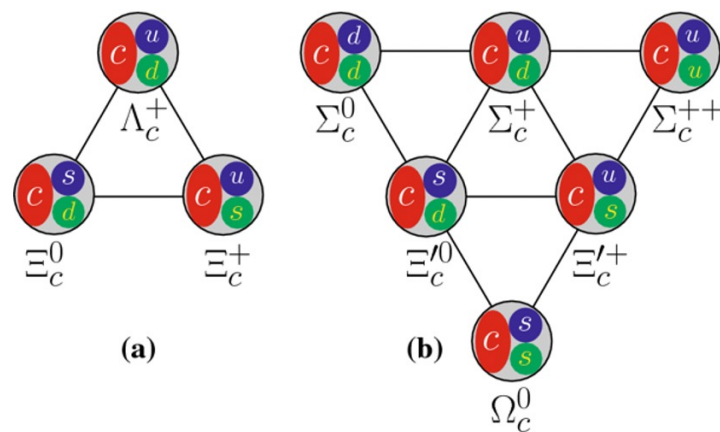




粲重子非轻衰变实验研究

李培荣

(prli@lzu.edu.cn)

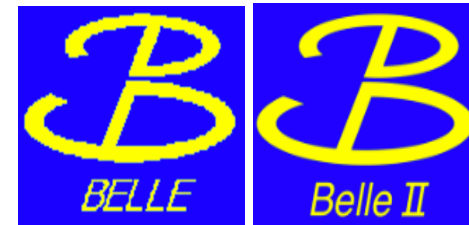
兰州大学

2025年8月6日

BESIII 粲强子物理研讨会

Outline

- **Introduction to the charmed baryons**
- **Selected recent results on charmed baryons from BESIII/LHCb/Belle/Belle II**
- **Prospect and Summary**



The charmed baryon family

- **Singly charmed baryons**

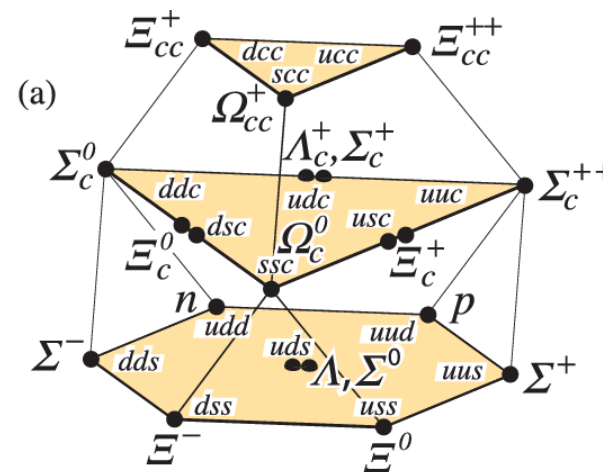
- ✓ Established ground states:

$$\Lambda_c^+, \Sigma_c, \Xi_c^{(\prime)}, \Omega_c$$

- ✓ Excited states are being explored

- **Observation of other doubly charmed baryon Ξ_{cc}^{++}**

- **No observations of other doubly or triply charmed baryons**

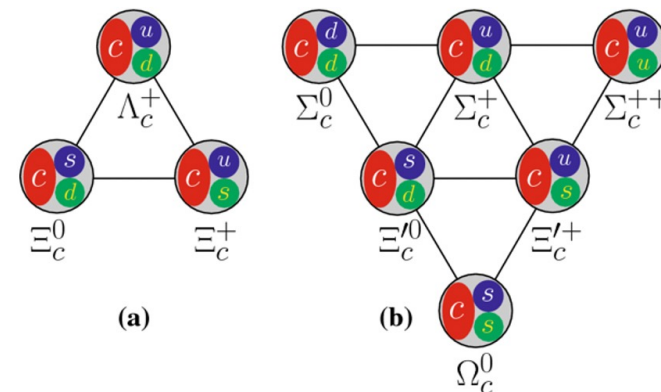


- Λ_c^+ : **decay only weakly, many recent experimental progress since 2014**

- Σ_c : **$B(\Sigma_c \rightarrow \Lambda_c^+ \pi) \sim 100\%$; $B(\Sigma_c \rightarrow \Lambda_c^+ \gamma)$?**

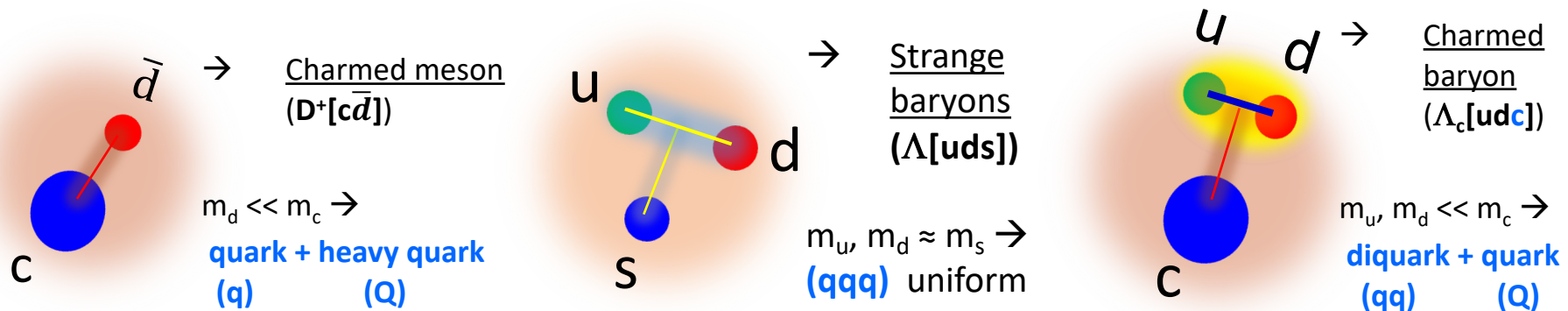
- Ξ_c : **decay only weakly; absolute BF measured with poor precision**

- Ω_c : **decay only weakly; no absolute BF measured**



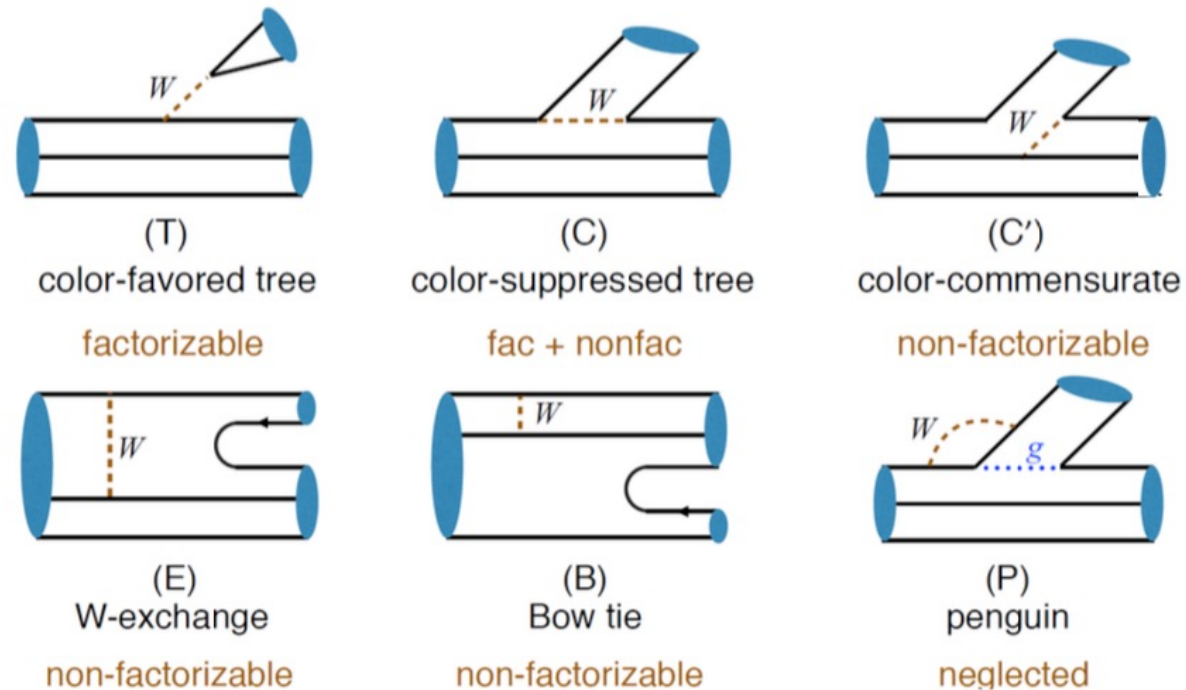
Λ_c^+ : The lightest charmed baryon spectroscopy

- Most of the charmed baryons will eventually decay to Λ_c^+ .
- The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.
- Naïve quark model picture: a heavy quark (c) with an unexcited spin-zero diquark ($u-d$). Diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark(HQET).
- Λ_c^+ may reveal more information of strong- and weak-interactions in charm region, complementary to D/Ds



Λ_c^+ weak decay picture in theory

- Contrary to charmed meson, W-exchange contribution is important. (No color suppress and helicity suppress)



- Phenomenology aim at explain data and predict important observables.
- Calculate what they can(HQET, factorization)+parametrize what they cannot + some non-perturbations **extracted from data**=> explain and predict.

Λ_c^+ Mode	BF($\times 10^{-3}$)	Experiment	Λ_c^+ Mode	BF($\times 10^{-3}$)	Experiment
$\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$	$23.7 \pm 5.1 (37\%)^\dagger$	ARGUS(1991)[24]	$\Lambda_c^+ \rightarrow p K^- e^+ \nu_e$	$0.88 \pm 0.18 (20\%)$	BESIII(2022)[29]
	$26.8 \pm 5.1 (19\%)^\dagger$	CELO(1994)[25]	$\Lambda_c^+ \rightarrow \Lambda(1405) e^+ \nu_e,$ $\Lambda(1405) \rightarrow p K^-$	$0.42 \pm 0.19 (45\%)$	BESIII(2022)[29]
	$36.3 \pm 4.3 (12\%)$	BESIII(2015)[30]			
	$35.6 \pm 1.3 (3.6\%)$	BESIII(2022)[31]	$\Lambda_c^+ \rightarrow \Lambda(1520) e^+ \nu_e$	$1.0 \pm 0.5 (50\%)$	BESIII(2022)[29]
$\Lambda_c^+ \rightarrow \Lambda \mu^+ \nu_\mu$	$34.9 \pm 5.3 (15\%)$	BESIII(2017)[32]	$\Lambda_c^+ \rightarrow p K_S^0 \pi^- e^+ \nu_e$	< 0.33	BESIII(2023)[33]
	$34.8 \pm 1.7 (4.9\%)$	BESIII(2023)[34]	$\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^- e^+ \nu_e$	< 0.39	BESIII(2023)[33]
$\Lambda_c^+ \rightarrow e^+ X$	$39.5 \pm 3.5 (8.9\%)$	BESIII(2018)[35]	$\Lambda_c^+ \rightarrow n e^+ \nu_e$	$3.57 \pm 0.37 (10\%)$	BESIII(2025)[36]
	$40.6 \pm 1.3 (3.2\%)$	BESIII(2023)[37]			
Ξ_c Mode	BF($\times 10^{-3}$)	Experiment	Ξ_c Mode	BF($\times 10^{-3}$)	Experiment
$\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$	$13.7 \pm 7.7 (56\%)^\dagger$	ARGUS(1993)[26]	$\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu$	$10.1 \pm 2.1 (21\%)^\dagger$	Belle(2021)[38]
	$44.3_{-17.8}^{+16.6} (40\%)^\dagger$	CLEO(1995)[27]	$\Xi_c^+ \rightarrow \Xi^0 e^+ \nu_e$	$67 \pm 39 (58\%)^\dagger$	CLEO(1995)[27]
	$19.7 \pm 5.3 (27\%)^\dagger$	ALICE(2021)[39]			
	$10.4 \pm 2.1 (20\%)^\dagger$	Belle(2021)[38]			
Ω_c^0 Mode	Ratio	Experiment	Ω_c^0 Mode	Ratio	Experiment
$\Omega_c^0 \rightarrow \Omega^0 e^+ \nu_e$	$2.4 \pm 1.1 (47\%)$	CLEO(2002)[28]	$\Omega_c^0 \rightarrow \Omega^0 \mu^+ \nu_\mu$	$1.94 \pm 0.21 (11\%)$	Belle(2022)[40]
	$1.98 \pm 0.15 (7.7\%)$	Belle(2022)[40]			

Table 2. Measurements of the BF's for the CF decays of the Λ_c^+ (in units of %).

Mode	BF	Experiment	Mode	BF	Experiment
Nucleon-involved					
$\Lambda_c^+ \rightarrow p K_S^0$	1.52 ± 0.09	BESIII(2016)[80]	$\Lambda_c^+ \rightarrow n K_S^0 \pi^+$	1.82 ± 0.25	BESIII(2017)[90]
$\Lambda_c^+ \rightarrow p K_L^0$	1.67 ± 0.07	BESIII(2024)[89]		1.86 ± 0.09	BESIII(2024)[91]
$\Lambda_c^+ \rightarrow p \bar{K}_S^0(700)^0 \rightarrow p K^- \pi^+$	0.19 ± 0.06	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow n \bar{K}_S^0 \pi^+ \pi^0$	0.85 ± 0.13	BESIII(2024)[92]
$\Lambda_c^+ \rightarrow p \bar{K}_0^*(892)^0 \rightarrow p K^- \pi^+$	1.38 ± 0.08	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow n K^- \pi^+ \pi^+$	1.90 ± 0.12	BESIII(2023)[129]
$\Lambda_c^+ \rightarrow p \bar{K}_0^*(1430)^0 \rightarrow p K^- \pi^+$	0.92 ± 0.18	LHCb(2023)[86]		1.87 ± 0.14	BESIII(2016)[80]
$\Lambda_c^+ \rightarrow \Delta(1232)^{++} K^- \rightarrow p \pi^+ K^-$	1.78 ± 0.05	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow p K_S^0 \pi^0$	2.12 ± 0.11	Belle(II)(2025)[144]
$\Lambda_c^+ \rightarrow \Delta(1600)^{++} K^- \rightarrow p \pi^+ K^-$	0.28 ± 0.10	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow p K_L^0 \pi^0$	2.02 ± 0.14	BESIII(2024)[89]
$\Lambda_c^+ \rightarrow \Delta(1700)^{++} K^- \rightarrow p \pi^+ K^-$	0.24 ± 0.06	LHCb(2023)[86]		0.41 ± 0.09	BESIII(2021)[145]
			$\Lambda_c^+ \rightarrow p K_S^0 \eta$	0.44 ± 0.03	Belle(2023)[146]
			$\Lambda_c^+ \rightarrow p K_S^0 \pi^+ \pi^-$	1.53 ± 0.14	BESIII(2016)[80]
			$\Lambda_c^+ \rightarrow p K_L^0 \pi^+ \pi^-$	1.69 ± 0.11	BESIII(2024)[89]
			$\Lambda_c^+ \rightarrow p K^- \pi^+$	$6.84^{+0.32}_{-0.36}$	Belle(2014)[81]
				5.84 ± 0.35	BESIII(2016)[80]
			$\Lambda_c^+ \rightarrow p K^- \pi^+ \pi^0$	4.53 ± 0.38	BESIII(2016)[80]
				4.42 ± 0.21	Belle(2017)[147]
Λ-involved					
$\Lambda_c^+ \rightarrow \Lambda \pi^+$	1.24 ± 0.08	BESIII(2016)[80]	$\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0$	7.01 ± 0.42	BESIII(2016)[80]
	1.31 ± 0.09	BESIII(2023)[126]		1.84 ± 0.26	BESIII(2019)[94]
$\Lambda_c^+ \rightarrow \Lambda p(770)^+$	4.06 ± 0.52	BESIII(2022)[93]	$\Lambda_c^+ \rightarrow \Lambda \pi^+ \eta$	1.84 ± 0.13	Belle(2021)[95]
$\Lambda_c^+ \rightarrow \Lambda a_0(980)^+$	1.23 ± 0.21	BESIII(2025)[94]		1.94 ± 0.13	BESIII(2025)[148]
$\Lambda_c^+ \rightarrow \Lambda(1405)\pi^+ \rightarrow p K^- \pi^+$	0.48 ± 0.19	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^- \pi^+$	3.81 ± 0.30	BESIII(2016)[80]
$\Lambda_c^+ \rightarrow \Lambda(1520)\pi^+ \rightarrow p K^- \pi^+$	0.12 ± 0.02	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$	0.30 ± 0.03	BESIII(2025)[134]
$\Lambda_c^+ \rightarrow \Lambda(1600)\pi^+ \rightarrow p K^- \pi^+$	0.32 ± 0.12	LHCb(2023)[86]		0.31 ± 0.05	BESIII(2025)[108]
$\Lambda_c^+ \rightarrow \Lambda(1670)\pi^+ \rightarrow p K^- \pi^+$	0.07 ± 0.02	LHCb(2023)[86]			
	0.27 ± 0.06	Belle(2021)[95]			
	0.27 ± 0.06	BESIII(2025)[148]			
$\Lambda_c^+ \rightarrow \Lambda(1690)\pi^+ \rightarrow p K^- \pi^+$	0.07 ± 0.02	LHCb(2023)[86]			
$\Lambda_c^+ \rightarrow \Lambda(2000)\pi^+ \rightarrow p K^- \pi^+$	0.60 ± 0.07	LHCb(2023)[86]			
Σ-involved					
$\Lambda_c^+ \rightarrow \Sigma^+ \pi^0$	1.18 ± 0.10	BESIII(2016)[80]	$\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$	4.25 ± 0.31	BESIII(2016)[80]
	0.41 ± 0.20	BESIII(2018)[96]		4.57 ± 0.28	Belle(2018)[149]
$\Lambda_c^+ \rightarrow \Sigma^+ \eta$	0.31 ± 0.05	Belle(2023)[98]	$\Lambda_c^+ \rightarrow \Sigma^+ \pi^0 \pi^0$	1.57 ± 0.15	Belle(2018)[149]
	0.38 ± 0.06	BESIII(2025)[97]	$\Lambda_c^+ \rightarrow \Sigma^0 \pi^+ \pi^0$	3.65 ± 0.30	Belle(2018)[149]
$\Lambda_c^+ \rightarrow \Sigma^+ \eta'$	1.34 ± 0.56	BESIII(2018)[96]	$\Lambda_c^+ \rightarrow \Sigma^0 \pi^+ \eta$	0.76 ± 0.08	Belle(2021)[95]
	0.42 ± 0.09	Belle(2023)[98]	$\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$	1.81 ± 0.19	BESIII(2017)[105]
	0.57 ± 0.18	BESIII(2025)[97]	$\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+ \pi^0$	2.11 ± 0.36	BESIII(2017)[105]
$\Lambda_c^+ \rightarrow \Sigma^+ \omega$	1.56 ± 0.21	BESIII(2016)[80]	$\Lambda_c^+ \rightarrow \Sigma^+ K^+ K^-$	0.38 ± 0.05	BESIII(2023)[150]
$\Lambda_c^+ \rightarrow \Sigma^+ \phi$	0.41 ± 0.09	BESIII(2023)[150]	$\Lambda_c^+ \rightarrow \Sigma^+ K^+ K_{\text{non-}\phi}^-$	0.20 ± 0.04	BESIII(2023)[150]
$\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$	1.27 ± 0.09	BESIII(2016)[80]	$\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$	0.08 ± 0.03	BESIII(2025)[108]
	1.22 ± 0.11	BESIII(2023)[126]			
$\Lambda_c^+ \rightarrow \Sigma(1385)^+ \pi^0$	0.59 ± 0.08	BESIII(2022)[93]			
	0.91 ± 0.20	BESIII(2019)[94]			
$\Lambda_c^+ \rightarrow \Sigma(1385)^+ \eta$	1.21 ± 0.12	Belle(2021)[95]			
	0.68 ± 0.08	BESIII(2025)[148]			
$\Lambda_c^+ \rightarrow \Sigma(1385)^0 \pi^+$	0.65 ± 0.10	BESIII(2022)[93]			
Ξ-involved					
$\Lambda_c^+ \rightarrow \Xi^0 K^+$	0.59 ± 0.09	BESIII(2018)[106]	$\Lambda_c^+ \rightarrow \Xi^0 K^+ \pi^0$	0.78 ± 0.17	BESIII(2024)[107]
$\Lambda_c^+ \rightarrow \Xi(1530)^0 K^+$	0.50 ± 0.10	BESIII(2018)[106]	$\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$	0.37 ± 0.06	BESIII(2025)[108]
	0.60 ± 0.11	BESIII(2024)[107]			

Table 3. The determined BF's for the CS decays of the Λ_c^+ (in units of 10^{-3}). Upper limits are set at 90% confidence level.

Mode	BF	Experiment	Mode	BF	Experiment
Nucleon-involved					
$\Lambda_c^+ \rightarrow n \pi^+$	0.66 ± 0.13	BESIII(2022)[126]	$\Lambda_c^+ \rightarrow n K^+ \pi^0$	< 0.71	BESIII(2024)[107]
$\Lambda_c^+ \rightarrow p \pi^0$	< 0.27	BESIII(2017)[117]	$\Lambda_c^+ \rightarrow n \pi^+ \pi^0$	0.64 ± 0.09	BESIII(2023)[129]
	< 0.08	Belle(2021)[109]	$\Lambda_c^+ \rightarrow n K_S^0 K^+$	$0.39^{+0.17}_{-0.14}$	BESIII(2024)[91]
	$0.16^{+0.07}_{-0.06}$	BESIII(2024)[118]	$\Lambda_c^+ \rightarrow n \pi^+ \pi^- \pi^+$	0.45 ± 0.08	BESIII(2023)[129]
	0.18 ± 0.04	BESIII(2025)[119]	$\Lambda_c^+ \rightarrow p \pi^+ \pi^-$	3.91 ± 0.40	BESIII(2016)[127]
				4.72 ± 0.28	LHCb(2018)[138]
$\Lambda_c^+ \rightarrow p \eta$	1.24 ± 0.30	BESIII(2017)[117]	$\Lambda_c^+ \rightarrow p K^+ K^-$	1.08 ± 0.07	LHCb(2018)[138]
	1.42 ± 0.12	Belle(2021)[109]	$\Lambda_c^+ \rightarrow p(K^+ K^-)_{\text{non-}\phi}$	0.55 ± 0.14	BESIII(2016)[127]
	1.57 ± 0.12	BESIII(2023)[120]	$\Lambda_c^+ \rightarrow p K_S^0 K_S^0$	0.24 ± 0.02	Belle(2023)[146]
	1.63 ± 0.33	BESIII(2024)[118]	$\Lambda_c^+ \rightarrow p \phi \pi^0$	< 0.15	Belle(2017)[147]
$\Lambda_c^+ \rightarrow p \eta'$	1.67 ± 0.80	LHCb(2024)[121]	$\Lambda_c^+ \rightarrow (p K^+ K^- \pi^0)_{\text{NR}}$	< 0.06	Belle(2017)[147]
	$0.56^{+0.25}_{-0.21}$	BESIII(2022)[123]	$\Lambda_c^+ \rightarrow p K^+ \pi^-$	0.16 ± 0.02	Belle(2016)[137]
$\Lambda_c^+ \rightarrow p \rho$	0.47 ± 0.10	Belle(2022)[122]		0.10 ± 0.01	LHCb(2018)[138]
$\Lambda_c^+ \rightarrow p \rho$	1.52 ± 0.44	LHCb(2024)[121]			
	0.94 ± 0.39	LHCb(2018)[124]			
	0.83 ± 0.11	Belle(2021)[125]			
	1.11 ± 0.21	BESIII(2023)[120]			
$\Lambda_c^+ \rightarrow p \omega$	0.98 ± 0.31	LHCb(2024)[121]			
$\Lambda_c^+ \rightarrow p \phi$	1.06 ± 0.22	BESIII(2016)[127]			
Λ-involved					
$\Lambda_c^+ \rightarrow \Lambda K^+$	0.62 ± 0.06	BESIII(2022)[131]	$\Lambda_c^+ \rightarrow \Lambda K^+ \pi^0$	< 2.0	BESIII(2024)[107]
	0.66 ± 0.04	Belle(2023)[132]		1.49 ± 0.29	BESIII(2024)[135]
$\Lambda_c^+ \rightarrow \Lambda K^{*+}$	$2.40 \pm 0.59(\theta_0 = 0^\circ)$	BESIII(2025)[134]	$\Lambda_c^+ \rightarrow \Lambda K_S^0 \pi^+$	1.73 ± 0.29	BESIII(2025)[134]
	$5.21 \pm 0.75(\theta_0 = 109^\circ)$	BESIII(2025)[134]	$\Lambda_c^+ \rightarrow \Lambda K^+ \pi^+ \pi^-$	0.41 ± 0.15	BESIII(2024)[135]
	$1.29 \pm 0.44(\theta_0 = 221^\circ)$	BESIII(2025)[134]			
Σ-involved					
$\Lambda_c^+ \rightarrow \Sigma^0 K^+$	0.47 ± 0.10	BESIII(2022)[133]	$\Lambda_c^+ \rightarrow \Sigma^+ K^+ \pi^-$	2.00 ± 0.28	BESIII(2023)[150]
	0.36 ± 0.03	Belle(2023)[132]	$\Lambda_c^+ \rightarrow \Sigma^+ K^+ \pi^- \pi^0$	< 0.01	BESIII(2023)[150]
$\Lambda_c^+ \rightarrow \Sigma^+ K_S^0$	0.48 ± 0.14	BESIII(2022)[133]	$\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^0$	< 1.8	BESIII(2024)[107]
				< 0.50	BESIII(2024)[151]
			$\Lambda_c^+ \rightarrow \Sigma^0 K^+ \pi^+ \pi^-$	< 0.65	BESIII(2024)[151]
			$\Lambda_c^+ \rightarrow \Sigma^- K^+ \pi^+$	0.38 ± 0.12	BESIII(2024)[136]

Table 4. The determined polarization parameters α of various Λ_c^+ decay modes.

Mode	polarization α	Experiment	Mode	polarization α	Experiment
Nucleon-involved			$\Lambda_c^+ \rightarrow \Lambda(1600)\pi^+$	0.2 ± 0.5	LHCb(2023)[86]
$\Lambda_c^+ \rightarrow pK_S^0$	0.18 ± 0.45	BESIII(2019)[153]	$\Lambda_c^+ \rightarrow \Lambda(1670)\pi^+$	0.82 ± 0.08	LHCb(2023)[86]
	-0.75 ± 0.10	LHCb(2024)[154]		0.21 ± 0.43	BESIII(2025)[148]
$\Lambda_c^+ \rightarrow p\bar{K}_0^*(700)^0$	-0.1 ± 0.7	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Lambda(1690)\pi^+$	0.958 ± 0.034	LHCb(2023)[86]
$\Lambda_c^+ \rightarrow p\bar{K}_0^*(1430)^0$	0.34 ± 0.14	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Lambda(2000)\pi^+$	-0.57 ± 0.19	LHCb(2023)[86]
$\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-$	0.55 ± 0.04	LHCb(2023)[86]	Σ-involved		
$\Lambda_c^+ \rightarrow \Delta(1600)^{++}K^-$	-0.50 ± 0.18	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Sigma^+\pi^0$	-0.57 ± 0.12	BESIII(2019)[153]
$\Lambda_c^+ \rightarrow \Delta(1700)^{++}K^-$	0.22 ± 0.08	LHCb(2023)[86]		-0.48 ± 0.03	Belle(2023)[98]
Λ-involved			$\Lambda_c^+ \rightarrow \Sigma^+\eta$	-0.99 ± 0.06	Belle(2023)[98]
$\Lambda_c^+ \rightarrow \Lambda\pi^+$	-0.80 ± 0.11	BESIII(2019)[153]	$\Lambda_c^+ \rightarrow \Sigma^+\eta'$	-0.46 ± 0.07	Belle(2023)[98]
	-0.755 ± 0.006	Belle(2023)[132]	$\Lambda_c^+ \rightarrow \Sigma^0\pi^+$	-0.73 ± 0.18	BESIII(2019)[153]
	-0.785 ± 0.007	LHCb(2024)[154]		-0.46 ± 0.02	Belle(2023)[132]
$\Lambda_c^+ \rightarrow \Lambda K^+$	-0.59 ± 0.05	Belle(2023)[132]i	$\Lambda_c^+ \rightarrow \Sigma(1385)^+\pi^0$	-0.917 ± 0.089	BESIII(2022)[93]
	-0.52 ± 0.05	LHCb(2024)[154]	$\Lambda_c^+ \rightarrow \Sigma(1385)^+\eta$	-0.61 ± 0.16	BESIII(2025)[148]
$\Lambda_c^+ \rightarrow \Lambda\rho(770)^+$	-0.763 ± 0.070	BESIII(2022)[93]	$\Lambda_c^+ \rightarrow \Sigma(1385)^0\pi^+$	-0.789 ± 0.113	BESIII(2022)[93]
$\Lambda_c^+ \rightarrow \Lambda a(980)^+$	$-0.91^{+0,20}_{-0.12}$	BESIII(2025)[148]	$\Lambda_c^+ \rightarrow \Sigma^0 K^+$	-0.54 ± 0.20	Belle(2023)[132]
$\Lambda_c^+ \rightarrow \Lambda(1405)\pi^+$	0.58 ± 0.28	LHCb(2023)[86]	Ξ-involved		
$\Lambda_c^+ \rightarrow \Lambda(1520)\pi^+$	0.93 ± 0.09	LHCb(2023)[86]	$\Lambda_c^+ \rightarrow \Xi^0 K^+$	0.01 ± 0.16	BESIII(2024)[158]

Table 5. The measured BF's of the Ξ_c^+ and Ξ_c^0 (in units of %).

Mode	$\mathcal{B}$	Experiment	Mode	$\mathcal{B}$	Experiment
$\Xi_c^0 \rightarrow \Lambda K_S^0$	0.33 ± 0.08	Belle(2022)[172]	$\Xi_c^0 \rightarrow p K^- K^- \pi^+$	0.58 ± 0.24	Belle(2019)[170]
$\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}$	0.33 ± 0.11	Belle(2021)[171]	$\Xi_c^0 \rightarrow \Lambda K^- \pi^+$	1.17 ± 0.38	Belle(2019)[170]
$\Xi_c^0 \rightarrow \Sigma^+ K^-$	0.18 ± 0.04	Belle(2022)[172]	$\Xi_c^0 \rightarrow \Lambda K^+ K^-$	0.05 ± 0.01	Belle(2013)[176]
$\Xi_c^0 \rightarrow \Sigma^+ K^{*-}$	0.61 ± 0.21	Belle(2021)[171]	$\Xi_c^0 \rightarrow \Lambda K^+ K_{\text{non-}\phi}^-$	0.04 ± 0.01	Belle(2013)[176]
$\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0}$	1.24 ± 0.37	Belle(2021)[171]	$\Xi_c^0 \rightarrow \Xi^0 K^+ K^-$	0.06 ± 0.01	Belle(2021)[175]
$\Xi_c^0 \rightarrow \Sigma^0 K_S^0$	0.05 ± 0.02	Belle(2022)[172]	$\Xi_c^+ \rightarrow p K_S^0$	0.07 ± 0.03	Belle(II)(2025)[185]
$\Xi_c^0 \rightarrow \Xi^0 \pi^0$	0.69 ± 0.14	Belle(II)(2024)[182]	$\Xi_c^+ \rightarrow p \phi$	0.012 ± 0.006	LHCb(2019)[181]
$\Xi_c^0 \rightarrow \Xi^0 \eta$	0.16 ± 0.04	Belle(II)(2024)[182]	$\Xi_c^+ \rightarrow \Lambda \pi^+$	0.05 ± 0.02	Belle(II)(2025)[185]
$\Xi_c^0 \rightarrow \Xi^0 \eta'$	0.12 ± 0.04	Belle(II)(2024)[182]	$\Xi_c^+ \rightarrow \Sigma^0 \pi^+$	0.12 ± 0.06	Belle(II)(2025)[185]
$\Xi_c^0 \rightarrow \Xi^- \pi^+$	1.80 ± 0.52	Belle(2019)[170]	$\Xi_c^+ \rightarrow \Sigma^+ K_S^0$	0.19 ± 0.09	Belle(II)(2025)[180]
$\Xi_c^0 \rightarrow \Xi^- K^+$	0.04 ± 0.01	Belle(2013)[176]	$\Xi_c^+ \rightarrow \Xi^0 \pi^+$	0.72 ± 0.32	Belle(II)(2025)[180]
$\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$	0.55 ± 0.18	LHCb(2020)[177]	$\Xi_c^+ \rightarrow \Xi^0 K^+$	0.05 ± 0.02	Belle(II)(2025)[180]
	0.54 ± 0.14	Belle(2023)[178]	$\Xi_c^+ \rightarrow p K^- \pi^+$	1.14 ± 0.39	LHCb(2020)[177]
				0.45 ± 0.22	Belle(2019)[179]
			$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$	2.86 ± 1.27	Belle(2019)[179]

Table 6. The measured polarization of the Ξ_c^0 .

Mode	polarization α	Experiment
$\Xi_c^0 \rightarrow \Lambda \bar{K}^*(892)^0$	0.15 ± 0.22	Belle(2021)[171]
$\Xi_c^0 \rightarrow \Sigma^+ K^*(892)^-$	-0.52 ± 0.30	Belle(2021)[171]
$\Xi_c^0 \rightarrow \Xi^- \pi^+$	-0.63 ± 0.03	Belle(2021)[38]
$\Xi_c^0 \rightarrow \Xi^0 \pi^0$	-0.90 ± 0.27	Belle(II)(2024)[182]

Table 7. The measured BF's of the Ω_c^0 with the relative mode $\Omega_c^0 \rightarrow \Omega^- \pi^+$. Upper limits are at 90% confidence level.

Mode	$\mathcal{B}$	Experiment	Mode	$\mathcal{B}$	Experiment
$\Omega_c^0 \rightarrow \Xi^0 \bar{K}^0$	1.64 ± 0.29	Belle(2018)[186]	$\Omega_c^0 \rightarrow \Sigma^- K^- K^- \pi^+$	< 0.32	Belle(2018)[186]
$\Omega_c^0 \rightarrow \Xi^- \pi^+$	0.25 ± 0.06	Belle(2023)[188]	$\Omega_c^0 \rightarrow \Xi^0 K^- \pi^+$	1.20 ± 0.18	Belle(2018)[186]
	0.16 ± 0.01	LHCb(2024)[189]	$\Omega_c^0 \rightarrow \Xi^- K^- \pi^+ \pi^+$	0.68 ± 0.08	Belle(2018)[186]
$\Omega_c^0 \rightarrow \Xi^- K^+$	< 0.07	Belle(2023)[188]	$\Omega_c^0 \rightarrow \Xi^- \bar{K}^0 \pi^+$	2.12 ± 0.28	Belle(2018)[186]
$\Omega_c^0 \rightarrow \Omega^- K^+$	< 0.29	Belle(2023)[188]	$\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^0$	2.00 ± 0.20	Belle(2018)[186]
	0.06 ± 0.01	LHCb(2024)[189]	$\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^- \pi^+$	0.32 ± 0.05	Belle(2018)[186]
$\Omega_c^0 \rightarrow \Lambda \bar{K}^0 \bar{K}^0$	1.72 ± 0.35	Belle(2018)[186]			

Charm Facilities

Charm factory

- **Threshold production**: No boost
- **Small X-section** : Lowest Statistics
- **Quantum coherence**
- **Inclusive charm, neutrals and neutrinos**
- **Absolute BF's**

$$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$$

$$e^+e^- \rightarrow D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$$

$$e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$$

BESIII, STCF in the future



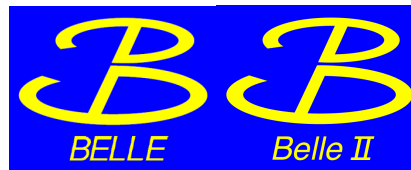
B factory

- Low background
- Low statistics
- Low boost
- Good for neutrals and neutrinos
- Some Absolute BF's

$$e^+e^- \rightarrow c\bar{c}$$

+ some other
Stuff

Belle / Belle II



Hadron collider

- High background
- High statistics
- High boost
- Challenging for neutrals and neutrinos
- Complex and biasing triggers

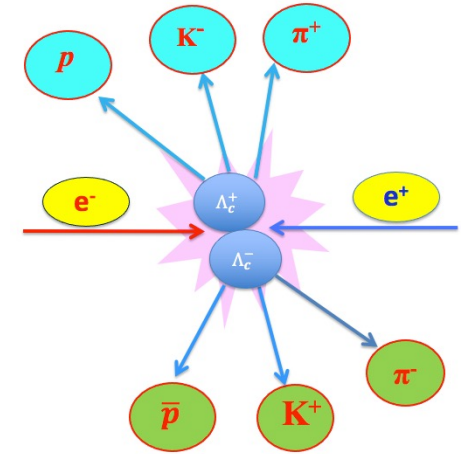
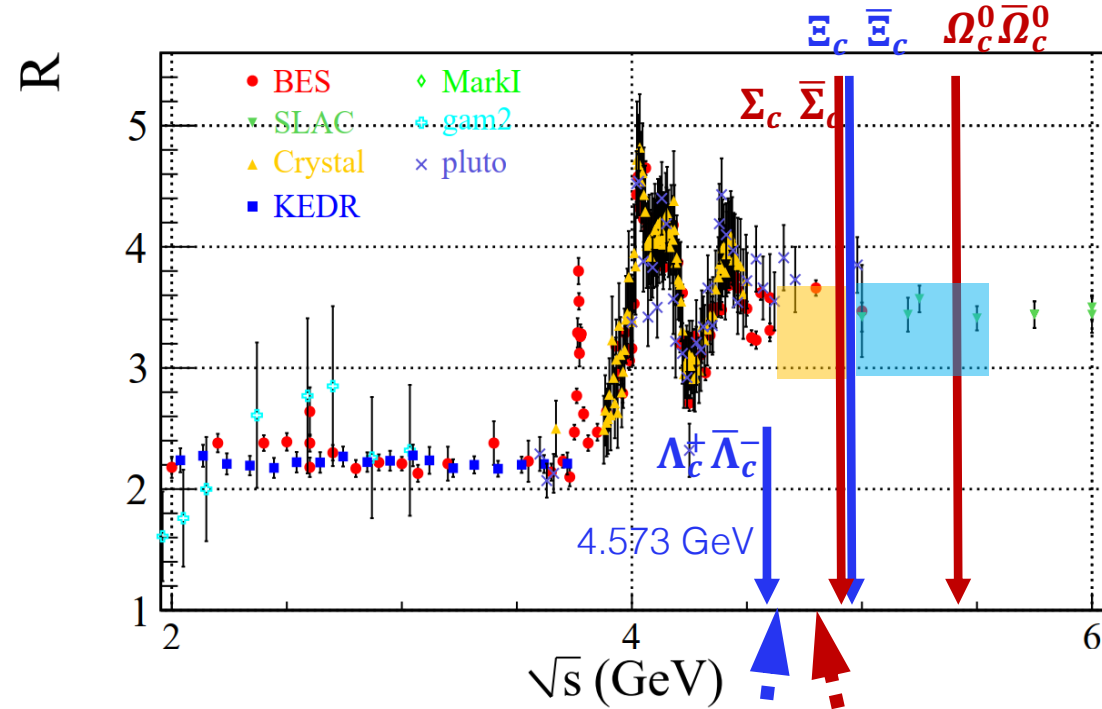
$$p\bar{p} \rightarrow c\bar{c}$$

+ lots of other
Stuff

LHCb



Charmed baryon thresholds



BESIII energy upgrades:
 4.6 GeV (Phase I, 2014)
 → 4.95 GeV (Phase II, 2021)
 → 5.6 GeV (Phase III, planned in 2026)

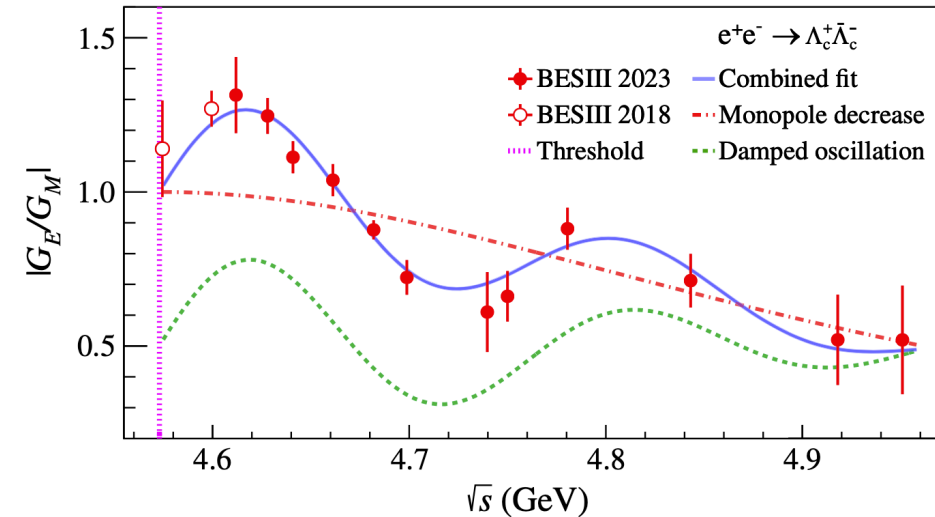
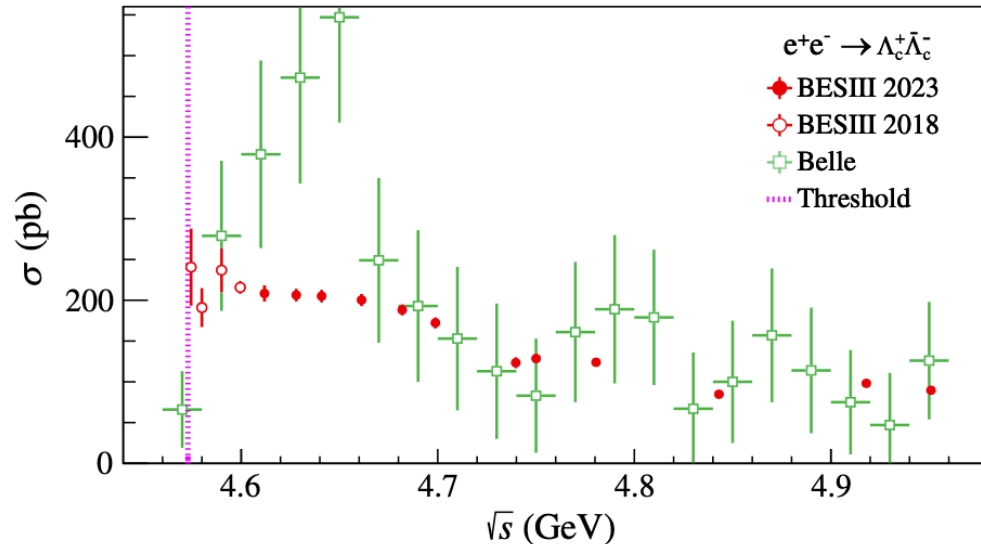
Production measurement near threshold

PRL 131.191901(2023)

- $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ cross section are measured at twelve energy points from 4.612-4.951 GeV.

$$\sigma_{\pm} = \frac{N_{ST}^{\pm}}{\epsilon_{ST}^{\pm} f_{ISR} f_{VP} \mathcal{L}_{int} N_{DT}} \sum_{n=1}^9 \left(\frac{N_{ST}^{\mp,n} \epsilon_{DT}^n}{\epsilon_{ST}^{\mp,n}} \right),$$

- Indicate no enhancement around Y(4630) resonance. => Conflict with Belle.
- $|G_E/G_M|$ ratio are derived by fitting to angular distribution.
- The oscillations on $|G_E/G_M|$ ratio is significantly observed with higher frequency than that of the proton. $\Rightarrow$ may imply a non-trivial structure of the lightest charmed baryon.



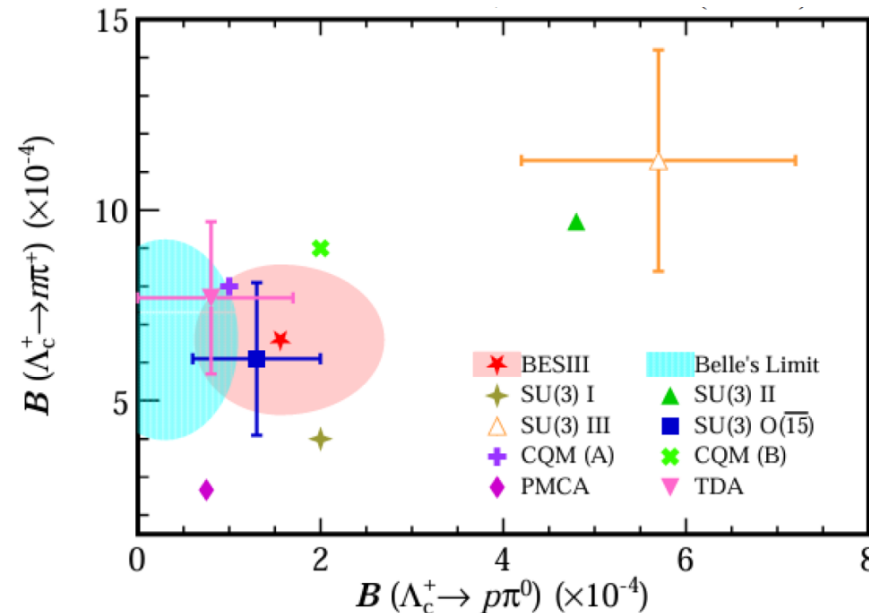
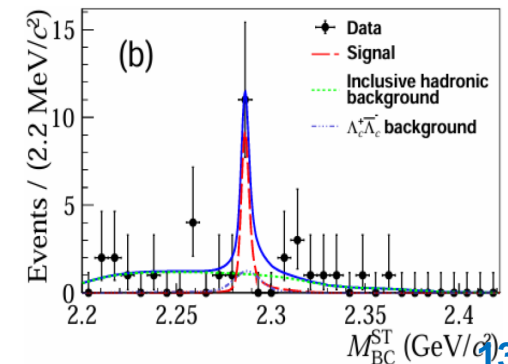
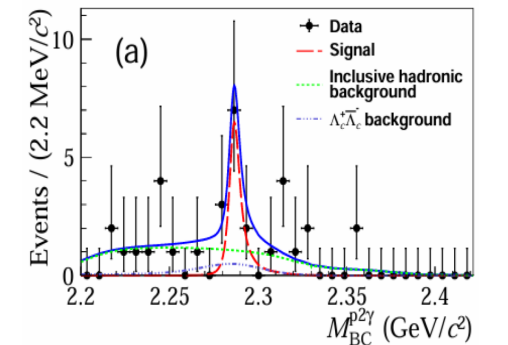
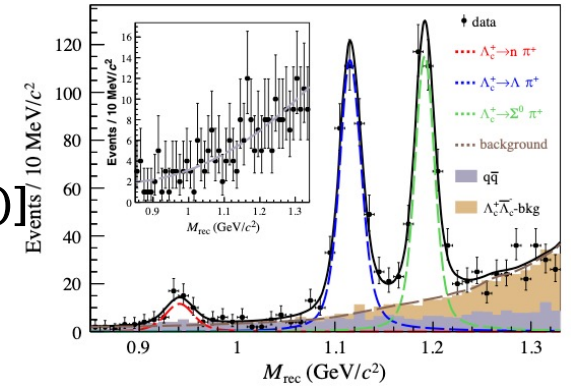
$\Lambda_c^+ \rightarrow n\pi^+$ and $\Lambda_c^+ \rightarrow p\pi^0$

PRL 128.142001 (2022)

PRD 109, L091101 (2024)

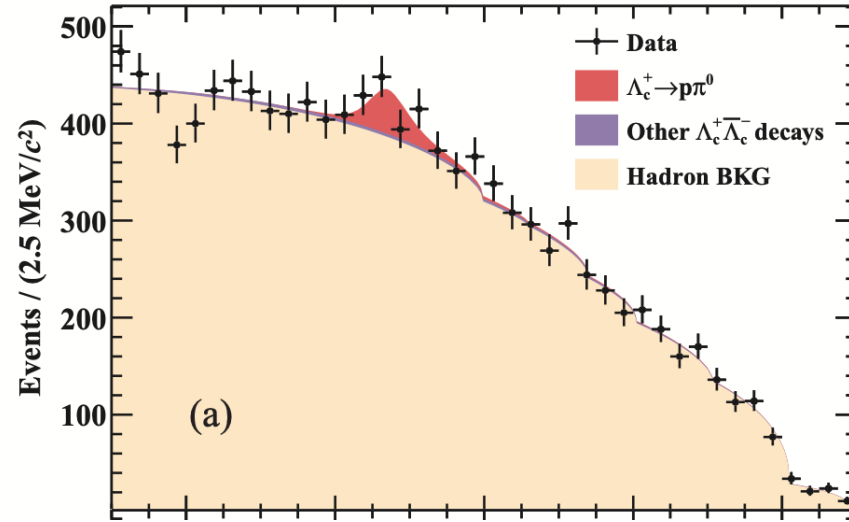
$N(n\pi^+) = 50 \pm 9$

- First singly Cabibbo-suppressed Λ_c^+ decay involved neutron was observed (7.3σ).
- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \rightarrow n\pi^+) = (6.6 \pm 1.2_{stat} \pm 0.4_{syst}) \times 10^{-4}$.
=> Consistent with SU(3) flavor asymmetry prediction [PLB790,225(2019),]
=> twice larger than the dynamical calculation based on pole model and CA [PRD97,074028(2018)]
- $R = \frac{\mathcal{B}(\Lambda_c^+ \rightarrow n\pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow p\pi^0)} > 7.2 @ 90\% C.L.$ ($\mathcal{B}(\Lambda_c^+ \rightarrow p\pi^0) < 8.0 \times 10^{-5} @ 90\% C.L.$ from Belle)
=> Disagrees with SU(3) asymmetry and dynamical calculation (2-4.7) while in consistent with SU(3) plus topological-diagram approach (9.6).
- $\mathcal{B}(\Lambda_c^+ \rightarrow p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.2_{syst}) \times 10^{-4}$; $R = 3.2^{+2.2}_{-1.2}$

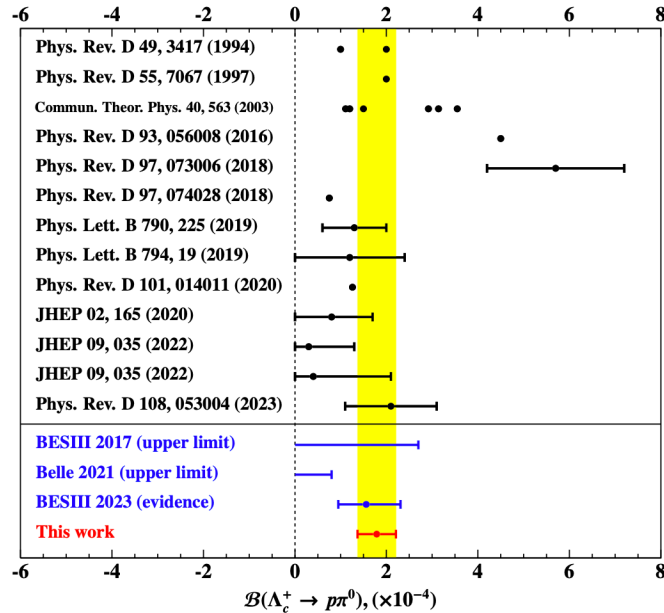
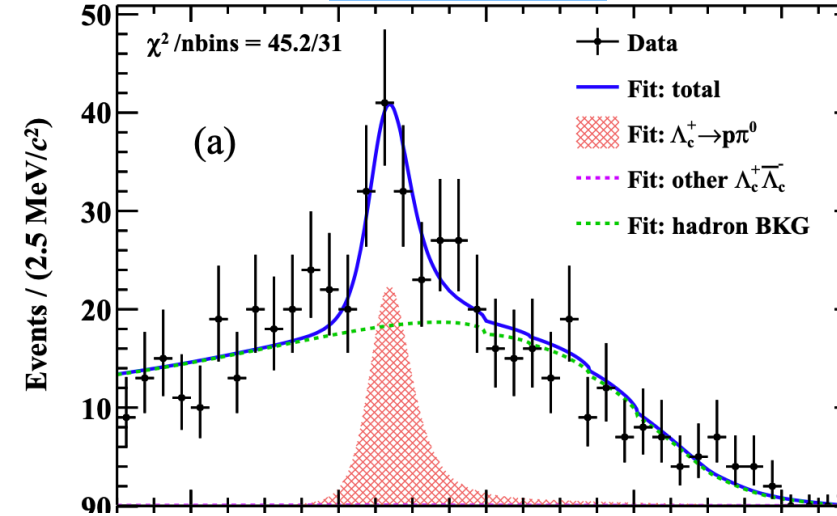


First observation of $\Lambda_c^+ \rightarrow p\pi^0$

Before DNN



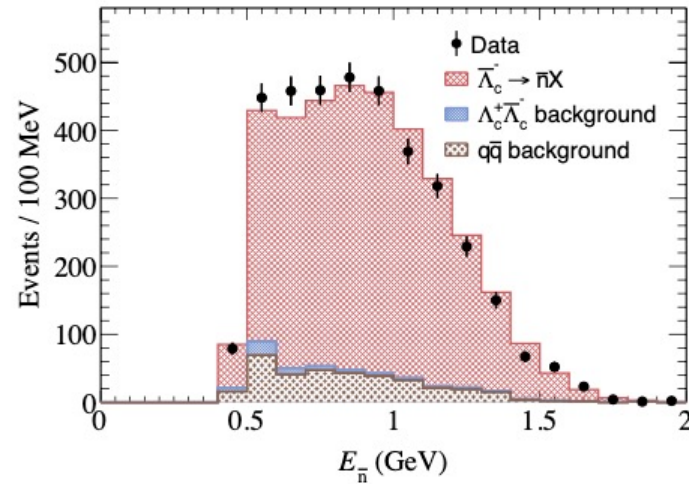
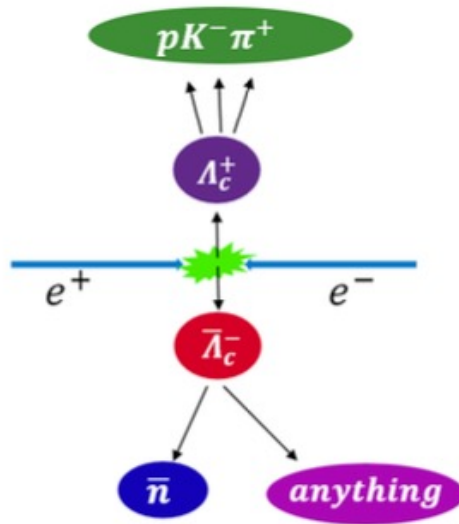
After DNN



- First observation of $\Lambda_c^+ \rightarrow p\pi^0$ with significance of 5.4σ .
- A sophisticated deep learning approach is employed.
- The absolute branching fraction is measured to be $\mathcal{B}(\Lambda_c^+ \rightarrow p\pi^0) = (1.79 \pm 0.39_{stat} \pm 0.11_{syst} \pm 0.08_{p\eta})\%$.
- Offering essential calibration for theoretical predictions.

BF measurement of $\bar{\Lambda}_c^- \rightarrow \bar{n}X$

PRD 108.L031101 (2023).



- The deposited energy in EMC is used to identify $\bar{n}$.
- Data-driven technique to model $\bar{n}$ behavior in the detector.
- Absolute BFs are measured to be
 $\mathcal{B}(\bar{\Lambda}_c^- \rightarrow \bar{n}X) = (33.5 \pm 0.7_{stat} \pm 1.2_{syst})\%$, precision up to 4%.
- All known exclusive process with neutron in final state is about 25% $\Rightarrow$ more space to be explored.
- Asymmetry between $\mathcal{B}(\Lambda_c^+ \rightarrow nX)$ and $\mathcal{B}(\Lambda_c^+ \rightarrow pX)$ is observed.

Experiment & Phenomenon

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_s^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]	-0.10	-0.70	0.70	0.71	0
Xu(1992), Pole [4]	0.51	-0.67	0.92	0.92	0
Cheng, Tseng(1992), Pole [5]	-0.49	-0.96	0.83	0.83	-
Cheng, Tseng(1993), Pole [6]	-0.49	-0.95	0.78	0.78	-
Żencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Żencaykowski(1994), Pole [8]	-0.66	-0.99	0.39	0.39	0
CLEO(1995) [9]	-	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	-	$-0.45 \pm 0.31 \pm 0.06$	-
Alakabha Datta(1995), CA [10]	-0.91	-0.94	-0.47	-0.47	-
Ivanov(1998), CCQM [11]	-0.97	-0.95	0.43	0.43	0
Sharma(1999), CA [12]	-0.99	-0.99	-0.31	-0.31	0
FOCUS(2006) [13]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
BESIII(2018) [14]	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.73 \pm 0.17 \pm 0.07$	$-0.57 \pm 0.10 \pm 0.07$	-

PHYSICAL REVIEW D **100**, 072004 (2019)

**Measurements of weak decay asymmetries
of $\Lambda_c^+ \rightarrow pK_s^0$, $\Lambda\pi^+$, $\Sigma^+\pi^0$, and $\Sigma^0\pi^+$**

- ✓ First $\Lambda_c^+ \rightarrow pK_s^0$.
- ✓ Most precise $\Lambda_c^+ \rightarrow \Lambda\pi^+$.
- ✓ The sign of $\Lambda_c^+ \rightarrow \Sigma\pi$.

Renaissance on the charmed baryon decay asymmetry from 2018!

Experiment & Phenomenon

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_s^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]	-0.10	-0.70	0.70	0.71	0
Xu(1992), Pole [4]	0.51	-0.67	0.92	0.92	0
Cheng, Tseng(1992), Pole [5]	-0.49	-0.96	0.83	0.83	-
Cheng, Tseng(1993), Pole [6]	-0.49	-0.95	0.78	0.78	-
Żencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Żencaykowski(1994), Pole [8]	-0.66	-0.99	0.39	0.39	0
CLEO(1995) [9]	-	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	-	$-0.45 \pm 0.31 \pm 0.06$	-
Alakabha Datta(1995), CA [10]	-0.91	-0.94	-0.47	-0.47	-
Ivanov(1998), CCQM [11]	-0.97	-0.95	0.43	0.43	0
Sharma(1999), CA [12]	-0.99	-0.99	-0.31	-0.31	0
FOCUS(2006) [13]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
BESIII(2018) [14]	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.73 \pm 0.17 \pm 0.07$	$-0.57 \pm 0.10 \pm 0.07$	-
Geng(2019), SU(3) [15]	$-0.89^{+0.26}_{-0.11}$	-0.87 ± 0.10	-0.35 ± 0.27	-0.35 ± 0.27	$0.94^{+0.06}_{-0.11}$
Zou(2020), CA [16]	-0.75	-0.93	-0.76	-0.76	0.90
BELLE(2022) [17, 18]	-	$-0.755 \pm 0.005 \pm 0.003$	$-0.463 \pm 0.016 \pm 0.008$	$-0.48 \pm 0.02 \pm 0.02$	-
Zhong(2022), SU(3) ^a [19]	-0.57 ± 0.21	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	$0.91^{+0.03}_{-0.04}$
Zhong(2022), SU(3) ^b [19]	-0.29 ± 0.24	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	0.99 ± 0.01
Liu(2023), Pole [20]	-0.81 ± 0.05	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.95 ± 0.02
Liu(2023), LP [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.92

- ✓ The decay asymmetry parameter of $\Lambda_c^+ \rightarrow \Xi^0 K^+$ significantly changed from 0 to almost 1.
- ✓ Quite urgent to validate experimentally.

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \rightarrow \Xi^0 K^+$

Phys. Rev. Lett. **132**, 031801(2024)

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+)$ ($\times 10^{-3}$)	$\alpha_{\Xi^0 K^+}$	$ A $ ($\times 10^{-2} G_F \text{ GeV}^2$)	$ B $ ($\times 10^{-2} G_F \text{ GeV}^2$)	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	-	-	-
Xu (1992), Pole [8]	1.0	0	0	7.94	-
Żencaykowski (1994), Pole [9]	3.6	0	-	-	-
Ivanov (1998), CCQM [10]	3.1	0	-	-	-
Sharma (1999), CA [11]	1.3	0	-	-	-
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	-
Zou (2020), CA [5]	7.1	0.90	4.48	12.10	-
Zhong (2022), SU(3) ^a [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	-
Zhong (2022), SU(3) ^b [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	-
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	-	-	-	-
PDG Fit (2022) [3]	5.5 ± 0.7	-	-	-	-

- $\Lambda_c^+ \rightarrow \Xi^0 K^+$ is pure W-exchange process which have significant contributions in charmed baryon decay.
- Nonfactorizable W-exchange diagram cannot be calculated using theoretical approaches.
- Long-standing puzzle on how large the S-wave amplitude.
- Experimental measurement of decay asymmetry is crucial and urgent.

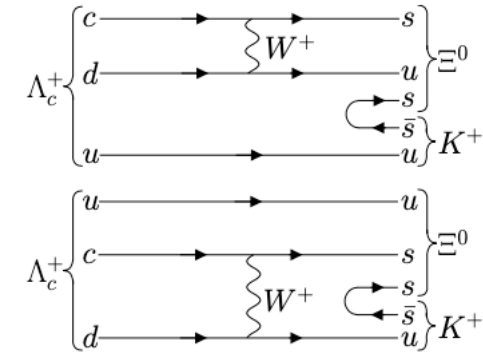


FIG. 1. Feynman diagrams for $\Lambda_c^+ \rightarrow \Xi^0 K^+$

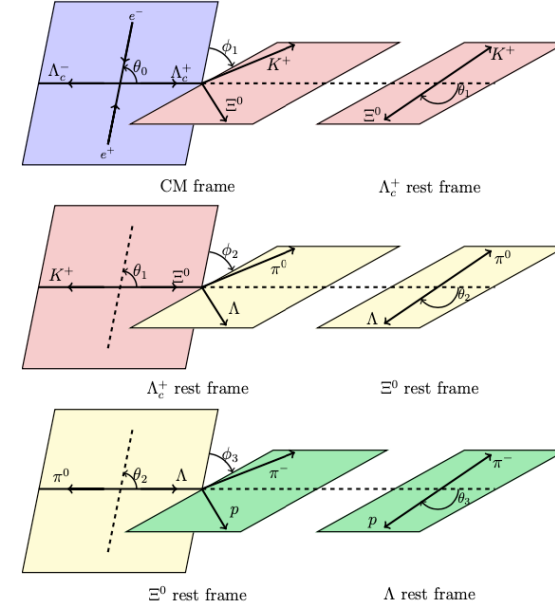
Decay asymmetry for pure W-exchange process $\Lambda_c^+ \rightarrow \Xi^0 K^+$

$$\alpha_{BP} = \frac{2\text{Re}(s^*p)}{|s|^2 + |p|^2}, \quad \beta_{BP} = \frac{2\text{Im}(s^*p)}{|s|^2 + |p|^2}, \quad \gamma_{BP} = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

Phys. Rev. Lett. 132, 031801(2024)

Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \rightarrow \Lambda_c^+(\lambda_1) \bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1, λ_2}
1	$\Lambda_c^+ \rightarrow \Xi^0(\lambda_3) K^+$	(θ_1, ϕ_1)	B_{λ_3}
2	$\Xi^0 \rightarrow \Lambda(\lambda_4) \pi^0$	(θ_2, ϕ_2)	C_{λ_4}
3	$\Lambda \rightarrow p(\lambda_5) \pi^-$	(θ_3, ϕ_3)	D_{λ_5}

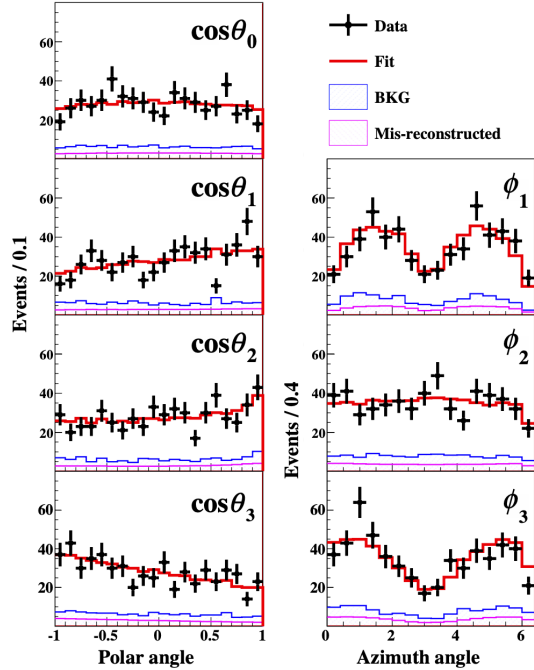
$$\begin{aligned} & \frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\cos\theta_2 d\cos\theta_3 d\phi_1 d\phi_2 d\phi_3} \\ & \propto 1 + \alpha_0 \cos^2 \theta_0 \\ & + (1 + \alpha_0 \cos^2 \theta_0) \alpha_{\Xi^0 K^+} + \alpha_{\Lambda \pi^0} \cos \theta_2 \\ & + (1 + \alpha_0 \cos^2 \theta_0) \alpha_{\Xi^0 K^+} + \alpha_{p \pi^-} \cos \theta_2 \cos \theta_3 \\ & + (1 + \alpha_0 \cos^2 \theta_0) \alpha_{\Lambda \pi^0} \alpha_{p \pi^-} \cos \theta_3 \\ & - (1 + \alpha_0 \cos^2 \theta_0) \alpha_{\Xi^0 K^+} \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \sin \theta_2 \sin \theta_3 \cos(\Delta_{\Lambda \pi^0} + \phi_3) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \alpha_{\Xi^0 K^+} + \sin \theta_1 \sin \phi_1 \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \alpha_{\Lambda \pi^0} \sin \theta_1 \sin \phi_1 \cos \theta_2 \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \alpha_{\Xi^0 K^+} + \alpha_{\Lambda \pi^0} \alpha_{p \pi^-} \sin \theta_1 \sin \phi_1 \cos \theta_3 \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \alpha_{p \pi^-} - \sin \theta_1 \sin \phi_1 \cos \theta_2 \cos \theta_3 \\ & - \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \sin \theta_1 \sin \phi_1 \sin \theta_2 \sin \theta_3 \cos(\Delta_{\Lambda \pi^0} + \phi_3) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \alpha_{\Lambda \pi^0} \cos \phi_1 \sin \theta_2 \sin(\Delta_{\Xi^0 K^+} + \phi_2) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \alpha_{\Lambda \pi^0} \cos \phi_1 \sin \theta_2 \cos(\Delta_{\Xi^0 K^+} + \phi_2) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \alpha_{p \pi^-} \cos \phi_1 \sin \theta_2 \cos(\Delta_{\Xi^0 K^+} + \phi_2) \cos \theta_3 \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \alpha_{p \pi^-} \cos \phi_1 \sin \theta_2 \sin(\Delta_{\Xi^0 K^+} + \phi_2) \cos \theta_3 \\ & - \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \cos \phi_1 \sin \theta_1 \sin(\Delta_{\Xi^0 K^+} + \phi_2) \sin \theta_3 \sin(\Delta_{\Lambda \pi^0} + \phi_3) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \cos \phi_1 \sin \phi_1 \cos \theta_2 \cos(\Delta_{\Xi^0 K^+} + \phi_2) \sin \theta_3 \cos(\Delta_{\Lambda \pi^0} + \phi_3) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \cos \phi_1 \cos \theta_2 \cos(\Delta_{\Xi^0 K^+} + \phi_2) \sin \theta_3 \sin(\Delta_{\Lambda \pi^0} + \phi_3) \\ & + \sqrt{1 - \alpha_0^2} \sin \Delta_0 \sin \theta_0 \cos \theta_0 \sqrt{1 - \alpha_{\Xi^0 K^+}^2} \sqrt{1 - \alpha_{\Lambda \pi^0}^2} \alpha_{p \pi^-} \cos \phi_1 \cos \theta_2 \sin(\Delta_{\Xi^0 K^+} + \phi_2) \sin \theta_3 \cos(\Delta_{\Lambda \pi^0} + \phi_3) \end{aligned}$$



- The joint angular distribution for $\Lambda_c^+ \rightarrow \Xi^0 K^+$ is derived based on helicity amplitude.

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \rightarrow \Xi^0 K^+$

Phys. Rev. Lett. 132, 031801(2024)

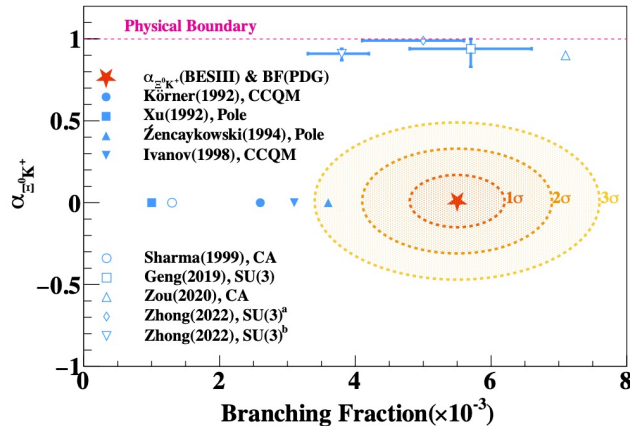


- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero $\Rightarrow$ strong identification for theoretical predictions.

$$\Gamma = \frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi} \left[\frac{(m_{\Lambda_c^+} + m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2} |A|^2 + \frac{(m_{\Lambda_c^+} - m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2} |B|^2 \right]$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p - \delta_s)}{|A|^2 + \kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan \frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2},$$



- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero. $\Rightarrow$ not considered in previous literature.
- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+)$ simultaneously.

Experiment & Phenomenon

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_s^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]	-0.10	-0.70	0.70	0.71	0
Xu(1992), Pole [4]	0.51	-0.67	0.92	0.92	0
Cheng, Tseng(1992), Pole [5]	-0.49	-0.96	0.83	0.83	-
Cheng, Tseng(1993), Pole [6]	-0.49	-0.95	0.78	0.78	-
Żencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Żencaykowski(1994), Pole [8]	-0.66	-0.99	0.39	0.39	0
CLEO(1995) [9]	-	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	-	$-0.45 \pm 0.31 \pm 0.06$	-
Alakabha Datta(1995), CA [10]	-0.91	-0.94	-0.47	-0.47	-
Ivanov(1998), CCQM [11]	-0.97	-0.95	0.43	0.43	0
Sharma(1999), CA [12]	-0.99	-0.99	-0.31	-0.31	0
FOCUS(2006) [13]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
BESIII(2018) [14]	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.73 \pm 0.17 \pm 0.07$	$-0.57 \pm 0.10 \pm 0.07$	-
Geng(2019), SU(3) [15]	$-0.89^{+0.26}_{-0.11}$	-0.87 ± 0.10	-0.35 ± 0.27	-0.35 ± 0.27	$0.94^{+0.06}_{-0.11}$
Zou(2020), CA [16]	-0.75	-0.93	-0.76	-0.76	0.90
BELLE(2022) [17, 18]	-	$-0.755 \pm 0.005 \pm 0.003$	$-0.463 \pm 0.016 \pm 0.008$	$-0.48 \pm 0.02 \pm 0.02$	-
Zhong(2022), SU(3) ^a [19]	-0.57 ± 0.21	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	$0.91^{+0.03}_{-0.04}$
Zhong(2022), SU(3) ^b [19]	-0.29 ± 0.24	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	0.99 ± 0.01
Liu(2023), Pole [20]	-0.81 ± 0.05	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.95 ± 0.02
Liu(2023), LP [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.99 ± 0.01
BESIII(2023) [21]	-	-	-	-	0.01 ± 0.16
Geng(2023), SU(3) [22]	-0.40 ± 0.49	-0.75 ± 0.01	-0.47 ± 0.02	-0.47 ± 0.02	-0.15 ± 0.14
Zhong(2024), TDA [23]	0.01 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.16 ± 0.13
Zhong(2024), IRA [23]	0.03 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.19 ± 0.12
PDG(for now) [24]	0.20 ± 0.50 (only BESIII)	-0.84 ± 0.09	-0.73 ± 0.18 (only BESIII)	-0.55 ± 0.11	-

Discussion on $\Lambda_c^+ \rightarrow \Xi^0 K^+$

Strong phase shift: $-1.55 \pm 0.25 \pm 0.05$ or $1.59 \pm 0.25 \pm 0.05$ $\alpha \propto \cos \sim 0.02$

Very different from hyperon decays $\longrightarrow$ strong phase ~ 0

Only a few
measurements

$$\Lambda^0 \rightarrow p\pi^-$$

$$\alpha = +0.65 \pm 0.02$$

$$\beta = -0.10 \pm 0.07$$

$$\gamma = +0.75 \pm 0.02$$

$$\beta/\alpha = -0.16 \pm 0.10$$

$$\Delta = -\arctan(\beta/\alpha) = 9.0^\circ \pm 5.5^\circ$$

$$|p|/|s| = 0.38 \pm 0.01$$

Phys. Rev. Lett. **19**, 391 (1967)

$$\Xi^- \rightarrow \Lambda^0 \pi^-$$

Parameter	This work
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2} \text{ rad}$
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$

$$\xi_P - \xi_S = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2} \text{ rad}$$

$$\delta_P - \delta_S = (-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$$

Strong phase shift

Nature 606 (2022) 7912, 64-69

Strong phase shift can be induced by re-scattering processes and loop effects.

✓ After consider the strong phase shift:

A. Observed channel $\Xi_c^0 \rightarrow \Sigma^+ K^-$ should have phase shift similar to $\Lambda_c^+ \rightarrow \Xi^0 K^+$.

B. Topological diagrammatic approach leads to a large α of order -0.93 for the decay $\Xi_c^+ \rightarrow \Xi^0 \pi^+$ even after the phase shift effect is incorporated.

Further confirmation is needed!

[arXiv:2310.05491](https://arxiv.org/abs/2310.05491)

[arXiv:2404.01350](https://arxiv.org/abs/2404.01350)

$$\alpha = \frac{2 \operatorname{Re}(S^* P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2 \operatorname{Im}(S^* P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\delta_P - \delta_S = 2 \arctan \frac{\beta \times \text{sign}}{\sqrt{\alpha^2 + \beta^2} + \alpha \times \text{sign}},$$

$$\alpha_1 = \frac{2|S||P| \cos(\delta_P - \delta_S)}{|S|^2 + |P|^2}, \quad \beta_1 = \frac{2|S||P| \sin(\delta_P - \delta_S)}{|S|^2 + |P|^2}.$$

$$S_1 = |S| e^{i\delta_S}, \quad P_1 = |P| e^{i\delta_P},$$

$$\alpha_2 = \frac{2\tilde{S}\tilde{P} \cos(\delta_P - \delta_S)}{|\tilde{S}|^2 + |\tilde{P}|^2}, \quad \beta_2 = \frac{2\tilde{S}\tilde{P} \sin(\delta_P - \delta_S)}{|\tilde{S}|^2 + |\tilde{P}|^2},$$

$$S_2 = \tilde{S} e^{i\delta_S}, \quad P_2 = \tilde{P} e^{i\delta_P},$$

$$\alpha_3 = \sin(2\zeta) \cos(\delta_P - \delta_S), \quad \beta_3 = \sin(2\zeta) \sin(\delta_P - \delta_S).$$

$$S_3 = |\mathcal{A}| \sin \zeta e^{i\delta_S}, \quad P_3 = |\mathcal{A}| \cos \zeta e^{i\delta_P}.$$

Table 1
Summary of experimental data on the parameters α, β , and ϕ and the phase shift, $\delta_P - \delta_S$, in various two-body nonleptonic decays of the Λ and Ξ hyperons and singly charmed baryon Λ_c^+ .

Experiment	Process	α or $\langle \alpha \rangle$	β or $\langle \beta \rangle$	ϕ or $\langle \phi \rangle$ (rad)	$\delta_P - \delta_S$ (rad)	Value of sign	$\delta_P - \delta_S$ (rad)	
							Eq. (10) with $\text{sign}=1$	Eq. (10) with $\text{sign}=-1$
Λ from $\pi^- p$ (1963) [14]	$\Lambda \rightarrow p \pi^-$	0.62 ± 0.07	-0.18 ± 0.24	...	-0.26 ± 0.35^a	Unknown	-0.28 ± 0.36	2.86 ± 0.36
Λ from $\pi^- p$ (1967) [15]		0.645 ± 0.017	-0.103 ± 0.065	-0.14 ± 0.10	-0.16 ± 0.10^a	Unknown	-0.16 ± 0.10	2.98 ± 0.10
E756 (2003) [18]	$\Xi^- \rightarrow \Lambda \pi^-$	-0.458 ± 0.012	-0.03 ± 0.04	-0.03 ± 0.05	0.06 ± 0.09	+1	-3.08 ± 0.09	0.06 ± 0.09
HyperCP (2004) [19]		-0.458 ± 0.012	-0.037 ± 0.015	-0.041 ± 0.016	0.080 ± 0.032	Unknown	-3.062 ± 0.031	0.079 ± 0.031
BESIII (2022) [20]		-0.373 ± 0.006	Positive	0.016 ± 0.016	-0.040 ± 0.037	Unknown	3.102 ± 0.036	-0.040 ± 0.036
BESIII (2022) [21]		-0.350 ± 0.018	Positive	0.073 ± 0.052	-0.20 ± 0.13	Unknown	2.95 ± 0.13	-0.19 ± 0.13
BESIII (2024) [22]		-0.371 ± 0.004	Negative	-0.013 ± 0.008	0.033 ± 0.023	Unknown	-3.109 ± 0.025	0.033 ± 0.025
BESIII (2023) [23]	$\Xi^0 \rightarrow \Lambda \pi^0$	-0.377 ± 0.003	Positive	0.005 ± 0.007	-0.013 ± 0.017	Unknown	3.129 ± 0.017	-0.012 ± 0.017
LHCb (2024) [24]	$\Lambda_c^+ \rightarrow \Lambda \pi^+$	-0.785 ± 0.007	0.378 ± 0.015	0.656 ± 0.027	2.693 ± 0.017	Unknown	2.693 ± 0.015	-0.449 ± 0.015
LHCb (2024) [24]	$\Lambda_c^+ \rightarrow \Lambda K^+$	-0.516 ± 0.046	0.33 ± 0.08	2.75 ± 0.11	2.57 ± 0.19	Unknown	2.58 ± 0.12	-0.56 ± 0.12
BESIII (2024) [13]	$\Lambda_c^+ \rightarrow \Xi^0 K^+$	0.01 ± 0.16	-0.64 ± 0.70	3.84 ± 0.90	$-1.55(1.59) \pm 0.25^b$	+1	$-1.55(1.59) \pm 0.25$	$1.59(-1.55) \pm 0.25$

Methods for measurement

➤ The definition of polarization parameters:

$$\left[\alpha = \frac{2\text{Re}(s^*p)}{|s|^2 + |p|^2} \quad \beta = \frac{2\text{Im}(s^*p)}{|s|^2 + |p|^2} \quad \gamma = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2} \right]$$

If s and p can be measured directly, all information will be derived.

Partial wave analysis is a good choice for multi-body decays.

TF-PWA

A general and user-friendly partial wave analysis framework

- Developed and updated by Yi Jiang @ UCAS
- Home page: <https://github.com/jiangyi15/tf-pwa>



s and p of all intermediate resonance states

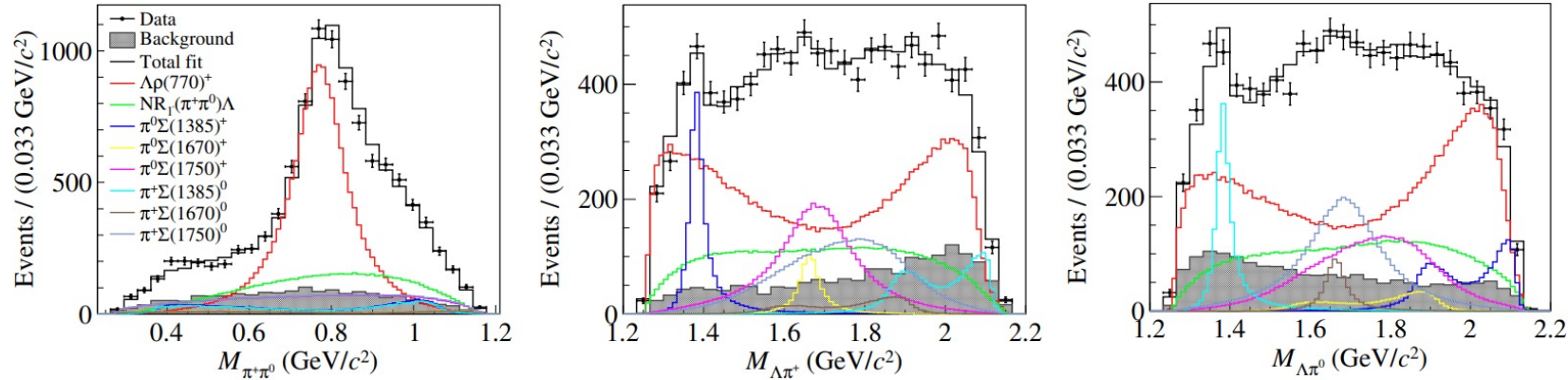


- ✓ Polarization parameters
- ✓ Branching fraction

Methods for measurement

Partial wave analysis of the charmed baryon hadronic decay $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0$

JHEP12(2022)033



	Result
$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \rho(770)^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma(1385)^+ \pi^0) \cdot \mathcal{B}(\Sigma(1385)^+ \rightarrow \Lambda \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0)}$	$(7.18 \pm 0.60 \pm 0.64)\%$
$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma(1385)^0 \pi^+) \cdot \mathcal{B}(\Sigma(1385)^0 \rightarrow \Lambda \pi^0)}{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^0)}$	$(7.92 \pm 0.72 \pm 0.80)\%$
$\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda \rho(770)^+)$	$(4.06 \pm 0.30 \pm 0.35 \pm 0.23) \times 10^{-2}$
$\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma(1385)^+ \pi^0)$	$(5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3}$
$\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma(1385)^0 \pi^+)$	$(6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3}$
$\alpha_{\Lambda \rho(770)^+}$	$-0.763 \pm 0.053 \pm 0.045$
$\alpha_{\Sigma(1385)^+ \pi^0}$	$-0.917 \pm 0.069 \pm 0.056$
$\alpha_{\Sigma(1385)^0 \pi^+}$	$-0.789 \pm 0.098 \pm 0.056$

More multi-body decays are underway!

✓ $\Lambda_c^+ \rightarrow p K^- \pi^+$ ✓ $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+ \eta$

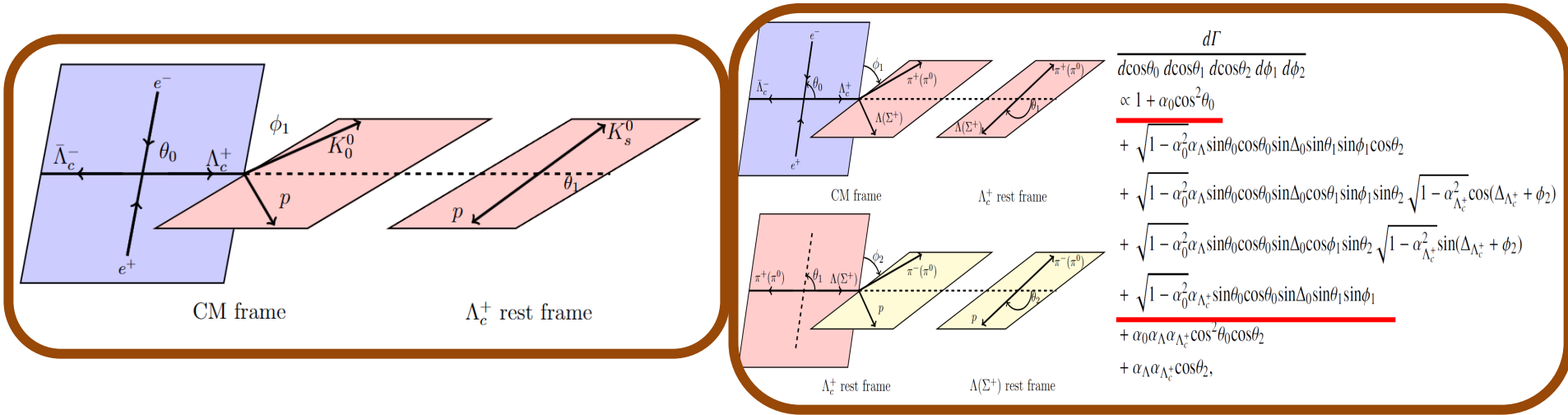
✓ $\Lambda_c^+ \rightarrow p K^- \pi^+ \pi^0$ ✓ $\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$

✓ $\Lambda_c^+ \rightarrow p K_S^0 \pi^0$ ✓ $\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$

✓ $\Lambda_c^+ \rightarrow n K_S^0 \pi^+$ ✓ ...

The α of all intermediate two-body processes will be measured!

Λ_c^+ polarization on BESIII



$$\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\phi_1} \propto 1 + \alpha_0 \cos^2 \theta_0 + \alpha_{\Lambda_c^+} \sqrt{1 - \alpha_0^2 \sin\theta_0 \cos\theta_0 \sin\Delta_0 \sin\theta_1 \sin\phi_1}$$

angular information from experiment

Λ_c^+ polarization parameters

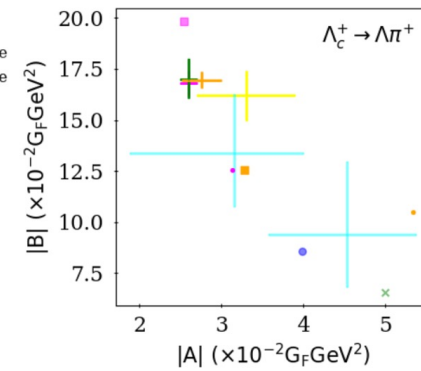
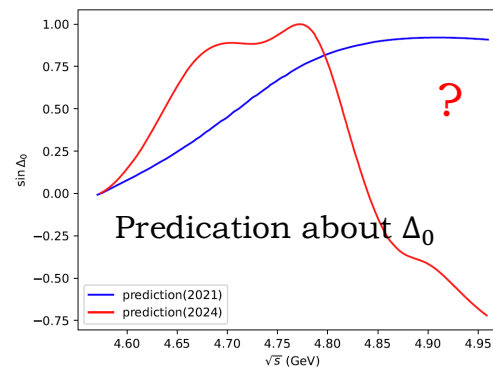
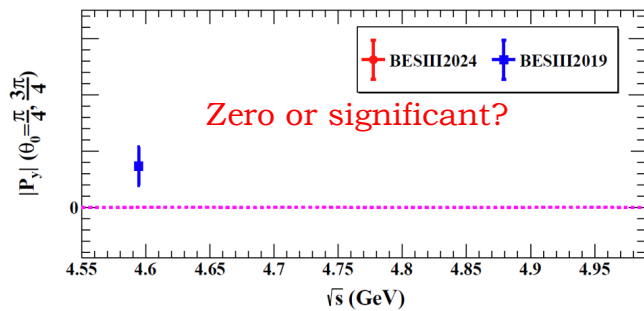
Λ_c^+ initial transverse polarization parameters

$$P_y(\alpha_0, \Delta_0, \theta_0) = c_0 \sqrt{1 - \alpha_0^2 \sin\theta_0 \cos\theta_0 \sin\Delta_0}$$

energy depended, relate to the form factor $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$

New Λ_c^+ polarization on BESIII

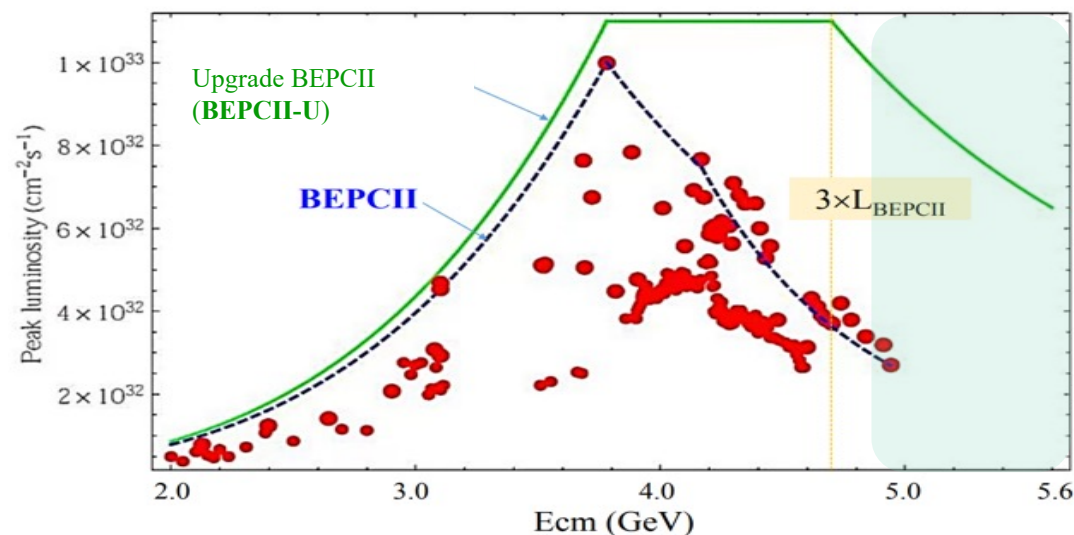
- Transverse polarization with energy from 4.60-4.95 GeV combined with $\Lambda_c^+ \rightarrow pK^-\pi^+$ channel(fixed all decay info. with LHCb input).
- Update 4 two-body decays polarization parameters with higher precision
- Strong/Weak phase shift
- α -induced CPV observables



Proposal of the upgrade BEPCII

An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021 and planned to be completed by the end of 2024

- ✓ **Improve luminosity by 3 times higher than current BEPCII at 4.7 GeV**
- ✓ **Extend the maximum energy to 5.6 GeV**

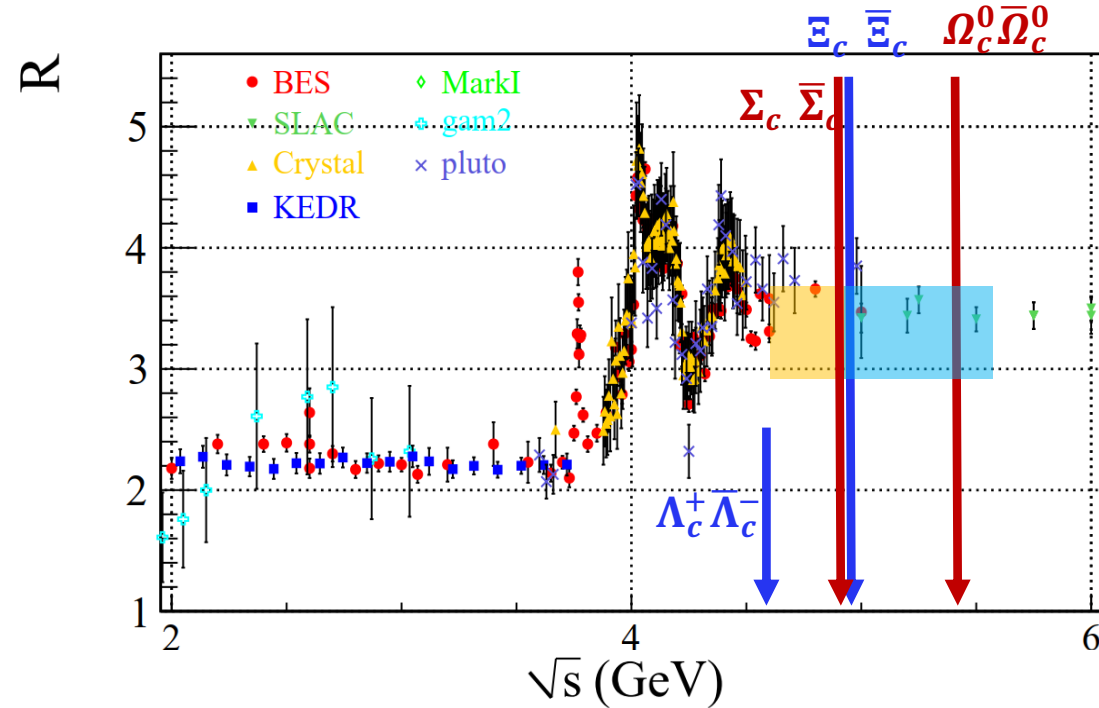
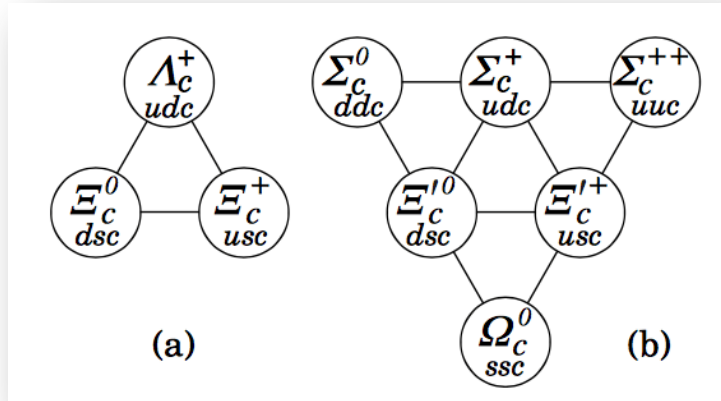


Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

1490 → 600 days

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
4.6 - 4.9 GeV	Charmed baryon/ XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+ \Lambda_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c \Sigma_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Heavier charmed baryons



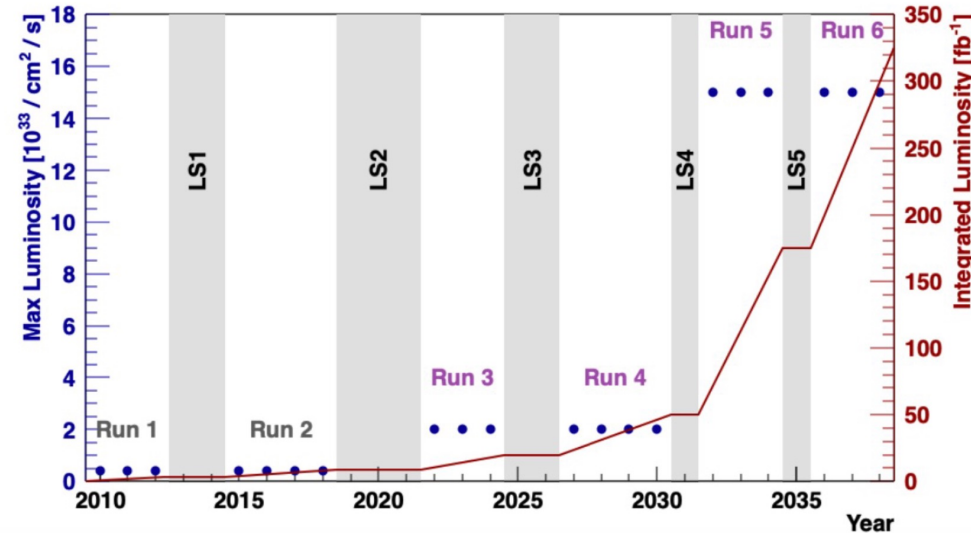
- **Energy thresholds**

- ✓ $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Sigma}_c^-$ 4.74 GeV
- ✓ $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Sigma}_c^- \pi$ 4.88 GeV
- ✓ $e^+ e^- \rightarrow \Sigma_c^+ \bar{\Sigma}_c^-$ 4.91 GeV
- ✓ $e^+ e^- \rightarrow \Xi_c^+ \bar{\Xi}_c^-$ 4.94 GeV
- ✓ $e^+ e^- \rightarrow \Omega_c^0 \bar{\Omega}_c^0$ 5.40 GeV

- Cover all the **ground-state charmed baryons**: studies on their production & decays, CPV search, **to help developing more reliable QCD-derived models in charm sector**
- Studies on the production and decays of **excited charmed baryons**

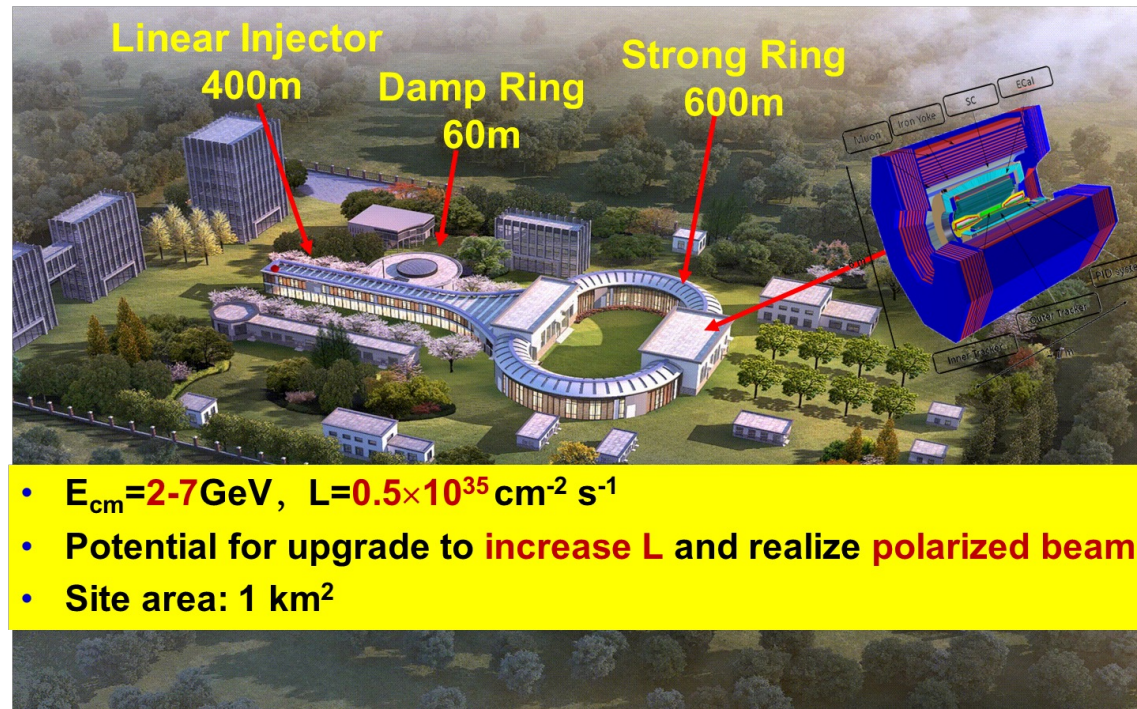
Future opportunity at LHCb

- RUN1&2: 9 fb^{-1}
- RUN3&4: 50 fb^{-1}
- ➔ x10 more statistics



- Further improvement on mass and lifetime measurement
- SCS and DCS hadronic decays
 - e.g. $\Xi_c^0 \rightarrow pK^-$, $\Xi_c^+ \rightarrow pK_S$, $\Omega_c^0 \rightarrow \Lambda K_S$, pK^-
- Semi-leptonic decays via b-baryon four-body decays
 - e.g. $\Lambda_c^+ \rightarrow pK^- \mu^+ \nu$, $p\pi^- \mu^+ \nu$; $\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu$; $\Xi_c^+ \rightarrow \Lambda \mu^+ \nu$; $\Omega_c^0 \rightarrow \Omega^- \mu^+ \nu$
- Decay asymmetries and CPV search via prompt production or b-baryon decays
 - e.g. $\Lambda_c^+ \rightarrow pK_S$, $\Lambda\pi^+$, ΛK^+ ; $\Xi_c^0 \rightarrow \Lambda K_S$, $\Xi^- \pi^+$, $\Xi^- K^+$; $\Omega_c^0 \rightarrow \Omega^- \pi^+$, $\Omega^- K^+$, $\Xi^- \pi^+$
- Amplitude analysis of multi-body hadronic decays

Super Tau-Charm Facility (STCF)



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032-2042	2043-2046
Form collaboration																
Conception design CDR																
R&D (TDR)																
Construction																
Operation																
Upgrade																

Anhui province and USTC have **officially endorsed 364M RMB R&D** project of STCF, and **great progress** is achieved; the **site** is preliminarily decided in Hefei, and **geological exploration** and **engineering design** is ongoing.

Will apply for the **construction (~4.5B RMB)** during the 15th five-year plan (2026-2030) from central government.

Summary

- **In the past year, many important results of charm baryon decays were reported by BESIII, Belle, and LHCb.**
- **Non-perturbative QCD is the main challenge. The theoretical calculations are hard for the Hadronic charm baryon decays.**
 - **Tools are improving.**
 - **Collaborations between theorists and experimentalists are crucial for accelerating research.**
- **The future of charm is promising. Lots of high quality data coming our way: LHCb, Belle II, BESIII(+upgrade)**
- **A dedicated charm facility, STCF, has been proposed in China. The R&D project with 364M RMB budget has been officially supported by Anhui province and USTC.**