22nd Conference on Flavor Physics and CP Violation

Charm results at Belle and Belle II

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On behalf of the Belle II Collaboration

Chulalongkorn University, Bangkok, Thailand, May 27, 2024

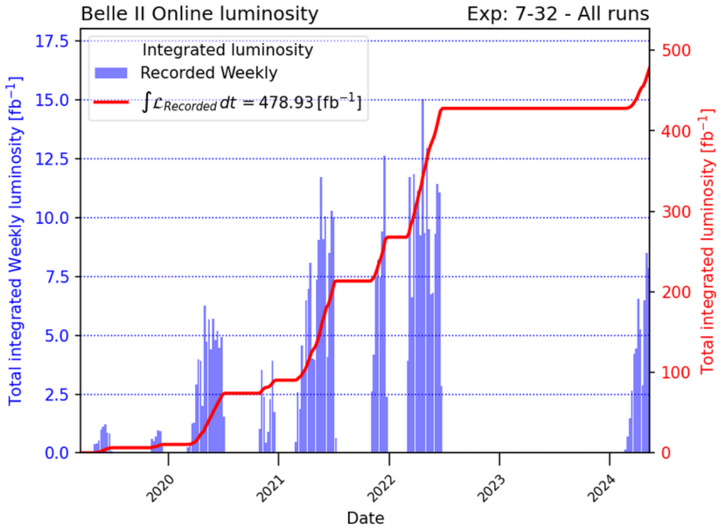
Outline

- Quick introduction to Belle (II)
- Belle results: Search for rare decays
  - ✓ $D^0 \to hh'e^+e^-$ preliminary, intended to PRL
  - ✓ $D \to p\ell$ PRD 109, L031101 (2024)
  - ✓ $\Xi_c^0 \to \Xi^0\ell^+\ell^-$ PRD 109, 052003 (2024)
- Belle and Belle II analysis: Charmed Baryon
  - ✓ $\Xi_c^0 \to \Xi^0 h^0$ preliminary, intended to JHEP
- Summary

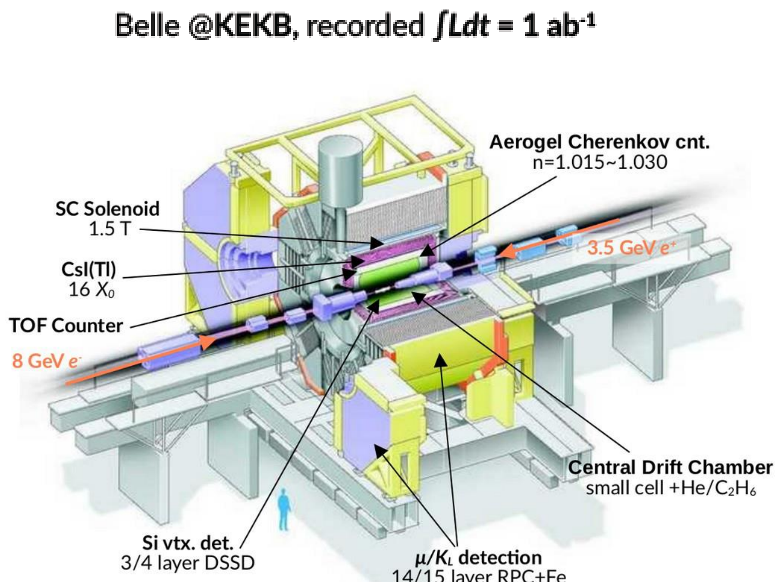
Experiments

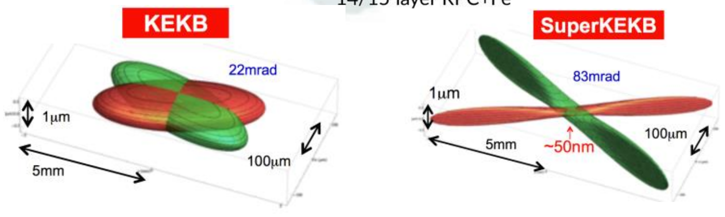
- ✓ Belle and Belle II operate at asymmetric $e^{+}e^{-}$ colliders
  - Collisions at or near $\Upsilon(4S)$, B-factories
  - KEKB (1999-2010), peak $\mathcal{L} = 2 \times 10^{34} cm^{-2} s^{-1}$
  - SuperKEKB, peak $\mathcal{L} = 4.7 \times 10^{34} cm^{-2} s^{-1}$

    just started Run2 (Feb. 2024)
  - Upgrade on collider and detector

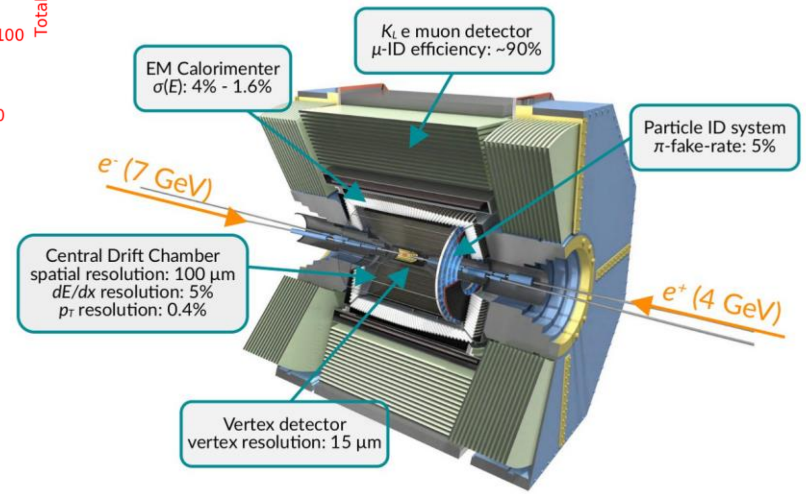


- ✓ Combined analyses at Belle & Belle II
  - $\sim 1.4\ ab^{-1}$ in total
  - Analyze Belle data with Belle II framework
  - For charm analyses, large statistics to improve precision



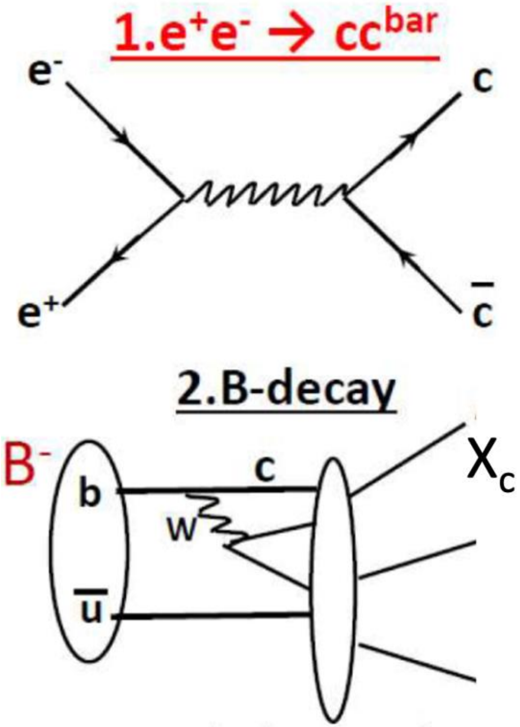


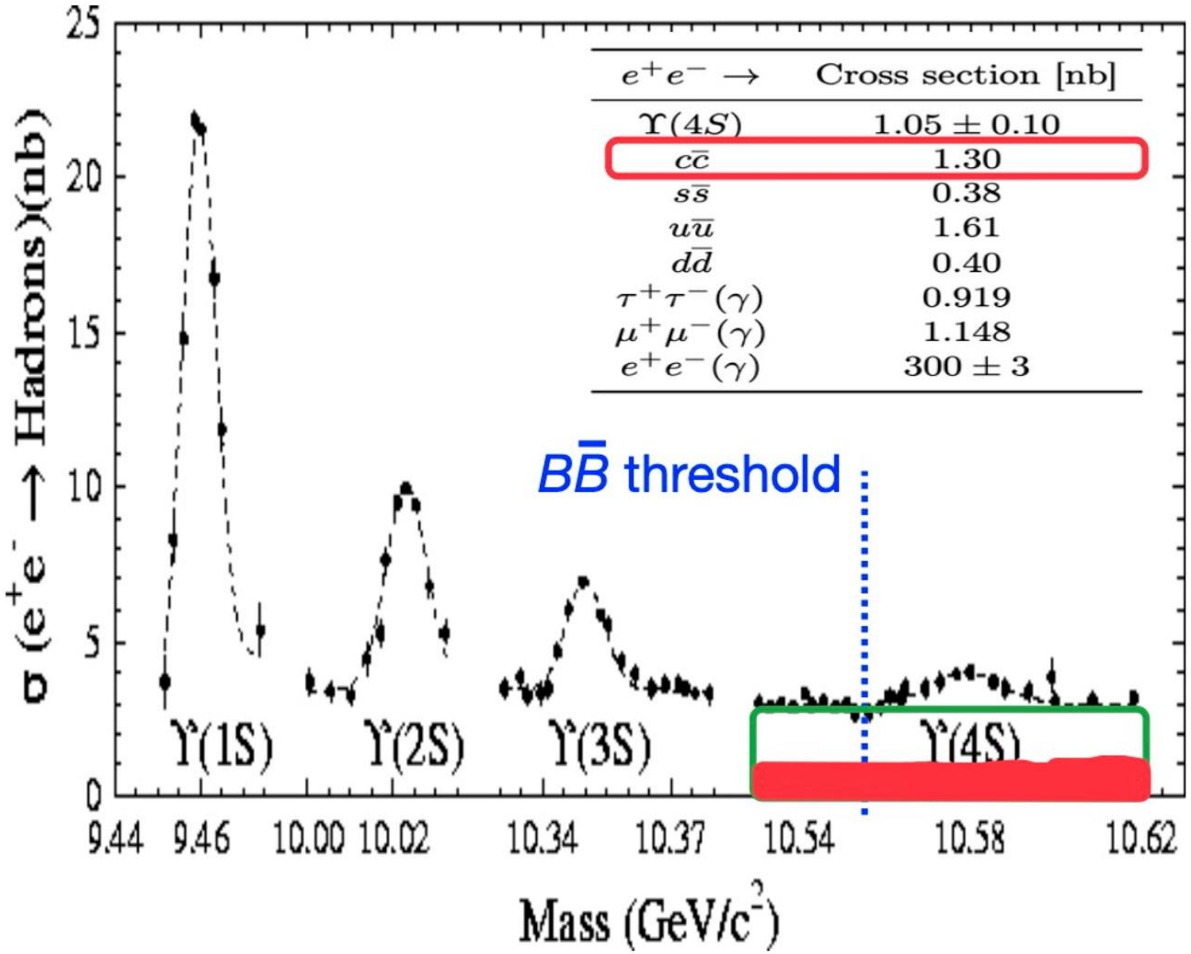
Belle II @SuperKEKB, recorded ∫Ldt = 424 fb^{-1} Run1 (2019-2022)



Charm physics at Belle (II)

- ✓ Two ways to produce the charm sample at B-factories
  - A large cross section for $e^+e^- \to c\bar{c}$ continuum process
  - B decays from $\Upsilon(4S) \to B\bar{B}$
- ✓ Full topics for charm physics
  - CP violation
  - D^0- $\bar{D}^0$ mixing
  - Amplitude analysis
  - Lifetime
  - Rare decay
  - Charmed baryon





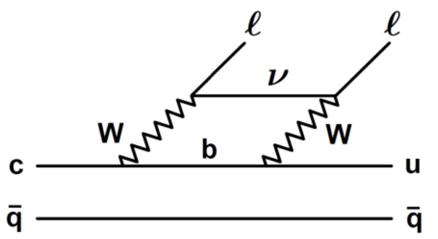
Search for $D^0 \to hh'e^+e^-$

PRELIMINARY
Belle 942/fb

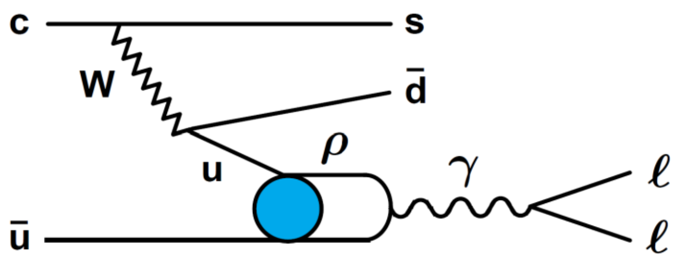
✓ Rare charmed meson decay

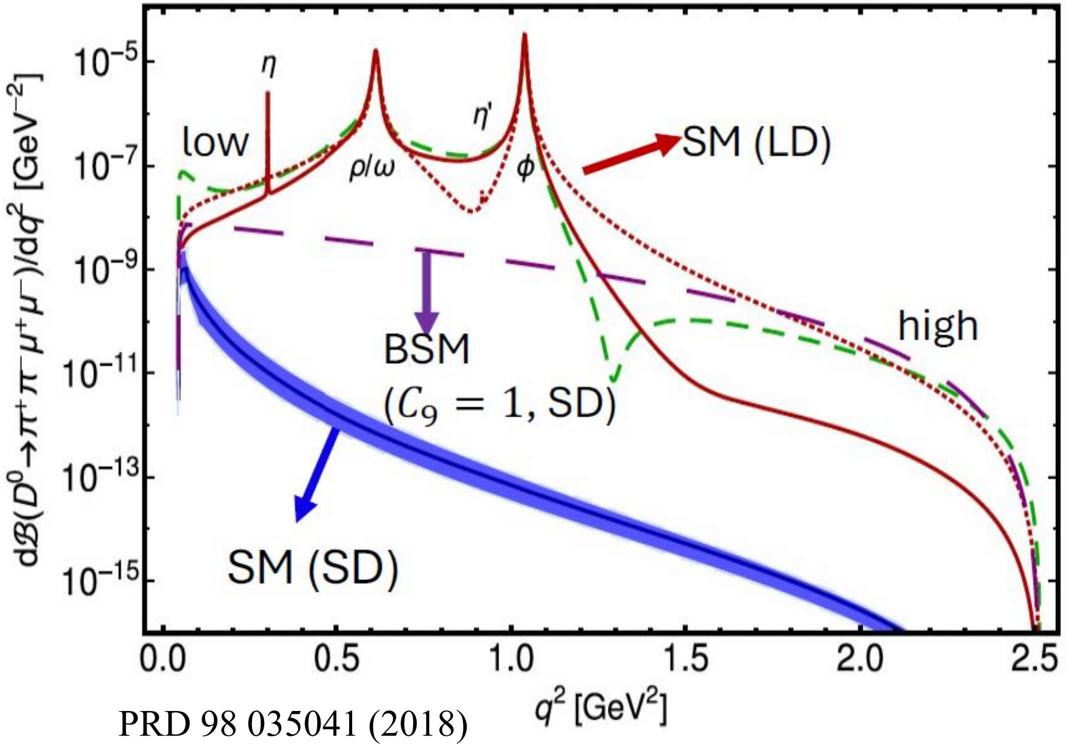
- Flavor changing neutral current (FCNC) $c \to u\ell\ell$ process is suppressed in the SM, sensitive to BSM
- LD contributions from vector meson dominance mode
- Search for new physics and LFU (Lepton Flavor Universality) tests

Short Distance (SD)



Long Distance (LD)





PRD 98 035041 (2018)

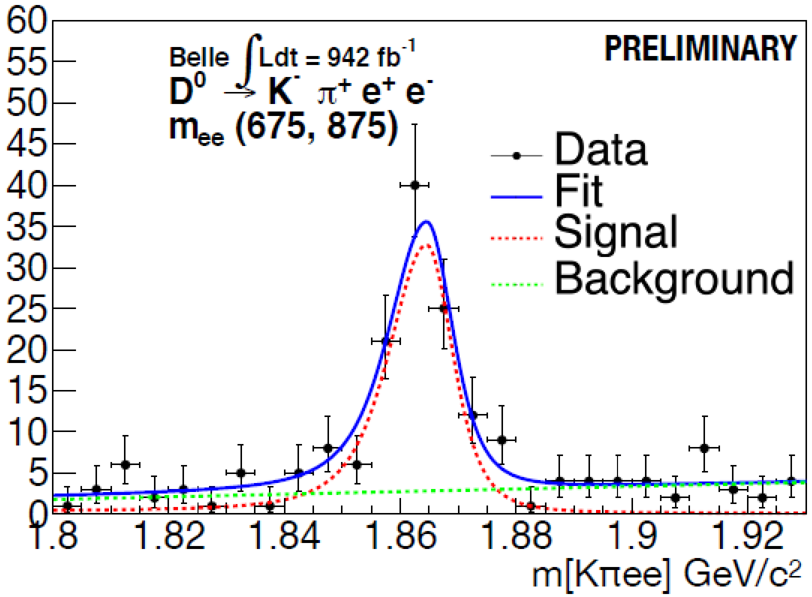
Previous measurements on BFs and ULs @90% [$\times 10^{-7}$]

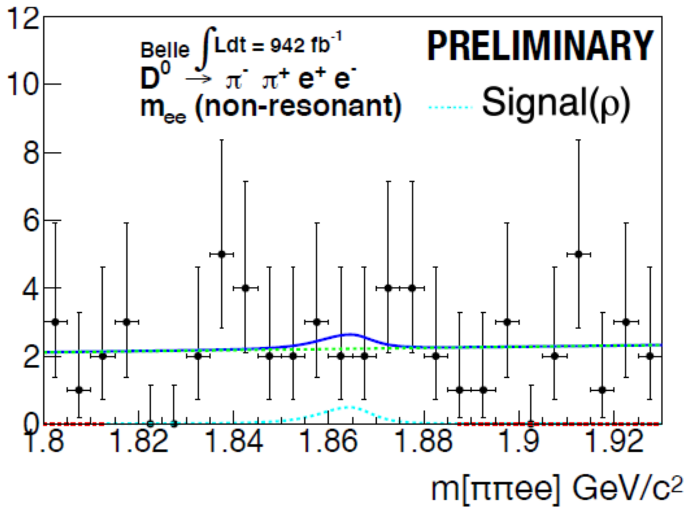
Experiment	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$
Babar (2019)			$40.0 \pm 5.0 \pm 2.3$ (ρ^0/ω) stat syst
BESIII (2019)	< 110	< 70	< 410
	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\mu^+\mu^-$
LHCb (2016-2017)	$1.54 \pm 0.27 \pm 0.19$	$9.64 \pm 0.48 \pm 1.10$	$4.17 \pm 0.12 \pm 0.40$ (ρ^0/ω)

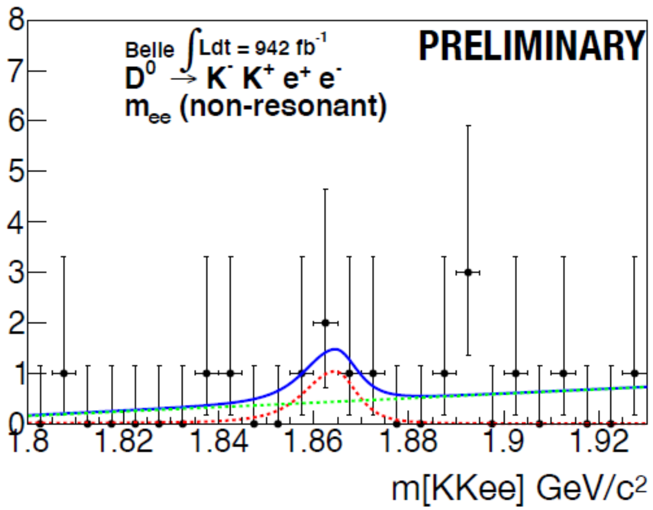
BABAR: PRL 122, 081802
BESIII: PRD 97, 072015 (2019)
LHCb: PLB517, 558(2016); PRL 119, 181805 (2017)

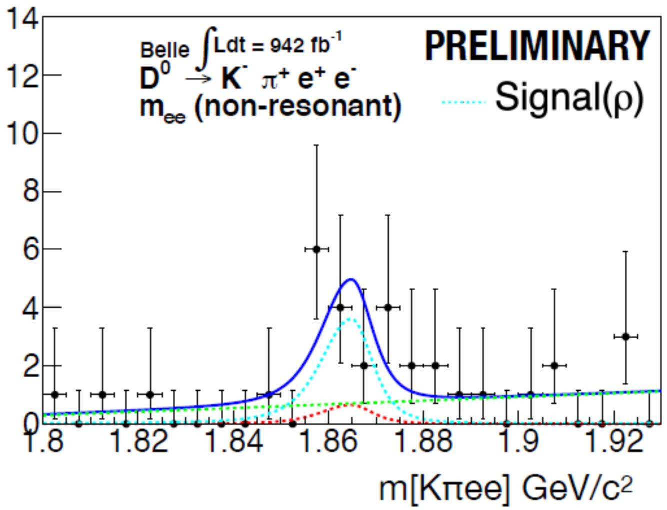
$D^0 \to hh'e^+e^-$ results

- ✓ Signal observed for $D^0 \to K^-\pi^+e^+e^-$ in ρ/ω region (11.8σ)
  - $\mathcal{B} = \left(39.6 \pm 4.5(\text{stat}) \pm 2.9(\text{syst})\right) \times 10^{-7}$
  - Compatible with BABAR and with SM expectation
- ✓ No significant signal observed in other channels and regions
  - $hh' = KK, K\pi, \pi\pi$; m_{ee} region: η, ρ/ω, ϕ, non-resonant
  - Set upper limits in (2.3-7.7)$\times 10^{-7}$ at 90% CL
  - World's best limits to date





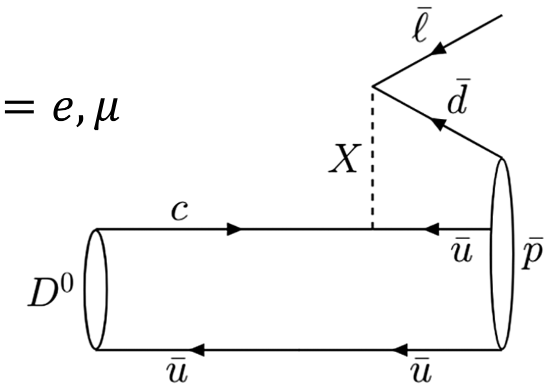




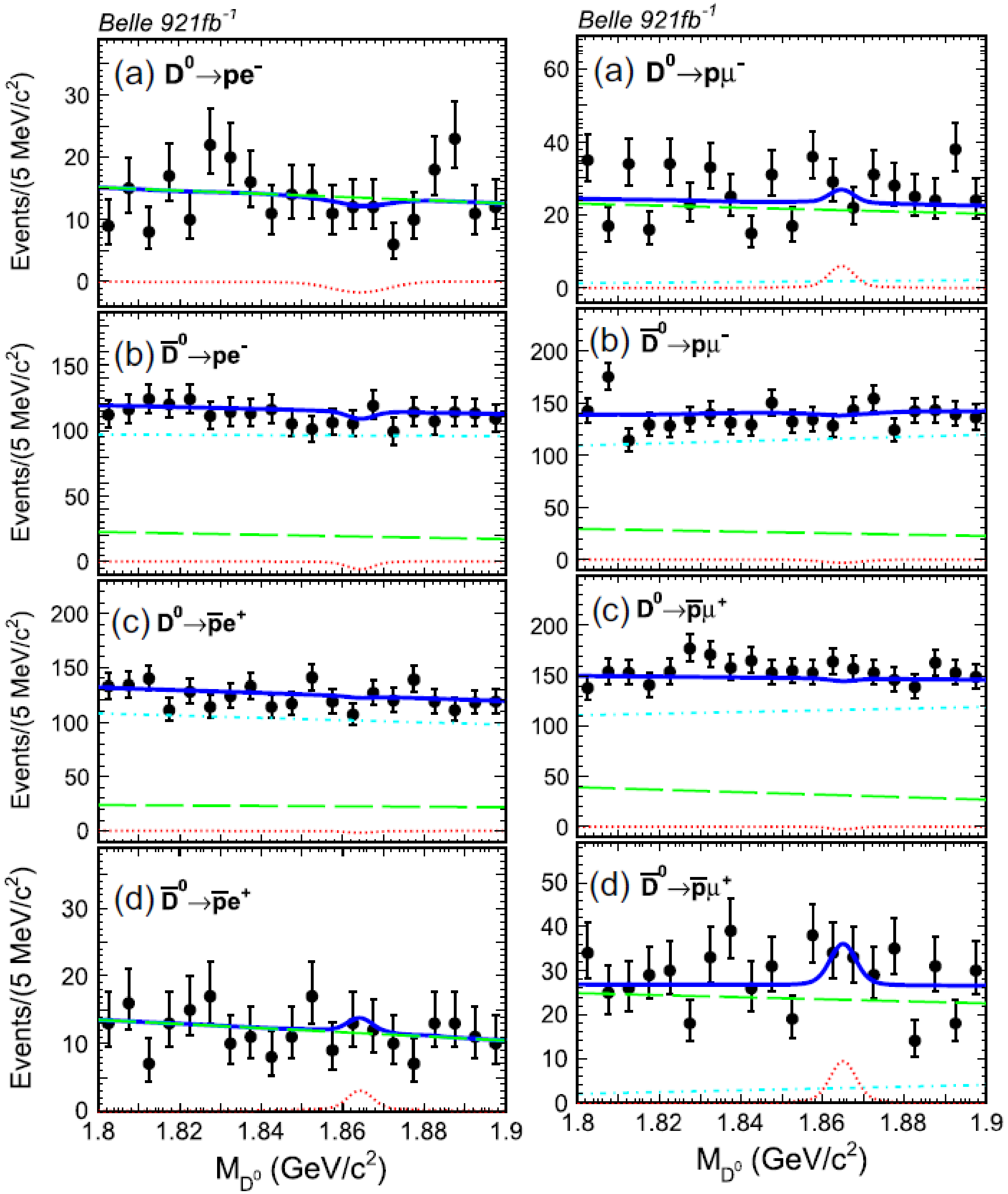
Search for neutral $D \to p\ell$

Belle 921/fb [PRD 109, L031101 (2024)]

- ✓ Baryon Number Violation (BNV) is one of the required conditions to explain matter-antimatter asymmetry
  - Some models[1-5] allow violation of baryon (B) and lepton (L) numbers with the difference $\Delta(B-L)=0$ conserved.
- ✓ Search in meson decays $D \to p\ell$
  - 8 channels in total for $D^0/\bar{D}^0$, $\ell = e, \mu$
  - X: non-SM gauge boson



- ✓ No significant signal observed
  - Set upper limits $(5-8)\times10^{-7}$ at 90% CL
  - Most stringent limit to date
  - First measurement for $D \to p\mu$ modes



[1] PRD 8, 1240 (1973) [2] PRL 32, 438 (1974) [3] PRD 20,776 (1979) [4] PLB 91, 222 (1980) [5] PLB 314, 336 (1993)

Search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$

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

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

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

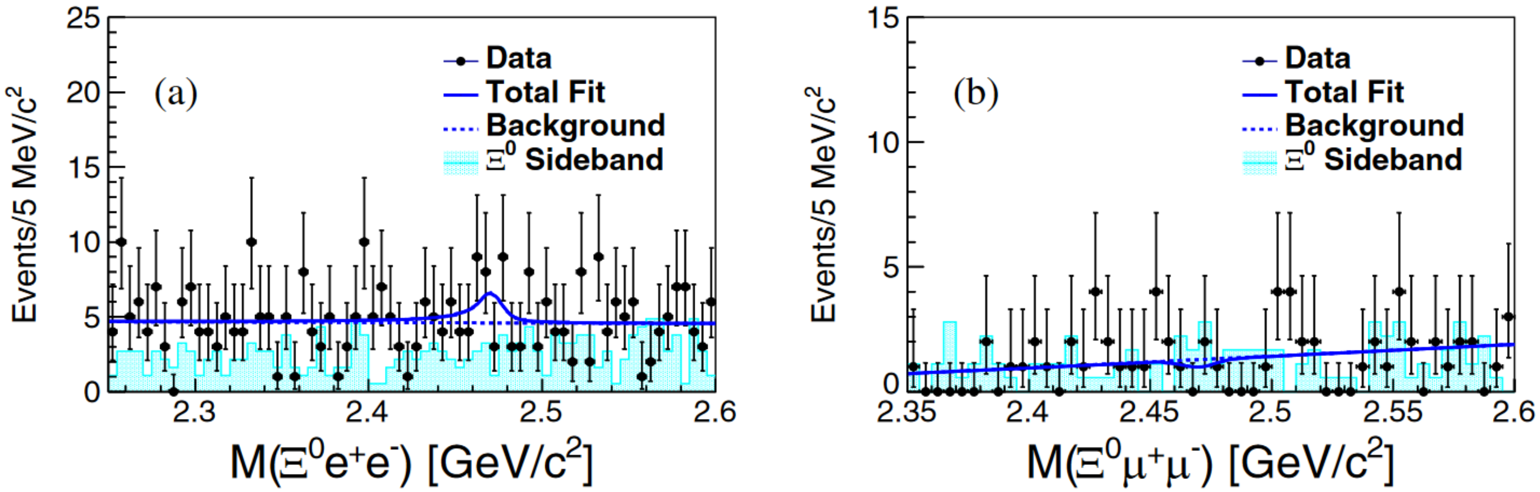
- Only upper limits of $\Lambda_c \to p\ell^+\ell^-$ decays were set for charmed baryons[1,2], which receive both W-exchange and FCNC process contributions.
- Theoretically face difficulties from the Hamiltonian helicity structure and hadronic form factors
- To understand W-exchange contribution in $\Lambda_c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

✓ First search for $\Xi_c^0 \to \Xi^0\ell^+\ell^-(\ell = e, \mu)$

- No significant signals observed
- set upper limits at 90% CL

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

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



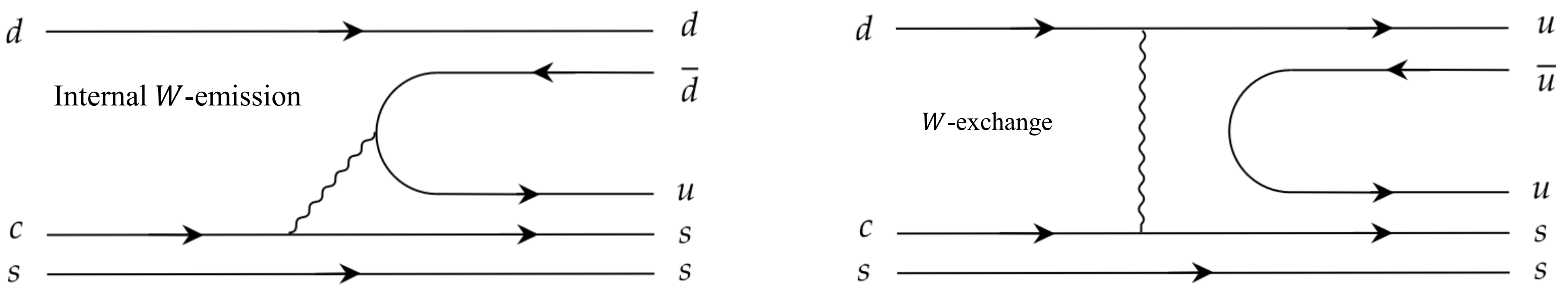
- Theoretical prediction gives upper limits at $2.35\ (2.25) \times 10^{-6}$ for electron (muon) mode[3]

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

PRELIMINARY
Belle + Belle II 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)$\times 10^{-3}$) and decay asymmetry parameters[see backup].
- Need experiment measurement to clarify the theoretical picture.

$\Xi_c^0 \to \Xi^0 h^0$ results

PRELIMINARY at Belle + Belle II 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

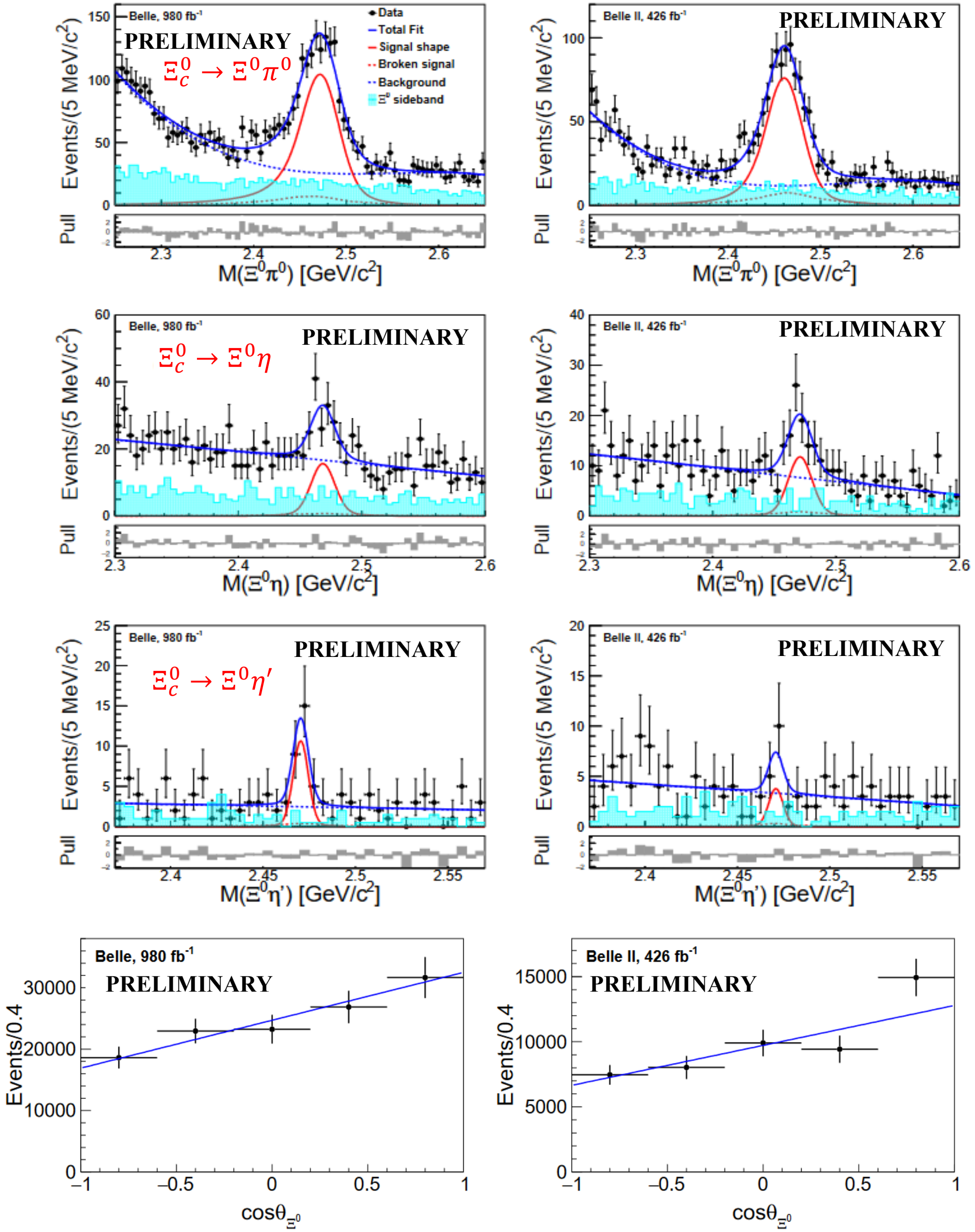
$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\text{stat.}) \pm 0.23(\text{syst.})$$

- 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)



Summary

- Belle and Belle II provide a unique environment for charm physics both in meson and baryon decays
  - sensitive in SM measurements and search for BSM physics
- Belle is still producing important measurements for more than 10 years after the end of data taking
  - Search for rare decays: tightest to date/first measurement
  - FCNC $D^0 \to hh'e^+e^-$
  - BNV $D \to p\ell$
  - Semi-leptonic $\Xi_c^0 \to \Xi^0\ell^+\ell^-$
- Belle + Belle II combined data sample provides the platform for further charm measurements
  - $\mathcal{B}$ and α measurements for $\Xi_c^0 \to \Xi^0 h^0$
- Belle II has started Run 2 data taking, expecting more physics results with a larger data sample

Thank you for your attention!

Backups

ULs ($\times 10^{-7}$) for $D^0 \to hh'ee$

m_{ee} region	[MeV/c^2]	Yield	Significance	$\mathcal{B}$	BELLE UL @ 90% CL	Efficiency (%)	BESIII (UL @ 90% CL)	BABAR (UL @ 90% CL)
$K^-K^+e^+e^-$							< 110	–
η	520-560	-	$< 0.1\sigma$	-	< 2.3	3.53 ± 0.04		
ρ^0/ω	> 675	2.6 ± 1.8	2.0σ	$1.2 \pm 0.9 \pm 0.1$	< 3.0	6.00 ± 0.06		
non-resonant	> 200 [a]	3.5 ± 3.3	1.5σ	$3.1 \pm 3.0 \pm 0.4$	< 7.7	3.19 ± 0.04		
$\pi^-\pi^+e^+e^-$							< 70	–
η	520-560	0.6 ± 2.3	0.3σ	$0.4 \pm 1.4 \pm 0.2$	< 3.2	5.31 ± 0.05		
ρ^0/ω	675-875	3.7 ± 4.1	0.9σ	$2.0 \pm 2.2 \pm 0.8$	< 6.1	5.69 ± 0.05		
ϕ	995-1035	3.6 ± 3.2	1.1σ	$1.1 \pm 1.1 \pm 0.2$	< 3.1	9.41 ± 0.06		
non-resonant	> 200	-0.2 ± 4.1	$< 0.1\sigma$	$-0.2 \pm 3.4 \pm 0.9$	< 7.2	3.69 ± 0.04		
$K^-\pi^+e^+e^-$							< 410	< 31*
η	520-560	4.0 ± 2.7	1.6σ	$2.2 \pm 1.5 \pm 0.5$	< 5.6	5.09 ± 0.04		
ρ^0/ω	675-875	110 ± 13	11.8σ	$39.6 \pm 4.5 \pm 2.9$	-	8.01 ± 0.06		
ϕ	990-1034	4.6 ± 2.4	2.5σ	$1.4 \pm 0.8 \pm 0.3$	< 2.9	9.19 ± 0.06		
non-resonant	> 560	2.2 ± 4.2	0.4σ	$1.3 \pm 2.4 \pm 0.6$	< 6.5	4.89 ± 0.09		

[a] Excluding resonance regions, which is same for all three modes.

BESIII PRD97(2019)072015
BABAR PRL122(2019)081802

ULs for $D \to p\ell$

TABLE I. Reconstruction efficiency (ϵ), signal yield (N_S), signal significance ($\mathcal{S}$), upper limit on the signal yield ($N_{p\ell}^{UL}$), and branching fraction ($\mathcal{B}$) at 90% confidence level for each decay mode.

Decay mode	ϵ (%)	N_S	$\mathcal{S}$ (σ)	N_{pl}^{UL}	$\mathcal{B} \times 10^{-7}$
$D^0 \to pe^-$	10.2	-6.4 ± 8.5		17.5	< 5.5
$\bar{D}^0 \to pe^-$	10.2	-18.4 ± 23.0		22.0	< 6.9
$D^0 \to \bar{p}e^+$	09.7	-4.7 ± 23.0		22.0	< 7.2
$\bar{D}^0 \to \bar{p}e^+$	09.6	7.1 ± 9.0	0.6	23.0	< 7.6
$D^0 \to p\mu^-$	10.7	11.0 ± 23.0	0.9	17.1	< 5.1
$\bar{D}^0 \to p\mu^-$	10.7	-10.8 ± 27.0		21.8	< 6.5
$D^0 \to \bar{p}\mu^+$	10.5	-4.5 ± 14.0		21.1	< 6.3
$\bar{D}^0 \to \bar{p}\mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5

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

[5] J. G. Körner and M. Krämer, *Exclusive non-leptonic charm baryon decays*, Z. Phys. C **55** (1992) 659.

[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.

[7] Q. P. Xu and A. N. Kamal, *Cabibbo-favored nonleptonic decays of charmed baryons*, Phys. Rev. D **46** (1992) 270.

[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.

[12] 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.

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

[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.

[18] Z. P. Xing, *et al.*, *Global analysis of measured and unmeasured hadronic two-body weak decays of antitriplet charmed baryons*, Phys. Rev. D **108** (2023) 053004.

Systematic uncertainties for $\mathcal{B}(\Xi_c^0 \to \Xi^0 h^0)$

Table 5. Relative systematic uncertainties (%) for branching fraction ratio measurements. The uncertainties in last two rows are correlated systematic uncertainties from intermediate branching fractions and background shape, and others are uncorrelated ones.

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
MC statistics	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 statistics	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

Values for $\mathcal{B}(\Xi_c^0 \to \Xi^0 h^0)$

Mode	$N^{\rm obs}_{\rm Belle}$	$\varepsilon_{\rm Belle}$ (%)	$N^{\rm obs}_{\rm Belle~II}$	$\varepsilon_{\rm Belle~II}$ (%)
$\Xi_c^0 \to \Xi^-\pi^+$	36340±348	13.92±0.05	13719±184	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

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

are taken from ref. [39]. We combine the Belle and Belle II branching fraction ratios and uncertainties using formulas in ref. [44]:

$$
\begin{aligned}
r &= \frac{r_1\sigma_2^2 + r_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2 + (r_1 - r_2)^2\epsilon_r^2}, \\
\sigma &= \sqrt{\frac{\sigma_1^2\sigma_2^2 + (r_1^2\sigma_2^2 + r_2^2\sigma_1^2)\epsilon_r^2}{\sigma_1^2 + \sigma_2^2 + (r_1 - r_2)^2\epsilon_r^2}},
\end{aligned}
\tag{5.3}
$$

where r_i, σ_i and ϵ_r are the branching fraction ratio, uncorrelated uncertainty, and relative correlated systematic uncertainty from each data sample, respectively. The branching

[44] G. D'Agostini, *On the use of the covariance matrix to fit correlated data*, Nucl. Instrum. Methods Phys. Res., Sect. A **346** (1994) 306.