Charm physics at Belle and Belle II experiments

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BELLE

Belle II

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Jan 18, 2024, Univ. of Sci & Tech of China (my alma mater ♡)

Outline

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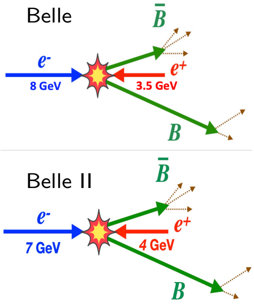
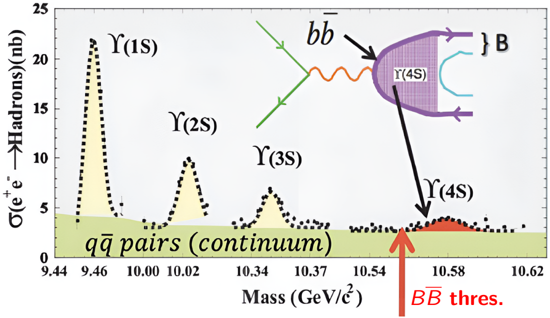
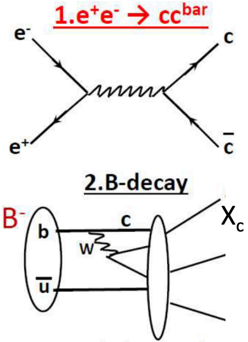
Charm production at Belle and Belle II

- At Belle (II), e^+e^- mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance decaying into $B\bar{B}$ in 96% of the time.
- Meanwhile, continuum processes $e^+e^- \to q\bar{q}$ ($q = u,\ d,\ s,\ c$) have large cross sections.
- Two ways to produce the charm sample: $e^+e^- \to c\bar{c}$ ($\sigma = 1.3$ nb), and $B \to$ charm decays.
- To date, Belle and Belle II have accumulated datasets with an integrated luminosity of 1.4 ab^{-1}.







Comparison of available charm samples

Experiment	Machine	C.M.	Luminosity	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 (8 → 20) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7 (\to 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	$\sim$ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	0.4 (→ 50) ab^{-1}	D^0: 6×10^8 ($\to 10^{11}$) $D_{(s)}^+$: 10^8 ($\to 10^{10}$) Λ_c^+: 10^7 ($\to 10^9$)	$\mathcal{O}$(1-10%) ★★	☺ high-efficiency detection of neutrals ☺ good trigger efficiency ☺ time-dependent analysis ☹ smaller cross-section than LHCb
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$D^{0,+}$, D_s^+: 10^9 Λ_c^+: 10^8 ★★☆		
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} (→ 23 → 50) fb^{-1}	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ very large production cross-section ☺ large boost, excellent time resolution ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0@3.77\,\text{GeV})$=3.61 nb, $\sigma(D^+D^-@3.77\,\text{GeV})$=2.88 nb, $\sigma(D_s^*D_s@4.17\,\text{GeV})$=0.967 nb; $\sigma(c\bar{c}@10.58\,\text{GeV})$=1.3 nb where each $c\bar{c}$ event averagely has 1.1/0.6/0.3 $D^0/D^+/D_s^+$ yields; $\sigma(D^0@CDF)$=13.3 μb, and $\sigma(D^0@LHCb)$=1661 μb, mainly from *Int. J. Mod. Phys. A* **29** *(2014)24,14300518*.

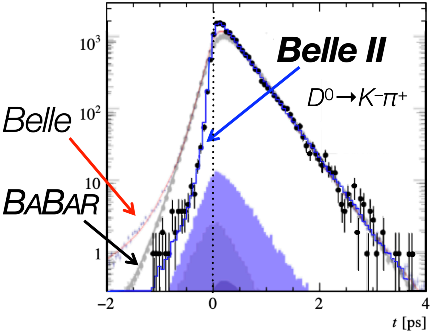
- BESIII, Belle II, and LHCb experiments have their advantages for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.

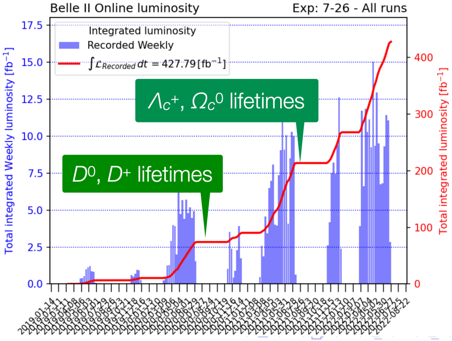
Outline

Charm lifetimes at Belle II

PRL 127, 211801 (2021); PRL 130, 071802 (2023); PRD 107, L031103 (2023)

- Hadron lifetimes are difficult to calculate theoretically, as they depend on nonperturbative effects arising from quantum chromodynamics (QCD).
- Comparing calculated values with measured values improves our understanding of QCD. [(FLAG) EPJC 82, 869 (2022)]
- At Belle II, the decay-time resolution is $\times 2$ better than that at Belle/BABAR.
- Based on the early Belle II dataset, the most precise charm lifetimes are measured: $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs, $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs, and $\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77$ fs as first precision measurements at Belle II.





Precise measurement of D_s^+ lifetime at Belle II

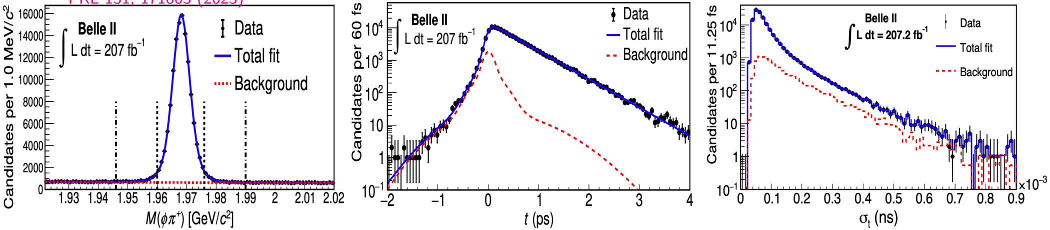
(Belle) PRL 131, 171803 (2023)

- A clear sample of $D_s^+ \to \phi\pi^+$ with 116K signals and 92% purity, is obtained using 207 fb^{-1}.
- Lifetime determined from unbinned ML fit to lifetime (t). The likelihood function for ith event:

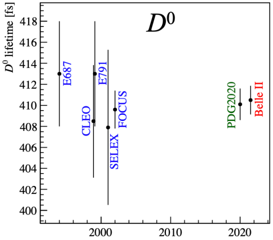
$$\mathcal{L}(\tau|t^i,\sigma_t^i) = f_{\text{sig}} P_{\text{sig}}(t^i|\tau,\sigma_t^i) P_{\text{sig}}(\sigma_t^i) + (1 - f_{\text{sig}}) P_{\text{bkg}}(t^i|\tau,\sigma_t^i) P_{\text{bkg}}(\sigma_t^i)$$

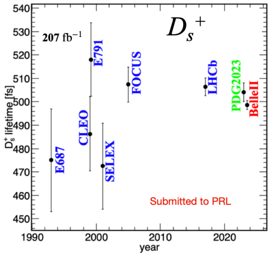
  where $P_{\text{sig}}(\sigma_t^i)$ and $P_{\text{bkg}}(\sigma_t^i)$ exist to avoid the Punzi bias [arXiv:physics/0401045].
- Result: $\tau_{D_s^+} = (499.5 \pm 1.7 \pm 0.9)$ fs; the world most precise measurement to date.
- The small systematic uncertainty demonstrates the excellent performance and understanding of the Belle II detector.

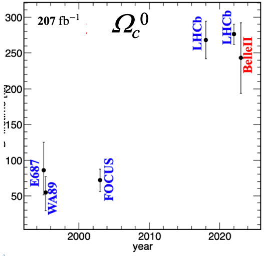
PRL 131, 171803 (2023)

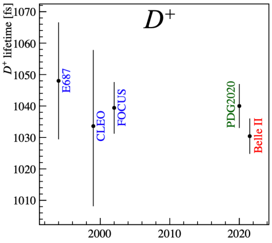


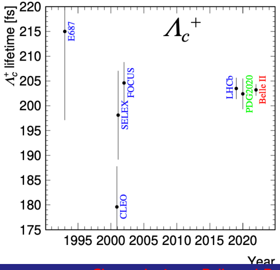
Charm lifetime summary











- In all cases except for Ω_c^0, Belle II has made the world's highest precision measurement (in some cases after 20 years)
- For Ω_c^0, the Belle II measurement confirms the longer lifetime measured by LHCb.

Outline

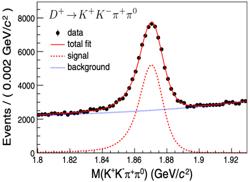
Branching fraction of charmed meson Cabibbo-suppressed decays

- Cabibbo-suppressed (CS) hadronic decays of charm mesons provide a powerful means to search for new physics. It is important to measure such decays with high precision.

- Singly Cabibbo-suppressed (SCS) charm decay: essential probes of charm CPV and new physics beyond the SM.
- Large charm sample at Belle and Belle II provides a good platform to measure their branching fractions ($\mathcal{B}$) precisely.
- Based on Belle full dataset, the first or most precise $\mathcal{B}$ results for charmed meson decays were reported recently:
- SCS decay:
  - $\mathcal{B}(D^+ \to K^+K^-\pi^+\pi^0) = (7.08 \pm 0.08 \pm 0.16 \pm 0.20) \times 10^{-3}$
  - $\mathcal{B}(D_s^+ \to K^+\pi^-\pi^+\pi^0) = (9.44 \pm 0.34 \pm 0.28 \pm 0.32) \times 10^{-3}$
  - $\mathcal{B}(D_s^+ \to K^+K^-K_S^0\pi^+) = (1.29 \pm 0.14 \pm 0.04 \pm 0.11) \times 10^{-4}$
- DCS decay:
  - $\mathcal{B}(D^+ \to K^+\pi^-\pi^+\pi^0) = (1.05 \pm 0.07 \pm 0.02 \pm 0.03) \times 10^{-3}$

  (confirm BESIII discovery of such significantly larger $\mathcal{B}$ than other known DCS decays)

PRD 107, 033003 (2023)



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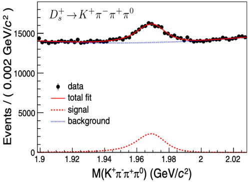
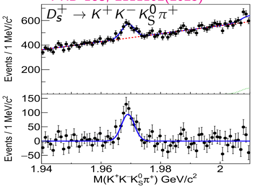


PRD 108, L111102(2023)



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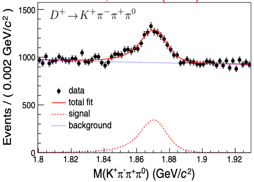
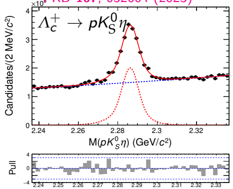


Branching fraction of charmed baryon decays

- The weak decays of charmed baryons provide an excellent platform for understanding QCD with transitions involving the charm quark. The decay amplitudes consist of factorizable and non-factorizable contributions.

- First or most precise $\mathcal{B}$ results for charmed baryon decays.
- CF decays:
  - $\mathcal{B}(\Lambda_c^+ \to p K_S^0 \eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$
  - $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta) = (3.14 \pm 0.35 \pm 0.17 \pm 0.25) \times 10^{-3}$
  - $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \eta') = (4.16 \pm 0.75 \pm 0.25 \pm 0.33) \times 10^{-3}$
- SCS and DCS decays:
  - $\mathcal{B}(\Lambda_c^+ \to p K_S^0 K_S^0) = (2.35 \pm 0.12 \pm 0.07 \pm 0.12) \times 10^{-4}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$
  - $\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 0.253 \pm 0.052 \pm 0.030$
  - $\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} < 0.070$

PRD **107**, 032004 (2023)



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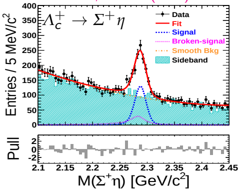

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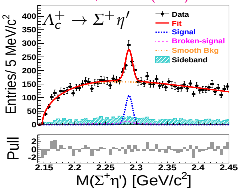

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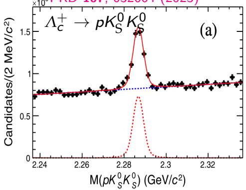
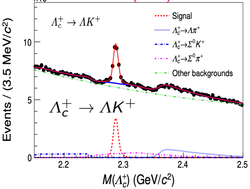
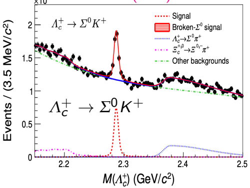


Sci. Bull. **68** (2023) 583

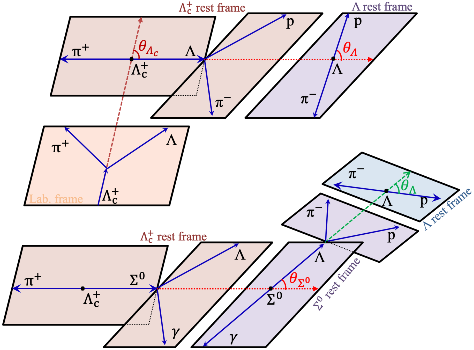


Sci. Bull. **68** (2023) 583



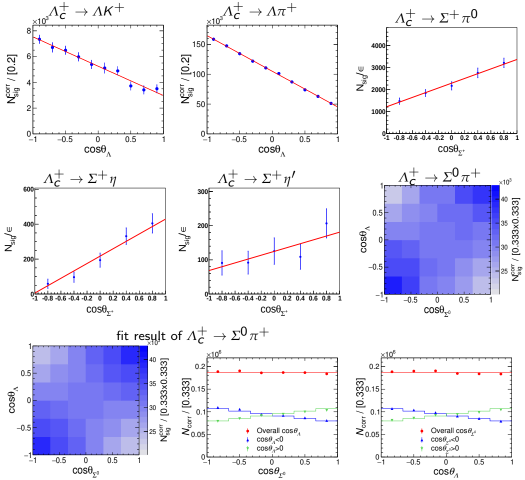
Decay asymmetry parameter α of charmed baryon decays

- The decay asymmetry parameter α was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays.
- In $1/2^+ \to 1/2^+ + 0^-$, $\alpha \equiv 2 \cdot \mathrm{Re}(S^* P)/(|S|^2 + |P|^2)$, where S and P denote the parity-violating S-wave and parity-conserving P-wave amplitudes, respectively.
- For $\Lambda_c^+ \to \Lambda h^+, \Sigma^+ h^0$ decays, the differential decay rate depends on α: $\boxed{\frac{dN(\Lambda_c^+ \to \Lambda h^+)}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda}$ where α_- is hyperon decay asymmetry parameter.
- For $\Lambda_c^+ \to \Sigma^0 h^+$ decays, considering $\alpha(\Sigma^0 \to \gamma\Lambda)$ is zero due to parity conservation for an electromagnetic decay, the differential decay rate $\boxed{\frac{dN(\Lambda_c^+ \to \Sigma^0 h^+)}{d\cos\theta_{\Sigma^0}\, d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda}$
- By studying the hyperon helicity angle, we can extract α of charmed baryon decays.



Decay asymmetry parameter α of charmed baryon decays

- Distribution of efficiency-corrected yields and the fitting result:



- No approaches based on various theories could successfully predict all these experimental α values.
  $\Rightarrow$ needs a joint effort from theory and experiment in future.

Decay	α at Belle	W.A. or BESIII
$\Lambda_c^+ \to pK_S^0$	–	0.18 ± 0.45 [a]
$\Lambda_c^+ \to \Lambda K^+$	-0.585 ± 0.052 [b]	–
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.54 ± 0.20 [b]	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.755 ± 0.006 [b]	-0.84 ± 0.09
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.463 ± 0.018 [b]	-0.73 ± 0.18 [c]
$\Lambda_c^+ \to \Sigma^+ \pi^0$	-0.480 ± 0.028 [d]	-0.55 ± 0.11
$\Lambda_c^+ \to \Sigma^+ \eta$	-0.990 ± 0.058 [d]	–
$\Lambda_c^+ \to \Sigma^+ \eta'$	-0.460 ± 0.067 [d]	–
$\Lambda_c^+ \to \Xi^0 K^+$	–	0.01 ± 0.16 [e]
$\Lambda_c^+ \to \Lambda \rho^+$	–	-0.76 ± 0.07 [f]
$\Lambda_c^+ \to \Sigma'^+ \pi^0$	–	-0.92 ± 0.09 [f]
$\Lambda_c^+ \to \Sigma'^0 \pi^+$	–	-0.79 ± 0.11 [f]
$\Xi_c^0 \to \Xi^- \pi^+$	-0.64 ± 0.05 [g]	$-0.56 \pm 0.39^{+0.10}_{-0.09}$ [h]
$\Xi_c^0 \to \Lambda \bar{K}^{*0}$	$+0.15 \pm 0.22$ [i]	–
$\Xi_c^0 \to \Sigma^+ K^{*-}$	-0.52 ± 0.30 [i]	–

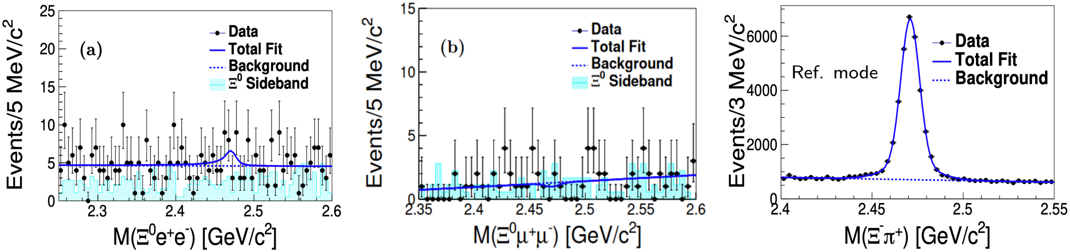
[a] BESIII, PRD **100**, 072004 (2019)
[b] Belle, Sci. Bull. **68**, 583 (2023)
[c] BESIII, PRD **100**, 072004 (2019)
[d] Belle, PRD **107**, 032003 (2023)
[e] BESIII, arXiv:2309.02774
[f] BESIII, JHEP **12**, 033 (2022)
[g] Belle, PRL **127**, 121803 (2021)
[h] CLEO, PRD 63, 111102 (2001)
[i] Belle, JHEP **06**, 160 (2021)

Outline

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

(Belle) arXiv:2312.02580

- In the Standard Model (SM), the weak-current interaction has an identical coupling to all lepton generations, which allows Lepton Flavor Universality (LFU) to be tested in the semileptonic decays of the hadrons.
- The $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ is one of such decays; measurement of both $\ell = e$ and μ decay rates would allow an LFU test to be performed.
- Result: $\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ e^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} < 6.7 \times 10^{-3}$ and $\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \mu^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} < 4.3 \times 10^{-3}$
  (PS: we still do not have any good absolute $\mathcal{B}$ result for Ξ_c^0 decays)



- A more precise analysis based on larger data samples collected by Belle II is expected in the future.

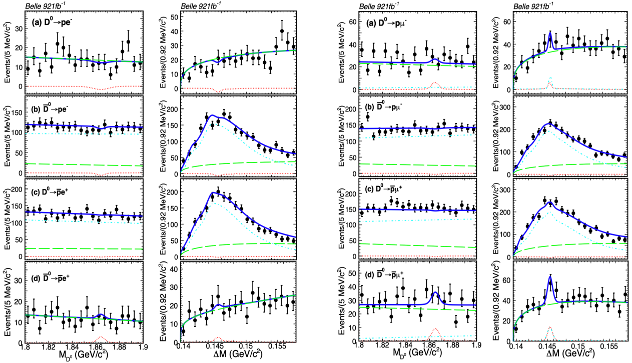
Search for $D \to p\ell$ at Belle

(Belle) arXiv:2310.07412

- Baryon number violation (BNV) is one of the crucial conditions to create the matter-antimatter asymmetry as observed in the universe.
- Several grand unified theories, supersymmetry and other SM extensions propose BNV processes of nucleons.
- $D \to p\ell$: baryon (B) and lepton (L) numbers violated but their difference conserved ($\Delta(B-L) = 0$)
- pre-Belle stringent limits: $\mathcal{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^{-6}$ and $\mathcal{B}(D^0 \to pe^-) < 2.2 \times 10^{-6}$ from BESIII.
- Recently, Belle performed such search.
  Stricter upper limits were set:
  $(5-8) \times 10^{-7}$ at a 90% C.L.

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
$\overline{D}^0 \to pe^-$	10.2	-18.4 ± 23.0	—	22.0	< 6.9
$D^0 \to \bar{p}e^+$	9.7	-4.7 ± 23.0	—	22.0	< 7.2
$\overline{D}^0 \to \bar{p}e^+$	9.6	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
$\overline{D}^0 \to p\mu^-$	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
$\overline{D}^0 \to \bar{p}\mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5



Outline

Why *CP* Violation and Charm CPV Special?

[A.D. Sakharov, Usp. Fiz. Nauk 161 (1991) 61]

Citations per year

- The violation of *CP*-symmetry: the combination of charge conjugation symmetry and parity asymmetry, is essential for elucidating the matter-antimatter asymmetry in the universe.
- The sole origin of *CP* violation (CPV) in SM arises from the single complex phase in the Cabibbo-Kobayashi-Maskawa matrix.
- However, this source is insufficient to account for the observed matter-antimatter asymmetry. $\Rightarrow$ we need to search for new CPV sources beyond SM (a lasting hot topic).
- Three necessary "Sakharov conditions" are:
  1) Baryon number violation; 2) *C* and *CP* violation; 3) Interactions out of thermal equilibrium.
- Charm CPV effect is very small ($\mathcal{O}(10^{-3})$ or smaller [a][b]). New Physics may enhance it [c][d].
- Study of charm CPV may help to understand the SM, and is a sensitive probe to search for New Physics.
- In 2019, *CP* violation in D^0 decays was found at LHCb: $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ).
  $\Rightarrow$ to understand this CPV, we need to study more channels and improve the precision on the existing measurements.
- CPV has been observed in all the open-flavored meson sector, but not yet established in the baryon sector.
  Baryogenesis, the process by which the baryon-antibaryon asymmetry of the universe developed, is directly related to baryon CPV [e].
  $\Rightarrow$ discovering the CPV in charmed baryon is one of main targets of charm physics.

[a] H.-n. Li, C.-D. Lu, and F.-S. Yu, PRD 86, 036012 (2012)
[b] H.-Y. Cheng and C.-W. Chiang, PRD 104, 073003 (2021)
[c] A. Dery and Y. Nir, JHEP 12, 104 (2019)
[d] M. Saur and F.-S. Yu, Sci. Bull. 65, 1428 (2020)
[e] M.E. Shaposhnikov, NPB 287, 757 (1987)

CPV in charm four-body decays

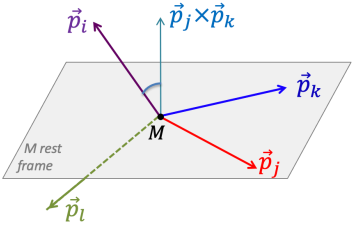
- Sensitivity of CPV relies on various physical decays, motivating CPV searches in diverse charm decays.
- The D four-body decay with large $\mathcal{B}$ and various intermediate processes provides different sample for CPV searches.
- CPV in D four-body decay was searched with triple-product asymmetries by the FOCUS, BABAR, LHCb and Belle experiments.
- Triple-product $C_T = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$ is calculated In the mother's rest frame, satisfing $CP(C_T) = -C(C_T) = -\overline{C}_T$.
- The T-odd asymmetries, taking for $D^\pm$ decays for example, are defined as

$$A_T(D^+) = \frac{N_+(C_T > 0) - N_+(C_T < 0)}{N_+(C_T > 0) + N_+(C_T < 0)} \quad \overline{A}_T(D^-) = \frac{N_-(-\overline{C}_T > 0) - N_-(-\overline{C}_T < 0)}{N_-(-\overline{C}_T > 0) + N_-(-\overline{C}_T < 0)}$$

- T-odd CP-asymmetry $a_{CP}^{\text{T-odd}} = \frac{1}{2}(A_T - \overline{A}_T)$, may be an observable complementary to the direct CPV (A_{CP}^{dir})

  With some conditions, $a_{CP}^{\text{T-odd}} \propto \sin\phi\cos\delta$ has largest value when $\delta = 0$ ($A_{CP}^{\text{dir}} \neq 0$ needs $\delta \neq 0$)

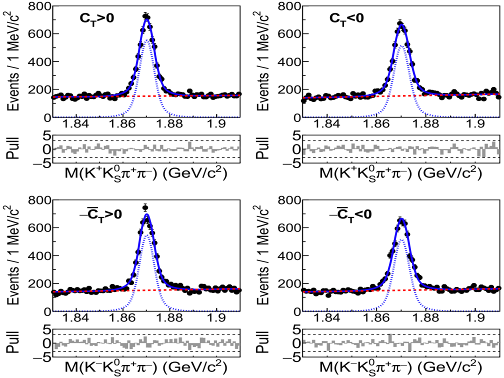
$M \to P_i P_j P_k P_l$

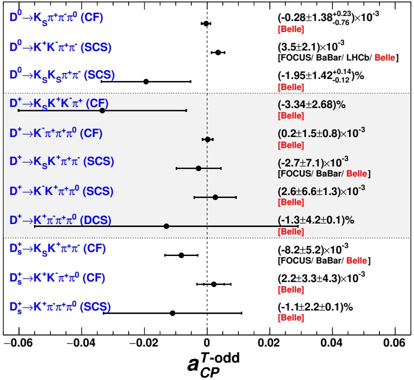


CPV in charm four-body decays

(Belle) PRD 107, 052001 (2023); PRD 108, L111102 (2023); arXiv:2305.12806

- Belle recently searched for CPV with T-odd correlations in decays of $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$, $D^+_{(s)} \to K_S^0 h^+\pi^+\pi^-$ and $D^+_{(s)} \to K h \pi^+\pi^0$.
- These $a_{CP}^{T\text{-odd}}$ results mostly are first or most precise measurement.



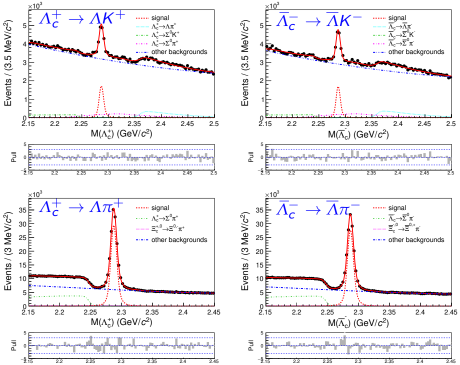


- $\sigma(a_{CP}^{T\text{-odd}})$ of all D mesons: reached $\mathcal{O}(0.1\%)$ level.
- Belle II/LHCb may improve the precision utilizing increased samples, and apply this method to charmed baryons.

direct CPV in $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

(Belle) Science Bulletin **68** (2023) 583

- The raw asymmetry of $\Lambda_c^+ \to \Lambda K^+$ includes several asymmetry sources:
  $A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_{\varepsilon}^{\Lambda} + A_{\varepsilon}^{K^+} + A_{\rm FB}^{\Lambda_c^+}$
  - $A_{CP}^{\Lambda_c^+ \to \Lambda K^+}$ ($A_{CP}^{\Lambda \to p\pi^-}$): CP asymmetry associated with Λ_c^+ (Λ) decay,
  - $A_{\varepsilon}^{\Lambda}$: detection asymmetry arising from efficiencies between Λ and $\bar{\Lambda}$.
  - $A_{\varepsilon}^{K^+}$: The $A_{\varepsilon}^{K^+}$ is removed by weighting $w_{\Lambda_c^+, \bar{\Lambda}_c^-} = 1 \mp A_{\varepsilon}^{K^+}[\cos\theta, p_T]$
  - $A_{\rm FB}^{\Lambda_c^+}$ arises from the forward-backward asymmetry (FBA) of Λ_c^+ production due to γ-Z^0 interference and higher-order QED effects in $e^+e^- \to c\bar{c}$ collisions.
- using CF mode $\Lambda_c^+ \to \Lambda\pi^+$ to remove the common asymmetry sources.
- Result: $\Delta A_{\rm raw} = A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+)$
  The reference mode and signal mode have nearly same Λ kinematic distributions, including the Λ decay length, the polar angle and the momentum of the proton and pion in the laboratory reference frame.



- $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
- $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$

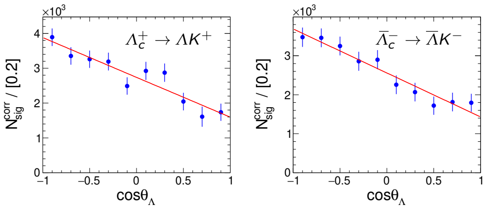
First $A_{CP}^{\rm dir}$ for SCS two-body decays of charmed baryons.

baryonic α-induced CPV in $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

(Belle) Science Bulletin **68** (2023) 583

(SCS) $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

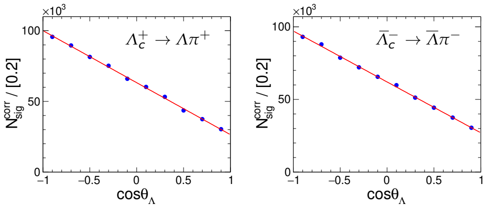
- Measure $\alpha/\bar{\alpha}$ for the separate $\Lambda_c^+/\overline{\Lambda}_c^-$ samples.
- Calculate $A_{CP}^{\alpha} \equiv (\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-})/(\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-})$.



- Result: $A_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$
  $A_{CP}^{\alpha}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.08 \pm 0.35 \pm 0.14$
  First A_{CP}^{α} results for charmed baryon SCS decays.
- No evidence of CPV is found.

(CF) $\Lambda_c^+ \to \Lambda \pi^+, \Sigma^0 \pi^+$

- Probe Λ-hyperon CPV in charmed baryon CF decays, inspired by arXiv:2208.01589.
- Under a reasonable assumption $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ in CF decays, we have $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = A_{CP}^{\alpha}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+}$.

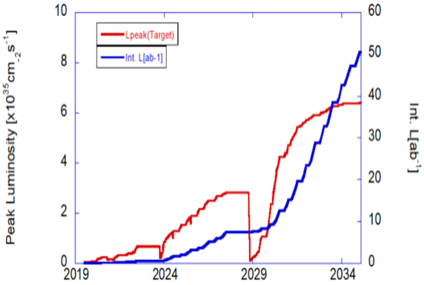


- Result: $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = +0.013 \pm 0.007 \pm 0.011$
  The first result of hyperon CPV in charm CF decays

Outline

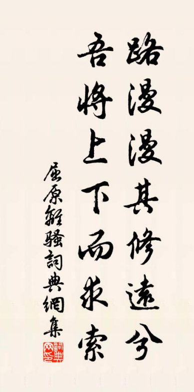
Summary

- Belle is lasting to produce the fruitful charm results although its data taking finished 13 years ago.
- My talk today includes some recent results on measurements of $\mathcal{B}$ and α, CPV searches in the charmed meson and baryon decays, several searches for rare or forbidden decays.
- Belle II has joined the game. A dataset with 424 fb^{-1} is available.
- First charm wave: utilizing the early dataset, we obtain the world best $\tau(D^{0,+})$, $\tau(D_s^+)$, and $\tau(\Lambda_c^+)$ (first Belle II precision measurements) and confirmation of LHCb $\tau(\Omega_c^0)$ result.
- More charm results utilizing 1.4 ab^{-1} of dataset at Belle and Belle II in 2024. and more luminosity (goal: 50 ab^{-1}) in the future at Belle II. Please stay tuned.



Homework of charm physics in my personal opinion

- first observation of charm CPV in singly decay channel and more channels of D mesons
  $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$ ($> 5\sigma$) and $A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$ (3.8σ)
  CP asymmetry in many SCS decay channels have been studied but with statistics limited.
- first evidence of indirect CPV in D^0 decays [Long term]
  still no signs for non-zero result in $|q/p| - 1$ and $\arg(q/p)$.
- first evidence of CPV in charmed baryon sector [Long term]
  currently only three studies $\Lambda_c^+ \to ph^+h^-$, $\Lambda_c^+ \to (\Lambda, \Sigma^0)K^+$, $\Xi_c^+ \to pK^-\pi^+$
- first observation of Ξ_{cc}^+ and Ω_{cc}^+ and their hadronic decays
- first observation of radiative decays of charmed baryons
- precise/first absolute $\mathcal{B}$ of the decays of charmed baryons (Ξ_c and Ω_c)
- more precise $\mathcal{B}$ results of charmed baryon SL decays
  e.g $\mathcal{B}(\Xi_c \to \Xi \ell \nu)$ and $\mathcal{B}(\Omega_c \to \Omega \ell \nu)$ results are not understood or to be improved precisely.
- $\mathcal{B}$ (and α) measurements for more charm decays or with improved precision
- amplitude analyses of charmed baryon decays with current/increased available datasets
- more sensitive searches for rare or forbidden charm decays [Long term]
- ......



"The road ahead is long and endless; yet high and low we'll search with our will unbending."

Back up

Thank you for your attention.

谢谢！

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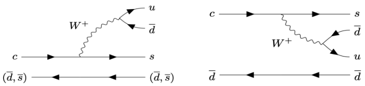
Alan's talk at CKM 2023

Why measure charm lifetimes?

Lenz, IJMP A30 (2015)
Lenz et al., JHEP 12 (2020) 199
King, Lenz et al., JHEP 08 (2022) 241
Gratrex et al., JHEP 07 (2022) 058

Theory:

- ***qualitatively*** *understood in terms of simple diagrams, e.g., $c \to s\, e^+ \nu$ partial width gives $G_F{}^2 m_c{}^5\, |V_{cs}|^2/(192\pi^3)$ dependence. Long D^+ lifetime can be understood as arising from destructive interference between spectator and color-suppressed amplitudes. But this doesn't include QCD...*



- ***to include QCD:*** *calculate using the Heavy Quark Expansion*

$$
\begin{aligned}
\Gamma(D) &= \frac{1}{2m_D}\sum_X \int_{PS} (2\pi)^4 \delta^{(4)}(p_D - p_X)\ |\langle X(p_X)|\mathcal{H}_{\rm eff}|D(p_D)\rangle|^2, \\
&\to \frac{1}{2m_D}{\rm Im}\langle D|\mathcal{T}|D\rangle \quad \text{where} \quad \mathcal{T} = i\int d^4x\, T\left\{\mathcal{H}_{\rm eff}(x)\,,\mathcal{H}_{\rm eff}(0)\right\} \\
&\to \Gamma_3 + \Gamma_5\frac{\langle \mathcal{O}_5\rangle}{m_c^2} + \Gamma_6\frac{\langle \mathcal{O}_6\rangle}{m_c^3} + \ldots + 16\pi^2\left(\tilde{\Gamma}_6\frac{\langle \tilde{\mathcal{O}}_6\rangle}{m_c^3} + \tilde{\Gamma}_7\frac{\langle \tilde{\mathcal{O}}_7\rangle}{m_c^4} + \ldots\right)
\end{aligned}
$$

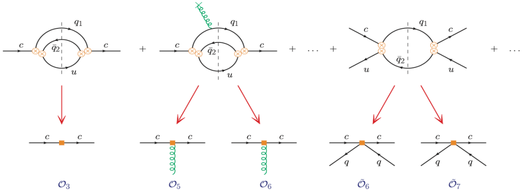
ΣX is sum over final states

via optical theorem

via Heavy Quark Expansion

Wilson coefficients Γ_i are expanded in powers of α_s and calculated perturbatively

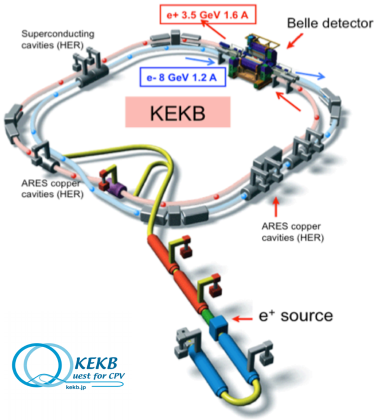
⇒ comparing lifetime calculations with measurements tests/improves our understanding of QCD

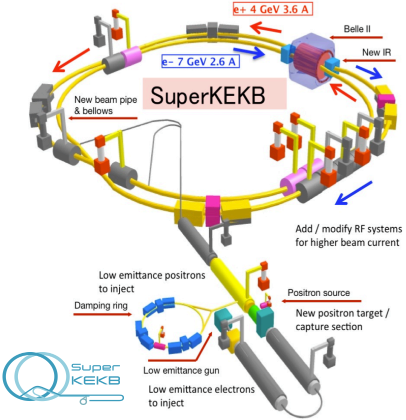


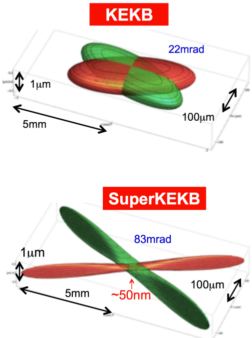
from KEKB to SuperKEKB

For more info, see Xiaolong's talk on Monday afternoon [link]

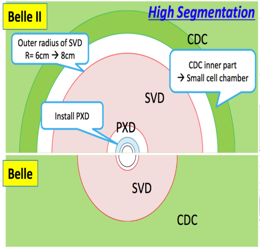
- As 1st and 2nd generation B-factories, KEKB and SuperKEKB have many similarities, and more differences:
  - Damping ring added to have low emittance positrons / use 'Nano-beam' scheme by squeezing the beta function at the IP.
  - beam energy: admit lower asymmetry to mitigate Touschek effects / beam current: $\times 2$ to contribute to higher luminosity.
  - SuperKEKB achieved the luminosity record of $4.7 \times 10^{34}\ cm^{-2}s^{-1}$.

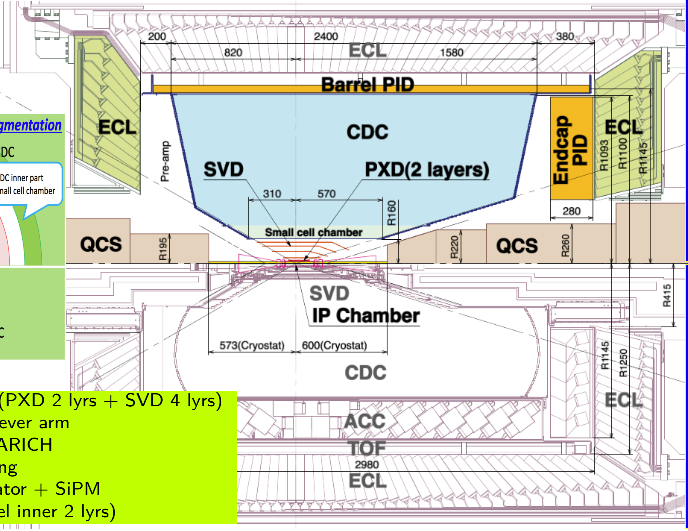






Detector: Belle II Vs. Belle





SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling
KLM: RPC → Scintillator + SiPM
(endcaps, barrel inner 2 lyrs)

Belle II

BELLE