Belle II 实验上粲物理研究的近期成果介绍

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Outline

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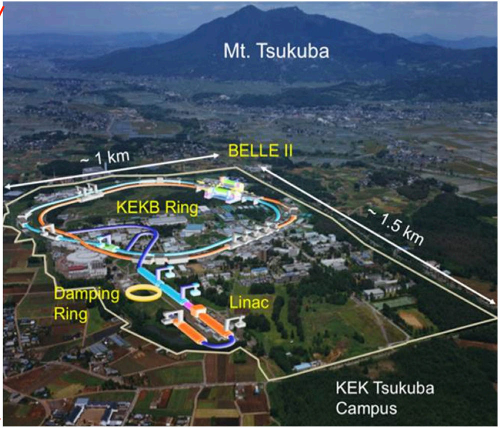
SuperKEKB and Belle II

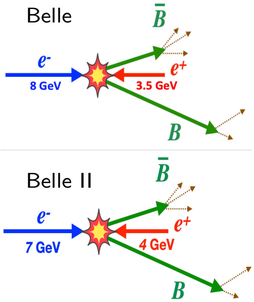
- 高能加速器研究机构（KEK: 高エネルギー加速器研究機構）
- SuperKEKB: 属于第二代“不对称 B 工厂”。
  - 周长3千米，地下11米
  - 实验大厅：筑波、日光、富士、大穗。
- 环上唯一探测器：Belle II 探测器
- “绝世美女二世”：Belle II 实验

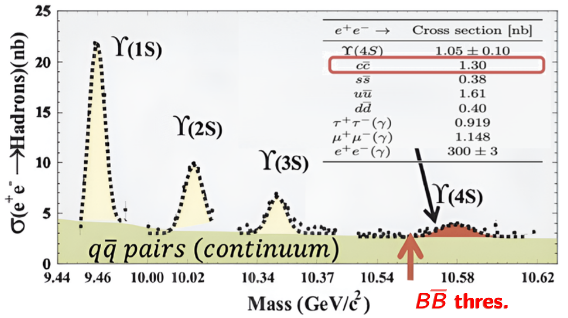
- “绝世美女一世”：Belle 实验
  1999--2010年采集 $\sim 1\ \text{ab}^{-1}$。
- B介子工厂：el (电子) + le (反电子)
- 设计目标：B 衰变中 CP 破坏。2001年实现。
  $\Rightarrow$ 2008诺贝尔奖 Kobayashi & Maskawa

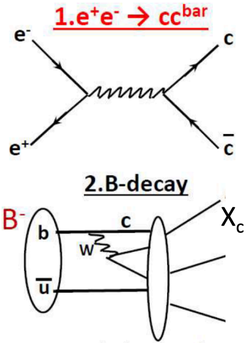


Charm production at Belle (II)

- 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.
- Belle II has two ways of charm production: (1) $e^+e^- \to c\bar{c}$; (2) $B \to$ charm decays.

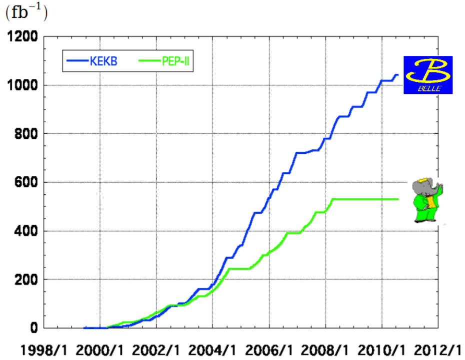






Luminosity at Belle (II)

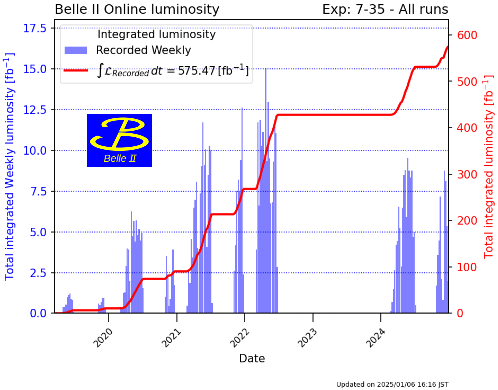
Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

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



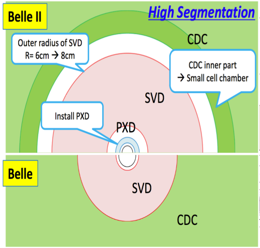
Comparison of available charm samples

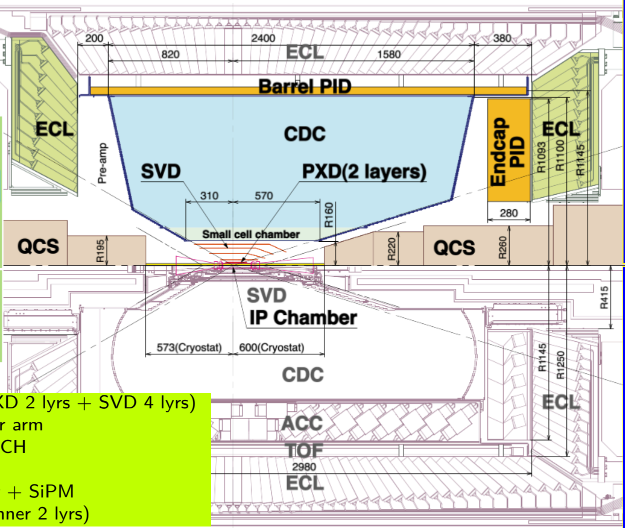
Experiment	Machine	C.M.	Luminosity(fb^{-1})	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	20 7.3 4.5	$D^{0,+}$: 10^8 D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	$\sim$ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle 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 $\sigma(D^0\bar{D}^0@3.77\,\text{GeV})$=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, with their advantages, are all ideal platforms for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.

Detector: Belle II Vs. Belle



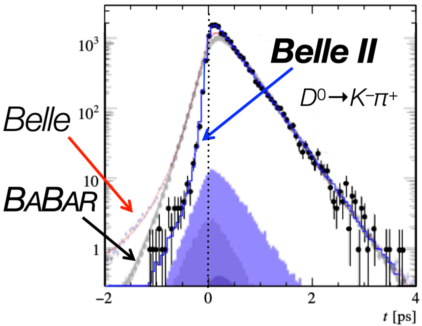


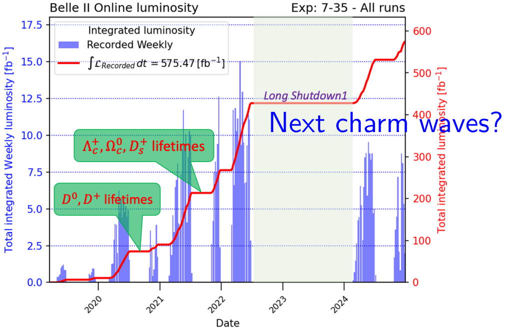
SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling
KLM: RPC → Scintillator + SiPM
(endcaps, barrel inner 2 lyrs)

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.



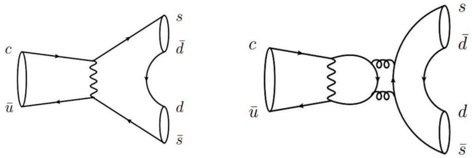


Outline

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

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

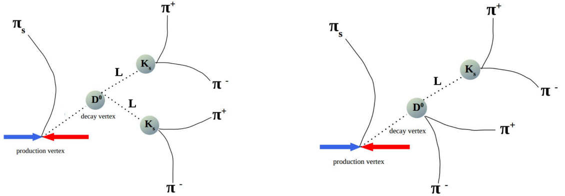
- The time-integrated CP asymmetry $A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$.
- It may be enhanced to be an observable level (the 1% level) within the Standard Model, due to the 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)]

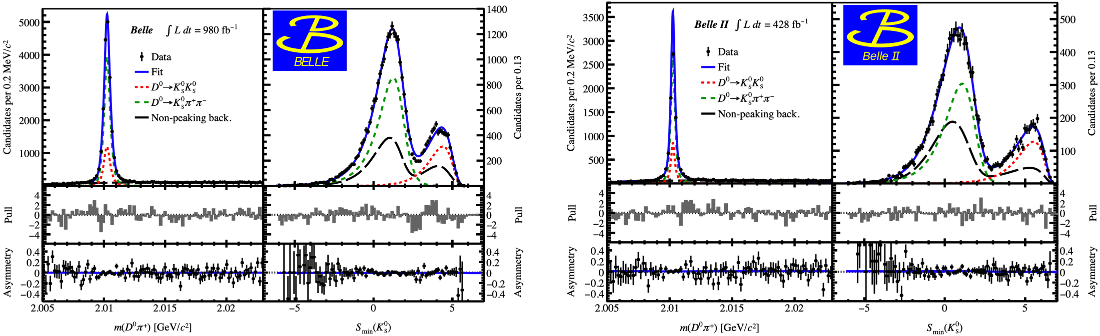
$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using D^{*+}-tagged sample (B+B2) PRD 111, 012015 (2025)

- 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 $D^0 \to K\overline{K}$: $A_{\text{raw}}^{K\overline{K}} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{\text{FB}}^{D^{*+}} + A_{CP}^{K\overline{K}} + A_{\varepsilon}^{\pi_s}$
- Use $D^0 \to K^+K^-$ as control mode, and $A_{CP}^{K^+K^-} = A_{CP}^{\text{dir}} + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$:
  - $A_{CP}^{\text{dir}}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \times 10^{-4}$: 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)]
- $A_{CP}^{K_S^0 K_S^0} = (A_{\text{raw}}^{K_S^0 K_S^0} - A_{\text{raw}}^{K^+K^-}) + A_{CP}^{K^+K^-}$ 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 $(m(D^0\pi_s), S_{\text{min}})$ of D^0 and $\bar{D}^0$ candidates for $D^0 \to K_S^0 K_S^0$ decays.
  - Flight significance variable $S_{\text{min}} = \log(\min(L_i/\sigma_i))$: 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

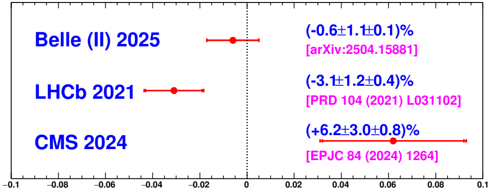
(B+B2) PRD 111, 012015 (2025)

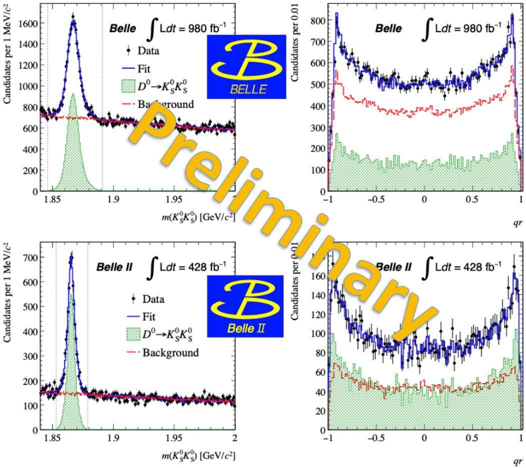


- Belle: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\%$ Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\%$
- Combined $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\%$: comparable to the world-best result: $\sigma_{\mathrm{LHCb}} = 1.3\%$
- Belle(II)+LHCb average: $(-2.3 \pm 0.9)\%$ 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}):
  $N_{\rm sig} = 14\,490 \pm 340$ and $A_{CP} = (+2.5 \pm 2.7 \pm 0.4)\%$
- Belle II sample (428 fb^{-1}):
  $N_{\rm sig} = 5\,180 \pm 120$ 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: $\boxed{A_{CP}(D^0 \to \pi^0\pi^0) = A_{\rm avg}^{\pi^0\pi^0} - A_{\rm avg}^{K\pi} + A_{\rm avg}^{K\pi,{\rm untag}}}$

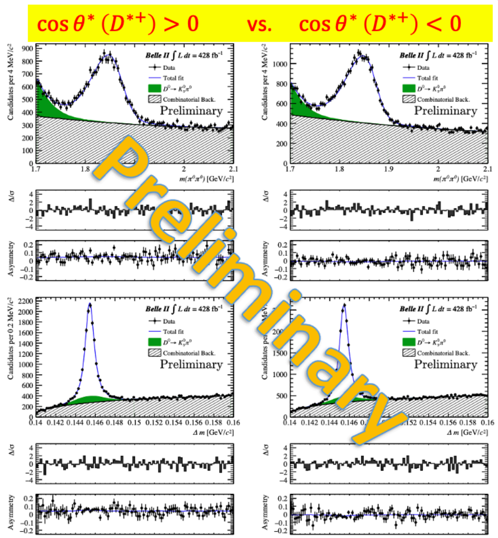
  here $A_{\rm avg}^f = \left(A^f(\cos\theta^* < 0) + A^f(\cos\theta^* > 0)\right)/2$ where $f = \pi^0\pi^0; K\pi; {\rm untag}$.

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

(B2) arXiv:2505.02912 (preliminary)

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

  consistent with CP symmetry and with Belle ($980\ \text{fb}^{-1}$): $(-0.03 \pm 0.64 \pm 0.10)\%$ [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].



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

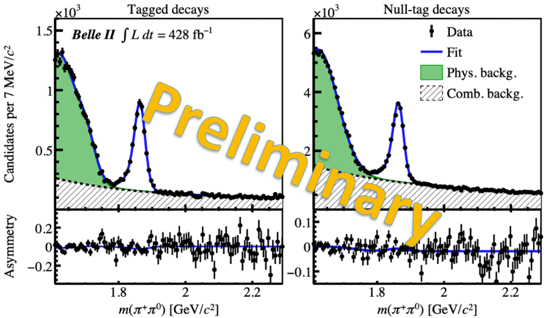
Preliminary result

- 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:

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

- 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.



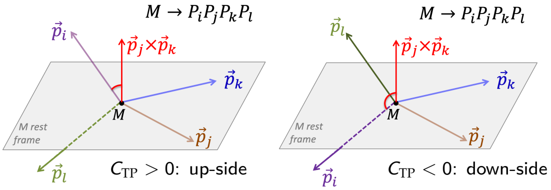
$N_{\text{sig}} = 5\,130 \pm 110$
$A_{CP} = (-3.9 \pm 1.8 \pm 0.2)\%$

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

Outline

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

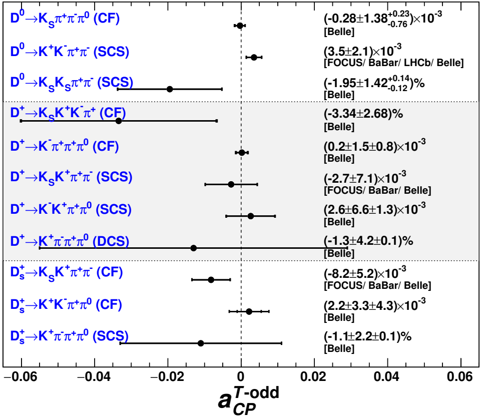
- CPV searches in several four-body D-decays at FOCUS, BABAR, LHCb and Belle using the triple-product (TP): $C_{\rm TP} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$.



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

- CPV in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$: 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

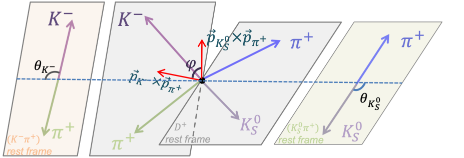
- We do the first CPV search with the quadruple-product (QP): in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$: $C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$, where the subscripts ('h' and 'l') denote the π^+ with higher and lower momentum, respectively,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

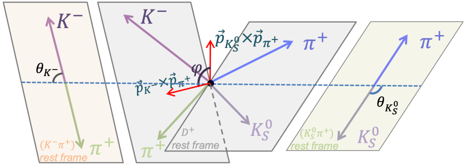
- $D \to V_a V_b$ (e.g. $D_{(s)}^+ \to \overline{K}^{*0} K^{*+}$ is a dominant process) amplitude involves terms of
  (1) $d_{1,0}^2(\theta_a) d_{1,0}^2(\theta_b) \sin\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\sin\varphi$,
  (2) $d_{1,0}^2(\theta_a) d_{1,0}^2(\theta_b) \cos\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\cos\varphi$.

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

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) $X = C_{\mathrm{TP}} = \vec{p}_{K^-} \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$: same sign as $\sin\varphi$.
  2) $X = C_{\mathrm{QP}} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$: same sign as $\cos\varphi$.
  3) $X = C_{\mathrm{TP}} C_{\mathrm{QP}}$: same sign as $\sin(2\varphi)$.
  4) $X = \cos\theta_{K_S^0} \cos\theta_{K^-}$.
  5) $X = \cos\theta_{K_S^0} \cos\theta_{K^-} C_{\mathrm{TP}}$: same sign as $\cos\theta_{K_S^0} \cos\theta_{K^-} \sin\varphi$,
  6) $X = \cos\theta_{K_S^0} \cos\theta_{K^-} C_{\mathrm{QP}}$: 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_{TP}, $C_{\mathrm{TP}} C_{\mathrm{QP}}$ and $\cos\theta_{K_S^0} \cos\theta_{K^-} C_{\mathrm{TP}}$); 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 $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$

JHEP 04 (2025) 036

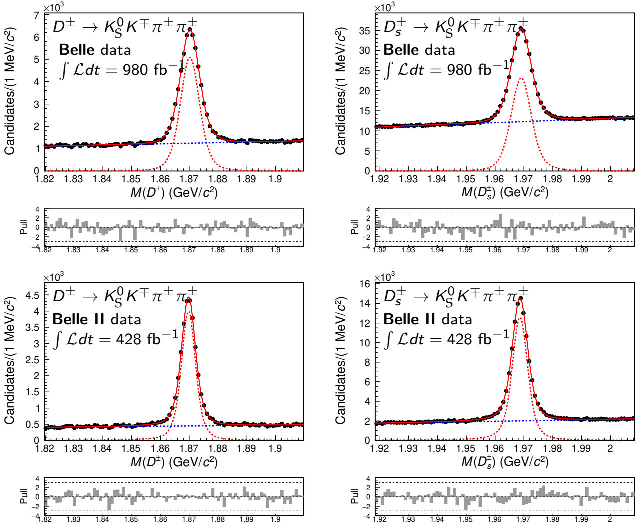


Table: Fitted signal and background yields in a window ± 10 MeV/c^2 around the nominal $D_{(s)}^+$ mass.

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 $A_{CP}^X(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$ JHEP 04 (2025) 036

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

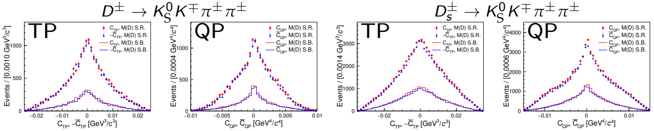


Table 2: Results for $\mathcal{A}_{CP}^X$ in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$ decays, where $X = C_{\rm TP}$ (1), $C_{\rm QP}$ (2), $C_{\rm TP}C_{\rm QP}$ (3), $\cos\theta_{K_S^0}\cos\theta_{K^-}$ (4), $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$ (5), and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$ (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

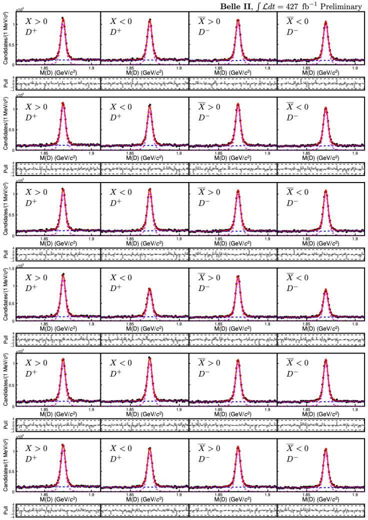


Figure 7: Fitted distributions for Belle II $D^\pm \to K_S^0 K^\mp \pi^\pm \pi^\pm$ data, for (top to bottom) $X = C_{\rm TP}$, $C_{\rm QP}$, $C_{\rm TP}C_{\rm QP}$, $\cos\theta_{K_S^0}\cos\theta_{K^-}$, $C_{\rm TP}\cos\theta_{K_S^0}\cos\theta_{K^-}$, and $C_{\rm QP}\cos\theta_{K_S^0}\cos\theta_{K^-}$.

Outline

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

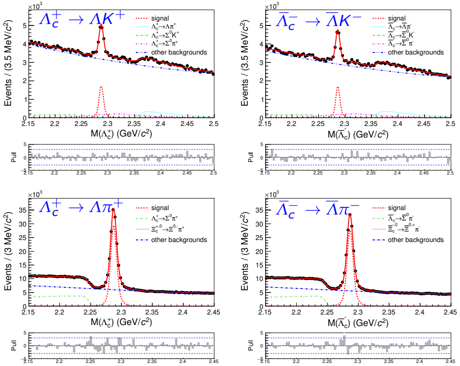
(Belle) Science Bulletin **68** (2023) 583

- 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.



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

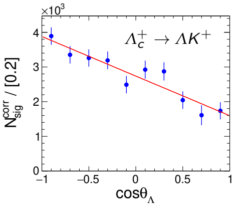
First $A_{CP}^{\rm dir}$ for SCS two-body decays of charmed baryons.

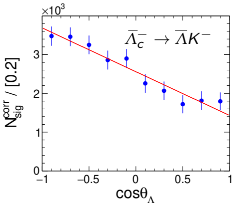
baryonic α-induced CPV in $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$

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

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

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

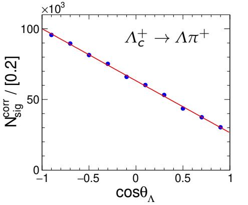


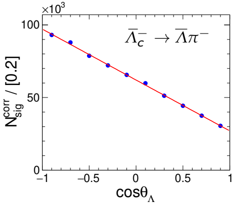


- Result: $A_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$
  $A_{CP}^{\alpha}(\Lambda_c^+ \to \Sigma^0 K^+) = +0.08 \pm 0.35 \pm 0.14$
  First A_{CP}^{α} results for charmed baryon SCS decays.
- No evidence of CPV is found.

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

- Probe Λ-hyperon CPV in charmed baryon CF decays, inspired by PLB 849 (2024) 138460.
- Under a reasonable assumption $\alpha_{\Lambda_c^+} = -\alpha_{\bar{\Lambda}_c^-}$ in CF decays, we have $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = A_{CP}^{\alpha}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\bar{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\bar{\Lambda}_c^-}\alpha_+}$.

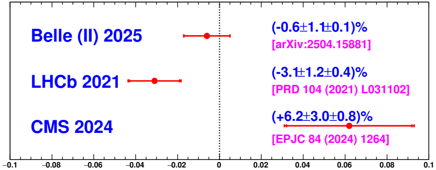




- Result: $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = +0.013 \pm 0.007 \pm 0.011$
  The first result of hyperon CPV in charm CF decays

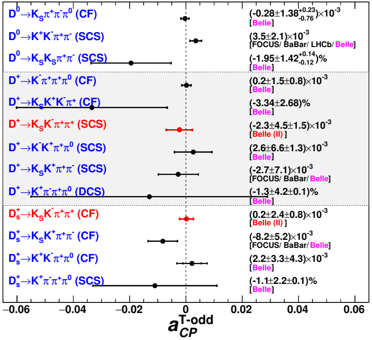
Summary: charm CPV searches at Belle (II)

- $A_{CP}(D^0 \to K_S^0 K_S^0)$ 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 because of superior performance in the reconstruction of neutral pions and displaced charged particles.
- CPV in charmed baryon decays at Belle II: results on the road, please stay tuned. Here recall Belle result of A_{CP}^{dir} and A_{CP}^{α} of $\Lambda_c^+ \to \Lambda K^+, \Sigma^0 K^+$.

- $A_{CP}^X(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$: first search for this mode.
  - $X = C_{\text{TP/QP}}$, $C_{\text{TP}} C_{\text{QP}}$, $\cos\theta_{K_S^0} \cos\theta_{K^-} (C_{\text{TP/QP}})$.
  - 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.

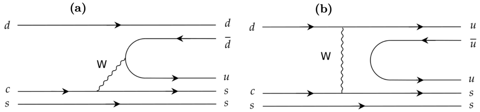


Outline

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

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

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

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

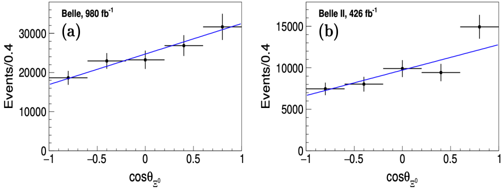
where $\theta_{\Xi^0} = \langle \vec{p}_\Lambda, -\vec{p}_{\Xi_c^0} \rangle$ in the Ξ^0 rest frame.

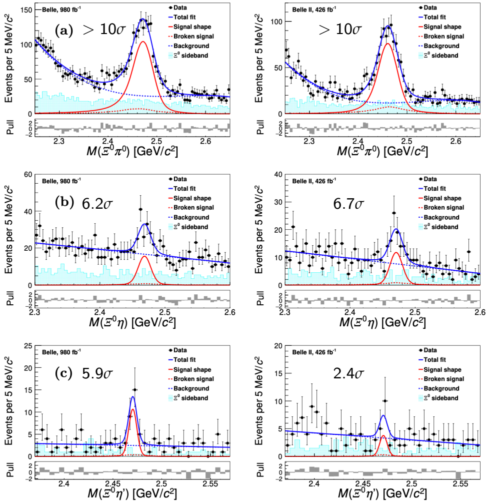
- Measurements of $\mathcal{B}$ and α: clarify the theoretical picture.

$\mathcal{B}(\Xi_c^0 \to \Xi^0 P^0)$ $(P^0 = \pi^0/\eta/\eta')$ 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:
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)/\mathcal{B}_{\rm ref} = 0.48 \pm 0.02 \pm 0.03$
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)/\mathcal{B}_{\rm ref} = 0.11 \pm 0.01 \pm 0.01$
  $\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')/\mathcal{B}_{\rm ref} = 0.08 \pm 0.02 \pm 0.01$
- Simultaneous fit on efficiency-corrected yields in helicity angle bins for Belle and Belle II samples:
  $\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15 \pm 0.23$



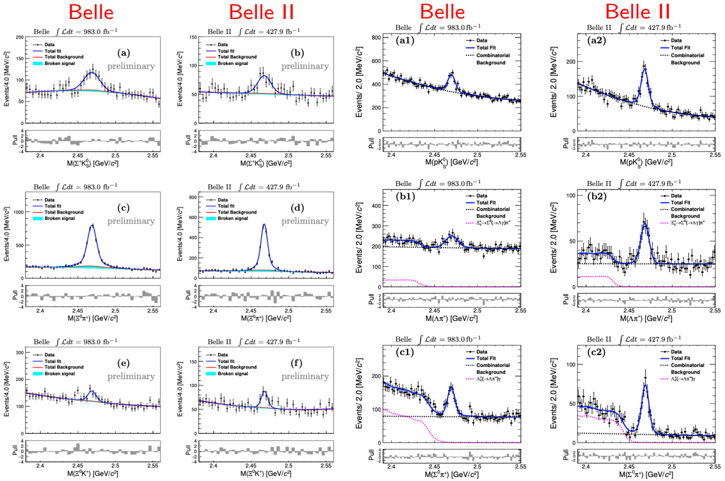


Outline

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

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

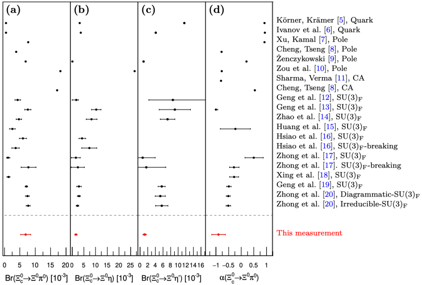
- $\mathcal{B}$-measurement for six hadronic weak decays of Ξ_c^+ baryon
- Using $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ as reference mode
- Two CF decays:
  $\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0)/\mathcal{B}_{\rm ref} = (6.7 \pm 0.7 \pm 0.3)\%$
  $\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+)/\mathcal{B}_{\rm ref} = (24.8 \pm 0.5 \pm 0.9)\%$
  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.



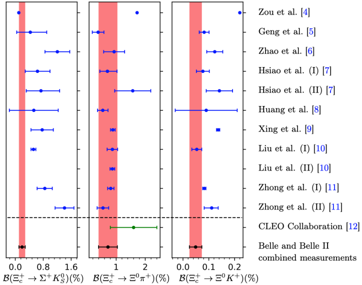
Summary of charmed baryon studies

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

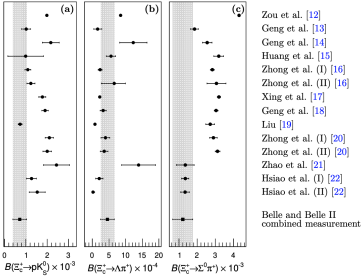
JHEP 10 (2024) 045



arXiv:2503.17643



JHEP 03 (2025) 061

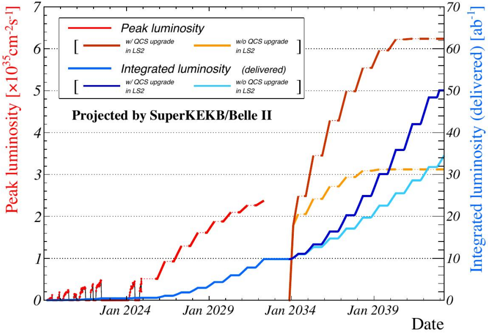


- These relative $\mathcal{B}$'s are almost the first or most precise results, providing important inputs for theoretical studies.
- Top priority for Ξ_c physics: precise measurement of absolute $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$ and $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$.

Outline

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 datasets, we welcome new charm waves:
  - 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-tagged sample (non-D^{*+} sample); 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. better purity/resolution and improved SNR significantly at Belle II compared to Belle.
  - CPV in charmed baryon, rare or forbidden decay, amplitude analysis, (semi-)leptonic decays, etc.
  - More results of charm physics 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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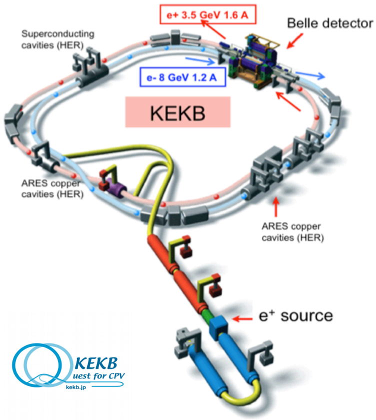
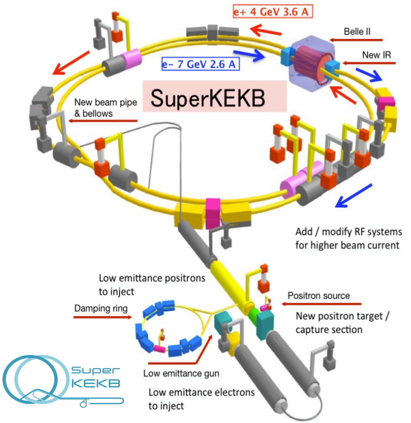
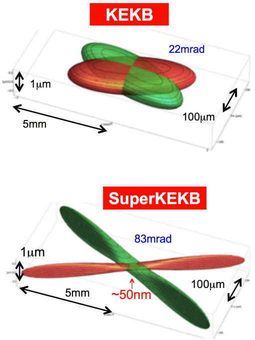
from KEKB to SuperKEKB

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







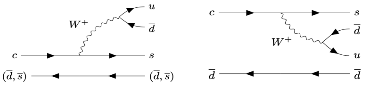
Alan's talk at CKM 2023

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

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

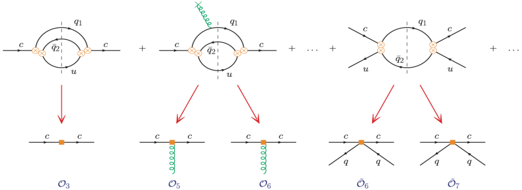
via optical theorem

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

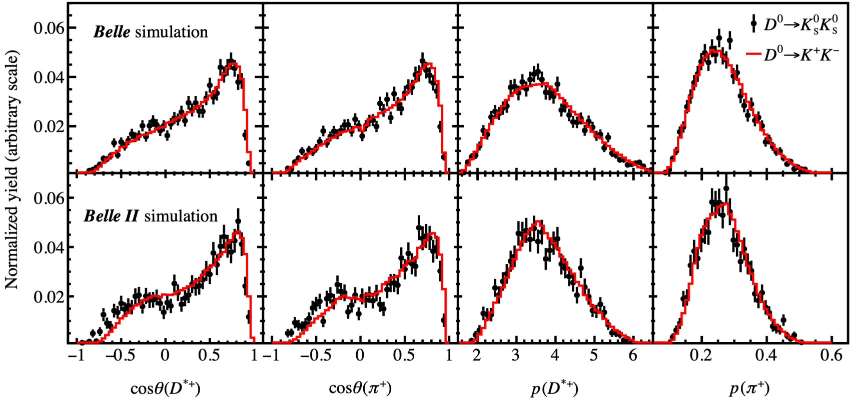
via Heavy Quark Expansion

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



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



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