Measurement of decay asymmetry parameter and search for *CP* violation in charmed baryon decays at Belle

Longke LI (李龙科)

University of Cincinnati

全国重味物理和 CP 破坏研讨会 (HFCPV2022), 12月10日于南京师范大学

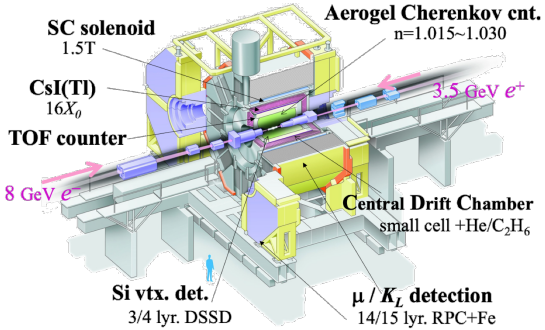
Outline

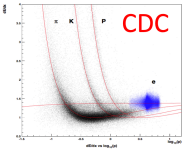
Outline

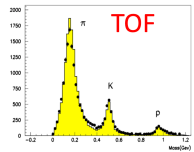
Belle experiment at KEKB

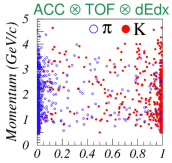
(For more info, see Wenbiao's talk yesterday.)

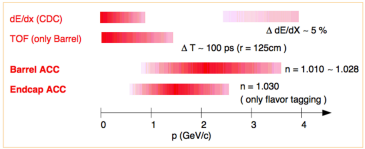
- KEKB: asymmetric-energy e^+e^- collider operating near $\Upsilon(4S)$ (above $B\bar{B}$ threshold), stopped operation in 2010.
- Belle detector: good performances on the momentum/vertex resolution and particle identification up to 3.5 GeV/c; $\sim$ 100% trigger efficiency for hadronic events with uniform decay-time acceptance, etc.
- Accumulated data set of ~ 1 ab^{-1}: not only a B-factory with large $B\bar{B}$ sample(772 millions), but also a tau-charm factory. $\Rightarrow$ a large charm sample from (1) $\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb; (2) $b \to c$ in B decays, to study charm physics.

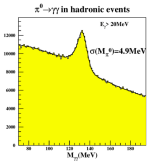












Recent Charm Results at Belle and Belle II

- Belle finished the final data set accumulation more than 12 years ago, but we are lasting to produce fruitful physical results. From the charm side, the recent results this year are listed below:

$A_{CP}^{\text{T-odd}}$ of $D_{(s)}^+ \to K^+ K_S^0 h^- \pi^+$	Preliminary result (to be submitted to PRD(L))
M and Γ of $\Lambda_c(2625)^+$	arXiv:2212.04062 (submitted to PRD)
$\Lambda\pi^\pm$ signals near $\bar{K}N(I=1)$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	arXiv:2211.11151 (submitted to PRL)
BF of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$	arXiv:2210.01995 (accepted by PRD)
BF of $\Omega_c^0 \to \Xi^-\pi^+$, Ξ^-K^+, Ω^-K^+	arXiv:2209.08583 (accepted by JHEP)
a threshold cusp at $\Lambda\eta$ in $\Lambda_c^+ \to pK^-\pi^+$	arXiv:2209.00050 (submitted to PRL)
BF/α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$	arXiv:2208.10825 (accepted by PRD)
BF/$A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$	arXiv:2208.08695 (submitted to Sci.Bull.)
(Belle II) Ω_c^0 lifetime	arXiv:2208.08573 (accepted by RPD(L))
BF/$a_{CP}^{T\text{-odd}}/A_{CP}$ of $D^0 \to K_S^0K_S^0\pi^+\pi^-$	arXiv:2207.07555 (submitted to PRD)
BF of $D^+ \to K^-K_S^0\pi^+\pi^+\pi^0$	arXiv:2207.06595 (submitted to PRD)
(Belle II) Λ_c^+ lifetime	arXiv:2206.15227 (accepted by PRL)
BF of $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$	arXiv:2206.12517 (accepted by PRD)
$\Lambda_c(2910)^+$ in $B \to \Sigma_c(2455)\pi p$	arXiv:2206.08822 (accepted by PRL)
BF of $\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv:2206.08527 (accepted by PRD)
BF of $D_{(s)}^+ \to K\pi\pi^+\pi^0$	arXiv:2205.02018 (accepted by PRD)
BF of $\Lambda_c^+ \to p\eta'$	JHEP 03 (2022) 090
BF of $\Xi_c^0 \to \Lambda K_S^0$, $\Sigma^0K_S^0$, and Σ^+K^-	PRD **105**, L011102 (2022)

Recent Charm Results at Belle and Belle II

- Belle finished the final data set accumulation more than 12 years ago, but we are lasting to produce fruitful physical results. From the charm side, the recent results this year are listed below:

$A_{CP}^{\text{T-odd}}$ of $D_{(s)}^+ \to K^+ K_S^0 h^- \pi^+$	Preliminary result (to be submitted to PRD(L))
⇒ M and Γ of $\Lambda_c(2625)^+$	arXiv:2212.04062 (submitted to PRD)
⇒ $\Lambda\pi^+$ signals near $\overline{K}N(I=1)$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	arXiv:2211.11151 (submitted to PRL)
⇒ BF of $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$	arXiv:2210.01995 (accepted by PRD)
⇒ BF of $\Omega_c^0 \to \Xi^-\pi^+$, Ξ^-K^+, Ω^-K^+	arXiv:2209.08583 (accepted by JHEP)
a threshold cusp at $\Lambda\eta$ in $\Lambda_c^+ \to pK^-\pi^+$	arXiv:2209.00050 (submitted to PRL)
⇒ BF/α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$	arXiv:2208.10825 (accepted by PRD)
⇒ BF/$A_{CP}^{\rm dir}/\alpha/A_{CP}^{\alpha}$ of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$	arXiv:2208.08695 (submitted to Sci.Bull.)
(Belle II) Ω_c^0 lifetime	arXiv:2208.08573 (accepted by RPD(L))
BF/$a_{CP}^{T\text{-odd}}/A_{CP}$ of $D^0 \to K_S^0K_S^0\pi^+\pi^-$	arXiv:2207.07555 (submitted to PRD)
BF of $D^+ \to K^-K_S^0\pi^+\pi^+\pi^0$	arXiv:2207.06595 (submitted to PRD)
(Belle II) Λ_c^+ lifetime	arXiv:2206.15227 (accepted by PRL)
⇒ BF of $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$	arXiv:2206.12517 (accepted by PRD)
⇒ $\Lambda_c(2910)^+$ in $B \to \Sigma_c(2455)\pi p$	arXiv:2206.08822 (accepted by PRL)
⇒ BF of $\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv:2206.08527 (accepted by PRD)
⇒ BF of $D_{(s)}^+ \to K\pi\pi^+\pi^0$	arXiv:2205.02018 (accepted by PRD)
⇒ BF of $\Lambda_c^+ \to p\eta'$	JHEP 03 (2022) 090
⇒ BF of $\Xi_c^0 \to \Lambda K_S^0$, $\Sigma^0K_S^0$, and Σ^+K^-	PRD **105**, L011102 (2022)

- most of them are contributed by Chinese as the first author. My talk covers two measurements of α and CP asymmetry for Λ_c^+ decays.

Outline

$A_{CP}^{\rm dir}$ and $\mathcal{B}$ of (SCS) $\Lambda_c^+ \to \Lambda K^+$, $\Sigma^0 K^+$ (arXiv:2208.08695, submitted to Sci. Bull.)

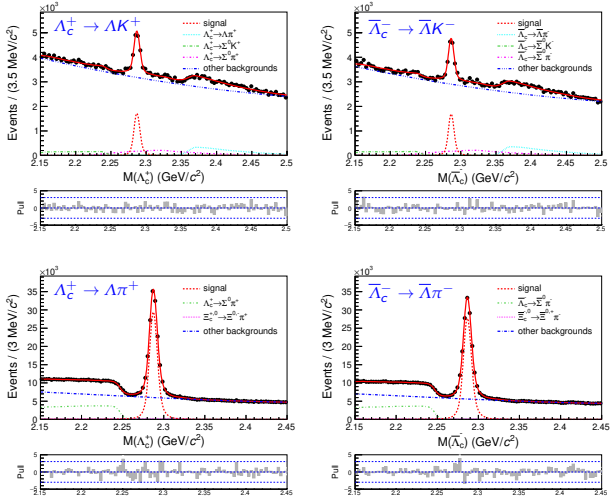
- To date, CPV has been observed in the open-flavored meson sector (i.e. K, D and B mesons), but not yet established in the baryon sector. While, Baryogenesis, the process by which the baryon-antibaryon asymmetry of the universe developed, is directly related to baryon CPV.
- Experimentally, no direct CPV searches in two-body SCS decays of charm baryons have been made to date.
- The raw asymmetry in the decays: $A_{\rm raw}(\Lambda_c^+ \to f) = \frac{N_{\rm sig}(\Lambda_c^+ \to f) - N_{\rm sig}(\overline{\Lambda}_c^- \to \overline{f})}{N_{\rm sig}(\Lambda_c^+ \to f) + N_{\rm sig}(\overline{\Lambda}_c^- \to \overline{f})}$
- Several sources contribute to the raw asymmetry:

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

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

  - $A_{CP}^{{\rm dir}\,\Lambda_c^+ \to \Lambda h^+}$ ($A_{CP}^{{\rm dir}\,\Lambda \to p\pi^-}$) is the direct CP asymmetry associated with the Λ_c^+ (Λ) decays,
  - A_ε^Λ ($A_\varepsilon^{h^+}$) is the detection asymmetry arising from efficiencies between Λ (h^+) and its anti-particle $\overline{\Lambda}$ (h^-),
    - $A_\varepsilon^{K^+}(p_T, \cos\theta)$ using CF samples $D^0 \to K^-\pi^+$ and $D_s^+ \to \phi\pi^+$; $A_\varepsilon^{\pi^+}(p_T, \cos\theta)$ using CF samples $D^+ \to K^-\pi^+\pi^+$ 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 $e^+e^- \to c\overline{c}$ collisions. The FBA is an odd function in $\cos\theta^*$, where θ^* is the Λ_c^+ production polar angle in the e^+e^- center-of-mass frame, but due to asymmetric acceptance, small residual asymmetry remains after integrating over $\cos\theta^*$.
- We have $\boxed{A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda \pi^+) = A_{CP}^{{\rm dir}\,\Lambda_c^+ \to \Lambda K^+} - A_{CP}^{{\rm dir}\,\Lambda_c^+ \to \Lambda \pi^+} = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+).}$

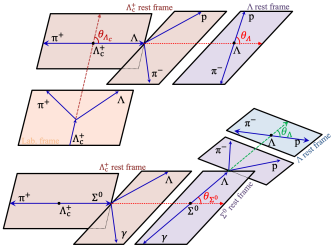
$A_{CP}^{\rm dir}$ and $\mathcal{B}$ of (SCS) $\Lambda_c^+ \to \Lambda K^+$, $\Sigma^0 K^+$ (arXiv:2208.08695, submitted to Sci. Bull.)



- Simultaneous fit on the $A_\xi^{h^+}$-weighted $\Lambda_c^\pm$ samples gives
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$,
  first CPV result of charmed baryon SCS two-body decays.
- Based on $M(\Lambda_c^+)$ fit on the combined $\Lambda_c^\pm$ sample and the efficiencies based on signal MC produced with our measured angular distribution, we measure $\frac{\mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm ref}} = \frac{N_{\rm sig}/\varepsilon_{\rm sig}}{N_{\rm ref}/\varepsilon_{\rm ref}}$.
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)} = (5.05 \pm 0.13 \pm 0.09)\%;$$
  (Vs. PDG: $4.7 \pm 0.9)\%$; BESIII recent result: $(4.78 \pm 0.39)\%$.)
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)} = (2.78 \pm 0.15 \pm 0.05)\%.$$
  (Vs. PDG: $(4.0 \pm 0.6)\%$; BESIII recent result: $(3.61 \pm 0.73)\%$.)
- Using the W.A. $\mathcal{B}(\Lambda_c^+ \to (\Lambda, \Sigma^0)\pi^+)$, we have
  $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$
  $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$.
  (Vs. PDG: $(6.1 \pm 1.2) \times 10^{-4}$ and $(5.2 \pm 0.8) \times 10^{-4}$)
  Both are consistent with W.A. but with significantly improved precision.

α and A_{CP}^{α} of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ (arXiv:2208.08695, submitted to Sci. Bull.)

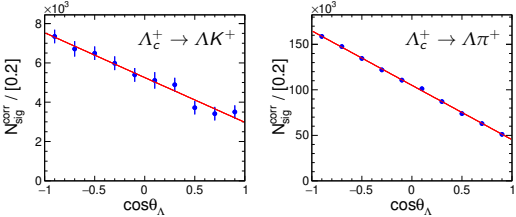
- The decay asymmetry parameter α was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays.
- In $1/2^+ \to 1/2^+ + 0^-$, $\boxed{\alpha \equiv 2 \cdot \mathrm{Re}(S^* P)/(|S|^2 + |P|^2)}$, where S and P denote the parity-violating S-wave and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



- Since α is CP-odd, the α-induced CP asymmetry: $\boxed{A_{CP}^{\alpha} \equiv \frac{\alpha_{\Lambda_c^+} - \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger}{\alpha_{\Lambda_c^+} + \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-}}{\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-}}}$
- In the case that $A_{CP}^{\rm dir}$ is zero, A_{CP}^{α} is given by the CPV in $\mathrm{Re}(S^* P)$. Therefore, A_{CP}^{α} provides an observable complementary to the $A_{CP}^{\rm dir}$ induced by decay widths.

α and A_{CP}^{α} of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ (arXiv:2208.08695, submitted to Sci. Bull.)

- $\cos\theta_\Lambda$ distributions of $\Lambda_c^+ \to \Lambda h^+$ after efficiency correction, fitted with $\boxed{1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda}$

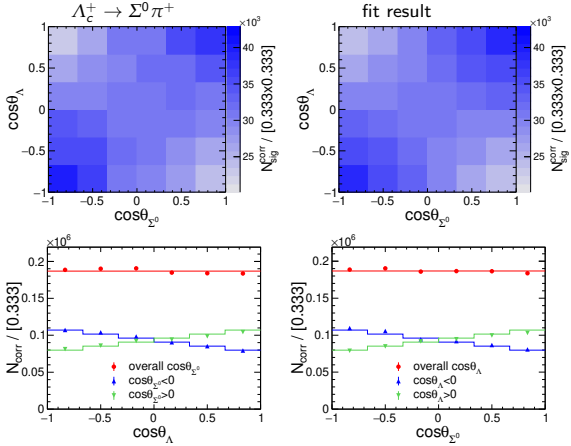


- Using the fitted slope factors and the average α_-, we have

$$\alpha_{avg}(\Lambda_c^+ \to \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018$$
$$\alpha_{avg}(\Lambda_c^+ \to \Lambda \pi^+) = -0.755 \pm 0.005 \pm 0.003$$
(vs. PDG: -0.84 ± 0.09)
$$\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 K^+) = -0.55 \pm 0.18 \pm 0.09$$
$$\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 \pi^+) = -0.463 \pm 0.016 \pm 0.008$$
(vs. PDG: -0.73 ± 0.18)

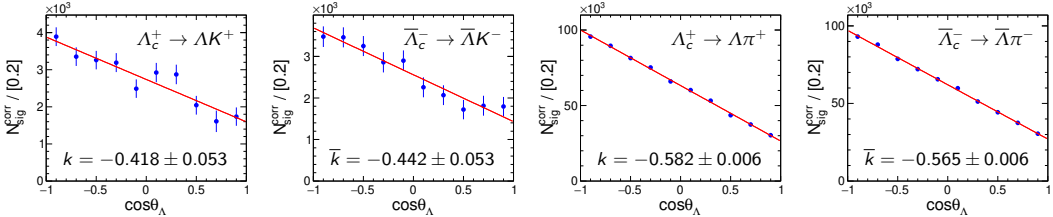
- First α results of SCS decays for charm baryons; and significantly improved results of CF Λ_c^+ decays.

- $(\cos\theta_\Lambda, \cos\theta_{\Sigma^0})$ 2D distributions of $\Lambda_c^+ \to \Sigma^0 h^+$ after efficiency correction, fitted with $\boxed{1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda}$



α and A^{α}_{CP} of $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ (arXiv:2208.08695, submitted to Sci. Bull.)

- Measure α values for Λ_c^+ and $\overline{\Lambda}_c^-$ decays separately. We obtain the first or most precise α and $A^{\alpha}_{CP}(\Lambda_c^+)$ results.



Channel	$k = \alpha_{\Lambda_c^+}\alpha_-$	$\overline{k} = \alpha_{\overline{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\overline{\Lambda}_c^-}$	A^{α}_{CP}	W.A. A^{α}_{CP}	our $A^{\alpha}_{CP}(\Lambda \to p\pi^-)$
$\Lambda_c^+ \to \Lambda K^+$	-0.418 ± 0.053	-0.442 ± 0.053	$-0.566 \pm 0.071 \pm 0.028$	$0.592 \pm 0.070 \pm 0.079$	$-0.023 \pm 0.086 \pm 0.071$	–	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.582 ± 0.006	-0.565 ± 0.006	$-0.784 \pm 0.008 \pm 0.006$	$0.754 \pm 0.008 \pm 0.018$	$+0.020 \pm 0.007 \pm 0.013$	-0.07 ± 0.22	$+0.017 \pm 0.007 \pm 0.012$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.43 ± 0.18	-0.37 ± 0.21	$-0.58 \pm 0.24 \pm 0.09$	$0.49 \pm 0.28 \pm 0.14$	$+0.08 \pm 0.35 \pm 0.14$	–	–
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.340 ± 0.016	-0.358 ± 0.017	$-0.452 \pm 0.022 \pm 0.023$	$0.473 \pm 0.023 \pm 0.035$	$-0.023 \pm 0.034 \pm 0.030$	–	$-0.026 \pm 0.034 \pm 0.030$
					combined:		$+0.013 \pm 0.007 \pm 0.011$

- For decay chains, $A^{\alpha}_{CP}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+}$. Under the SM with $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ for these CF Λ_c^+ decays, $A^{\alpha}_{CP}(\text{total}) = A^{\alpha}_{CP}(\Lambda \to p\pi^-)$. $\Rightarrow$ search for hyperon CPV in charm CF decays for the first time.
- No evidence of CPV in baryon decays (charmed baryon Λ_c^+ and hyperon Λ) is found.

Outline

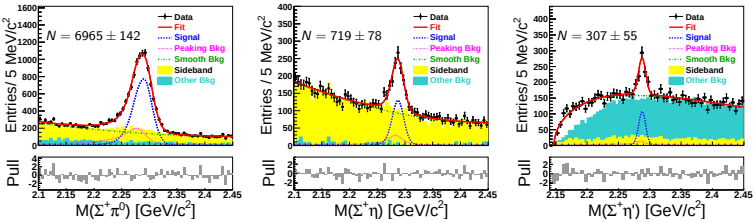
$\mathcal{B}$ and α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$ at Belle (arXiv:2208.10825, accepted by PRD)

- Theoretical predictions by various models vs. experimental results:

Decay	Kerner [a]	Ivanov [b]	Piotr [c]	Sharma [d]	Zou [e]	Geng [f]	Experiment
$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)(\%)$	0.16	0.11	0.90	0.57	0.74	0.32±0.13	0.44±0.20
$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')(\%)$	1.28	0.12	0.11	0.10	–	1.44±0.56	1.5±0.6
$\alpha(\Lambda_c^+ \to \Sigma^+\pi^0)$	0.70	0.43	0.39	−0.31	−0.76	−0.35±0.27	−0.55±0.11
$\alpha(\Lambda_c^+ \to \Sigma^+\eta)$	0.33	0.55	0.00	−0.91	−0.95	−0.40±0.47	–
$\alpha(\Lambda_c^+ \to \Sigma^+\eta')$	−0.45	−0.05	−0.91	0.78	–	$1.00^{+0.00}_{-0.17}$	–

- $\Lambda_c^+ \to \Sigma^+(\eta, \eta')$ are totally contributed by the nonfactorizable diagrams.

- We choose $\Lambda_c^+ \to \Sigma^+\pi^0$ ($\mathcal{B} = (1.25 \pm 0.10)\%$) as reference mode.



[a] ZPC **55**, 659 (1992)
[b] PRD **57**, 5632 (1998)
[c] PRD **50**, 5787 (1994)
[d] EPJC **7**, 217 (1999)
[e] PRD **49**, 3417 (1994)
[f] PLB **794**, 19 (2019)

a) BESIII reported [CPC **43**, 083002 (2019)]
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 3.5 \pm 2.1 \pm 0.4\ (1.6\sigma)$$
b) Only $\alpha_{\Sigma^+\pi^0}$ from CLEO II and BESIII:
$$\alpha_{\Sigma^+\pi^0} = -0.55 \pm 0.11$$
c) The isospin symmetry demands $\mathcal{B}$ and α of $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ shall be equal. [PLB **794**, 19 (2019)]

- Based on full Belle data, we have
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.25 \pm 0.03 \pm 0.01$$
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)} = 0.33 \pm 0.06 \pm 0.02$$
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 1.34 \pm 0.28 \pm 0.08\ (1.2\sigma)$$

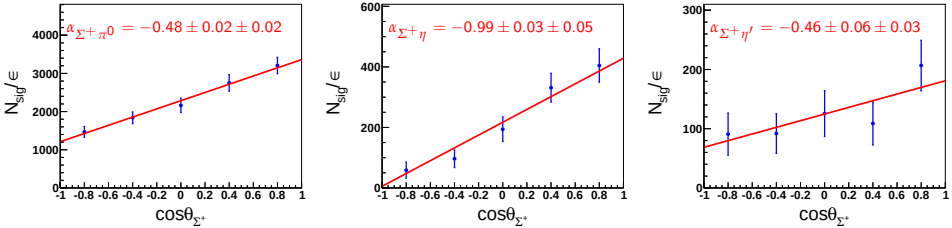
- Using $\mathcal{B}$ of reference mode, we have
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.17 \pm 0.25) \times 10^{-3}$$
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.25 \pm 0.33) \times 10^{-3}$$
which are the most precise results to date.

$\mathcal{B}$ and α of $\Lambda_c^+ \to \Sigma^+(\pi^0, \eta, \eta')$ at Belle (arXiv:2208.10825, accepted by PRD)

- The differential decay rate depends on the decay asymmetry parameter $\alpha_{\Sigma^+ h^0}$ and the helicity angle of Σ^+.

$$\frac{dN(\Lambda_c^+ \to \Sigma^+ h^0)}{d\cos\theta_{\Sigma^+}} \propto 1 + \alpha_{\Sigma^+ h^0} \alpha_{p\pi^0} \cos\theta_{\Sigma^+}$$

- Perform $M(\Lambda_c^+)$ fits in five bins of $\cos\theta_{\Sigma^+}$ distribution individually, then do the efficiency correction bin-by-bin of $\cos\theta_{\Sigma^+}$ distributions:

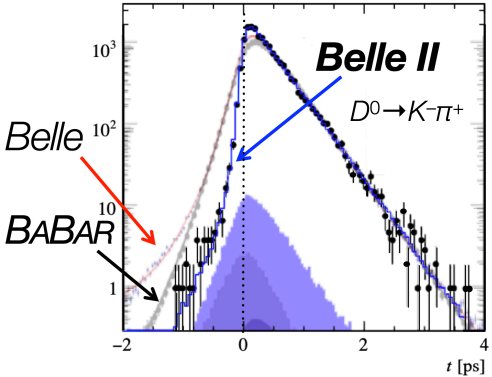


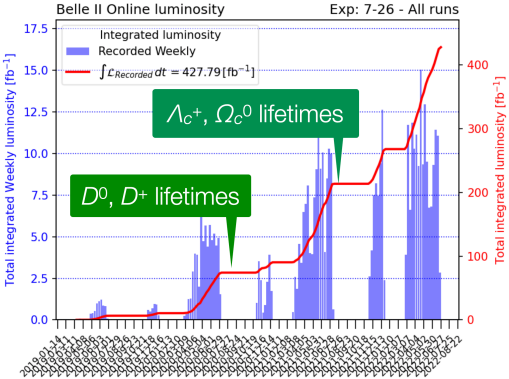
- This $\alpha_{\Sigma^+\pi^0}$ agrees with W.A. ($\alpha_{\Sigma^+\pi^0} = -0.55 \pm 0.11$) (improved $x3$); the other two measured for the first time.
- Comparing with $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$ as aforementioned, their agreement within 1σ shows consistency with the prediction from the isospin symmetry [PLB **794**, 19 (2019)].

Outline

High precision vertex ⇒ charm lifetimes at Belle II

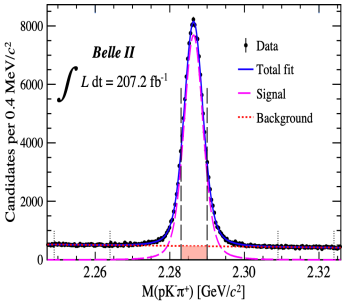
- The impact parameter resolution is ×2 better than Belle/BaBar, which shows up in decay-time distribution.
- Benefited from this, the charm lifetimes are measured using the early data set, as listed in luminosity plot.
- We (Belle II) totally have accumulated 428 fb^{-1} of data set in. Now we are under the long-shut one.

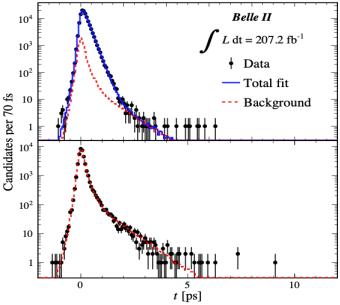




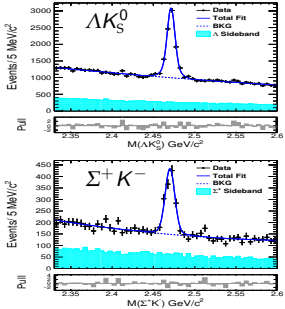
Charmed baryons at Belle II (arXiv:2206.15227 (PRL), arXiv:2208.08573 (PRD(L)), PRD **105**, L011102 (2022))

$\Lambda_c^+ \to pK^-\pi^+$ at Belle II, 207 fb^{-1}





Ξ_c^0 at Belle, 980 fb^{-1}



- First wave is charm lifetimes: world-best $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs, $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs; and $\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77$ fs (first Belle II precision measurements) where their tiny syst. uncertainties demonstrate the excellent performance and understanding of the Belle II detector. (2) we confirm LHCb's result $\tau(\Omega_c^0) = 243 \pm 48 \pm 11$ fs is not the shortest one, inconsistent with pre-LHCb average at 3.4σ.
- More Belle α and CPV results could be achieved, but Belle+Belle II dataset is recommended for all new analyses.
- Charm results based on on Belle+Belle II data set will come out in coming one or two years.

Outline

Summary

- Belle is still producing unique results in flavor physics although the data-taking finished 12 years ago.
  - $\mathcal{B}$, M, Γ, α, amplitude analysis.
  - charm mixing, CP asymmetry, $A_{CP}^{\text{T-odd}}$ asymmetry.
  - rare or forbidden decays, charm spectroscopy.
- Belle recent $\mathcal{B}$ and α results of charmed baryon decays are world-leading, especially α results with improvement of one order of magnitude.

Decay	α results at Belle	WA
$\Lambda_c^+ \to pK_S^0$	–	0.18 ± 0.45
$\Lambda_c^+ \to \Lambda K^+$	-0.585 ± 0.052	–
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.54 ± 0.20	–
$\Lambda_c^+ \to \Lambda\pi^+$	-0.755 ± 0.006	-0.84 ± 0.09
$\Lambda_c^+ \to \Sigma^0\pi^+$	-0.463 ± 0.018	-0.73 ± 0.18
$\Lambda_c^+ \to \Sigma^+\pi^0$	-0.480 ± 0.028	-0.55 ± 0.11
$\Lambda_c^+ \to \Sigma^+\eta$	-0.990 ± 0.058	–
$\Lambda_c^+ \to \Sigma^+\eta'$	-0.460 ± 0.067	–
$\Xi_c^0 \to \Xi^-\pi^+$	-0.63 ± 0.03	-0.56 ± 0.39
$\Xi_c^0 \to \Lambda\bar{K}^{*0}$	$+0.15 \pm 0.22$	–
$\Xi_c^0 \to \Sigma^+K^{*-}$	-0.52 ± 0.30	–

- First $A_{CP}^{\rm dir}$ result for SCS two-body decays of charmed baryons.
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$,
- Most precise A_{CP}^{α} results for four Λ_c^+ decays; $A_{CP}^{\alpha}(\Lambda \to p\pi^-)$ firstly measured via CF charm decays (with $O(1\%)$).
- Belle II has already joined the game. Now it is under Long Shutdown 1. The collected dataset is 428 fb^{-1}.
- More charm results from Belle (II) are on the road in the coming years, e.g. T-odd asymmetry in multi-body decays; direct CP asymmetry in the decays of charmed hadrons. And some new techniques are developing to achieve better results.
- With increasing dataset, Belle II is promising to make the essential contributions to the flavor physics.
- *"Charm is now a fast-moving discipline—one that can be considered complementary to beauty for its potential to test the CKM paradigm and to probe for New Physics effects. For flavor physicists, this is truly the age of charm."—from [Ann. Rev. Nucl. Part. Sci. 71 (2021) 59]*
  粲物理现在是快速发展的领域——它是对美物理的补充，具有潜力来检验 CKM 和探索新物理。对味物理学家来说，这正是粲物理的时代（充满魅力的时代）。

Back up

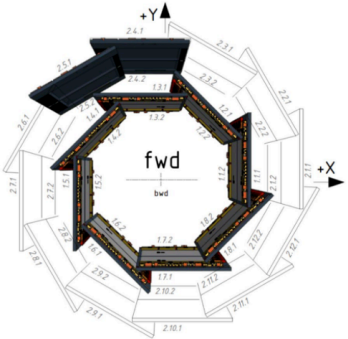
Special thanks to Fu-Sheng Yu, Di Wang, Chia-Wei Liu for valuable and helpful discussions on these measurements of α and CP asymmetry in charmed baryon decays.

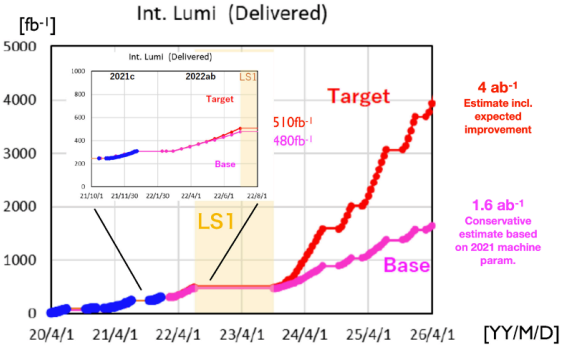
Thank you for your attentions.

谢谢！

Dr. Long-Ke LI (李龙科)
Department of Physics,
University of Cincinnati (UC)
lilongke_ustc
lilk@ucmail.uc.edu
lilongke@mail.ustc.edu.cn

Status of Belle II: under Long-Shutdown1 (LS1) now





- PXD2 installation (fully re-installed)
  Due to problems in ladder gluing, only half of designed PXD (full L1+2 L2 ladders) was installed in 2018/2019
- TOP MCP-PMT replacement
- Additional shields for BG mitigation
- Collimator system upgrade (LER)
- Beam pipe upgrade at injection point (HER)

- Except the charm lifetime measurements, more charm analyses are on-going based on full LS1 data set. (some of them use Belle+Belle II data sets.)
  - CPV asymemtry in charmed mesons and baryons
  - D^0-$\overline{D}^0$ mixing with model-independent method
  - Branching fraction of charmed baryon decays
  - ……

Systematic uncertainties of $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+$ measurements

Sources (10^{-2})	$A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+)$	$A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+)$
$A_\varepsilon^{K^+}$ map	$^{+0.08}_{-0.02}$	± 0.04
$A_\varepsilon^{\pi^+}$ map	± 0.04	$^{+0.05}_{-0.25}$
Signal shape	± 0.05	± 0.14
Background shape	-0.02	-0.31
Fit bias	$+0.06$	$+0.26$
Λ asymmetry	-0.02	-0.04
Total syst.	$^{+0.12}_{-0.07}$	$^{+0.30}_{-0.43}$
vs stat.	± 2.6	± 5.4

Sources	$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda K^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+)}$	$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+\to\Sigma^0\pi^+)}$
PID efficiency correction	1.7%	1.7%
Signal shape	0.2%	0.4%
Background shape	–	0.1%
BCS effect	0.1%	0.4%
Efficiency ratio	0.2%	0.4%
Total	1.7%	1.8%
Vs. $\sigma(\text{stat.})$	2.7%	5.4%
Vs. $\sigma(\mathcal{B}_{\rm ref.})$	5.4%	5.4%

- Absolute systematic uncertainties (in units of 10^{-2}) for decay asymmetry parameters and the α-induced CP asymmetries: $\alpha_{\rm avg}/\alpha_{\Lambda_c^+}/\alpha_{\overline{\Lambda}_c^-}/A_{CP}^\alpha$ in each decay mode (the fifth items in $\Lambda_c^+ \to \Lambda\pi^+/\Sigma^0\pi^+$ are for $A_{CP}^\alpha(\Lambda)$).

Sources (10^{-2})	$\Lambda_c^+ \to \Lambda K^+$	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Sigma^0 K^+$	$\Lambda_c^+ \to \Sigma^0\pi^+$
$\cos\theta$ bins	0.8/1.5/1.5/1.4	0.0/0.1/0.2/0.2/0.16	7.4/6.9/ 9.9/ 8.4	0.7/1.5/3.3/1.9/1.9
Efficiency curve	0.2/0.5/0.1/0.4	0.2/0.3/0.1/0.3/0.29	1.4/1.1/ 1.8/ 0.9	0.1/0.5/0.4/0.9/0.9
Fit bias	1.6/2.3/7.7/6.9	0.2/0.3/1.7/1.2/1.15	4.1/5.7/10.3/11.7	0.4/1.7/0.9/2.1/2.1
$\alpha_\mp(\Lambda \to p\pi^-)$	0.2/0.3/0.4/0.6	0.2/0.4/0.5/0.6/–	0.2/0.3/ 0.3/ 0.6	0.1/0.2/0.3/0.6/–
Total syst.	1.8/2.8/7.9/7.1	0.3/0.6/1.8/1.4/1.20	8.6/9.0/14.4/14.4	0.8/2.3/3.5/3.0/3.0
vs. stat.	4.9/7.1/7.0/8.7	0.5/0.8/0.8/0.7/0.74	19/24/28/34	1.6/2.2/2.3/3.5/3.5

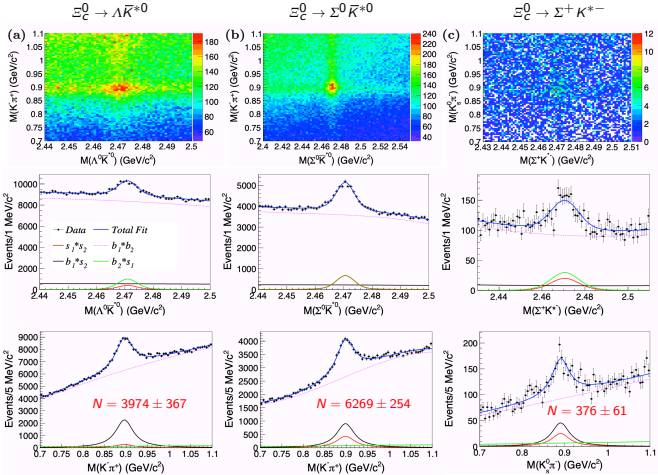
$\mathcal{B}$ and α of $\Xi_c^0 \to (\Lambda, \Sigma^0)\bar{K}^{*0}$ and $\Sigma^+ K^{*-}$ at Belle (JHEP 06 (2021) 160)

- We measure $\mathcal{B}$ and α of three CF Ξ_c^0 decays of which the final state is a combination of a hyperon and a vector particle.
- The signal yields are extracted via $M_{\Xi_c^0}$-M_{K^*} 2D fit. See the figures with achieved signal yields.
- Then we have their $\mathcal{B}$'s relative to that of $\Xi_c^0 \to \Xi^- \pi^+$ after considering the efficiency.

$$\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.18 \pm 0.02 \pm 0.01$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.69 \pm 0.03 \pm 0.03$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^+K^{*-})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 0.34 \pm 0.06 \pm 0.02$$

- Finally, using the W.A. $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$, we have absolute $\mathcal{B}$'s below for the first time:

$$\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^{*0}) = (3.3 \pm 0.3 \pm 0.2 \pm 1.0(\mathcal{B}_{\rm ref})) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0\bar{K}^{*0}) = (12.4 \pm 0.5 \pm 0.5 \pm 3.6(\mathcal{B}_{\rm ref})) \times 10^{-3}$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^+K^{*-}) = (6.1 \pm 1.0 \pm 0.4 \pm 1.8(\mathcal{B}_{\rm ref})) \times 10^{-3}$$

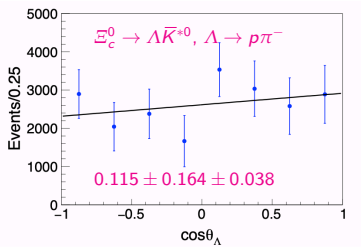


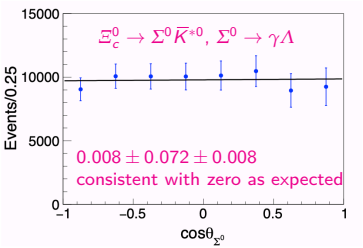
$\mathcal{B}$ and α of $\Xi_c^0 \to (\Lambda, \Sigma^0)\bar{K}^{*0}$ and $\Sigma^+ K^{*-}$ at Belle (JHEP 06 (2021) 160)

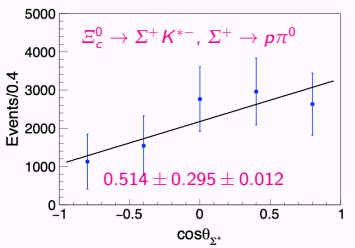
- Taking $\Xi_c^0 \to \Lambda \bar{K}^{*0}$ for example, the differential decay rate depends on decay asymmetry parameters and $\cos\theta_\Lambda$

$$\boxed{\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha(\Xi_c^0 \to \Lambda\bar{K}^{*0})\alpha(\Lambda \to p\pi^-)\cos\theta_\Lambda}$$

- We extract the $\alpha_{\Xi_c^0}\alpha_{(\Lambda,\Sigma^0,+)}$ via the fits on the efficiency-corrected $\cos\theta_\Lambda$ or $\cos\theta_\Sigma$ distributions:







- The $\alpha(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})$ can not be measured via 1D $\cos\theta_{\Sigma^0}$ distribution due to $\alpha(\Sigma^0 \to \gamma\Lambda) = 0$ in an electromagnetic decay.
- Using the W.A. $\alpha(\Lambda \to p\pi^-) = 0.747 \pm 0.010$ and $\alpha(\Sigma^+ \to p\pi^0) = -0.980 \pm 0.017$, we finally, for the first time, have $\alpha(\Xi_c^0 \to \Lambda\bar{K}^{*0}) = 0.15 \pm 0.22 \pm 0.05$ and $\alpha(\Xi_c^0 \to \Sigma^+ K^{*-}) = -0.52 \pm 0.30 \pm 0.02$.