Recent charm results at Belle and Belle II experiments

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第三届高能物理理论与实验融合发展研讨会

2024年11月3日于大连

感谢邀请。我与大连的美丽相约

- 2016年8月第一次来大连，参加 BESIII R-QCD 研讨会。⇒ 到高能所做博后这事“谈妥”。
- 2019年5月第二次来大连，参加 Belle II 中国组研讨会。⇒ 收到辛辛那提大学的博士后 offer。
- 今年我入职湖南师大，有幸再来大连这个“福地”。

D^0-$\bar{D}^0$ Mixing and CP Violation in D^0 Three-body Decays via Time-dependent Amplitude Analyses at B-factories

Longke Li, Ziping Zhang, Wenbiao Yan

[1]University of Science and Technology of China (USTC)

Aug. 16-19, 2016, BES III R&QCD Workshop, LNNU at Dalian

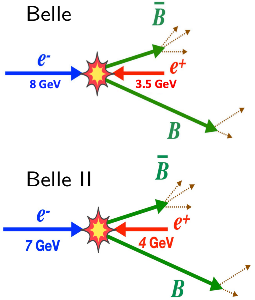
2016年于大连

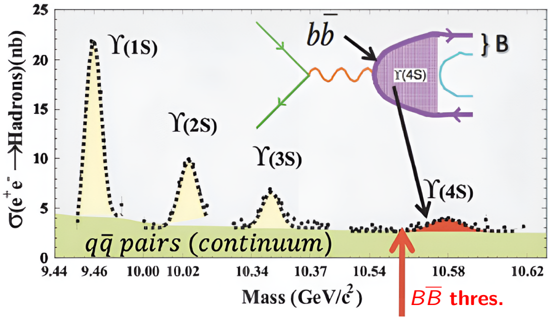
2019年于大连

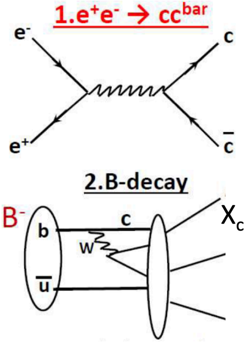
Outline

Charm production at Belle and Belle II

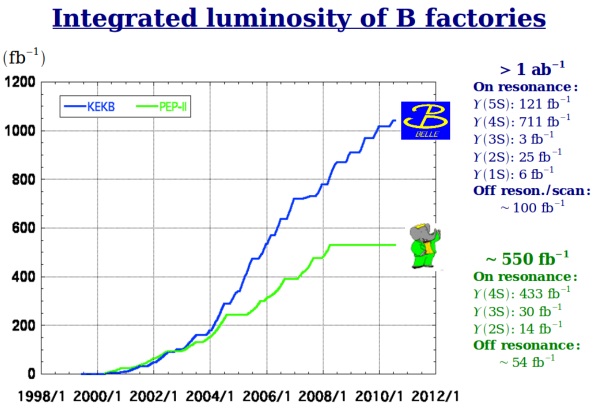
- At Belle (II), e^+e^- mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance decaying into $B\bar{B}$ in 96% of the time.
- Meanwhile, continuum processes $e^+e^- \to q\bar{q}$ $(q = u,\, d,\, s,\, c)$ have large cross sections.
- Two ways to produce the charm sample: $e^+e^- \to c\bar{c}$ $(\sigma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



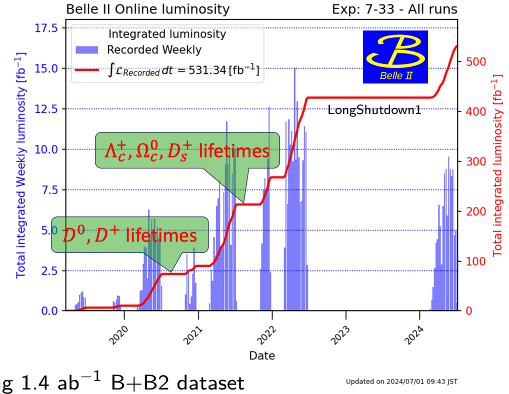




Luminosity at Belle and Belle II



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

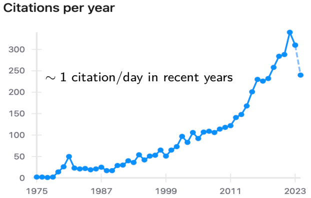
Charm results at Belle and Belle II in latest two years

我主导或参与的分析占30%

- Charm lifetimes:
  - $\tau(D_s^+)$ [PRL 131, 171803 (2023)] / $\tau(\Lambda_c^+)$ [PRL 130, 071802 (2023)] / $\tau(\Omega_c^0)$ [PRD 107, L031103 (2023)]
- Charm *CP* violation:
  - $\mathcal{A}_{CP}^{\rm TP}(D^0 \to K_S^0 K_S^0 \pi^+\pi^-)$ [PRD 107, 052001 (2023)] / $\mathcal{A}_{CP}^{\rm TP}(D_{(s)}^+ \to K^+ K_S^0 h^+ h^-)$ [PRD 108, L11102 (2023)] / $\mathcal{A}_{CP}^{\rm TP}(D_{(s)}^+ \to K h \pi^+ \pi^0)$ [arXiv:2305.12806] / $\mathcal{A}_{CP}^{\rm dir}, \mathcal{A}_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+)$ [Science Bulletin 68 (2023) 583] / $\mathcal{A}_{CP}^{X}(D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+)$ [using TP and QP, arXiv:2409.15777] / $A_{CP}(D^0 \to K_S^0 K_S^0)$ [preliminary]
- D^0-$\overline{D}^0$ mixing:
  - model-independent measurement of mixing parameter in $D^0 \to K_S^0 \pi^+\pi^-$ [arXiv:2410.22961]
- $\mathcal{B}$ and α of hadronic decays:
  - $\mathcal{B}(D_{(s)}^+ \to K^+ h^- \pi^+ \pi^0)$ [PRD 107, 033003 (2023)] / $\mathcal{B}(\Xi_c^0 \to \Xi^0(\pi^0, \eta, \eta'))$ and $\alpha(\Xi_c^0 \to \Xi^0 \pi^0)$ [JHEP 10 (2024) 045] / $\mathcal{B}(\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta'))$ and $\alpha(\Lambda_c^+ \to \Sigma^+ \pi^0)$ [PRD 107, 032003 (2023)] / $\mathcal{B}(\Lambda_c^+ \to p K_S^0 (K_S^0, \eta))$ [PRD 107, 032004 (2023)] / $\mathcal{B}(\Omega_c^0 \to \Xi^- h^+, \Omega^- K^+)$ [JHEP 01 (2023) 055] / $\mathcal{B}(\Lambda_c^+ \to p K_S^0 \pi^0)$ [preliminary] / $\mathcal{B}(\Xi_c^+ \to p K_S^0, \Lambda \pi^+, \Sigma^0 \pi^+)$ [preliminary]
- Rare or forbidden decays:
  - $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ [PRD 109, 052003 (2024)] / $D^0 \to p\ell$ [PRD 109, L031101 (2024)] / $D^0 \to h^- h^{(\prime)+} e^+ e^-$ [preliminary]
- Spectrum:
  - $\Lambda_c(2880, 2940)^+ \to p D^0$ [PRD 110, 032021 (2024)] / $\Lambda_c(2910)^+ \to \Sigma_c(2455)^0 \pi^+$ [PRL 130, 031901 (2023)] / $\Lambda_c(2625)^+ \to \Sigma_c^{0,++} \pi^{+,-}$ [PRD 107, 032008 (2023)] / $\Sigma(1435)^* \to \Lambda \pi^\pm$ in $\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$ [PRL 130, 151903 (2023)]

Why CPV and Charm CPV Special?

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



- 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.

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[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)

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:

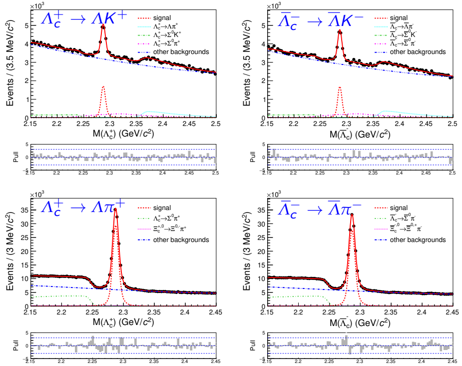
$$A_{\text{raw}}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\text{FB}}^{\Lambda_c^+}$$

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

  - $A_{CP}^{\Lambda_c^+ \to \Lambda h^+}$ ($A_{CP}^{\Lambda \to p\pi^-}$): 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 $D^0 \to K^-\pi^+\pi^0$
  - $A_{\text{FB}}^{\Lambda_c^+}$ 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: $\Delta A_{\text{raw}} = A_{\text{raw}}^{\text{corr}}(\Lambda_c^+ \to \Lambda K^+) - A_{\text{raw}}^{\text{corr}}(\Lambda_c^+ \to \Lambda \pi^+) = A_{CP}^{\text{dir}}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\text{dir}}(\Lambda_c^+ \to \Lambda \pi^+) = A_{CP}^{\text{dir}}(\Lambda_c^+ \to \Lambda K^+)$

  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.



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

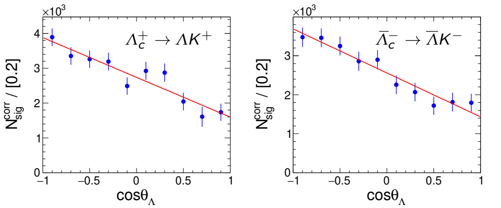
First A_{CP}^{dir} for SCS two-body decays of charmed baryons.

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

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

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

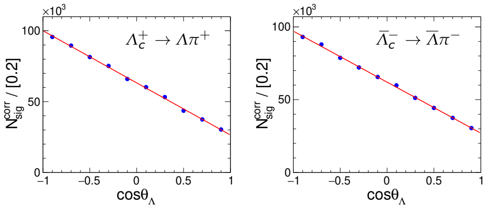
- Measure $\alpha/\bar{\alpha}$ for the separate $\Lambda_c^+/\overline{\Lambda}_c^-$ samples.
- Calculate $\mathcal{A}_{CP}^{\alpha} \equiv (\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-})/(\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-})$.



- 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) $\Lambda_c^+ \to \Lambda \pi^+, \Sigma^0 \pi^+$ 多听听理论报告

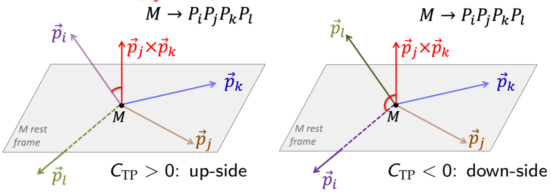
- Probe Λ-hyperon CPV in charmed baryon CF decays, inspired by PLB 849 (2024) 138460 (JP Wang, FS Yu).
- Under a reasonable assumption $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ in CF decays, we have $\mathcal{A}_{CP}^{\alpha}(\Lambda \to p\pi^-) = \mathcal{A}_{CP}^{\alpha}(\text{total})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



- 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

CPV searches using triple product (Belle and Belle II), arXiv:2409.15777

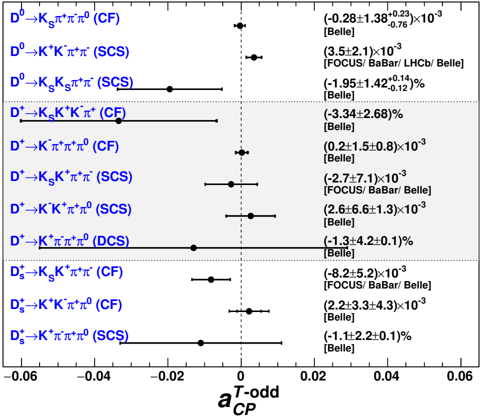
- CPV searches in several four-body D-decays at FOCUS, BABAR, LHCb and Belle using the triple-product (TP): $X = C_{\mathrm{TP}} = \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_k)$.



C_{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 using quadruple product

(Belle and Belle II), arXiv:2409.15777

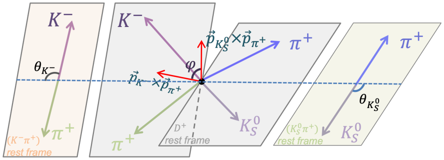
- We do the first CPV search with the quadruple-product (QP): in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$: $X = C_{\rm QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$, where the subscripts ('h' and 'l') denote the π^+ with higher and lower momentum, respectively, 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) $d^2_{1,0}(\theta_a) d^2_{1,0}(\theta_b) \cos\varphi \propto \sin(2\theta_a)\sin(2\theta_b)\cos\varphi$.

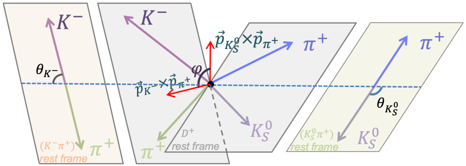
- two more observables for CPV searches[a]:
  - $X = \cos\theta_{K^0_S} \cos\theta_{K^-} C_{\rm TP}$: same sign as $\cos\theta_{K^0_S} \cos\theta_{K^-} \sin\varphi$,
  - $X = \cos\theta_{K^0_S} \cos\theta_{K^-} C_{\rm QP}$: same sign as $\cos\theta_{K^0_S} \cos\theta_{K^-} \cos\varphi$.

- $X = \cos\theta_{K^0_S} \cos\theta_{K^-}$ 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)

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

(Belle and Belle II), arXiv:2409.15777

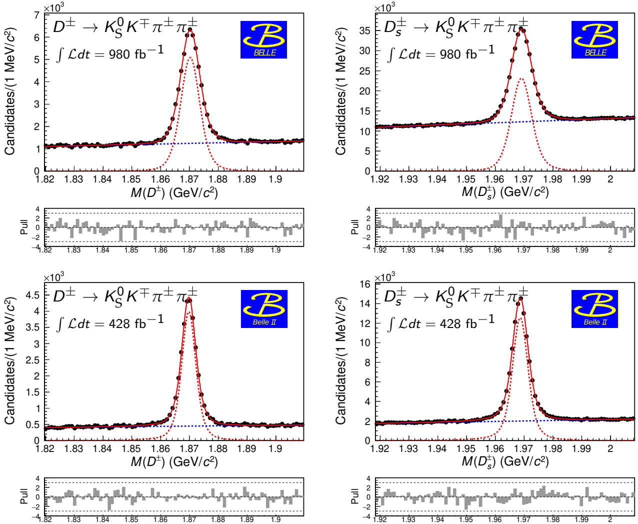


Table: Fitted signal and background yields in a window ± 10 MeV/c^2 around the nominal $D_{(s)}^+$ mass.

Component	$D^+ \to K_S^0 K^- \pi^+ \pi^+$	
	Belle	Belle II
Signal (N_{sig})	44048 ± 288	26738 ± 199
Background (N_{bkg})	24844 ± 88	8964 ± 53
Ratio (N_{sig}/N_{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_{sig}/N_{bkg})	0.9	2.3

Simultaneous fit for $\mathcal{A}_{CP}^{X}$ measurement

(Belle and Belle II), arXiv:2409.15777

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

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

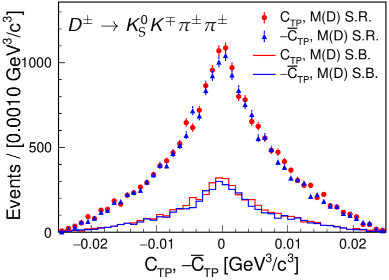
$$A_{\overline{X}}(D_{(s)}^-) = \frac{N_-(\overline{X}>0) - N_-(\overline{X}<0)}{N_-(\overline{X}>0) + N_-(\overline{X}<0)}$$

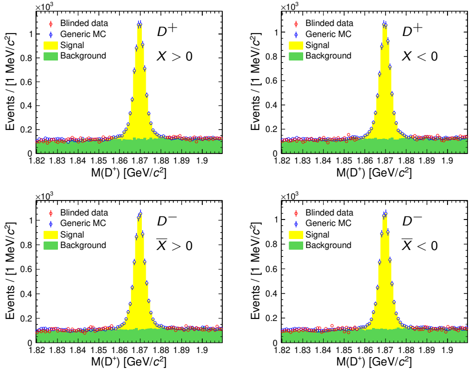
$$\mathcal{A}_{CP}^{X} = \frac{1}{2}(A_X(D_{(s)}^+) - A_{\overline{X}}(D_{(s)}^-))$$

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

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

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





Final $\mathcal{A}_{CP}^X$ measurement in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$ (Belle and Belle II), arXiv:2409.15777

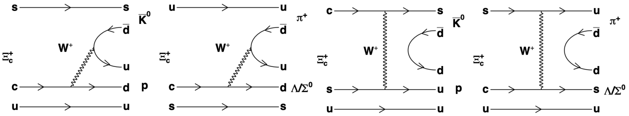
- combining the results from Belle and Belle II experiments: $\mathcal{A}_{CP}^X(\text{avg.}) = \frac{\mathcal{A}_{CP}^{B1}/\sigma_{B1}^2 + \mathcal{A}_{CP}^{B2}/\sigma_{B2}^2}{1/\sigma_{B1}^2 + 1/\sigma_{B2}^2}$, and its uncertainty $\sigma_{\mathcal{A}_{CP}^X(\text{avg.})} = \frac{1}{\sqrt{1/\sigma_{B1}^2 + 1/\sigma_{B2}^2}}$, 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

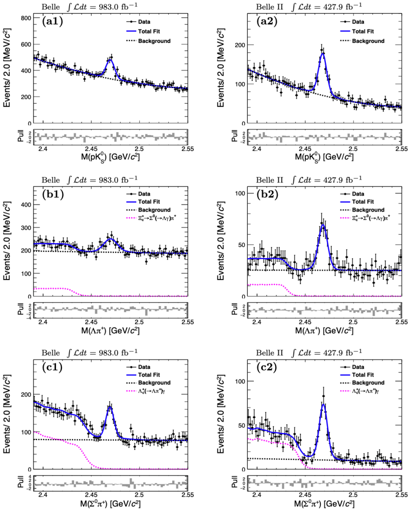
Observation of (SCS) $\Xi_c^+ \to pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$

(Belle and Belle II) Preliminary, 主导: 复旦 + 吉大 + 湖南师大

- In hadronic decays of charmed baryons, nonfactorizable contributions from the internal W-emission and W-exchange diagrams play an essential role and cannot be neglected. e.g.

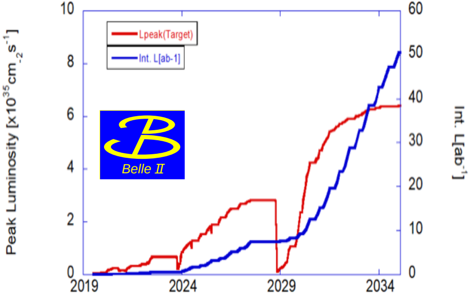


- SCS charm decays provide good probes for CP violation.
- First observation of such SCS Ξ_c^+-decays using B+B2 data:
- $\dfrac{\mathcal{B}(\Xi_c^+ \to pK_S^0)}{\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (2.47 \pm 0.16 \pm 0.07)\%$
- $\dfrac{\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (1.56 \pm 0.14 \pm 0.09)\%$
- $\dfrac{\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (4.13 \pm 0.26 \pm 0.22)\%$
- using W.A. $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$ to obtain their absolute $\mathcal{B}$'s.



总结和展望

- Belle II 已经加入"战场"，现可使用 (B+B2)1.5 ab^{-1} 的数据。
- 粲物理成果正在持续产生：继第一波粲强子寿命的高精度测量后，现在我们迎来了多方位的研究工作：
  - 粲介子 CP 破坏的寻找：首个粲 CPV 结果，新方法、新模式
  - 粲重子 CP 破坏的寻找（遗憾没有底味重子源）
  - 粲强子衰变的分支比、角分布、振幅的分析。
  - 粲强子激发态的寻找和研究。
- 理论与实验融合、实验与实验合作，取得了很好的成果。
  - 多听听理论家的报告（线上、线下）
  - 多和理论家喝咖啡或茶（"闲"聊）
  - 在高校院系间，多串串门
- 青椒的我再接再厉，正争取各种合作与交流的机会。
  - 例如和湖南师大的理论团队交流讨论：谱学和 CPV 等。
  - 例如和辽师合作：粲重子新型衰变模式和粲重子激发态的寻找等。
- 未来 Belle II 更多数据，更多交流与合作，更多重要结果。



Back up

Thank you for your attention.

谢谢！

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Comparison of available charm samples

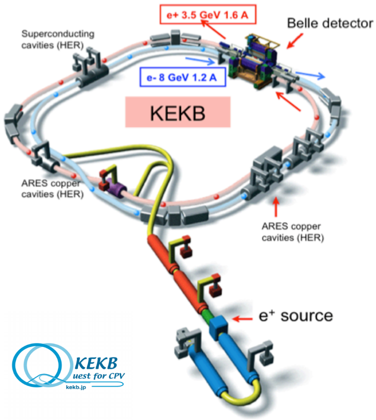
Experiment	Machine	C.M.	Luminosity(fb^{-1})	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	20 7.3 4.5	$D^{0,+}$: 10^8 D_s^+: 5×10^6 Λ_c^+: 0.8×10^6 ★☆	$\sim$ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	500 ($\rightarrow$ 50000)	D^0: 10^9 ($\rightarrow 10^{11}$) $D_{(s)}^+$: 10^8 ($\rightarrow 10^{10}$) Λ_c^+: 10^7 ($\rightarrow 10^9$)	$\mathcal{O}$(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 ($\rightarrow$ 23 $\rightarrow$ 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

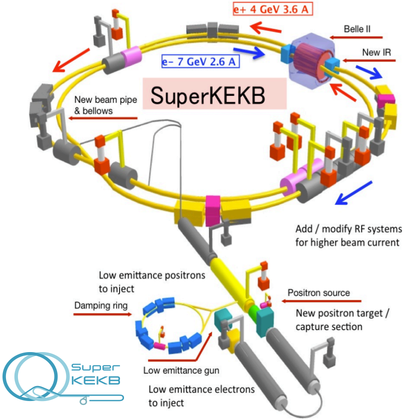
Here uses $\sigma(D^0\bar{D}^0@3.77\,\mathrm{GeV})$=3.61 nb, $\sigma(D^+D^-@3.77\,\mathrm{GeV})$=2.88 nb, $\sigma(D_s^*D_s@4.17\,\mathrm{GeV})$=0.967 nb; $\sigma(c\bar{c}@10.58\,\mathrm{GeV})$=1.3 nb where each $c\bar{c}$ event averagely has 1.1/0.6/0.3 $D^0/D^+/D_s^+$ yields; $\sigma(D^0@CDF)$=13.3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

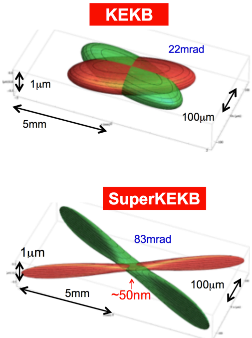
- BESIII, Belle II, and LHCb experiments have their advantages for charm studies.

from KEKB to SuperKEKB

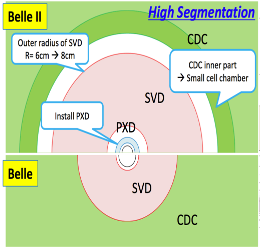
- As 1st and 2nd generation B-factories, KEKB and SuperKEKB have many similarities, and more differences:
  - Damping ring added to have low emittance positrons / use 'Nano-beam' scheme by squeezing the beta function at the IP.
  - beam energy: admit lower asymmetry to mitigate Touschek effects / beam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

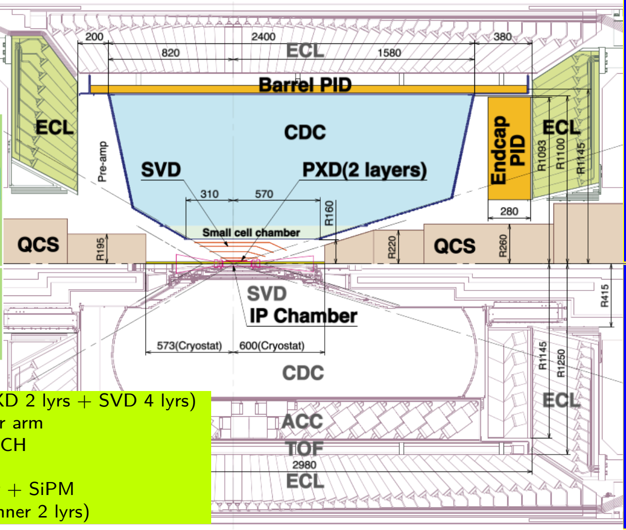


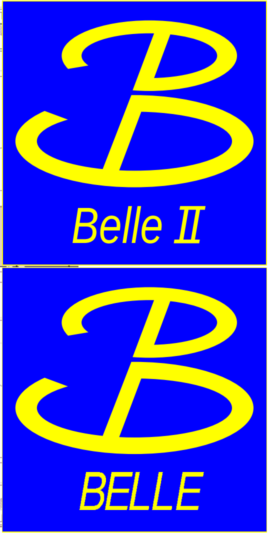




Detector: Belle II Vs. Belle







- 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)

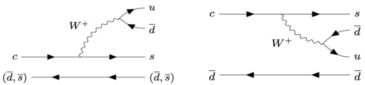
Alan's talk at CKM 2023

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

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

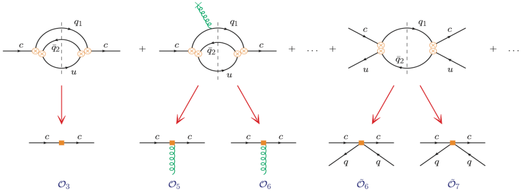
via optical theorem

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

via Heavy Quark Expansion

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

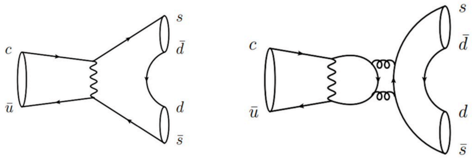
⇒ comparing lifetime calculations with measurements tests/improves our understanding of QCD



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

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

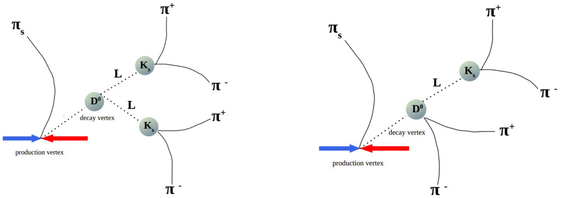
- The time-integrated CP asymmetry $\mathcal{A}_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$.
- It may be enhanced to be an observable level (the 1% level) within the Standard Model, 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}): $\mathcal{A}_{CP}^{K_S^0 K_S^0} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$ 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)]

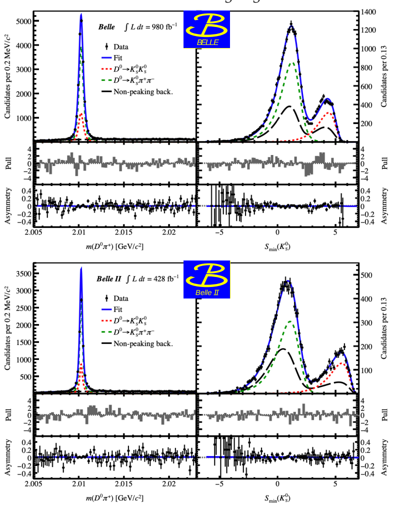
Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

- 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 $D^0 \to K_S^0 \pi^+\pi^-$.

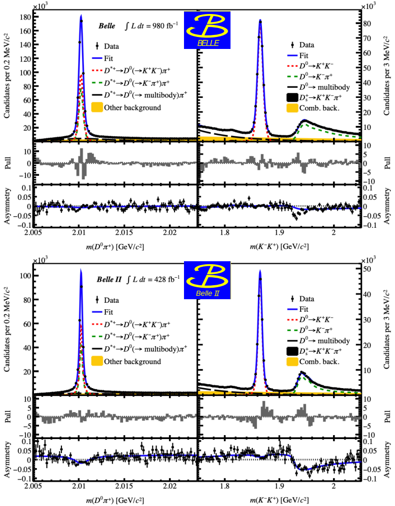


Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ Preliminary

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



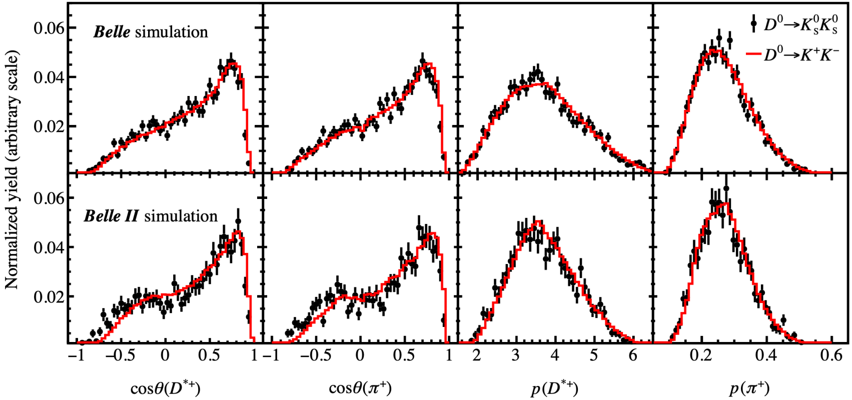
$D^0 \to K^+ K^-$



Preliminary results:

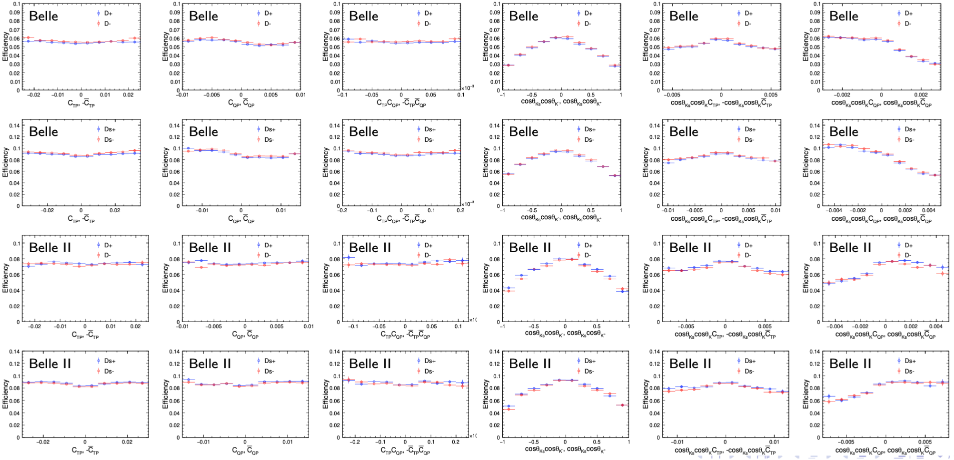
- $A_{raw}(D^0 \to K_S^0 K_S^0)$:
  - Belle: $(-1.0 \pm 1.6)\%$
  - Belle II: $(-0.6 \pm 2.3)\%$
- $A_{raw}(D^0 \to K^+ K^-)$:
  - Belle: $(0.17 \pm 0.19)\%$.
  - Belle II: $(1.61 \pm 0.27)\%$.
- final $A_{CP}(D^0 \to K_S^0 K_S^0)$:
  - Belle: $(-1.1 \pm 1.6 \pm 0.1)\%$).
  - Belle II: $(-2.2 \pm 2.3 \pm 0.1)\%$).
  - 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 $D^{+,0} \to \pi^{+,0}\pi^0$).

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



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

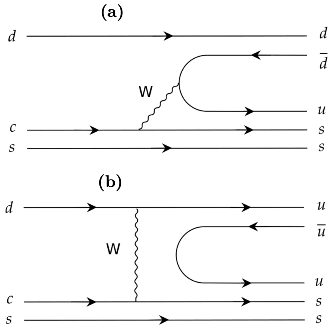
$$A_X(D^+_{(s)}) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)} \qquad A_{\overline{X}}(D^-_{(s)}) = \frac{N_-(\overline{X}>0) - N_-(\overline{X}<0)}{N_-(\overline{X}>0) + N_-(\overline{X}<0)} \qquad \mathcal{A}^X_{CP} = \frac{1}{2}\left(A_X(D^+_{(s)}) - A_{\overline{X}}(D^-_{(s)})\right)$$



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

(Belle and Belle II), JHEP 10 (2024) 045

- The internal W-emission and W-exchange amplitudes in $\Xi_c^0 \to \Xi^0 h^0$, to which only the nonfactorizable amplitude contribute.



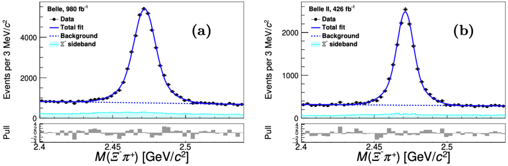
- Predictions of $\mathcal{B}$ (units of 10^{-3}) and asymmetry parameter (α):

Reference	Model	$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$	$\alpha(\Xi_c^0 \to \Xi^0\pi^0)$
Körner, Krämer [5]	Quark	0.5	3.2	11.6	0.92
Ivanov et al. [6]	Quark	0.5	3.7	4.1	0.94
Xu, Kamal [7]	Pole	7.7	-	-	0.92
Cheng, Tseng [8]	Pole	3.8	-	-	−0.78
Żenczykowski [9]	Pole	6.9	0.1	0.9	0.21
Zou et al. [10]	Pole	18.2	26.7	-	−0.77
Sharma, Verma [11]	CA	-	-	-	−0.8
Cheng, Tseng [8]	CA	17.1	-	-	0.54
Geng et al. [12]	$SU(3)_F$	4.3 ± 0.9	$1.7^{+1.0}_{-1.7}$	$8.6^{+11.0}_{-6.3}$	-
Geng et al. [13]	$SU(3)_F$	7.6 ± 1.0	10.3 ± 2.0	9.1 ± 4.1	$-1.00^{+0.07}_{-0.00}$
Zhao et al. [14]	$SU(3)_F$	4.7 ± 0.9	8.3 ± 2.3	7.2 ± 1.9	-
Huang et al. [15]	$SU(3)_F$	2.56 ± 0.93	-	-	-0.23 ± 0.60
Hsiao et al. [16]	$SU(3)_F$	6.0 ± 1.2	$4.2^{+1.6}_{-1.3}$	-	-
Hsiao et al. [16]	$SU(3)_F$-breaking	3.6 ± 1.2	7.3 ± 3.2	-	-
Zhong et al. [17]	$SU(3)_F$	$1.13^{+0.59}_{-0.49}$	1.56 ± 1.92	$0.683^{+3.272}_{-3.268}$	$0.50^{+0.37}_{-0.35}$
Zhong et al. [17]	$SU(3)_F$-breaking	$7.74^{+2.52}_{-2.32}$	$2.43^{+2.79}_{-2.90}$	$1.63^{+5.09}_{-5.14}$	$-0.29^{+0.20}_{-0.17}$
Xing et al. [18]	$SU(3)_F$	1.30 ± 0.51	-	-	-0.28 ± 0.18
Geng et al. [19]	$SU(3)_F$	7.10 ± 0.41	2.94 ± 0.97	5.66 ± 0.93	-0.49 ± 0.09
Zhong et al. [20]	Diagrammatic-$SU(3)_F$	7.45 ± 0.64	2.87 ± 0.66	5.31 ± 1.33	-0.51 ± 0.08
Zhong et al. [20]	Irreducible-$SU(3)_F$	7.72 ± 0.65	2.28 ± 0.53	5.66 ± 1.62	-0.51 ± 0.09

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

(Belle and Belle II), JHEP 10 (2024) 045

- Choose $\Xi_c^0 \to \Xi^-\pi^+$ as normalization mode:

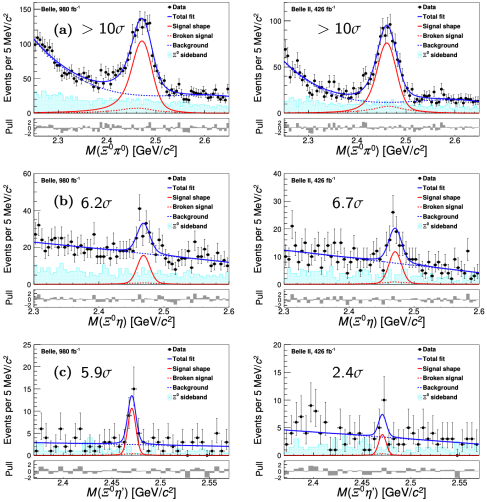


- Yields of ref. mode N_{sig}: (B) 3.6×10^4, (B2) 1.4×10^4.
- Combine $\mathcal{B}$-results at Belle/Belle II:

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.48 \pm 0.02 \pm 0.03$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.11 \pm 0.01 \pm 0.01$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.08 \pm 0.02 \pm 0.01$$

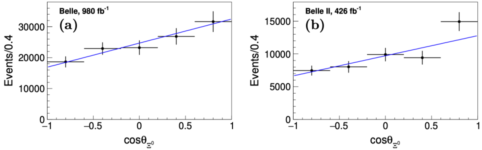


Measurement of $\mathcal{B}(\Xi_c^0 \to \Xi^0(\pi^0/\eta/\eta'))$ and $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ (Belle and Belle II), JHEP 10 (2024) 045

- In $1/2^+ \to 1/2^+ + 0^-$, decay asymmetry parameter $\boxed{\alpha \equiv 2 \cdot \mathrm{Re}(S^* P)/(|S|^2 + |P|^2)}$, where S and P denote the parity-violating S-wave and parity-conserving P-wave amplitudes, respectively.
- The differential decay rate of $\Xi_c^0 \to \Xi^0 h^0$:

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

- Simultaneous fit result:
$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15 \pm 0.23$



- Comparison results with predictions: