Hadronic decays of charmed hadron and *CP* violation at Belle (II)

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Outline

1. Charm sample at Belle (II)
2. $A_{CP}(D^0 \to K^0_S K^0_S)$
3. $A_{CP}(D^{0,+} \to \pi^{0,+}\pi^0)$
4. $A^X_{CP}(D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+)$
5. $\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$
6. $\mathcal{B}(\Xi_c^+ \to BP)$
7. Summary

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3. $A_{CP}(D^{0,+} \to \pi^{0,+}\pi^0)$
4. $A_{CP}^X(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$
5. $\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$
6. $\mathcal{B}(\Xi_c^+ \to BP)$
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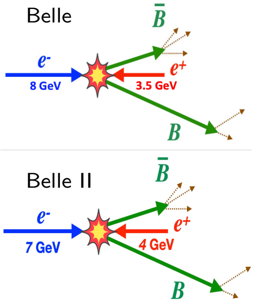
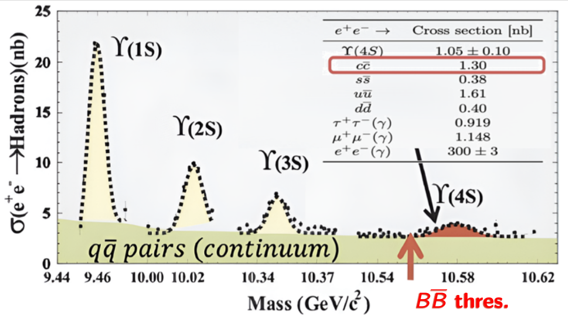
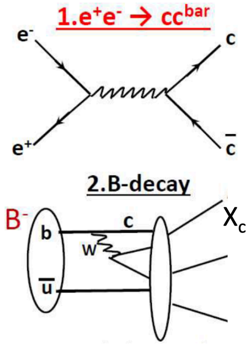
Charm production at Belle and Belle II

- 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.

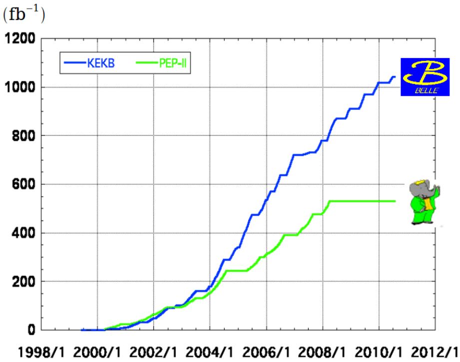






Luminosity at Belle (II)

Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 25 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan:

~100 fb^{-1}

~ 550 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

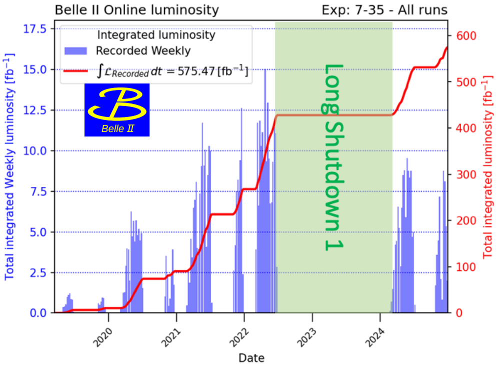
Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

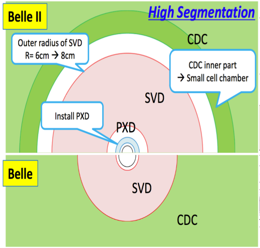
Off resonance:

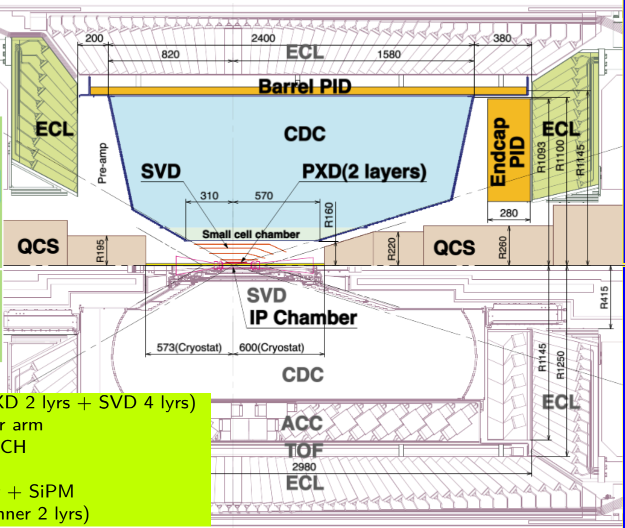
~ 54 fb^{-1}

In Dec. 2024, SuperKEKB made new W.R. $5.1 \times 10^{34}\ cm^{-2}s^{-1}$



Detector: Belle II Vs. Belle



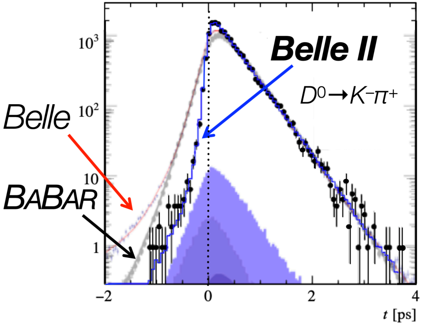


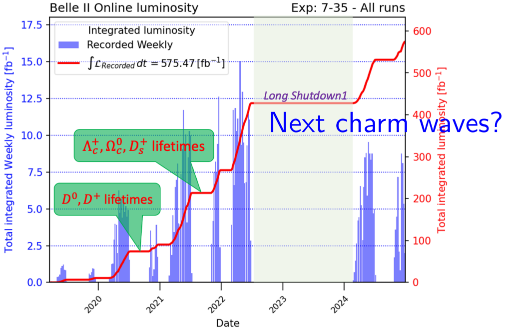
- SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
- CDC: small cell, long lever arm
- ACC+TOF → TOP+ARICH
- ECL: waveform sampling
- KLM: RPC → Scintillator + SiPM (endcaps, barrel inner 2 lyrs)

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)]
- Based on early datasets, Belle II reported 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; and confirmed the new charmed baryon lifetime hierarchy found by LHCb $\tau(\Omega_c^0)$ result.



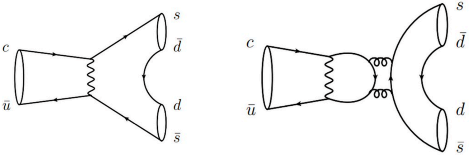


Outline

$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using D^{*+}-tagged sample

(B+B2) PRD 111, 012015 (2025)

- The time-integrated CP asymmetry $A_{CP}(D^0 \to K_S^0 K_S^0) = \dfrac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$.
- 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)]

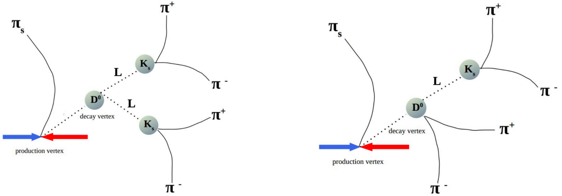


- World average: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\%$ is dominated by
  - Belle (921 fb^{-1}): $A_{CP} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$ using $D^0 \to K_S^0 \pi^0$ as control mode [(Belle) PRL 119, 171801 (2017)]
  - LHCb (6 fb^{-1}): $A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ using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

$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using D^{*+}-tagged sample

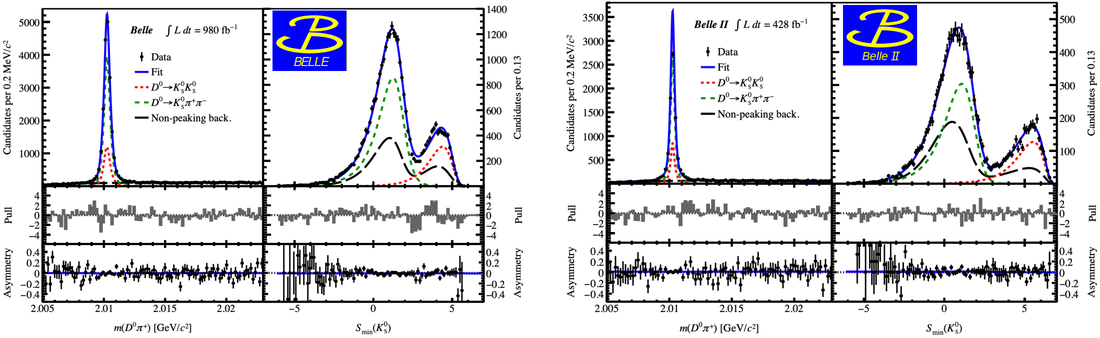
(B+B2) PRD 111, 012015 (2025)

- Measure $A_{CP}(D^0 \to K_S^0 K_S^0)$ based on $D^{*+} \to D^0 \pi_s^+$ sample at B+B2 (totally 1.4 ab^{-1}).
- Raw asymmetry of $D^0 \to K\overline{K}$: $A_{\rm raw}^{K\overline{K}} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} = A_{\rm FB}^{D^{*+}} + A_{CP}^{K\overline{K}} + A_{\varepsilon}^{\pi_s}$
- Use $D^0 \to K^+K^-$ as control mode, and $A_{CP}^{K^+K^-} = A_{CP}^{\rm dir} + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$:
  - $A_{CP}^{\rm dir}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \times 10^{-4}$: direct CP asymmetry [(LHCb) 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 [(LHCb) PRD 104, 072010 (2021)]
- $A_{CP}^{K_S^0K_S^0} = (A_{\rm raw}^{K_S^0K_S^0} - A_{\rm raw}^{K^+K^-}) + A_{CP}^{K^+K^-}$ assuming that the nuisance asymmetries are identical between two decays, or that they can be made so by widthing the control sample.
- 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 $D^0 \to K_S^0 \pi^+\pi^-$.



$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using D^{*+}-tagged sample

(B+B2) PRD 111, 012015 (2025)



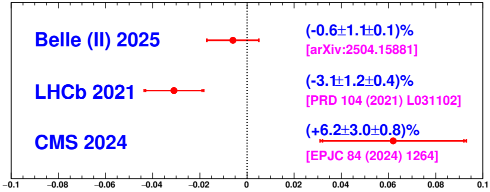
- Belle: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\%$ Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\%$
- Combined $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\%$: comparable to the world-best result: $\sigma_{\text{LHCb}} = 1.3\%$
- Belle(II)+LHCb average: $(-2.3 \pm 0.9)\%$ vs. CMS: $(6.2 \pm 3.1)\%$: 2.6σ diff. $\Rightarrow$ preciser result needed

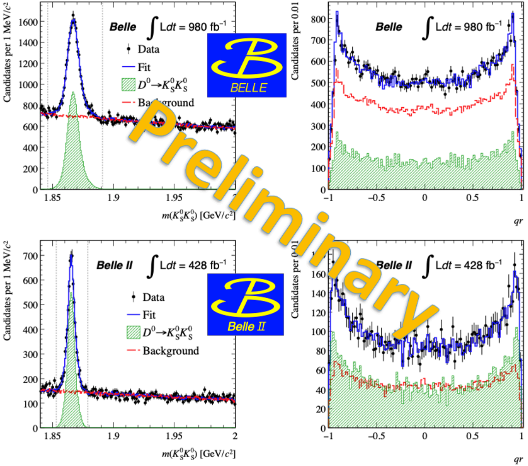
$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using an independent sample

(B+B2) arXiv:2504.15881 (preliminary)

- Using an independent sample tagged by opposite-side flavor tagging for $e^+e^- \to c\bar{c}$ events [(B2) PRD 107, 112010 (2023)]
- Candidates that are also reconstructed in the D^{*+}-tagged analysis in previous slide are removed.

- Belle sample (980 fb^{-1}):
  $N_{\text{sig}} = 14\,490 \pm 340$ and $A_{CP} = (+2.5 \pm 2.7 \pm 0.4)\%$
- Belle II sample (428 fb^{-1}):
  $N_{\text{sig}} = 5\,180 \pm 120$ and $A_{CP} = (-0.1 \pm 3.0 \pm 0.3)\%$
- Their combined results based on such independent sample:
  $A_{CP}(D^0 \to K_S^0 K_S^0) = (+1.3 \pm 2.0 \pm 0.2)\%$
- Combining it with previous result from D^{*+}-tagged sample:
  $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.6 \pm 1.1 \pm 0.1)\%$ most precise





Outline

CPV searches in isospin-related $D^{0,+} \to \pi^{0,+}\pi^0$ modes

- The following sum-rule for CPV in $D \to \pi\pi$ decays; it helps to determine the source of CPV:

$$R = \frac{A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

  - if $R \neq 0$, CPV from $\Delta I = 1/2$ amplitude; if $R = 0$ and at least one $A_{CP}^{\rm dir} \neq 0$, CPV from a beyond-SM $\Delta I = 3/2$ amplitude.
  - the $\mathcal{B}$'s and τ have been well-measured (by BESIII/Belle II/etc.)
  - $A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$: precise; first evidence of direct CPV in a specific D decay (by LHCb).

- Raw asymmetry of $D^0 \to \pi^0\pi^0$ from the $D^{*+} \to D^0\pi_s^+$ sample:

$$\boxed{A_{\rm raw}(D^0 \to \pi^0\pi^0) = A_{CP}(D^0 \to \pi^0\pi^0) + A_{\rm prod}^{D^{*+}} + A_\varepsilon^{\pi_s}}$$

  - $A_{\rm prod}^{D^{*+}}$: being an odd function of $\cos\theta^*$, i.e. the cosine of the charmed-meson polar angle in e^+e^- c.m.s
  - $A_\varepsilon^{\pi_s}$: using tagged and untagged $D^0 \to K^-\pi^+$ samples.

- Time-integrated CP asymmetry: $\boxed{A_{CP}(D^0 \to \pi^0\pi^0) = A_{\rm avg}^{\pi^0\pi^0} - A_{\rm avg}^{K\pi} + A_{\rm avg}^{K\pi,\rm untag}}$

  here $A_{\rm avg}^f = \left(A^f(\cos\theta^* < 0) + A^f(\cos\theta^* > 0)\right)/2$ where $f = \pi^0\pi^0; K\pi; \rm untag.$

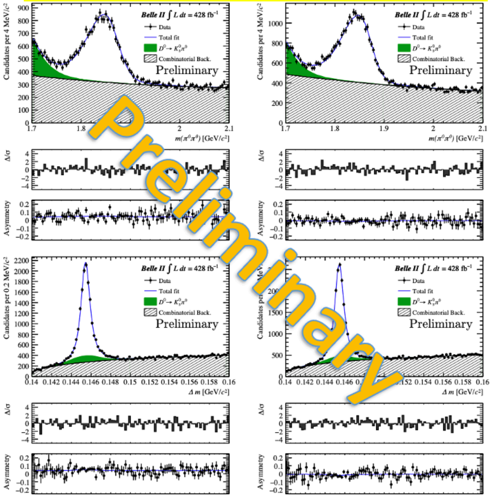
$A_{CP}(D^0 \to \pi^0\pi^0)$ at Belle II

(B2) arXiv:2505.02912 (preliminary)

- Utilizing data split in the forward and backward bins: $N_{\text{sig}} = 14\,100 \pm 130$ and $11\,550 \pm 110$.
- Result at Belle II (428 fb^{-1})
  $A_{CP}(D^0 \to \pi^0\pi^0) = (+0.30 \pm 0.72 \pm 0.20)\%$

  consistent with CP symmetry and with Belle (980 fb^{-1}): $(-0.03 \pm 0.64 \pm 0.10)\%$ [PRL 112 (2014) 211601]
- It's 15% less precision than Belle result; an improved precision per luminosity which leverages Belle II's superior capabilities in the reconstruction of neutral pions.
- Using our result, $A_{CP}^{\pi^+\pi^-}$ and ΔY from LHCb, W.A. $A_{CP}^{\pi^+\pi^0}$ and $\mathcal{B}$'s and $\tau(D^{0,+})$, we have $R = (1.5 \pm 2.5) \times 10^{-3}$. It shows that this measurement improves the precision of the sum rule by $\sim 20\%$ compared to the current determination by HFLAV [PRD 107 (2023) 052008].

$\cos\theta^*(D^{*+}) > 0$ vs. $\cos\theta^*(D^{*+}) < 0$



$A_{CP}(D^+ \to \pi^+\pi^0)$ at Belle II

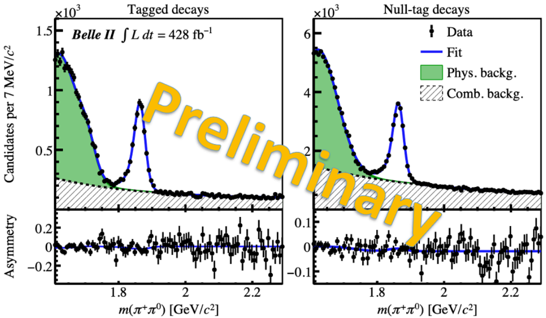
Preliminary result

- Utilizing a sample of $e^+e^- \to c\bar{c}$ data collected by Belle II (with high momentum requirement).
- Using $D^+ \to K_S^0\pi^+$ to eliminate common asymmetry sources: A^D_{prod} and $A^{\pi^+}_{\varepsilon}$, thus CP asymmetry of interest:

$$A_{CP}^{\pi^+\pi^0} = A_{\text{raw}}^{\pi^+\pi^0} - A_{\text{raw}}^{K_S^0\pi^+} + A^{\overline{K}^0}$$

- Combined result at Belle II (428 fb^{-1}): $A_{CP}(D^+ \to \pi^+\pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%$ (most precise)
- 30% improved precision compared to Belle (921 fb^{-1}): $(+2.31 \pm 1.24 \pm 0.23)\%$ [PRD 97 (2018) 011101]
- due to the substantially better purity achieved through an improved event selection, which exploits Belle II's superior performance in the reconstruction of neutral pions and displaced charged particles.

- Split sample: D^+ from $D^{*+} \to D^+\pi^0$ decay or not.



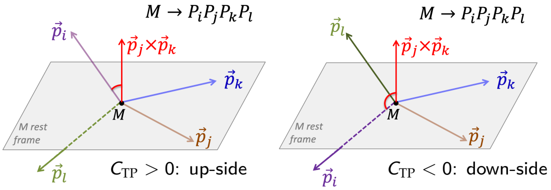
$N_{\text{sig}} = 5\,130 \pm 110$, $A_{CP} = (-3.9 \pm 1.8 \pm 0.2)\%$

$N_{\text{sig}} = 18\,510 \pm 240$, $A_{CP} = (-1.1 \pm 1.0 \pm 0.1)\%$

Outline

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

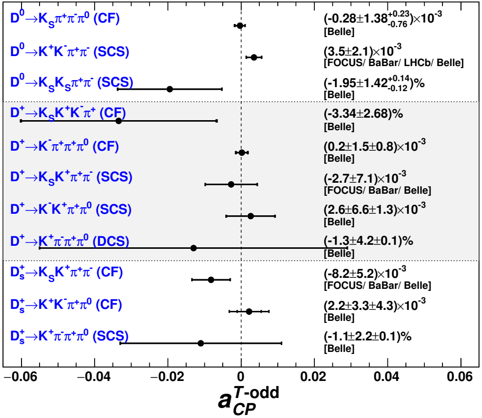
- CPV searches in several four-body D-decays at FOCUS, BABAR, LHCb and Belle using the triple-product (TP): $C_{\rm TP} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$.



$C_{\rm TP}$ 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 $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$ using quadruple-product correlations

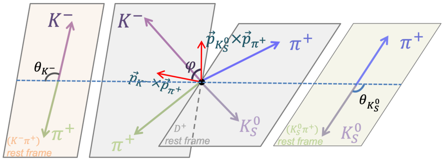
- We do the first CPV search with the quadruple-product (QP): in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$: $C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$, where the subscripts ('h' and 'l') denote the π^+ with higher and lower momentum, respectively,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

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

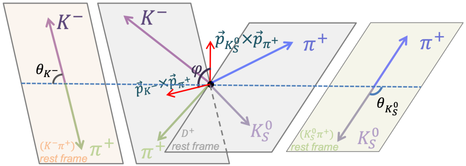
- $D \to V_a V_b$ (e.g. $D_{(s)}^+ \to \overline{K}^{*0} K^{*+}$ is a dominant process) amplitude involves terms of
  (1) $d_{1,0}^2(\theta_a) d_{1,0}^2(\theta_b) \sin\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\sin\varphi$,
  (2) $d_{1,0}^2(\theta_a) d_{1,0}^2(\theta_b) \cos\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\cos\varphi$.

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

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



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



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

[a] Z.-H. Zhang, Phys. Rev. D **107**, L011301 (2023)
[b] G. Durieux and Y. Grossman, Phys. Rev. D **92**, 076013 (2015)

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

(B+B2) JHEP 04 (2025) 036

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

$$A_X(D_{(s)}^+) = \frac{N(X>0) - N(X<0)}{N(X>0) + N(X<0)} \qquad \overline{A}_{\overline{X}}(D_{(s)}^-) = \frac{\overline{N}(\overline{X}>0) - \overline{N}(\overline{X}<0)}{\overline{N}(\overline{X}>0) + \overline{N}(\overline{X}<0)}$$

- CP-violating parameter: $a_{CP}^X = \frac{1}{2}(A_X - \overline{A}_{\overline{X}})$ (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 $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

(B+B2) JHEP 04 (2025) 036

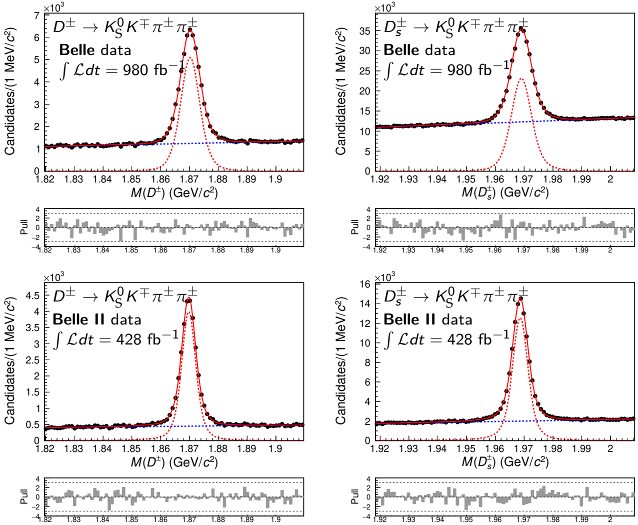


Table: Fitted signal and background yields in a window ± 10 MeV$/c^2$ around the nominal $D^+_{(s)}$ mass.

Component	$D^+ \to K_S^0 K^- \pi^+ \pi^+$	
	Belle	Belle II
Signal (N_{sig})	44048 ± 288	26738 ± 199
Background (N_{bkg})	24844 ± 88	8964 ± 53
Ratio ($N_{\text{sig}}/N_{\text{bkg}}$)	1.8	3.0

Component	$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	
	Belle	Belle II
Signal (N_{sig})	210743 ± 780	92000 ± 393
Background (N_{bkg})	245285 ± 280	39997 ± 114
Ratio ($N_{\text{sig}}/N_{\text{bkg}}$)	0.9	2.3

Measurement of $A_{CP}^X(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$

(B+B2) JHEP 04 (2025) 036

- $C_{\rm TP}$ and $C_{\rm QP}$ at Belle II ($\int \mathcal{L}dt = 428\ \text{fb}^{-1}$):

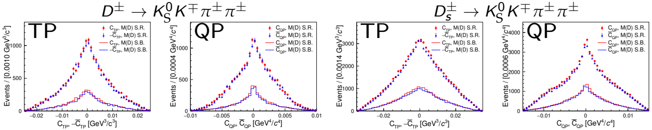


Table 2: Results for $\mathcal{A}_{CP}^X$ in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$ decays, where $X = C_{\rm TP}$ (1), $C_{\rm QP}$ (2), $C_{\rm TP}C_{\rm QP}$ (3), $\cos\theta_{K_S^0}\cos\theta_{K^-}$ (4), $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$ (5), and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$ (6). The significance of the combined $\mathcal{A}_{CP}^X$ result from $\mathcal{A}_{CP}^X = 0$ is listed in the last column.

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^+	(1)	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	(2)	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	(3)	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	(4)	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	(5)	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	(6)	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D_s^+	(1)	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	(2)	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	(3)	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	(4)	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	(5)	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	(6)	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ

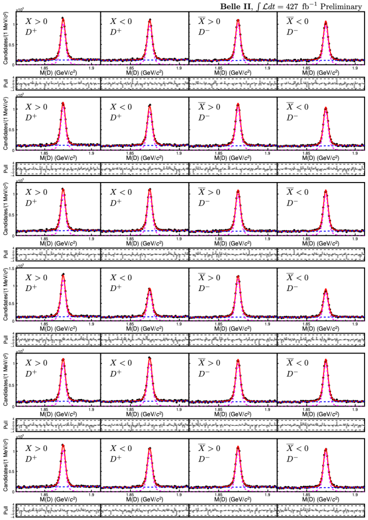
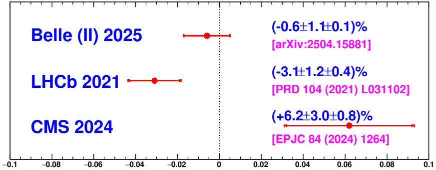


Figure 7: Fitted distributions for Belle II $D^\pm \to K_S^0 K^\mp \pi^\pm \pi^\pm$ data, for (top to bottom) $X = C_{\rm TP}$, $C_{\rm QP}$, $C_{\rm TP}C_{\rm QP}$, $\cos\theta_{K_S^0}\cos\theta_{K^-}$, $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$, and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$.

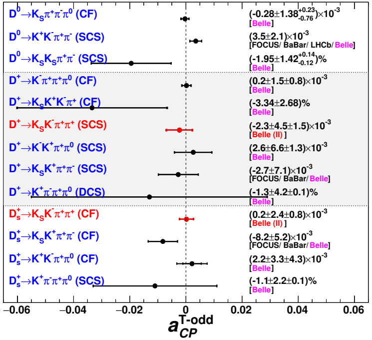
Summary: charm CPV searches at Belle (II)

- $A_{CP}(D^0 \to K_S^0 K_S^0)$ using D^{*+} and non-D^{*+} tagged samples at Belle (II):



- $A_{CP}(D^{0,+} \to \pi^{+,0}\pi^0)$ at Belle II (428 fb^{-1}):
  $A_{CP}^{\pi^0\pi^0} = (+0.30 \pm 0.72 \pm 0.20)\%$ (vs. $\sigma_{B1} = 0.65\%$)
  $A_{CP}^{\pi^+\pi^0} = (-1.9 \pm 0.9 \pm 0.1)\%$ (vs. $\sigma_{B1} = 1.3\%$)
  An improved precision per luminosity at Belle II, because of superior performance in the reconstruction of neutral pions and displaced charged particles.
- Working on more charm decays. Please stay tuned.

- $A_{CP}^X(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$: first search for this mode.
  - $X = C_{\mathrm{TP/QP}}$, $C_{\mathrm{TP}} C_{\mathrm{QP}}$, $\cos\theta_{K_S^0} \cos\theta_{K^-} (C_{\mathrm{TP/QP}})$.
  - most precise $a_{CP}^{T\text{-odd}}$ for D^+ SCS decays and D_s^+ decays; and the other A_{CP}^X results: the first such measurements.



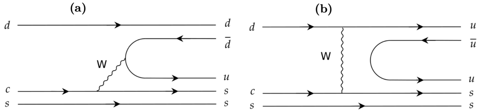
Outline

$\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ ($P^0 = \pi^0/\eta/\eta'$) and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$

(B+B2) JHEP 10 (2024) 045

- In hadronic weak decays of charmed baryons, nonfactorizable contributions from W-emission and W-exchange diagrams play an essential role and cannot be neglected; leading to difficulties for theoretical predictions.

- For $\Xi_c^0 \to \Xi^0 h^0$ decays, only the nonfactorizable amplitude contributes to the internal W-emission and W-exchange amplitudes.



- Various approaches describe the nonfactorizable effects: the covariant confined quark model, the pole model (Pole), current algebra (CA), and $SU(3)_F$ flavor symmetry, etc.

- Parity violation study in charmed baryon decays via $1/2^+ \to 1/2^+ + 0^-$: decay asymmetry parameter α is related to interference between parity-violating S-wave and parity-conserving P-wave amplitudes.

$$\alpha \equiv 2 \cdot \mathrm{Re}(S^* P)/(|S|^2 + |P|^2)$$

- It leads to an asymmetry in the angular decay distribution:

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

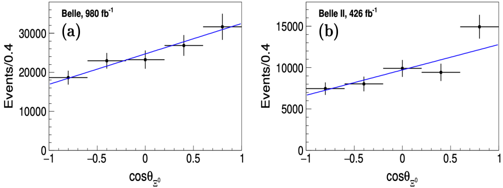
where $\theta_{\Xi^0} = \left\langle \vec{p}_\Lambda, -\vec{p}_{\Xi_c^0} \right\rangle$ in the Ξ^0 rest frame.

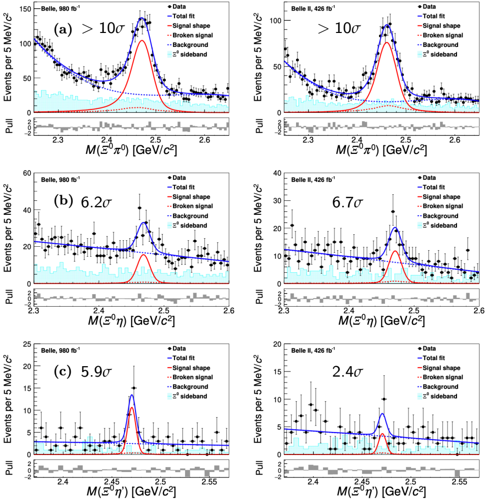
- Measurements of $\mathcal{B}$ and α: clarify the theoretical picture.

$\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ ($P^0 = \pi^0/\eta/\eta'$) and $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$

(B+B2) JHEP 10 (2024) 045

- Based on 1.4 ab^{-1} dataset from Belle and Belle II.
- Using $\Xi_c^0 \to \Xi^-\pi^+$ as reference mode (obtained yields $N = 5.0 \times 10^4$)
- Combining $\mathcal{B}$-results from Belle/Belle II samples:
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)/\mathcal{B}_{\text{ref}} = 0.48 \pm 0.02 \pm 0.03$
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)/\mathcal{B}_{\text{ref}} = 0.11 \pm 0.01 \pm 0.01$
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')/\mathcal{B}_{\text{ref}} = 0.08 \pm 0.02 \pm 0.01$
- Simultaneous fit on efficiency-corrected yields in helicity angle bins for Belle and Belle II samples:
  $\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15 \pm 0.23$



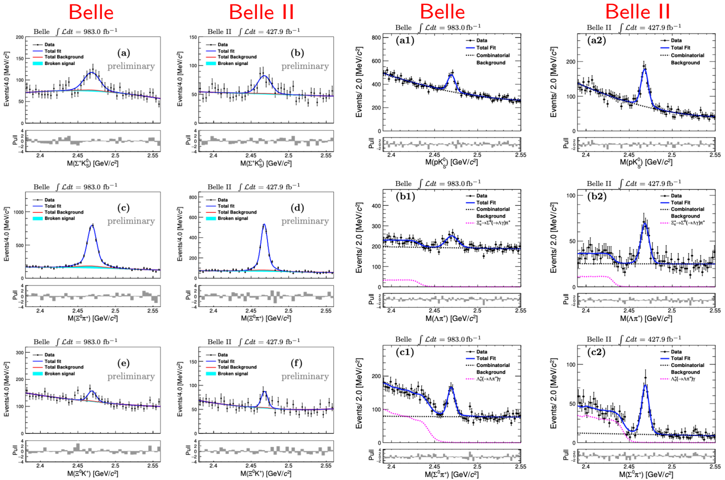


Outline

Measurement of $\mathcal{B}(\Xi_c^+ \to BP)$

(B+B2) arXiv:2503.17643, JHEP 03 (2025) 061

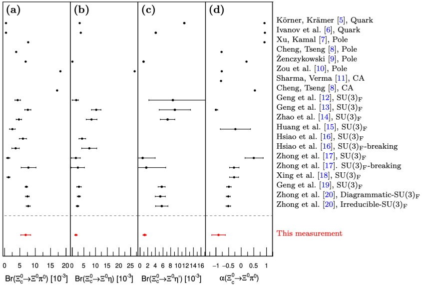
- $\mathcal{B}$-measurement for six hadronic weak decays of Ξ_c^+ baryon
- Using $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ as reference mode
- Two CF decays:
  $\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0)/\mathcal{B}_{\rm ref} = (6.7 \pm 0.7 \pm 0.3)\%$
  $\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+)/\mathcal{B}_{\rm ref} = (24.8 \pm 0.5 \pm 0.9)\%$
  Four SCS decays:
  $\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+)/\mathcal{B}_{\rm ref} = (1.7 \pm 0.3 \pm 0.1)\%$
  $\mathcal{B}(\Xi_c^+ \to p K_S^0)/\mathcal{B}_{\rm ref} = (2.47 \pm 0.16 \pm 0.07)\%$
  $\mathcal{B}(\Xi_c^+ \to \Lambda \pi^+)/\mathcal{B}_{\rm ref} = (1.56 \pm 0.14 \pm 0.09)\%$
  $\mathcal{B}(\Xi_c^+ \to \Sigma^0 \pi^+)/\mathcal{B}_{\rm ref} = (4.13 \pm 0.26 \pm 0.22)\%$
- Belle II has better resolution and mostly has higher significance than Belle.
- These SCS decays: first observed, and may provide samples for CPV searches in charmed baryon sector in the future.



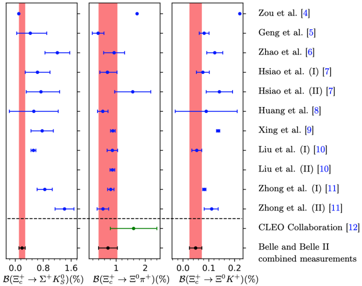
Summary of charmed baryon studies

- Based on B+B2 (1.4 ab^{-1}), we reported studies of 5 CF and 4 SCS decays of $\Xi_c^{0,+}$ baryons:

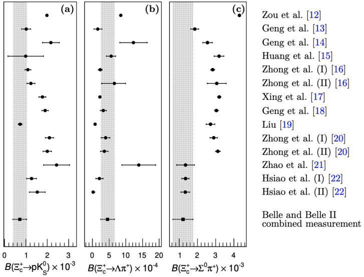
JHEP 10 (2024) 045



arXiv:2503.17643



JHEP 03 (2025) 061



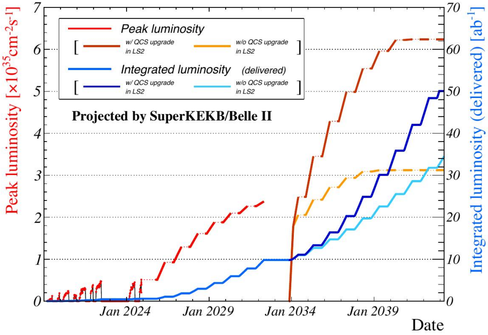
- These relative $\mathcal{B}$'s are almost the first or most precise results, providing important inputs for theoretical studies.
- Top priority for Ξ_c physics: precise measurement of absolute $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$ and $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$.

Outline

1. Charm sample at Belle (II)
2. $A_{CP}(D^0 \to K^0_S K^0_S)$
3. $A_{CP}(D^{0,+} \to \pi^{0,+}\pi^0)$
4. $A^X_{CP}(D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+)$
5. $\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$
6. $\mathcal{B}(\Xi_c^+ \to BP)$
7. **Summary**

Summary

- Belle II has collected dataset of 575 fb^{-1} and SuperKEKB made a W.R. luminosity: $5.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- After the first charm wave: precise charm lifetimes based on early dataset, we welcome new charm waves at Belle (II):
  - Charm CPV in charmed meson decays: $D^0 \to K_S^0 K_S^0$, $D^{0,+} \to \pi^{0,+}\pi^0$, and $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$.
    new flavor-tagging method; new reference mode; new variables (C_{QP}); etc.
  - Study of hadronic decays of charmed baryons: $\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$, six Ξ_c^+ decays.
    Belle II has better purity/resolution and higher signal-noise-ratio than Belle.
  - More studies on hadronic decays of charmed hadron and CPV searches based on current available datasets at Belle (II), and the final dataset (Belle II target luminosity 50 ab^{-1}) in the future. Please stay tuned.



Back up

Thanks for your attention.

谢谢！

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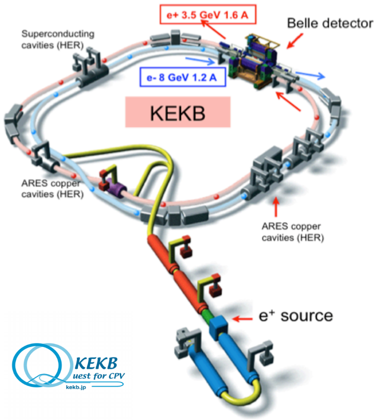
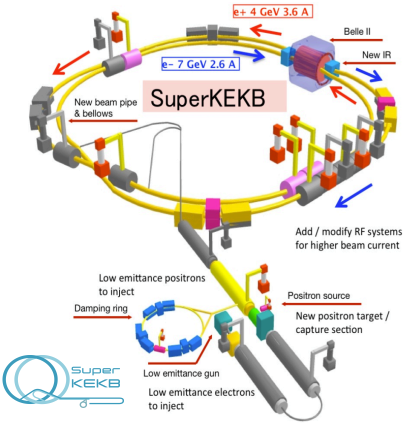
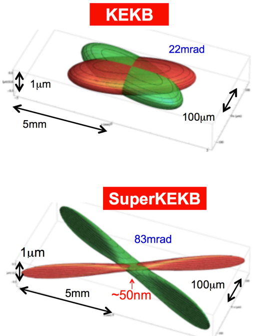
from KEKB to SuperKEKB

- 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 $5.1 \times 10^{34}\ cm^{-2}s^{-1}$.







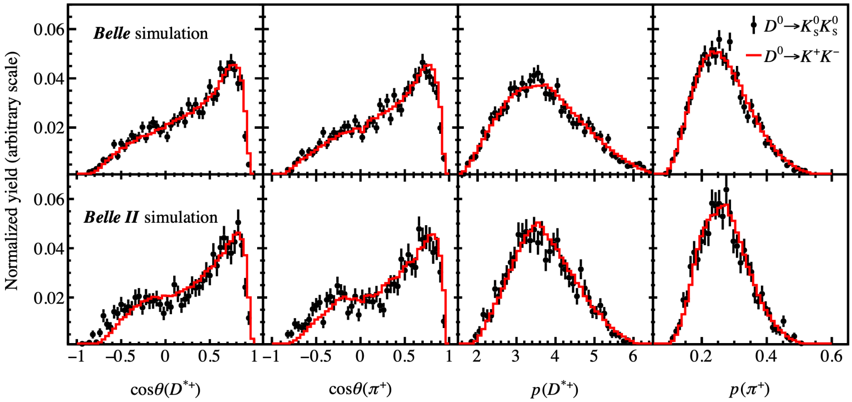
Comparison of available charm samples

Experiment	Machine	C.M.	Luminosity(fb^{-1})	N_{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	600 ($\to$ 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 ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0$@3.77 GeV$)$=3.61 nb, $\sigma(D^+D^-$@3.77 GeV$)$=2.88 nb, $\sigma(D_s^*D_s$@4.17 GeV$)$=0.967 nb; $\sigma(c\bar{c}$@10.58 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, with their advantages, are all ideal platforms for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.

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



X-dependent efficiency in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$