Charm Physics at Belle and Belle II

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on behalf of the Belle and Belle II collaborations

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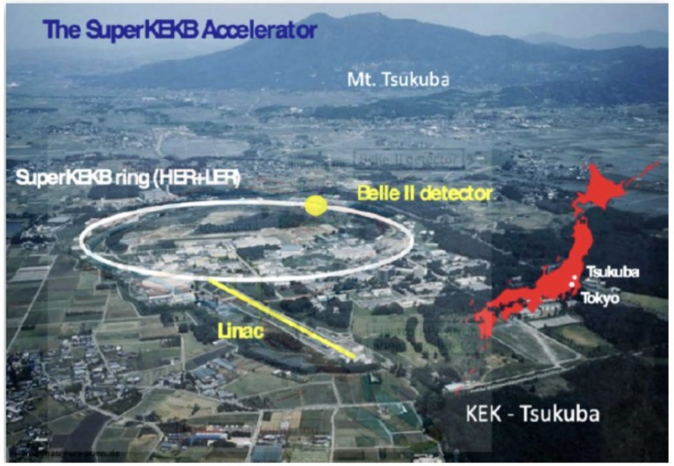
Outline

- Belle and Belle II experiments
- Charmed mesons
  - Search for *CP* violation in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^-$ decays — Belle + Belle II [arXiv: 2409.15777]
  - Time-integrated *CP* asymmetry in $D^0 \to K^0_S K^0_S$ decays — Belle + Belle II [PRD 111, 012015 (2025)]
  - D^0-$\overline{D}^0$ mixing parameters in $D^0 \to K^0_S \pi^+ \pi^-$ decays — Belle + Belle II [arXiv: 2410.22961]
- Charmed baryons
  - Two-body decays of Ξ^0_c — Belle + Belle II [JHEP 10 045 (2024)]
  - Two-body decays of Ξ^+_c — Belle + Belle II [arXiv: 2412.10677; PRELIMINARY]
- Summary

KEKB and Super-KEKB colliders

- KEKB and Super-KEKB are asymmetric e^+e^- colliders.
- Collisions mainly at $\sqrt{s} = 10.58$ GeV, *i.e.* at $\Upsilon(4S)$ resonance.



KEKB

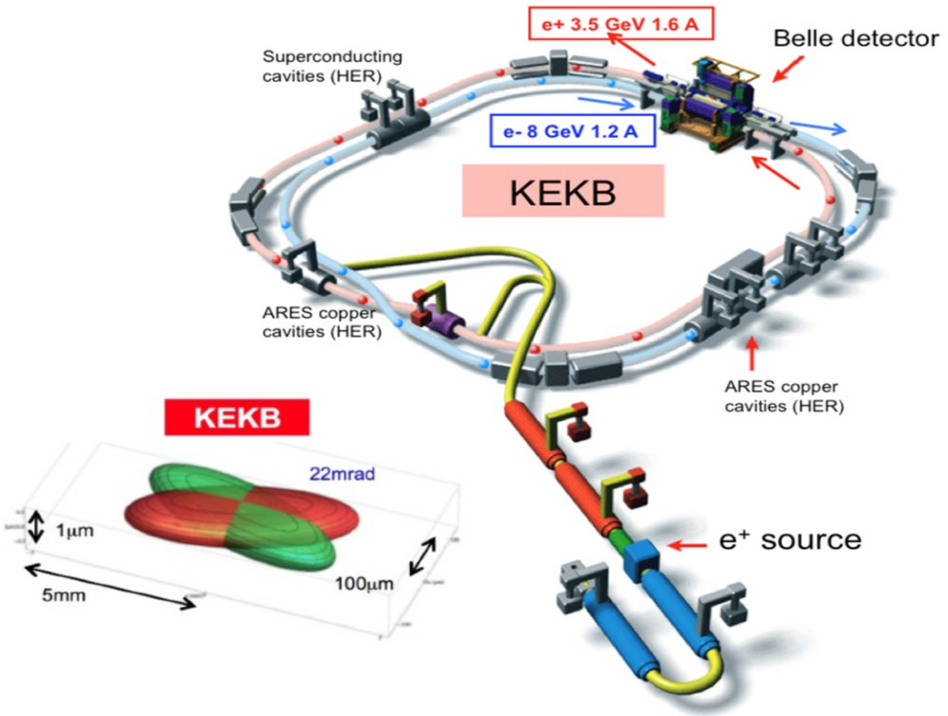
1999-2010

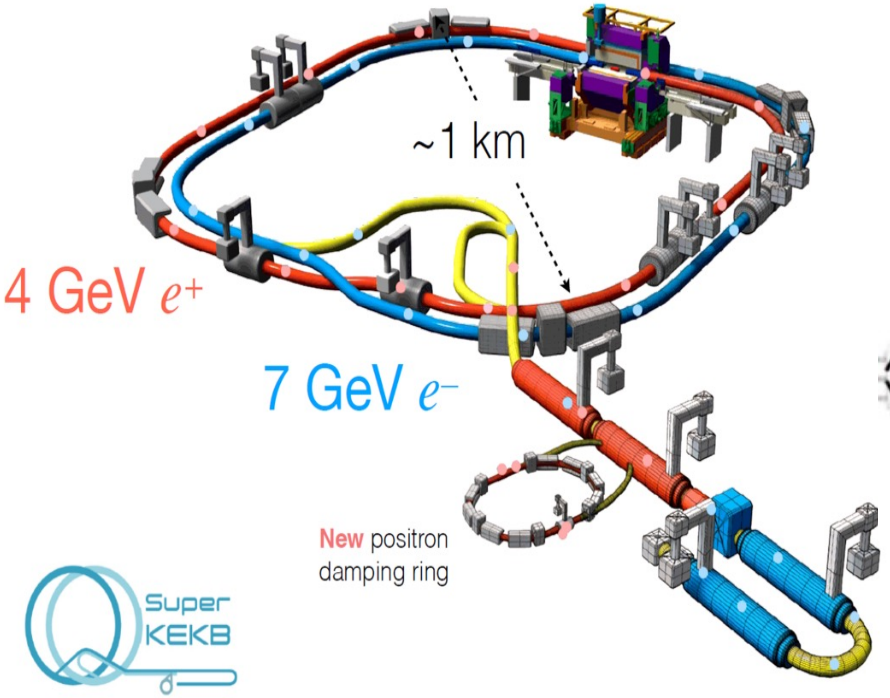
- $e^+(3.5\ \mathrm{GeV})e^-(8\ \mathrm{GeV})$
- $L_{\mathrm{peak}}: 2.1\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

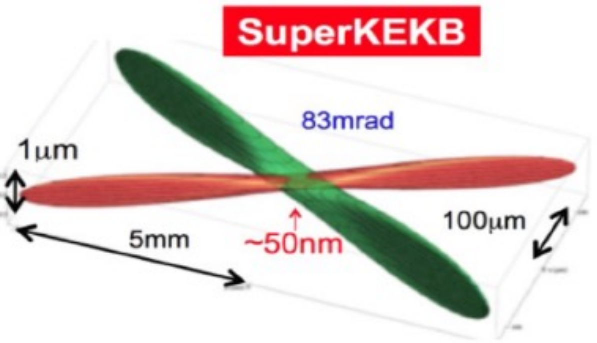
Super-KEKB

2019-current

- $e^+(4\ \mathrm{GeV})e^-(7\ \mathrm{GeV})$
- $L_{\mathrm{peak}}: 5.1\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [achieved]







Belle and Belle II detectors

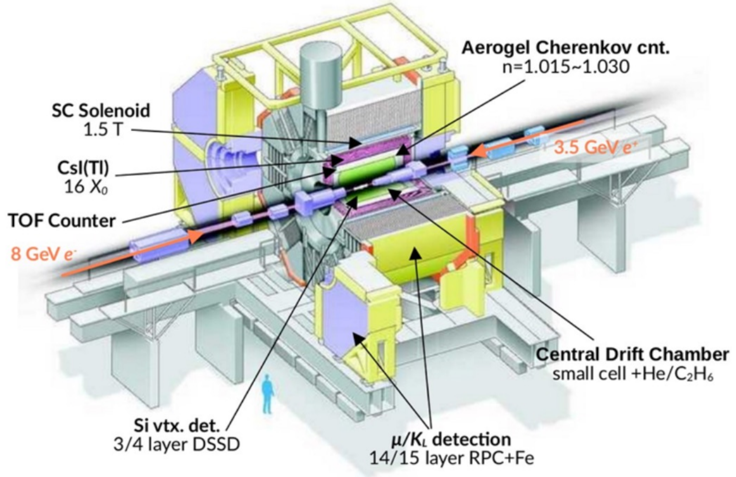
➢Belle and Belle II operate at asymmetric e^+e^- colliders

- Belle @ KEKB (1999-2010): L_{int}~1 ab^{-1}.
- Belle II @ Super-KEKB (2019-current):

  Run 1(2019-2022): L_{int}~428fb^{-1};

  Run 2(2024~): L_{int}~150 fb^{-1}.

BELLE@KEKB



➢Belle and Belle II are now **synergic** experiments.

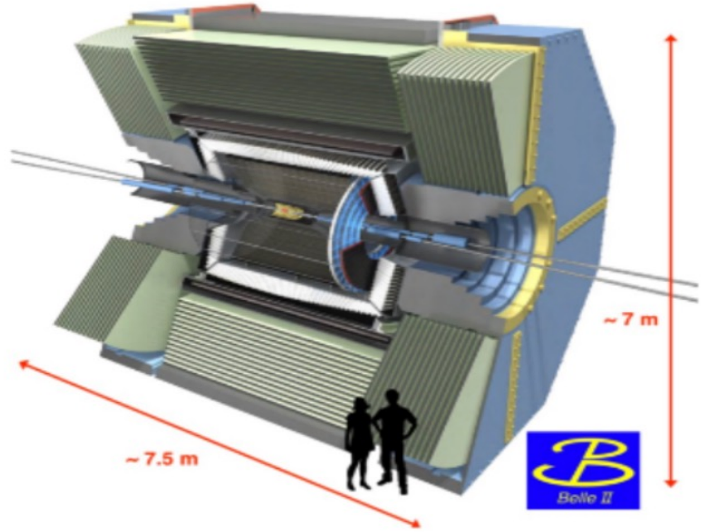
✓ Belle data can be analyzed within the Belle II software framework.

✓ Common review procedures since summer of 2023.

✓ Especially important for charm analyses, where large statistics is crucial to improve the precision.

Streamlines combined analyses

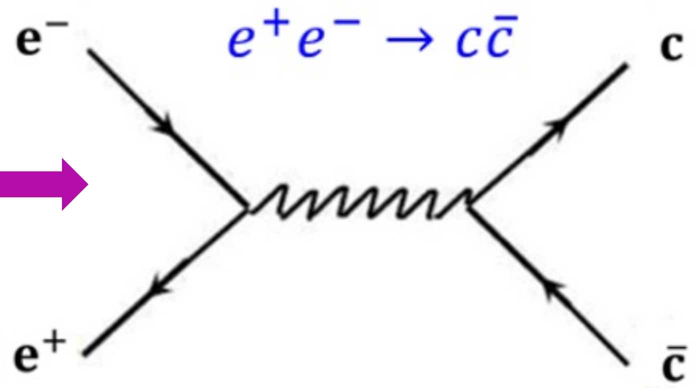
BELLE II @SuperKEKB



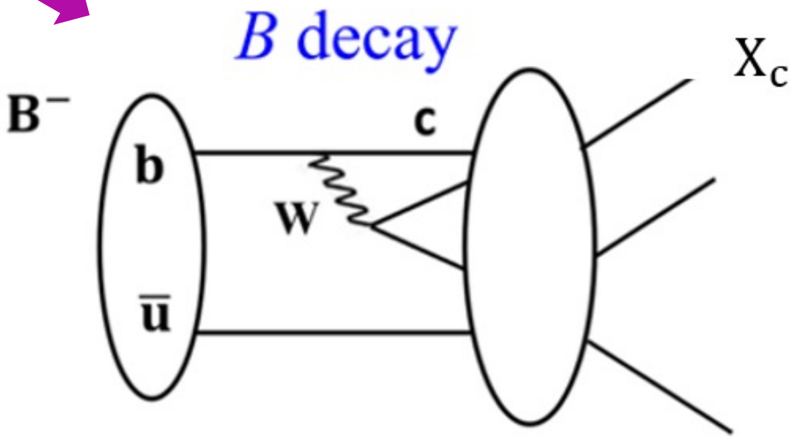
Charm physics at Belle (II)

- ➢ Belle and Belle II are primarily B-meson factories, but not only.
- ✓ Per ab^{-1}(events × 10^9): 1.1 $B\bar{B}$, 1.3 $c\bar{c}$, 2.1 $q\bar{q}$, 0.9 $\tau\bar{\tau}$

- ➢ Two ways to produce the charm hadrons at B-factories:
- • Two charmed hadrons produced from continuum, along with fragmentation particles: $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb @ $\sqrt{s} = 10.58$ GeV.



- • One or more charmed hadrons produced in B decays: $e^+e^- \to \Upsilon(4S) \to B\bar{B} \to X_c$



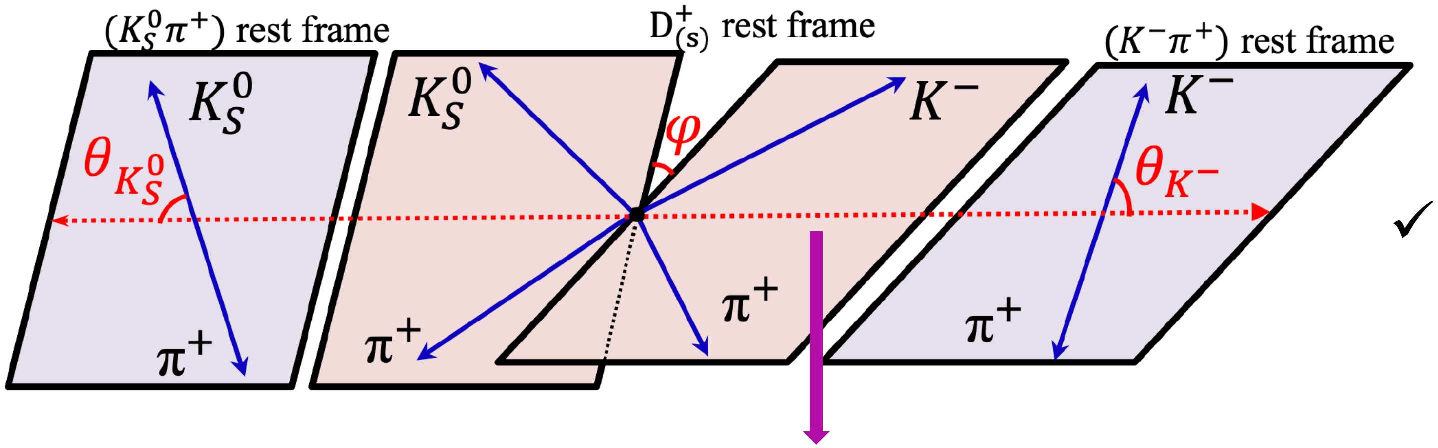
- ➢ Full topics for charm physics:

- • *CP* violation
- • Lifetimes of charm hadrons
- • Charmed baryons
- • D^0-$\bar{D}^0$ mixing
- • Rare decay
- • …

Search for CP violation in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^-$ decays

➤ First search for CP violation in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ decays using six observables (X) based on the triple product and quadruple product of the momenta of final-state particles, and the particles' helicity angles.

1. Triple-product (TP) $C_{TP} = \vec{p}_{K^-} \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$
2. Quadruple-product (QP) $C_{QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$
3. $C_{TP} C_{QP}$
4. $\cos\theta_{K^0_S} \cos\theta_{K^-}$
5. $\cos\theta_{K^0_S} \cos\theta_{K^-} C_{TP}$
6. $\cos\theta_{K^0_S} \cos\theta_{K^-} C_{QP}$



The direction of $(K\pi)$ system's momentum in the $D^+_{(s)}$ rest frame

Belle + Belle II~1.4/ab arXiv: 2409.15777

✓ The asymmetries about zero:

$$A_X(D^+_{(s)}) = \frac{N(X>0) - N(X<0)}{N(X>0) + N(X<0)}$$

$$\bar{A}_{\bar{X}}(D^-_{(s)}) = \frac{\bar{N}(\bar{X}>0) - \bar{N}(\bar{X}<0)}{\bar{N}(\bar{X}>0) + \bar{N}(\bar{X}<0)}$$

A_X and $\bar{A}_{\bar{X}}$ are CP-conjugate quantities.

✓ CP-violating parameter:

$$A^X_{CP} = \frac{A_X(D^+_{(s)}) - \bar{A}_{\bar{X}}(D^-_{(s)})}{2}$$

$A^X_{CP} \neq 0$ indicates CP violation

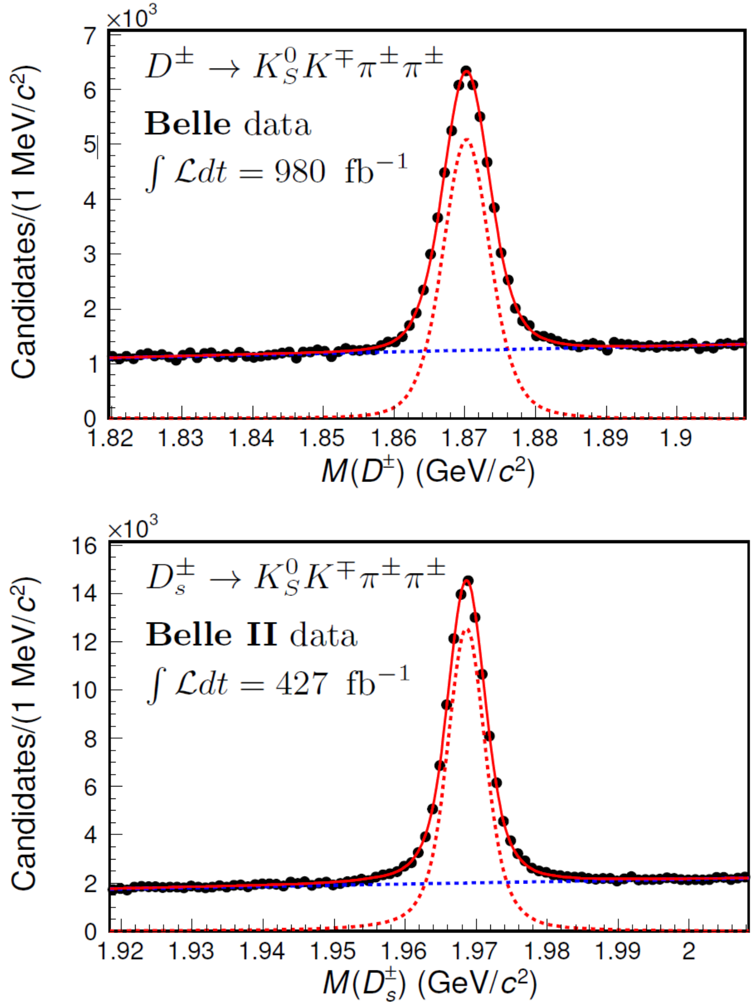
Search for *CP* violation in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^-$ decays

- The A^X_{CP} is extracted by performing a simultaneous fit to the $M(D_{(s)})$ distributions of four subsamples as determined by the charge of $D_{(s)}$ and the sign of X.

Belle + Belle II~1.4/ab arXiv: 2409.15777

✓ No evidence for CPV is found. The last column indicates the significance of the combined result from $A^X_{CP} = 0$.

	X	A^X_{CP} Belle	A^X_{CP} Belle II	Combined A^X_{CP}	Significance
D^+	$C_{\rm TP}$	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	$C_{\rm QP}$	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	$C_{\rm TP}\,C_{\rm QP}$	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	$\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	$C_{\rm TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	$C_{\rm QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D^+_s	$C_{\rm TP}$	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	$C_{\rm QP}$	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	$C_{\rm TP}\,C_{\rm QP}$	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	$\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	$C_{\rm TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	$C_{\rm QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ



✓ Most precise measurements of triple-product asymmetry for D^+_s decays and for SCS D^+ decays.

✓ The first use of the other A^X_{CP} asymmetries to search for *CP* violation in the charm sector.

Time-integrated *CP* asymmetry in $D^0 \to K_S^0 K_S^0$

- The $D^0 \to K_S^0 K_S^0$ is a singly Cabibbo-suppressed decay, which involves the interference between $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes.

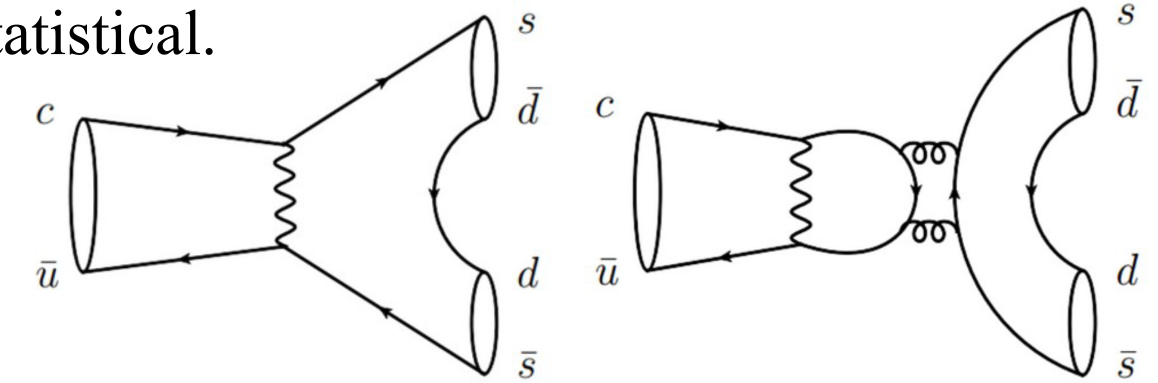
Belle + Belle II~1.4/ab PRD 111 012015 (2025)

- Such interference can generate *CP* asymmetries at the 1% level.

[PRD 99, 113001 (2019); PRD 92, 054036 (2015)]

- The world-average value of the *CP* asymmetry, $A_{CP}(D^0 \to K_S^0 K_S^0)$: $(-1.9 \pm 1.0)\%$, is limited by statistical.

$$A_{CP} \equiv \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$



$A_{CP}(D^0 \to K_S^0 K_S^0) = -0.02 \pm 1.53(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.17$ (cont. mode) Belle [PRL 119, 171801 (2017)]

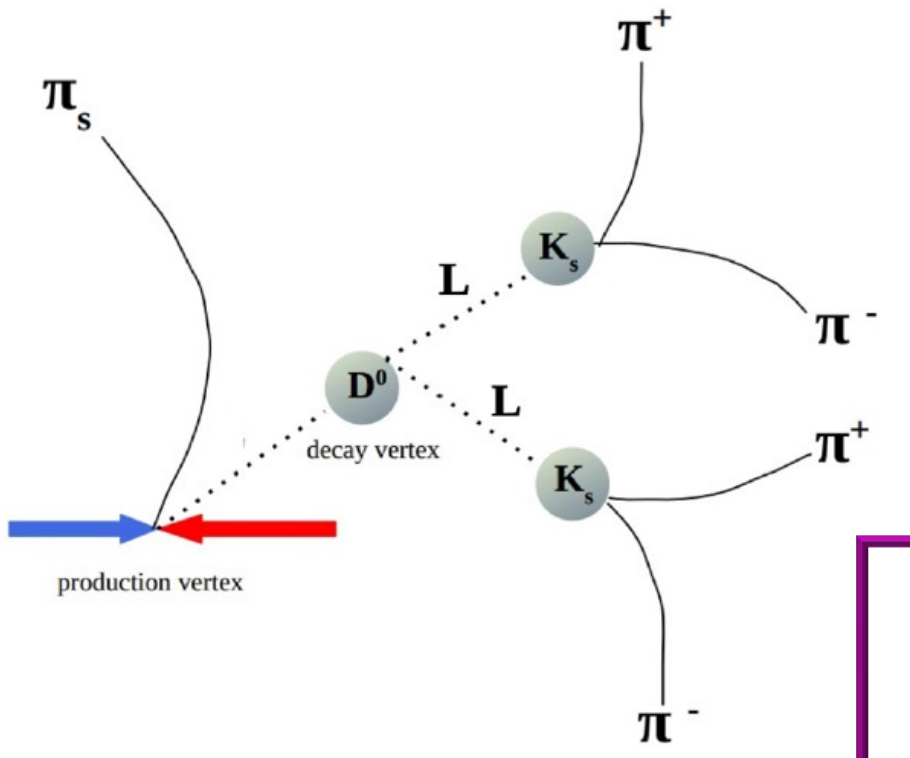
$A_{CP}(D^0 \to K_S^0 K_S^0) = -3.1 \pm 1.2(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.2$ (cont. mode) LHCb [PRD 104, L031102 (2021)]

- There are nuisance asymmetries induced by production and detection mechanisms: taking $D^0 \to K^+K^-$ as a control channel to calibrate A_{CP}.

Time-integrated *CP* asymmetry in $D^0 \to K_S^0 K_S^0$

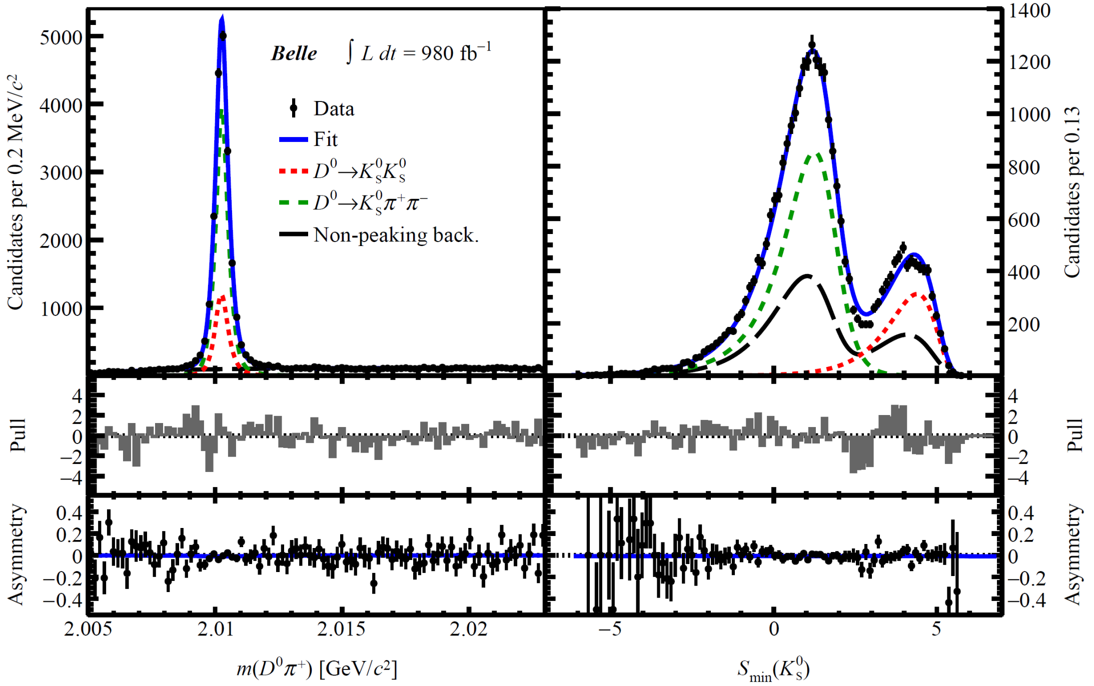
- K_S^0 flight distance used to separate the signal from $D^0 \to K_S^0\pi^+\pi^-$ decay.
- Define the separation variable:

$$S_{min}(K_S^0) = \log[\min(L_1/\sigma_{L1}, L_2/\sigma_{L2})]$$



- Signal extracted from a fit to $m(D^0\pi^+)$ and $S_{min}(K_S^0)$.

Belle + Belle II~1.4/ab PRD 111 012015 (2025)



Belle: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\%$

Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\%$

Belle + Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\%$

D^0-$\bar{D}^0$ mixing parameters in $D^0 \to K_S^0\pi^+\pi^-$ decays

- D^0-$\bar{D}^0$ mixing parameters: $|D_{1,2}> = p|D^0> + q|\bar{D}^0>$

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Mass of the $D_{1/2}$ state   Width of the $D_{1/2}$ state

- World average values: [PRD 107 052008 (2023)]

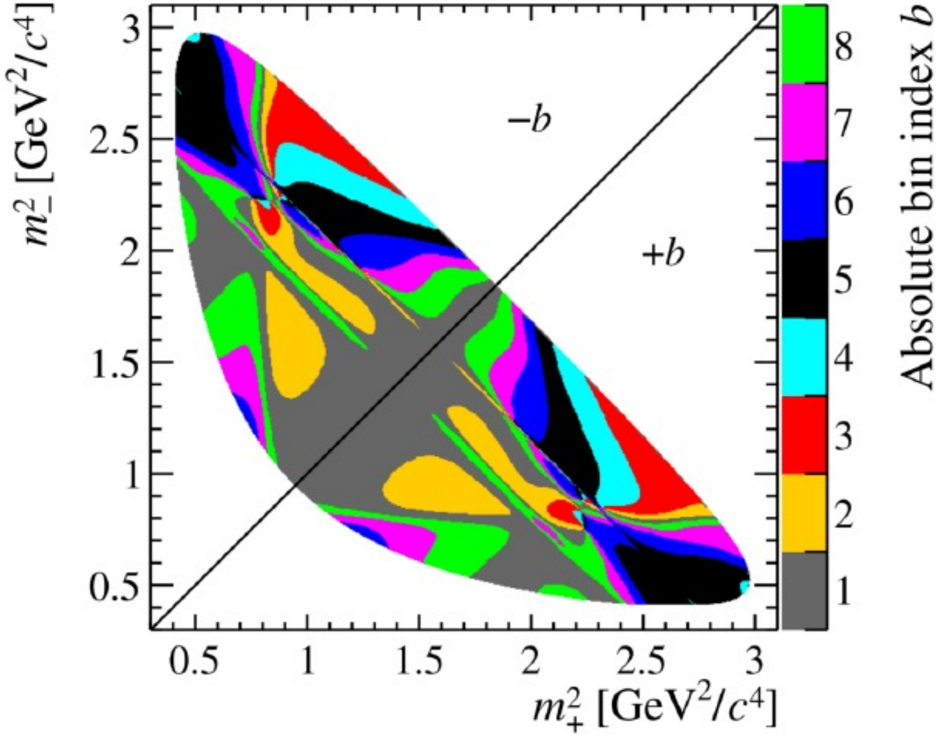
$x = (4.07 \pm 0.44)\times 10^{-3}$ $|q/p| = 0.994^{+0.016}_{-0.015}$

$y = (6.45^{+0.24}_{-0.23})\times 10^{-3}$ $\arg(q/p) = (-2.6^{+1.1}_{-1.2})°$

- By splitting the Dalitz plot into bins, the need for an explicit amplitude model is avoided.
- Using combined Belle and Belle II datasets, we perform a model-independent measurement of the D^0-$\bar{D}^0$mixing parameters using D^{*+}-tagged $D^0 \to K_S^0\pi^+\pi^-$ decays.

Belle + Belle II~1.3/ab arXiv: 2410.22961

[PRD 82 112006 (2010)]



$$m_\pm^2 = \begin{cases} m^2(K_S^0\pi^\pm) \text{ for initially produced } D^0 \\ m^2(K_S^0\pi^\mp) \text{for initially produced } \bar{D}^0 \end{cases}$$

D^0-$\bar{D}^0$ mixing parameters in $D^0 \to K_S^0\pi^+\pi^-$ decays

- Signal and background are separated using fits to 2D distributions of D^0 mass and energy released in D^{*+}.
- The mixing parameters are determined using a fit to the (t, σ_t) distributions of the candidates populating the signal region and split into the 16 Dalitz plot bins.

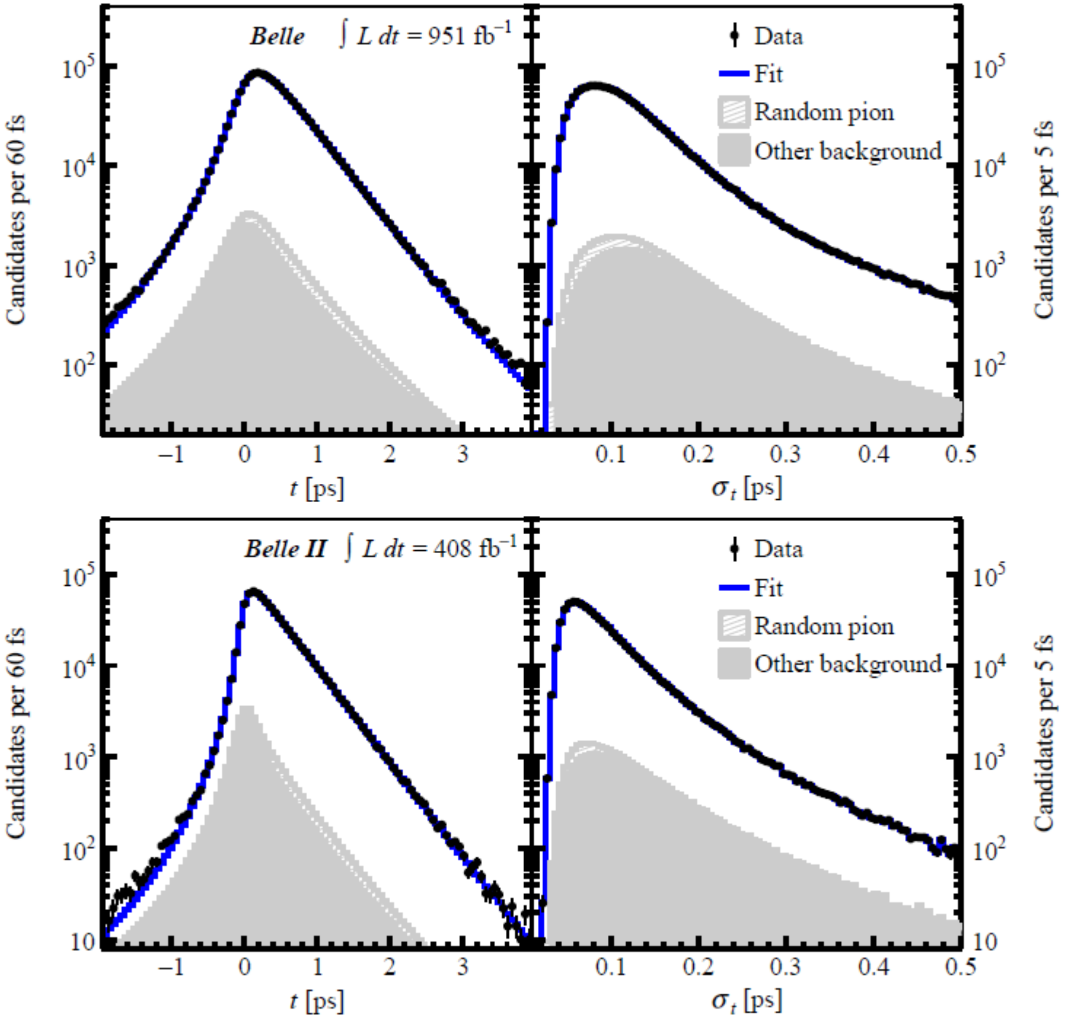
$$x = (4.0 \pm 1.7 \pm 0.4)\times 10^{-3}$$

$$y = (2.9 \pm 1.4 \pm 0.3)\times 10^{-3}$$

- These results are about 20% and 14% more precise than the model-dependent Belle measurement!

[PRD 89 091103 (2014)]

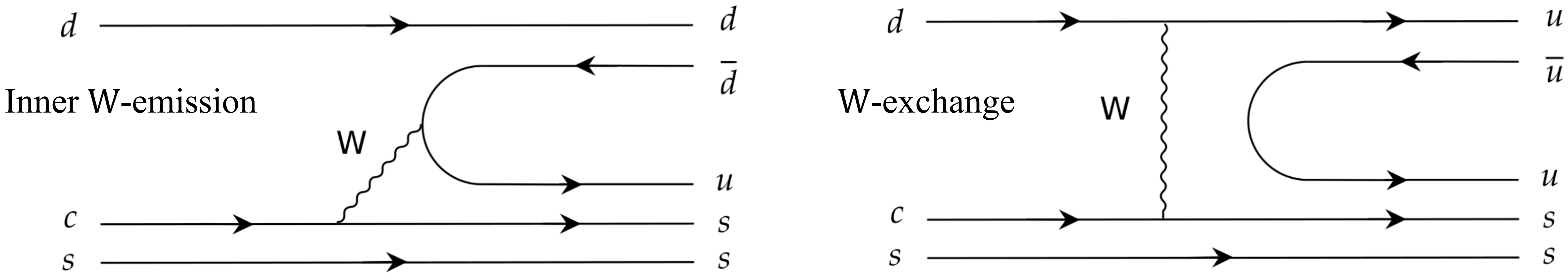
Belle + Belle II~1.3/ab arXiv: 2410.22961



Sample average purity 95.8%

Study of two-body decays of Ξ_c^0 and Ξ_c^+

- In hadronic weak decays of charmed baryons, nonfactorizable contributions play a crucial role and pose significant challenges for theoretical predictions.



- In 2019, Belle measured the absolute branching fractions of $\Xi_c^0 \to \Xi^-\pi^+$[1] and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$[2], sparking renewed interest in the study of Ξ_c^0 and Ξ_c^+ decays.
- Theoretical calculations for the two-body hadronic weak decays of Ξ_c^0 and Ξ_c^+ have been performed based on dynamical model calculations and SU(3) flavor symmetry methods [3-9].
- Using the combined data from Belle and Belle II to search for new decay modes of Ξ_c^0 and Ξ_c^+, and to validate different theoretical models.

[1] PRL 122 (2019) 082001; [2] PRD 100 (2019) 031101; [3] PLB 794 (2019) 19; [4] PRD 101 (2020) 014011; [5] JHEP 02 (2020) 165; [6] JHEP 09 (2022) 035; [7] JHEP 03 (2022) 143; [8] PRD 108 (2023) 053004; [9] JHEP 02 (2023) 235…

Observations of $\Xi_c^0 \to \Xi^0 h^0, h^0 = \pi^0/\eta/\eta'$

- The Cabibbo-favored decays $\Xi_c^0 \to \Xi^0\pi^0$, $\Xi^0\eta$, and $\Xi^0\eta'$ are observed for the first time.
- Taking the $\Xi_c^0 \to \Xi^-\pi^+$ as the normalization mode, the ratios of branching fractions are measured to be:

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = (0.48 \pm 0.02 \pm 0.03)$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = (0.11 \pm 0.01 \pm 0.01)$$

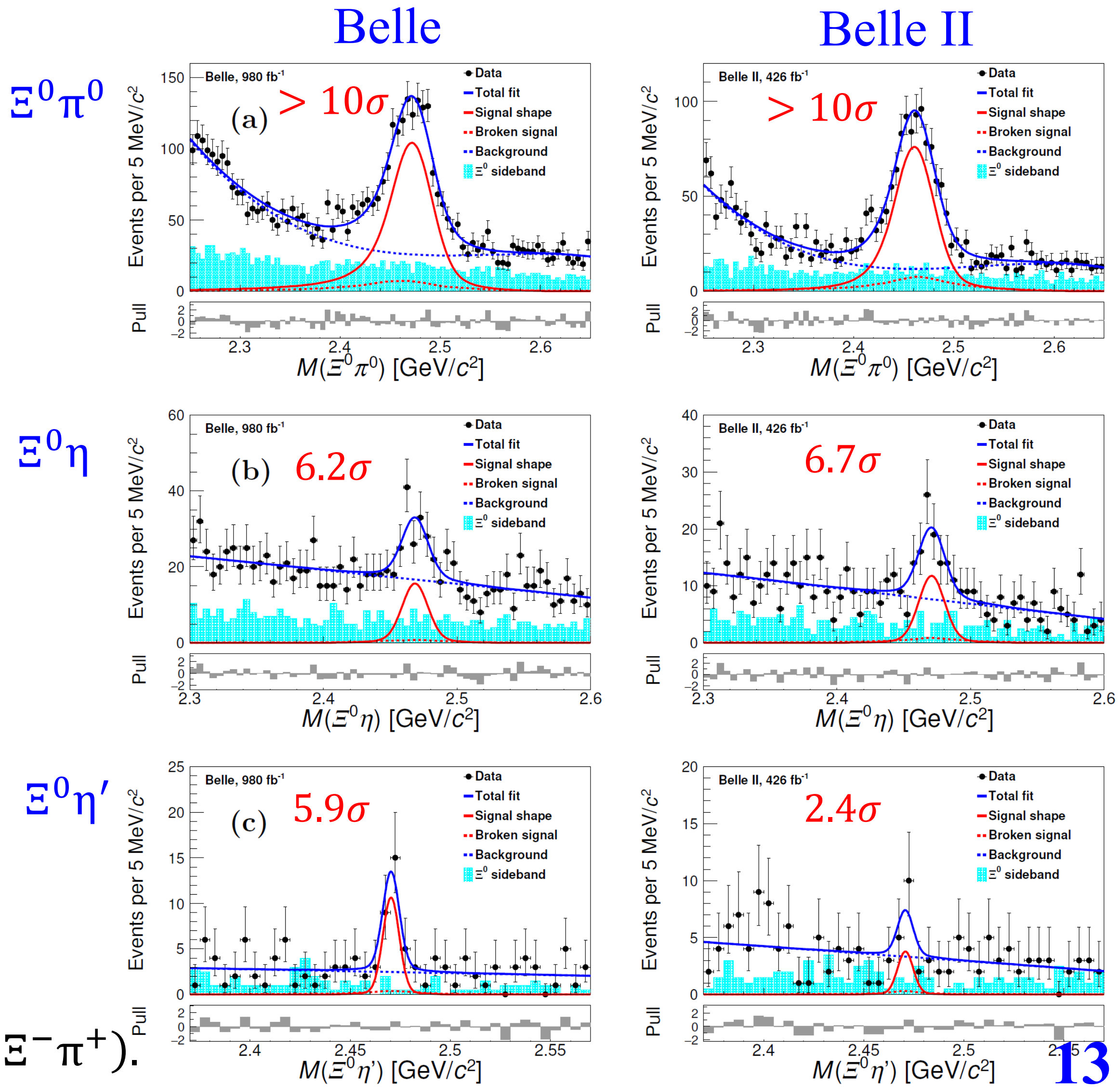
$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = (0.08 \pm 0.02 \pm 0.01)$$

- Taking $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.43 \pm 0.32)\%$, we obtain

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3 \pm 0.5 \pm 1.5)\times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.4)\times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3 \pm 0.1 \pm 0.3)\times 10^{-3}$$

The first and second uncertainties above are statistical and systematic, respectively, while the third ones arise from the uncertainty in $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$.

Belle + Belle II~1.4/ab JHEP 10 (2024) 045



Measurement of α asymmetry of $\Xi_c^0 \to \Xi^0\pi^0$

- The interference between the parity-violating and parity-conserving amplitudes leads to an asymmetry in the angular decay distribution, quantified by the parameter α:

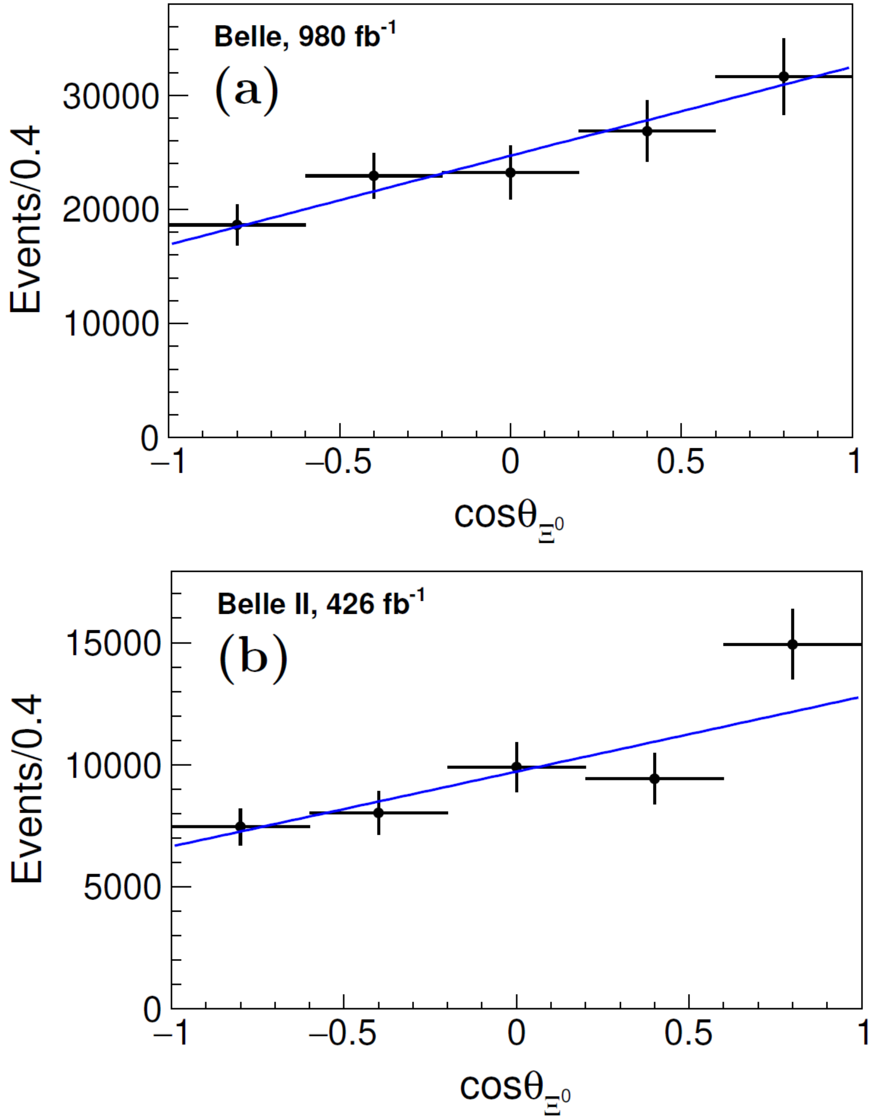
$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0\pi^0)\alpha(\Xi^0 \to \Lambda\pi^0)\cos\theta_{\Xi^0}$$

- $\alpha(\Xi^0 \to \Lambda\pi^0) = -0.349 \pm 0.009$
- θ_{Ξ^0} is the angle between the Λ momentum vector and the direction opposite to the Ξ_c^0 momentum vector in the Ξ^0 rest frame.

- By performing a simultaneous fit to Belle and Belle II data, we obtain

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

Belle + Belle II~1.4/ab JHEP 10 (2024) 045



Measurements of branching fractions of Ξ_c^+ decays

- The singly Cabibbo-suppressed decays $\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, $\Sigma^0\pi^+$, and Ξ^0K^+, as well as Cabibbo-favored decay $\Xi_c^+ \to \Sigma^+K_S^0$ are observed for the first time.
- Taking the $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ as the normalization mode, the absolute branching fractions are measured to be:

Belle + Belle II~1.4/ab arXiv: 2412.10677; PRELIMINARY

$\mathcal{B}(\Xi_c^+ \to pK_S^0) = (7.16 \pm 0.46 \pm 0.20 \pm 3.21)\times10^{-4}$

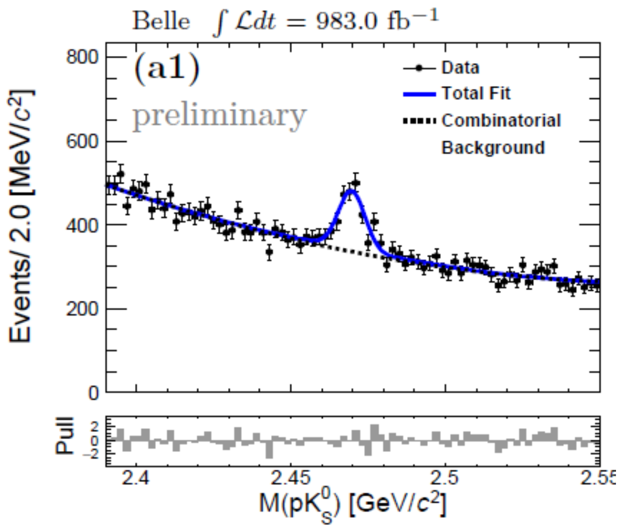
$\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+) = (4.52 \pm 0.41 \pm 0.26 \pm 2.03)\times10^{-4}$

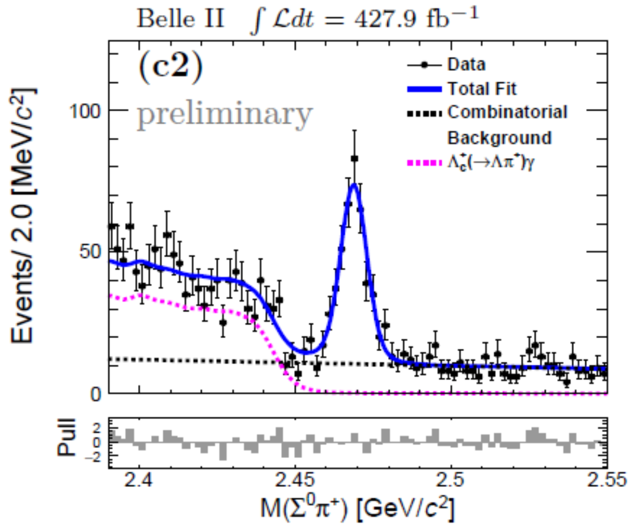
$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+) = (1.20 \pm 0.08 \pm 0.07 \pm 0.54)\times10^{-3}$

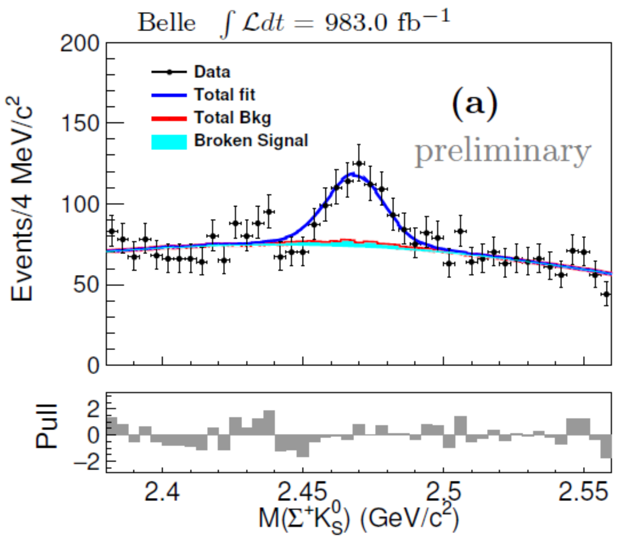
$\mathcal{B}(\Xi_c^+ \to \Sigma^+K_S^0) = (1.86 \pm 0.20 \pm 0.08 \pm 0.83)\times10^{-3}$

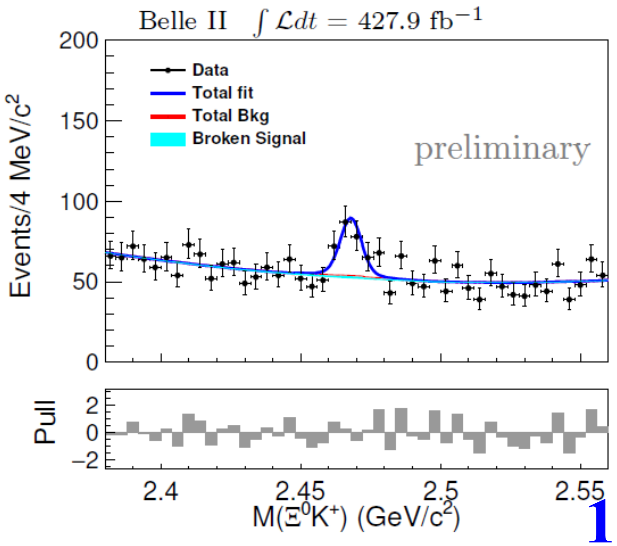
$\mathcal{B}(\Xi_c^+ \to \Xi^0K^+) = (0.46 \pm 0.07 \pm 0.02 \pm 0.21)\times10^{-3}$

$\mathcal{B}(\Xi_c^+ \to \Xi^0\pi^+) = (6.77 \pm 0.24 \pm 0.30 \pm 3.03)\times10^{-3}$









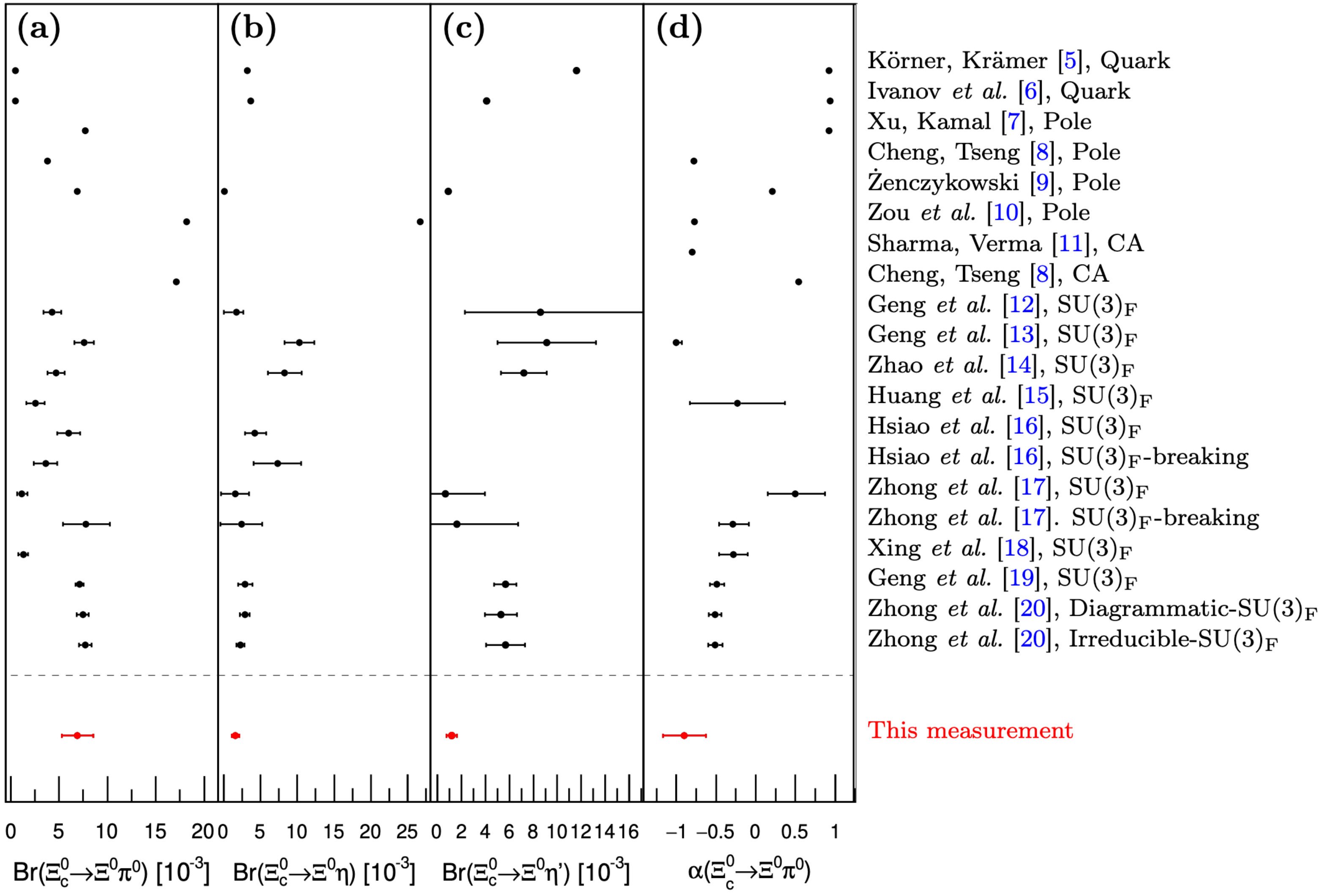
Summary

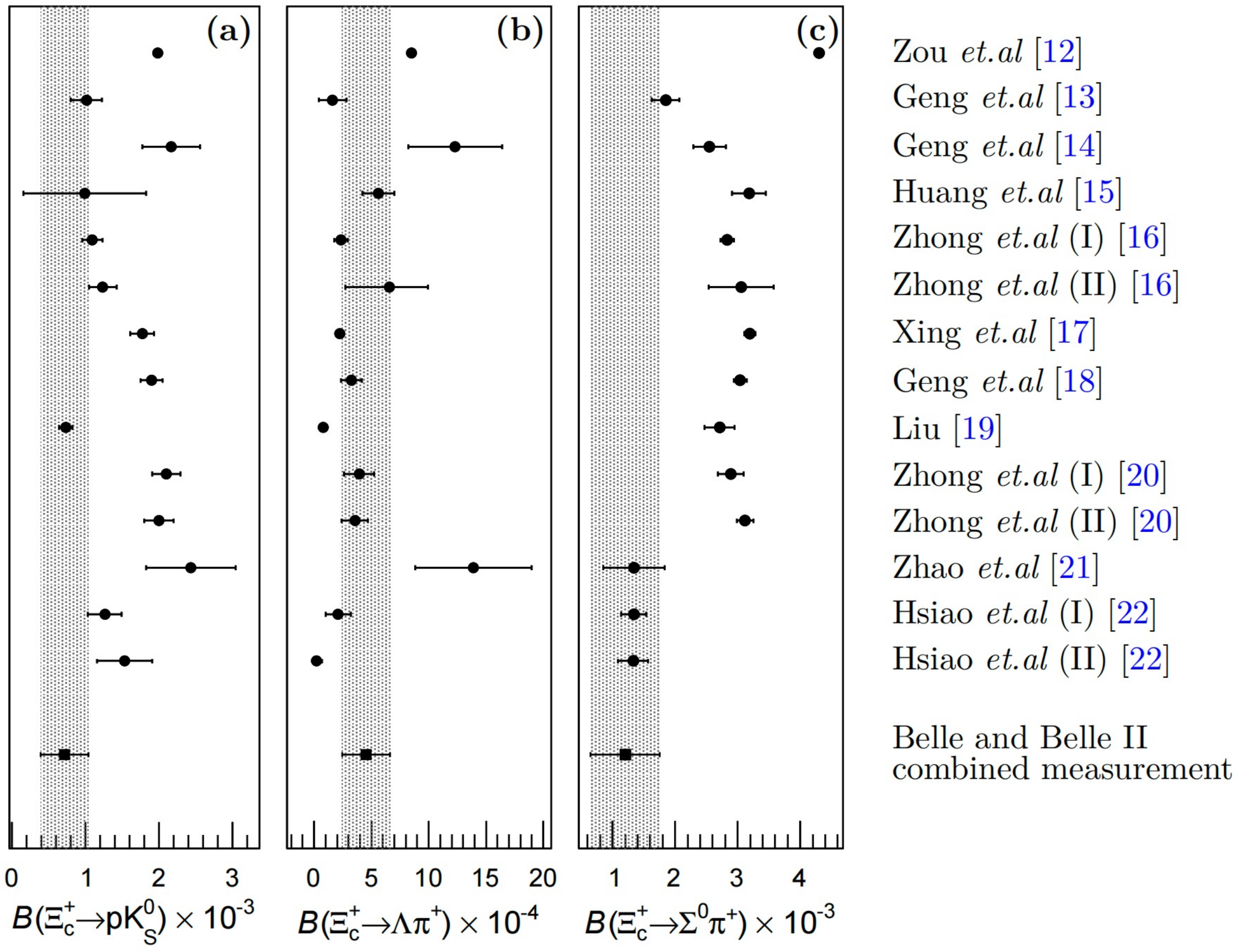
- Belle and Belle II offer a unique environment and sensitivity for SM measurements, as well as for the search for *CP* violation in the charm sector.

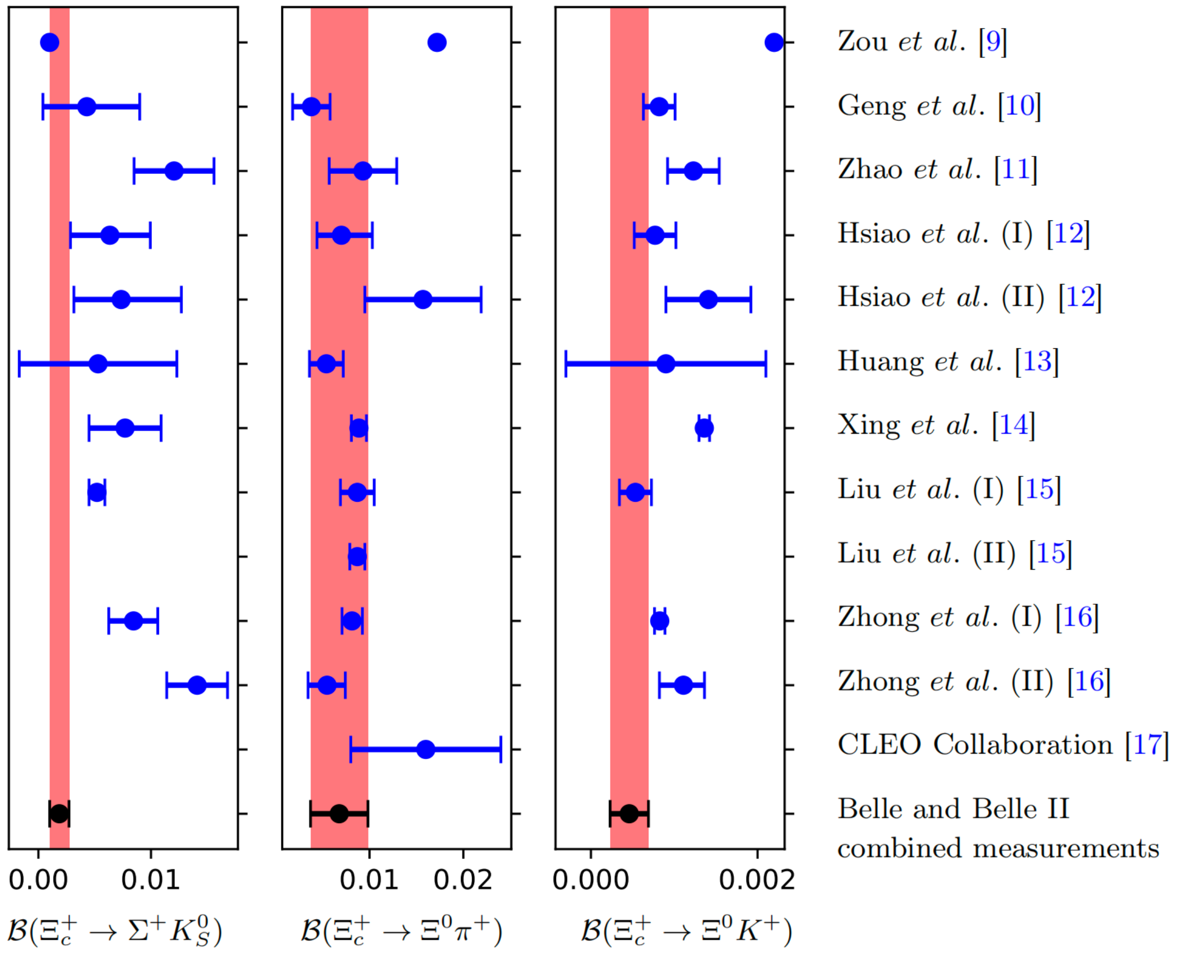
- In the past year, some fascinating results have been achieved in the search for *CP* violation of D mesons, measurement of D^0-$\overline{D}^0$ mixing, and the $\Xi_c^{+/0}$ decays using the combined data from Belle and Belle II.

- Belle II has started data taking for Run 2, and more precise and improved results are on the way. Stay tuned!

Backup


(a)
(b)
(c)
(d)
Körner, Krämer [5], Quark
Ivanov et al. [6], Quark
Xu, Kamal [7], Pole
Cheng, Tseng [8], Pole
Żenczykowski [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
0 5 10 15 20
0 5 10 15 20 25
0 2 4 6 8 10 12 14 16
−1 −0.5 0 0.5 1
$Br(\Xi_c^0 \to \Xi^0 \pi^0)$ [10^{-3}]
$Br(\Xi_c^0 \to \Xi^0 \eta)$ [10^{-3}]
$Br(\Xi_c^0 \to \Xi^0 \eta')$ [10^{-3}]
$\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$


(a)
(b)
(c)
Zou et.al [12]
Geng et.al [13]
Geng et.al [14]
Huang et.al [15]
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
0 1 2 3
$B(\Xi_c^+ \to pK_S^0) \times 10^{-3}$
0 5 10 15 20
$B(\Xi_c^+ \to \Lambda\pi^+) \times 10^{-4}$
1 2 3 4
$B(\Xi_c^+ \to \Sigma^0\pi^+) \times 10^{-3}$


Zou et al. [9]
Geng et al. [10]
Zhao et al. [11]
Hsiao et al. (I) [12]
Hsiao et al. (II) [12]
Huang et al. [13]
Xing et al. [14]
Liu et al. (I) [15]
Liu et al. (II) [15]
Zhong et al. (I) [16]
Zhong et al. (II) [16]
CLEO Collaboration [17]
Belle and Belle II combined measurements
0.00 0.01
$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0)$
0.01 0.02
$\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+)$
0.000 0.002
$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+)$