Charmed Baryon Decays at BESIII

Shenghui Zeng
On behalf of BESIII collaboration

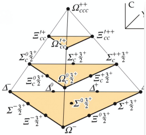
Beautiful and Charming Baryon Workshop, IPPP, UK
September 10, 2024

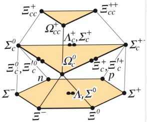
Outline

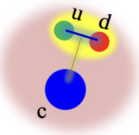
Motivation

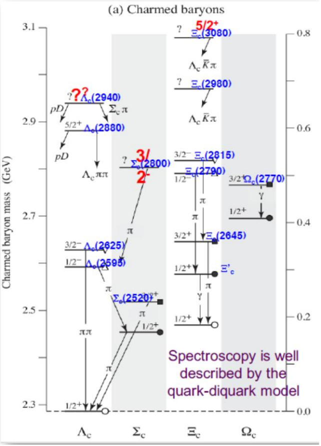
Charm baryon spectrum

- Single Charmed Baryons
  - The established $\Lambda_c^+, \Sigma_c, \Xi_c, \Omega_c$
  - More excited states being explored
- Doubly Charmed Baryon Ξ_{cc}^{++} observed
- Triply charmed baryons?
- Λ_c^+: the bound states
  - Important for bottom baryon study
- A heavy quark (c) and an unexcited spin-zero diquark($u-d$)
  - HQET: diquark correlation is enhanced by weak color magnetic interaction with heavy quark
  - Invoving both strong and weak interactions full fill the information for Charm region

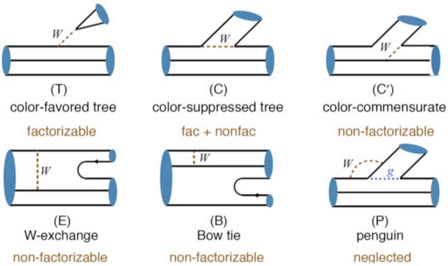




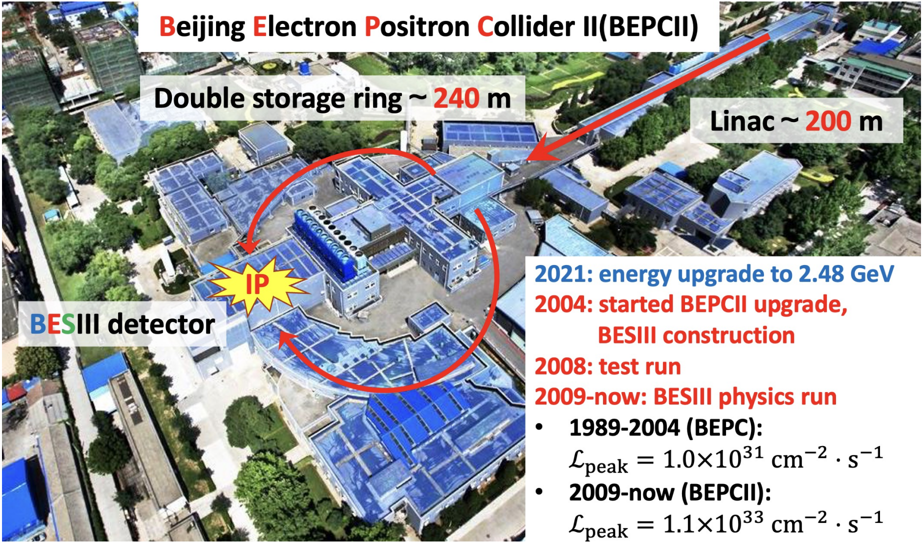




- Trick in theory
  - Λ_c^+ right in the perturbative energy region
  - Both factorizable and nonfactorizable diagram involved in the Λ_c^+ decay
- Many phenomenological models are developed to explain the data and predict observables
    - HQET, factorization
    - Constituent Quark Model, pole model+current algebra
    - SU(3) quark flavour symmetry, topological diagram (paramarized, fit to data)
    - LQCD (First principle)
    - Chiral perturbation theory



BEPCII and BESIII



2021: energy upgrade to 2.48 GeV

2004: started BEPCII upgrade, BESIII construction

2008: test run

2009-now: BESIII physics run

- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

Superconducting solenoid

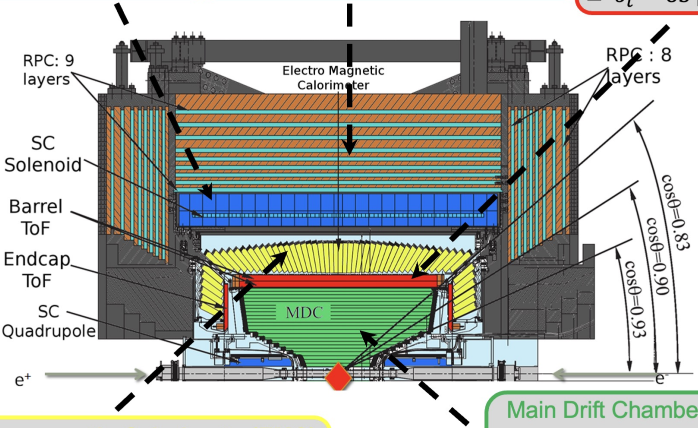
- 1.0 T

Muon Counter (MUC)

- 9 layers (barrel) + 8 layers (end-cap)

Time Of Flight (TOF)

- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



Electromagnetic Calorimeter(EMC)

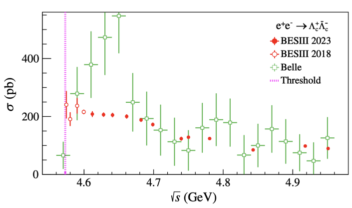
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

Main Drift Chamber (MDC)

- $\sigma_{xy} = 130\ \mu\text{m}$
- $\Delta P/P = 0.5\%$ @ 1.0 GeV
- $\sigma_{dE/dx} = 6 - 7\%$

Data Samples

Phys. Rev. Lett. 131, 191901 (2023)



Sample	E_{cms}/MeV	$\mathscr{L}_{Bhabha}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84
4740	4739.70±0.20±0.30	163.87±0.07±0.87
4750	4750.05±0.12±0.29	366.55±0.10±1.94
4780	4780.54±0.12±0.30	511.47±0.12±2.71
4840	4843.07±0.20±0.31	525.16±0.12±2.78
4920	4918.02±0.34±0.34	207.82±0.08±1.10
4950	4950.93±0.36±0.38	159.28±0.07±0.84

Chin. Phys. C 46, 113003 (2022)

- In 2014, BESIII took 35 days data at 4.6 GeV with luminosity 0.587 fb^{-1} $\sim 0.1M\Lambda_c^+\bar{\Lambda}_c^-$
- During 2020-2021, BESIII took new data samples at charm baryon pair threshold
- Two major changes in BEPCII machine:
  - Max beam energy: 2.30 $\to$ 2.35 (2020) $\to$ 2.48 GeV (2021)
  - Top-up injection: data taking efficiency increased by 20-30%
- New data samples taken during 2021-2022
  - 3.9 fb^{-1} scan at 4.61, 4.63, 4.64, 4.66, 4.68, 4.7 GeV (186 days in 2020) $\sim 0.66M\Lambda_c^+\bar{\Lambda}_c^-$
  - 1.93 fb^{-1} scan at 4.74, 4.75, 4.78, 4.84, 4.92, 4.95 GeV (99 days in 2022) $\sim 0.21M\Lambda_c^+\bar{\Lambda}_c^-$
    - Accessible to $\Sigma_c/\Xi_c/\Lambda_c^*$ production and decays

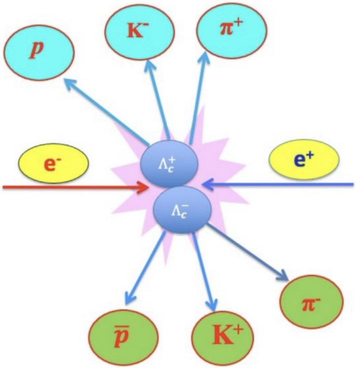
Pair production and tag method

- $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$: production without accompanying hadrons near threshold
- Clean backgrounds and well constrained kinematics

$$\Delta E = E_{\Lambda_c} - E_{\text{beam}}$$

$$M_{BC} = \sqrt{E_{\text{beam}}^2/c^4 - p^2/c^2}$$

- **Single Tag (ST) method:** detect one of the $\Lambda_c^+\bar{\Lambda}_c^-$
  - Higher efficiencies, relative higher background
  - Full reconstruction
- **Double Tag (DT) method:** detect both $\Lambda_c^+\bar{\Lambda}_c^-$
  - Lower efficiencies, relative lower background
  - Partial reconstruction:
    - undetectable particles in the final state: ν, n, K_L
  - Systematic uncertainties are mostly canceled



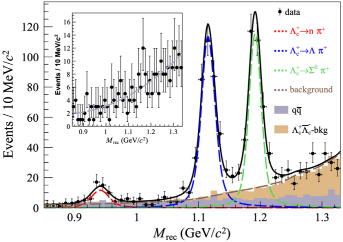
Recent physics results

Recent studies on Λ_c^+ hadronic measurements at BESIII

- Λ_c^+ hadronic decays (two-body)
  - $\Lambda_c^+ \to n\pi^+$ — Phys. Rev. Lett. 128, 142001 (2022).
  - $\Lambda_c^+ \to p\eta'$ — Phys. Rev. D 106, 072002 (2023).
  - $\Lambda_c^+ \to p\eta, p\omega$ — JHEP 11, 137 (2023).
  - $\Lambda_c^+ \to p\pi^0, p\eta$ — Phys. Rev. D 109, L091101 (2024).
  - $\Lambda_c^+ \to \Lambda K^+$ — Phys. Rev. D 106, L111101 (2022).
  - $\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K^0$ — Phys. Rev. D 106, 052003 (2022).
  - $\Lambda_c^+ \to \Xi^0 K^+$ — Phys. Rev. Lett. 132, 031801 (2024).
- Λ_c^+ hadronic decays (multi-body)
  - $\Lambda_c^+ \to \Sigma^+ K^+ K^-, \Sigma^+\phi, \Sigma^+ K^+ \pi^- (\pi^0)$ — JHEP 09, 125 (2023).
  - $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+, nK^-\pi^+\pi^-$ — Chin. Phys. C 47, 023001 (2023).
  - $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0 K^+$ — Phys. Rev. D 109, 072010 (2024).
  - $\Lambda_c^+ \to \bar{n}X$ — Phys. Rev. D 108, L031101 (2023).
  - $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ — JHEP 12, 013 (2022).
  - $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$ — Phys. Rev. D 109, 032003 (2024).
  - $\Lambda_c^+ \to \Sigma^- K^+\pi^+$ — Phys. Rev. D 109, L071103 (2024)
  - $\Lambda_c^+ \to \Xi^- K^+\pi^0, nK^+\pi^0, \Sigma^0 K^+\pi^0, \Lambda K^+\pi^0$ — Phys. Rev. D 109, 052001 (2024).
  - $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$ — Phys. Rev. D 109, 053005 (2024).
  - $\Lambda_c^+ \to \Lambda\pi^+\eta$ — arXiv:2407.12270.
  - $\Lambda_c^+ \to pK_{L,S}^0, pK_{L,S}^0\pi^+\pi^-, pK_{L,S}^0\pi^0$ — JHEP 09, 007 (2024).

Phys. Rev. Lett. 128, 142001 (2022).

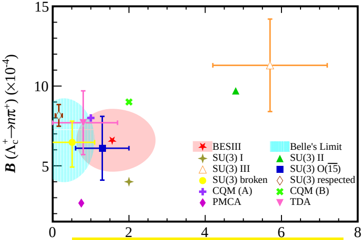
- First observation of SCS $\Lambda_c^+ \to n\pi^+$ with a significance of 7.3σ
- BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{stat.} \pm 0.4_{syst.}) \times 10^{-4}$
- 'Bones' from recoil mass spectrum
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08_{stat.} \pm 0.05_{syst.}) \times 10^{-2}$
  - $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08_{stat.} \pm 0.07_{syst.}) \times 10^{-2}$ Consistent with previous measurements from BESIII
- $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} > 7.2$ at 90% C.L. with the input from Belle $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ at 90% C.L.



Measurement of $\Lambda_c^+ \to p\pi^0, p\eta, p\eta', p\omega$

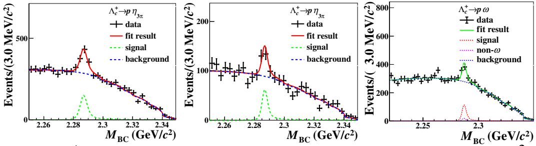
Phys. Rev. D 109, L091101 (2024).

- First evidence (3.7σ) of $\Lambda_c^+ \to p\pi^0$ with $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$
- Ratio of $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} = 3.2^{+2.2}_{-1.2}$
  - Consistent with most of phenomenological predictions
  - Contour plot shows the importance of considering $\mathcal{O}(15)$, which link to nonfactorizable contribution

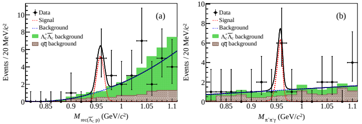


Phys. Rev. D 106, 072002 (2023).

JHEP 11, 137 (2023).



- $\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.57 \pm 0.11_{stat.} \pm 0.04_{syst.}) \times 10^{-3}$
  - Most precise measurement to date
- $\mathcal{B}(\Lambda_c^+ \to p\omega) = (1.11 \pm 0.20_{stat.} \pm 0.07_{syst.}) \times 10^{-3}$

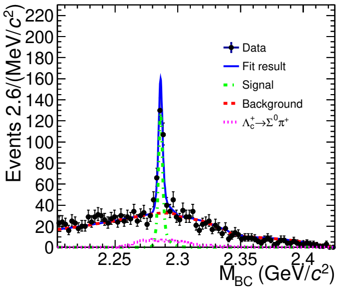


- $\mathcal{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04}) \times 10^{-4}$
  - Consistent with the Belle measurement
  - Higher than the Constituent Quark Model prediction

Measurement of $\Lambda_c^+ \to \Lambda K^+$

Phys. Rev. D 106, L111101 (2022).

- Measurement relative to the CF decay $\Lambda_c^+ \to \Lambda\pi^+$
- $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)} = (4.78 \pm 0.34_{stat.} \pm 0.20_{syst.})\%$
  - Consistent with $(7.4 \pm 1.0_{stat.} \pm 1.2_{syst.})\%$ from Belle and $(4.4 \pm 0.4_{stat.} \pm 0.3_{syst.})\%$ from Babar
  - Naive estimation of factorizable contribution$\sim$ $(\tan\theta_c f_K/f_\pi)^2 = 7.6\%$ and careful calculation $\mathcal{R}_{\text{frac}} = (7.43 \pm 0.14)\%$
  - Different from Λ_b decay: $\mathcal{B}(\Lambda_b \to \Lambda_c^+ K^-)/\mathcal{B}(\Lambda_b \to \Lambda_c^+\pi^-) = 7.31 \pm 0.16_{stat.} \pm 0.16_{syst.}\%$
  - Is the nonfactorizable contributions in Λ_c^+ decay are important and being underestimated?



- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.21 \pm 0.44_{stat.} \pm 0.26_{syst.} \pm 0.34_{ref.})\%$
  - Significantly lower ($\sim 40\%$) than the predictions based on SU(3) quark flavour symmetry, Constituent Quark Model and current algebra

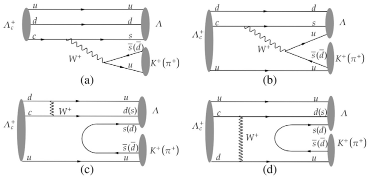
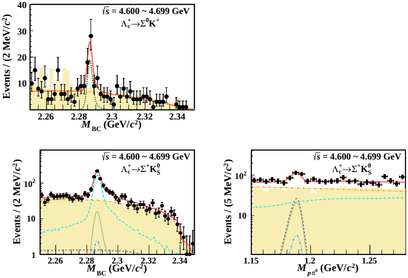


TABLE I. Theoretical predictions on the branching fraction of $\Lambda_c^+ \to \Lambda K^+$.

Theoretical predictions	$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)$ ($\times 10^{-3}$)
$SU(3)$ flavor symmetry [8]	1.4
Constituent quark model [14]	1.2
Current algebra [15]	1.06
Diquark picture [16]	0.18–0.39
$SU(3)$ flavor symmetry [17]	0.46 ± 0.09

Measurement of $\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S^0$

- Two SCS decays only receive non-factorizable contributions
- $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)} =$ $(0.0361 \pm 0.0073_{stat.} \pm 0.0005_{syst.})\%$
- $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-)} =$ $(0.0106 \pm 0.0031_{stat.} \pm 0.0004_{syst.})\%$
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) =$ $(4.7 \pm 0.9_{stat.} \pm 0.1_{syst.} \pm 0.3_{ref.}) \times 10^{-4}$
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0) =$ $(4.8 \pm 1.4_{stat.} \pm 0.2_{syst.} \pm 0.3_{ref.}) \times 10^{-4}$
    - First observation of $\Lambda_c^+ \to \Sigma^+ K_S^0$
    - $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$ is consistent with the Belle and Babar measurement
    - Consistent with the SU(3) quark flavour symmetry prediction
- $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)} =$ $(0.98 \pm 0.35_{stat.} \pm 0.04_{syst.} \pm 0.08_{ref.})$
- Korner-Pati-Woo theorem is confirmed



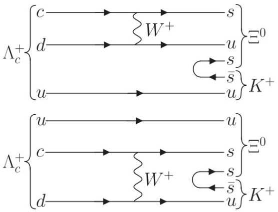
	$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$
QCD corrections [2]	2(8)	2(4)
MIT bag model [3]	7.2 ± 1.8	7.2 ± 1.8
Diagrammatic analysis [4]	5.5 ± 1.6	9.6 ± 2.4
$SU(3)_F$ flavor symmetry [5]	5.4 ± 0.7	5.4 ± 0.7
IRA method [6]	5.0 ± 0.6	1.0 ± 0.4
PDG 2020 [28]	5.2 ± 0.8	···

Phys. Rev. D 106, 052003 (2022).

Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

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

- $\Lambda_c^+ \to \Xi K^+$ is pure W-exchange process and highly contributes to the Λ_c^+ decay
- nonfactorizable contributions can not be calculated with phenomenological models
- Long-standing puzzle on how large the S-wave amplitude.



Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\|A\|$ $(\times 10^{-2} G_F$ GeV$^2)$	$\|B\|$ $(\times 10^{-2} G_F$ 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 [6]	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) [2]	5.5 ± 0.7	...	...	...	...

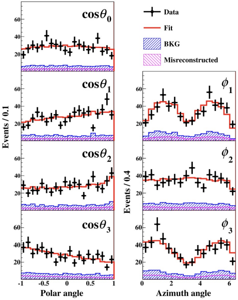
- Experimental measurement of decay asymmetry is crucial and urgent.

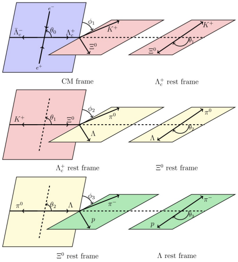
Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

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

$$\beta_{\rm BP} = \sqrt{1-\alpha_{BP}^2}\sin\Delta_{\rm BP} \quad \gamma_{\rm BP} = \sqrt{1-\alpha_{\rm BP}^2}\cos\Delta_{\rm BP}$$

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

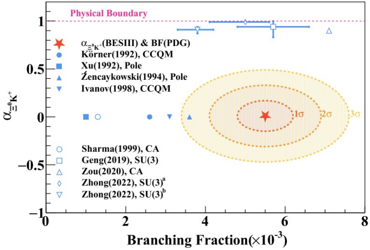




Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	$\mathcal{A}_{\lambda_1,\lambda_2}$
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	$\mathcal{B}_{\lambda_3}$
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	$\mathcal{C}_{\lambda_4}$
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	$\mathcal{D}_{\lambda_5}$

Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

- Decay asymmetry results:
  - $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat.} \pm 0.03_{syst.}$
  - $\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90_{stat.} \pm 0.17_{syst.}$
  - $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat.} \pm 0.13_{syst.}$
  - $\gamma_{\Xi^0 K^+} = 0.77 \pm 0.58_{stat.} \pm 0.11_{syst.}$
- $\alpha_{\Xi^0 K^+}$ is consistent with zero
  - Strong identification from theoretical predictions



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

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

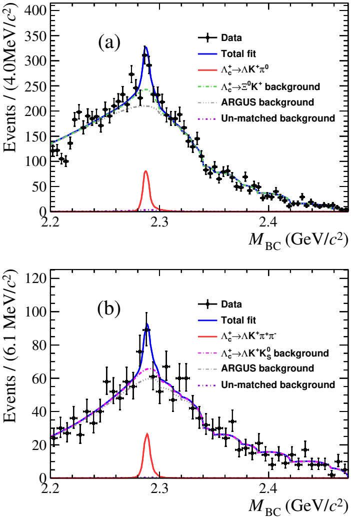
$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2}$$

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

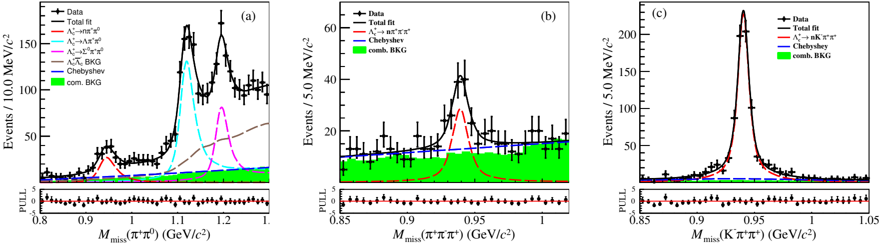
Measurement of $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$

Phys. Rev. D 109, 032003 (2024).

- Two SCS decays were measured relative to the CF conunterparts $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+\to\Lambda K^+\pi^0)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)} = (2.09 \pm 0.39_{stat.} \pm 0.07_{syst.}) \times 10^{-2}$ $\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+\to\Lambda K^+\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^+\pi^-)} = (1.13 \pm 0.41_{stat.} \pm 0.06_{syst.}) \times 10^{-2}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^0) = (1.49 \pm 0.27_{stat.} \pm 0.05_{syst.} \pm 0.08_{ref.}) \times 10^{-3}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-) = (4.13 \pm 1.48_{stat.} \pm 0.20_{syst.} \pm 0.33_{ref.}) \times 10^{-4}$
- First observation of $\Lambda_c^+ \to \Lambda K^+\pi^0$ and first evidence of $\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^0)$ deviated with the phenomenological predictions based on $SU(3)$ quark flavour symmetry with $\mathcal{H}_6$ with $\sim 3\sigma$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-)$ is consistent with the Babar experiment.



First observation of $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+, nK^-\pi^+\pi^+$



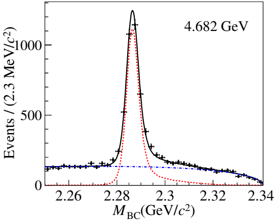
- Two SCS $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+$ and one CF $\Lambda_c^+ \to nK^-\pi^+\pi^+$ decay was firstly observed.
- Absolute BFs are measured to be:
  - $\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0) = (0.64 \pm 0.09_{stat.} \pm 0.02_{syst.})\%$
  - $\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0)} = 0.72 \pm 0.11$
    - A useful input for the isospin symmetry
  - $\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+) = (0.45 \pm 0.07_{stat.} \pm 0.03_{syst.})\%$
  - $\mathcal{B}(\Lambda_c^+ \to nK^+\pi^-\pi^+) = (1.90 \pm 0.08_{stat.} \pm 0.09_{syst.})\%$
    - $\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to nK^+\pi^-\pi^+)} = 0.24 \pm 0.04$
    - Consistent with the $|V_{cd}|/|V_{cs}| = (0.224 \pm 0.005)$

Chin. Phys. C 47, 023001 (2023).

Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

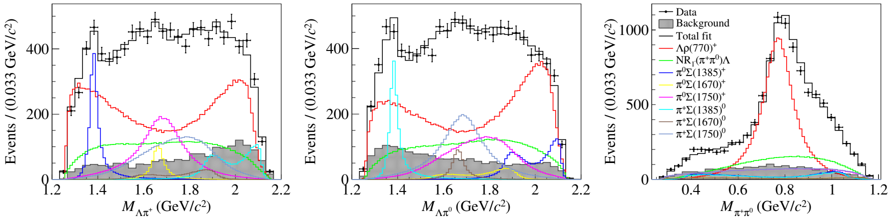
JHEP 12, 033 (2022).

- First PWA for charmed baryon decay at BESIII
- About 10K events survived with purity of $> 80\%$
- FFs and decay asymmetry of $\Lambda_c^+ \to \Lambda\rho(770)^+, \Sigma(1385)\pi$ are extracted



$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^{\rho}_{\frac{1}{2},1}|^2 - |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 - |H^{\rho}_{-\frac{1}{2},0}|^2}{|H^{\rho}_{\frac{1}{2},1}|^2 + |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 + |H^{\rho}_{-\frac{1}{2},0}|^2}$$
$$= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{1}{2}} - g^{\rho}_{1,\frac{3}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{3}{2}} + g^{\rho}_{1,\frac{1}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right)}{|g^{\rho}_{0,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{3}{2}}|^2 + |g^{\rho}_{2,\frac{3}{2}}|^2}.$$

$$\alpha_{\Sigma(1385)\pi} = \frac{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 - |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2}{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 + |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2} = \frac{2\Re\left(g^{\Sigma(1385)}_{1,\frac{3}{2}} \cdot \bar{g}^{\Sigma(1385)}_{2,\frac{3}{2}}\right)}{|g^{\Sigma(1385)}_{1,\frac{3}{2}}|^2 + |g^{\Sigma(1385)}_{2,\frac{3}{2}}|^2}.$$



Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

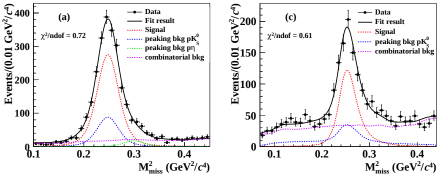
	Result
$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+\to\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.18 \pm 0.60 \pm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

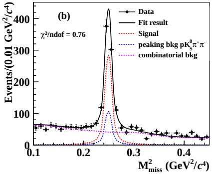
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.070	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.089	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

- No theoretical predictions can well describe the FFs and decay asymmetry simultaneously
- Fruitful results are extracted, providing the crucial information to extend the understanding of the dynamics of Λ_c^+ hadronic decays.

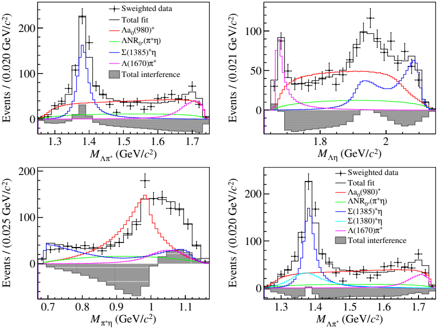
More new results

arXiv:2407.12270.





JHEP 09, 007 (2024).



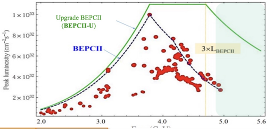
- First $K_S - K_L$ asymmetry measurement in charmed baryon decays.
- No obvious asymmetry is observed, and is consistent with $SU(3)$ quark flavour symmetry prediction
- Important input to calculate the DCS decay amplitude Invoving neutral kaons

- First observation of $\Lambda_c^+ \to \Lambda a(980)^+$
- First evidence of penta-quark candidate $\Sigma^+(1380)$ is observed in $\Lambda\pi^+$ spectrum

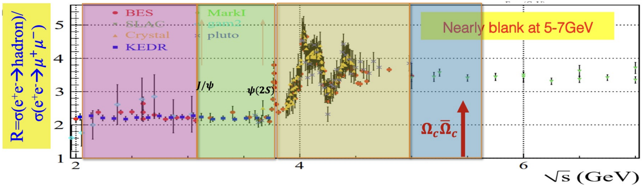
Future prospects and summary

Proposal of BEPCII-U

- The BEPCII-U plans accomplish its upgrade by 2025
- 3 times luminosity than current BEPCII at 4.7 GeV
- Extended energy range from 4.95 GeV to 5.6 GeV



- $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$
- $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^\pi$
- $e^+e^- \to \Sigma_c^+\bar{\Sigma}_c^-$
- $e^+e^- \to \Xi_c^{\bar{\Xi}_c}$
- $e^+e^- \to \Omega_c^{\bar{\Omega}_c}$



Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
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

Summary

- BEPCII energy upgrade during 2020-201 has improved the BESIII capability in Λ_c^+ physics by accumulating more statustics at different energy points and pose a great opportunity to study the Λ_c^+ production and decays.
- BESIII has been playing a significant role in the study of Λ_c^+ decays.
- Fruitful Λ_c^+ results have been published during 2022-2024
- More physics results coming soon
- BEPCII-U upgrade will provide more opportunities for charm baryon physics