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

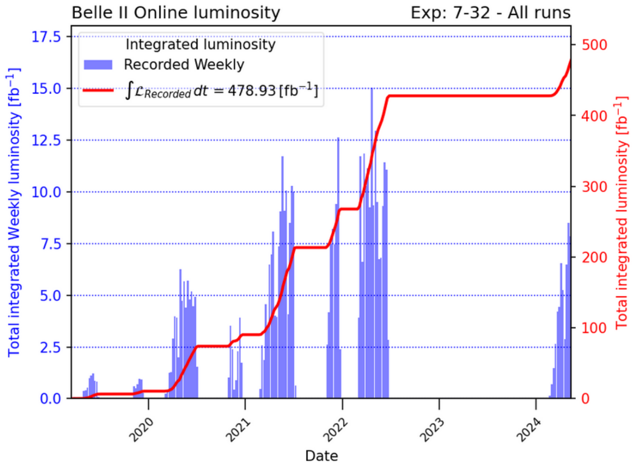
- Quick introduce to Belle (II)
- CPV for Charmed mesons
  - ✓ $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$ arXiv:2305.12806, submitted to PRD
- Charmed Baryon
  - ✓ $\Xi_c^0 \to \Xi^0 h^0$ preliminary, intended to JHEP
- Search for rare decay
  - ✓ $D^0 \to hh' e^+ e^-$ preliminary, intended to PRL
  - ✓ $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ PRD 109, 052003 (2024)
  - ✓ $D \to p\ell$ PRD 109, L031101 (2024)
- Summary

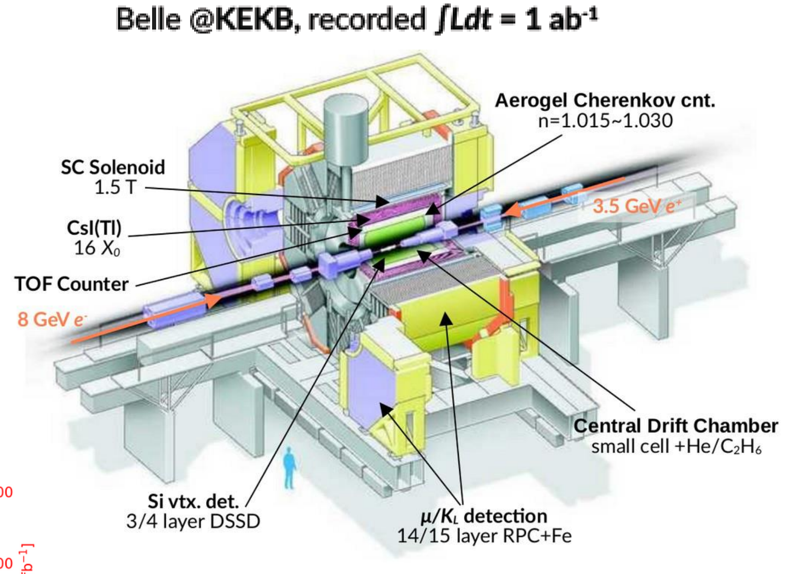
Experiments

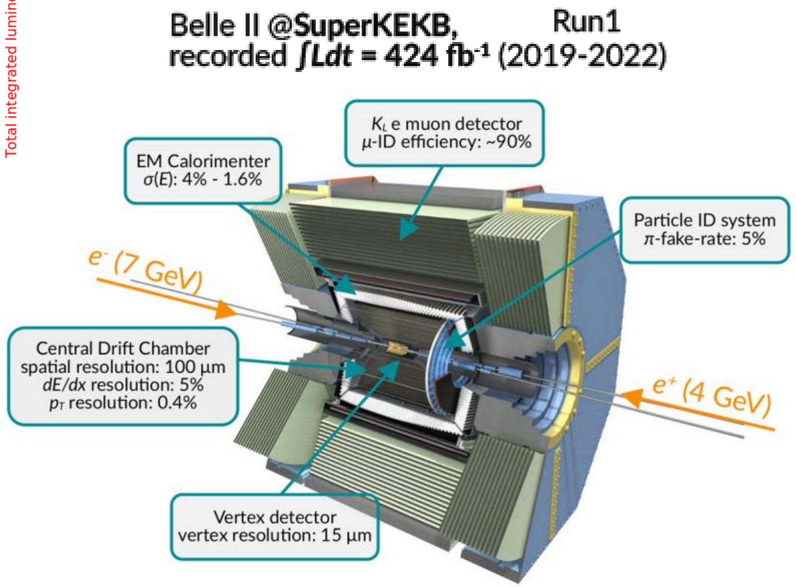
✓ Belle and Belle II operate at asymmetric e^+e^- colliders

- KEKB (2009-2010), 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)
- Collisions at or near $\Upsilon(4S)$, B-factories



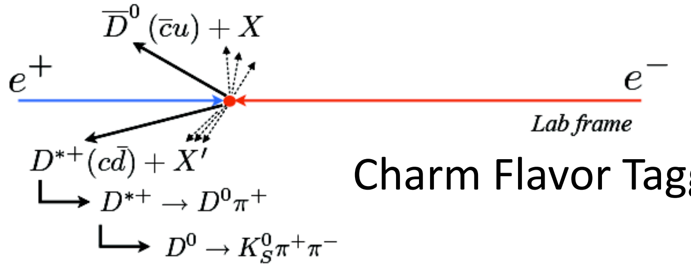




✓ Combined analyses at Belle & Belle II

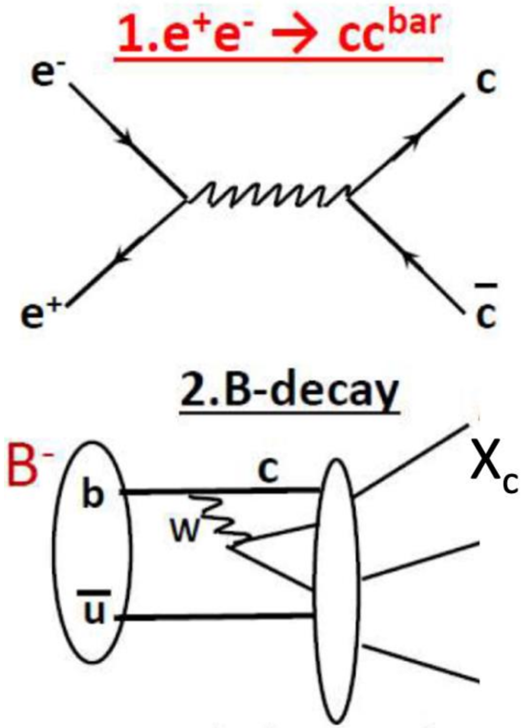
- $\sim 1.4\ ab^{-1}$ in total
- Analyze Belle data with Belle II framework
- Common review procedures
- For charm analyses, large statistics is crucial to improve precision

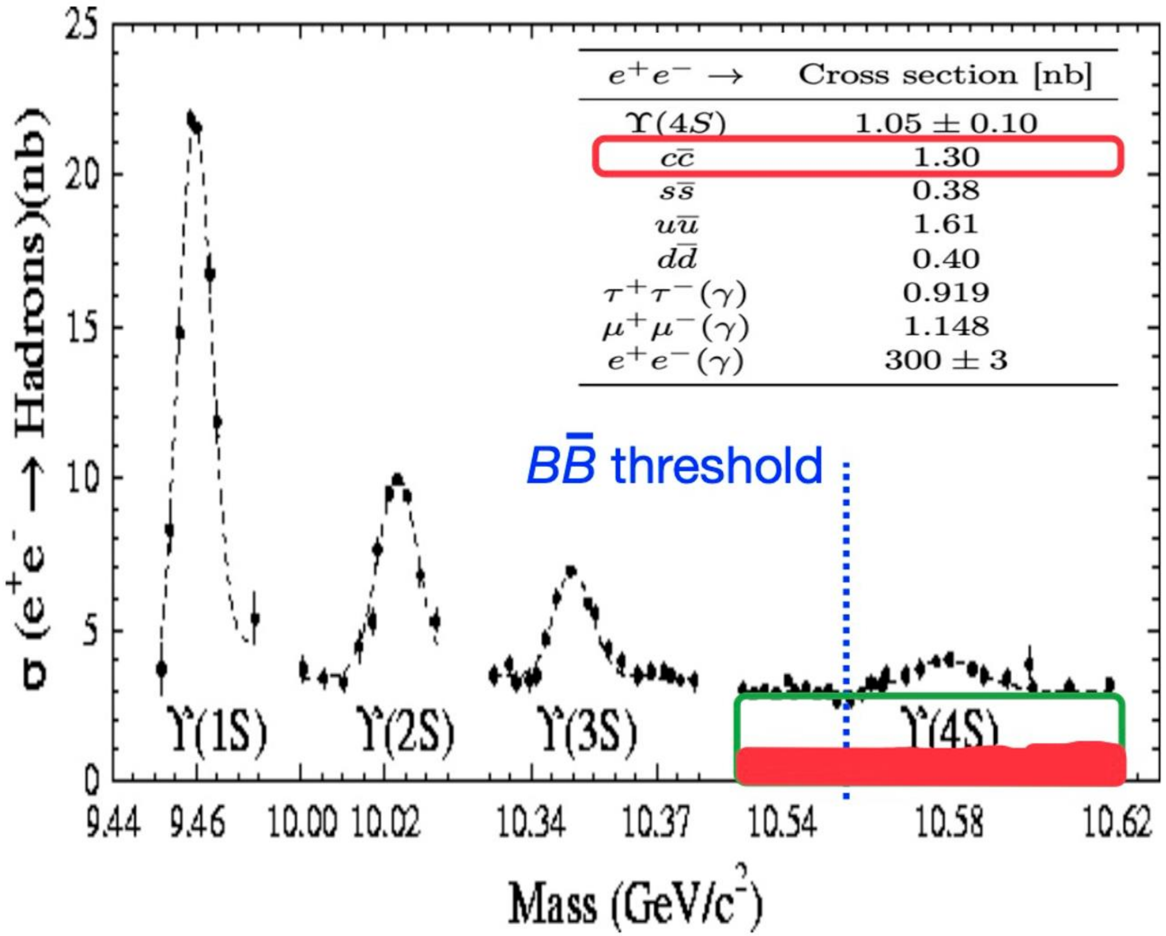
Charm physics at Belle (II)

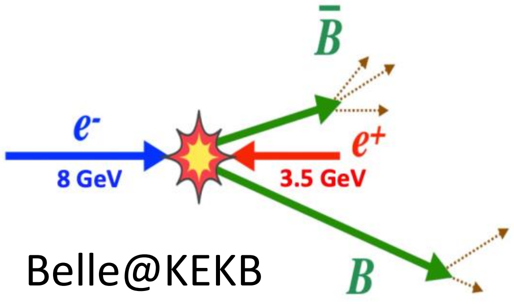


Charm Flavor Tagging

- ✓ Two ways to produce the charm sample at B-factories
  - A large cross section for $e^+e^- \to c\bar{c}$ continuum process
  - e^+e^- collider at 10.58 GeV to make $\Upsilon(4S)$ resonance decaying into $B^0\bar{B}^0$ and B^+B^- in 96% of the time
- ✓ Full topics for charm physics

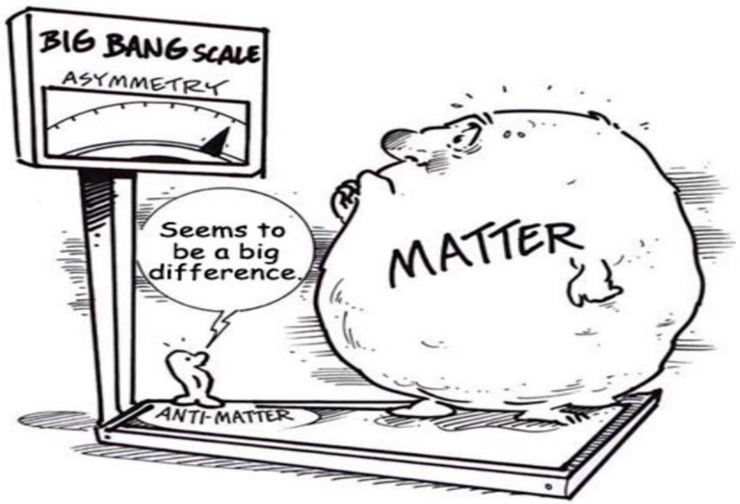






Belle@KEKB

Charm CP Violation

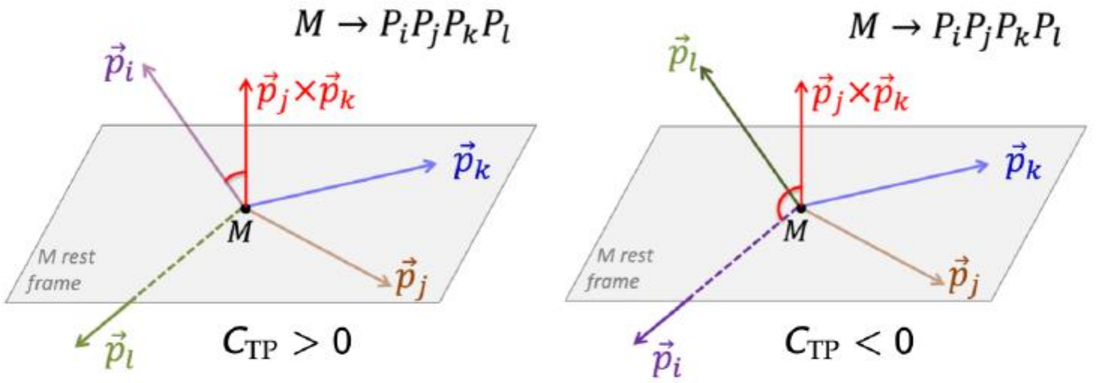


- ✓ Charge-parity violation (CPV) is essential for elucidating the matter-antimatter asymmetry in the universe [Pisma Zh. Theor. Fiz. 5. 32(1967)]
  - In the SM, CPV from the complex phase of the CKM matrix is not large enough.
  - Search for new CPV sources.
- ✓ Charm CPV is notably small, $\leq \mathcal{O}(10^{-3})$ [PRD 86, 036012(2012)]
  - Difficult for theoretical predictions due to low-energy strong-interaction effect
  - Sensitive to the New Physics [PRD 88, 074011 (2013)]
- ✓ First and only observation of charm CPV by LHCb [PRL 122, 211803 (2019)]
  - $\Delta A_{CP}(D^0 \to KK, \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$ (>5σ)
  - First evidence (3.8σ) for direct CPV in $D^0 \to \pi^-\pi^+$ [PRL 131, 091802 (2023)]
  - CPV in other charm decays is yet to be observed.
- ✓ Continue searching for CPV in charm hadrons to understand its origin, SM, and search for New Physics
  - We need to study more channels and observables and improve the precision of measurements
  - Belle (II) mainly contribute with channels with neutral particles in the final state

a_{CP}^{T-odd} observable

✓ Indirectly search for CP violation under CPT symmetry conservation

- Triple mixed product $C_T = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$



So-called 'up-down asymmetry': $\vec{p}_i$ at the up- (down-) side of $\vec{p}_j \times \vec{p}_k$ plane

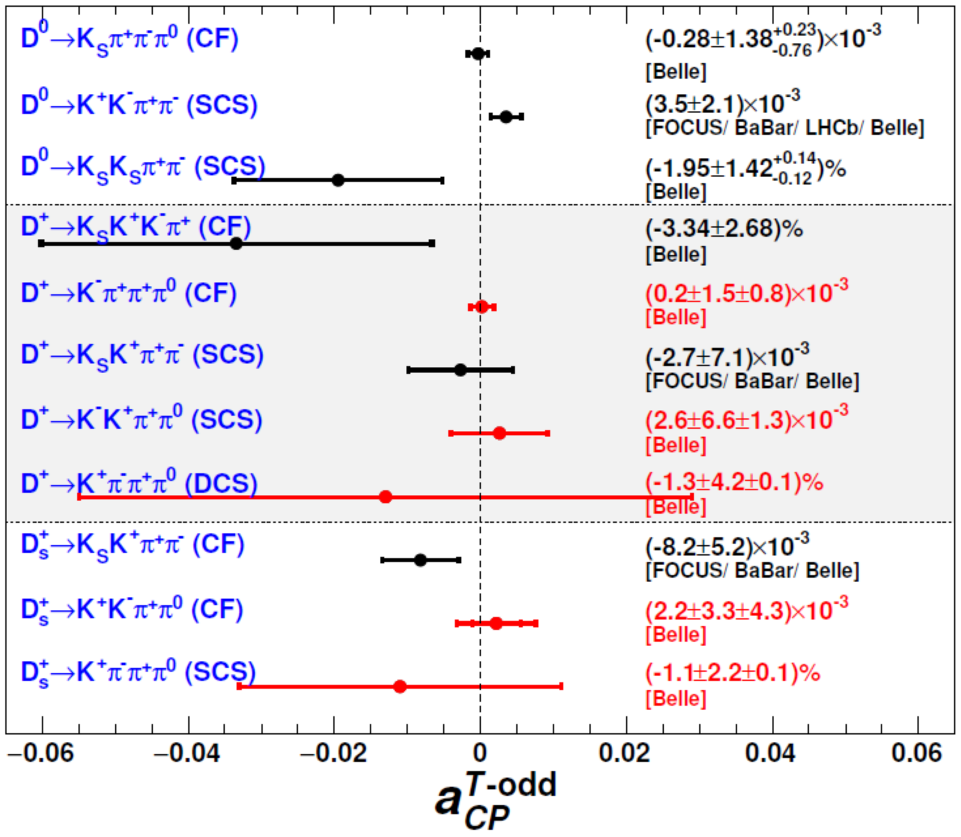
- Build asymmetries:

$$A_T = \frac{N(C_T>0)-N(C_T<0)}{N(C_T>0)+N(C_T<0)} \quad \bar{A}_T = \frac{\bar{N}(-\bar{C}_T>0)-\bar{N}(-\bar{C}_T<0)}{\bar{N}(-\bar{C}_T>0)+\bar{N}(-\bar{C}_T<0)}$$

- T-odd CP-violating asymmetry

$$a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)$$

Recent measurement



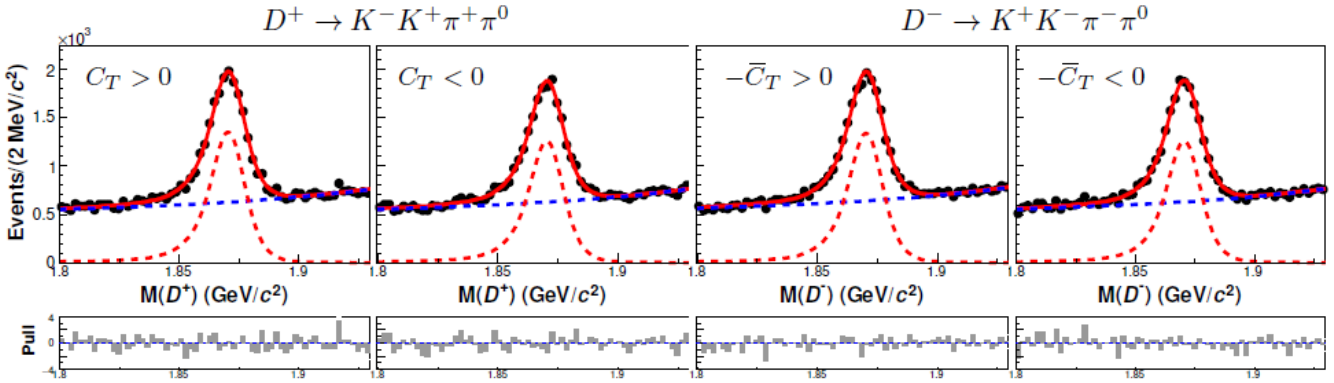
a_{CP}^{T-odd} for $D_{(s)}^+ \to K^\pm h^\pm \pi^+ \pi^0$

Belle 980/fb [arXiv:2305.12806]
submitted to PRD

✓ No evidence of global CPV

- reach 10^{-3} level

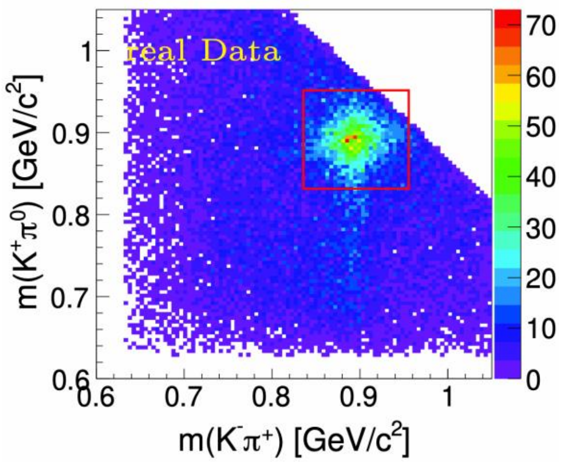
SCS	$a_{CP}^{T\text{-odd}}(D^+ \to K^- K^+ \pi^+ \pi^0)$	$=$	$(+2.6 \pm 6.6 \pm 1.3) \times 10^{-3}$
DCS	$a_{CP}^{T\text{-odd}}(D^+ \to K^+ \pi^- \pi^+ \pi^0)$	$=$	$(-1.3 \pm 4.2 \pm 0.1) \times 10^{-2}$
CF	$a_{CP}^{T\text{-odd}}(D^+ \to K^- \pi^+ \pi^+ \pi^0)$	$=$	$(+0.2 \pm 1.5 \pm 0.8) \times 10^{-3}$
SCS	$a_{CP}^{T\text{-odd}}(D_s^+ \to K^+ \pi^- \pi^+ \pi^0)$	$=$	$(-1.1 \pm 2.2 \pm 0.1) \times 10^{-2}$
CF	$a_{CP}^{T\text{-odd}}(D_s^+ \to K^- K^+ \pi^+ \pi^0)$	$=$	$(+2.2 \pm 3.3 \pm 4.3) \times 10^{-3}$



✓ No evidence of local CPV in subregion for dominant resonances

- Vector mesons: ϕ, ρ, K^*

Subregion	$D_{(s)}^+ \to VV$	Signal region (SR)	$a_{CP}^{T\text{-odd}}$ ($\times 10^{-2}$)
(1) SCS	$D^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	$0.85 \pm 0.95 \pm 0.25$
(2) SCS	$D^+ \to \bar{K}^{*0} K^{*+}$	$K^{*(0,+)}$-SR, veto ϕ-SR	$0.17 \pm 1.26 \pm 0.13$
(3) CF	$D^+ \to \bar{K}^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	$0.25 \pm 0.25 \pm 0.13$
(4) SCS	$D_s^+ \to K^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	$6.2 \pm 3.0 \pm 0.4$
(5) SCS	$D_s^+ \to K^{*+}\rho^0$	K^{*+}-SR, ρ^0-SR	$1.7 \pm 6.1 \pm 1.5$
(6) CF	$D_s^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	$0.31 \pm 0.40 \pm 0.43$
(7) CF	$D_s^+ \to \bar{K}^{*0} K^{*+}$	$K^{*(0,+)}$-SR, veto ϕ-SR	$0.26 \pm 0.76 \pm 0.37$



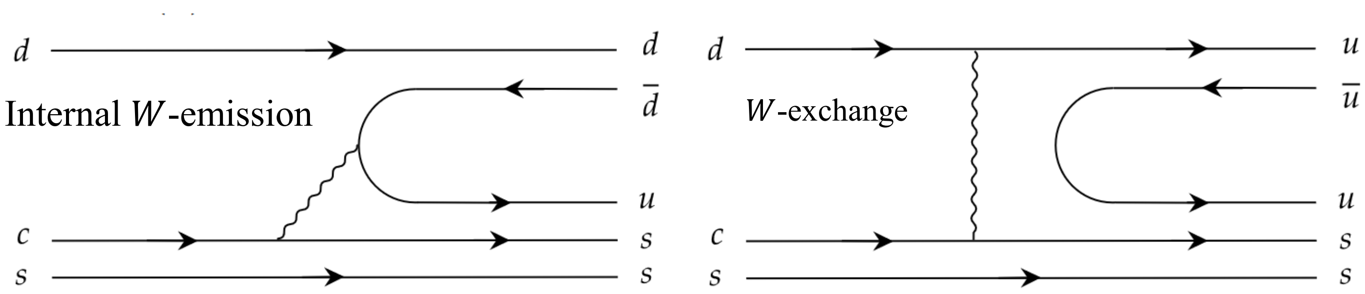
$D^+ \to \bar{K}^{*0} K^{*+}$
for example

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.



[1] Z. Phys. C 55, 659 (1992)
[2] PRD 57, 6532 (1998)
[3] PRD 46, 270 (1992)
[4] PRD 48, 4188 (1993)
[5] PRD 50, 5787 (1994)
[6] PRD 101, 014011 (2020)
[7] EPJC 7, 217 (1999)
[8] PRD 97, 073006 (2018)
[9] PLB 794, 19 (2019)
[10] JHEP 02, 165 (2020)
[11] JHEP 03, 143 (2022)
[12] JHEP 09, 35 (2022)
[13] JHEP 02, 235 (2023)
[14] PRD 108, 053004 (2023)

- Serval theoretical approaches developed to deal with nonfactorizable contributions, give various predictions on branching fractions (in unit of 10^{-3}) and decay asymmetry parameters[1-14].
- Need experiment measurement to clarify the theoretical picture.

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

✓ First measurements of the branching fractions using combined data

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

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

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

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

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

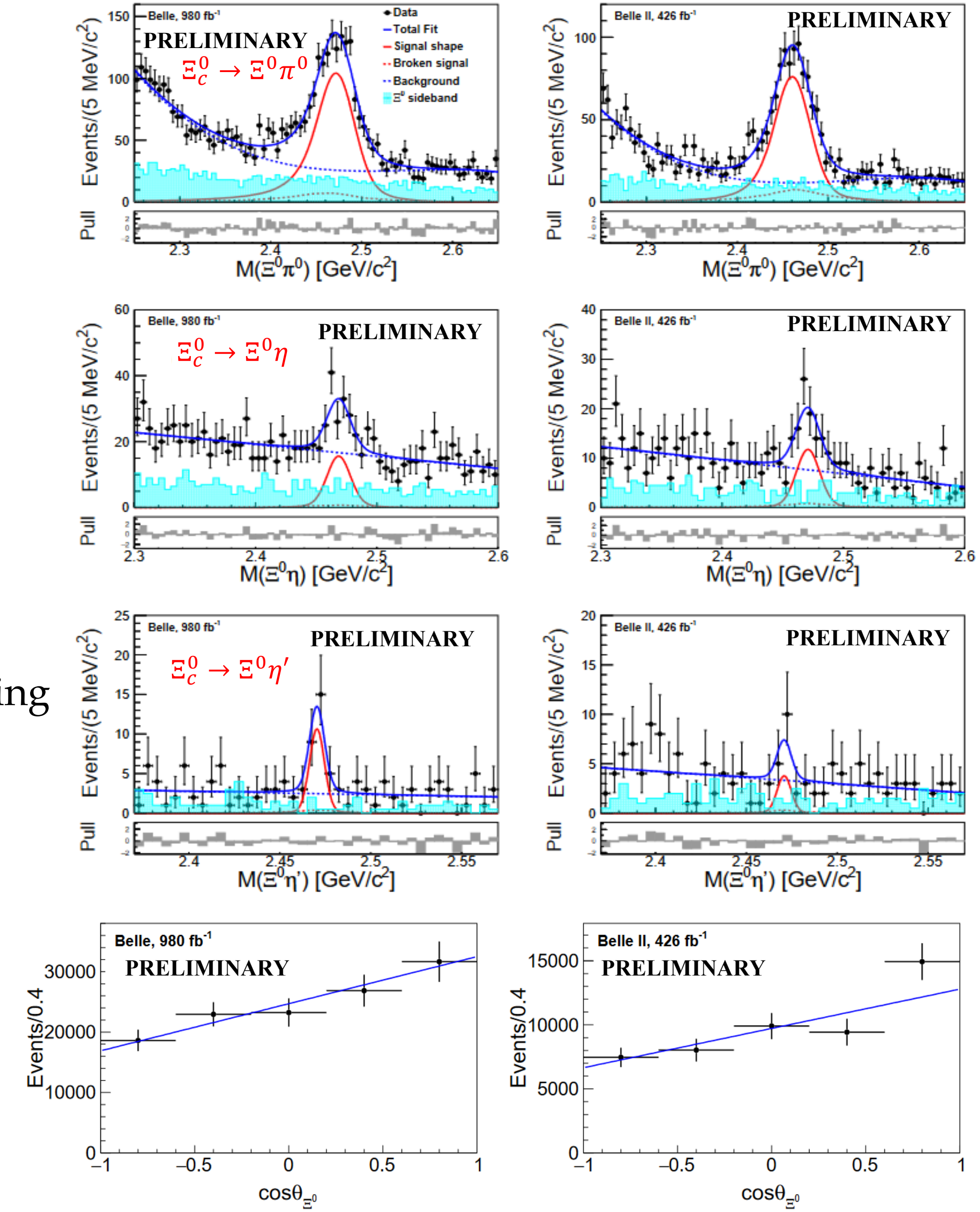
$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\text{stat.}) \pm 0.23(\text{syst.})$$

- through a simultaneous fit to Belle and Belle II data samples depending on differential decay rate

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

- taking $\alpha(\Xi^0 \to \Lambda\pi^0) = -0.349 \pm 0.009$(PDG)
- 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)

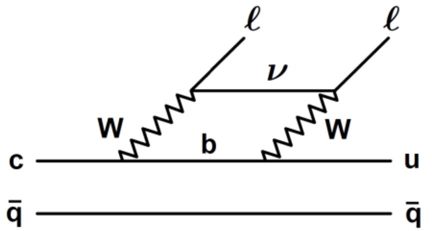


Search for $D^0 \to hh'e^+e^-, h^{(\prime)} = K, \pi$

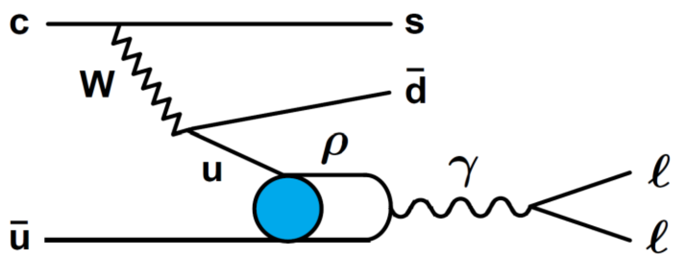
PRELIMINARY
Belle 942/fb

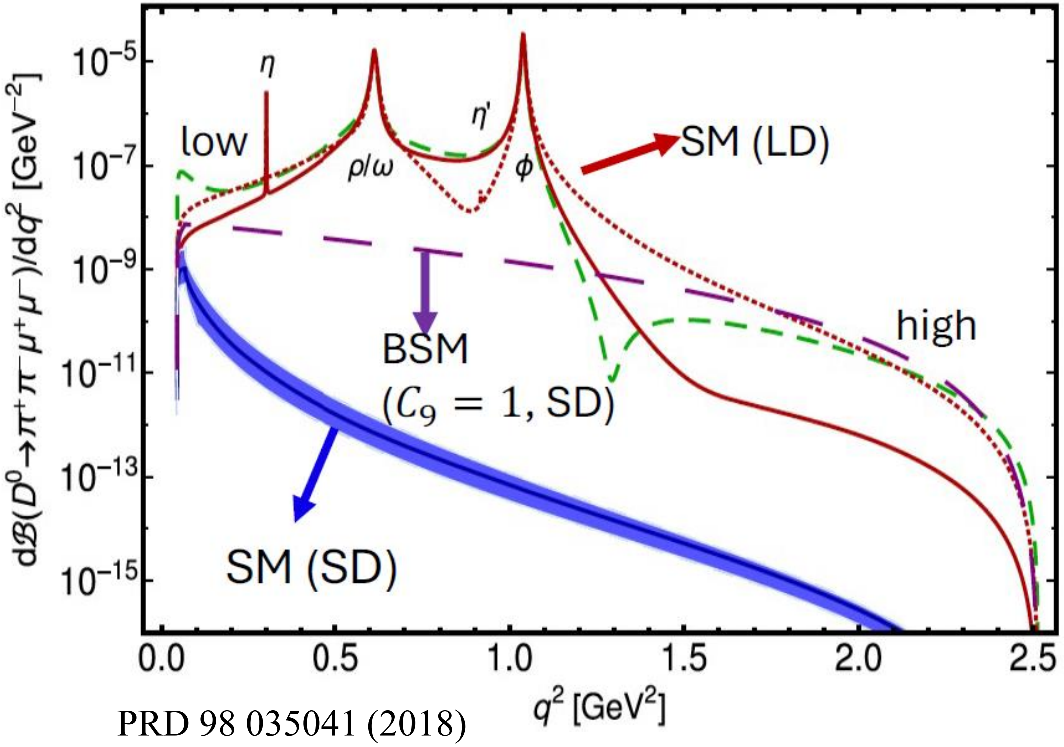
- ✓ Rare charmed meson decay
  - Flavor changing neutral current (FCNC) $c \to u\ell\ell$ process is suppressed in the SM, sensitive to BSM
  - LD contributions from vector meson dominance (VMD) mode dominate
  - Search for new physics and LFU (Lepton Flavor Universality) tests

Short Distance (SD)



Long Distance (LD)





PRD 98 035041 (2018)

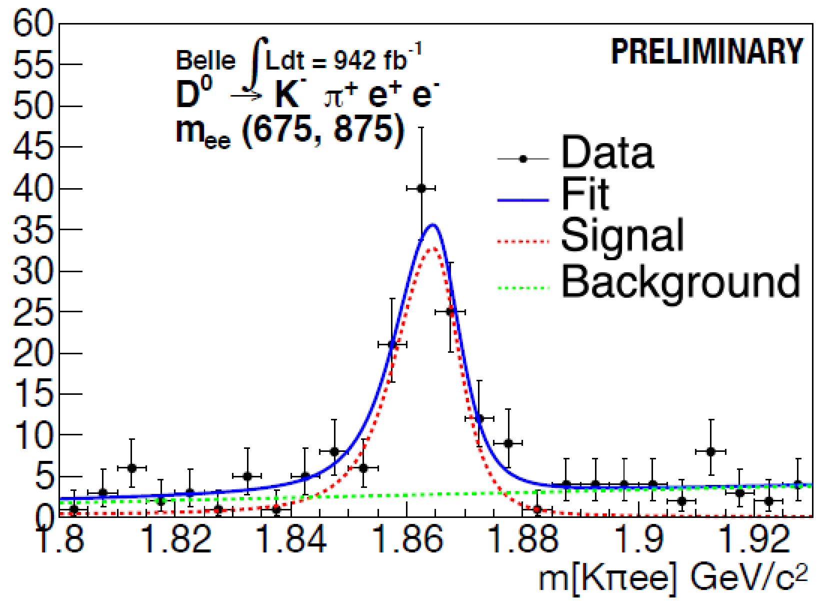
Measured BFs and ULs @90% [$\times 10^{-7}$]

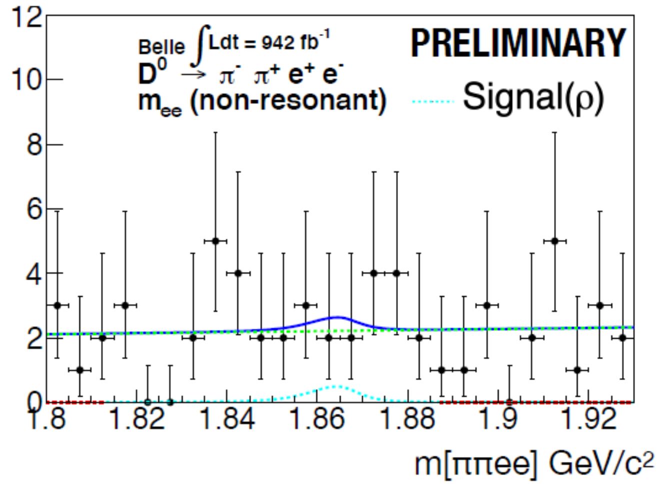
Experiment	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$
Babar (2019)			$40.0 \pm 5.0 \pm 2.3$ (ρ^0/ω) stat syst
BESIII (2019)	< 110	< 70	< 410
	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\mu^+\mu^-$
LHCb (2016-2017)	$1.54 \pm 0.27 \pm 0.19$	$9.64 \pm 0.48 \pm 1.10$	$4.17 \pm 0.12 \pm 0.40$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

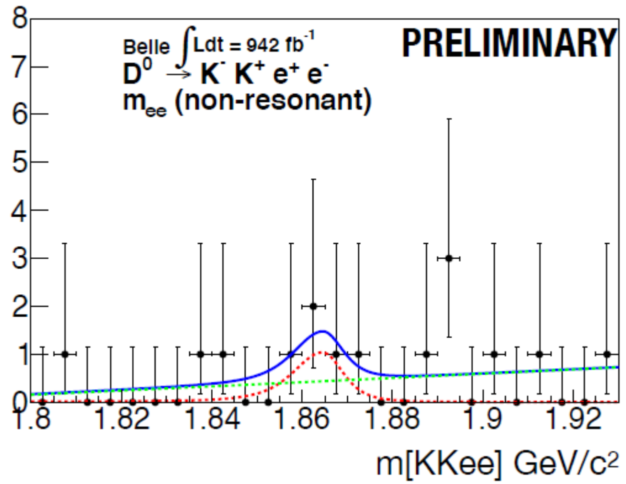
BABAR: PRL 122, 081802
BESIII: PRD 97, 072015 (2019)
LHCb: PLB517, 558(2016); PRL 119, 181805 (2017)

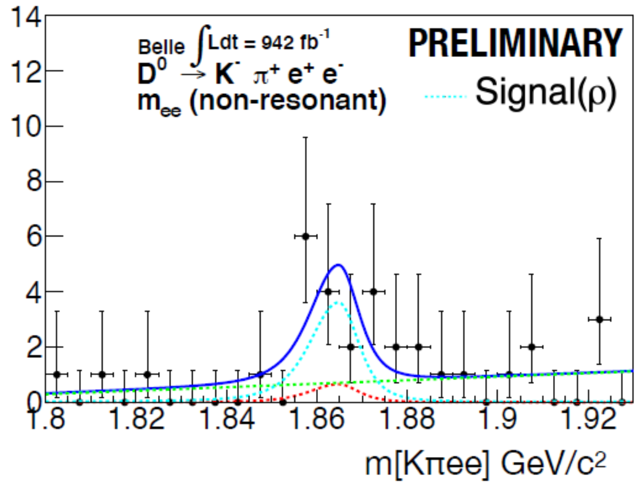
$D^0 \to hh'e^+e^-$ results

- ✓ 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 signal observed in other channels and regions
  - Set upper limits in $[2.3, 7.7] \times 10^{-7}$ at 90% CL
  - Tightest to date
  - No BSM contributions are found in non-resonant regions
  - Taking $D^0 \to K^-\pi^+\pi^-\pi^+$ as reference mode









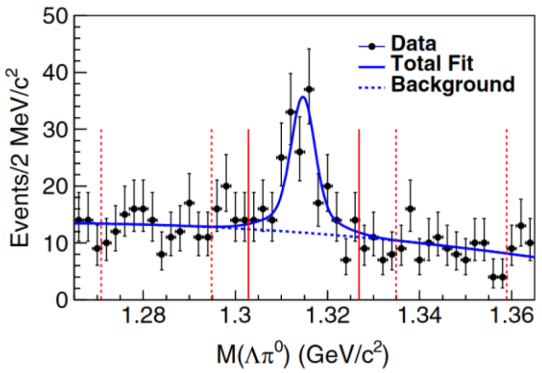
Search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$

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.
- If observed, the signal channels would allow to test LFU

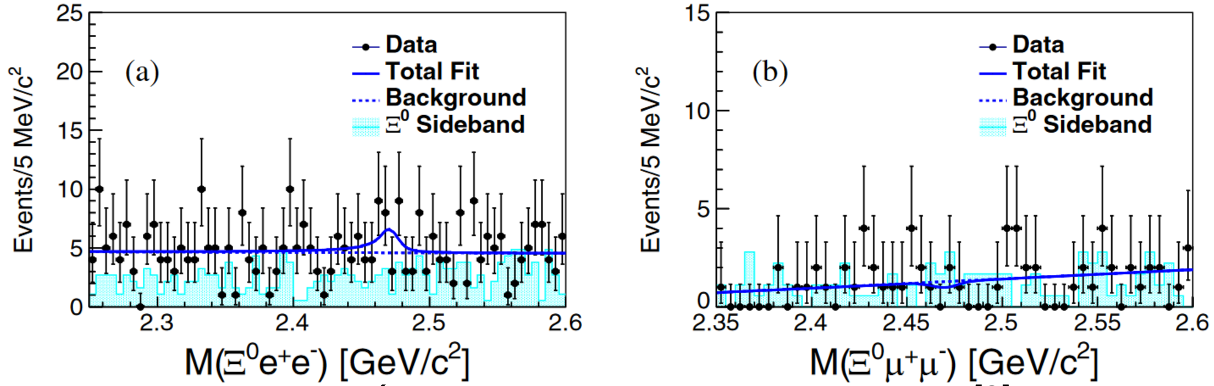


✓ First search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^- (\ell = e, \mu)$

- Fully reconstruct with $\Xi^0 \to \Lambda\pi^0$ ($\sim$100 signals)
- Take $\Xi_c^0 \to \Xi^- \pi^+$ as reference mode
- 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]

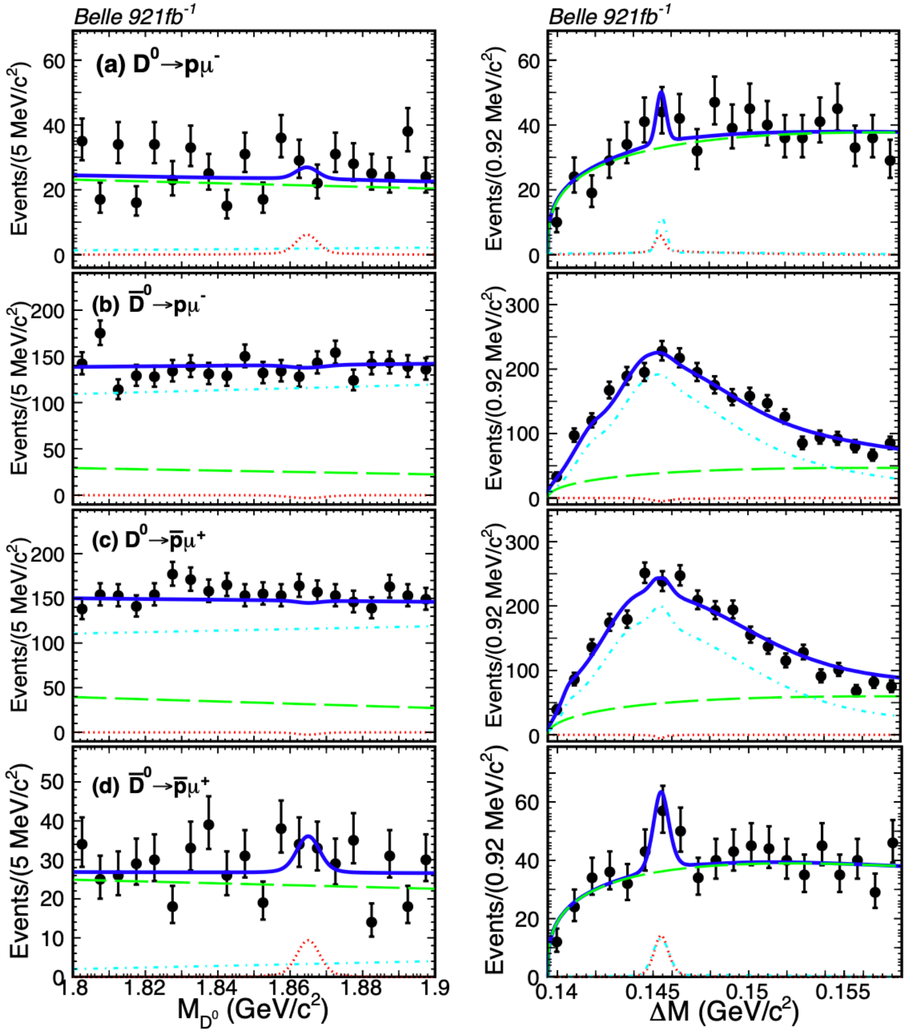
Search for neutral $D \to p\ell$

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, B and L separately violated with $\Delta(B-L)=0$
  - $D \to p\ell$ for $D^0, \bar{D}^0$ with $\ell = e, \mu$
  - Use $D \to K\pi$ as reference mode
- ✓ No signal observed
  - Set upper limits $(5-8)\times 10^{-7}$ at 90% CL

Decay mode	ϵ (%)	N_S	$\mathcal{S}$ (σ)	N^{UL}_{pl}	$\mathcal{B}\times 10^{-7}$
$D^0 \to pe^-$	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

- Most stringent limit for electron modes to date
- First measurement for muon channels



[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)

Summary

- Belle and Belle II provide a unique environment for charm physics both in meson and baryon decays, sensitively in SM measurements and search for physics beyond the SM
- Belle is still producing important measurements for more than 10 years after the end of data taking
  - Search for T-odd CPV in $D^+_{(s)} \to K^\pm h^\pm \pi^+ \pi^0$
  - Search for rare decays: FCNC $D^0 \to hh' e^+ e^-$, semi-leptonic $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$, BNV $D \to p\ell$
- 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
- Analyses ongoing… (Unblinded, not released yet)
  - Search for CPV for $D^0 \to K_S^0 K_S^0$
  - a_{CP}^{T-odd} in $D^+_{(s)} \to K_S^0 K^- \pi^+ \pi^+$ for more observables
  - Mixing in $D^0 \to K_S \pi\pi$
  - Precise $\mathcal{B}(\Lambda_c^+ \to p K_S^0 \pi^0)$ measurement

Thank you for your attention!

Backups

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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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 ($n_{\rm broken}/n_{\rm sig}$)	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

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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