Charm Physics at Belle and Belle II

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Outline

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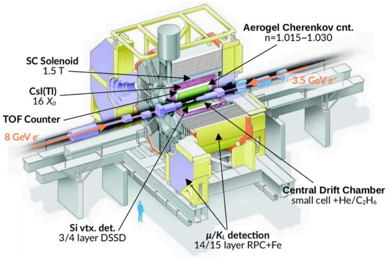
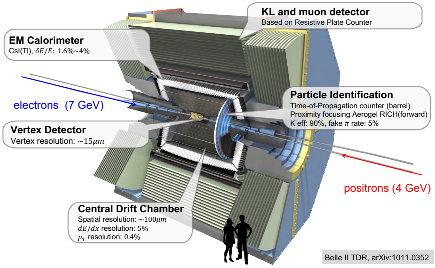
Charm physics at Belle and Belle II

- Belle and Belle II operate at e^+e^- center-of-mass energy $\sqrt{s} = 10.58\,\mathrm{GeV}$ to produce the $\Upsilon(4S)$, which decays to $B\bar{B}$ with branching fraction $> 96\%$.
- Continuum production $e^+e^- \to q\bar{q}$ with $q \in \{u, d, s, c\}$ has a large cross section.
- Mainly use prompt charm from $e^+e^- \to c\bar{c}(\sigma \approx 1.3\,\mathrm{nb})$ for charm analyses, rather than charm from B decays.
- Produced charm mesons and baryons: $D^{(*)}$, $D_s^{(*)}$, Λ_c^+, $\Xi_c^{+,0}$, and Ω_c^0.
- Datasets & detector
  - Belle (1999–2010): $\int \mathcal{L}dt = 980\,\mathrm{fb}^{-1}$.
  - Belle II (2019–present): $\int \mathcal{L}dt = 575\,\mathrm{fb}^{-1}$ (Run 1: $428\,\mathrm{fb}^{-1}$); improvements over Belle(vertexing and tracking performance, ECL cluster background suppression, and so on).



Belle detector



Belle II detector

Outline

$D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$ at Belle and Belle II

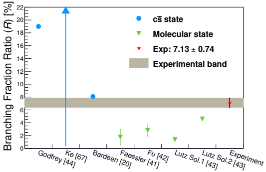
arXiv:2510.27174, submitted to *PRL* -

- First observation.
- Motivation: mass of $D_{s0}^*(2317)^+$ is much lower than the quark model predictions of the lowest $c\bar{s}$ mesons with the corresponding J^P quantum number.
- Precise absolute branching fraction is unknown.

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	(100^{+0}_{-20}) %		298
Γ_2	$D_s^+\gamma$	<5 %	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	<6 %	CL=90%	

- Branching ratio measurements: $\dfrac{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)}$

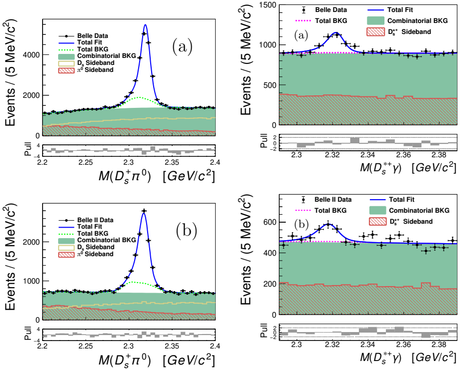
  decay chain: $D_s^+(\to \phi\pi, K^*K)$, $D_s^{*+}(\to D_s^+\gamma)$
- Comparison between theoretical predictions and measurement:



predictions based on the light front quark model [67] and chiral quark model [20] agree with measurement under the pure $c\bar{s}$ state.

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

PDG: $m(D_{s0}^*(2317)^+) = 2317.8 \pm 0.5$ MeV$/c^2$



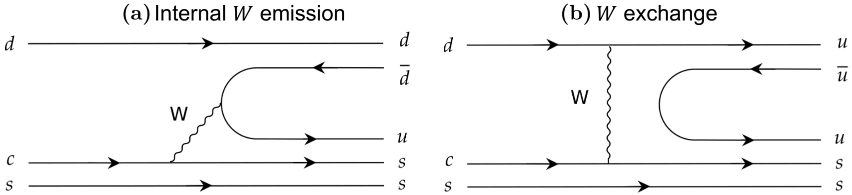
Fits: Belle (top) and Belle II (bottom).

- Ratio$= (7.14 \pm 0.70_{\text{stat.}} \pm 0.23_{\text{syst.}})$%

$\Xi_c^0 \to \Xi^0 h (h = \pi^0, \eta, \eta')$ at Belle and Belle II

JHEP 10 (2024) 045

- Diagrams:



- CF(Cabibbo-favored) decays and only nonfactorizable amplitudes contribute to.
  - For theoretical predictions, various approaches have been developed.

$\Xi_c^0 \to \Xi^0 h (h = \pi^0, \eta, \eta')$ at Belle and Belle II

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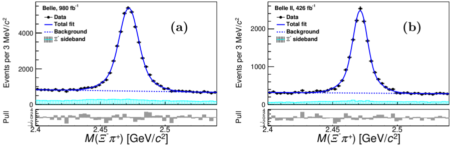
- First observations.
- Abundant measurements on Ξ_c^0 have been done by Belle, including $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) \to$ use as reference.
- Branching ratio measurements:

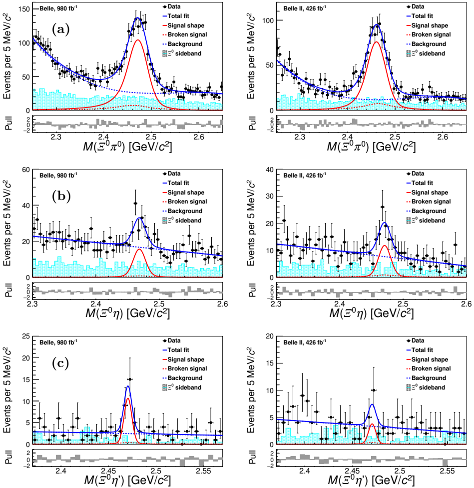
$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 h)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = \frac{N_{\Xi^0 h}}{N_{\Xi^-\pi^+}} \cdot \frac{\epsilon_{\Xi^-\pi^+}}{\epsilon_{\Xi^0 h}} \cdot \frac{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}{\mathcal{B}(\Xi^0 \to \Lambda\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)\mathcal{B}(h)}$$

Mode	Belle yield	$\varepsilon_{\text{Belle}}$ (%)	Belle II yield	$\varepsilon_{\text{Belle II}}$ (%)
$\Xi_c^0 \to \Xi^-\pi^+$	$(363 \pm 3) \times 10^2$	13.92 ± 0.05	$(137 \pm 2) \times 10^2$	13.38 ± 0.03
$\Xi_c^0 \to \Xi^0\pi^0$	1315 ± 66	1.09 ± 0.01	869 ± 46	1.71 ± 0.01
$\Xi_c^0 \to \Xi^0\eta$	81 ± 15	0.80 ± 0.01	60 ± 11	1.12 ± 0.01
$\Xi_c^0 \to \Xi^0\eta'$	23 ± 6	0.46 ± 0.01	8 ± 4	0.81 ± 0.01



Mode	Belle	Belle II	Combined
$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.47 \pm 0.02 \pm 0.03$	$0.51 \pm 0.03 \pm 0.05$	$0.48 \pm 0.02 \pm 0.03$
$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.10 \pm 0.02 \pm 0.01$	$0.14 \pm 0.02 \pm 0.02$	$0.11 \pm 0.01 \pm 0.01$
$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.12 \pm 0.03 \pm 0.01$	$0.06 \pm 0.03 \pm 0.01$	$0.08 \pm 0.02 \pm 0.01$

PDG: $m(\Xi_c^0) = 2470.44 \pm 0.28\ \mathrm{MeV}/c^2$

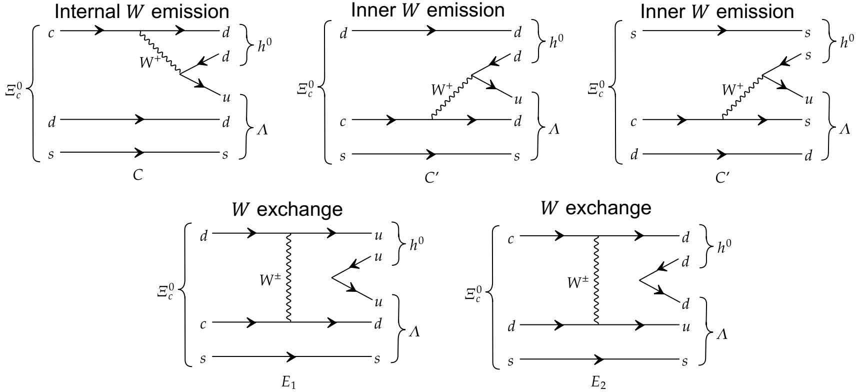


Fits: Belle (left) and Belle II (right).

$\Xi_c^0 \to \Lambda h (h = \pi^0, \eta, \eta')$ at Belle and Belle II

arXiv:2510.20882, submitted to *PRD*

- Diagrams:



- Theorists have provided a lot of predictions of the $B_c \to BM$ decays, where B_c denotes the anti-triplet charm baryon and $B(M)$ the octet baryon(meson).
- All SCS(singly Cabibbo-suppressed) decays, first two observations(η and η').

$\Xi_c^0 \to \Lambda h (h = \pi^0, \eta, \eta')$ at Belle and Belle II

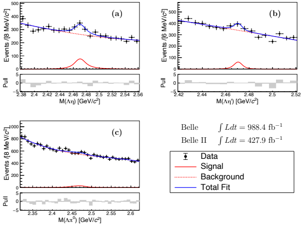
arXiv:2510.20882, submitted to *PRD*

- Branching ratio measurements
  - Reference mode: $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$.
- Stack Belle and Belle II data.
- Absolute branching ratio:

$$\mathcal{B}(\Xi_c^0 \to \Lambda\eta) = (5.95 \pm 1.30 \pm 0.32 \pm 1.13) \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^0 \to \Lambda\eta') = (3.55 \pm 1.17 \pm 0.17 \pm 0.68) \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^0 \to \Lambda\pi^0) < 5.2 \times 10^{-4} (90\% \text{ C.L. limit})$$

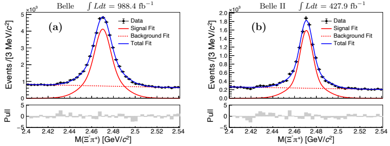
uncertainties: stat., syst., and from $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$.

PDG: $m(\Xi_c^0) = 2470.44 \pm 0.28 \mathrm{MeV}/c^2$

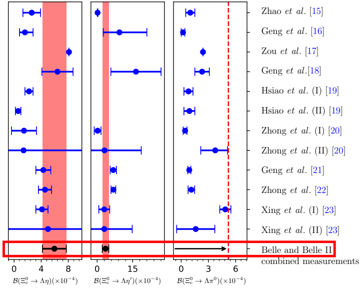


Decays	N_{fit}
$\Xi_c^0 \to \Xi^- \pi^+$ (Belle)	30230 ± 281
$\Xi_c^0 \to \Xi^- \pi^+$ (Belle II)	11579 ± 161
$\Xi_c^0 \to \Lambda\eta, \eta \to \gamma\gamma$ $\Xi_c^0 \to \Lambda\eta, \eta \to \pi^+\pi^-\pi^0$	262 ± 57
$\Xi_c^0 \to \Lambda\eta', \eta' \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$ $\Xi_c^0 \to \Lambda\eta', \eta' \to \eta\pi^+\pi^-, \eta \to \pi^+\pi^-\pi^0$ $\Xi_c^0 \to \Lambda\eta', \eta' \to \pi^+\pi^-\gamma$	101 ± 33
$\Xi_c^0 \to \Lambda\pi^0$	190 ± 120

PDG: $m(\Xi_c^0) = 2470.44 \pm 0.28 \mathrm{MeV}/c^2$



Theoretical predictions

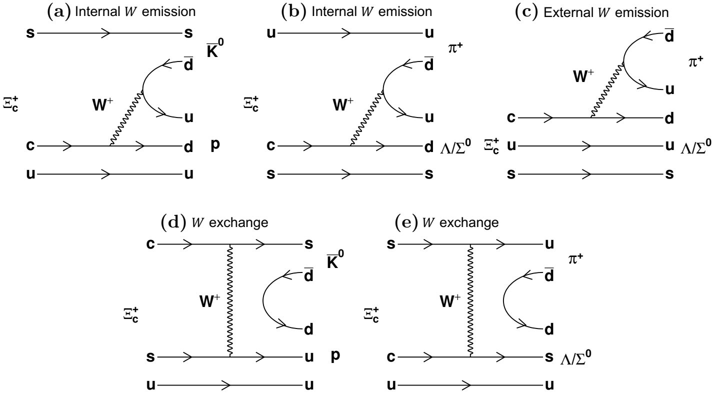


- Theoretical predictions: various approaches with $SU(3)_F$ symmetry.

$\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$ at Belle and Belle II

JHEP 03 (2025) 061

- Diagrams:



- First observation of SCS decays $\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$, each with significance $> 10\sigma$, using the combined Belle and Belle II samples.

$\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+$ at Belle and Belle II

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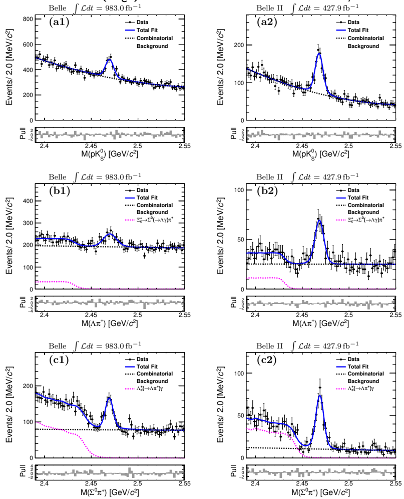
- Use the well-measured normalization mode $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ as the reference.
- Branching-fraction ratios are determined as

$$\frac{\mathcal{B}(\Xi_c^+\to\text{sig})}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)} = \frac{N_{\text{sig}}}{N_{\Xi^-\pi^+\pi^+}} \cdot \frac{\epsilon_{\Xi^-\pi^+\pi^+}}{\epsilon_{\text{sig}}} \cdot \frac{\mathcal{B}_{\text{ref,int}}}{\mathcal{B}_{\text{sig,int}}}\,.$$

- Absolute branching fraction:
  - uncertainties: statistical, systematic, and external (from $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$).

Mode	$\mathcal{B}$ $[10^{-4}]$
$\mathcal{B}(\Xi_c^+ \to pK_S^0)$	$(7.16 \pm 0.46 \pm 0.20 \pm 3.21)$
$\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+)$	$(4.52 \pm 0.41 \pm 0.26 \pm 2.03)$
$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+)$	$(1.20 \pm 0.08 \pm 0.07 \pm 0.54)$

PDG: $m(\Xi_c^+) = 2467.71 \pm 0.23\ \text{MeV}/c^2$



Fits: Belle (left) and Belle II (right).

$\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, $\Sigma^0\pi^+$ at Belle and Belle II

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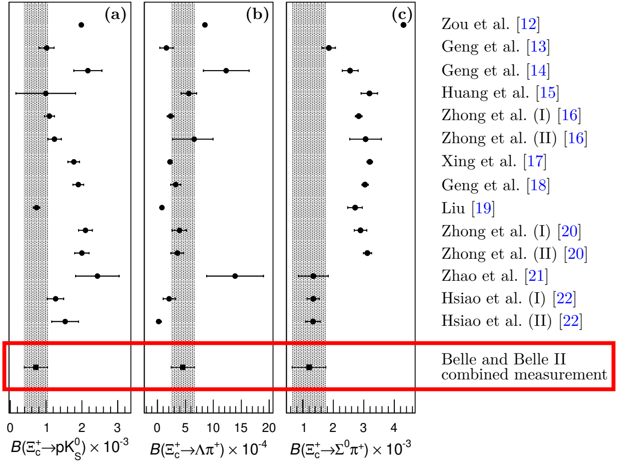
- Theoretical branching fraction predictions.



Various approaches with $SU(3)_F$ symmetry.

Several theory predictions are in tension with these values.

[12] J. Zou, F. Xu, G. Meng and H.-Y. Cheng, *Two-body hadronic weak decays of antitriplet charmed baryons*, *Phys. Rev. D* **101** (2020) 014011 [arXiv:1910.13626] [INSPIRE].

[13] C.Q. Geng, Y.K. Hsiao, C.-W. Liu and T.-H. Tsai, *Antitriplet charmed baryon decays with SU(3) flavor symmetry*, *Phys. Rev. D* **97** (2018) 073006 [arXiv:1801.03276] [INSPIRE].

[14] C.Q. Geng, C.-W. Liu and T.-H. Tsai, *Asymmetries of anti-triplet charmed baryon decays*, *Phys. Lett. B* **794** (2019) 19 [arXiv:1902.06189] [INSPIRE].

[15] F. Huang, Z.-P. Xing and X.-G. He, *A global analysis of charmless two body hadronic decays for anti-triplet charmed baryons*, *JHEP* **03** (2022) 143 [*Erratum ibid.* **09** (2022) 087] [arXiv:2112.10556] [INSPIRE].

[16] 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 [arXiv:2210.12728] [INSPIRE].

[17] Z.-P. Xing, X.-G. He, F. Huang and C. Yang, *Global analysis of measured and unmeasured hadronic two-body weak decays of antitriplet charmed baryons*, *Phys. Rev. D* **108** (2023) 053004 [arXiv:2305.14854] [INSPIRE].

[18] C.-Q. Geng et al., *Complete determination of $SU(3)_F$ amplitudes and strong phase in $\Lambda_c^+ \to \Xi^0 K^+$*, *Phys. Rev. D* **109** (2024) L071302 [arXiv:2310.05491] [INSPIRE].

[19] C.-W. Liu, *Nonleptonic two-body weak decays of charmed baryons*, *Phys. Rev. D* **109** (2024) 033004 [arXiv:2308.07754] [INSPIRE].

[20] H. Zhong, F. Xu and H.-Y. Cheng, *Analysis of hadronic weak decays of charmed baryons in the topological diagrammatic approach*, *Phys. Rev. D* **109** (2024) 114027 [arXiv:2404.01350] [INSPIRE].

[21] 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 [arXiv:1811.07265] [INSPIRE].

[22] 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) 035 [arXiv:2111.04124] [INSPIRE].

$\Xi_c^+ \to \Sigma^+ K_S^0, \Xi^0\pi^+, \Xi^0 K^+$ at Belle and Belle II

JHEP 08 (2025) 195

- Precise $\mathcal{B}$ measurement for $\Xi_c^+ \to \Sigma^+ K_S^0$ and $\Xi_c^+ \to \Xi^0\pi^+$ (both CF), and first observation of $\Xi_c^+ \to \Xi^0 K^+$ (SCS).
- Branching fractions are obtained from ratios normalized to the reference mode $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$:

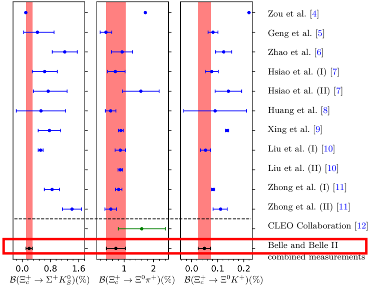
$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.194 \pm 0.021 \pm 0.009 \pm 0.087)\%$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0\pi^+) = (0.728 \pm 0.014 \pm 0.027 \pm 0.326)\%$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+) = (0.049 \pm 0.007 \pm 0.003 \pm 0.022)\%$$

Uncertainties are statistical, systematic, and reference mode.

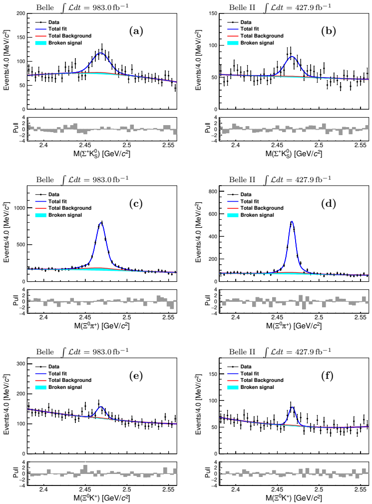
Mode	Belle (yield)	Belle II (yield)
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	$(487 \pm 4) \times 10^2$	$(196 \pm 2) \times 10^2$
$\Xi_c^+ \to \Sigma^+ K_S^0$	288 ± 41	(182 ± 31)
$\Xi_c^+ \to \Xi^0\pi^+$	(2782 ± 74)	(1469 ± 40)
$\Xi_c^+ \to \Xi^0 K^+$	(138 ± 31)	(100 ± 20)

- Results are broadly consistent with several model predictions; none are excluded.

Theoretical predictions



PDG: $m(\Xi_c^+) = 2467.71 \pm 0.23$ MeV$/c^2$

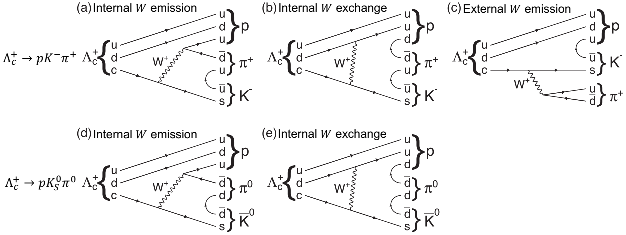


Fits: Belle (left) and Belle II (right).

$\Lambda_c^+ \to pK_S^0\pi^0$ at Belle

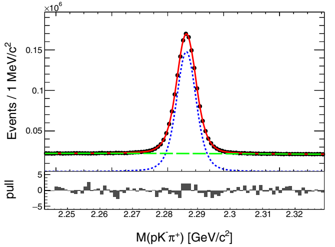
PRD 112 (2025) 012013

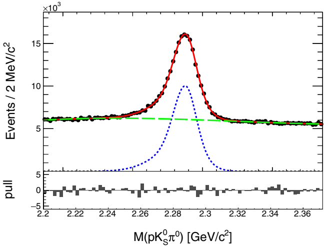
- Diagarms:



Dataset: Belle 980fb^{-1}

PDG: $m(\Lambda_c^+) = 2286.46 \pm 0.14\mathrm{MeV}/c^2$





- Examining Isospin properties of the weak interaction.
  - Improves uncertainty of previous CLEO result.
    - $\dfrac{\mathcal{B}(\Lambda_c^+ \to pK_S^0\ \pi^0)}{\mathcal{B}(\Lambda_c^+ \to pK^-\ \pi^+)} = 0.339 \pm 0.002 \pm 0.009$
- With PDG value of $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.24 \pm 0.28)\%$, $\mathcal{B}(\Lambda_c^+ \to pK_S^0\ \pi^0) = (2.12 \pm 0.01 \pm 0.05 \pm 0.10)\%$ unceratinties: stat., syst., and from $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

Outline

CP Violation in Charm Meson and Baryon

Charm

- Since charm transitions probe the up-type sector, they allow us to search for CP-violating interactions that do not appear in kaon or B-meson decays.
- $A_{CP}(X_c \to f) \equiv \frac{\Gamma(X_c \to f) - \Gamma(\bar{X}_c \to \bar{f})}{\Gamma(X_c \to f) + \Gamma(\bar{X}_c \to \bar{f})}$
- Raw asymmetry including production and detection asymmetries is extracted from a fit to invariant mass.
$A_N \equiv \frac{N(X_c \to f) - N(\bar{X}_c \to \bar{f})}{N(X_c \to f) + N(\bar{X}_c \to \bar{f})} = A_{CP}(X_c \to f) + A_{prod}(X_c) + A_{det}(f)$.

Meson

- The first and only observation of CPV by LHCb [PRL122(2019)211803, PRL131(2023)091802]
$\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ [5.3σ]
Followed by a 3.8σ evidence of direct CPV in $D^0 \to \pi^+\pi^-$.

Baryon

- CPV searches in baryons complement meson studies.
- Observation of CPV in b-baryon decays by LHCb [Nature643(2025)1223]
$A_{CP}(\Lambda_b \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$
- U-spin sum rules, analogous to those linking $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ [PRD99(2019)033005]:
$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0$

CP violation in $D \to \pi\pi$

- $D^0 \to \pi^+\pi^-$
  - This is the only decay channel in charm mesons with more than 3σ evidence for CP violation.
  - In the Standard Model, CP violation arises from the interference between a tree-level amplitude and a suppressed QCD loop amplitude, involving a $\Delta I = 1/2$ change in isospin [PRD 85 (2012) 114036].
- $D^+ \to \pi^+\pi^0$
  - This decay has $I = 2$ and can only occur from an $I = 1/2$ initial state through a $\Delta I = 3/2$ transition.
  - Any observation of this decay would indicate physics beyond the Standard Model.
- $D^0 \to \pi^0\pi^0$
  - Can have $I = 0$ or $I = 2$ and hence can have nonzero direct CP asymmetries in SM.
  - Isospin sum rule:

$$R = \frac{A_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\mathrm{dir}}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\mathrm{dir}}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)},$$

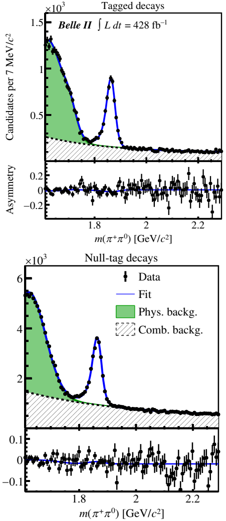
  where τ_{D^0} and τ_{D^+} are the lifetimes of D^0 and D^+ mesons, and $\mathcal{B}_{+-}$, $\mathcal{B}_{00}$ and $\mathcal{B}_{+0}$ are the D meson branching fractions to $\pi^+\pi^-$, $\pi^0\pi^0$ and $\pi^+\pi^0$ decays.

$D^+ \to \pi^+\pi^0$ at Belle II

PRD 112 (2025) L031101

- The raw asymmetry is extracted from a fit to the D^+ invariant-mass distribution:
$$A^{\pi^+\pi^0} = \frac{N(D^+\to\pi^+\pi^0)-N(D^-\to\pi^-\pi^0)}{N(D^+\to\pi^+\pi^0)+N(D^-\to\pi^-\pi^0)} = A_{CP}(D^+\to\pi^+\pi^0)+A_P^D+A_\varepsilon^{\pi^+}.$$
- Events are categorized into D^*-tagged ($D^{*+}\to D^+\pi^0$) and untagged samples to improve measurement precision.
- Asymmetries from production and detection are corrected using the control channel $D^+\to K_S\pi^+$.
- $A_{CP} = (-1.8 \pm 0.9 \pm 0.1)\%$ — consistent with no CP violation.
- The statistical precision is roughly 30% better than the previous Belle measurement, thanks to the higher signal purity at Belle II.
- The precision slightly surpasses that of the corresponding LHCb measurement ($9\,\mathrm{fb}^{-1}$ dataset).

PDG: $m(D^+) = 1869.5 \pm 0.4\,\mathrm{MeV}/c^2$

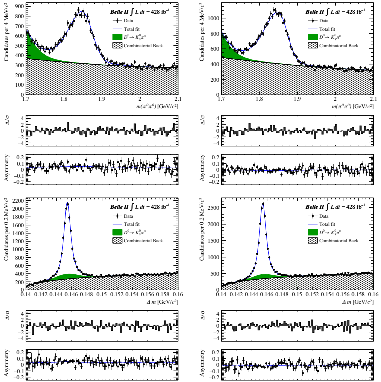


$D^0 \to \pi^0\pi^0$ at Belle II

PRD 112 (2025) 012006

- Use $D^{*+} \to D^0\pi^+$ to determine the D^0 flavor.
  - And a dedicated BDT to suppress the large 4γ background.
- The raw asymmetry is determined from a fit to the D^+ invariant-mass distribution: $A^{\pi^+\pi^0} = \frac{N[D^{*+}\to(D^0\to\pi^0\pi^0)\pi^+]-N[D^{*-}\to(\bar{D}^0\to\pi^0\pi^0)\pi^-]}{N[D^{*+}\to(D^0\to\pi^0\pi^0)\pi^+]+N[D^{*-}\to(\bar{D}^0\to\pi^0\pi^0)\pi^-]} = A_{CP}(D^0 \to \pi^0\pi^0) + A_P^{D^*} + A_\varepsilon^{\pi^+}$
- Raw asymmetry extracted from a fit to the D^0 mass and ΔM, the $D^{*+} - D^0$ mass difference.
- Production asymmetry (odd in $cos\theta_{CM}$) removed by averaging A_{raw} of forward ($cos\theta_{CM} > 0$) and backward ($cos\theta_{CM} < 0$) decays
- Detection asymmetries are corrected using the $D^0 \to K^-\pi^+$ control mode.
- $A_{CP} = (0.30 \pm 0.72 \pm 0.20)\%$ — which is only 15% less precise than BELLE but with half of the statistics. [PRL112(2014)211601]
- Isospin sum rule $R = (3.1 \pm 2.3) \times 10^{-3}$, precision improved by 25%, including the new result of $A_{CP}(D^+ \to \pi^+\pi^0)$.

PDG: $m(D^0) = 1864.84 \pm 0.05\,\text{MeV}/c^2$



Left: $cos\theta_{CM} < 0$, right: $cos\theta_{CM} > 0$.

$D^0 \to \pi^+\pi^-\pi^0$ at Belle II

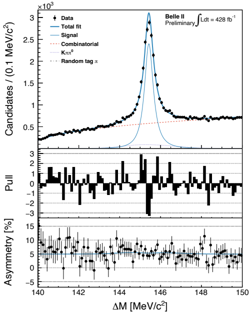
arXiv:2510.21224, to be submitted to *PRD*

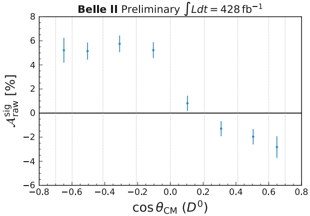
- SCS three-body decay, interference of several amplitudes.
- Use $D^{*+} \to D^0\pi^+$ to determine the D^0 flavor.
- The raw asymmetry is determined from a fit to the D^+ invariant-mass distribution:

$$A^{\pi^+\pi^-\pi^0} = \frac{N[D^{*+}\to(D^0\to\pi^+\pi^-\pi^0)\pi^+]-N[D^{*-}\to(\bar{D}^0\to\pi^+\pi^-\pi^0)\pi^-]}{N[D^{*+}\to(D^0\to\pi^+\pi^-\pi^0)\pi^+]+N[D^{*-}\to(\bar{D}^0\to\pi^+\pi^-\pi^0)\pi^-]} =$$
$$A_{CP}(D^0 \to \pi^+\pi^-\pi^0) + A_P^{D^*} + A_\varepsilon^{\pi^+}$$

- Raw asymmetry extracted from a fit to the D^0 mass and ΔM, the $D^{*+} - D^0$ mass difference.
- A simultaneous fit is performed in 8 bins of $\cos\theta_{CM}$, and $A_{\rm raw}$ is symmetrically averaged around 0 to cancel the production asymmetry.
- Detection asymmetries are corrected using the control channel $D^0 \to K^-\pi^+$.
- $A_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$
  - Achieves 34% better precision than BABAR with only 10% more integrated luminosity.
  - Currently the most precise measurement of this quantity.

$\cos\theta_{CM} \in [-0.208, 0)$



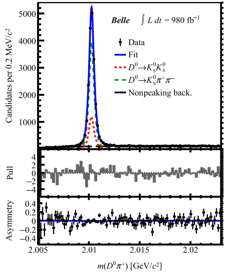


$D^0 \to K_S^0 K_S^0$ at Belle II

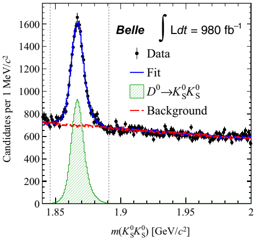
PRD 111 (2025) 012015, *PRD* 111 (2025) 012017

- CP violation can be enhanced up to $\mathcal{O}(1\%)$ due to large interference from the W-exchange tree-level process.
- D^{*+}-tagged Belle + Belle II analysis:
  $A_{CP} = (-1.4 \pm 1.3 \pm 0.1)\%$
- Opposite-side tagged Belle + Belle II analysis:
  $A_{CP} = (1.3 \pm 2.0 \pm 0.2)\%$
  - Uses a novel MVA-based flavour-tagging technique exploiting the rest-of-event information, with the output included in the fit together with the D^0 mass.
- Combined analysis (D^{*+}-tagged + Opposite-side tagged):
  $A_{CP} = (-0.6 \pm 1.1 \pm 0.1)\%$
  - The opposite-side tagged sample effectively adds ~40% more statistics to the traditional D^{*+}-tagged measurement.
  - Achieves precision (statistical + systematic) comparable to the latest LHCb Run 3 result (6/fb).

PDG: $m(D^{*+}) = 2010.226 \pm 0.05\,\mathrm{MeV}/c^2$



PDG: $m(D^0) = 1864.84 \pm 0.05\,\mathrm{MeV}/c^2$



$\Xi_c^+ \to \Sigma^+ h^+ h^-, \Lambda_c^+ \to p h^+ h^- (h = \pi, K)$ at Belle II arXiv:2509.25765, submitted to *PRD*

- The production asymmetry($A_{prod}(X_c)$, odd in $\cos\theta_{CM}$) is eliminated by averaging raw asymmetry of forward and backward decays:

$$A_N' = \frac{A_N(\cos\theta_{CM}>0) + A_N(\cos\theta_{CM}<0)}{2}$$

$$A_{CP}(\Xi_c \to \Sigma hh) = A_N'(\Xi_c \to \Sigma hh) - A_N'(\Lambda_c \to \Sigma hh)$$

$$A_{CP}(\Lambda_c \to phh) = A_N'(\Lambda_c \to phh) - A_N'(\Lambda_c \to p\pi^+ K^-) - A_N'(D^0 \to \pi^+ K^- \pi^+ \pi^-)$$

- First measurement of A_{CP} in SCS three-body charm baryon decays.

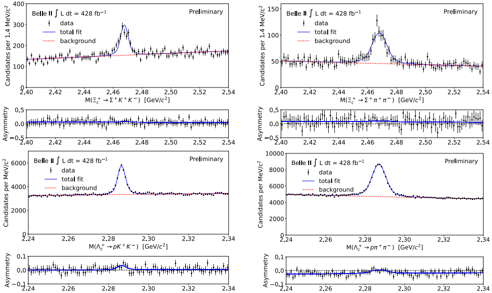
$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^- K^+) = (3.7 \pm 6.6 \pm 0.6)\%$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^- \pi^+) = (9.5 \pm 6.8 \pm 0.5)\%$$
$$A_{CP}(\Lambda_c^+ \to p K^- K^+) = (3.9 \pm 1.7 \pm 0.7)\%$$
$$A_{CP}(\Lambda_c^+ \to p \pi^- \pi^+) = (0.3 \pm 1.0 \pm 0.2)\%$$

- Within statistical uncertainties, consistent with CP symmetries.
- U-spin symmetry test with $\sim 7\%$ precision.

$$A_{CP}(\Lambda_c \to pKK) + A_{CP}(\Xi_c \to \Sigma\pi\pi) = (13.4 \pm 7.0 \pm 0.9)\%$$
$$A_{CP}(\Lambda_c \to p\pi\pi) + A_{CP}(\Xi_c \to \Sigma KK) = (4.0 \pm 6.6 \pm 0.7)\%$$

PDG: $m(\Xi_c^+) = 2467.71 \pm 0.23 \mathrm{MeV}/c^2$,

PDG: $m(\Lambda_c^+) = 2286.46 \pm 0.14 \mathrm{MeV}/c^2$



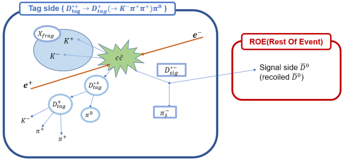
Outline

1. Charm Physics at Belle/Belle II
2. Branching fractions and searches for rare decays
   - $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$
   - $\Xi_c^0 \to \Xi^0 h (h = \pi^0, \eta, \eta')$
   - $\Xi_c^0 \to \Lambda h (h = \pi^0, \eta, \eta')$
   - $\Xi_c^+ \to p K_S^0, \Lambda\pi^+, \Sigma^0\pi^+$
   - $\Xi_c^+ \to \Sigma^+ K_S^0, \Xi^0\pi^+, \Xi^0 K^+$
   - $\Lambda_c^+ \to p K_S^0 \pi^0$
3. Charm CP violation search
   - $D \to \pi\pi$
   - $D^0 \to \pi^+\pi^-\pi^0$
   - $D^0 \to K_S^0 K_S^0$
   - $\Xi_c^+ \to \Sigma^+ h^+ h^-, \Lambda_c^+ \to p h^+ h^- (h = \pi, K)$
4. Korean group in Belle II charm physics
5. Summary

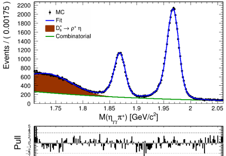
Korean group in Belle II charm physics

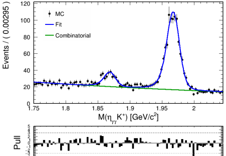
Recent studies

- Yonsei university(Prof. Youngjoon Kwon)
  - Search for $D^0 \to$ invisible: soon to be WG review
    $e^+e^- \to c\bar{c} \to D^{(*)}_{\text{tag}} X_{\text{frag}} D^{*+},\ D^{*+} \to D^0\pi^+$.



  - A_{CP} and branching fraction of $D^+_{(s)} \to \eta h^+ (h = \pi, K)$: soon to be WG review



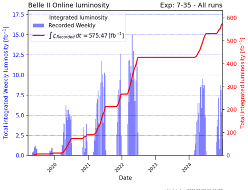


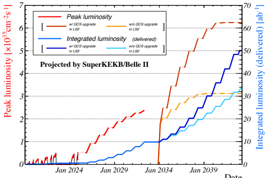
- Korea university(Prof. Jung-Keun Ahn)
  - $\Lambda_c^+ \to pK^0_S\pi^0$: published, slide 15
- Korea university(Prof. Eunil Won)
  - A_{CP} and $\mathcal{B}$ measurements in $D^+_{(s)} \to h^+\omega(h = \pi, K)$: ongoing
- Soongsil university(Prof. Doris Yangsoo Kim)
  - $\mathcal{B}$ measurements in $D^0 \to K^0_S K^0_S \pi^0, D^0 \to K^0_S K^0_S \eta$: ongoing

Outline

Summary

- Belle($\sim 1\mathrm{ab}^{-1}$) and Belle II($\sim 0.5\mathrm{ab}^{-1}$) provide a e^+e^- environment with high sensitivity to SM tests and BSM searches in charm meson and baryon decays.
  - Meson:
    - First observation of $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$.
    - Search for CPV in D mesons:
      $D^+ \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$, $D^0 \to \pi^+\pi^-\pi^0$, $D^0 \to K_S^0 K_S^0$
  - Baryon:
    - First observations of Ξ_c decays:
      $\Xi_c^+ \to pK_S^0,\ \Lambda\pi^+,\ \Sigma^0\pi^+,\ \Xi K^+$
      $\Xi_c^0 \to \Xi^0\pi^0,\ \Xi^0\eta,\ \Xi^0\eta',\ \Lambda\eta,\ \Lambda\eta'$
    - Improved measurements of branching fractions for Ξ_c and Λ_c.
    - First measurement of A_{CP} in singly Cabibbo-suppressed three-body charm-baryon decays:
      $\Xi_c^+ \to \Sigma^+ h^+ h^-$, $\Lambda_c^+ \to p\, h^+ h^-$ $(h = \pi, K)$
- Data taking restarts two days ago; more statistics are coming.





Thank you for your attention!

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Belle II

YONSEI UNIVERSITY 1885 연세대학교

$D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$

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Table I: The summary of the systematic uncertainties of the measurement of the branching fraction ratio $\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)/\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)$ (in %).

Source	$D_s^+\pi^0$	$D_s^{*+}\gamma$
Fit region and background pdf	0.8	1.3
Fixed pdf parameters	0.7	2.5
Cross-feed or broken signal	0.6	0.7
x_p reweighting	0.5	
MC sample size	0.5	
Sum	3.2	

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

Sources	$\frac{\mathcal{B}(\Xi_c^+\to pK_S^0)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$ Belle	Belle II	$\frac{\mathcal{B}(\Xi_c^+\to\Lambda\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$ Belle	Belle II	$\frac{\mathcal{B}(\Xi_c^+\to\Sigma^0\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$ Belle	Belle II
Tracking	0.7	0.7	0.7	0.7	0.7	0.7
Particle identification	0.1	0.2	0.1	0.1	0.1	0.1
K_S^0 reconstruction	0.8	2.6	...	...	...	...
Λ reconstruction	0.5	0.3	0.3	0.2	0.3	0.2
Photon reconstruction	...	...	...	...	2.0	1.1
Mass resolution	0.2	0.2	0.4	0.5	0.7	0.8
Dalitz efficiency correction	1.3	1.5	1.3	1.5	1.3	1.5
Branching fraction	0.8	0.8	0.0	0.0	0.0	0.0
Fit Uncertainty	2.5	2.5	5.9	5.9	5.1	5.1
Sum in quadrature	3.2	4.1	6.1	6.2	5.7	5.5

Table 3. Relative systematic uncertainties (%) in the measurements of branching fraction ratios. The uncertainties due to intermediate branching fractions and fit uncertainty are common to Belle and Belle II; the other uncertainties are independent.

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

Source	$\frac{\mathcal{B}(\Xi_c^+\to\Sigma^+K_S^0)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^+\to\Xi^0\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^+\to\Xi^0K^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$	
	Belle	Belle II	Belle	Belle II	Belle	Belle II
Tracking	0.7	0.7	1.4	1.4	1.4	1.4
PID	0.1	0.2	0.1	0.1	0.1	0.2
π^0 reconstruction	2.2	4.2	2.4	4.3	2.3	4.3
K_S^0 reconstruction	0.8	2.3	—	—	—	—
Λ reconstruction	0.5	0.7	—	—	—	—
Mass resolution	1.4	1.6	0.4	0.6	1.1	1.4
MC sample size	1.0	1.0	1.0	1.0	1.0	1.0
Dalitz efficiency-correction	1.5	1.7	1.5	1.7	1.5	1.7
Fit uncertainty	3.7	4.8	0.9	1.0	5.3	4.3
Background shape	1.5	1.5	2.4	2.4	2.2	2.2
Intermediate states $\mathcal{B}$	1.0	1.0	0.1	0.1	0.1	0.1
Total	5.4	7.6	4.3	5.7	6.7	7.1

Table 3. Relative systematic uncertainties (%) on the results of branching fraction ratios. The uncertainties in the last two rows, due to intermediate branching fractions and background shape, are common to Belle and Belle II; the other uncertainties are independent. Since the $\Lambda \to p\pi^-$ decay is reconstructed in $\Xi_c^+ \to \Xi^0\pi^+$ and $\Xi_c^+ \to \Xi^0 K^+$, the $\mathcal{B}(\Lambda \to p\pi^-)$ uncertainty and the uncertainty due to the $\Lambda \to p\pi^-$ reconstruction efficiency cancel in the ratios of $\frac{\mathcal{B}(\Xi_c^+\to\Xi^0\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$ and $\frac{\mathcal{B}(\Xi_c^+\to\Xi^0K^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$.

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

Source	$\frac{\mathcal{B}(\Xi_c^0\to\Xi^0\pi^0)}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^0\to\Xi^0\eta)}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^0\to\Xi^0\eta')}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$	
	Belle	Belle II	Belle	Belle II	Belle	Belle II
Tracking	0.7	0.8	0.7	0.7	1.0	1.5
$\pi^\pm$ PID	0.4	0.2	0.4	0.2	1.4	0.2
π^0 reconstruction	4.4	8.8	2.3	4.3	2.3	4.2
Photon reconstruction	-	-	4.0	2.0	4.0	1.9
Simulation sample size	0.8	0.7	0.9	0.9	1.2	1.0
α uncertainty	1.1	1.2	3.0	3.4	1.0	3.5
Ξ^0 signal mass window	0.5	2.0	0.5	2.0	0.5	2.0
Normalization mode sample size	1.0	1.3	1.0	1.3	1.0	1.3
Broken-signal ratio ($n_{\text{broken}}/n_{\text{sig}}$)	2.1	1.5	3.5	3.6	3.6	5.7
Broken-signal PDF	0.2	0.1	7.3	7.5	2.0	1.1
Mass resolution	-	-	7.2	7.0	2.4	1.4
Intermediate states $\mathcal{B}$	-	-	0.5	0.5	1.3	1.3
Background shape	4.9	4.9	9.2	9.2	6.8	6.8
Total	7.2	10.6	15.3	15.6	9.9	11.2

Table 5. Fractional systematic uncertainties (%) on the relative branching-fraction results. The uncertainties in the last two rows, due to intermediate branching fractions and background shape, are common to Belle and Belle II; the other uncertainties are independent. Since the $\Lambda \to p\pi^-$ decay is reconstructed in each decay mode, the $\mathcal{B}(\Lambda \to p\pi^-)$ uncertainty and the uncertainty due to the $\Lambda \to p\pi^-$ reconstruction efficiency cancel in the ratio to the reference mode $\Xi_c^0 \to \Xi^-\pi^+$.

$\Xi_c^0 \to \Lambda h (h = \pi^0, \eta, \eta')$

Table II. Fractional systematic uncertainties (%) on the branching ratios from different sources. Systematic uncertainties associated with the fitting procedures are treated as multiplicative for $\Xi_c^0 \to \Lambda\eta/\Lambda\eta'$ and as additive for the unobserved mode $\Xi_c^0 \to \Lambda\pi^0$. The total uncertainties are calculated by first summing the uncertainties from different sources in quadrature for Belle and Belle II separately, and then deriving the results from the luminosity-weighted average of these sums.

Source	$\frac{\mathcal{B}(\Xi_c^0\to\Lambda\eta)}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^0\to\Lambda\eta')}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$		$\frac{\mathcal{B}(\Xi_c^0\to\Lambda\pi^0)}{\mathcal{B}(\Xi_c^0\to\Xi^-\pi^+)}$	
	Belle	Belle II	Belle	Belle II	Belle	Belle II
Tracking efficiency	0.77%	1.07%	1.51%	2.13%	0.64%	0.80%
π^+ PID	1.49%	0.21%	2.24%	0.24%	1.39%	0.20%
π^0 reconstruction	0.24%	1.67%	0.18%	0.65%	1.45%	4.13%
Photon reconstruction	3.35%	0.84%	2.54%	0.98%	—	—
π^0 veto	2.23%	1.02%	0.71%	0.34%	—	—
Λ momentum	0.56%	0.34%	0.55%	0.68%	0.20%	0.82%
MC sample size	1.08%	0.82%	1.15%	1.08%	0.67%	0.45%
Intermediate states $\mathcal{B}$	0.47%	0.47%	0.85%	0.85%	0.06%	0.06%
Fit procedure	5.54%	5.54%	4.83%	4.84%	0.17%	0.33%
Total	5.35%		4.77%		2.04%	
Normalization mode $\mathcal{B}$			18.89%			

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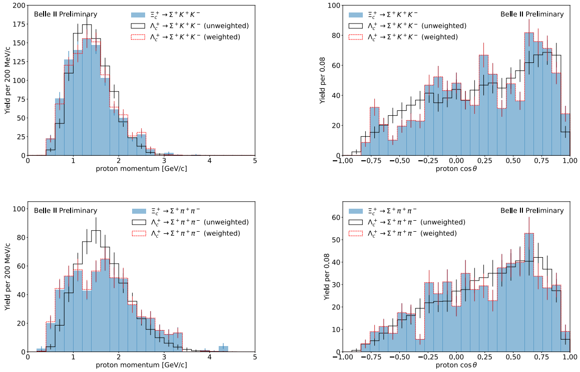
$\Lambda_c^+ \to pK_S^0\pi^0$

TABLE I. Sources of systematic uncertainties for the relative branching fraction, $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

Sources	Value (%)
K_S^0 reconstruction	1.57
π^0 reconstruction	1.54
Fit function	0.60
MC statistics	0.58
Dalitz plot binning	0.68
PID of K^- and π^+	0.34
Tracking of K^- and π^+	0.70
Total	2.57

$\Xi_c^+ \to \Sigma^+ h^+ h^-, \Lambda_c^+ \to p h^+ h^- (h = \pi, K)$



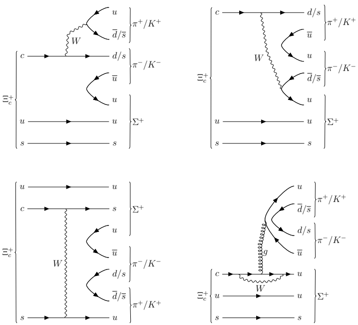


Table II: Uncertainties on A_{CP} (in %).

Source	Ξ_c^+		Λ_c^+	
	$\Sigma^+ K^+ K^-$	$\Sigma^+ \pi^+ \pi^-$	$p K^+ K^-$	$p \pi^+ \pi^-$
Fit model	0.4	0.4	0.4	0.1
Weighting	0.1	0.2	0.3	0.1
Residual A_{p}	0.2	0.1	0.1	0.1
$A_{\mathrm{d}}(h^+h^-)$	0.4	0.2	0.4	0.1
Total systematic	0.6	0.5	0.7	0.2
Statistical	6.6	6.8	1.7	1.0