Charm *CP* violation at Belle and Belle II experiments

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Outline

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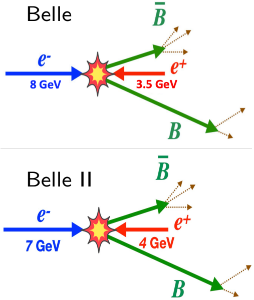
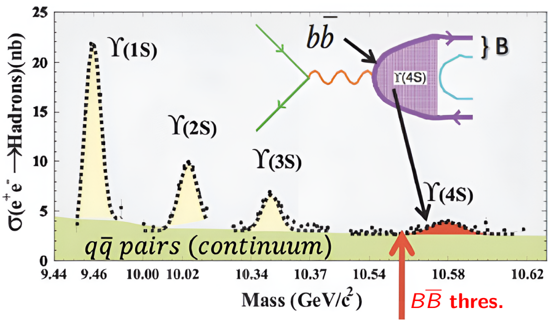
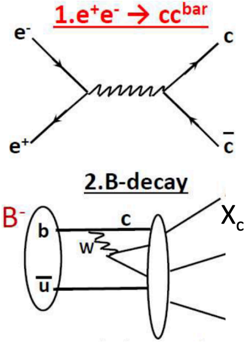
Charm production at Belle and Belle II

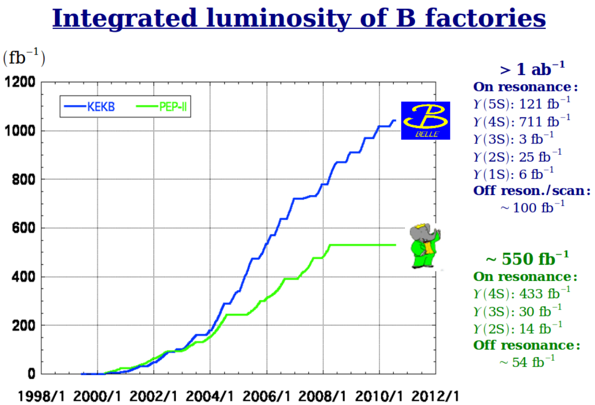
- At Belle (II), e^+e^- mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance decaying into $B\bar{B}$ in 96% of the time.
- Meanwhile, continuum processes $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) have large cross sections.
- Two ways to produce the charm sample: $e^+e^- \to c\bar{c}$ ($\sigma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



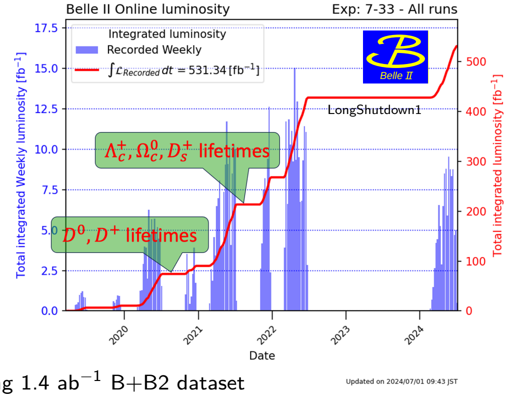




Luminosity at Belle and Belle II



First wave: charm lifetimes based on the early data set
PRL 127, 211801 (2021); PRL 131, 171803 (2023);
PRD 107, L031103 (2023); PRL 130, 071802 (2023).



New waves using 1.4 ab^{-1} B+B2 dataset

Comparison of available charm samples

Experiment	Machine	C.M.	Luminosity(fb^{-1})	$N_{\rm prod}$	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	20 7.3 4.5	$D^{0,+}$: 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	500 ($\to$ 50000)	D^0: 10^9 ($\to 10^{11}$) $D^+_{(s)}$: 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	1000	$D^{0,+}$, D_s^+: 10^9 Λ_c^+: 10^8 ★★☆		
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 6+9 ($\to$ 23 $\to$ 50)	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ very large production cross-section ☺ large boost, excellent time resolution ☺ more charm sources ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0 @3.77\,{\rm GeV})$=3.61 nb, $\sigma(D^+D^- @3.77\,{\rm GeV})$=2.88 nb, $\sigma(D_s^* D_s @4.17\,{\rm GeV})$=0.967 nb; $\sigma(c\bar{c}@10.58\,{\rm GeV})$=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.
- Today I report the recent charm CPV results from Belle II.

Why CPV and Charm CPV Special?

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

Citations per year

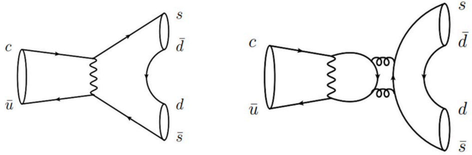
- CPV is essential for elucidating the matter-antimatter asymmetry in the universe.
- Three necessary "Sakharov conditions" are:
  1) Baryon number violation; 2) C and CPV; 3) Interactions out of thermal equilibrium.
- The sole origin of CPV in Standard Model arising from the single complex phase of CKM matrix, 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).
- Charm CPV effect is very small ($\mathcal{O}(10^{-3})$ or smaller [a b]). New Physics may enhance it [c d].
- In 2019, CP violation in D decays was found at LHCb [e]: $\Delta\mathcal{A}_{CP}(D^0 \to K^+K^-, \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ).
  Recently LHCb report the first evidence for direct CPV in a specific D decay [f]: $A^{\rm dir}_{\pi\pi} = (2.32 \pm 0.61) \times 10^{-3}$.
  $\Rightarrow$ to understand this CPV, 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 [g].
  $\Rightarrow$ CPV search in charmed baryon is one of main targets of charm physics at Belle II.

[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] LHCb, PRL 122, 211803 (2019)
[f] LHCb, PRL 131, 091802 (2023)
[g] M.E. Shaposhnikov, NPB 287, 757 (1987)

Outline

Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

- The time-integrated CP asymmetry $\mathcal{A}_{CP}(D^0 \to K_S^0 K_S^0) = \dfrac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$.
- It may be enhanced to be an observable level (the 1% level) within the Standard Model, due to the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes. [PRD 99, 113001 (2019), PRD 86, 014023 (2012), PRD 92, 054036 (2015)]



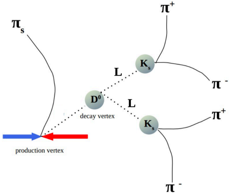
- World average: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\%$ is dominated by
  - Belle (921 fb^{-1}): $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$ using $D^0 \to K_S^0 \pi^0$ as control mode [PRL 119, 171801 (2017)]
  - LHCb (6 fb^{-1}): $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ using $D^0 \to K^+ K^-$ as control mode [PRD 104, L031102 (2021)]
- $\mathcal{A}_{CP}(D^0 \to K^+ K^-)$: recently improved by LHCb, uncertainty $< 0.1\%$ [PRL 131, 091802 (2023)]

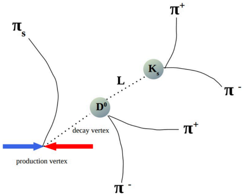
Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

- Measure $\mathcal{A}_{CP}(D^0 \to K_S^0 K_S^0)$, using $D^0 \to K^+K^-$ as control mode, with $D^{*+} \to D^0 \pi_s^+$ sample at B+B2 (1.4 ab^{-1}).

$$A_{\rm raw}(D^0 \to f) = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{\rm FB}^{D^{*+}} + A_{CP}^{D^0 \to f} + A_{\varepsilon}^{\pi_s}$$

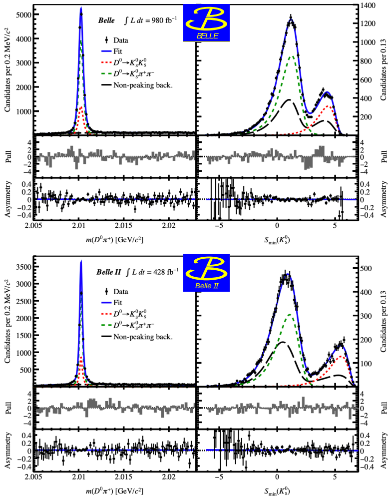
- $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (A_{\rm raw}^{K_S^0 K_S^0} - A_{\rm raw}^{K^+K^-}) + \mathcal{A}_{CP}^{K^+K^-}$ assuming that the nuisance asymmetries are identical between two decays, or that they can be made so by weighting the control sample.
- $A_{CP}^{D^0 \to K^+K^-} = A_{CP}^{\rm dir}(D^0 \to K^+K^-) + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$ [PRL 131, 091802 (2023), PRD 104, 072010 (2021)]
  - $A_{CP}^{\rm dir}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \times 10^{-4}$: direct CP asymmetry [PRL 131, 091802 (2023)]
  - $\Delta Y = (-1.0 \pm 1.1) \times 10^{-4}$: CPV in mixing and in the interference between mixing and decay [PRD 104, 072010 (2021)]
- Unbinned fit to $(m(D^0\pi_s), S_{\rm min})$ of D^0 and $\bar{D}^0$ candidates for $D^0 \to K_S^0 K_S^0$ decays.
  - Flight significance variable $S_{\rm min} = \log(\min(L_i/\sigma_i))$: separate the peaking background $D^0 \to K_S^0 \pi^+\pi^-$.



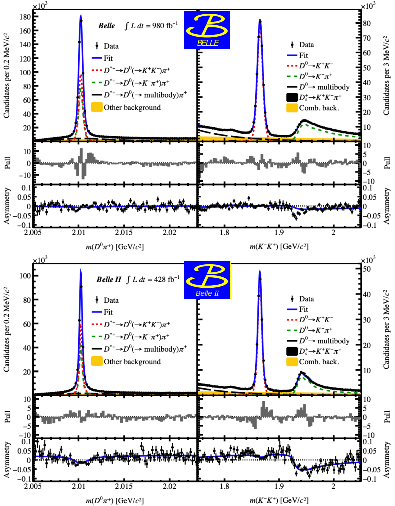


Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ Preliminary

$D^0 \to K_S^0 K_S^0$



$D^0 \to K^+K^-$



Preliminary results:

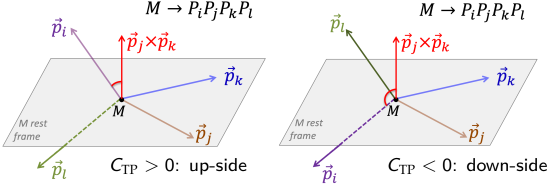
- $A_{\text{raw}}(D^0 \to K_S^0 K_S^0)$:
  - Belle: $(-1.0 \pm 1.6)\%$
  - Belle II: $(-0.6 \pm 2.3)\%$
- $A_{\text{raw}}(D^0 \to K^+ K^-)$:
  - Belle: $(0.17 \pm 0.19)\%$.
  - Belle II: $(1.61 \pm 0.27)\%$.
- final $A_{CP}(D^0 \to K_S^0 K_S^0)$:
  - Belle: $(-1.1 \pm 1.6 \pm 0.1)\%$).
  - Belle II: $(-2.2 \pm 2.3 \pm 0.1)\%$).
  - combined: $(-1.4 \pm 1.3 \pm 0.1)\%$.
- Comparable precision to the world-best measurement from LHCb (6 fb^{-1}): $\sigma = 1.3\%$.
- An update using the non-D^{*+} sample is under working.
- Also CPV in other channels (e.g $D^{+,0} \to \pi^{+,0}\pi^0$).

Outline

CPV searches in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ using triple-product correlations

arXiv:2409.15777

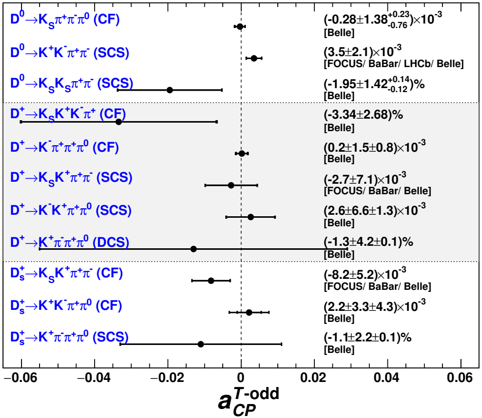
- CPV searches in several four-body D-decays at FOCUS, BABAR, LHCb and Belle using the triple-product (TP): $C_{\rm TP} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$.



$C_{\rm TP}$ asymmetry: so-called 'up-down asymmetry'

- CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$: never been searched. They have large branching fractions $\mathcal{B} = 0.23\%(1.53\%)$ $\Rightarrow \mathcal{O}(10^5)$ signals expected, inspiring us to obtain their precise $a_{CP}^{T\text{-odd}}$ results for the first time.

Current world averages of all $a_{CP}^{T\text{-odd}}$ measurements:



CPV searches in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ using quadruple-product correlations arXiv:2409.15777

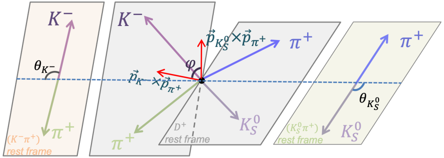
- We do the first CPV search with the quadruple-product (QP): in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$: $C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$, where the subscripts ('h' and 'l') denote the π^+ with higher and lower momentum, respectively, of two identical π^+ in the final state.

- $D \to V_a V_b$ (e.g. $D^+_{(s)} \to \overline{K}^{*0} K^{*+}$ is a dominant process) amplitude involves terms of
  (1) $d^2_{1,0}(\theta_a) d^2_{1,0}(\theta_b) \sin\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\sin\varphi$,
  (2) $d^2_{1,0}(\theta_a) d^2_{1,0}(\theta_b) \cos\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\cos\varphi$.

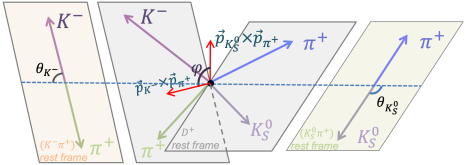
- two more observables for CPV searches[a]:
  - $\cos\theta_{K^0_S}\cos\theta_{K^-}\, C_{\rm TP}$: same sign as $\cos\theta_{K^0_S}\cos\theta_{K^-}\sin\varphi$,
  - $\cos\theta_{K^0_S}\cos\theta_{K^-}\, C_{\rm QP}$: same sign as $\cos\theta_{K^0_S}\cos\theta_{K^-}\cos\varphi$.

- $\cos\theta_{K^0_S}\cos\theta_{K^-}$ is used for charm CPV searches; its asymmetry is the so-called 'two-fold forward-backward asymmetry'[b].

$C_{\rm QP} > 0$: $\vec{p}_{K^-}$ at left-side of $\vec{p}_{K^0_S\pi^+}(\vec{p}_{K^0_S} \times \vec{p}_{\pi^+})$ plane



$C_{\rm QP} < 0$: $\vec{p}_{K^-}$ at right-side of $\vec{p}_{K^0_S\pi^+}(\vec{p}_{K^0_S} \times \vec{p}_{\pi^+})$ plane



$C_{\rm QP}$ asymmetry: so-called 'left-right asymmetry'.

[a] G. Durieux and Y. Grossman, Phys. Rev. D **92**, 076013 (2015)

[b] Z.-H. Zhang, Phys. Rev. D **107**, L011301 (2023)

Motivation: first CPV searches for $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

arXiv:2409.15777

- We search for CPV with a set of six kinematic observables (X) linked to various decay amplitude terms.
- For $D^+_{(s)}$ decays:
  (1) $X = C_{\rm TP} = \vec{p}_{K^-} \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$: same sign as $\sin\varphi$.
  (2) $X = C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$: same sign as $\cos\varphi$.
  (3) $X = C_{\rm TP} C_{\rm QP}$: same sign as $\sin(2\varphi)$.
  (4) $X = \cos\theta_{K^0_S} \cos\theta_{K^-}$.
  (5) $X = \cos\theta_{K^0_S} \cos\theta_{K^-} C_{\rm TP}$: same sign as $\cos\theta_{K^0_S} \cos\theta_{K^-} \sin\varphi$,
  (6) $X = \cos\theta_{K^0_S} \cos\theta_{K^-} C_{\rm QP}$: same sign as $\cos\theta_{K^0_S} \cos\theta_{K^-} \cos\varphi$.
- For $D^-_{(s)}$ decays: $\overline{X} = \eta^{CP}_X X$, where $\eta^{CP}_X = -1$ for ($C_{\rm TP}$, $C_{\rm TP} C_{\rm QP}$ and $\cos\theta_{K^0_S} \cos\theta_{K^-} C_{\rm TP}$); while $\eta^{CP}_X = +1$ for others.
- The kinematic asymmetries for $D^+_{(s)}$ and $D^-_{(s)}$ decays:

$$A_X(D^+_{(s)}) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)} \qquad A_{\overline{X}}(D^-_{(s)}) = \frac{N_-(\overline{X}>0) - N_-(\overline{X}<0)}{N_-(\overline{X}>0) + N_-(\overline{X}<0)}$$

- CP-violating parameter: $\mathcal{A}^X_{CP} = \frac{1}{2}(A_X(D^+_{(s)}) - A_{\overline{X}}(D^-_{(s)}))$ (the factor 1/2 is required for normalization) to avoid a fake signal of CPV arising from the final state interaction (FSI) effects.

Signal yield extraction of $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ arXiv:2409.15777

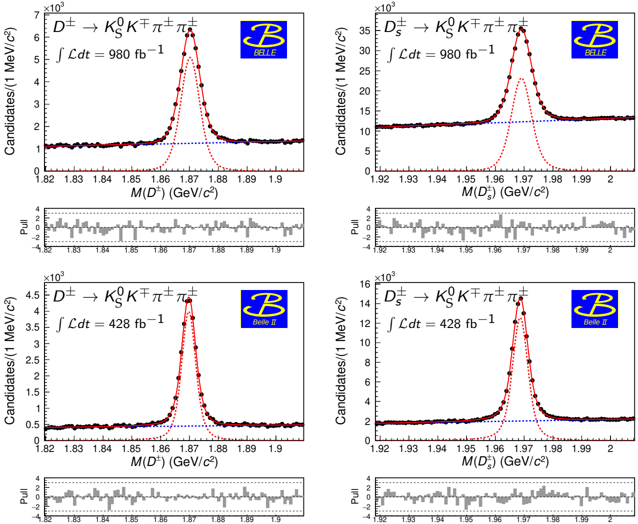


Table: Fitted signal and background yields in a window ± 10 MeV$/c^2$ around the nominal $D^+_{(s)}$ mass.

Component	$D^+ \to K^0_S K^- \pi^+ \pi^+$	
	Belle	Belle II
Signal ($N_{\rm sig}$)	44048 ± 288	26738 ± 199
Background ($N_{\rm bkg}$)	24844 ± 88	8964 ± 53
Ratio ($N_{\rm sig}/N_{\rm bkg}$)	1.8	3.0
Component	$D_s^+ \to K^0_S K^- \pi^+ \pi^+$	
	Belle	Belle II
Signal ($N_{\rm sig}$)	210743 ± 780	92000 ± 393
Background ($N_{\rm bkg}$)	245285 ± 280	39997 ± 114
Ratio ($N_{\rm sig}/N_{\rm bkg}$)	0.9	2.3

Simultaneous fit for $\mathcal{A}_{CP}^{X}$ measurement in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$

arXiv:2409.15777

- The sample is divided into four X-subsamples by the charm flavor and the sign of X-variables:

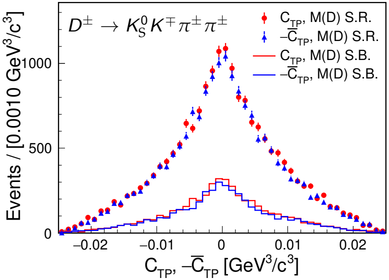
$$A_X(D^+) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)}$$

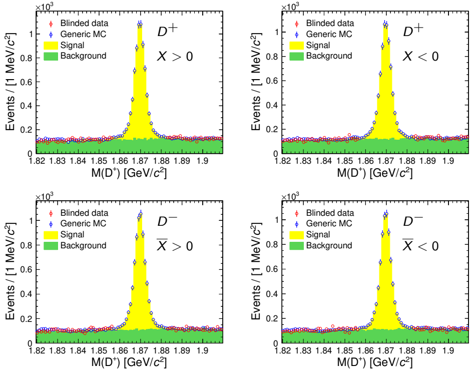
$$A_{\overline{X}}(D^-) = \frac{N_-(\overline{X}>0) - N_-(\overline{X}<0)}{N_-(\overline{X}>0) + N_-(\overline{X}<0)}$$

$$N_D(X>0) = \frac{N_+}{2}(1+A_X) \qquad N_{D^-}(\overline{X}>0) = \frac{N_-}{2}(1+A_X-2\mathcal{A}_{CP}^{X})$$

$$N_{D^+}(X<0) = \frac{N_+}{2}(1-A_X) \qquad N_{D^-}(\overline{X}<0) = \frac{N_-}{2}(1-A_X+2\mathcal{A}_{CP}^{X})$$

Belle II data, $\int \mathcal{L}dt = 428\ \text{fb}^{-1}$





Simultaneous fit for $\mathcal{A}_{CP}^{X}$ measurement in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$ arXiv:2409.15777

- We perform a simultaneous fit on these four X-subsamples with eight floated parameters: N_+, N_-, A_X, and a_{CP}^X along with background yield per subsample.

Decay	X	$\mathcal{A}_{CP}^{X}$ (10^{-3}) at Belle	$\mathcal{A}_{CP}^{X}$ (10^{-3}) at Belle II
D^+	(1)	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$
	(2)	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$
	(3)	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$
	(4)	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$
	(5)	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$
	(6)	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$
D_s^+	(1)	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$
	(2)	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$
	(3)	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$
	(4)	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$
	(5)	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$
	(6)	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$

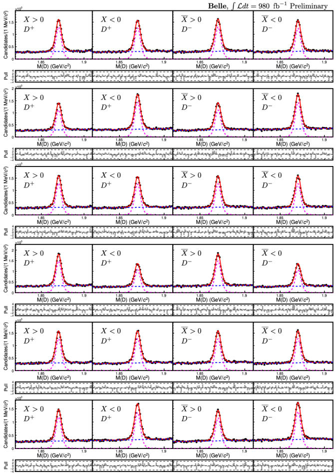


Figure 5: Fitted distributions for Belle $D^\pm \to K_S^0 K^\mp \pi^\pm \pi^\pm$ data, for (top to bottom) $X = C_{\rm TP}$, $C_{\rm QP}$, $C_{\rm TP}C_{\rm QP}$, $\cos\theta_{K_S^0}\cos\theta_{K^-}$, $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$, and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$.

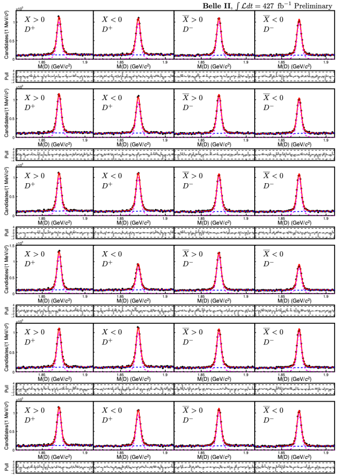


Figure 7: Fitted distributions for Belle II $D^\pm \to K_S^0 K^\mp \pi^\pm \pi^\pm$ data, for (top to bottom) $X = C_{\rm TP}$, $C_{\rm QP}$, $C_{\rm TP}C_{\rm QP}$, $\cos\theta_{K_S^0}\cos\theta_{K^-}$, $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$, and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$.

Final $\mathcal{A}_{CP}^{X}$ measurement in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$

arXiv:2409.15777

- combining the results from Belle and Belle II experiments: $\mathcal{A}_{CP}^{X}(\text{avg.}) = \frac{\mathcal{A}_{CP}^{B1}/\sigma_{B1}^2 + \mathcal{A}_{CP}^{B2}/\sigma_{B2}^2}{1/\sigma_{B1}^2 + 1/\sigma_{B2}^2}$, and its uncertainty $\sigma_{\mathcal{A}_{CP}^{X}(\text{avg.})} = \frac{1}{\sqrt{1/\sigma_{B1}^2 + 1/\sigma_{B2}^2}}$, where σ_{B_1} and σ_{B_2} are the total uncertainties (i.e. $\sigma_{\text{stat}} \oplus \sigma_{\text{syst}}$) at Belle and Belle II.
- The $\mathcal{A}_{CP}^{X}$ results at Belle and Belle II and their combined results:

Decay	X	$\mathcal{A}_{CP}^{X}$ (10^{-3}) at Belle	$\mathcal{A}_{CP}^{X}$ (10^{-3}) at Belle II	Combined $\mathcal{A}_{CP}^{X}$ (10^{-3})	Significance
$D^+ \to K_S^0 K^- \pi^+ \pi^+$	C_{TP}	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	C_{QP}	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	$C_{\text{TP}} C_{\text{QP}}$	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-}$	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\text{TP}}$	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\text{QP}}$	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	C_{TP}	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	C_{QP}	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	$C_{\text{TP}} C_{\text{QP}}$	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-}$	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\text{TP}}$	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\text{QP}}$	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ

Outline

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

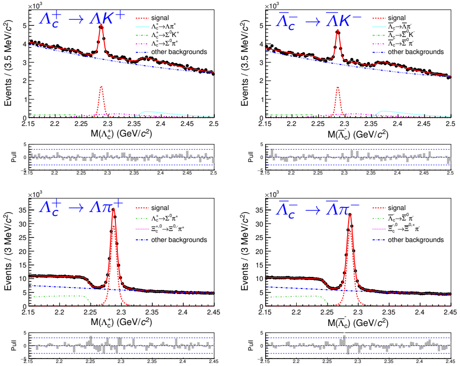
(Belle) Science Bulletin **68** (2023) 583

- The raw asymmetry of $\Lambda_c^+ \to \Lambda h^+$ includes several asymmetry sources:

$$A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$$

$$A_{\rm raw}(\Lambda_c^+ \to \Lambda \pi^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda \pi^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{\pi^+} + A_{\rm FB}^{\Lambda_c^+}$$

  - $A_{CP}^{\Lambda_c^+ \to \Lambda h^+}$ ($A_{CP}^{\Lambda \to p\pi^-}$): CP asymmetry associated with Λ_c^+ (Λ) decay,
  - A_ε^{Λ}: detection asymmetry arising from efficiencies between Λ and $\bar{\Lambda}$.
  - $A_\varepsilon^{h^+}$: removed by widthing $w_{\Lambda_c^+, \bar{\Lambda}_c^-} = 1 \mp A_\varepsilon^{K^+}[\cos\theta, p_T]$
    - $A_\varepsilon^{K^+}$: $D^0 \to K^-\pi^+$ and $D_s^+ \to \phi\pi^+$
    - $A_\varepsilon^{\pi^+}$: $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$
  - $A_{\rm FB}^{\Lambda_c^+}$ 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.
- 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.



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

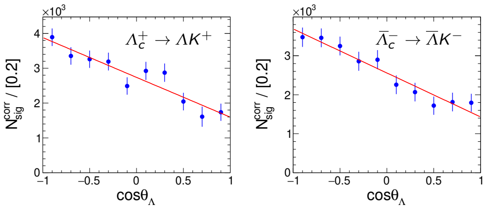
First $A_{CP}^{\rm dir}$ for SCS two-body decays of charmed baryons.

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

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

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

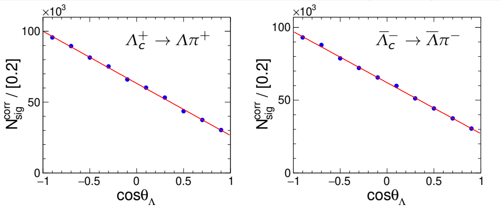
- Measure $\alpha/\bar{\alpha}$ for the separate $\Lambda_c^+/\overline{\Lambda}_c^-$ samples.
- Calculate $\mathcal{A}_{CP}^{\alpha} \equiv (\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-})/(\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-})$.



- Result: $\mathcal{A}_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$
  $\mathcal{A}_{CP}^{\alpha}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.08 \pm 0.35 \pm 0.14$
  First $\mathcal{A}_{CP}^{\alpha}$ 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 PLB 849 (2024) 138460 (JP Wang, FS Yu).
- Under a reasonable assumption $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ in CF decays, we have $\mathcal{A}_{CP}^{\alpha}(\Lambda \to p\pi^-) = \mathcal{A}_{CP}^{\alpha}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+}$.

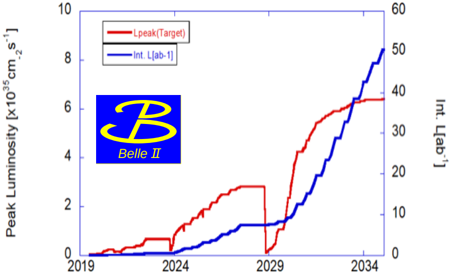


- Result: $\mathcal{A}_{CP}^{\alpha}(\Lambda \to p\pi^-) = +0.013 \pm 0.007 \pm 0.011$
  The first result of hyperon CPV in charm CF decays

Outline

Summary: charm CPV results at Belle II

- Belle II experiment has joined the game. A dataset of (B+B2) 1.5 ab^{-1} is available.
- After the wave of charm lifetimes, new waves (e.g first charm CPV results) start:
- Time-integrated CP asymmetry of $D^0 \to K^0_S K^0_S$ is updated:
  - precision: 1.3%, new variable used w.r.t Belle result; better control mode;
  - next: new sample; more luminosity.
- First CPV search in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ using TP/QP correlations.
  - precision: 0.5% for D^+ decay; $<$ 0.3% for D^+_s decay.
  - most precise $a^{T\text{-odd}}_{CP}$ for D^+ SCS decays and D^+_s CF decays; and the other a^X_{CP} results are the first such measurements.
  - next: more channels; CPV search in $D \to [P \to [V \to P_1 P_2] P_3] P_4$?
- CPV in decays of charmed baryons ($\Lambda^+_c \to \Lambda h^+$ at Belle); CPV in $\Lambda^+_c \to \Lambda K^0_S h^+$ (TPA/QPA), $\Lambda^+_c \to \Sigma^+ K^0_S$ (α): on the road.
- Recent results on charmed baryon: see Suxian's talk.
- More charm CPV results with increasing luminosity in the future.
- Please stay tuned in the Belle II channel.



Any suggestions are welcome.

Back up

Thank you for your attention.

谢谢！

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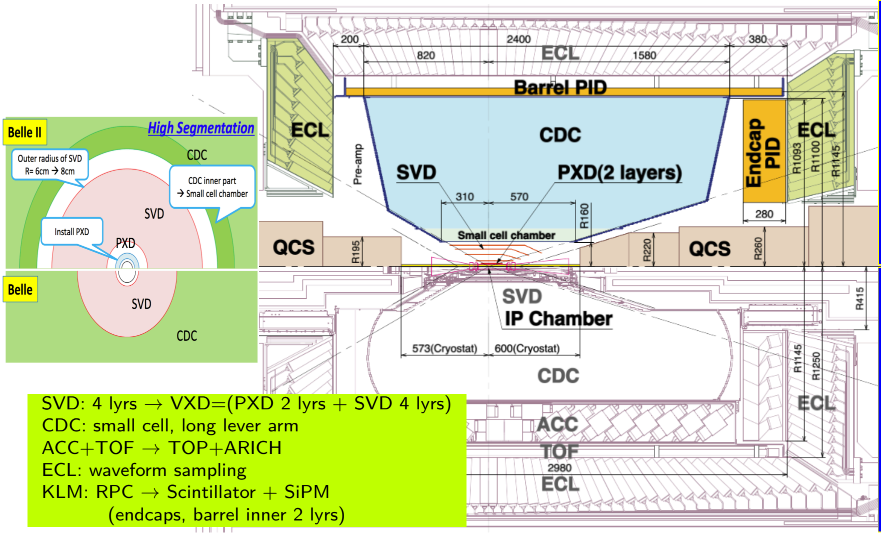
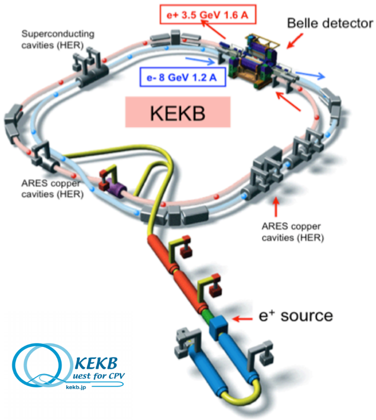
Detector: Belle II Vs. Belle

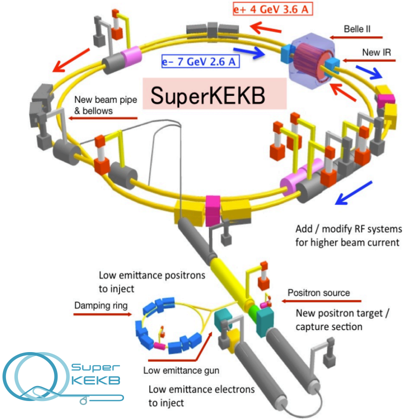


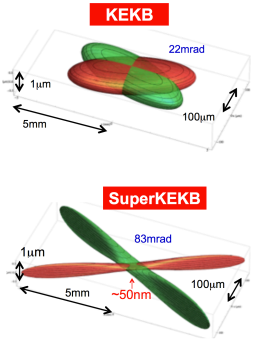
- SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
- CDC: small cell, long lever arm
- ACC+TOF → TOP+ARICH
- ECL: waveform sampling
- KLM: RPC → Scintillator + SiPM (endcaps, barrel inner 2 lyrs)

from KEKB to SuperKEKB

- 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 $4.7 \times 10^{34}\ cm^{-2}s^{-1}$.







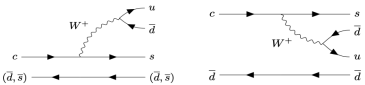
Alan's talk at CKM 2023

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*

$$\Gamma(D) = \frac{1}{2m_D}\sum_X \int_{PS} (2\pi)^4 \delta^{(4)}(p_D - p_X)\ |\langle X(p_X)|\mathcal{H}_{\rm eff}|D(p_D)\rangle|^2,$$

ΣX is sum over final states

$$\to \frac{1}{2m_D}{\rm Im}\langle D|\mathcal{T}|D\rangle \quad \text{where} \quad \mathcal{T} = i\int d^4x\, T\left\{\mathcal{H}_{\rm eff}(x)\,,\mathcal{H}_{\rm eff}(0)\right\}$$

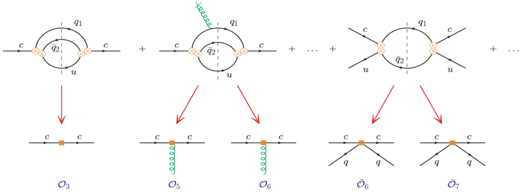
via optical theorem

$$\to \Gamma_3 + \Gamma_5\frac{\langle \mathcal{O}_5\rangle}{m_c^2} + \Gamma_6\frac{\langle \mathcal{O}_6\rangle}{m_c^3} + \ldots + 16\pi^2\left(\tilde{\Gamma}_6\frac{\langle \tilde{\mathcal{O}}_6\rangle}{m_c^3} + \tilde{\Gamma}_7\frac{\langle \tilde{\mathcal{O}}_7\rangle}{m_c^4} + \ldots\right)$$

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

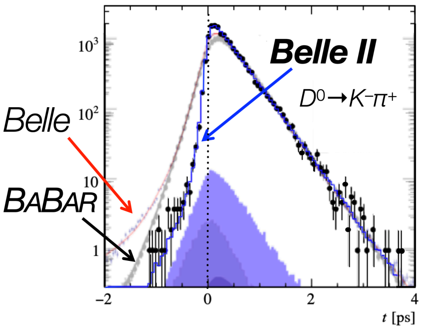


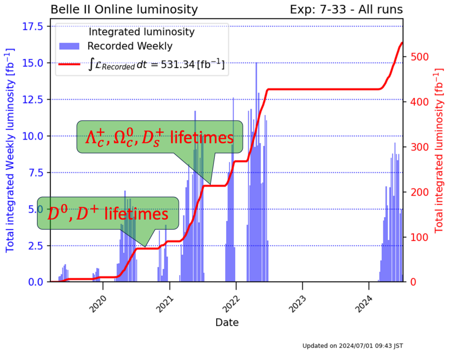
A. J. Schwartz — *Charm lifetimes, semileptonic decays at Belle II* — *CKM 2023* — 2

Charm lifetimes

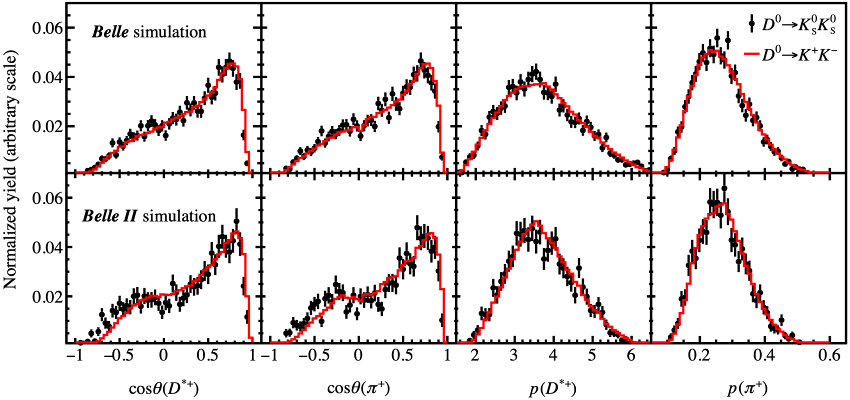
PRL 127, 211801 (2021); PRL 130, 071802 (2023); PRD 107, L031103 (2023); PRL 131, 171803 (2023

- Hadron lifetimes are difficult to calculate theoretically, as they depend on nonperturbative arising from QCD.
- Comparing calculated values with measured values improves our understanding of QCD. [(FLAG) EPJC 82, 869 (2022)]
- Belle II early dataset gave the most precise charm lifetimes: $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs, $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs, $\tau_{D_s^+} = (499.5 \pm 1.7 \pm 0.9)$ fs, and $\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77$ fs.
- confirm the new charmed baryon lifetime hierarchy found by LHCb $\tau(\Omega_c^0)$ result.

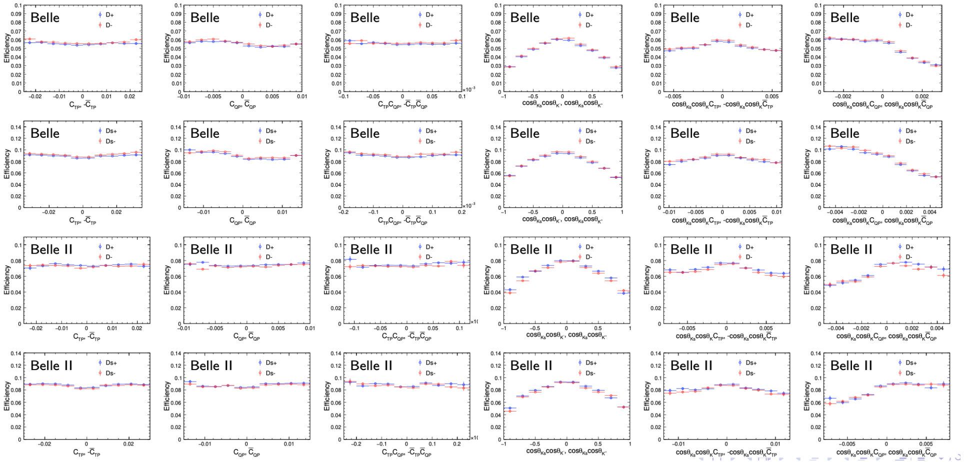




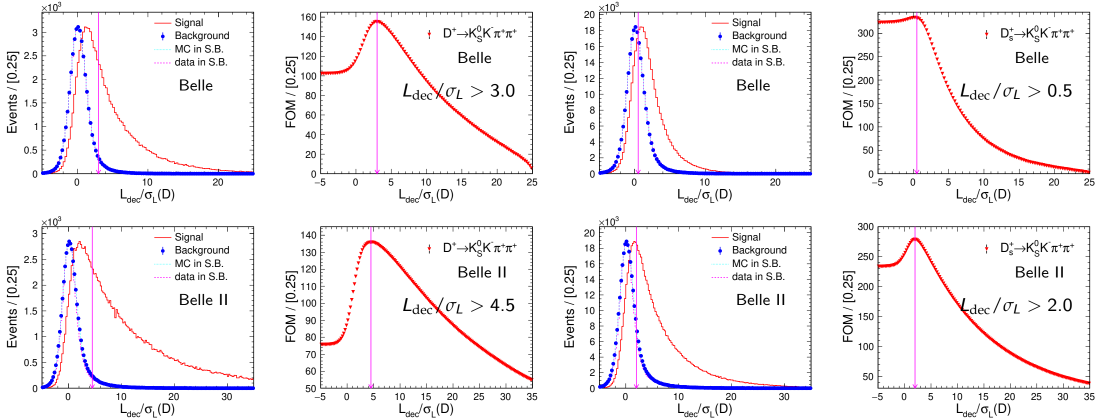
Equalization of kinematic-parameter distributions of $D^0 \to K_S^0 K_S^0, K^+ K^-$



X-dependent efficiency in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$



Event selection and optimization: $D^+_{(s)}$ flight significance $L_{\rm dec}/\sigma_L(D^+_{(s)})$



- This flight significance of D^+ is more efficient than D_s^+ due to longer lifetime in D^+;
- This flight significance is more efficient at Belle II than Belle because of an improved time resolution at Belle II.