# Rare and Radiative Charm Decays with Belle and Belle II

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On behalf of Belle and Belle II Collaborations

**12th International Workshop on Charm Physics, May 12-May 16, 2025, Shanghai, China**

# Talk Outline

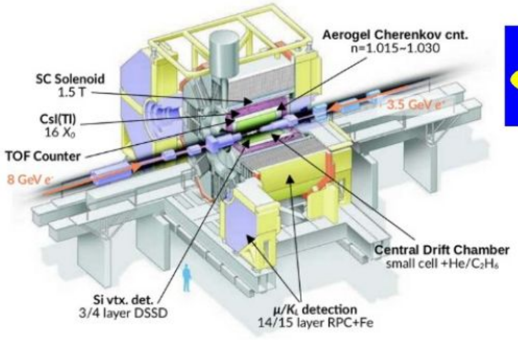
- Introduction
- Belle and Belle II detectors
- Search for rare decays:
  - SCS $\Xi_c^+$ decays
  - $\Xi_c^0 \to \Xi_0 h^0$ ($h^0 = \pi^0, \eta, \eta'$)
  - SL $\Xi_c \to \Xi^0 \ell^+ \ell^-$
  - FCNC $D^0 \to h h' e^+ e^-$
  - $\Lambda_c^+$ Decays
  - BNV $D \to p\ell$
- Summary

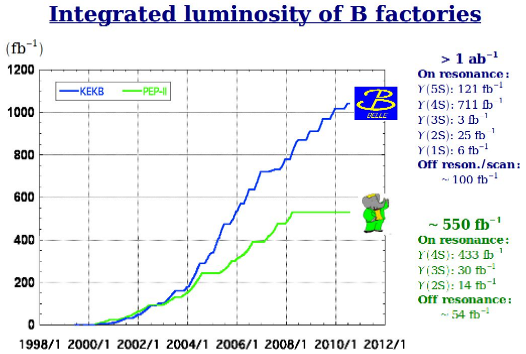
# Introduction

- Charm quark is the only up-type quark that can have flavor oscillations.
- Charm decays provide a unique window on new physics (NP) affecting the up-type quark dynamics.
- FCNC decays ($c \to u$) are sensitive to New Physics - forbidden at the tree level and highly suppressed due to the GIM mechanism in SM.
- Rare charm decays that simultaneously violate B and L but conserve $\Delta(B-L)$ help probe various GUT and many SM extensions.

# Belle and Belle II

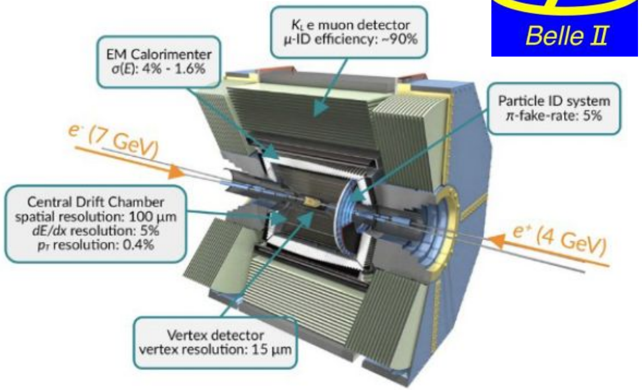
- Belle and Belle II operate(d) at asymmetric $e^+e^-$ colliders at or near the Υ(4S) resonance
- KEKB (1999 - 2010), Peak lumi = $2\text{x}10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$, $L_{int}$ = 1/ab
  Belle @ KEKB, $L_{int}$ > 1/ab
- SuperKEKB, Peak Lumi = $5.1\text{x}10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
  Belle II @ SuperKEKB
  Run 1 (2019 - 2022), $L_{int}$ = 0.42/ab
  Run 2 (2024 – present), $L_{int}$ = 0.15/ab

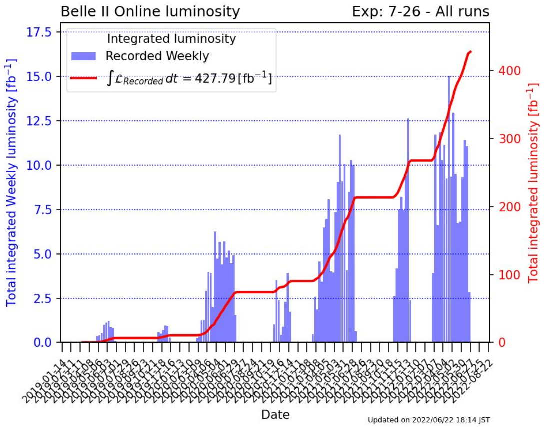


# Belle and Belle II

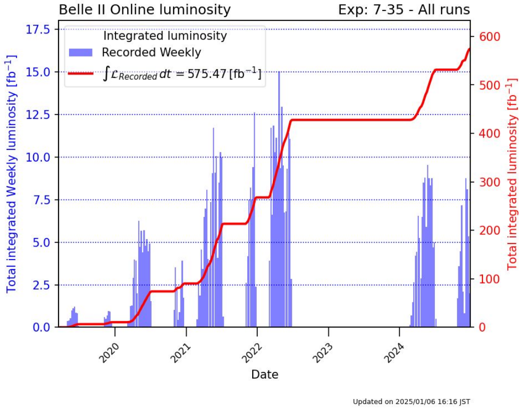
Belle II: Enhanced or same performance compared to Belle




Belle & Belle II are now synergic experiments

- Belle data can be analyzed with the Belle II software
- Analyses with combined data samples; Common review process in place



# Belle II Physics Potential

Belle II operates mainly at $\sqrt{s}$ = 10.58 GeV:

- $\sigma(e^+ e^- \to b\bar{b}) \sim 1.1$ nb

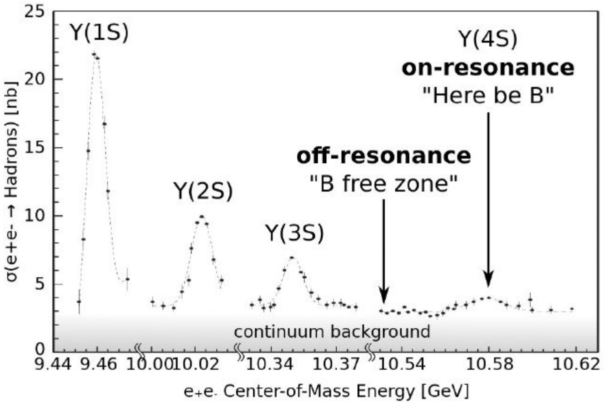
$L_{peak} = 2.7 \times 10^{34}\ cm^{-2}\ s^{-1} \to 30\ B\bar{B}$ /s

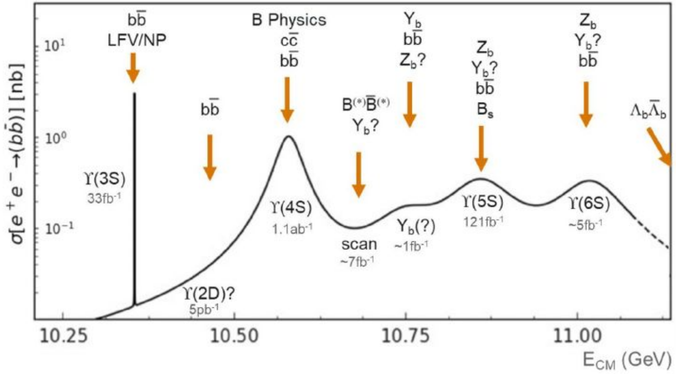
- $\sigma(e^+ e^- \to \tau\tau) \sim 0.9$ nb
- $\sigma(e^+ e^- \to c\bar{c}) \sim 1.3$ nb

→ B & τ & c factory

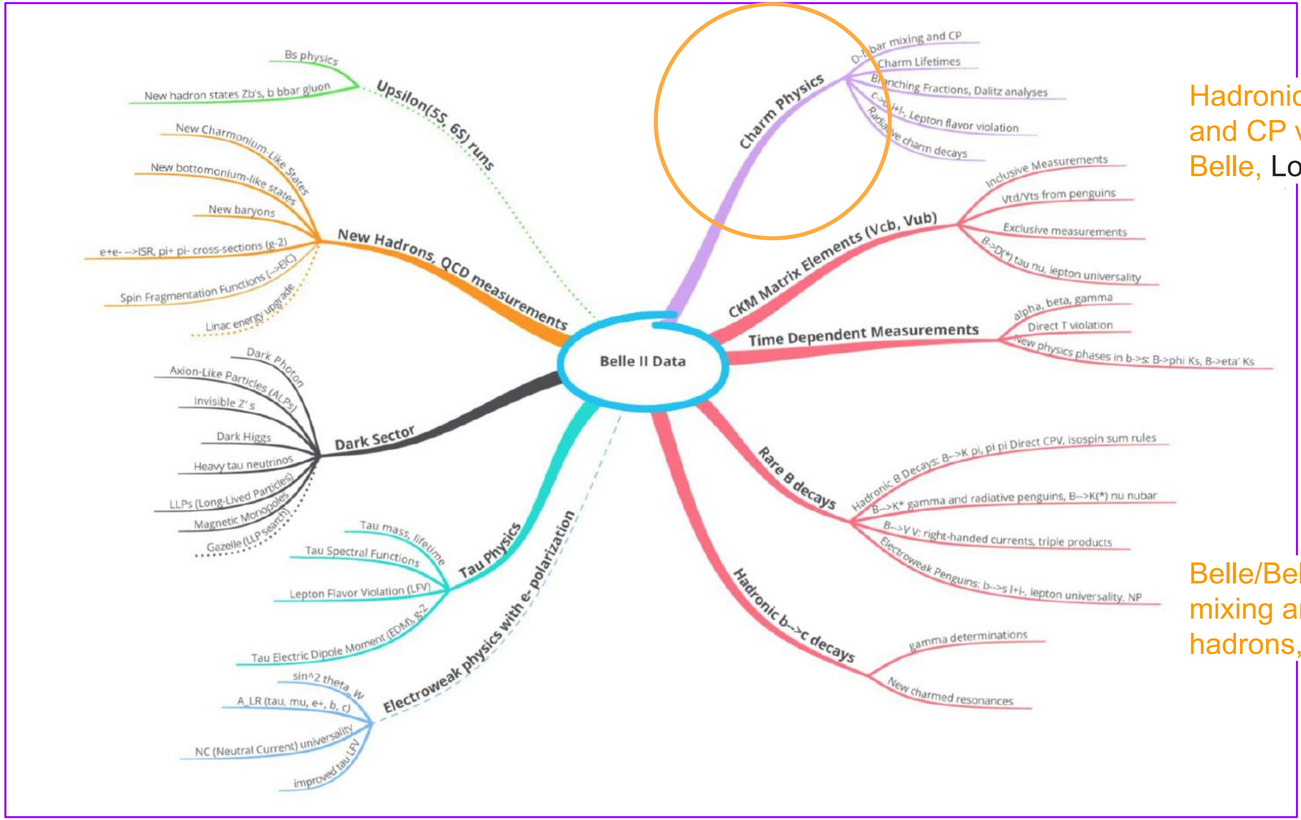
B Factories can extend their physics programs with non-Y(4S) data

- Belle II: 2019 unique energy scan at ~10.75 GeV



# Belle II Physics Program




Hadronic decays of charmed hadro[ns] and CP violation with Belle II and Belle, Longke Li

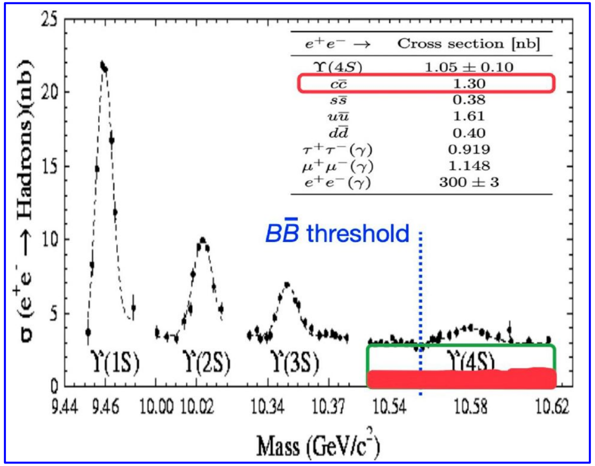
Quarkonium spectroscopy at Belle and Belle II, Sen Jia

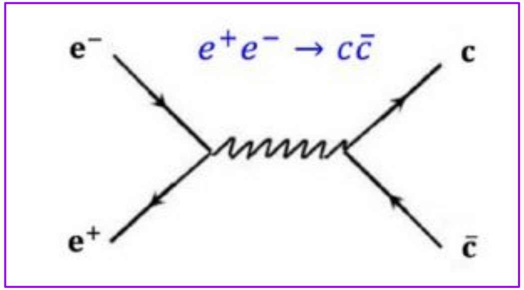
Belle/Belle-II results for D-Dbar mixing and lifetimes of charmed hadrons, Yinghui Guan

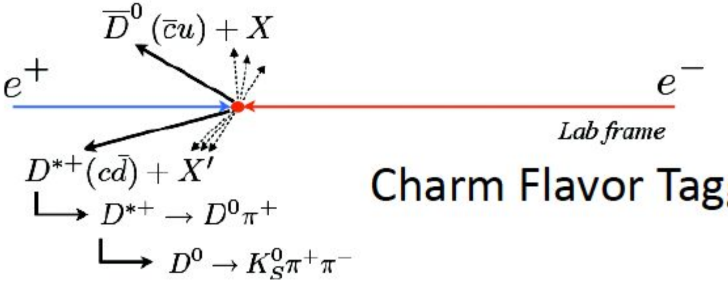
# Charm Production at Belle (II)

Two ways of producing charm at B-Factories:

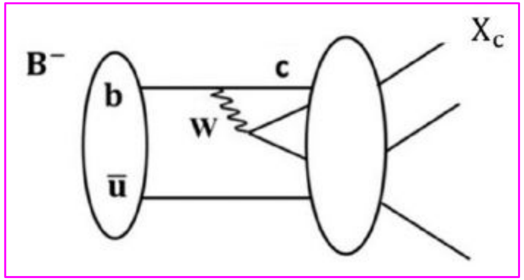
- Two charmed hadrons produced from continuum
- One or more charmed hadrons produced in B decays




Charm Flavor Tagging




$$e^+e^- \to c\bar{c} \to D_{\text{tag}} X_{\text{frag}} D_{\text{sig}}$$

# Charm Physics Program

Rich physics program:

• Mesons: Precise measurement in Cabibbo-suppressed decays,
non-SM physics can contribute at a detectable level
Most interesting probes: CPV measurements, expect low values in charm sector ($O(10^{-3})$)

• Baryons: Conflicting or missing predictions for BF and lifetimes
results → to verify models

# $\Xi_c^+$ Branching Fractions

JHEP03(2025)061
arXiv:2503.17643

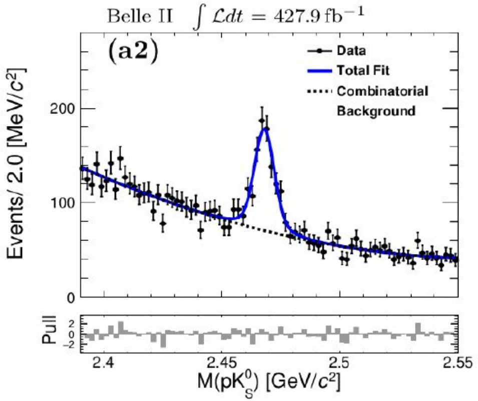
$\Xi^+_c$ decay channels: (many) not yet measured
Currently many predictions
→ need measurement to rule out some of them

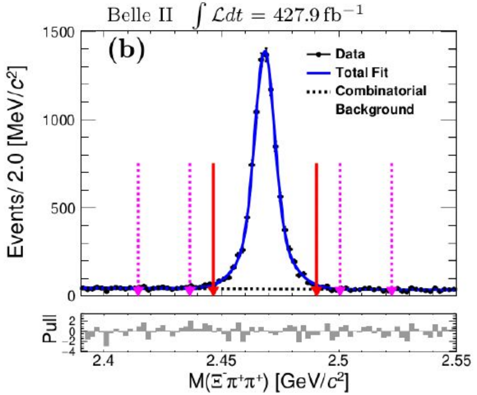
**Reconstruct:**

- (CF) $\Xi^+_c \to \Sigma^+ K_S$, $\Xi^+_c \to \Xi^0\pi^+$
- (SCS) $\Xi^+_c \to \Xi^0 K$, $\Xi^+_c \to pK_S$, $\Xi^+_c \to \Lambda\pi$, $\Xi^+_c \to \Sigma\pi$

**Analysis strategy:**

- Reconstruct intermediate baryons Λ, Σ, Ξ, optimize selection ranges on each invariant mass
- Signal yields: fitting the invariant mass
- Branching fractions: $\Xi^+_c \to \Xi^- \pi^+\pi^+$ as normalization mode

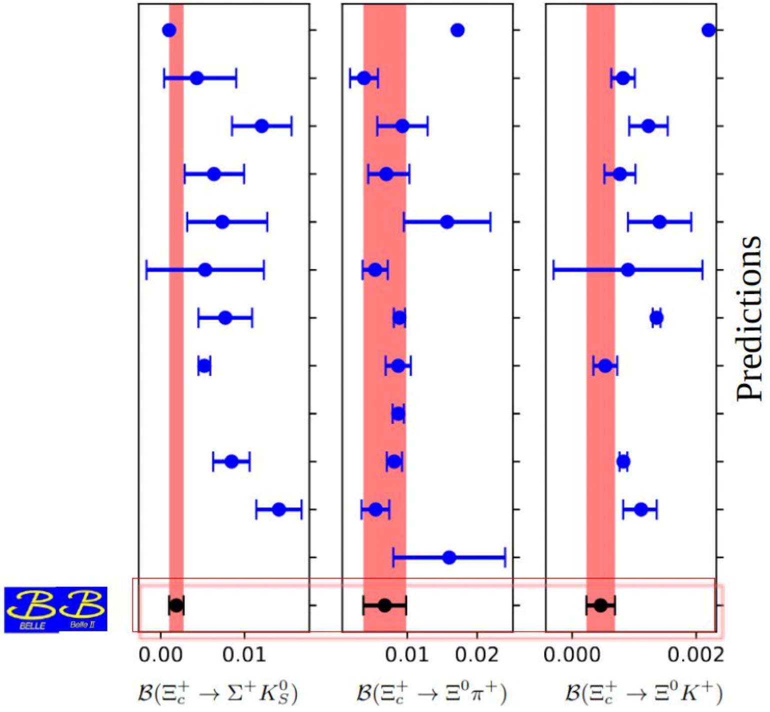


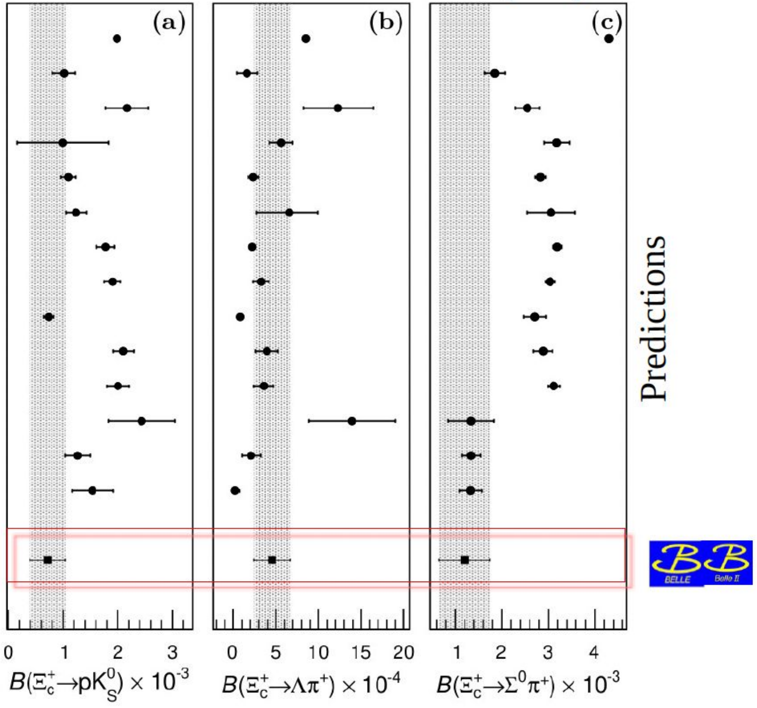
# $\Xi_c^+$ Branching Fractions

First or most precise measurements!

arXiv:2503.17643

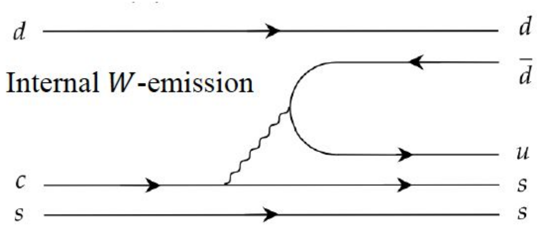


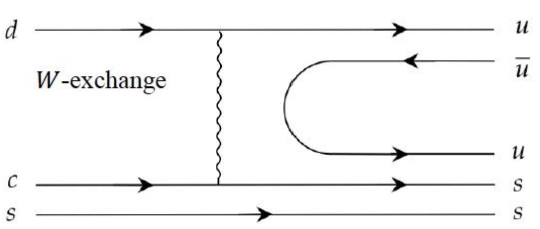

JHEP03(2025)061



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

- Hadronic two-body decay of charmed baryons: Non-factorizable amplitudes from internal W-emission and W-exchange diagram lead to the difficulties for theoretical predictions
- Several theoretical approaches developed to deal with non-factorizable contributions give various predictions on branching fractions (in units of $10^{-3}$) and decay asymmetry parameters [1-14].
- Need experimental measurement to clarify the theoretical picture.





[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)

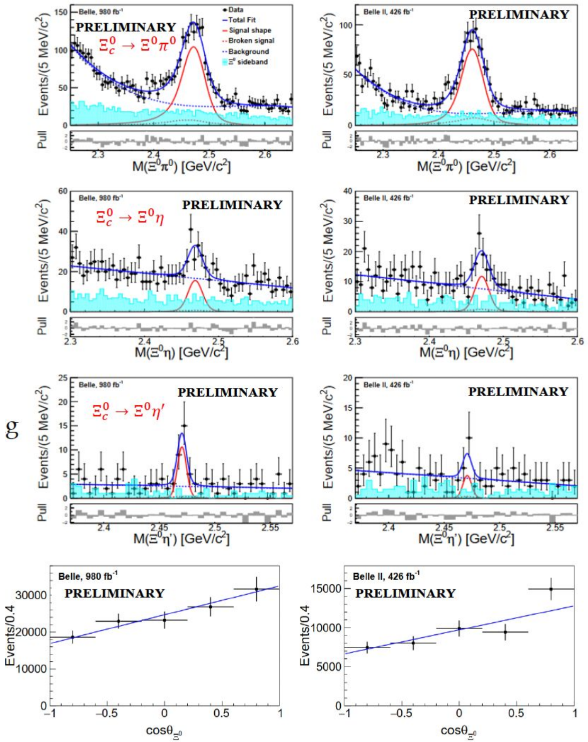
# $\Xi_c \to \Xi^0 h^0$ ($h^0 = \pi^0, \eta, \eta'$)

JHEP10(2024)045
**arXiV: 2406.04642**

- First Belle + Belle II combined measurement
  - $\mathcal{B}(\Xi_c \to \Xi^0\pi^0) = 6.9 \pm 0.3 \pm 0.5 \pm 1.5\,(\text{norm.}) \times 10^{-3}$
  - $\mathcal{B}(\Xi_c \to \Xi^0\eta) = 1.6 \pm 0.2 \pm 0.2 \pm 0.4\,(\text{norm.}) \times 10^{-3}$
  - $\mathcal{B}(\Xi_c \to \Xi^0\eta') = 1.2 \pm 0.3 \pm 0.1 \pm 0.3\,(\text{norm.}) \times 10^{-3}$
- Reference mode: $\Xi_c \to \Xi^-\pi^+$
- Rules out several theoretical models; Favors predictions in SU(3) flavor symmetry [JHEP 02, 235 (2023)]
- First asymmetry parameter $\alpha(\Xi_c \to \Xi^0\pi^0) = -0.90 \pm 0.15 \pm 0.23$
- through a simultaneous fit to Belle and Belle II data samples depending on differential decay rate

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

- Taking $\alpha(\Xi_c \to \Lambda\pi^0) = -0.349 \pm 0.009$ (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)

# $\Xi_c \rightarrow \Xi^0 \ell^+ \ell^-$

PRD 109, 052003 (2024)

[1] PRD 84, 072006(2011)
[2] PRD 97, 091101(2018)

- No neutrinoless semileptonic decays of charmed baryons observed yet.
- Only upper limits of $\Lambda_c \rightarrow p\ell^+\ell^-$ decays were set for charmed baryons [1,2], which receive both W-exchange and FCNC process contributions.
- Theoretical prediction gives upper limits at 2.35 (2.25) × $10^{-6}$ for electron (muon) mode.
- If observed, the signal channels would allow test LFU.
- First search for $\Xi_c^0 \rightarrow \Xi_0 \ell^+\ell^-$ ($\ell = e, \mu$)

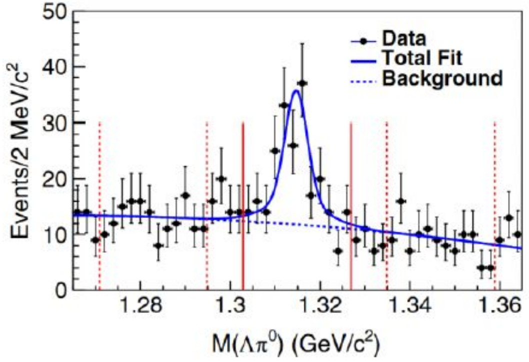
  Fully reconstruct with $\Xi^0 \rightarrow \Lambda\pi^0$

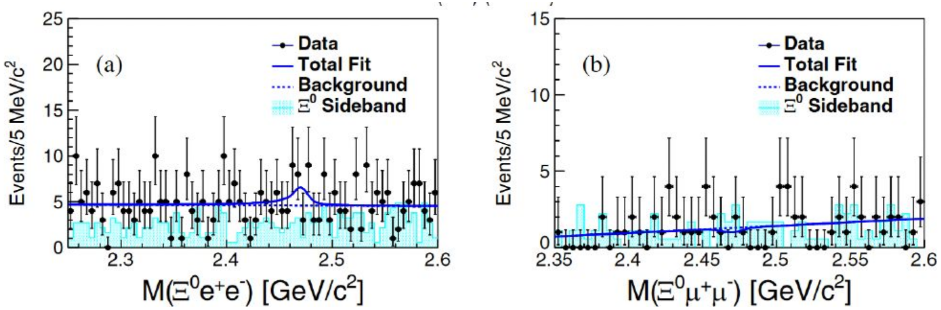
  Reference mode: $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- No significant signals observed

  Set upper limits at 90% CL:

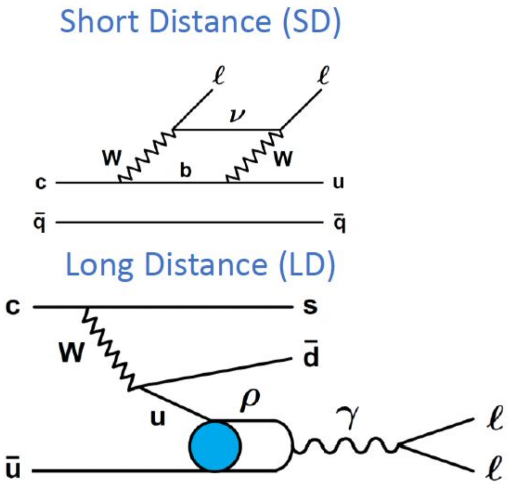
  $\mathcal{B}(\Xi_c^0 \rightarrow \Xi_0 e^+ e^-) < 9.9 \times 10^{-5}$

  $\mathcal{B}(\Xi_c^0 \rightarrow \Xi_0 \mu^+ \mu^-) < 6.5 \times 10^{-5}$

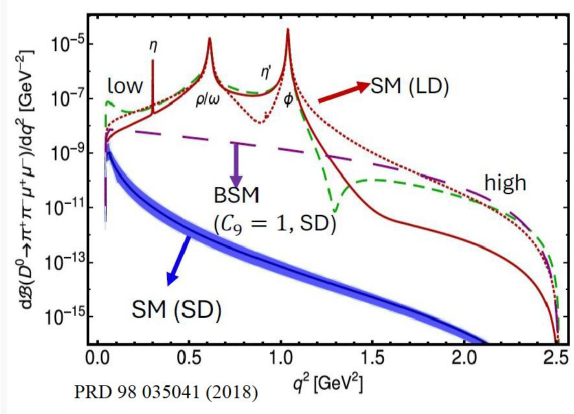


# $D^0 \to h h' e^+ e^-$ ($h^{(\prime)} = K, \pi$)




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

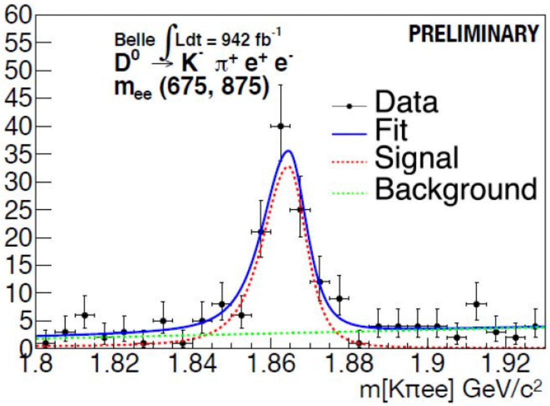



Measured BFs or ULs at 90% CL [$\times 10^{-7}$]

| | $KKee$ | $\pi\pi ee$ | $K\pi ee$ |
|---|---|---|---|
| BABAR | – | – | $40.0 \pm 5.0 \pm 2.3$ ($\rho/\omega$)<br>$< 31$ (non-resonant) |
| BESIII | $< 110$ | $< 70$ | $< 410$ |
| | $KK\mu\mu$ | $\pi\pi\mu\mu$ | $K\pi\mu\mu$ |
| LHCb | $1.54 \pm 0.27 \pm 0.19$ | $9.64 \pm 0.48 \pm 1.10$ | $4.17 \pm 0.12 \pm 0.40$ ($\rho/\omega$) |

BABAR: PRL 122, 081802 (2019)
BESIII: PRD 97, 072015 (2019)
LHCb: PRL 119, 181805 (2017) PLB 517, 558

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



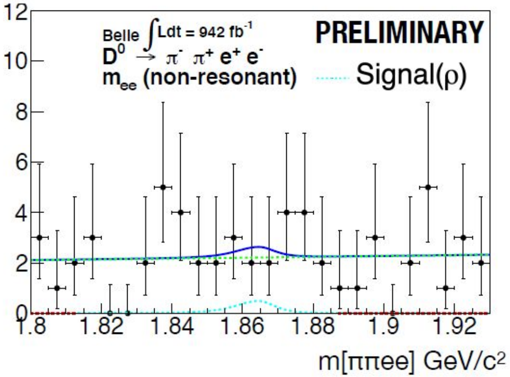

Signal observed for $D^0 \to K^-\pi^+e^+e^-$ in $\rho/\omega$ region ($11.8\sigma$)

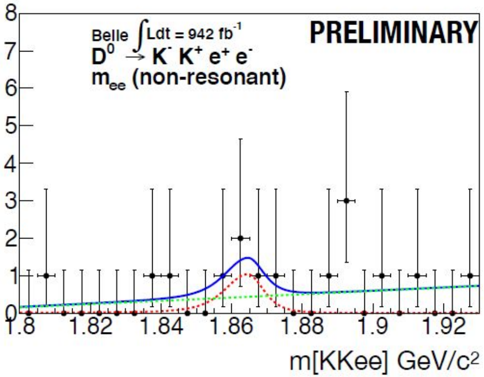
$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$

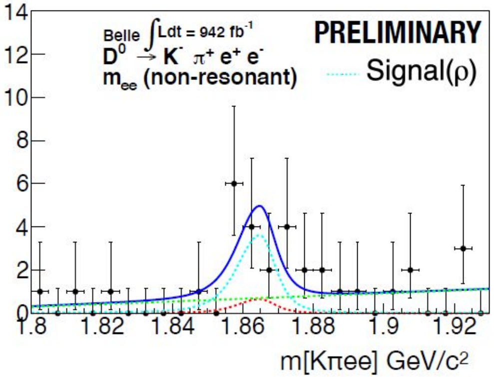
- Compatible with BABAR and with SM expectation

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
- Reference mode: $D^0 \to K^-\pi^+\pi^-\pi^+$



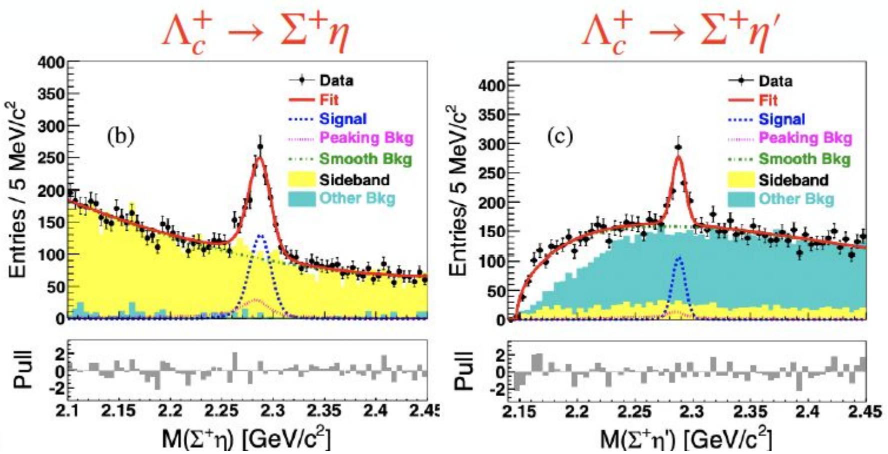



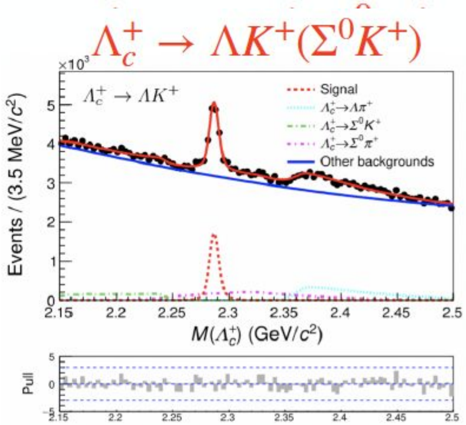
# $\Lambda_c^+$ Decays

CF Decays

Belle 980/fb, PRD **107**, 032003 (2023)




Belle 980/fb,
Science Bulletin **68**, 583 (2023)



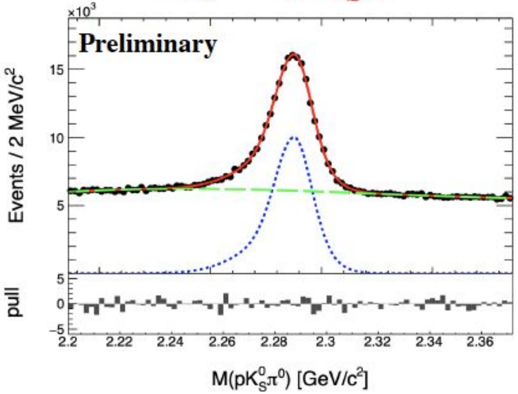

- $B(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.17 \pm 0.25) \times 10^{-3}$
- $B(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.17 \pm 0.25) \times 10^{-3}$
- $B(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$

# $\Lambda_c^+$ Decays

SCS Decays

arXiv:2503.04371

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

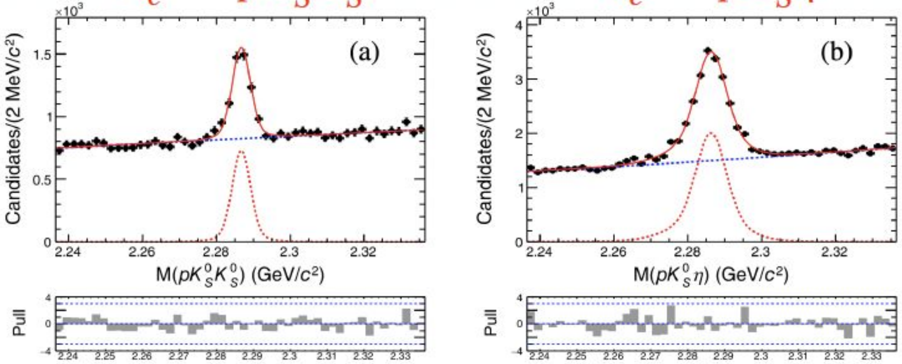



$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0) = (2.12 \pm 0.01 \pm 0.05 \pm 0.10)\%,$$

First or most precise BF measurements

Belle 980/fb, PRD **103**, 032004 (2023)

$\Lambda_c^+ \to pK_S^0K_S^0$ $\Lambda_c^+ \to pK_S^0\eta$




- $B(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.07 \pm 0.04) \times 10^{-4}$
- $B(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$
- $B(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$

# $D^0 \to p\ell$

[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)

- Baryon Number Violation (BNV) is a required condition to explain the observed matter-antimatter asymmetry.
- Nucleon BNV allowed in several BSM theories ([1]-[5]), with $\Delta(B - L) = 0$, where B (L) is the baryon (lepton) number
- Interest in search for BNV processes also in meson decays [allowed e.g. in GUT, leptoquarks]
- D ➔ pl(e/μ) simultaneously violates B and L but conserves $\Delta(B-L)$.
- Branching fractions for D ➔ $pe^+$ are predicted to be of the order of $10^{-39}$.
- Using Belle data, search for D ➔ pl(e/μ) done with D ➔ $K\pi$ as control channel.

PRD 109, L031101 (2024)

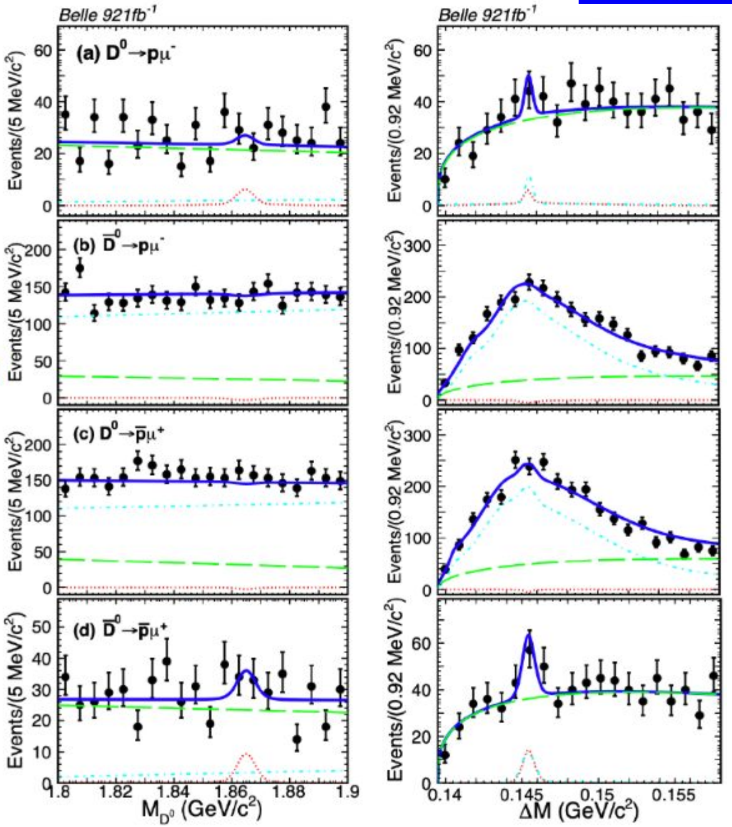
# $D^0 \to p\ell(\ell = e, \mu)$

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

✓ No signal observed

Most stringent limit for electron modes to date

- First measurement for muon channels



# Summary

- Belle and Belle II provide a unique environment for charm physics, both in meson and baryon decays.
- Belle is still producing important measurements more than a decade after the end of data taking.
- Belle + Belle II combined data sample provides an excellent platform for further charm measurements. Several ongoing analyses, such as $D^{*}{}_{s}{}^{0}(2317)^{+} \to D^{*+}{}_{s}\,\gamma$, $D_{s}{}^{*+} \to D_{s}{}^{+}\,\pi^{0}/\gamma$, $D_{s} \to \rho\gamma/K^{*}\gamma$.
- Belle II has started Run 2 data taking, expecting more physics results with a larger data sample.

# $\Xi_c^+$ Invariant Mass Fits