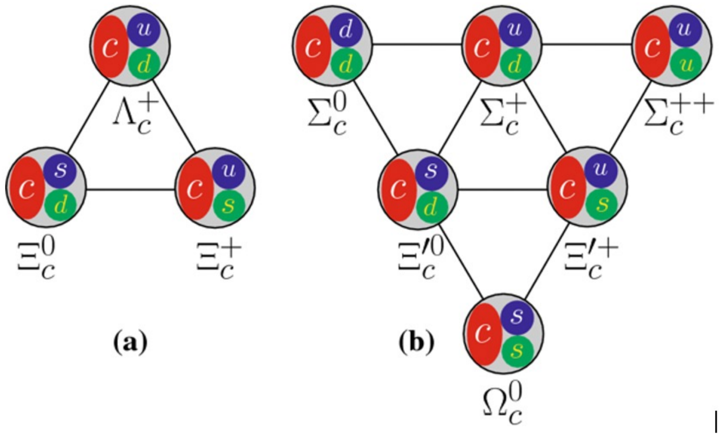

粲重子非轻衰变实验研究

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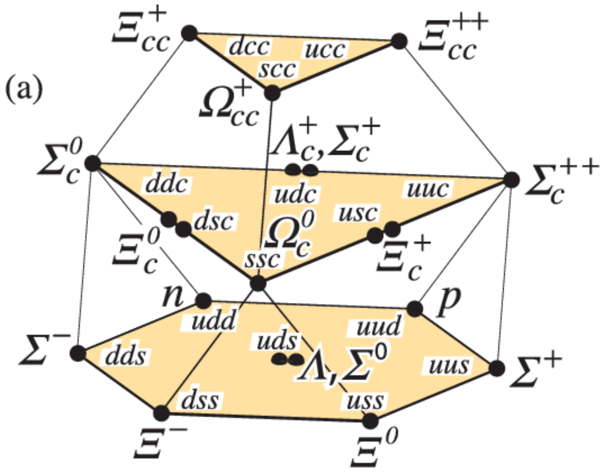
Outline

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

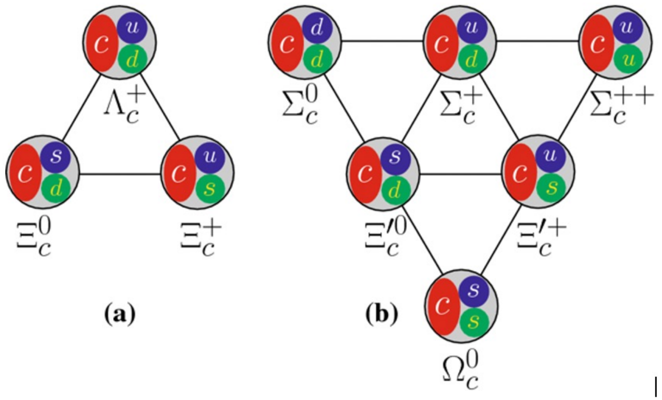
The charmed baryon family

- **Singly charmed baryons**
  - ✓ **Established ground states:**

    Λ_c^+, Σ_c , $\Xi_c^{(\prime)}$, Ω_c
  - ✓ **Excited states are being explored**
- **Observation of other doubly charmed baryon Ξ_{cc}^{++}**
- **No observations of other doubly or triply charmed baryons**

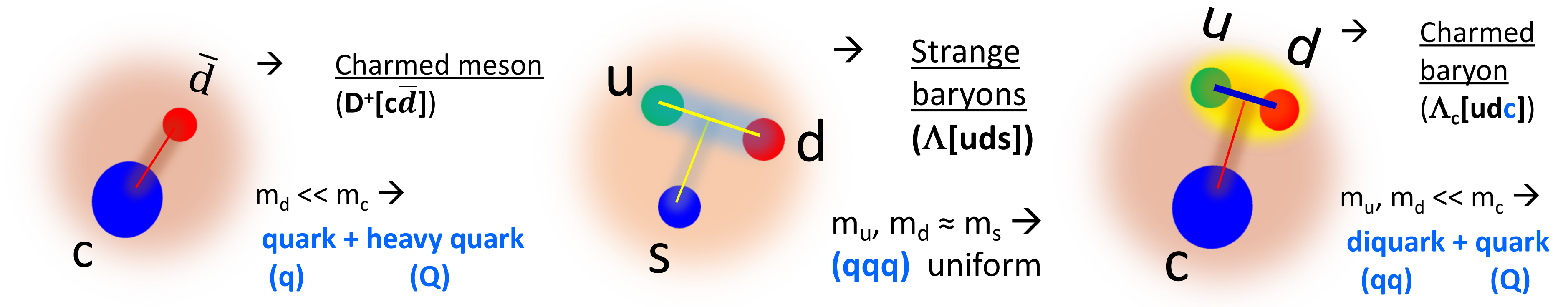


- Λ_c^+: decay only weakly, many recent experimental progress since 2014
- Σ_c : $B(\Sigma_c \to \Lambda_c^+\pi)\sim 100\%$; $B(\Sigma_c \to \Lambda_c^+\gamma)$?
- Ξ_c : decay only weakly; absolute BF measured with poor precision
- Ω_c : decay only weakly; no absolute BF measured



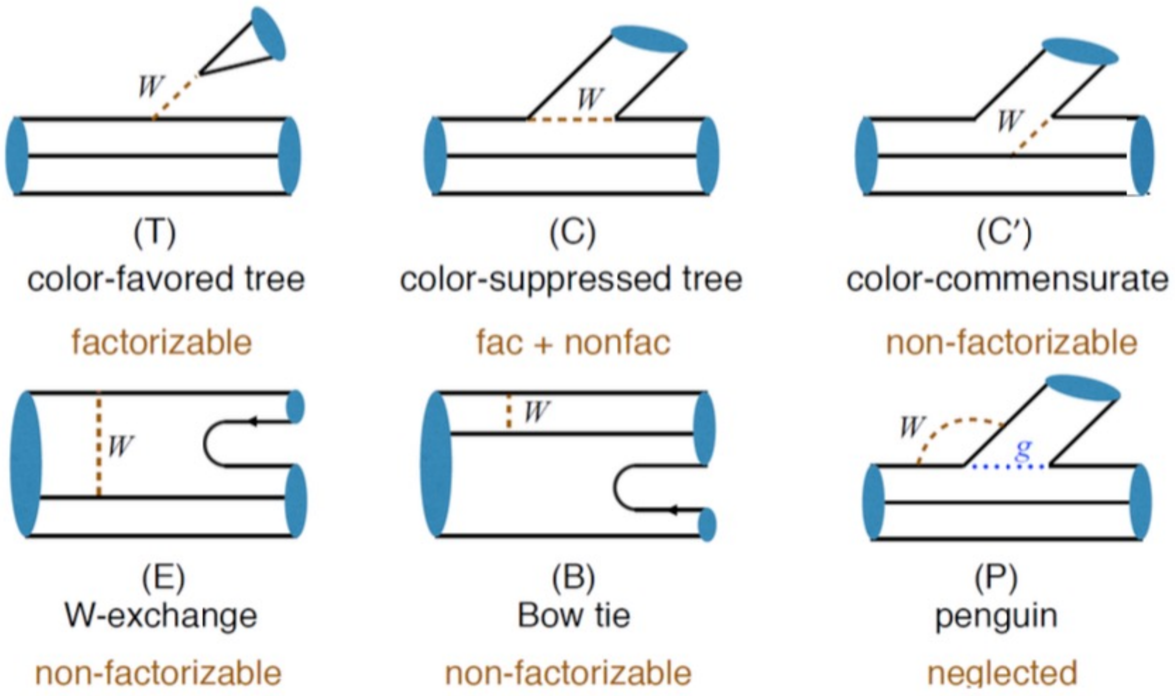
Λ_c^+: The lightest charmed baryon spectroscopy

- 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($\times10^{-3}$)	Experiment	Λ_c^+ Mode	BF($\times10^{-3}$)	Experiment
$\Lambda_c^+ \to \Lambda e^+\nu_e$	$23.7\pm5.1(37\%)^\dagger$	ARGUS(1991)[24]	$\Lambda_c^+ \to pK^-e^+\nu_e$	$0.88\pm0.18(20\%)$	BESIII(2022)[29]
	$26.8\pm5.1(19\%)^\dagger$	CELO(1994)[25]	$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$, $\Lambda(1405)\to pK^-$	$0.42\pm0.19(45\%)$	BESIII(2022)[29]
	$36.3\pm4.3(12\%)$	BESIII(2015)[30]			
	$35.6\pm1.3(3.6\%)$	BESIII(2022)[31]	$\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$	$1.0\pm0.5(50\%)$	BESIII(2022)[29]
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	$34.9\pm5.3(15\%)$	BESIII(2017)[32]	$\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$	<0.33	BESIII(2023)[33]
	$34.8\pm1.7(4.9\%)$	BESIII(2023)[34]	$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$	<0.39	BESIII(2023)[33]
$\Lambda_c^+ \to e^+X$	$39.5\pm3.5(8.9\%)$	BESIII(2018)[35]	$\Lambda_c^+ \to ne^+\nu_e$	$3.57\pm0.37\ (10\%)$	BESIII(2025)[36]
	$40.6\pm1.3(3.2\%)$	BESIII(2023)[37]			

Ξ_c Mode	BF($\times10^{-3}$)	Experiment	Ξ_c Mode	BF($\times10^{-3}$)	Experiment
$\Xi_c^0 \to \Xi^-e^+\nu_e$	$13.7\pm7.7(56\%)^\dagger$	ARGUS(1993)[26]	$\Xi_c^0 \to \Xi^-\mu^+\nu_\mu$	$10.1\pm2.1(21\%)^\dagger$	Belle(2021)[38]
	$44.3^{+16.6}_{-17.8}(40\%)^\dagger$	CLEO(1995)[27]	$\Xi_c^+ \to \Xi^0e^+\nu_e$	$67\pm39(58\%)^\dagger$	CLEO(1995)[27]
	$19.7\pm5.3(27\%)^\dagger$	ALICE(2021)[39]			
	$10.4\pm2.1(20\%)^\dagger$	Belle(2021)[38]			

Ω_c^0 Mode	Ratio	Experiment	Ω_c^0 Mode	Ratio	Experiment
$\Omega_c^0 \to \Omega^0e^+\nu_e$	$2.4\pm1.1(47\%)$	CLEO(2002)[28]	$\Omega_c^0 \to \Omega^0\mu^+\nu_\mu$	$1.94\pm0.21(11\%)$	Belle(2022)[40]
	$1.98\pm0.15(7.7\%)$	Belle(2022)[40]			

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

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

Table 3. The determined BFs 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					
$\Lambda_c^+ \to n\pi^+$	0.66 ± 0.13	BESIII(2022)[126]	$\Lambda_c^+ \to nK^+\pi^0$	<0.71	BESIII(2024)[107]
$\Lambda_c^+ \to p\pi^0$	<0.27	BESIII(2017)[117]	$\Lambda_c^+ \to n\pi^+\pi^0$	0.64 ± 0.09	BESIII(2023)[129]
	<0.08	Belle(2021)[109]	$\Lambda_c^+ \to nK_S^0K^+$	$0.39^{+0.17}_{-0.14}$	BESIII(2024)[91]
	$0.16^{+0.07}_{-0.06}$	BESIII(2024)[118]	$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	0.45 ± 0.08	BESIII(2023)[129]
	0.18 ± 0.04	BESIII(2025)[119]	$\Lambda_c^+ \to p\pi^+\pi^-$	3.91 ± 0.40	BESIII(2016)[127]
$\Lambda_c^+ \to p\eta$	1.24 ± 0.30	BESIII(2017)[117]		4.72 ± 0.28	LHCb(2018)[138]
	1.42 ± 0.12	Belle(2021)[109]	$\Lambda_c^+ \to pK^+K^-$	1.08 ± 0.07	LHCb(2018)[138]
	1.57 ± 0.12	BESIII(2023)[120]	$\Lambda_c^+ \to p(K^+K^-)_{\text{non-}\phi}$	0.55 ± 0.14	BESIII(2016)[127]
	1.63 ± 0.33	BESIII(2024)[118]	$\Lambda_c^+ \to pK_S^0K_S^0$	0.24 ± 0.02	Belle(2023)[146]
	1.67 ± 0.80	LHCb(2024)[121]	$\Lambda_c^+ \to p\phi\pi^0$	<0.15	Belle(2017)[147]
$\Lambda_c^+ \to p\eta'$	$0.56^{+0.25}_{-0.21}$	BESIII(2022)[123]	$\Lambda_c^+ \to (pK^+K^-\pi^0)_{\text{NR}}$	<0.06	Belle(2017)[147]
	0.47 ± 0.10	Belle(2022)[122]	$\Lambda_c^+ \to pK^+\pi^-$	0.16 ± 0.02	Belle(2016)[137]
$\Lambda_c^+ \to p\rho$	1.52 ± 0.44	LHCb(2024)[121]		0.10 ± 0.01	LHCb(2018)[138]
$\Lambda_c^+ \to p\omega$	0.94 ± 0.39	LHCb(2018)[124]			
	0.83 ± 0.11	Belle(2021)[125]			
	1.11 ± 0.21	BESIII(2023)[120]			
	0.98 ± 0.31	LHCb(2024)[121]			
$\Lambda_c^+ \to p\phi$	1.06 ± 0.22	BESIII(2016)[127]			
Λ-involved					
$\Lambda_c^+ \to \Lambda K^+$	0.62 ± 0.06	BESIII(2022)[131]	$\Lambda_c^+ \to \Lambda K^+\pi^0$	<2.0	BESIII(2024)[107]
	0.66 ± 0.04	Belle(2023)[132]		1.49 ± 0.29	BESIII(2024)[135]
$\Lambda_c^+ \to \Lambda K^{*+}$	$2.40\pm0.59(\theta_0=0°)$	BESIII(2025)[134]	$\Lambda_c^+ \to \Lambda K_S^0\pi^+$	1.73 ± 0.29	BESIII(2025)[134]
	$5.21\pm0.75(\theta_0=109°)$	BESIII(2025)[134]	$\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-$	0.41 ± 0.15	BESIII(2024)[135]
	$1.29\pm0.44(\theta_0=221°)$	BESIII(2025)[134]			
Σ-involved					
$\Lambda_c^+ \to \Sigma^0K^+$	0.47 ± 0.10	BESIII(2022)[133]	$\Lambda_c^+ \to \Sigma^+K^+\pi^-$	2.00 ± 0.28	BESIII(2023)[150]
	0.36 ± 0.03	Belle(2023)[132]	$\Lambda_c^+ \to \Sigma^+K^+\pi^-\pi^0$	<0.01	BESIII(2023)[150]
$\Lambda_c^+ \to \Sigma^+K_S^0$	0.48 ± 0.14	BESIII(2022)[133]	$\Lambda_c^+ \to \Sigma^0K^+\pi^0$	<1.8	BESIII(2024)[107]
				<0.50	BESIII(2024)[151]
			$\Lambda_c^+ \to \Sigma^0K^+\pi^+\pi^-$	<0.65	BESIII(2024)[151]
			$\Lambda_c^+ \to \Sigma^-K^+\pi^+$	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			$\Lambda_c^+ \to \Lambda(1600)\pi^+$	0.2 ± 0.5	LHCb(2023)[86]
$\Lambda_c^+ \to pK_S^0$	0.18 ± 0.45	BESIII(2019)[153]	$\Lambda_c^+ \to \Lambda(1670)\pi^+$	0.82 ± 0.08	LHCb(2023)[86]
	-0.75 ± 0.10	LHCb(2024)[154]		0.21 ± 0.43	BESIII(2025)[148]
$\Lambda_c^+ \to p\bar{K}_0^*(700)^0$	-0.1 ± 0.7	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda(1690)\pi^+$	0.958 ± 0.034	LHCb(2023)[86]
$\Lambda_c^+ \to p\bar{K}_0^*(1430)^0$	0.34 ± 0.14	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda(2000)\pi^+$	-0.57 ± 0.19	LHCb(2023)[86]
$\Lambda_c^+ \to \Delta(1232)^{++}K^-$	0.55 ± 0.04	LHCb(2023)[86]	**Σ-involved**		
$\Lambda_c^+ \to \Delta(1600)^{++}K^-$	-0.50 ± 0.18	LHCb(2023)[86]	$\Lambda_c^+ \to \Sigma^+\pi^0$	-0.57 ± 0.12	BESIII(2019)[153]
$\Lambda_c^+ \to \Delta(1700)^{++}K^-$	0.22 ± 0.08	LHCb(2023)[86]		-0.48 ± 0.03	Belle(2023)[98]
Λ-involved			$\Lambda_c^+ \to \Sigma^+\eta$	-0.99 ± 0.06	Belle(2023)[98]
$\Lambda_c^+ \to \Lambda\pi^+$	-0.80 ± 0.11	BESIII(2019)[153]	$\Lambda_c^+ \to \Sigma^+\eta'$	-0.46 ± 0.07	Belle(2023)[98]
	-0.755 ± 0.006	Belle(2023)[132]	$\Lambda_c^+ \to \Sigma^0\pi^+$	-0.73 ± 0.18	BESIII(2019)[153]
	-0.785 ± 0.007	LHCb(2024)[154]		-0.46 ± 0.02	Belle(2023)[132]
$\Lambda_c^+ \to \Lambda K^+$	-0.59 ± 0.05	Belle(2023)[132]i	$\Lambda_c^+ \to \Sigma(1385)^+\pi^0$	-0.917 ± 0.089	BESIII(2022)[93]
	-0.52 ± 0.05	LHCb(2024)[154]	$\Lambda_c^+ \to \Sigma(1385)^+\eta$	-0.61 ± 0.16	BESIII(2025)[148]
$\Lambda_c^+ \to \Lambda\rho(770)^+$	-0.763 ± 0.070	BESIII(2022)[93]	$\Lambda_c^+ \to \Sigma(1385)^0\pi^+$	-0.789 ± 0.113	BESIII(2022)[93]
$\Lambda_c^+ \to \Lambda a(980)^+$	$-0.91^{+0,20}_{-0.12}$	BESIII(2025)[148]	$\Lambda_c^+ \to \Sigma^0 K^+$	-0.54 ± 0.20	Belle(2023)[132]
$\Lambda_c^+ \to \Lambda(1405)\pi^+$	0.58 ± 0.28	LHCb(2023)[86]	**Ξ-involved**		
$\Lambda_c^+ \to \Lambda(1520)\pi^+$	0.93 ± 0.09	LHCb(2023)[86]	$\Lambda_c^+ \to \Xi^0 K^+$	0.01 ± 0.16	BESIII(2024)[158]

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

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

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

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

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

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

$$e^+e^- \to \psi(3770) \to D\bar{D}$$
$$e^+e^- \to D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$$
$$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$$

BESIII, STCF in the future

B factory

- **Low background**
- **Low statistics**
- **Low boost**
- **Good for neutrals and neutrinos**
- **Some Absolute BFs**

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

+ some other Stuff

Belle / Belle II

Hadron collider

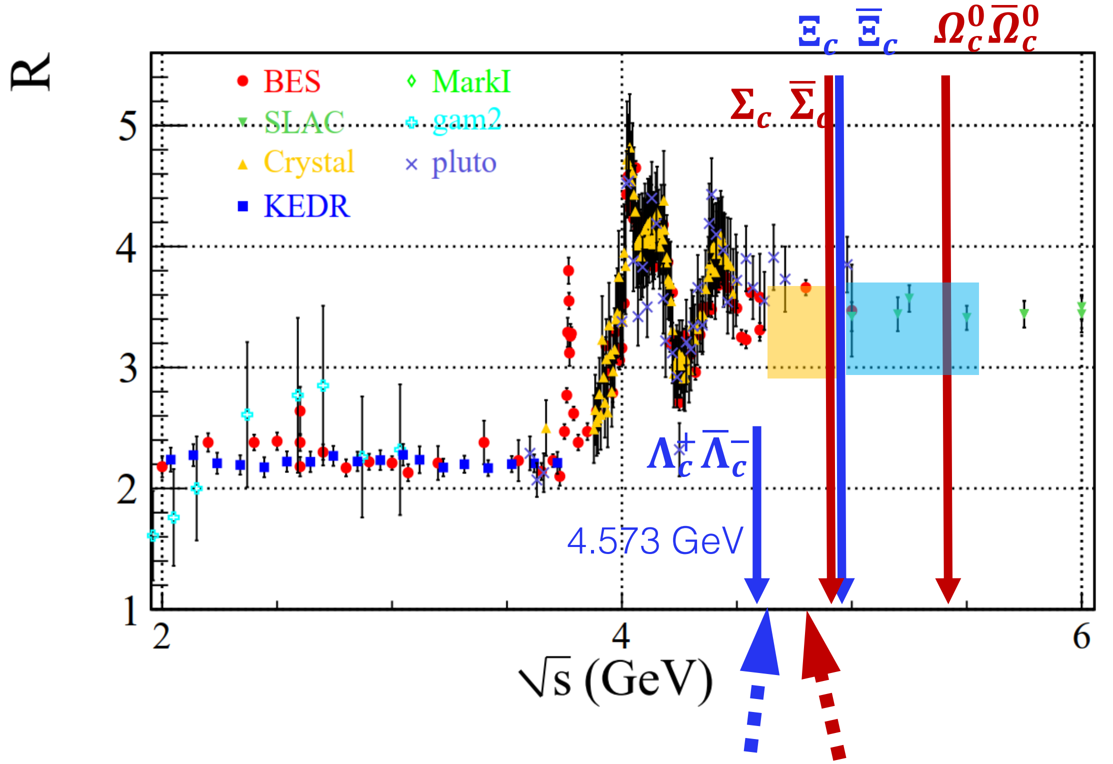
- **High background**
- **High statistics**
- **High boost**
- **Challenging for neutrals and neutrinos**
- **Complex and biasing triggers**

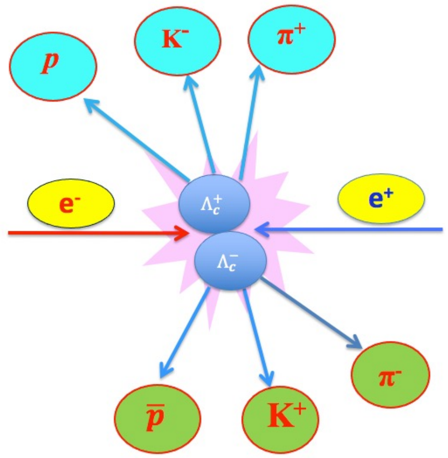
$$p\bar{p} \to c\bar{c}$$

+ 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)

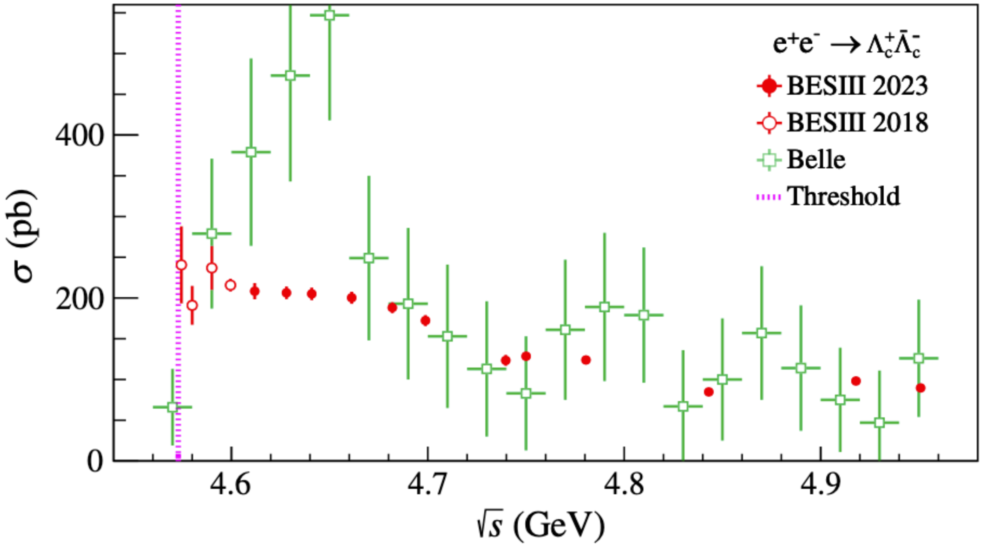
Production measurement near threshold

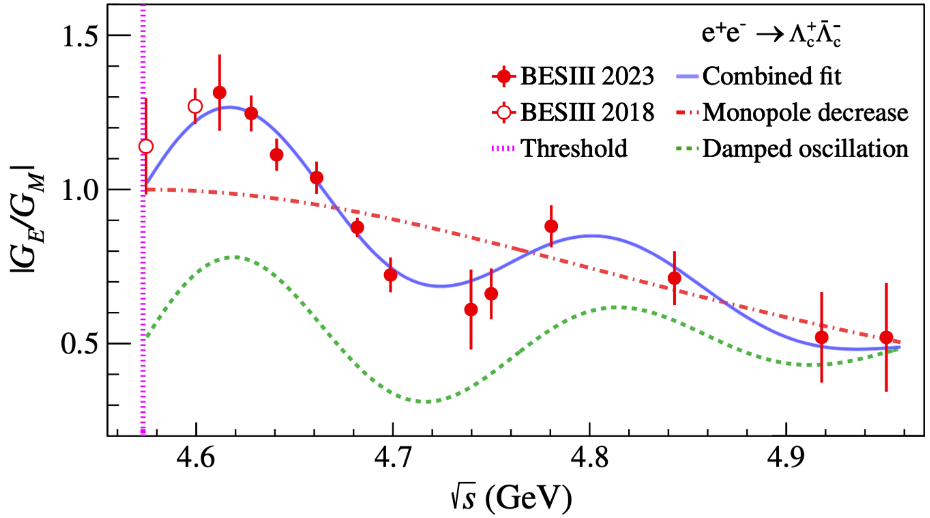
PRL 131.191901(2023)

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

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

- 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.





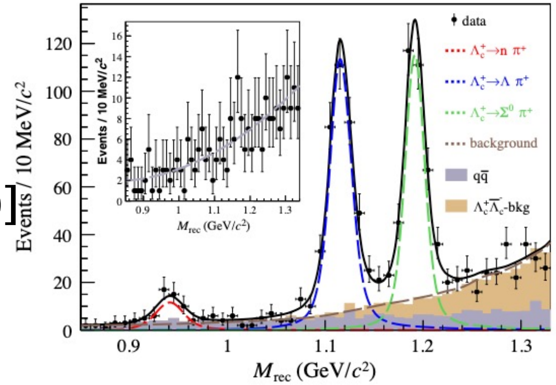
$\Lambda_c^+ \to n\pi^+$ and $\Lambda_c^+ \to p\pi^0$

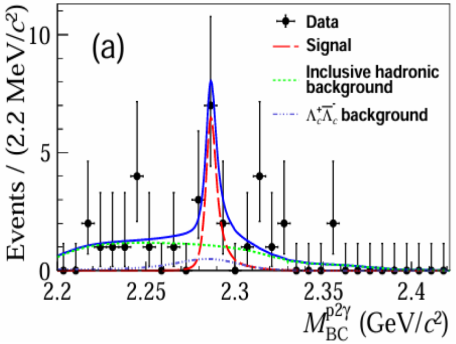
PRL 128.142001 (2022)

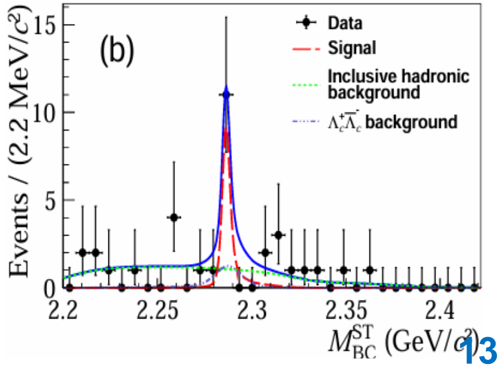
PRD 109, L091101 (2024)

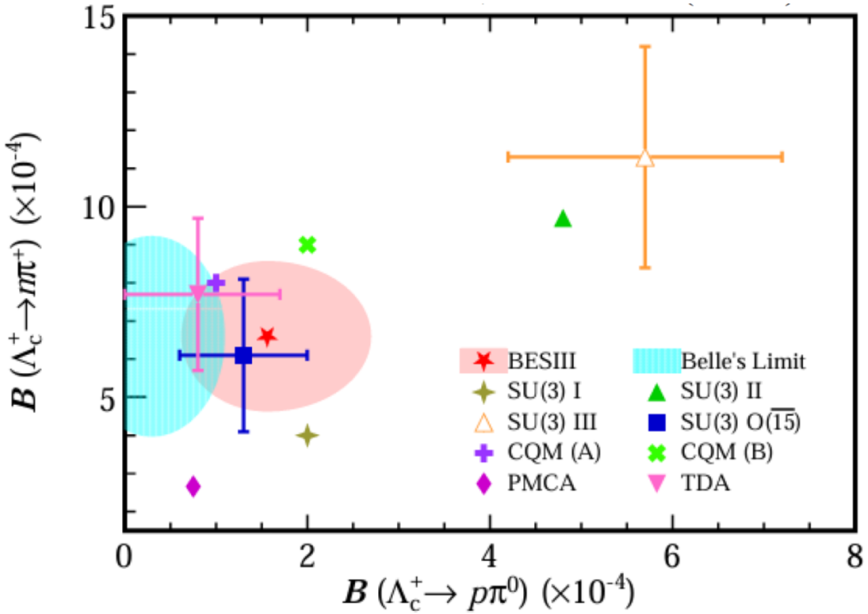
N($n\pi^+$)=50±9

- First singly Cabibbo-suppressed Λ_c^+ decay involved neutron was observed(7.3σ).
- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{stat} \pm 0.4_{syst}) \times 10^{-4}$.
  =>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)]
- $R = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} > 7.2 @ 90\% C.L.$ ($\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ @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).
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.2_{syst}) \times 10^{-4}$; $R = 3.2^{+2.2}_{-1.2}$



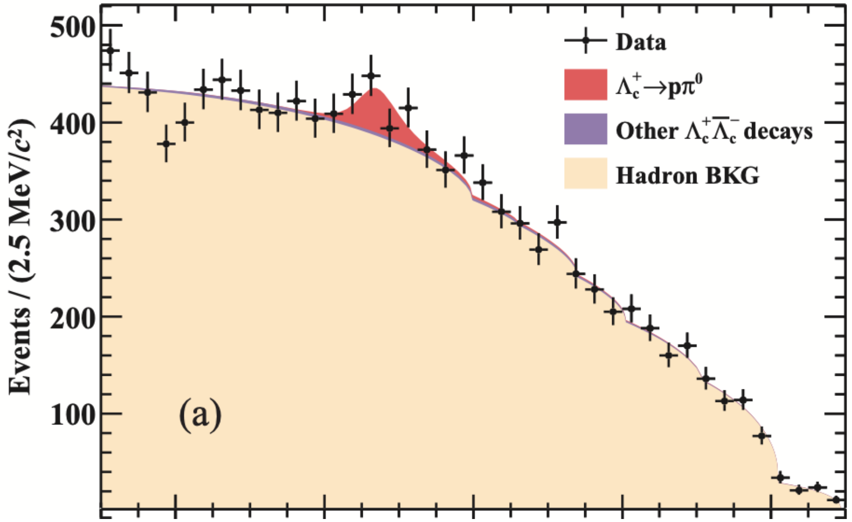




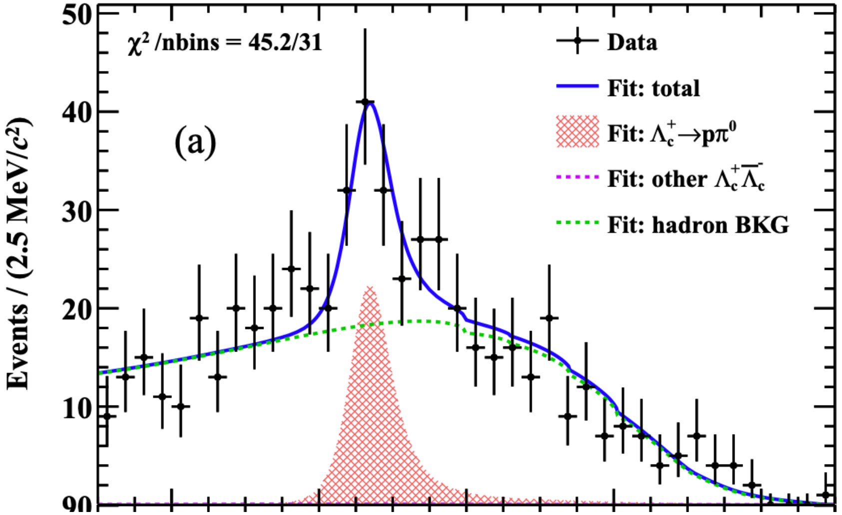


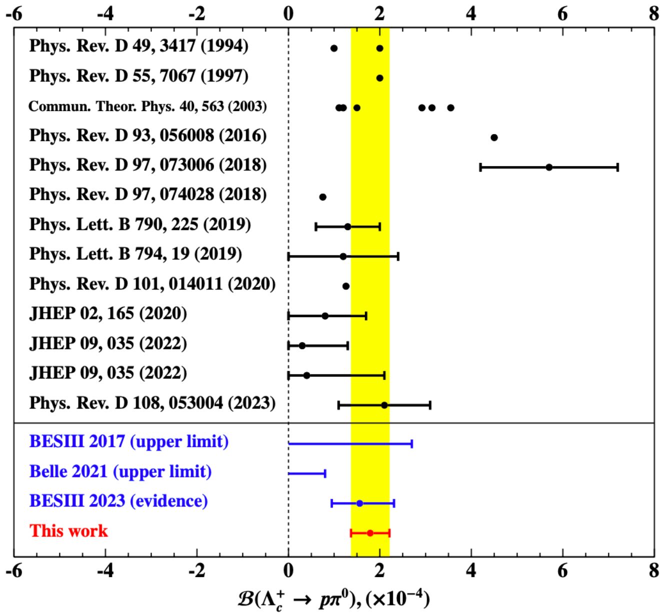
First observation of $\Lambda_c^+ \to p\pi^0$

Before DNN



After DNN

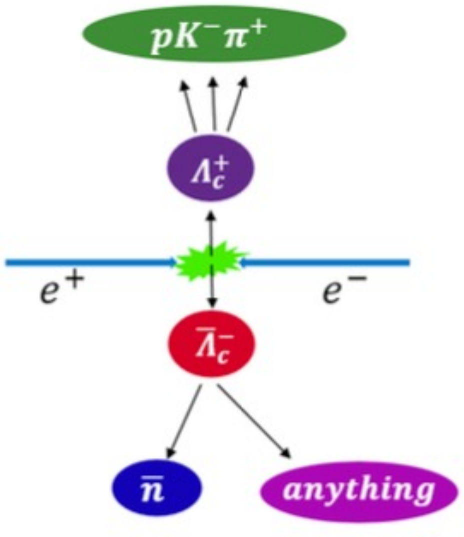


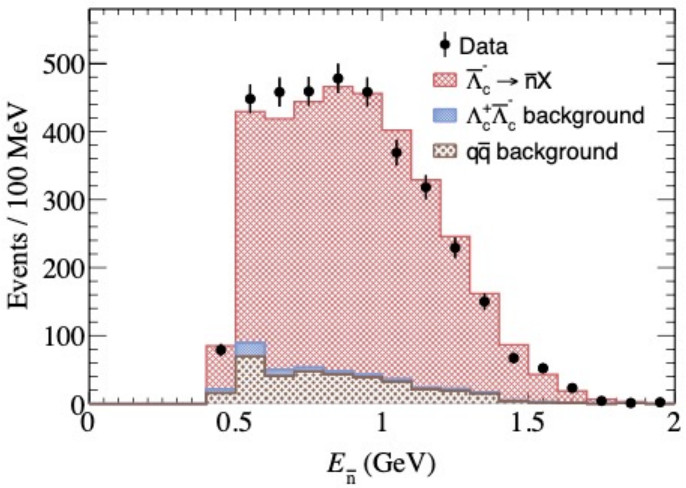


- First observation of $\Lambda_c^+ \to p\pi^0$ with significance of 5.4σ.
- A sophisticated deep learning approach is employed.
- The absolute branching fraction is measured to be $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.79 \pm 0.39_{stat} \pm 0.11_{syst} \pm 0.08_{p\eta})\%$.
- Offering essential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

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

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
  $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n}X) = (33.5 \pm 0.7_{stat} \pm 1.2_{syst})\%$, precision up to 4%.
- All known exclusive process with neutron in final state is about 25%=>more space to be explored.
- Asymmetry between $\mathcal{B}(\Lambda_c^+ \to nX)$ and $\mathcal{B}(\Lambda_c^+ \to pX)$ is observed.

Experiment & Phenomenon

Predictions and measurements	$\alpha^{pK_S^0}_{\Lambda_c^+}$	$\alpha^{\Lambda\pi^+}_{\Lambda_c^+}$	$\alpha^{\Sigma^0\pi^+}_{\Lambda_c^+}$	$\alpha^{\Sigma^+\pi^0}_{\Lambda_c^+}$	$\alpha^{\Xi^0 K^+}_{\Lambda_c^+}$
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	-
Źencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Źencaykowski(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 $\Lambda_c^+ \to pK_s^0$, $\Lambda\pi^+$, $\Sigma^+\pi^0$, and $\Sigma^0\pi^+$

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

Renaissance on the charmed baryon decay asymmetry from 2018!

Experiment & Phenomenon

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0K^+}$
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	0.02

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

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

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Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A \rvert$ $(\times 10^{-2} G_F$ GeV$^2)$	$\lvert B \rvert$ $(\times 10^{-2} G_F$ GeV$^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	-	-	-
Xu (1992), Pole [8]	1.0	0	0	7.94	-
Źencaykowski (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	-	-	-	-

- $\Lambda_c^+ \to \Xi^0 K^+$ 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.

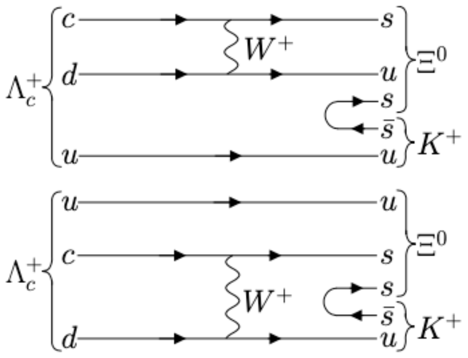

FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

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

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

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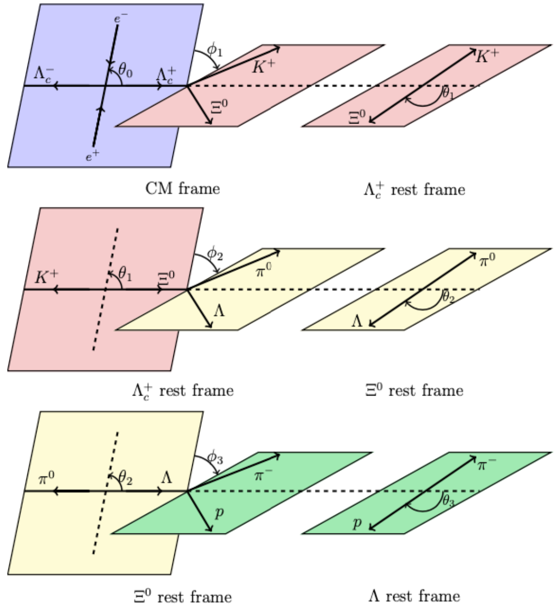
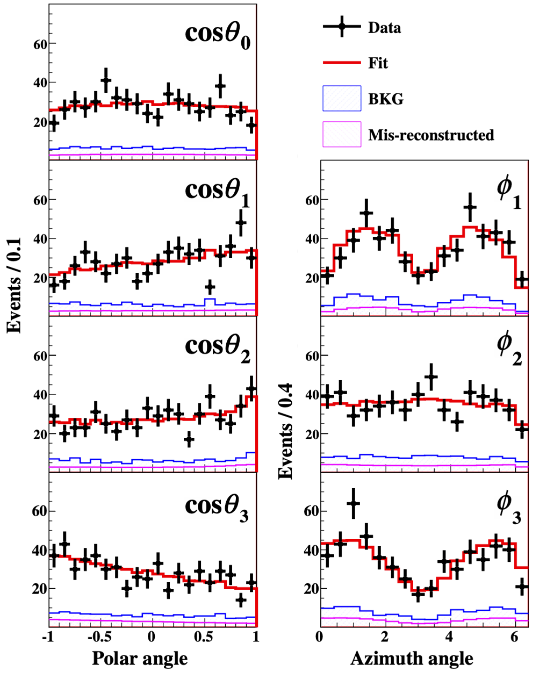
Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	D_{λ_5}

$$\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^2_{\Lambda\pi^0}}\ \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^2_{\Lambda\pi^0}}\ \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^2_{\Xi^0 K^+}}\ \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^2_{\Xi^0 K^+}}\ \alpha_{\Lambda\pi^0}\cos\theta_1\sin\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^2_{\Xi^0 K^+}}\ \alpha_{p\pi^-}\cos\theta_1\sin\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^2_{\Xi^0 K^+}}\ \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^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_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^2_{\Xi^0 K^+}}\ \sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_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^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\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^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \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 $\Lambda_c^+ \to \Xi^0 K^+$ is derived based on helicity amplitude.

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



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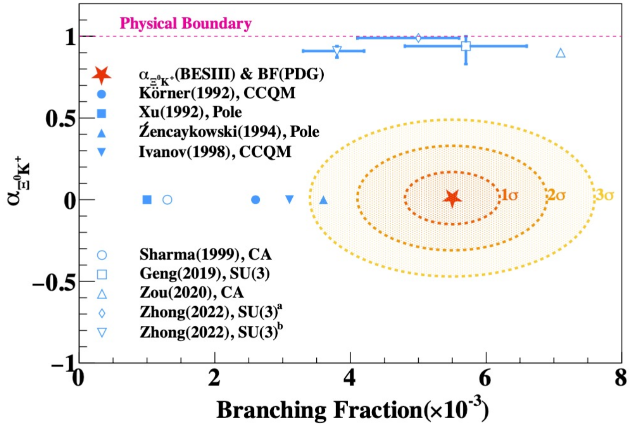
- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero=>strong identification for theoretical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

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

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

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



- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero.=>not considered in previous literature.
- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ 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	-
Źencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Źencaykowski(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	0.02
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	-

New results?

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0K^+}$
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	-
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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]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
$\sim 587pb^{-1}$ 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]	$-0.89^{+[illegible]}_{-0.11}$	-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	$0.91^{+0.03}_{-0.04}$
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Liu(2023), LP [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	-0.02
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	-

$\sim 6.4fb^{-1}$ BESIII(2024?) ★

$stat.\ un. \downarrow$

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

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 ➡ strong phase ~ 0

Only a few measurements

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

$\alpha = +0.65 \pm 0.02$

$\beta = -0.10 \pm 0.07$

$\gamma = +0.75 \pm 0.02$

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

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

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

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

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

Parameter	This work
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ 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 $\Xi_c^0 \to \Sigma^+ K^-$ should have phase shift similar to $\Lambda_c^+ \to \Xi^0 K^+$.

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

Further confirmation is needed!

arXiv:2310.05491
arXiv:2404.01350

Methods for measurement

- The definition of polarization parameters:

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

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**

↓

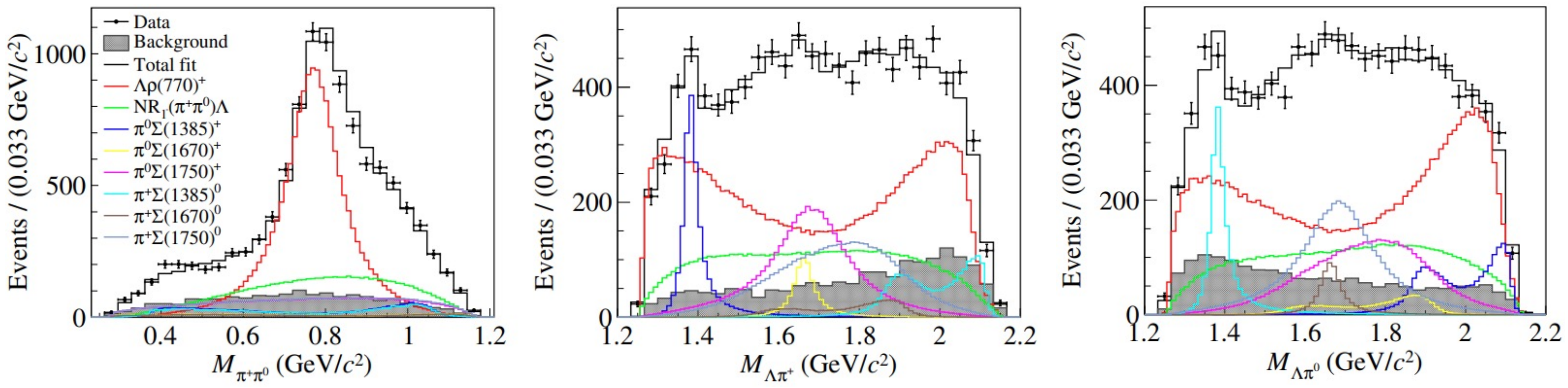
s and p of all intermediate resonance states →

- ✓ Polarization parameters
- ✓ Branching fraction

Methods for measurement

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

JHEP12(2022)033



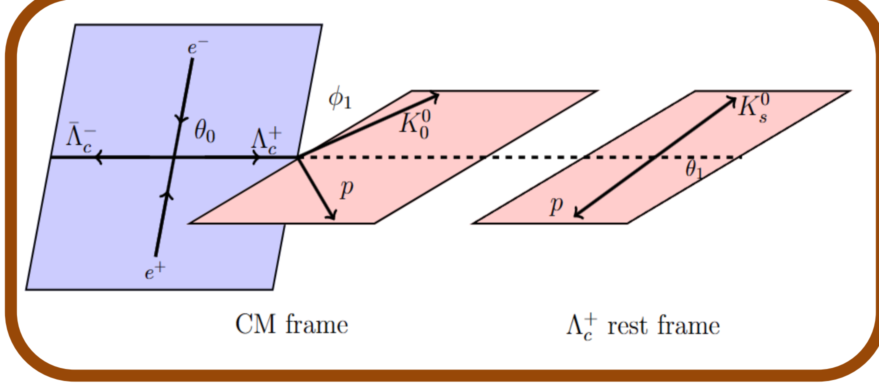
	Result
$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+\to\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.18 \pm 0.60 \pm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

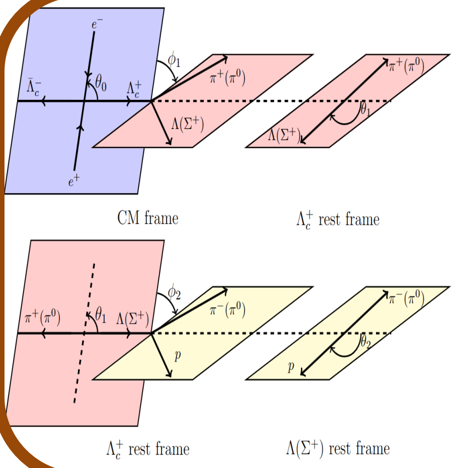
More multi-body decays are underway!

- ✓ $\Lambda_c^+ \to pK^-\pi^+$
- ✓ $\Lambda_c^+ \to \Lambda^0\pi^+\eta$
- ✓ $\Lambda_c^+ \to pK^-\pi^+\pi^0$
- ✓ $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$
- ✓ $\Lambda_c^+ \to pK_s^0\pi^0$
- ✓ $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$
- ✓ $\Lambda_c^+ \to nK_s^0\pi^+$
- ✓ …

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

Λ_c^+ polarization on BESIII





$$\frac{d\Gamma}{d\cos\theta_0\, d\cos\theta_1\, d\cos\theta_2\, d\phi_1\, d\phi_2}$$
$$\propto 1 + \alpha_0\cos^2\theta_0$$
$$+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\theta_0\cos\theta_0\sin\Delta_0\sin\theta_1\sin\phi_1\cos\theta_2$$
$$+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\theta_0\cos\theta_0\sin\Delta_0\cos\theta_1\sin\phi_1\sin\theta_2 \sqrt{1-\alpha_{\Lambda_c^+}^2}\cos(\Delta_{\Lambda_c^+}+\phi_2)$$
$$+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\theta_0\cos\theta_0\sin\Delta_0\cos\phi_1\sin\theta_2 \sqrt{1-\alpha_{\Lambda_c^+}^2}\sin(\Delta_{\Lambda_c^+}+\phi_2)$$
$$+ \sqrt{1-\alpha_0^2}\alpha_{\Lambda_c^+} \sin\theta_0\cos\theta_0\sin\Delta_0\sin\theta_1\sin\phi_1$$
$$+ \alpha_0\alpha_\Lambda\alpha_{\Lambda_c^+}\cos^2\theta_0\cos\theta_2$$
$$+ \alpha_\Lambda\alpha_{\Lambda_c^+}\cos\theta_2,$$

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

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

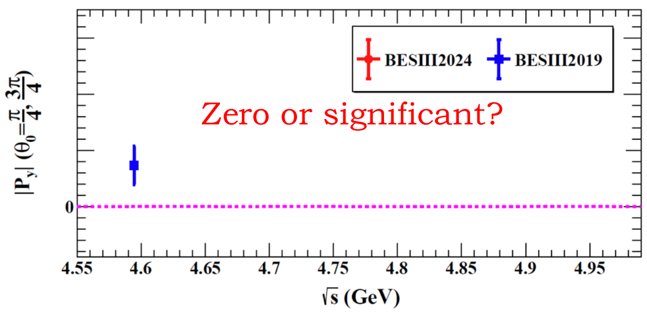
New Λ_c^+ polarization on BESIII

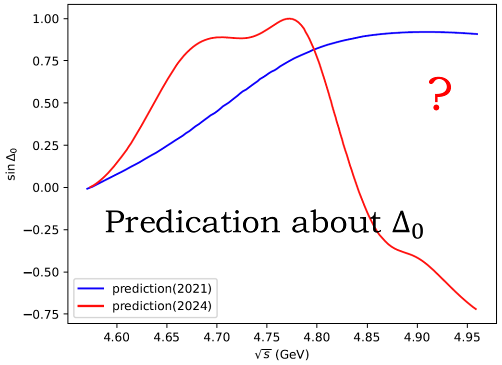
— Transverse polarization with energy from 4.60-4.95 GeV combined with $\Lambda_c^+ \to pK^-\pi^+$ channel(fixed all decay info. with LHCb input).

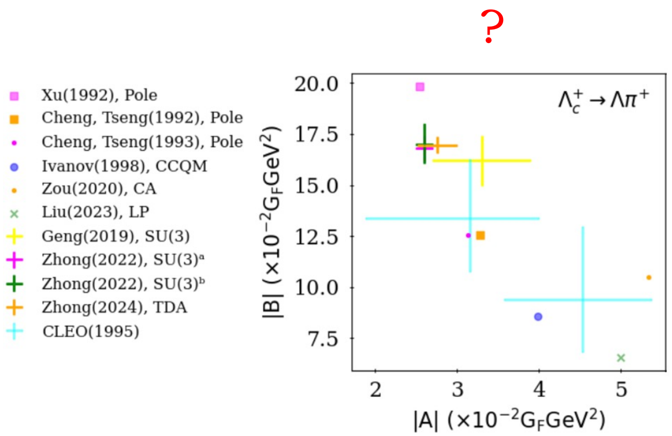
— Update 4 two-body decays polarization parameters with higher precision

— Strong/Weak phase shift

— α-induced CPV observables







Eur. Phys. J. Plus 136, no.9, 949 (2021)
Chinese Physics Letters 41, 021302 (2024)

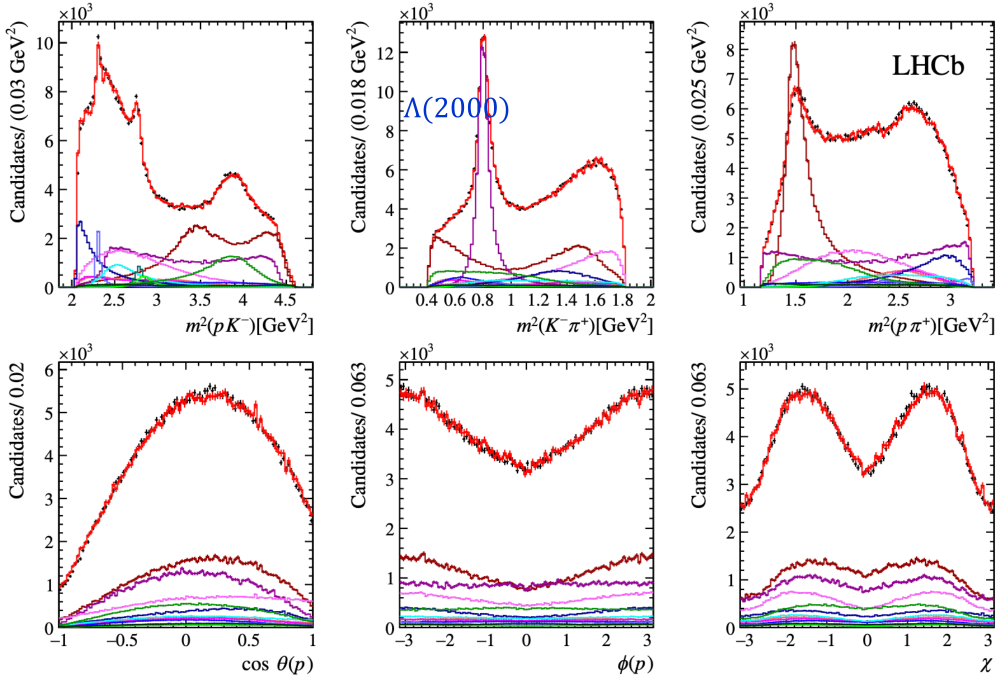
coming soon!

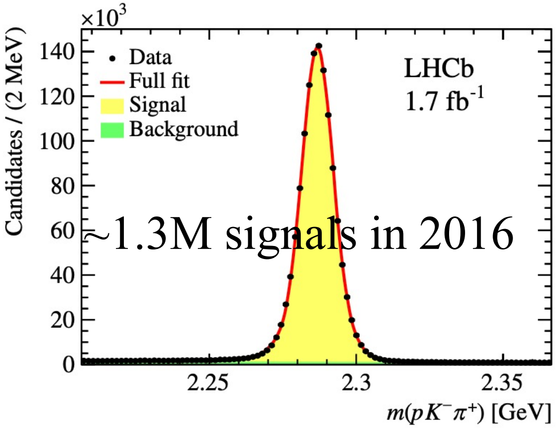
$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

Phys. Rev. D 108, 012023 (2023)

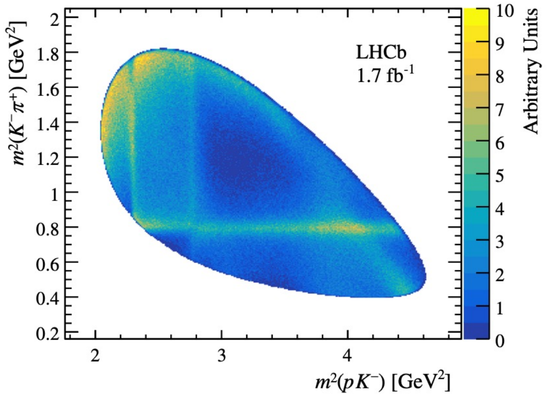
Λ_c^+ signals are selected via $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$ from dataset taken in 2016, where only a subset of 0.4 M signals are employed

5-dim fit





~1.3M signals in 2016



Resonance	Fit fraction (%)
$\Lambda(1405)$	7.7
$\Lambda(1520)$	1.86
$\Lambda(1600)$	5.2
$\Lambda(1670)$	1.18
$\Lambda(1690)$	1.19
$\Lambda(2000)$	9.58
$\Delta(1232)^{++}$	28.60
$\Delta(1600)^{++}$	4.5
$\Delta(1700)^{++}$	3.90
$K_0^*(700)$	3.02
$K^*(892)$	22.14
$K_0^*(1430)$	14.7

Resonance	α
Model $\sqrt{3}S$	0.662
$K^*(892)$ $\sqrt{3}S$	0.873
$\Lambda(1405)$	−0.58
$\Lambda(1520)$	−0.925
$\Lambda(1600)$	−0.20
$\Lambda(1670)$	−0.817
$\Lambda(1690)$	−0.958
$\Lambda(2000)$	−0.57
$\Delta(1232)^{++}$	−0.548
$\Delta(1600)^{++}$	−0.50
$\Delta(1700)^{++}$	−0.216
$K_0^*(700)$	−0.06
$K_0^*(1430)$	−0.34

Λ_c^+ polarization and $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

Phys. Rev. D 108, 012023 (2023)

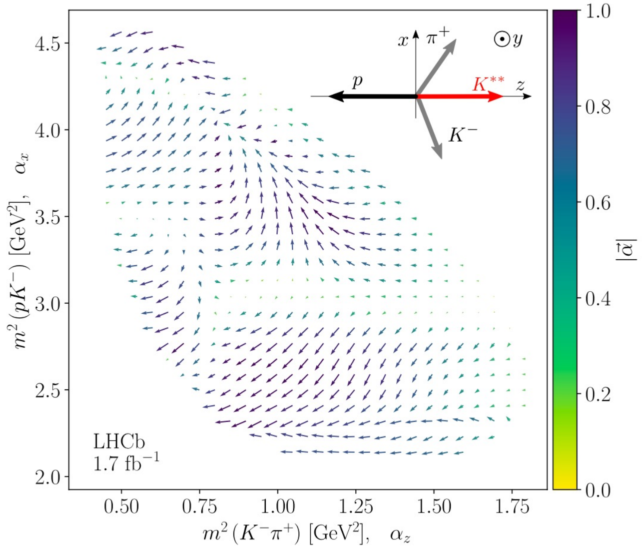
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x ($\tilde{B}$)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y ($\tilde{B}$)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z ($\tilde{B}$)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

A large Λ_c^+ polarization is found in b semi-leptonic decays $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$

- The obtained representation can facilitate polarization measurements of the Λ_c^+ baryon and eases inclusion of the $\Lambda_c^+ \to pK^-\pi^+$ decay mode in hadronic amplitude analyses.
- At BESIII, the transverse polarization of Λ_c^+ can be obtained via $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

JHEP 07, 228 (2023)

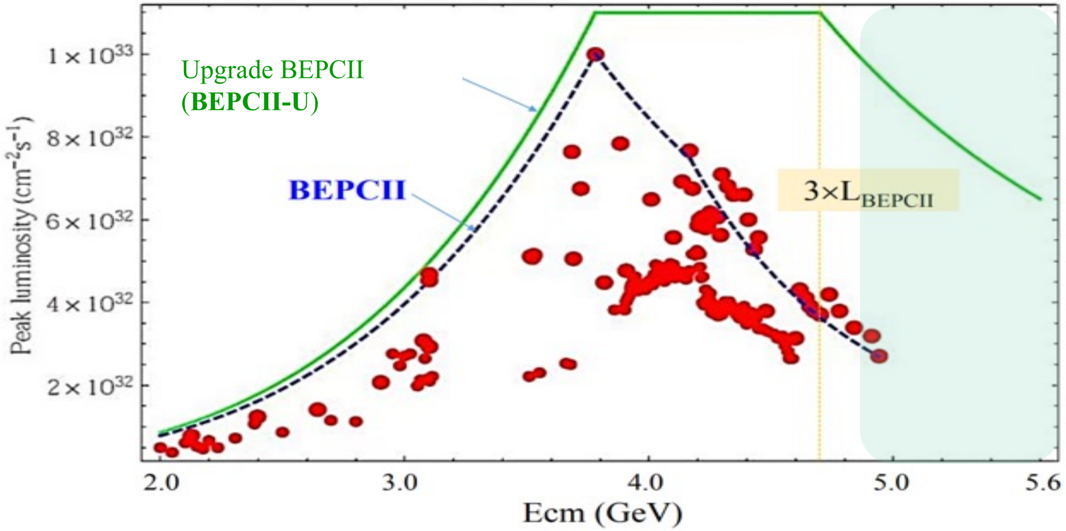
The amplitude model is used to produce the distribution of the kinematic-dependent polarimeter vector in the space of Mandelstam variables to express the polarized decay rate in a model-independent way.



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**

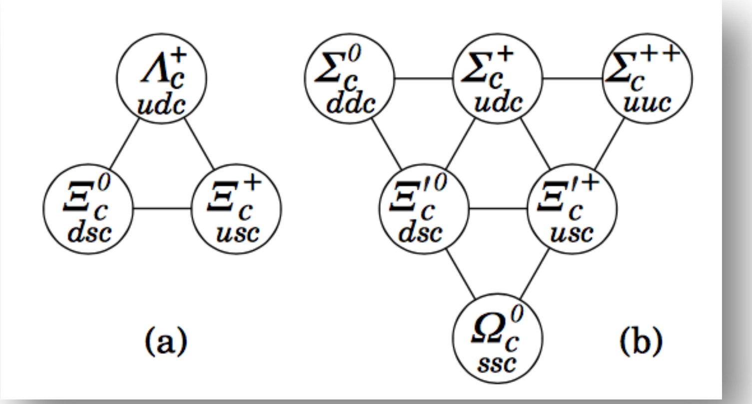


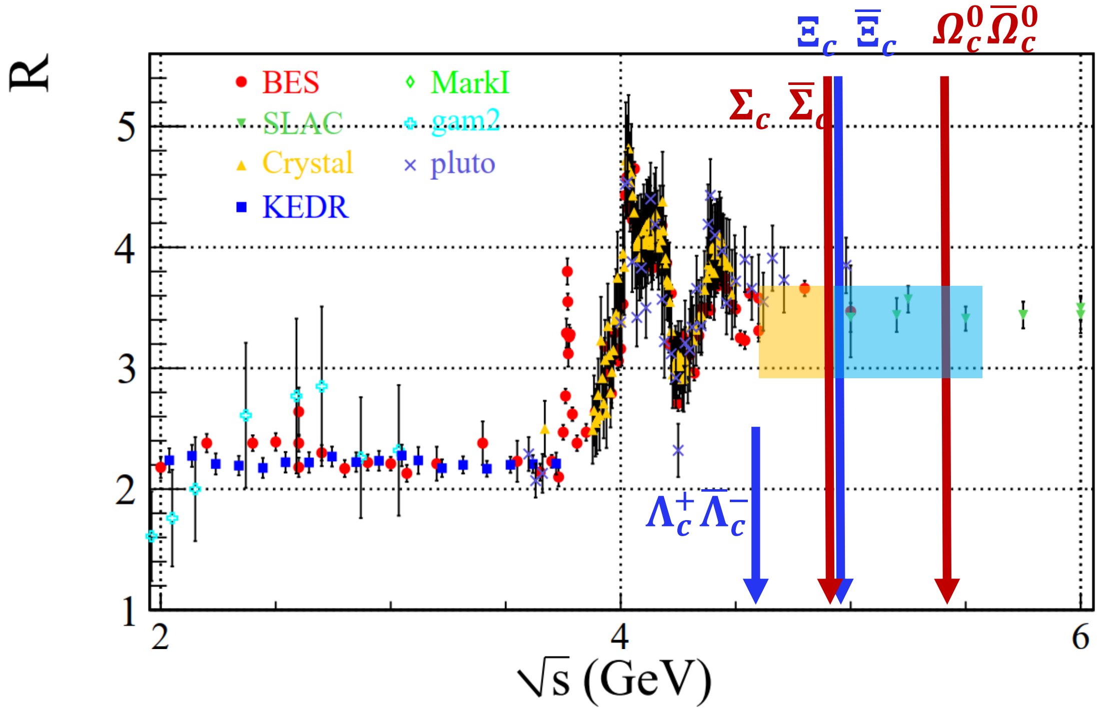
Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

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	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ 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





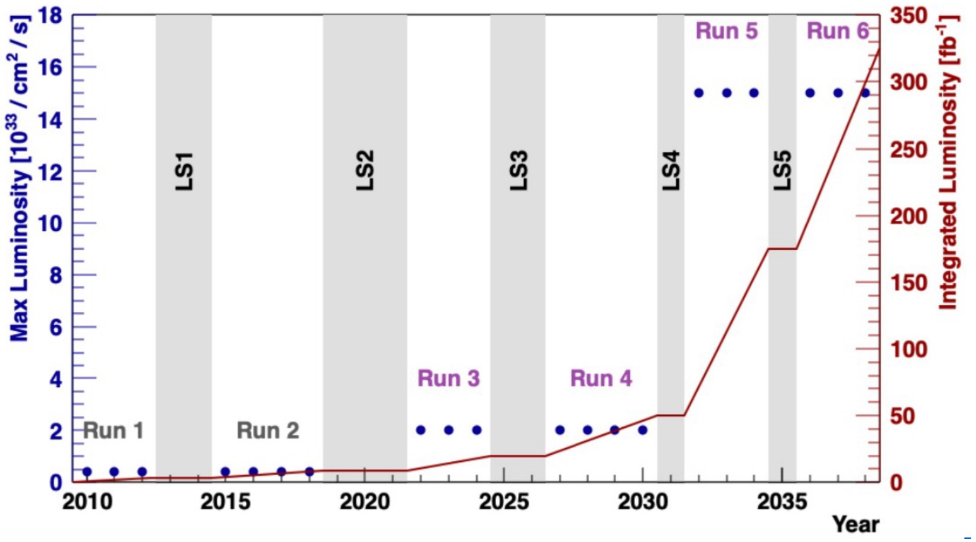
- **Energy thresholds**
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ **4.74 GeV**
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ **4.88 GeV**
  - ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ **4.91 GeV**
  - ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ **4.94 GeV**
  - ✓ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$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

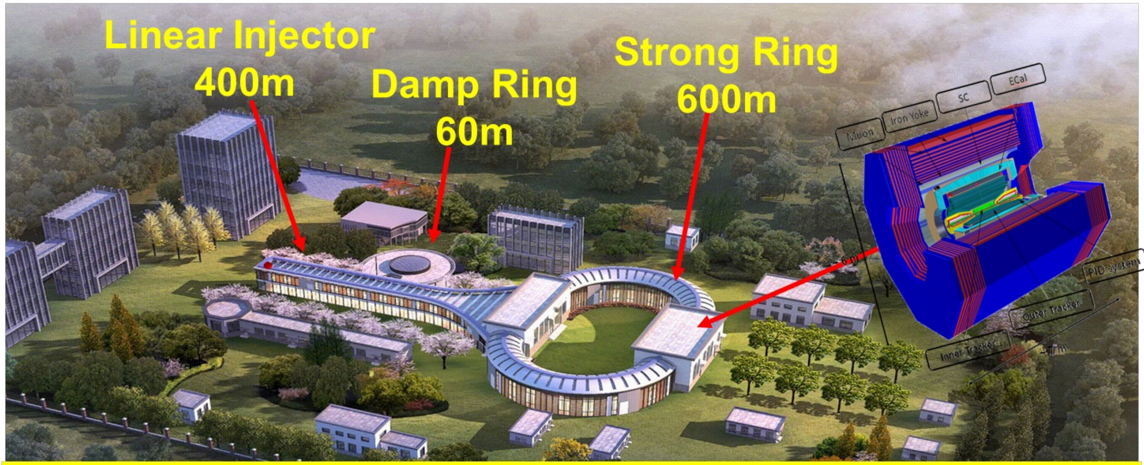
- RUN1&2: 9 fb^{-1}
- RUN3&4: 50 fb^{-1}

➔ x10 more statistics



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

Super Tau-Charm Facility (STCF)



- E_{cm}=2-7GeV， L=0.5×10^{35} cm^{-2} s^{-1}
- Potential for upgrade to increase L and realize polarized beam
- Site area: 1 km^2

	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 provice 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.**