Rare and baryonic decays of charmed hadrons at Belle and Belle II

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EPS-HEP 2025

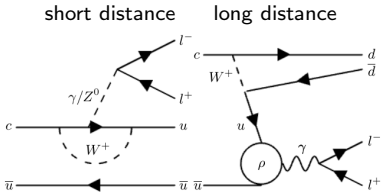
Outline

- Rare decays
  - $D^0 \to K^-\pi^+e^+e^-,\ \pi^+\pi^-e^+e^-,\ K^+K^-e^+e^-$
  - $\Xi_c^0 \to \Xi^0\ell^+\ell^-$
- Branching fractions
  - $\Xi_c^0 \to \Xi^0\pi^0,\ \Xi^0\eta,\ \Xi^0\eta'$
  - $\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$
  - $\Xi_c^+ \to \Sigma^+K_S^0,\ \Xi^0\pi^+,\ \Xi^0K^+$
  - $\Lambda_c^+ \to pK_S^0\pi^0$
- Excited charm baryons
  - search in $\Lambda_c^+\eta$ final state
  - Br's of $\Lambda_c(2880)^+,\ \Lambda_c(2940)^+ \to \Lambda_c^+\eta,\ pD^0$

Data sets: Belle 980 fb^{-1}, Belle II 428 fb^{-1}

$D^0 \to K^-\pi^+e^+e^-,\ \pi^+\pi^-e^+e^-,\ K^+K^-e^+e^-$ Belle 942 fb^{-1}

- $c \to u\ell^+\ell^-$ are FCNC transitions
  - forbidden in SM at tree level
  - proceed through electroweak box or loop diagrams
  - further suppressed by GIM mechanism
- $D^0 \to hh'\ell^+\ell^-$: short and long distance contributions
  - short distance: $\mathcal{B} \sim 2 \times 10^{-9}$
  - long distance: $\mathcal{B}$ up to 2×10^{-6}
- NP can enhance decay rates



Data analysis

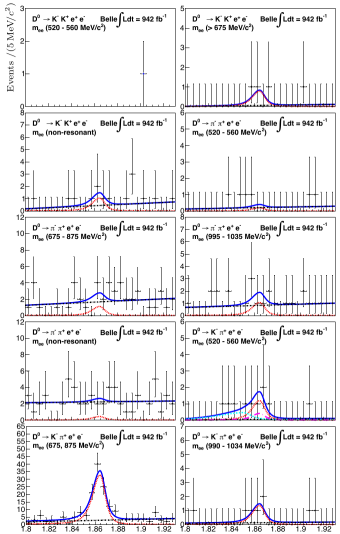
- Reconstructed in $D^{*+} \to D^0\pi^+$
  - $p^*(D^{*+}) > 2.5\ \mathrm{GeV/c}$ to suppress background
  - particle identification of K, π and e
  - electron bremsstrahlung recovery, $m_{ee} > 200\ \mathrm{MeV/c^2}$ to suppress BG from π^0/η
  - vertex fits

$D^0 \to K^-\pi^+e^+e^-$, $\pi^+\pi^-e^+e^-$, $K^+K^-e^+e^-$ Belle 942 fb^{-1}

Results (preliminary) to be submitted to PRDL

- Branching fractions measured relative to $D^0 \to K^-\pi^+\pi^-\pi^+$
  - in m_{ee} regions of η, ρ/ω, ϕ and non-resonant
- Significant signal in ρ/ω region of $D^0 \to K^-\pi^+e^+e^-$
  $$\mathcal{B} = (39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$$
  $\to$ most precise to date
- Others not seen $\to$ 90% CL UL's

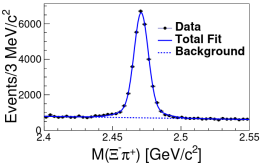
	$K^+K^-e^+e^-$	$\pi^+\pi^-e^+e^-$	$K^-\pi^+e^+e^-$
η	2.3×10^{-7}	3.2×10^{-7}	5.6×10^{-7}
ρ^0/ω	3.0×10^{-7}	6.1×10^{-7}	-
ϕ		3.1×10^{-7}	2.9×10^{-7}
non-res.	7.7×10^{-7}	8.1×10^{-7}	



$\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ Belle 980 fb^{-1}

- First search for these decays ($\ell = e, \mu$) PRD 109, 052003 (2024)
  - UL predictions based on $\Lambda_c^+ \to p\mu^+\mu^-$ (LHCb): $< 2.3 \times 10^{-6}$
- Normalization mode: $\Xi_c^0 \to \Xi^-\pi^+$, $\mathcal{B} = (1.43 \pm 0.32)\%$ [PDG2022]
- Data analysis
  - intermediate states reconstructed in $\Xi^{0/-} \to \Lambda\pi^{0/-}$, $\Lambda \to p\pi^-$
  - momentum cut to suppress background
  - particle identification
  - vertex fits (mass constrained for intermediate states)
- Results
  - no signals observed → 90% credible upper limits determined

$$\mathcal{B}(\Xi_c^0 \to \Xi^0 e^+ e^-) < 9.9 \times 10^{-5}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-) < 6.5 \times 10^{-5}$$



Branching fractions of charmed baryons

- Nonfactorizable amplitudes arising from internal W-emission and W-exchange lead to difficulties for theoretical predictions
  - various approaches have been developed
- Measurements of branching fractions will help to clarify the theoretical picture

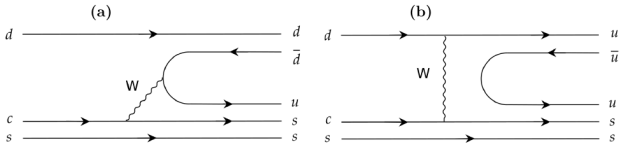


Figure 1. Feynman diagrams for (a) internal W-emission and (b) W-exchange in $\Xi_c^0 \to \Xi^0 h^0$

- Data analysis is pretty much similar among different decay modes
  - momentum cut to suppress background (mostly from B decays)
  - particle identification
  - vertex fits (mass constrained for intermediate states, IP constrained for final state)
  - best candidate selection (usually based on vertex fit quality)

$\Xi_c^0 \to \Xi^0\pi^0,\ \Xi^0\eta,\ \Xi^0\eta'$ Belle + Belle II, 980 + 426 fb^{-1}

JHEP10 (2024) 045

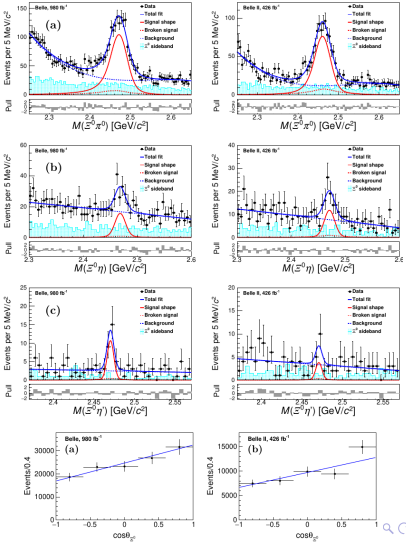
- Intermediate states reconstructed in $\Xi^{0/-} \to \Lambda\pi^{0/-}$, $\Lambda \to p\pi^-$, $\eta' \to \pi^+\pi^-\eta$, $\eta/\pi^0 \to \gamma\gamma$
- Normalization mode: $\Xi_c^0 \to \Xi^-\pi^+$, $\mathcal{B} = (1.43 \pm 0.27)\%$ [PDG2024]
- Significant signals observed
- Branching fractions

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3_{\rm stat} \pm 0.5_{\rm syst} \pm 1.3_{\rm norm}) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2_{\rm stat} \pm 0.2_{\rm syst} \pm 0.3_{\rm norm}) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3_{\rm stat} \pm 0.1_{\rm syst} \pm 0.2_{\rm norm}) \times 10^{-3}$$

- Asymmetry parameter

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

→ first measurements of these decays



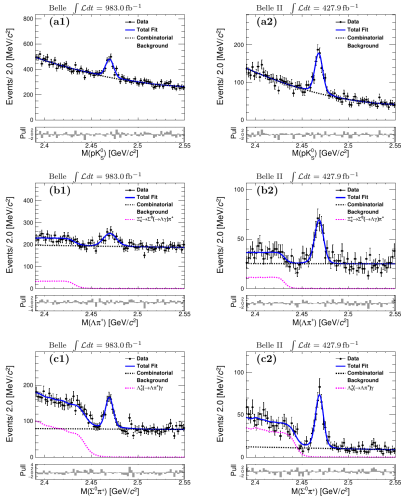
$\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$ Belle + Belle II, 983 + 428 fb^{-1}

JHEP03 (2025) 061

- Singly Cabibbo-suppressed decays
- Intermediate states reconstructed in $K_S^0 \to \pi^+\pi^-$, $\Sigma^0 \to \Lambda\gamma$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$
- Normalization mode: $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, $\mathcal{B} = (2.9 \pm 1.3)\%$ [Belle, PRD 100 (2019) 031101]
- Significant signals observed
- Branching fractions

$$\mathcal{B}(\Xi_c^+ \to pK_S^0) = (7.16 \pm 0.46_{\rm stat} \pm 0.20_{\rm syst} \pm 3.21_{\rm norm}) \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+) = (4.52 \pm 0.41_{\rm stat} \pm 0.26_{\rm syst} \pm 2.03_{\rm norm}) \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+) = (12.0 \pm 0.8_{\rm stat} \pm 0.7_{\rm syst} \pm 5.4_{\rm norm}) \times 10^{-4}$$

$\to$ first observations of these decays (each one $> 10\sigma$)



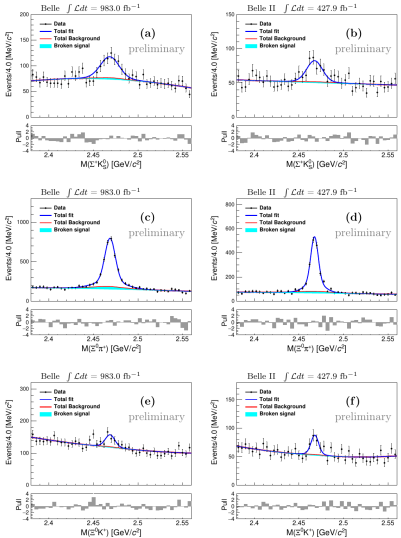
$\Xi_c^+ \to \Sigma^+ K_S^0,\ \Xi^0\pi^+,\ \Xi^0 K^+$ Belle + Belle II, 983 + 428 fb^{-1}

Submitted to JHEP (arXiv:2503.17643)

- Cabibbo-favored and singly Cabibbo-suppressed decays
- Intermediate states reconstructed in $\Xi^{0/-} \to \Lambda\pi^{0/-}$, $\Lambda \to p\pi^-$, $\Sigma^+ \to p\pi^0$, $K_S^0 \to \pi^+\pi^-$
- Normalization mode: $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, $\mathcal{B} = (2.9 \pm 1.3)\%$ [PDG 2024]
- Significant signals observed
- Branching fractions (preliminary)

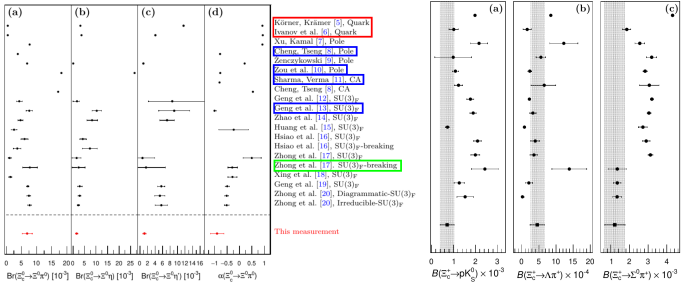
$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (1.94 \pm 0.21_{\text{stat}} \pm 0.09_{\text{syst}} \pm 0.87_{\text{norm}}) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0\pi^+) = (7.19 \pm 0.14_{\text{stat}} \pm 0.24_{\text{syst}} \pm 3.22_{\text{norm}}) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+) = (4.9 \pm 0.7_{\text{stat}} \pm 0.2_{\text{syst}} \pm 2.2_{\text{norm}}) \times 10^{-4}$$
$$R(\Xi^0 K^+/\Xi^0\pi^+) = (0.068 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}})$$

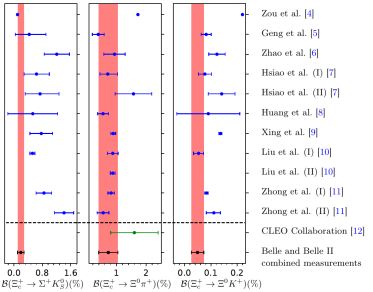
→ first measurements ($\Sigma^+ K_S^0$, $\Xi^0 K^+$), most precise ($\Xi^0\pi^+$)



Comparison with theory predicitons

- Theory predicitons mostly not far from measurements
- We cannot rule-out any predictions





→ see backup slides

$\Lambda_c^+ \to pK_S^0\pi^0$ Belle 980 fb^{-1}

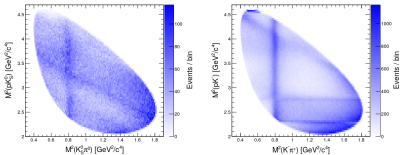
Accepted in PRD (arXiv:2503.04371)

- Improved Br measurement
- Normalization mode: $\Lambda_c^+ \to pK^-\pi^+$, $\mathcal{B} = (6.24 \pm 0.28)\%$ [PDG 2024]
- Signal yields: 128k ($pK_S^0\pi^0$) and 1.4M ($pK^-\pi^+$)
- Results (preliminary)

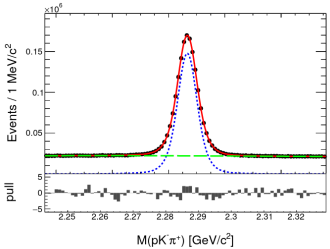
$\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0) = (2.12 \pm 0.01_{\rm stat} \pm 0.05_{\rm syst} \pm 0.10_{\rm norm})\%$

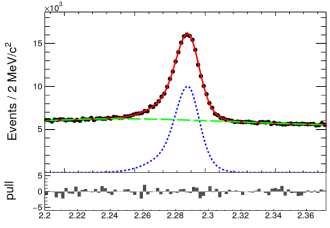
$\to$ consistent w/ BESIII, more precise

$\to$ systematics dominated by K_S^0/π^0 reconstruction



amplitude analysis planned in near future





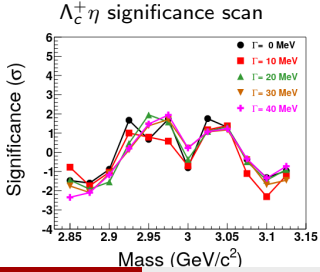
Excited charm baryons

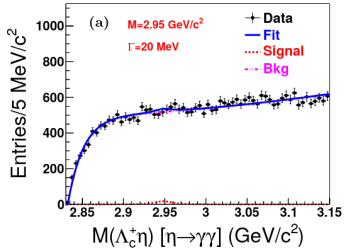
Belle 980 fb^{-1}

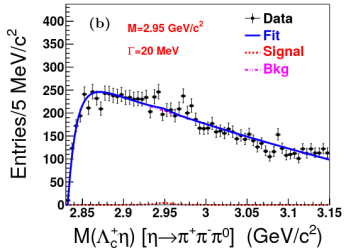
PRD 110, 032021 (2024)

Search in $\Lambda_c^+\eta$ final state

- Motivation: excited hyperons seen in $\Lambda\eta$ final state
- Intermediate states reconstructed in $\Lambda_c^+ \to pK^-\pi^+/pK_S^0$, $\eta \to \gamma\gamma/\pi^0\pi^+\pi^-$
- No excited states seen in mass range 2.85 - 3.125 GeV/c







Excited charm baryons

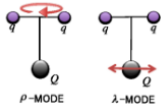
Belle 980 fb^{-1}

Branching-fraction ratios of $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$

PRD 110, 032021 (2024)

- decaying to $\Lambda_c^+\eta$ and pD^0
- relative to $\Sigma_c(2455)\pi$
- Intermediate states reconstructed in $D^0 \to K^-\pi^+/K^-\pi^+\pi^0/K^-\pi^+\pi^-\pi^+$, $\Sigma_c(2455) \to \Lambda_c^+\pi$
- Results

$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07$$
$$R_{pD^0}(2940) = 3.59 \pm 0.21 \pm 0.56$$
$$R_{\Lambda_c^+\eta}(2880) < 0.13 \text{ (90\% CL)}$$
$$R_{\Lambda_c^+\eta}(2940) < 1.11 \text{ (90\% CL)}$$

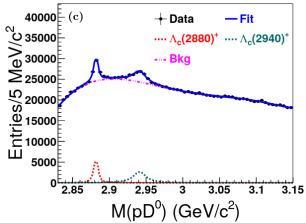


→ first measurements

→ results suggest [T. Yoshida et. al., PRD 92, 114029 (2015)]

$\Lambda_c(2880)^+$ is ρ-mode excited state (predom. to heavy baryon light meson)

$\Lambda_c(2940)^+$ is λ-mode excited state (predom. to light baryon heavy meson)



Conclusions

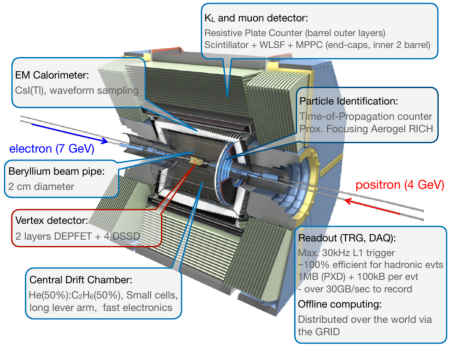
- Recent measurements of rare and baryonic decays of charmed hadrons at Belle and Belle II have been presented.
- Many of these decays have been measured or observed for the first time.
- Work on this topics continues.
- New results can be expected soon.

Backup: Belle and Belle II

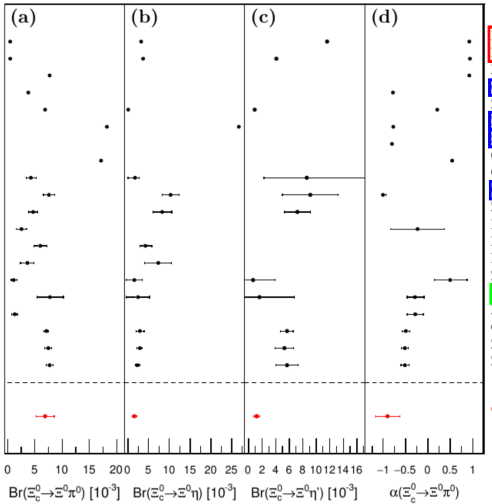
- B-factory experiments at KEK, Tsukuba, Japan
  - asymmetric e^+e^- colliders (KEKB, SuperKEKB) running at or near $\Upsilon(4S)$
  - $c\bar{c}$ production cross-section similar to $B\overline{B}$

- Belle (1999 - 2010)
  - general purpose spectrometer
    - vertexing, tracking, neutrals detection, PID
  - KEKB: $\mathcal{L} = 2 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - collected 1 ab^{-1}
- Belle II (2019 -)
  - upgraded Belle spectrometer
    - most components replaced $\rightarrow$ better performance
  - SuperKEKB: nano-beam optics
    - 20$\times$ smaller beam spot
  - target luminosity: 30 $\times$ KEKB
  - goal to collect 50 ab^{-1}

Belle II spectrometer



Backup: $\Xi_c^0 \to \Xi^0\pi^0,\ \Xi^0\eta,\ \Xi^0\eta'$

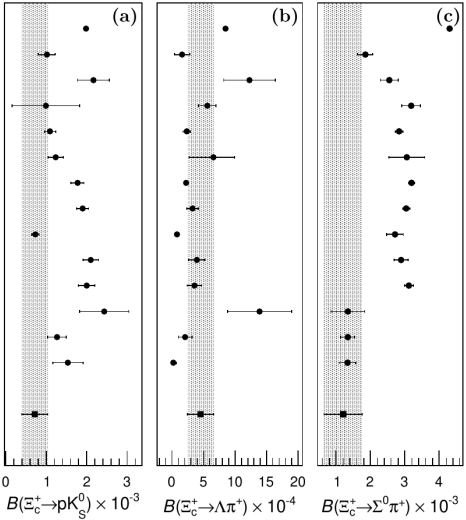


Körner, Krämer [5], Quark
Ivanov et al. [6], Quark
Xu, Kamal [7], Pole
Cheng, Tseng [8], Pole
Zenczykowski [9], Pole
Zou et al. [10], Pole
Sharma, Verma [11], CA
Cheng, Tseng [8], CA
Geng et al. [12], $SU(3)_F$
Geng et al. [13], $SU(3)_F$
Zhao et al. [14], $SU(3)_F$
Huang et al. [15], $SU(3)_F$
Hsiao et al. [16], $SU(3)_F$
Hsiao et al. [16], $SU(3)_F$-breaking
Zhong et al. [17], $SU(3)_F$
Zhong et al. [17], $SU(3)_F$-breaking
Xing et al. [18], $SU(3)_F$
Geng et al. [19], $SU(3)_F$
Zhong et al. [20], Diagrammatic-$SU(3)_F$
Zhong et al. [20], Irreducible-$SU(3)_F$

This measurement

- $SU(3)_F$-breaking model predictions [17] consistent with our Br. measurements but not with α
- predictions for α are consistent with our measurement for the pole model [8, 10], CA model [11] and $SU(3)_F$ model [13]
- covariant confined quark model [5, 6] is mildly disfavored

Backup: $\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$



Zou et al. [12]
Geng et al. [13]
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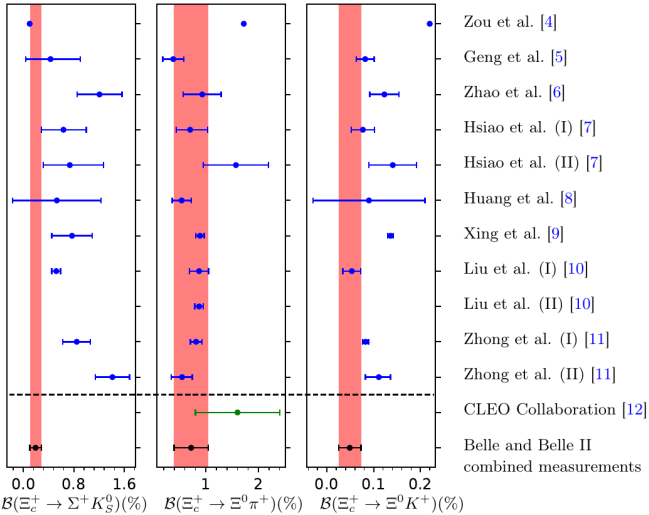
Zhong et al. (I) [16]
Zhong et al. (II) [16]
Xing et al. [17]
Geng et al. [18]
Liu [19]
Zhong et al. (I) [20]
Zhong et al. (II) [20]
Zhao et al. [21]
Hsiao et al. (I) [22]
Hsiao et al. (II) [22]

Belle and Belle II combined measurement

- predictions (except first one) are within 4σ of our measurements
- predictions for $\Lambda\pi^+$ mode are all within 2σ of our measurement
- most predictions for pK_S^0 and $\Sigma^0\pi^+$ modes are somewhat higher than our measurements

Backup: $\Xi_c^+ \to \Sigma^+ K_S^0$, $\Xi^0 \pi^+$, $\Xi^0 K^+$



- good agreement for $\Xi^0 \pi^+$ decay except [4]
- somewhat higher predictions for the other two decay modes