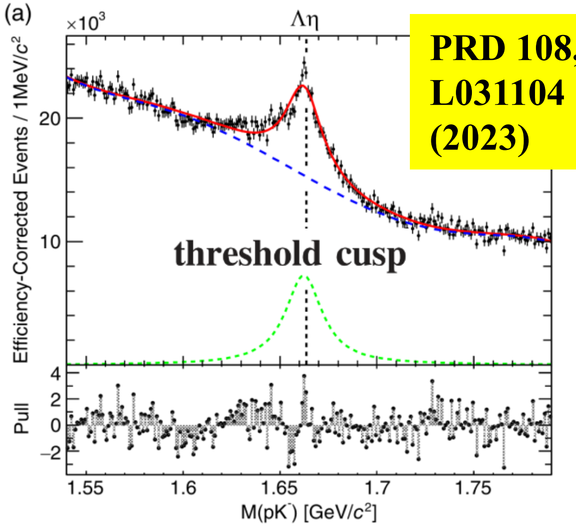
PRL. 130, 031901 (2023)



Study of the $\Lambda\eta$ channel suggests $\Lambda_c^+\eta$ an interesting channel:

(1) $\Lambda(2000) \to \Lambda\eta$

(2) Threshold cusp

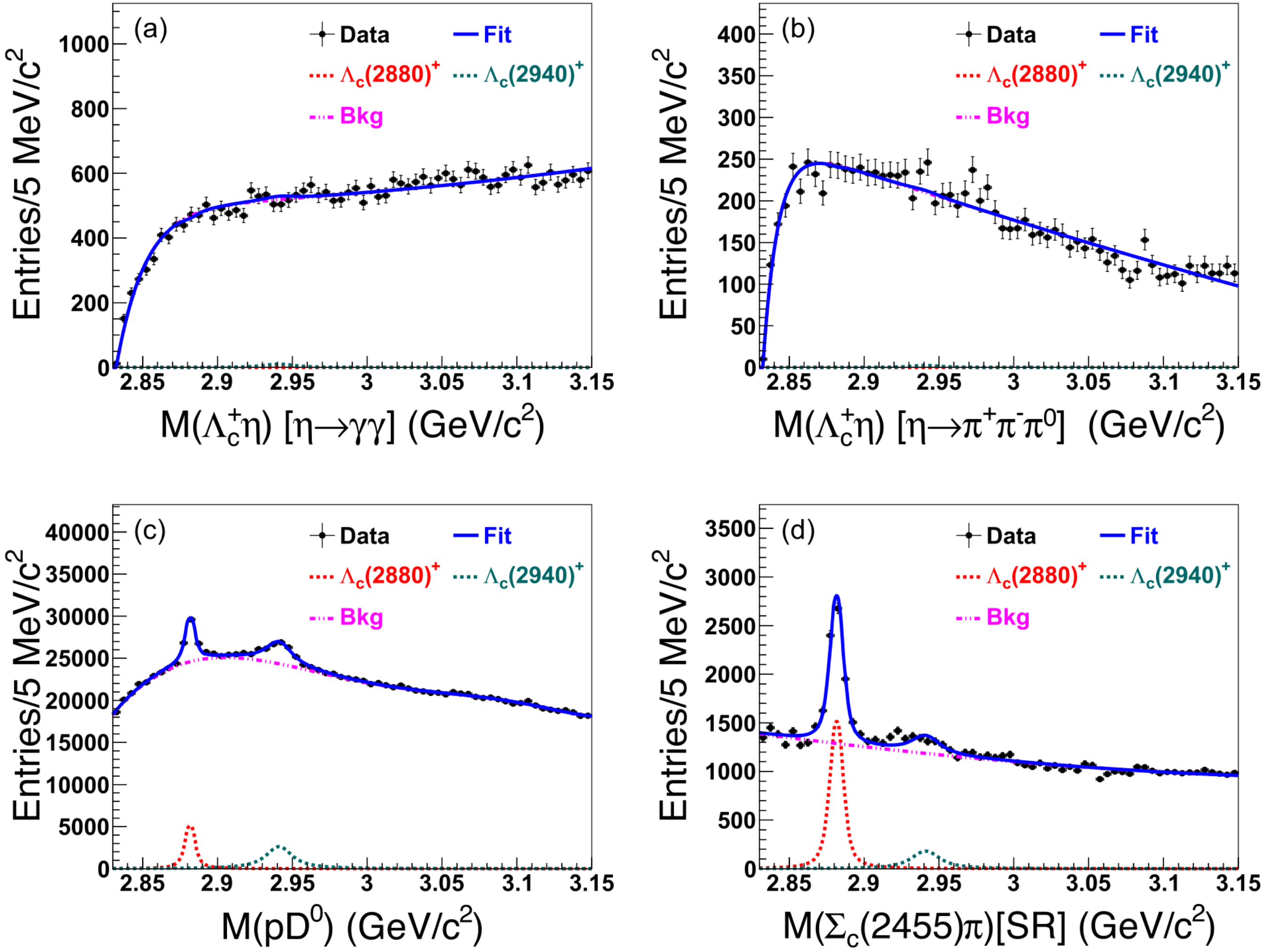


PRD 108, L031104 (2023)

Any signal in $\Lambda_c^+\eta$ is likely to be an excited Λ_c^+ rather than a Σ_c state.

Search for excited charmed baryons in $\Lambda_c^+\eta$ system

Belle 980/fb PRD 110, 032021 (2024)



- No significant excess is found in the M($\Lambda_c\eta$) spectrum. This is in contrast to excited hyperons, where resonances decaying into $\Lambda\eta$ have been observed.
- Clear $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signals are observed in the pD^0 mass spectrum.
- Ratio to $\Sigma_c(2455)\pi$:

$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07,$$
$$R_{pD^0}(2940) = 3.59 \pm 0.21 \pm 0.56,$$

First measurement

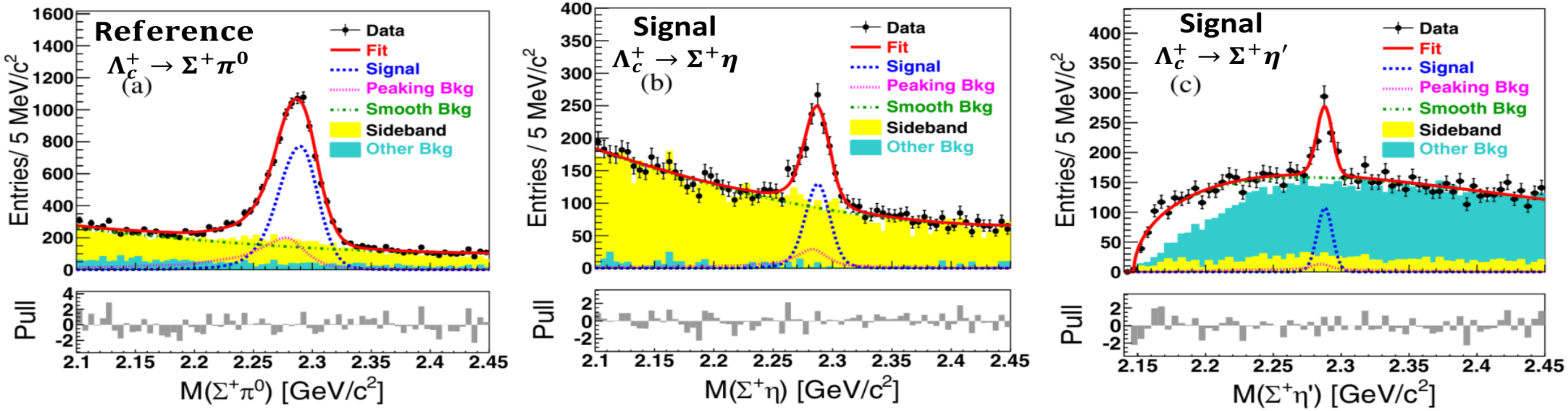
Branching fractions of Λ_c^+ decays

Belle 980/fb, PRD **107**, 032003 (2023)

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

$\Sigma^+ \to p\pi^0$; $\eta' \to \eta\pi\pi$; $\eta \to \gamma\gamma$

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



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

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

statistical   systematical   from $B(\Lambda_c^+ \to \Sigma^+\pi^0)$

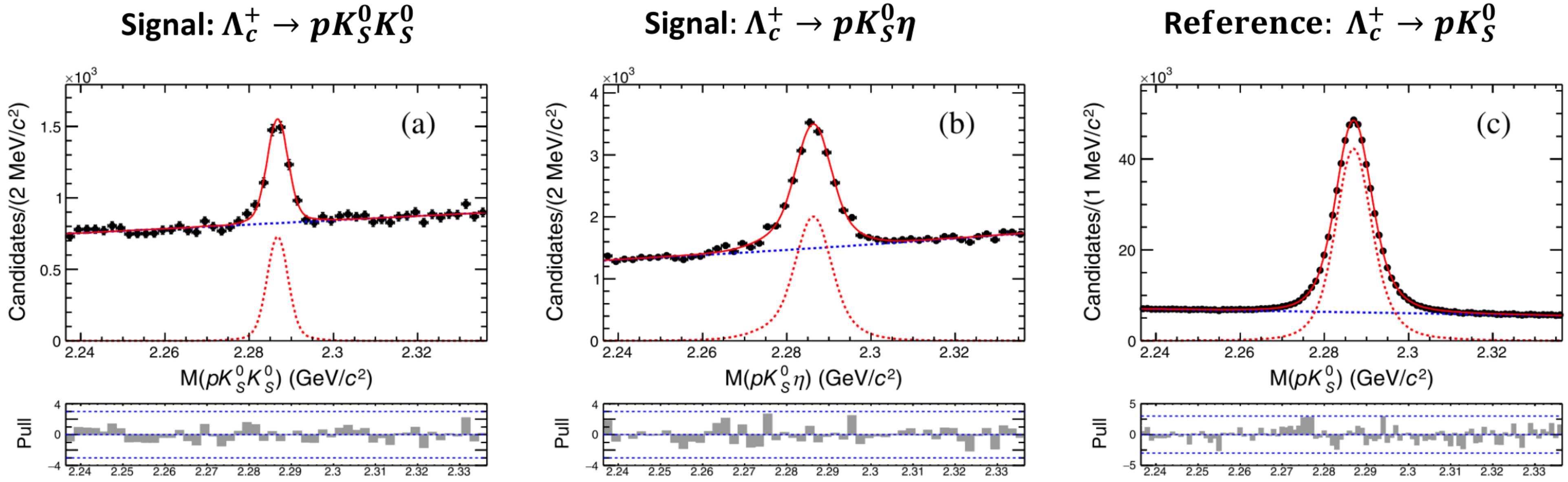
PDG: $B(\Lambda_c^+ \to \Sigma^+\eta) = (4.4 \pm 2.0) \times 10^{-3}$

PDG: $B(\Lambda_c^+ \to \Sigma^+\eta') = (15 \pm 6) \times 10^{-3}$

Consistent with PDG.
Most precise result to date

Branching fractions of Λ_c^+ decays

Belle 980/fb, PRD **103**, 032004 (2023)



Branching fraction

$$\frac{B(\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta)}{B(\Lambda_c^+ \to pK_S^0)} = \frac{y(\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta)}{B_{\mathrm{PDG}} \times y(\Lambda_c^+ \to pK_S^0)}$$

(y is the efficiency-corrected yield).

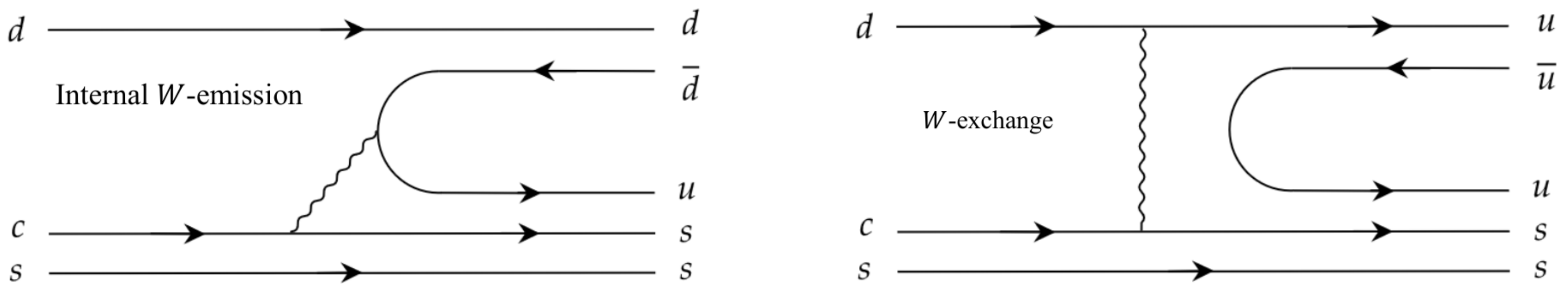
- $\frac{B(\Lambda_c^+ \to pK_S^0K_S^0)}{B(\Lambda_c^+ \to pK_S^0)} = (1.48 \pm 0.08 \pm 0.04) \times 10^{-2}$ ➡ $B(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.07 \pm 0.12) \times 10^{-4}$
  - ➢ First observation
- $\frac{B(\Lambda_c^+ \to pK_S^0\eta)}{B(\Lambda_c^+ \to pK_S^0)} = (2.73 \pm 0.06 \pm 0.13) \times 10^{-1}$ ➡ $B(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$
  - ➢ Consistent with world average value $(4.15 \pm 0.90) \times 10^{-3}$ and threefold improvement in precision.

Branching fractions of $\Xi_c^0 \to \Xi^0 h^0 (h^0 = \pi^0, \eta, \eta')$

JHEP 10 (2024) 045
Belle + Belle I 1.4/ab

✓ Hadronic two-body decay of charmed baryons

- Nonfactorizable amplitudes from internal W-emission and W-exchange diagram lead to the difficulties for theoretical predictions
- Feynman diagrams[CJPH 78, 324 (2022)] for Cabibbo-favored signal modes $\Xi_c^0 \to \Xi^0 h^0$, only nonfactorizable amplitudes contribute to.



- Serval theoretical approaches developed to deal with nonfactorizable contributions, give various predictions on branching fractions ((0.5-26.7)× 10^{-3}) and decay asymmetry parameters[see backup].
- Need experiment measurement to clarify the theoretical picture.

Branching fractions of $\Xi_c^0 \to \Xi^0 h^0 (h^0 = \pi^0, \eta, \eta')$

JHEP 10 (2024) 045
Belle + Belle I 1.4/ab

✓ First measurements of the branching fractions

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3(\text{stat.}) \pm 0.5(\text{syst.}) \pm 1.5(\text{norm.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.}) \pm 0.4(\text{norm.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3(\text{stat.}) \pm 0.1(\text{syst.}) \pm 0.3(\text{norm.})) \times 10^{-3}$$

- taking $\Xi_c^0 \to \Xi^-\pi^+$ as reference mode
- favoring predictions in SU(3) flavor symmetry [JHEP 02, 235 (2023)]

✓ First asymmetry parameter $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ measurement

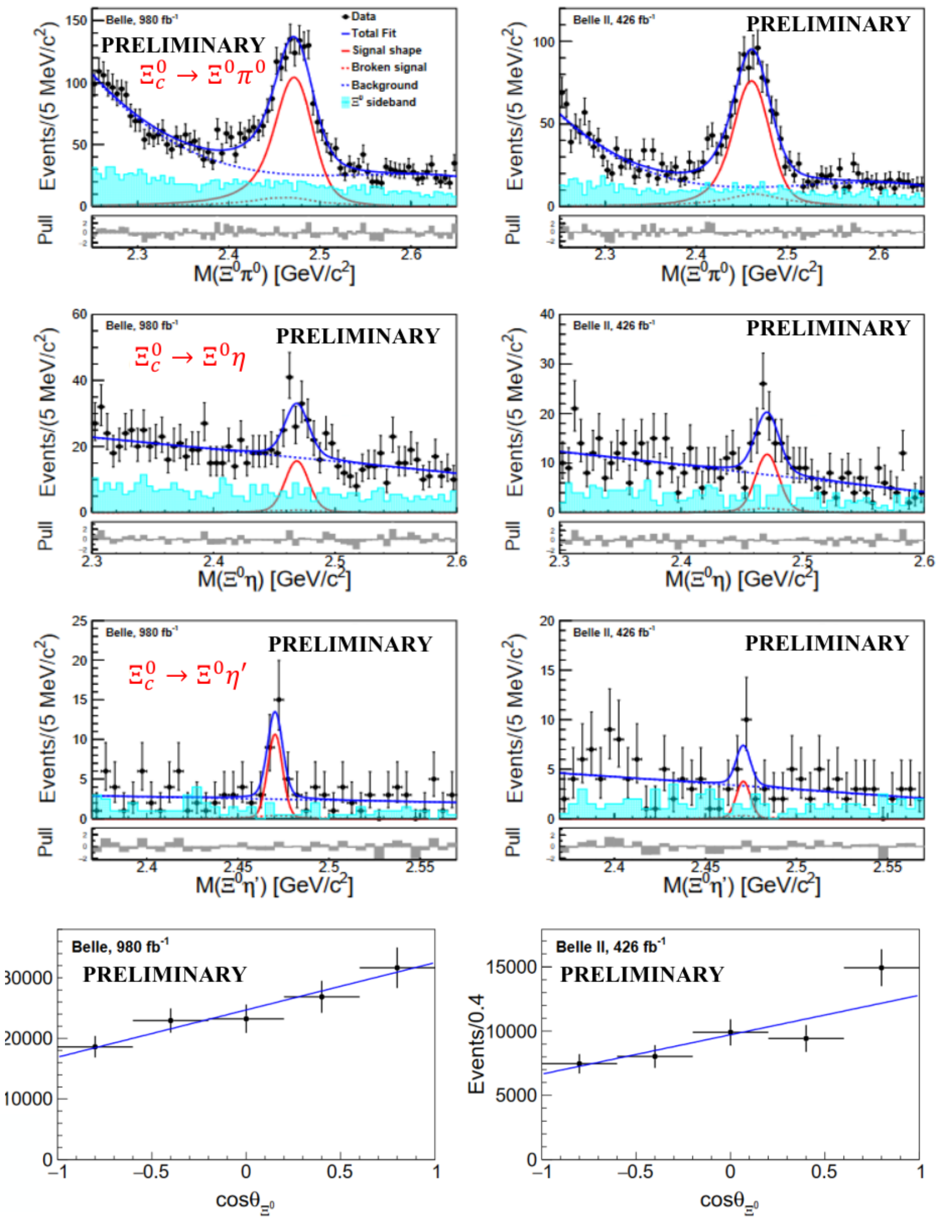
$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\text{stat.}) \pm 0.23(\text{syst.})$$

- through a simultaneous fit depending on differential decay rate

$$\frac{dN}{dcos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)cos\theta_{\Xi^0}$$

- consistent with predictions[1-4]

[1]PRD 48, 4188 (1993) [2] PRD 101, 014011 (2020) [3] EPJC 7, 217 (1999) [4]PLB 794, 19 (2019)



First Belle + Belle II combined charm measurement

First search for $\Xi_c^0 \to \Xi^0 l^+ l^-$

Belle 980/fb [PRD 109, 052003 (2024)]

✓ No neutrino-less semileptonic decays of charmed baryons observed yet.

- Only upper limits of $\Lambda_c \to p\ell^+\ell^-$ decays were set for charmed baryons[1,2], which receive both W-exchange and FCNC process contributions.
- Theoretically face difficulties from the Hamiltonian helicity structure and hadronic form factors
- To understand W-exchange contribution in $\Lambda_c \to p\ell^+\ell^-$
- If observed, the signal channels would allow to test LFU

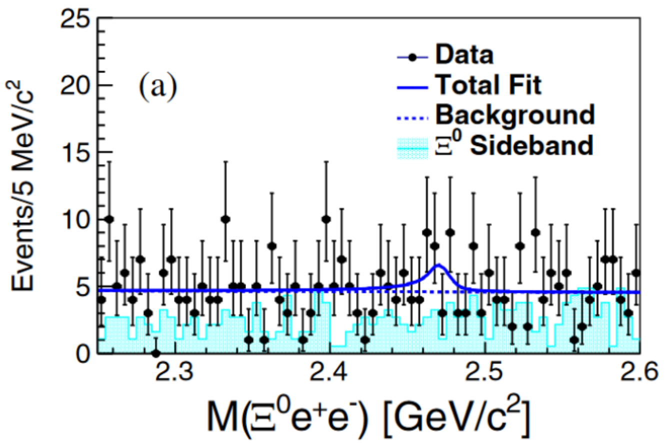
[1] PRD 84, 072006(2011)
[2] PRD 97, 091101(2018)
[3] PRD 103, 013007 (2021)

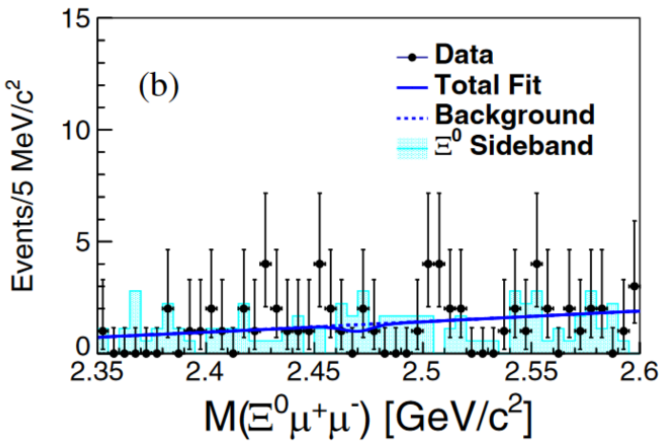
- **Belle Result**: No significant signal was observed but consistent with SM

➡ First set upper limits set at 90% CL:

	Measured	SM prediction
$\mathcal{B}(\Xi_c^0 \to \Xi^0 e^+ e^-)$	< 9.9 x 10^{-5}	< 2.35 x 10^{-6}
$\mathcal{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-)$	< 6.5 x 10^{-5}	< 2.25 x 10^{-6}

SM prediction: PRD **103**, 013007 (2021)



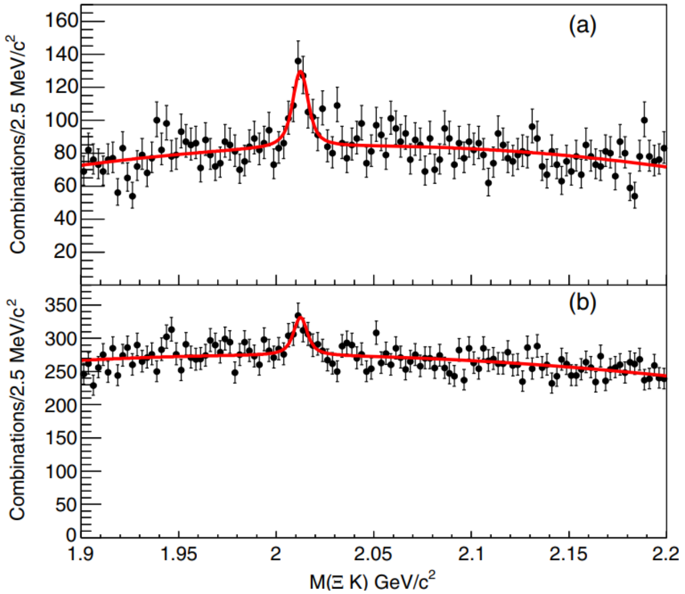


Study of $\Omega(2012) \rightarrow \Xi(1530)\bar{K}$

Belle $\Upsilon(1S, 2S, 3S)$
Arxiv:2207.03090

- The $\Omega(2012)$ was first observed in 2018 by the Belle experiment in decays to $\Xi^0 K^-$ and $\Xi^- \bar{K}^0$ near $\Upsilon(1S, 2S, 3S)$.

PRL 121, 052003 (2018)



$M = (2012.4 \pm 0.9)$ MeV
$\Gamma = \left(6.4^{+3.0}_{-2.7}\right)$ MeV

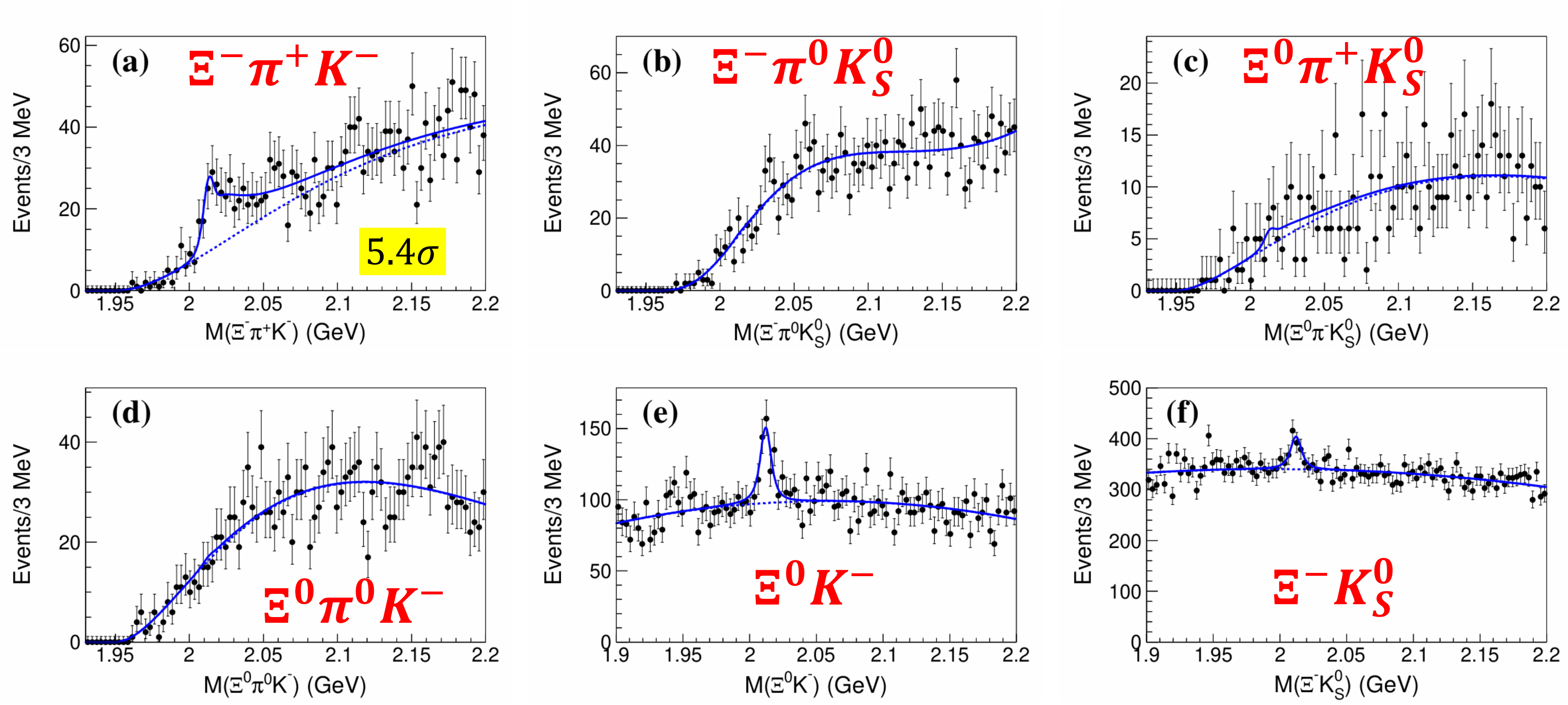
- There are mainly two interpretations for $\Omega(2012)$: a standard baryon and a $\Xi(1530)\bar{K}$ molecule
- A large rate for $\Omega(2012) \rightarrow \Xi(1530)\mathrm{K}$ was predicted in the molecule scenario:

$$\frac{B(\Omega(2012) \rightarrow \Xi(1530)\bar{\mathrm{K}})}{B(\Omega(2012) \rightarrow \Xi\mathrm{K})} = 0.18 - 0.86$$

- Measuring the branching fraction for $\Omega(2012) \rightarrow \Xi(1530)\bar{K} \rightarrow \Xi\pi K$ may inform us about the internal structure of $\Omega(2012)$.

Study of $\Omega(2012) \to \Xi(1530)\bar{K}$

Belle $\Upsilon(1S, 2S, 3S)$
Arxiv:2207.03090



$$\frac{B(\Omega(2012) \to \Xi(1530)\bar{K})}{B(\Omega(2012) \to \Xi K)} = 0.99 \pm 0.26 \pm 0.06$$

➢ First observation of $\Omega(2012) \to \Xi(1530)\bar{K}$

Summary

- **Belle & Belle II provide a unique environment & unique sensitivity for SM measurements as well as for the search for physics beyond the SM in the charm sector.**
  - significant room to improve the basic knowledge of baryon decays (BR,…)
- **BELLE is still producing important measurements after more than 10 years after the end of data taking**
  - Search for the new excited charmed baryons
  - Branching fraction measurements of the Λ_c^+ and Ξ_c^0 decays
  - Study of Semi-leptonic decay $\Xi_c^0 \to \Xi^0 l^+ l^-$
- **First BELLE + Belle II combined analysis of the $\Xi_c^0 \to \Xi^0 h^0$ decays rules out several theoretical approaches proposed to deal with non-factorizable amplitudes**
- **Belle II has started Run 2 data taking, expecting more physics results with a larger data sample**

Thanks for your attention!

Backup

Comparison of available charm samples

Experiment	Machine	C.M.	Luminosity	$N_{\rm prod}$	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 (8 $\to$ 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7 (\to 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	0.4 ($\to$ 50) ab^{-1}	D^0: 6×10^8 $(\to 10^{11})$ $D^+_{(s)}$: 10^8 $(\to 10^{10})$ Λ_c^+: 10^7 $(\to 10^9)$		☺ high-efficiency detection of neutrals ☺ good trigger efficiency ☺ time-dependent analysis ☹ smaller cross-section than LHCb
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$D^{0,+}, D_s^+$: 10^9 Λ_c^+: 10^8 ★★☆	$\mathcal{O}$(1-10%) ★★	
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} ($\to$ 23 $\to$ 50) fb^{-1}	5×10^{12} 10^{13} ★★★★	★	☺ very large production cross-section ☺ large boost, excellent time resolution ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0 @3.77\,\text{GeV})$=3.61 nb, $\sigma(D^+D^- @3.77\,\text{GeV})$=2.88 nb, $\sigma(D_s^* D_s @4.17\,\text{GeV})$=0.967 nb; $\sigma(c\bar{c}@10.58\,\text{GeV})$=1.3 nb where each $c\bar{c}$ event averagely has 1.1/0.6/0.3 $D^0/D^+/D_s^+$ yields; $\sigma(D^0 @CDF)$=13.3 μb, and $\sigma(D^0 @LHCb)$=1661 μb, mainly from *Int. J. Mod. Phys. A* **29** *(2014)24,14300518.*

- BESIII, Belle II, and LHCb experiments have their advantages for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.

Backup

Theoretical Predictions for $\Xi_c^0 \to \Xi^0 h^0$

Table 1. Theoretical predictions for the branching fractions and decay asymmetry parameters for $\Xi_c^0 \to \Xi^0 h^0$ decays. Branching fractions are given in units of 10^{-3}.

Reference	Model	$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$	$\alpha(\Xi_c^0 \to \Xi^0\pi^0)$
Körner, Krämer [5]	quark	0.5	3.2	11.6	0.92
Ivanov *et al.* [6]	quark	0.5	3.7	4.1	0.94
Xu, Kamal [7]	pole	7.7	-	-	0.92
Cheng, Tseng [8]	pole	3.8	-	-	-0.78
Żenczykowski [9]	pole	6.9	1.0	9.0	0.21
Zou *et al.* [10]	pole	18.2	26.7	-	-0.77
Sharma, Verma [11]	CA	-	-	-	-0.8
Cheng, Tseng [8]	CA	17.1	-	-	0.54
Geng *et al.* [12]	$SU(3)_F$	4.3 ± 0.9	$1.7^{+1.0}_{-1.7}$	$8.6^{+11.0}_{-6.3}$	-
Geng *et al.* [13]	$SU(3)_F$	7.6 ± 1.0	10.3 ± 2.0	9.1 ± 4.1	$-1.00^{+0.07}_{-0.00}$
Zhao *et al.* [14]	$SU(3)_F$	4.7 ± 0.9	8.3 ± 2.3	7.2 ± 1.9	-
Huang *et al.* [15]	$SU(3)_F$	2.56 ± 0.93	-	-	-0.23 ± 0.60
Hsiao *et al.* [16]	$SU(3)_F$	6.0 ± 1.2	$4.2^{+1.6}_{-1.3}$	-	-
Hsiao *et al.* [16]	$SU(3)_F$-breaking	3.6 ± 1.2	7.3 ± 3.2	-	-
Zhong *et al.* [17]	$SU(3)_F$	$1.13^{+0.59}_{-0.49}$	1.56 ± 1.92	$0.683^{+3.272}_{-3.268}$	$0.50^{+0.37}_{-0.35}$
Zhong *et al.* [17]	$SU(3)_F$-breaking	$7.74^{+2.52}_{-2.32}$	$2.43^{+2.79}_{-2.90}$	$1.63^{+5.09}_{-5.14}$	$-0.29^{+0.20}_{-0.17}$
Xing *et al.* [18]	$SU(3)_F$	1.30 ± 0.51	-	-	-0.28 ± 0.18

- Ref. [17] with breaking scenario suits best for $\mathcal{B}$ measurements

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[6] M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, and A. G. Rusetsky, *Exclusive nonleptonic decays of bottom and charm baryons in a relativistic three-quark model: Evaluation of nonfactorizing diagrams*, Phys. Rev. D **57** (1998) 5632.

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[8] H. Y. Cheng and B. Tseng, *Cabibbo-allowed nonleptonic weak decays of charmed baryons*, Phys. Rev. D **48** (1993) 4188.

[9] P. Żenczykowski, *Nonleptonic charmed-baryon decays: Symmetry properties of parity-violating amplitudes*, Phys. Rev. D **50** (1994) 5787.

[10] J. Q. Zou, F. R. Xu, G. B. Meng, and H. Y. Cheng, *Two-body hadronic weak decays of antitriplet charmed baryons*, Phys. Rev. D **101** (2020) 014011.

[11] K. K. Sharma and R. C. Verma, *A study of weak mesonic decays of Λ_c and Ξ_C baryons on the basis of HQET results*, Eur. Phys. J. C **7** (1999) 217.

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[14] H. J. Zhao, Y. L. Wang, Y. K. Hsiao, and Y. Yu, *A Diagrammatic Analysis of Two-Body Charmed Baryon Decays with Flavor Symmetry*, JHEP **02** (2020) 165.

[15] F. Huang, Z. P. Xing, and X. Z. He, *A global analysis of charmless two body hadronic decays for anti-triplet charmed baryons*, JHEP **03** (2022) 143.

[16] Y. K. Hsiao, Y. L. Wang, and H. J. Zhao, *Equivalent $SU(3)_f$ approaches for two-body anti-triplet charmed baryon decays*, JHEP **09** (2022) 35.

[17] H. Zhong, F. Xu, Q. Wen and Y. Gu, *Weak decays of antitriplet charmed baryons from the perspective of flavor symmetry*, JHEP **02** (2023) 235.

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Branching fractions of $\Xi_c^0 \to \Xi^0 h^0 (h^0 = \pi^0, \eta, \eta')$

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Belle + Belle II 1.4/ab

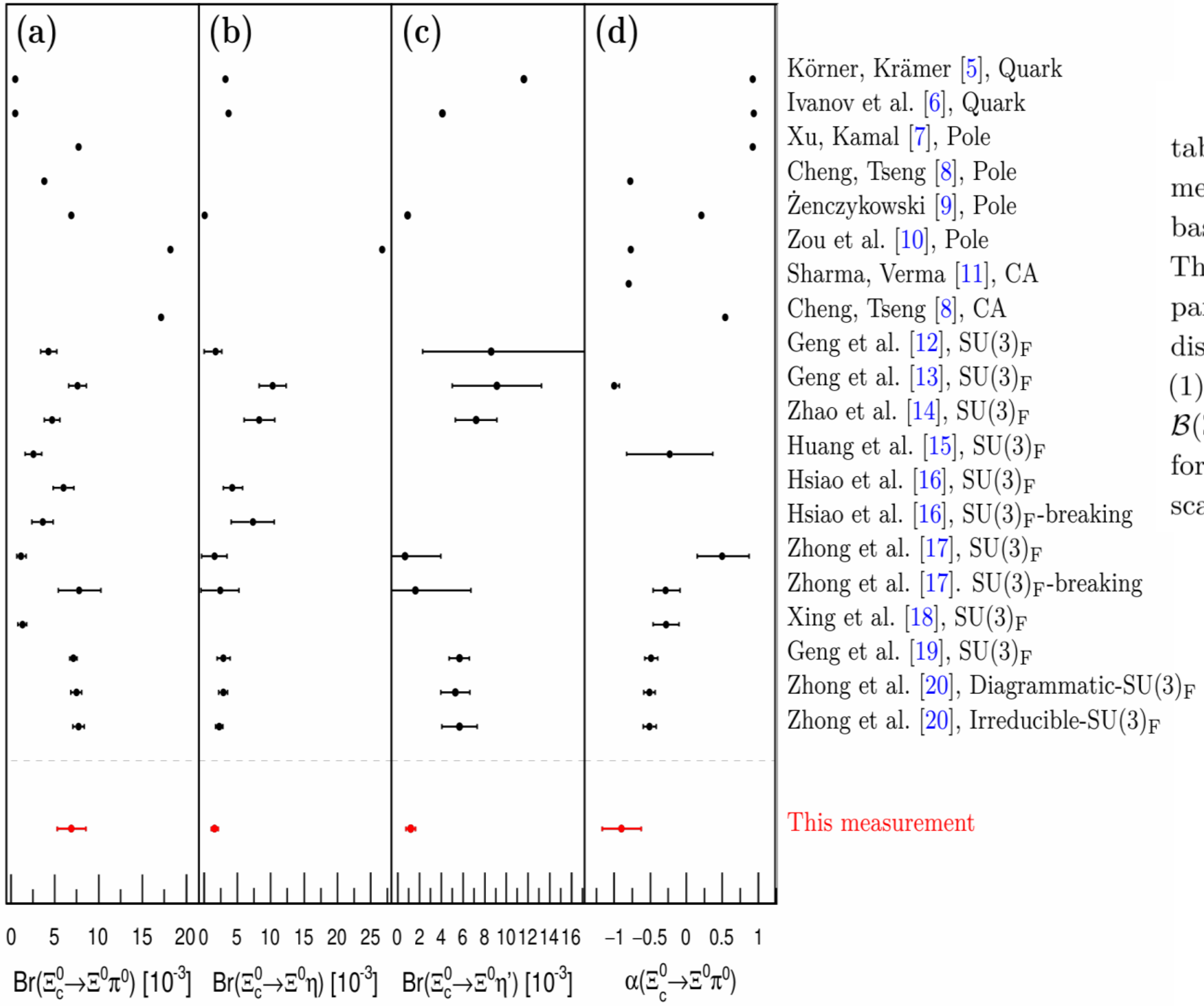

Figure 6 shows the comparisons of our measurements with theoretical predictions from table 1. A recent result [17] based on the SU(3)$_F$-breaking model is consistent with each measured $\mathcal{B}(\Xi_c^0 \to \Xi^0 h^0)$. The measured value of $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ is consistent with predictions based on the pole model [8, 10], CA [11], and SU(3)$_F$ flavor symmetry [13] approaches. The central values of our measurements of the absolute branching fractions and asymmetry parameter of $\Xi_c^0 \to \Xi^0\pi^0$, indicate that the covariant confined quark model [5, 6] is mildly disfavored for each result, and disagree with the predictions by more than 2σ for the following: (1) $\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$ in refs. [8, 10, 15, 18]; (2) $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$ in refs. [9, 10, 13, 19, 20]; (3) $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$ in refs. [14, 19, 20]; and (4) $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ in refs. [7, 9, 17–20]. The results for the ratios, (8.1), (8.2), and (8.3), are independent of the Ξ_c^0 absolute branching fraction scale and may also be compared to theoretical models.

favoring predictions in SU(3) flavor symmetry [JHEP 02, 235 (2023)]

Study of $\Omega(2012) \to \Xi(1530)\bar{K}$

Flatté-like function is

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

with those from Ref. [16]. The mass of $\Omega(2012)^-$ is

$$m_{\Omega(2012)^-} = (2012.5 \pm 0.7 \pm 0.5)\ \text{MeV}.$$

The values of g_3 and g_2 are

$$g_3 = (38.9^{+31.1}_{-38.9} \pm 9.0) \times 10^{-2},$$
$$g_2 = (1.7^{+0.3}_{-0.3} \pm 0.3) \times 10^{-2}.$$

The value of g_3/g_2 is

$$g_3/g_2 = (22.9^{+17.9}_{-22.4} \pm 2.2).$$

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{3 \times \mathcal{B}(\Omega(2012)^- \to \Xi(1530)^0 K^- \to \Xi^-\pi^+K^-)}{\mathcal{B}(\Omega(2012)^- \to \Xi^-\bar{K}^0) + \mathcal{B}(\Omega(2012)^- \to \Xi^0 K^-)},$$