BESIII 粲重子物理的进展

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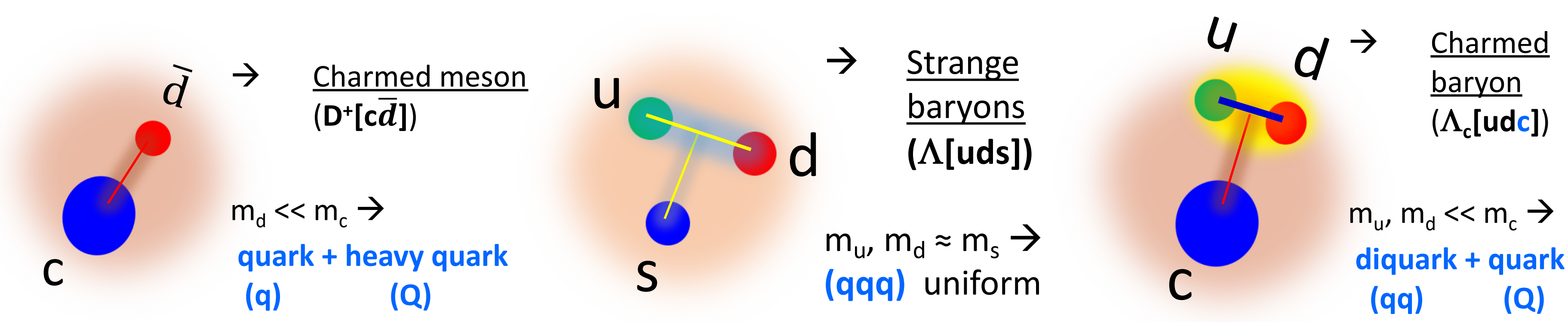
Λ_c^+: The lightest charmed baryon spectroscopy

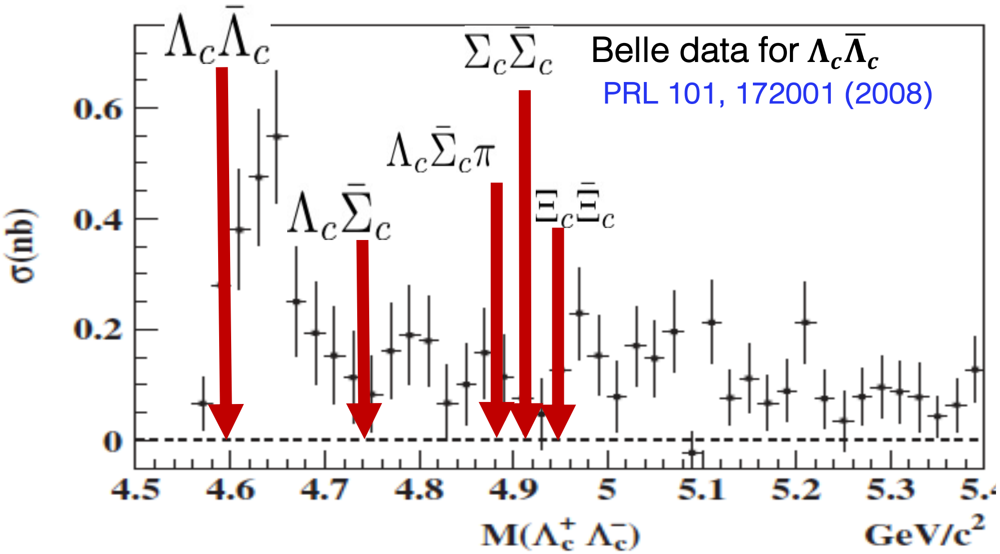
- Most of the charmed baryons will eventually decay to Λ_c^+.
- The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.
- Naïve quark model picture: a heavy quark (c) with an unexcited spin-zero diquark (u-d). Diquark correlation is enhanced by 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



New data samples in 2020 and 2021

Two major changes in BEPCII machine:

- **max beam energy: 2.30➔2.35(2020)➔ 2.48 GeV(2021)**
- **top-up injection:** data taking efficiency increased by 20~30%



CPC46.113003(2022)

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

Available data for charmed baryons

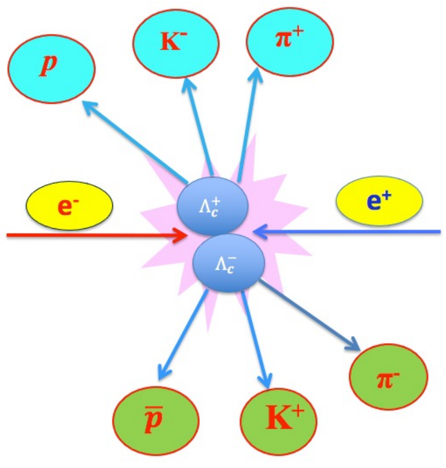
- ✓ 0.567 fb^{-1} at 4.6 GeV (35 days in 2014)
- ✓ 3.9 fb^{-1} scan at 4.61, 4.63, 4.64, 4.66, 4.68, 4.7 GeV (186 days in 2020)
- ✓ 1.93 fb^{-1} scan at 4.74, 4.75, 4.78, 4.84, 4.92, 4.95 GeV (99 days in 2021)
- 8x Λ_c data that those at 4.6GeV.(~0.77M $\Lambda_c^+\bar{\Lambda}_c^-$)
- accessible to $\Sigma_c/\Xi_c/\Lambda_c^*$ prod. & decays

Production measurement near threshold

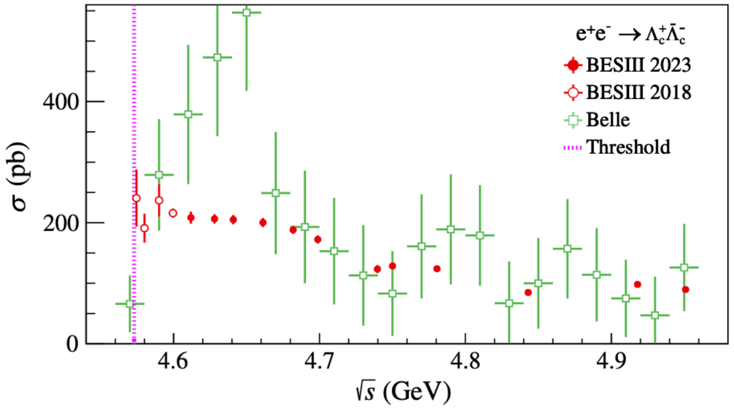
PhysRevLett.131.191901(2023)

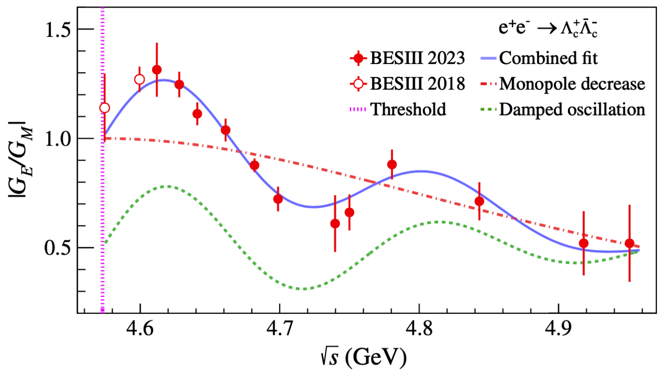
- $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ cross section are measured at twelve energy points from 4.612-4.951GeV .

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



- 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.





Production measurement near threshold

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

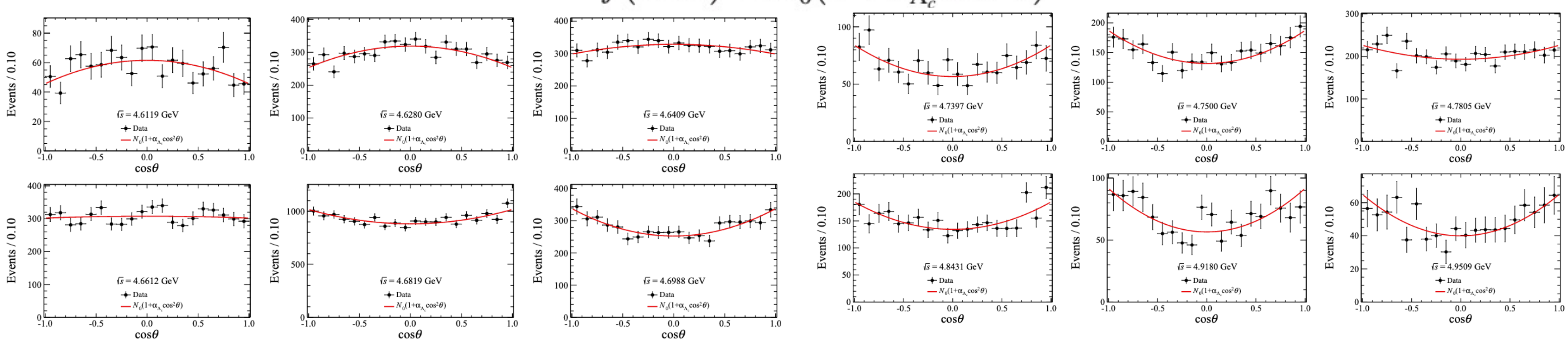
PhysRevLett.131.191901(2023)

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	σ (pb)	$\lvert G_{\rm eff}\rvert$ (10^{-2})	α_{Λ_c}	$\lvert G_E/G_M\rvert$	$\lvert G_M\rvert$ (10^{-2})
4.6119	103.7	$208.4 \pm 6.9 \pm 7.0$	$49.2 \pm 0.8 \pm 0.8$	$-0.26 \pm 0.09 \pm 0.01$	$1.31 \pm 0.12 \pm 0.01$	$43.5 \pm 3.3 \pm 1.5$
4.6280	521.5	$206.4 \pm 3.1 \pm 6.9$	$45.5 \pm 0.3 \pm 0.8$	$-0.21 \pm 0.04 \pm 0.01$	$1.25 \pm 0.06 \pm 0.01$	$41.8 \pm 1.5 \pm 1.5$
4.6409	551.6	$205.1 \pm 3.0 \pm 6.9$	$43.4 \pm 0.3 \pm 0.7$	$-0.09 \pm 0.05 \pm 0.01$	$1.11 \pm 0.05 \pm 0.01$	$41.8 \pm 1.4 \pm 1.4$
4.6612	529.4	$200.3 \pm 2.9 \pm 6.8$	$40.6 \pm 0.3 \pm 0.7$	$-0.02 \pm 0.05 \pm 0.01$	$1.04 \pm 0.05 \pm 0.01$	$40.2 \pm 1.4 \pm 1.4$
4.6819	1667.4	$188.1 \pm 1.6 \pm 6.3$	$37.7 \pm 0.2 \pm 0.6$	$0.15 \pm 0.03 \pm 0.01$	$0.88 \pm 0.03 \pm 0.01$	$39.2 \pm 0.8 \pm 1.3$
4.6988	535.5	$172.3 \pm 2.7 \pm 6.0$	$35.1 \pm 0.3 \pm 0.6$	$0.34 \pm 0.07 \pm 0.01$	$0.72 \pm 0.06 \pm 0.01$	$38.2 \pm 1.4 \pm 1.3$
4.7397	163.9	$123.5 \pm 4.2 \pm 5.0$	$28.2 \pm 0.5 \pm 0.6$	$0.49 \pm 0.16 \pm 0.03$	$0.61 \pm 0.13 \pm 0.02$	$31.4 \pm 2.4 \pm 1.3$
4.7500	366.6	$128.5 \pm 2.8 \pm 4.4$	$28.5 \pm 0.3 \pm 0.5$	$0.42 \pm 0.10 \pm 0.01$	$0.66 \pm 0.08 \pm 0.01$	$31.4 \pm 1.6 \pm 1.1$
4.7805	511.5	$124.0 \pm 2.4 \pm 4.2$	$27.2 \pm 0.3 \pm 0.5$	$0.17 \pm 0.07 \pm 0.01$	$0.88 \pm 0.07 \pm 0.01$	$28.2 \pm 1.2 \pm 1.0$
4.8431	525.2	$84.8 \pm 2.0 \pm 2.9$	$21.6 \pm 0.3 \pm 0.4$	$0.38 \pm 0.10 \pm 0.01$	$0.71 \pm 0.09 \pm 0.01$	$23.4 \pm 1.3 \pm 0.8$
4.9180	207.8	$98.1 \pm 3.3 \pm 3.5$	$22.4 \pm 0.4 \pm 0.4$	$0.62 \pm 0.17 \pm 0.01$	$0.52 \pm 0.15 \pm 0.01$	$25.3 \pm 1.9 \pm 0.9$
4.9509	159.3	$89.6 \pm 3.6 \pm 3.1$	$21.2 \pm 0.4 \pm 0.4$	$0.63 \pm 0.21 \pm 0.01$	$0.52 \pm 0.18 \pm 0.01$	$24.1 \pm 2.2 \pm 0.9$

$$\alpha_{\Lambda_c} = \frac{1-\kappa R^2}{1+\kappa R^2}.$$

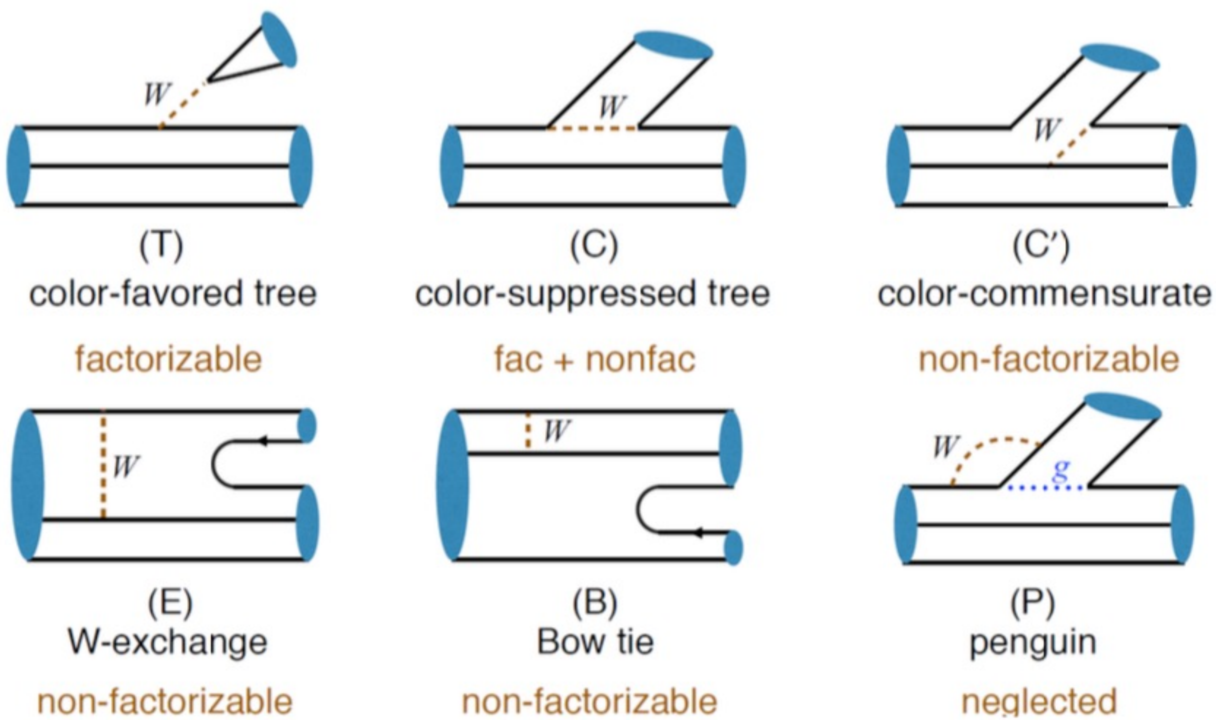
$$R = |G_E/G_M|$$

$$f(\cos\theta) = N_0(1+\alpha_{\Lambda_c}\cos^2\theta)$$



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.

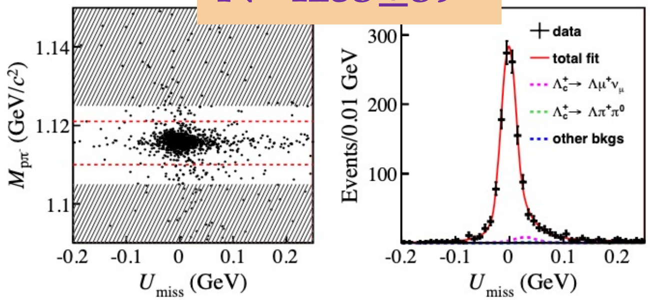
Recent studies on the Λ_c^+ measurments at BESIII

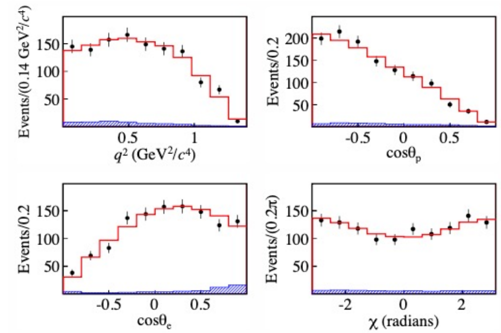
- Λ_c^+ leptonic decays
  - $\Lambda_c^+ \to \Lambda e^+\nu_e, \Lambda\mu^+\nu_\mu$: PRL 129.231803 (2022). PRD 108.L031105 (2023).
  - $\Lambda_c^+ \to pK^-e^+\nu_e$: PRD 106.112010 (2022).
  - $\Lambda_c^+ \to Xe^+\nu_e$: PRD 107.052005 (2023).
  - $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_S^0\pi^-e^+\nu_e$: PLB 843.137993 (2023).
- Λ_c^+ hadronic decays(two body)
  - $\Lambda_c^+ \to n\pi^+$: PRL 128.142001 (2022).
  - $\Lambda_c^+ \to p\eta'$: PRD 106.072002 (2022).
  - $\Lambda_c^+ \to p\eta, p\omega$: JHEP 11.137 (2023).
  - $\Lambda_c^+ \to p\pi^0, p\eta$: arXiv2311.06883.
  - $\Lambda_c^+ \to \Lambda K^+$: PRD 106.L111101 (2022).
  - $\Lambda_c^+ \to \Sigma^0K^+, \Sigma^+K_S^0$: PRD 106.052003 (2022).
  - $\Lambda_c^+ \to \Xi^0K^+$: PRL132.031801(**2024**).
- Λ_c^+ hadronic decays(multi-body)
  - $\Lambda_c^+ \to n\pi^+\pi^0$、$n\pi^+\pi^-\pi^+$、$nK^-\pi^+\pi^+$: CPC 47.023001 (2023).
  - $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$: PRD 109.072010(**2024**).
  - $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$: PRD 109.072010(**2024**).
  - $\bar{\Lambda}_c^- \to \bar{n}X$: PRD 108.L031101 (2023).
  - $\Lambda_c^+ \to \Lambda\pi^+\pi^0$: JHEP 12.033 (2022).
  - $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$: PRD 109.032003(**2024**).
  - $\Lambda_c^+ \to \Sigma^-K^+\pi^+$: PRD(L) 109.L071103(**2024**).
  - $\Lambda_c^+ \to \Xi^0K^+\pi^0$: PRD 109.052001(**2024**).

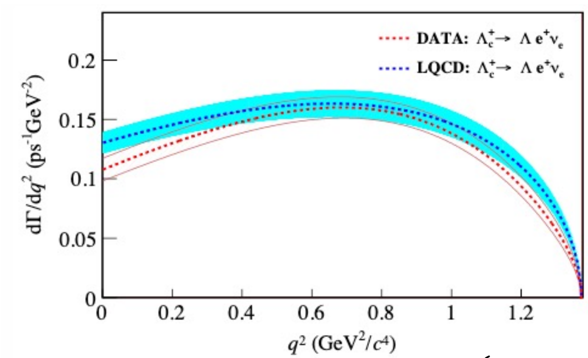
Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

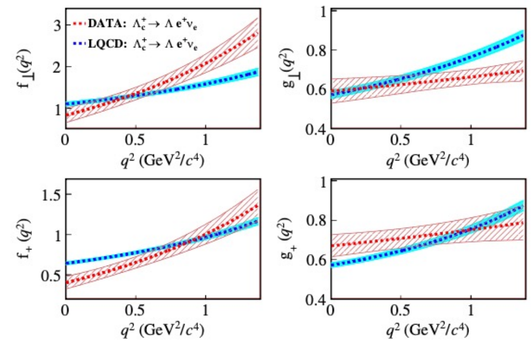
PRL 129,231803(2022)

N=1253±39









- BF is updated to be $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = \left(3.56 \pm 0.11_{stat} \pm 0.07_{syst}\right)\%$=>precision improved.
- Helicity amplitude deduced form factors can be extracted with 4D fitting to data.
- The differential decay rate is roughly consistent with LQCD calculation while discrepancies can be noticed on FFs show different kinematic behaviors.
- |Vcs| element from charmed baryons is measured to be $0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda c}}$ which is consistent with the value obtained in charmed mesons decay.

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

arXiv2309.02774(PRL accepted)

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A \rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\lvert B \rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (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.

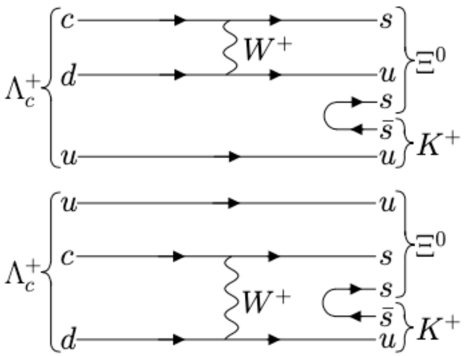


FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

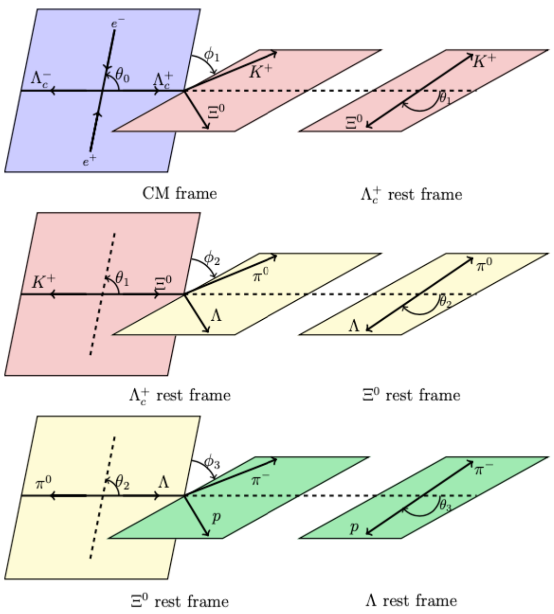
Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

arXiv2309.02774(PRL accepted)

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

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}

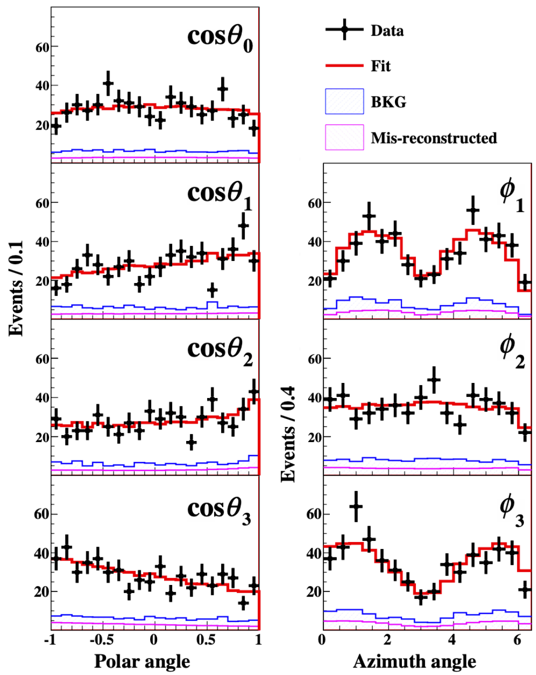
$$
\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0\ d\cos\theta_1\ d\cos\theta_2\ d\cos\theta_3\ d\phi_1\ d\phi_2\ d\phi_3} \\
&\propto 1 + \alpha_0\cos^2\theta_0 \\
&+ (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0K^+}\alpha_{\Lambda\pi^0}\cos\theta_2 \\
&+ (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0K^+}\alpha_{p\pi^-}\cos\theta_2\cos\theta_3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



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

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

PRL132.031801(**2024**)

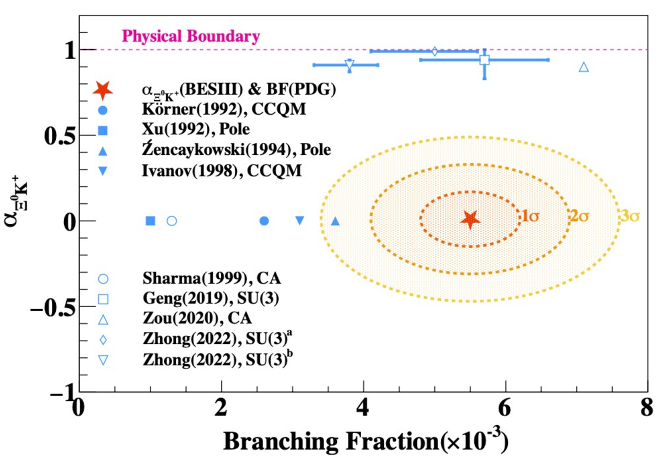


- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero=>strong identification for theoretical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

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

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

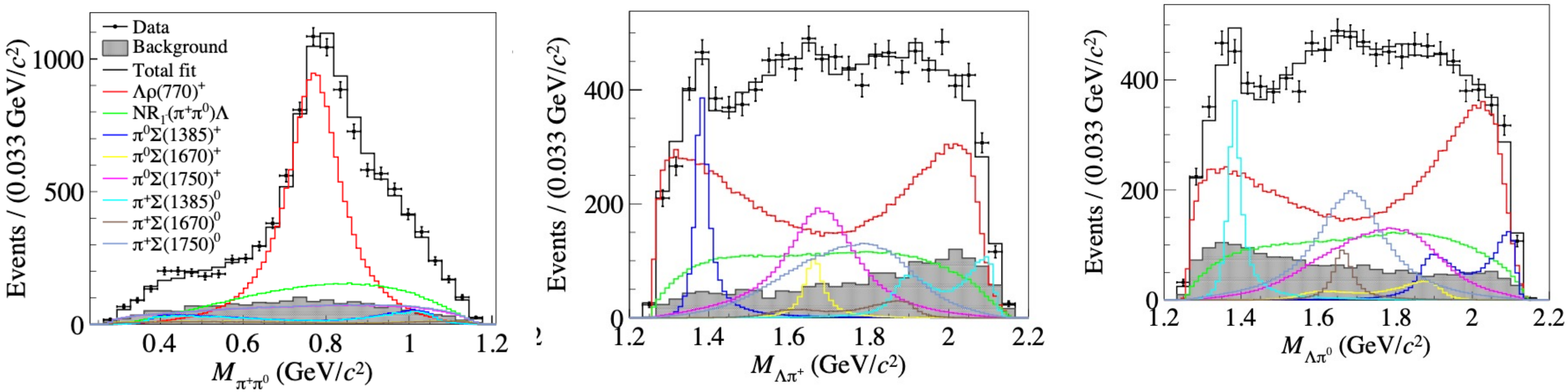
$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2},$$



- 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.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).



Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-0.77 ± 0.23	2.90 ± 0.63	$5.1\,\sigma$
$\Sigma(1670)^0\pi^+$	0.41 ± 0.07	2.77 ± 0.20	2.65 ± 0.58	$5.2\,\sigma$
$\Sigma(1750)^+\pi^0$	1.75 ± 0.21	-1.73 ± 0.11	16.6 ± 2.2	$10.1\,\sigma$
$\Sigma(1750)^0\pi^+$	1.83 ± 0.21	1.34 ± 0.11	17.5 ± 2.3	$10.2\,\sigma$
$\Lambda + NR_{1^-}$	4.05 ± 0.47	2.16 ± 0.13	29.7 ± 4.5	$10.5\,\sigma$

- About 10K events survived which purity is larger than 80%.
- PWA based on helicity amplitude is performed.
- Interference mostly exist between $\Lambda\rho(770)$ and $\Sigma(1385)^{0/+}\pi^{+/0}$.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^+) + 0^-(\pi^0)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1385)^+}_{1,\frac{3}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1385)^+}_{2,\frac{3}{2}}$	1.29 ± 0.25	2.82 ± 0.18

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1385)^0}_{1,\frac{3}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1385)^0}_{2,\frac{3}{2}}$	1.70 ± 0.38	2.70 ± 0.22

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^+) + 0^-(\pi^0)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1670)^+}_{1,\frac{3}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1670)^+}_{2,\frac{3}{2}}$	1.39 ± 0.42	0.85 ± 0.26

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1670)^0}_{1,\frac{3}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1670)^0}_{2,\frac{3}{2}}$	0.74 ± 0.18	0.29 ± 0.24

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^+) + 0^-(\pi^0)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1750)^+}_{0,\frac{1}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1750)^+}_{1,\frac{1}{2}}$	0.45 ± 0.10	-2.28 ± 0.22

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1750)^0}_{0,\frac{1}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1750)^0}_{1,\frac{1}{2}}$	0.38 ± 0.10	-2.03 ± 0.20

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(\rho(770)^+)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\rho}_{0,\frac{1}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\rho}_{1,\frac{1}{2}}$	0.48 ± 0.12	-1.69 ± 0.12
$g^{\rho}_{1,\frac{3}{2}}$	0.90 ± 0.10	0.48 ± 0.13
$g^{\rho}_{2,\frac{3}{2}}$	0.55 ± 0.08	-0.04 ± 0.18

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(NR_{1^-})$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{NR}_{0,\frac{1}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{NR}_{1,\frac{1}{2}}$	0.94 ± 0.12	-0.49 ± 0.16
$g^{NR}_{1,\frac{3}{2}}$	0.21 ± 0.09	-2.84 ± 0.53
$g^{NR}_{2,\frac{3}{2}}$	0.33 ± 0.14	-1.92 ± 0.30

$\frac{1}{2}^+(\Lambda) \to \frac{1}{2}^+(p) + 0^-(\pi^-)$		
Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Lambda}_{0,\frac{1}{2}}$	1.0 (fixed)	0.0 (fixed)
$g^{\Lambda}_{1,\frac{1}{2}}$	0.435376 (fixed)	0.0 (fixed)

$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^{\rho}_{\frac{1}{2},1}|^2 - |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 - |H^{\rho}_{-\frac{1}{2},0}|^2}{|H^{\rho}_{\frac{1}{2},1}|^2 + |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 + |H^{\rho}_{-\frac{1}{2},0}|^2}$$

$$= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{1}{2}} - g^{\rho}_{1,\frac{3}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{3}{2}} + g^{\rho}_{1,\frac{1}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right)}{|g^{\rho}_{0,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{3}{2}}|^2 + |g^{\rho}_{2,\frac{3}{2}}|^2}. \tag{4.28}$$

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

- Decay asymmetry parameters can be obtained by the fit results of the partial wave amplitudes.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (57.2 \pm 4.2 \pm 4.9)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) \cdot \mathcal{B}(\Sigma(1385)^+ \to \Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.18 \pm 0.60 \pm 0.64)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) \cdot \mathcal{B}(\Sigma(1385)^0 \to \Lambda\pi^0)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.92 \pm 0.72 \pm 0.80)\%.$$

$$\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+) = (4.06 \pm 0.30 \pm 0.35 \pm 0.23)\%,$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) = (5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) = (6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3},$$

$$\alpha_{\Lambda\rho(770)^+} = -0.763 \pm 0.053 \pm 0.039,$$

$$\alpha_{\Sigma(1385)^+\pi^0} = -0.917 \pm 0.069 \pm 0.046,$$

$$\alpha_{\Sigma(1385)^0\pi^+} = -0.789 \pm 0.098 \pm 0.056.$$

Table 9. The comparison among this work, various theoretical calculations and PDG results. Here, the uncertainties of this work are the combined uncertainties. "—" means unavailable.

	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 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

- NO theoretical models is able to explain both BFs and decay asymmetries simultaneously.
- Fruitful results are extracted which provide crucial input to extend the understanding of dynamics of charmed baryon hadronic decays.

Coming soon stay tunned

- $\Lambda_c^+ \to n e^+ \nu_e$(release soon)
- $\Lambda_c^+ \to \Sigma^+ \pi^- e^+ \nu_e$、 $\Sigma^- \pi^+ e^+ \nu_e$
- $\Lambda_c^+ \to p \pi^- e^+ \nu_e$
- $\Lambda_c^+ \to n K_s^0 e^+ \nu_e$

- $\Lambda_c^+ \to p K_L^0$、 $p\phi$
- $\Lambda_c^+ \to p K_s^0$、 $\Lambda \pi^+$、 $\Sigma^0 \pi^+$、 $\Sigma^+ \pi^0$(Decay asymmetry and polarization study)

- $\Lambda_c^+ \to n K^+ \pi^0$(DCS)
- $\Lambda_c^+ \to p K^- \pi^+$、 $p K_S^0 \pi^0$、 $p K_L^0 \pi^0$
- $\Lambda_c^+ \to \Lambda K_s^0 K^+$、$\Lambda K_s^0 \pi^+ (\Lambda K^{*+})$
- $\Lambda_c^+ \to \Sigma^0 \pi^+ \pi^0$、 $\Sigma^+ \pi^+ \pi^-$ 、 $\Sigma^- \pi^+ \pi^+$
- $\Lambda_c^+ \to \Sigma^+ K^+ K^+$ (ϕ)、 $\Sigma^+ K^+ \pi^- (\pi^0)$、 $\Sigma^0 K_s^0 K^+$、
- $\Lambda_c^+ \to \Xi^- K^+ \pi^+$、$\Xi^0 K_s^0 K^+$

- $\Lambda_c^+ \to p K^- \pi^+ \pi^0$ 、 $p K_L^0 \pi^+ \pi^-$

- $\Lambda_c^+ \to \Lambda X$、$K_s^0 X$、$pX$

课题整体目标、指标

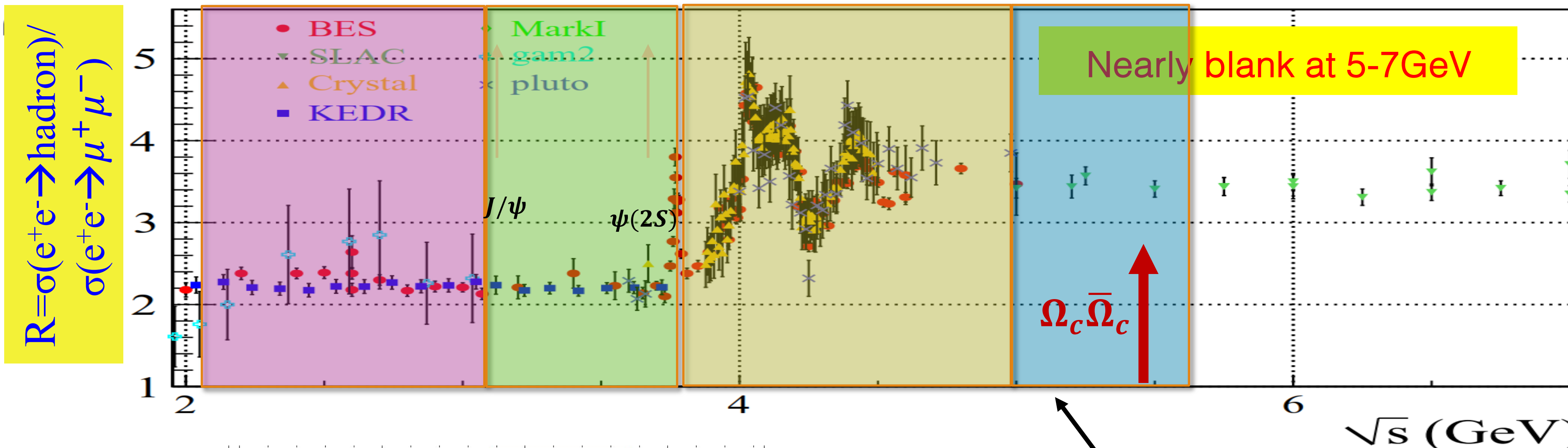
课题目标、成果与考核指标表

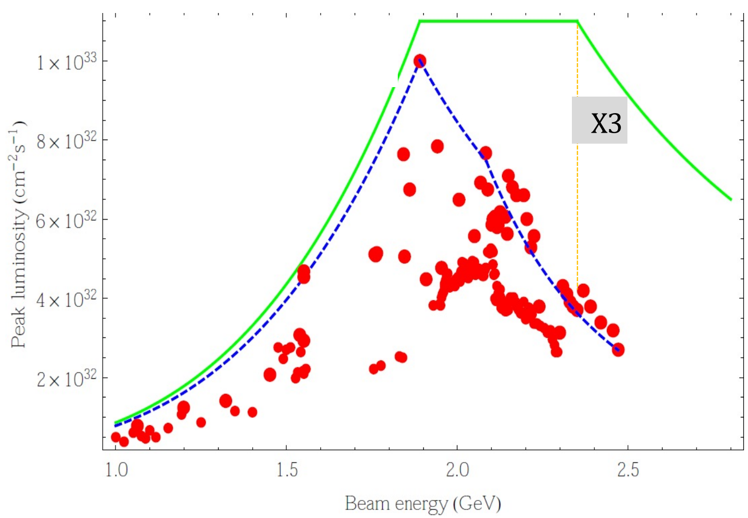
课题目标[1]	成果名称	成果类型	考核指标[2]：指标名称	考核指标[2]：立项时已有指标值/状态	考核指标[2]：中期指标值/状态[3]	考核指标[2]：完成时指标值/状态	考核方式（方法）及评价手段[4]
（限 500 字以内。）首次发现或寻找Λ_c^+的 4 项新半轻衰变；精确测 $\Lambda_c^+ \to \Lambda l^+ \nu$ 衰变的形状因子；强子末态衰变过程至少 5 项相对精度好于 10%; Λ_c^+弱衰变的不对称参数精度最好可达 4%；首次测量或者更精确测量 2 个Λ_c^+单举过程。建立分波分析工具，完成 1 项三体分波分析工作；发表论文 10 篇以上	Λ_c^+的半轻衰变研究	□新理论 □新原理 □新产品 □新技术 ■新方法 □关键部件 □数据库 □软件 □应用解决方案 □实验装置/系统 □临床指南/规范 □工程工艺 □标准 ■论文 □发明专利 □其他	Λ_c^+的半轻衰变研究成果；论文数量	半轻过程仅测量了$\Lambda_c^+ \to \Lambda l^+ \nu$衰变率；无衰变形状因子测量	首次发现或寻找Λ_c^+的 2 项新半轻衰变；首次绝对精确测$\Lambda_c^+ \to \Lambda l^+ \nu$衰变的形状因子；发表论文 1 篇	首次发现或寻找Λ_c^+的 4 项新半轻衰变；首次绝对精确测$\Lambda_c^+ \to \Lambda l^+ \nu$衰变的形状因子；发表论文 3 篇	正式文章发表
	Λ_c^+的强子弱衰变研究	同上	Λ_c^+的强子弱衰变研究成果；论文数量	卡比玻压低的强子末态衰变过程相对误差高于 20%;含中子末态仅发表 2 个过程的研究；无 K_L 末态的实验研究；Λ_c^+弱衰变的不对称参数精度大于 10%	发现 2 个卡比玻压低强子末态衰变过程，精度好于 10%；发现 2 项包含中子和 K_L 末态的衰变过程；Λ_c^+弱衰变的不对称参数精度最好可达 4%；发表论文 2 篇	完成 5-10 项卡比玻压低的Λ_c^+强子末态衰变过程以及包含中子和 K_L 末态的衰变过程，至少 5 项精度好于 10%；发表 2 项 Λ_c^+弱衰变的不对称参数测量，最好精度可达 4%；发表论文 6-8 篇	正式文章发表
	Λ_c^+单举过程精确测量	同上	Λ_c^+的单举衰变研究成果；论文数量	BESIII 实验发表了对$\Lambda_c^+ \to \Lambda$+X, e+X, K_S+X 3 个过程的测量结果	首次测量或者更精确测量 1 个Λ_c^+单举过程。	首次测量或者更精确测量 2 个Λ_c^+单举过程。发表论文 2 篇	正式文章发表
	粲重子分波分析	同上	粲重子分波分析；论文数量	BESII 实验上无相关研究	建立完成分波分析工具开发	建立分波分析工具；发表 1 篇三体衰变分波分析工作	正式文章发表
科技报告考核指标	序号	报告类型[5]	数量	提交时间		公开类别及时限[6]	

其他目标与考核指标: 无

Proposal of the BEPCII upgrade

- optimized energy at 2.35 GeV with luminosity 3 times higher than the current BEPCII.





4.95 ~ 5.6 GeV: new energy coverage of BEPCII-upgrade

Energy thresholds

✓	$\Lambda_c^+\bar{\Sigma}_c^-$	4.74 GeV
✓	$\Lambda_c^+\bar{\Sigma}_c\ \pi$	4.88 GeV
✓	$\Sigma_c\ \bar{\Sigma}_c$	4.91 GeV
✓	$\Xi_c\ \bar{\Xi}_c$	4.95 GeV
✓	$\Omega_c^0\bar{\Omega}_c^0$	5.4 GeV

Prospect Charm Baryons data sample at BESIII

Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The right-most column shows the number of required data taking days with the current (T_C) and upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

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 2020-2021 has improved the BESIII capability in Λ_c physics by accumulating more statistics at different energy points and pose opportunity to study Λ_c^+ production and decays.

- BESIII has been playing significant role in studying Λ_c decays

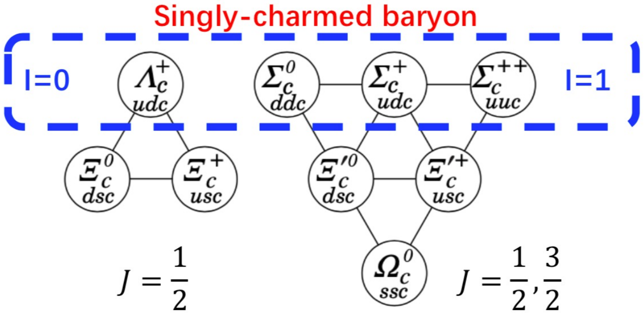
- Many new results of Λ_c decays have been published in 2022 and 2023.

- Proposal of BEPCII upgrade (3x luminosity and energy up to 5.6 GeV) will greatly extend the physics opportunities in c-baryon sector.

Thanks

Energy thresholds

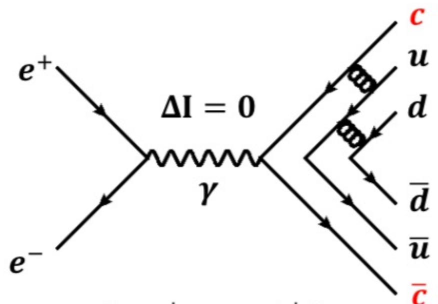
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74~4.87 GeV
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-(2595)(\bar{\Sigma}_c\ \pi)$ 4.88 GeV
- ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
- ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.95 GeV



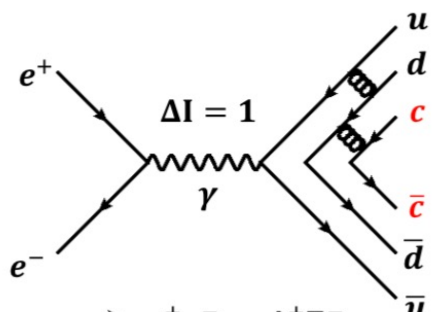
The Born cross-section **ratios** between $\Lambda_c^+\Lambda_c^- + c.c.$ and $\Lambda_c^-\Sigma_c^+ + c.c.$ at different energy points can provide more information about the production of $c\bar{c}$ or $q\bar{q}$ from vacuum.

BESIII Cross sections for $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ and $\Sigma_c\ \bar{\Sigma}_c$

- $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ **above 4.74 GeV:** An interesting isospin violating process to understand the QCD dynamics at charm sector
  - ✓ A cross section scan slightly above 4.74 GeV will be useful for comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and $\Lambda_c^+\bar{\Sigma}_c^-$
  - ✓ $\sigma(\Lambda_c^+\bar{\Sigma}_c^-)/\sigma(\Lambda_c^+\bar{\Lambda}_c^-)$ v.s. $\sigma(\Lambda\bar{\Sigma})/\sigma(\Lambda\bar{\Lambda})$
    ➔ vaccum pol. to $c\bar{c}$ v.s. $s\bar{s}$
  - ✓ If observed, study the polarizations and form factors
- $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ **around 4.91 GeV:**
  - ✓ Cross section comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
    ➔ good diquark v.s. bad diquark
  - ✓ Study the polarizations and form factors in $e^+e^- \to \Sigma_c^0\bar{\Sigma}_c^0$ and $\Sigma_c^+\bar{\Sigma}_c^-$



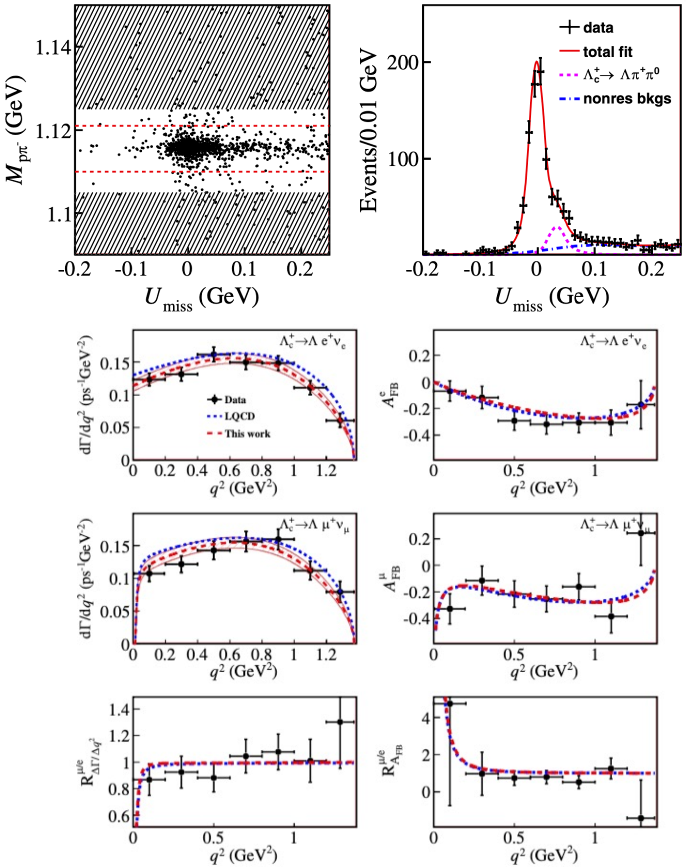
➢ $e^+e^- \to \Lambda_c^+\Lambda_c^-$



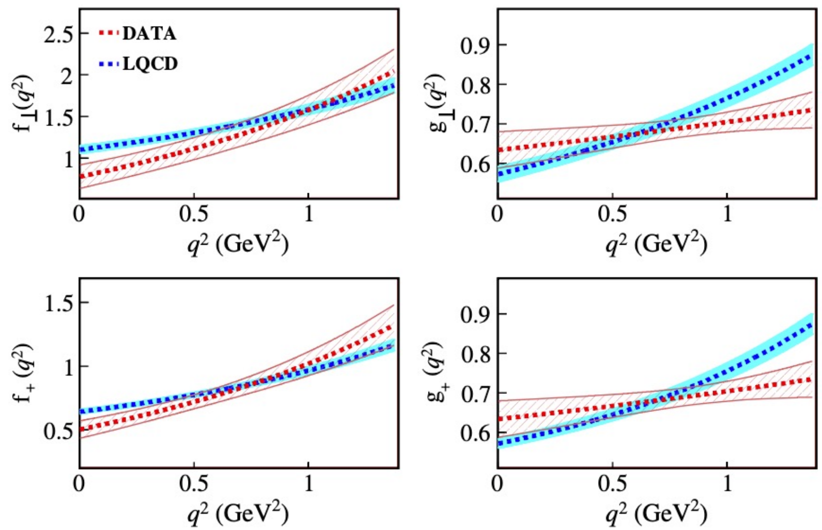
➢ $e^+e^- \to \Lambda_c^+\Sigma_c^-$

Form factors of $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

PRD 108.L031105 (2023)



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta'_\ell\, d\cos\theta_p\, d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4}\cdot\frac{Pq^2(1-m_\ell^2/q^2)^2}{24M_{\Lambda_c}^2}\Big\{\frac{3}{8}(1-\cos\theta'_\ell)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p) + \frac{3}{8}(1+\cos\theta'_\ell)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p) + \frac{3}{4}\sin^2\theta'_\ell[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)] + \frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta'_\ell\sin\theta_p \times[(1-\cos\theta'_\ell)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta'_\ell)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}] + \mathcal{H}_{m_\ell^2}\Big\},$$



- BF is updated to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)= (3.48 \pm 0.14_{stat} \pm 0.10_{syst})\%$=>3times more precise than prior results.
- Lepton flavor universality are reported $(0.98 \pm 0.05_{stat} \pm 0.03_{syst})$ =>compatible with Standard Model(0,97).
- Form-factors parameters for$\Lambda_c^+ \to \Lambda l^+\nu_l$ are determined to test and calibrate for LQCD.

BF Measurements of $\Lambda_c^+ \to pK^- e^+ \nu_e$

PRD 106.112010 (2022).

N($pK^- e^+ \nu_e$)=33.5±6.3

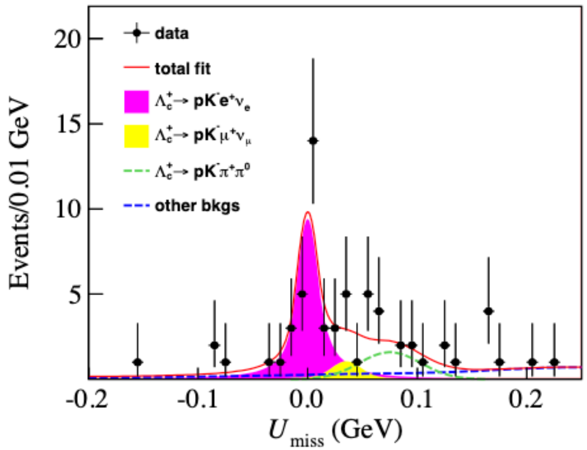
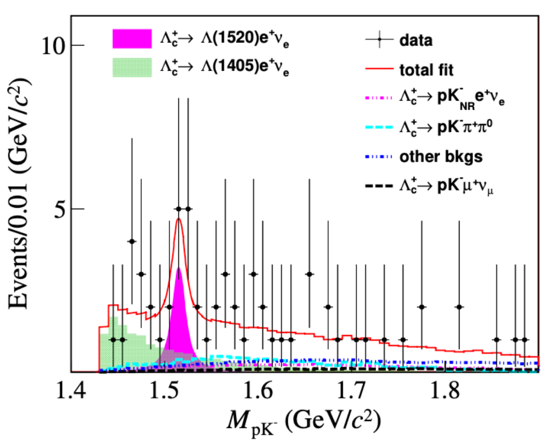


TABLE I. Comparison of $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)/\Lambda(1405)e^+\nu_e)$ [in $\times 10^{-3}$] between theoretical calculations and this measurement. The BF of $\Lambda(1405) \to pK^-$ is unknown.

	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	––	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12, 13]	0.512 ± 0.082	––
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42 \pm 0.19 \pm 0.04}{\mathcal{B}(\Lambda(1405) \to pK^-)}$

- $\Lambda_c^+ \to pK^- e^+ \nu_e$ is firstly observed with significance of 8.2σ.

N($\Lambda(1520) e^+ \nu_e$)=8.4±4.3
N($\Lambda(1405) e^+ \nu_e$)=14.8±6.7



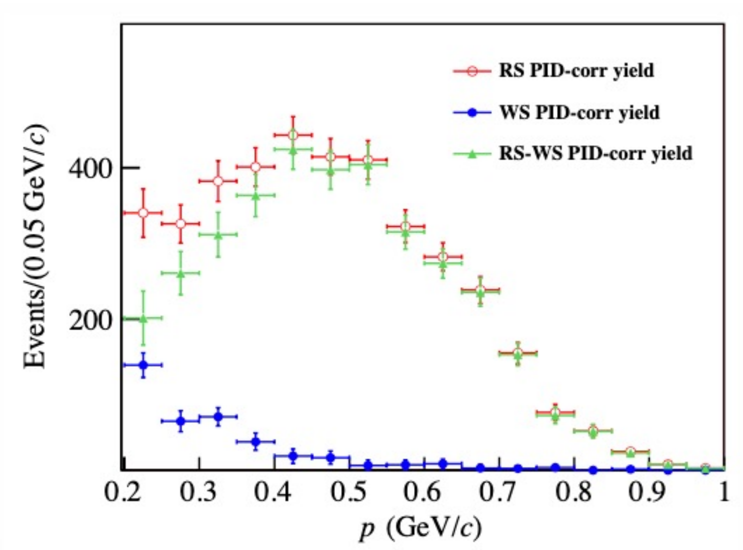
- Evidence of $\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e$ (3.3σ) and $\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e$ (3.2σ) are found.

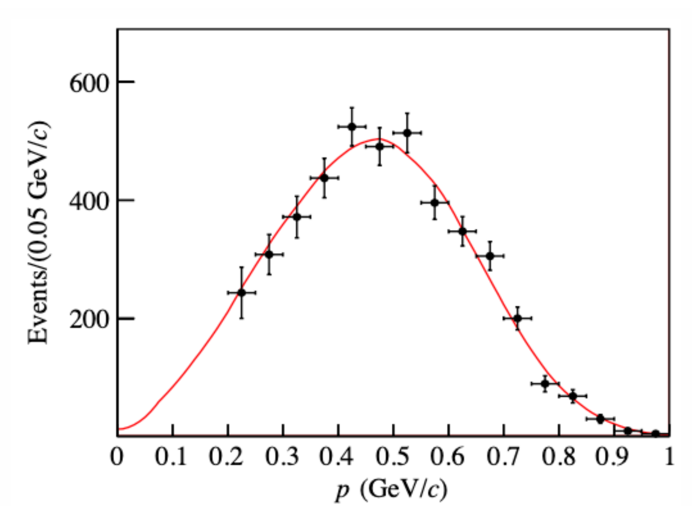
- BFs are measured to be :
  $\mathcal{B}(\Lambda_c^+ \to pK^- e^+ \nu_e) = (0.88 \pm 0.17_{stat} \pm 0.07_{syst}) \times 10^{-3}$,
  $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)\, e^+ \nu_e) = (1.36 \pm 0.56_{stat} \pm 0.11_{syst}) \times 10^{-3}$ and
  $\mathcal{B}(\Lambda_c^+ \to pK^-_{non-\Lambda(1520)} e^+ \nu_e) = (0.53 \pm 0.15_{stat} \pm 0.06_{syst}) \times 10^{-3}$.

- $R = \frac{\mathcal{B}(\Lambda_c^+ \to pK^- e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = (2.1 \pm 0.4_{stat} \pm 0.1_{syst})\%$
  => the only observed SL channel beyond $\Lambda_c^+ \to \Lambda\, l^+ \nu_l$

BF measurement of $\Lambda_c^+ \to X e^+ \nu_e$

PRD 107.052005 (2023).





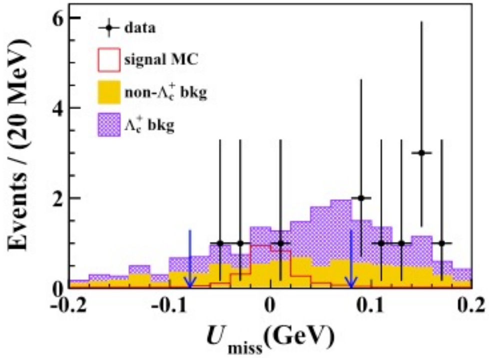
- WS technique is used to subtract charge symmetric backgrounds in each momentum bin.
- PID unfolding approach is performed to obtained the positron yields which is suffered from the contamination of other particle types(π^+、K^+、p).
- Extrapolation of positron momentum spectrum to whole phase space region.
- BF is measured to be $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10_{stat} \pm 0.09_{syst})\%$=>precision improved compared with PRL121,251801(2018).
- $\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\Gamma(D \to X e^+ \nu_e)} = (1.28 \pm 0.05)\%$ => improve the power to identify different predications. =>HQE(1.2), EQM(1.67)

PRD49,1310(1994)

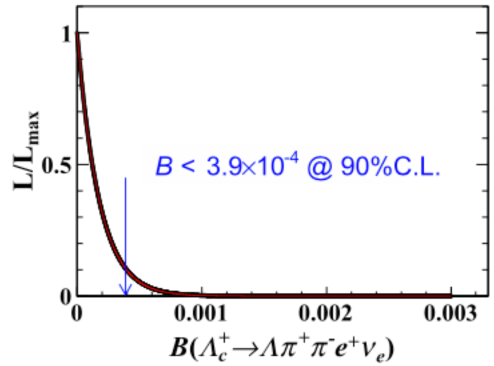
PRD83,034025(2011)
PRD86,014017(2012)

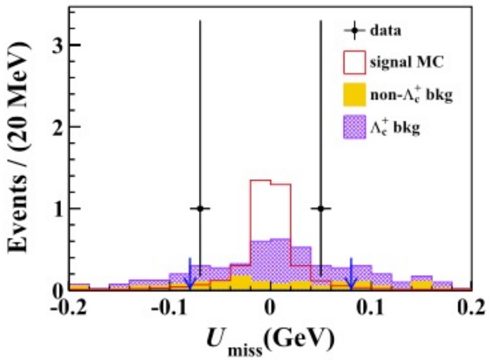
$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$, $pK_S^0\pi^- e^+\nu_e$

PLB 843.137993 (2023)



(a)





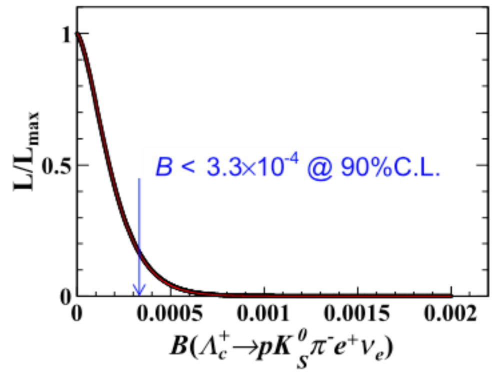


Table 1
The BFs for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ predicted by different theoretical models, in units of 10^{-4}.

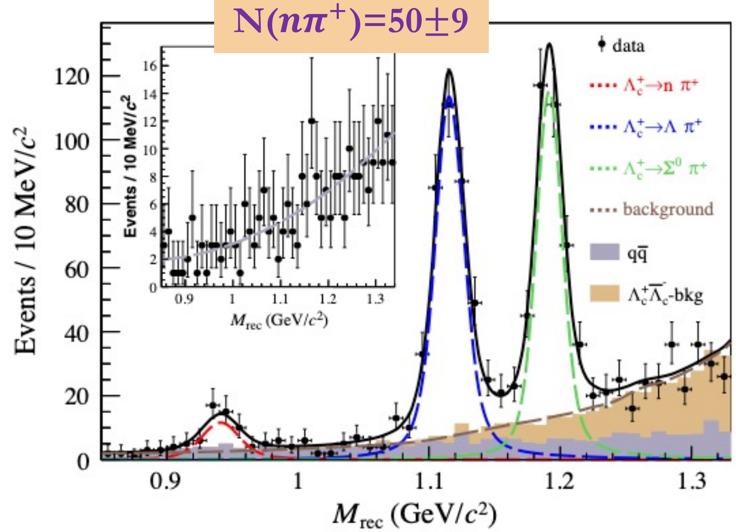
Λ^* state	CQM [8]	NRQM [9]	LFQM [10]	LQCD [11]
$\Lambda(1520)$	10.00	5.94	--	5.12 ± 0.82
$\Lambda(1600)$	4.00	1.26	(0.7 ± 0.2)	--
$\Lambda(1890)$	--	3.16×10^{-2}	--	--
$\Lambda(1820)$	--	1.32×10^{-2}	--	--

- 4.5fb^{-1} e^+e^- annihilation data are used to search $\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$, $pK_S^0\pi^- e^+\nu_e$
- No significant signal is observed and hence the upper limits on BFs are set to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e) < 3.9\times10^{-4}$ and $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e) < 3.3\times10^{-4}$ at 90% CL.
- $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+\nu_e) < 4.3\times10^{-3}$ and $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600) e^+\nu_e) < 9.0\times10^{-3}$ at 90% CL assuming all $\Lambda\pi^+\pi^-$ combinations come from Λ^*.
- Limited sensitivity to identify different theoretical calculations.

First observation of $\Lambda_c^+ \to n\pi^+$

PRL 128.142001 (2022).

$N(n\pi^+)=50\pm9$



- First singly Cabibbo-suppressed Λ_c^+ decay involved neutron was observed(7.3σ).

- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+)= \left(6.6 \pm 1.2_{stat} \pm 0.4_{syst}\right)\times10^{-4}$.
  =>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)]

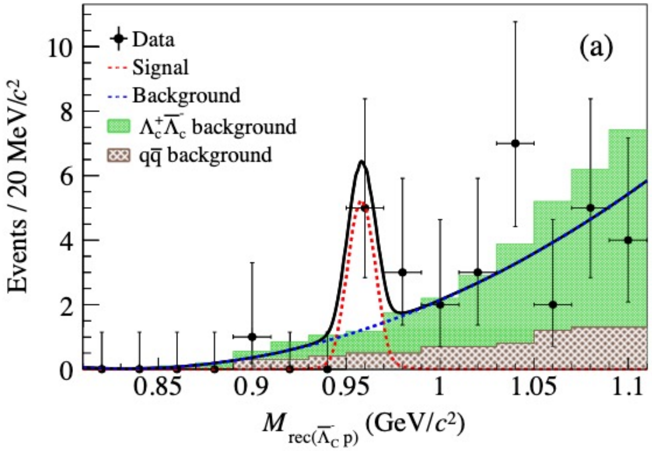
- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)= \left(1.31 \pm 0.08_{stat} \pm 0.05_{syst}\right)\times10^{-2}$=>Consistent with previous BESIII results
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)= \left(1.22 \pm 0.08_{stat} \pm 0.07_{syst}\right)\times10^{-2}$ =>Consistent with previous BESIII results

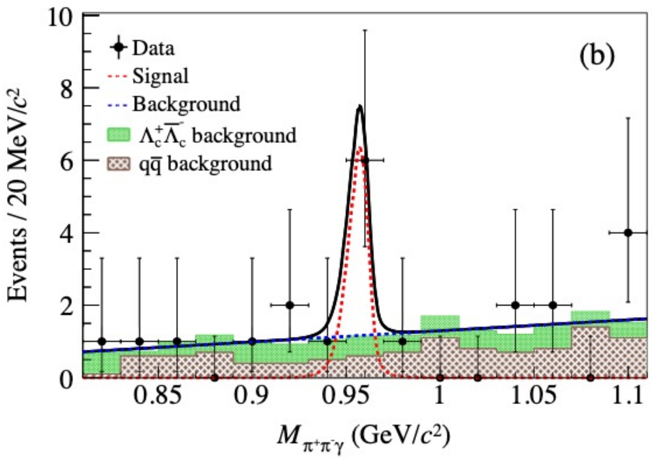
- $R = \frac{\mathcal{B}(\Lambda_c^+\to n\pi^+)}{\mathcal{B}(\Lambda_c^+\to p\pi^0)} > 7.2@90\%C.L.$ ($\mathcal{B}(\Lambda_c^+ \to p\pi^0)< 8.0\times10^{-5}$ @90%C.L.from Belle)
  =>Disagrees with SU(3) flavor asymmetry and dynamical calculation (2-4.7) while in consistent with SU(3) plus topological-diagram approach(9.6).

First observation of $\Lambda_c^+ \to p\eta'$

PRD 106.072002 (2022).

N($p\eta', \pi^+\pi^-\eta$)=$4.9^{+3.2}_{-2.6}$





N($p\eta', \gamma\pi^+\pi^-$)=$4.3^{+2.6}_{-2.2}$

TABLE VI. Comparison of the measured branching fraction (in 10^{-4}) of $\Lambda_c^+ \to p\eta'$ to theoretical predictions and the Belle result.

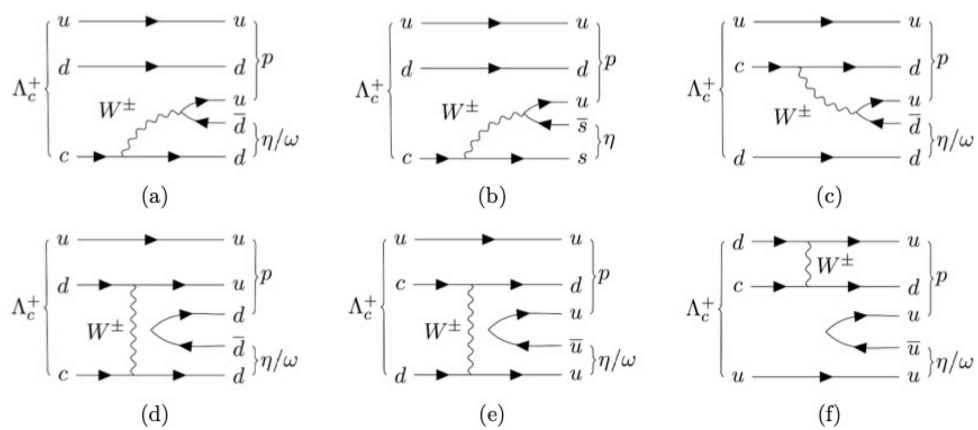
	$\Lambda_c^+ \to p\eta'$
BESIII	$5.62^{+2.46}_{-2.04} \pm 0.26$
Belle [19]	4.73 ± 0.97
Sharma *et al.* [41]	4–6
Uppal *et al.* [42]	0.4–2
Geng *et al.* [17]	$12.2^{+14.3}_{-8.7}$

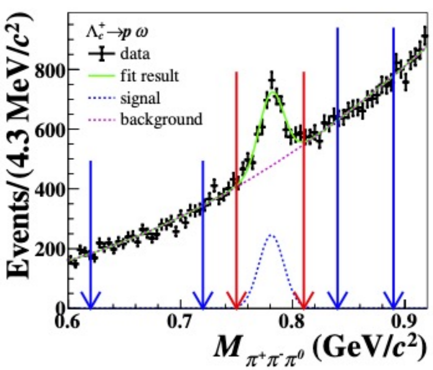
- An evidence of singly Cabibbo-suppressed $\Lambda_c^+ \to p\eta'$ decay was obtained(3.6σ).
- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \to p\eta')= (5.62^{+2.46}_{-2.04} \pm 0.26)\times 10^{-4}$.
  =>Consistent with Belle's relative measurement.
  => obviously higher than Constituent quark model
- The statistics of data is quite limited.

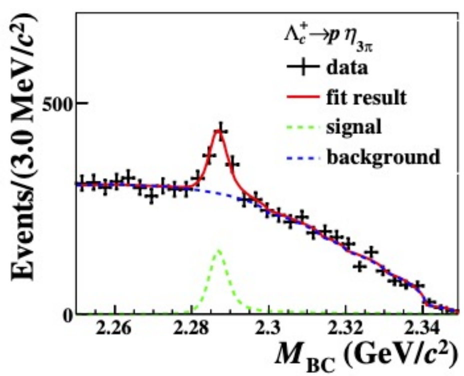
$\Lambda_c^+ \to p\eta, p\omega$

JHEP 11.137 (2023).

		$\mathcal{B}(\Lambda_c^+ \to p\eta)$	$\mathcal{B}(\Lambda_c^+ \to p\omega)$
BESIII		$1.24 \pm 0.28 \pm 0.10$ [22]	—
LHCb		—	$0.94 \pm 0.32 \pm 0.22$ [23]
Belle		$1.42 \pm 0.05 \pm 0.11$ [24]	$0.827 \pm 0.075 \pm 0.075$ [25]
This paper		$1.57 \pm 0.11 \pm 0.04$	$1.11 \pm 0.20 \pm 0.07$
Current algebra	Uppal [13]	0.3	—
	Cheng [26]	1.28	—
SU(3) flavor symmetry	Sharma [14]	$0.2^a(1.7^b)$	—
	Geng [27]	$1.25^{+0.38}_{-0.36}$	—
	Geng [28]	1.30 ± 0.10	—
	Hsiao [29]	1.24 ± 0.21	—
	Geng [30]	—	0.63 ± 0.34
	Hsiao [31]	—	1.14 ± 0.54
	Zhong [32]	$1.36^a(1.27^b)$	—
Topological diagram method	Hsiao [33]	1.42 ± 0.23^c (1.47 ± 0.28^d)	—
Heavy quark effective theory	Singer [34]	—	0.36 ± 0.02



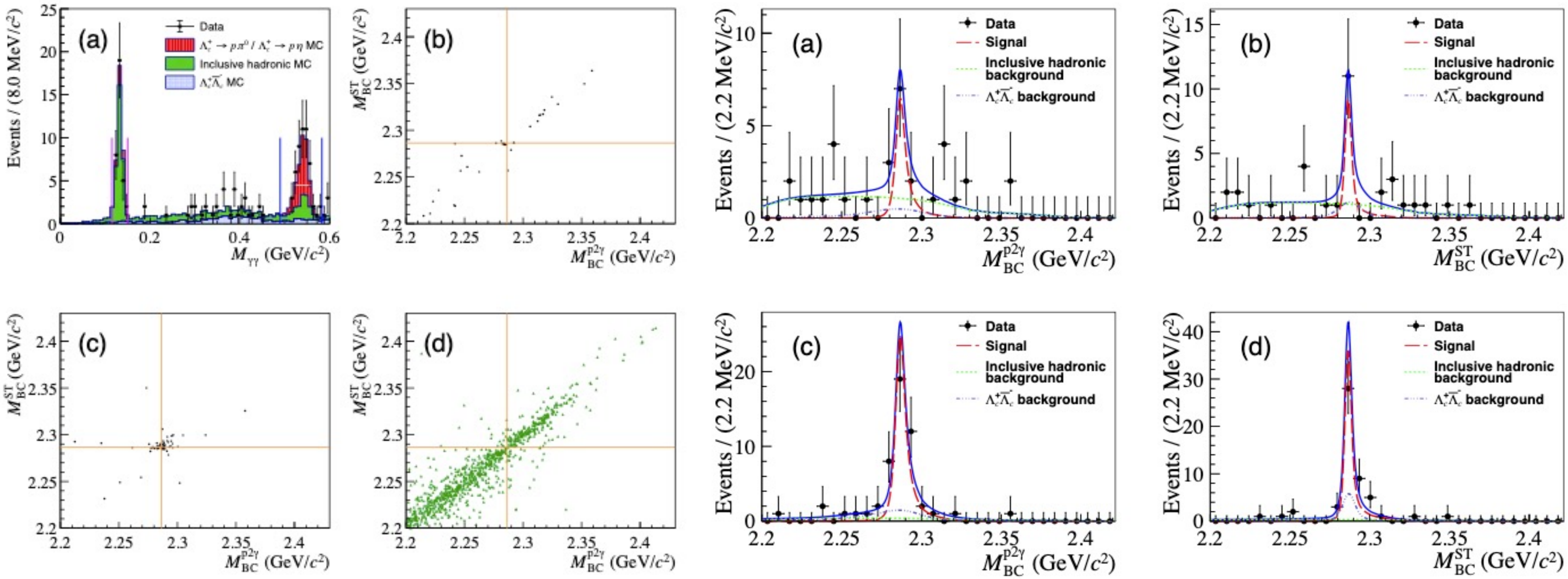




- $\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.57 \pm 0.11_{stat} \pm 0.04_{syst}) \times 10^{-3}$
- $\mathcal{B}(\Lambda_c^+ \to p\omega) = (1.11 \pm 0.20_{stat} \pm 0.07_{syst}) \times 10^{-3}$
- Most precise single measurement to date
- Provide more stringent test for different theoretical models.

$\Lambda_c^+ \to p\pi^0, p\eta$

arXiv2311.06883.



- Simultaneous fit to DT data sample at different c.m. energies, yields
- $\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.63 \pm 0.31_{stat} \pm 0.11_{syst})\times 10^{-3}$ [6.9σ]=》 precision worse than ST method.
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.20)\times 10^{-4}$ [3.7σ]=> first evidence
- result distinctly exceeds the upper limit measured by Belle($< 8.0\times 10^{-5}$)
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0) = 4.2^{+2.2}_{-1.9}$=> consistent with various phenomenological predictions

BF measurement of $\Lambda_c^+ \to \Lambda K^+$

PRD 106.L111101 (2022)

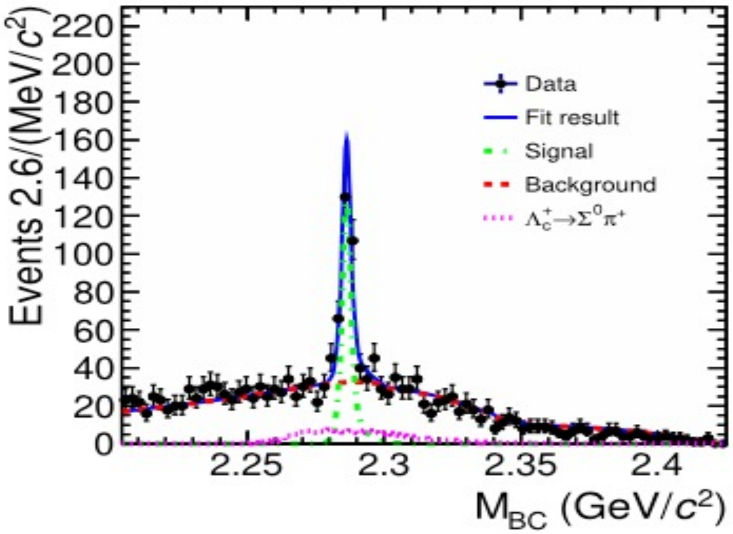


TABLE I. Theoretical predictions on the branching fraction of $\Lambda_c^+ \to \Lambda K^+$.

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

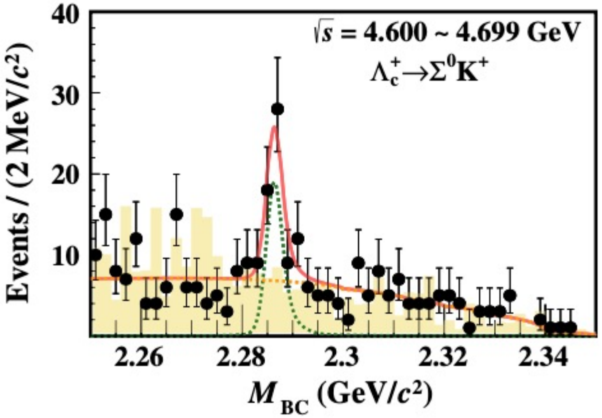
- Singly Cabibbo-suppressed BF are measured relative to the CF process.
- $R = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+)} = (4.78 \pm 0.34_{stat} \pm 0.20_{syst})\%$
  =>Consistent with Belle $(7.4 \pm 1.0_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}})\%$ and BaBar $(4.4 \pm 0.4_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}})\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.21 \pm 0.44_{stat} \pm 0.26_{syst} \pm 0.34_{ref})\times 10^{-4}$
  =>significantly lower(~40%) than the prediction based on pure SU(3) flavor symmetry, constituent quark model and current algebra. =>nonfactorizable contribution are underestimated?

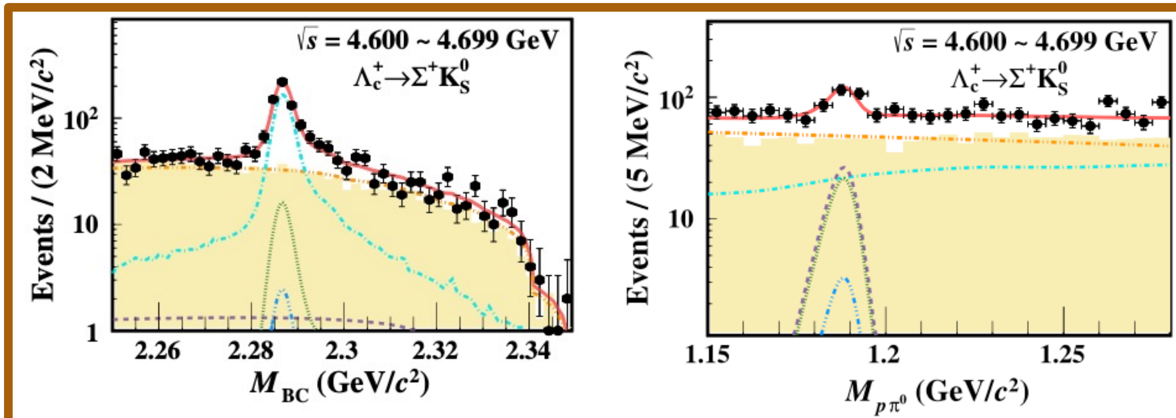
BF measurement of $\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_s^0$

PRD 106.052003 (2022).

N($\Sigma^0 K^+$)=43.4±4.2

N($\Sigma^+ K_s^0$)=43.6±6.0





- Two singly Cabibbo-suppressed decays which only receive nonfactorizable contribution are observed.
- 2D fitting is performed for $\Lambda_c^+ \to \Sigma^+ K_s^0$ since the contamination of $\Lambda_c^+ \to p K_s^0 \pi^0$

- $R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)} = 0.0361 \pm 0.0073_{stat} \pm 0.0005_{syst}$

  $R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-)} = 0.0106 \pm 0.0031_{stat} \pm 0.0004_{syst}$

- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (4.7 \pm 0.9_{stat} \pm 0.1_{syst} \pm 0.3_{ref}) \times 10^{-4}$

  $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_s^0) = (4.8 \pm 1.4_{stat} \pm 0.2_{syst} \pm 0.3_{ref}) \times 10^{-4}$

  First measurement for $\Lambda_c^+ \to \Sigma^+ K_s^0$.

  $\Lambda_c^+ \to \Sigma^0 K^+$ is consistent and comparable with Belle and BaBar.

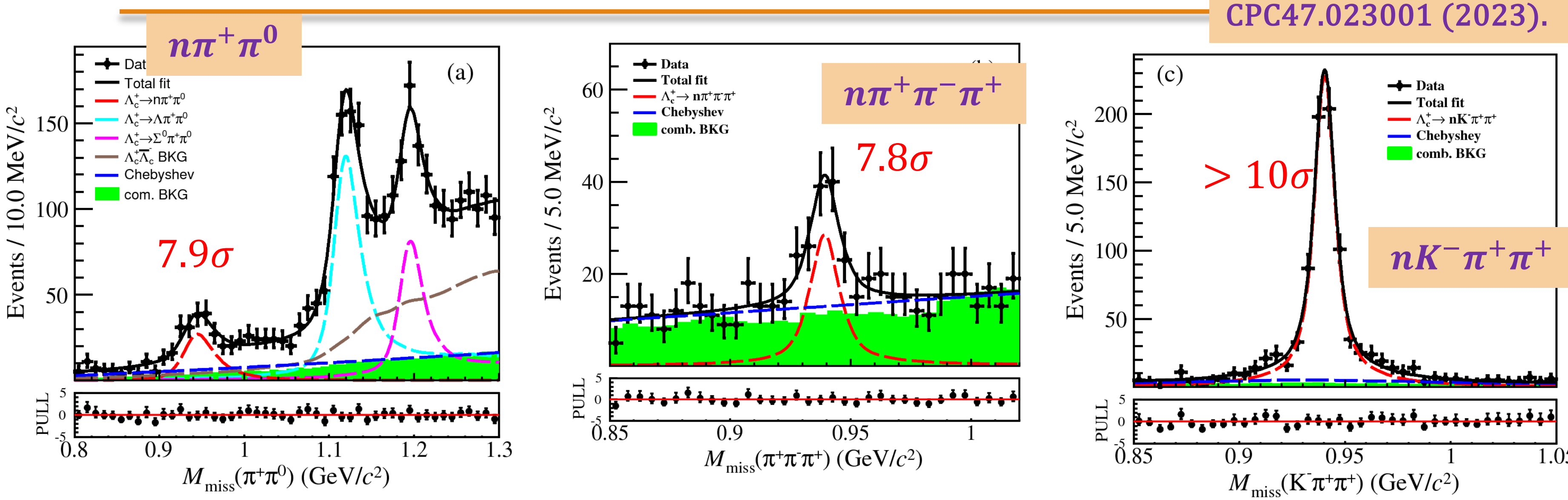
  In consistent with SU(3) flavor symmetry.

TABLE I. Comparison of various theoretical predictions and the experimental values for $\mathcal{B}(\Lambda_c^+ \to \Sigma K)$ (in unit of 10^{-4}). In Ref. [2], alternative assignments to QCD corrections give different predictions as shown in the parentheses. The theoretical uncertainties in Ref. [3] are estimated to be 25%, arising from a slight change of the MIT bag radius.

	$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$
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	...

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

CPC47.023001 (2023).



- Two singly Cabibbo-suppressed $\Lambda_c^+ \to n\pi^+\pi^0$、$n\pi^+\pi^-\pi^+$ decays and one CF $\Lambda_c^+ \to nK^-\pi^+\pi^+$ was firstly observed.
- Absolute BFs are measured to be

  $\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0) = (0.64 \pm 0.09_{stat} \pm 0.02_{syst})\%$

  $\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+) = (0.45 \pm 0.07_{stat} \pm 0.03_{syst})\%$

  $\mathcal{B}(\Lambda_c^+ \to nK^-\pi^+\pi^+) = (1.90 \pm 0.08_{stat} \pm 0.09_{syst})\%$
- $\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0)} = 0.72 \pm 0.11$ =>crucial inputs for SU(3) flavor symmetry.
- $\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0)}{\mathcal{B}(\Lambda_c^+ \to n\pi^+)} = 9.7 \pm 2.4$ => intermediate resonances contributions needs to decouple.
- $\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to nK^-\pi^+\pi^+)} = 0.24 \pm 0.04$=>consistent with $|V_{cd}|/|V_{cs}| = 0.224 \pm 0.005$.

$\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$

PRD 109.072010(**2024**).

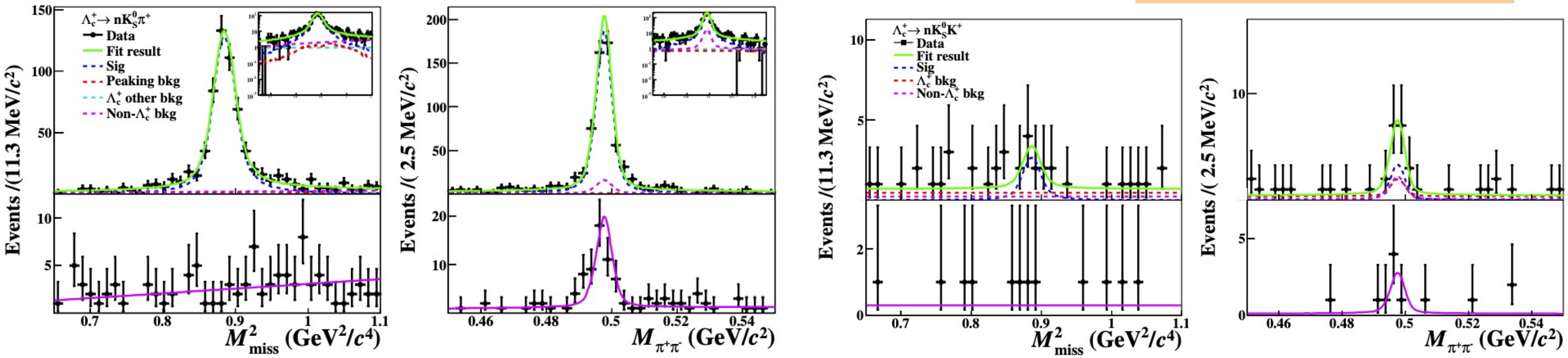


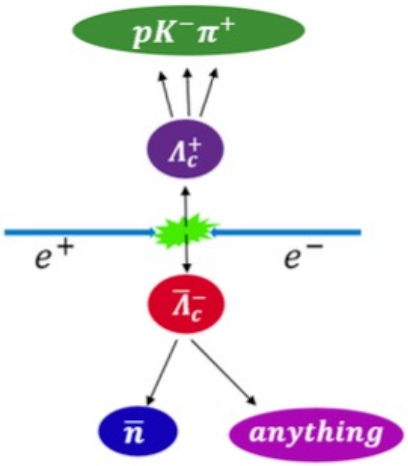
TABLE VI. Comparisons of the BFs of $\Lambda_c^+ \to nK_S^0\pi^+$ and $\Lambda_c^+ \to nK_S^0K^+$ between experimental measurements and theoretical predictions.

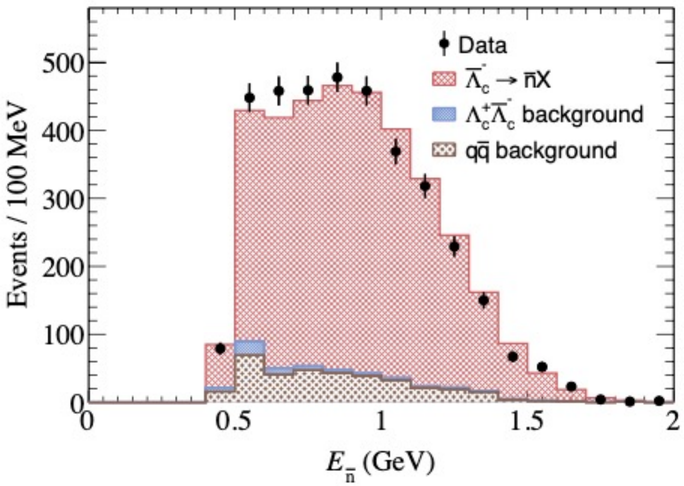
	$n\bar{K}^0\pi^+$ ($\times 10^{-2}$)	$n\bar{K}^0K^+$ ($\times 10^{-4}$)
Geng [33]	0.9 ± 0.8	59 ± 13
Cen [34]	1.1 ± 0.1	31 ± 9
Previous result [7]	3.64 ± 0.50	-
This work	$3.72 \pm 0.16 \pm 0.08$	$8.6^{+3.7}_{-3.0} \pm 0.7$

- The precision of $\mathcal{B}(nK_S^0\pi^+)$ improved by a factor of 2.8
- First evidence for singly-Cabibbo-suppressed decay $\Lambda_c^+ \to nK_S^0K^+$[3.7$\sigma$]
- Tension with SU(3) flavor symmetry prediction=>More detailed dynamic analysis should be further studied.

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

PRD 108.L031101 (2023).

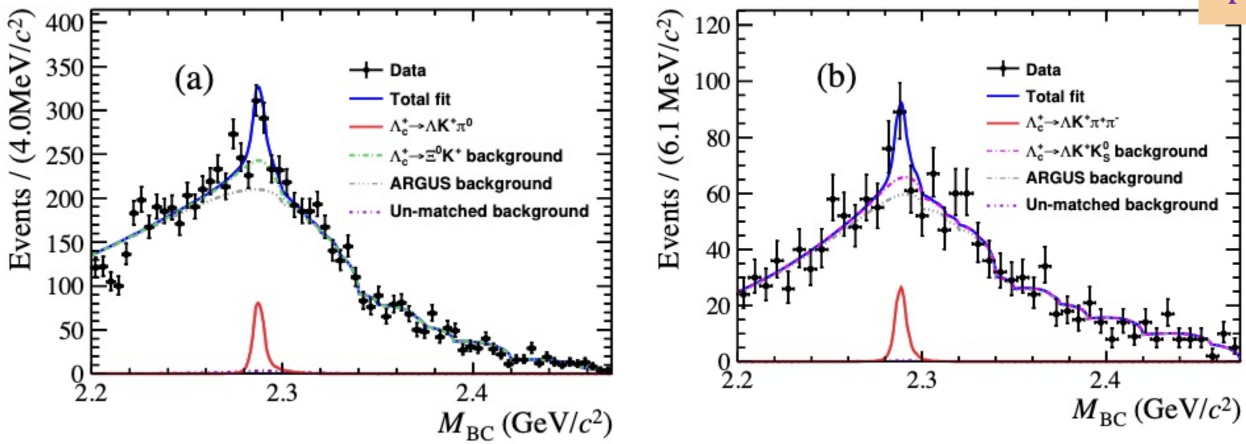




- The deposited energy in EMC is used to identify $\bar{n}$.
- Data-driven technique to model $\bar{n}$ behavior in the detector.
- Absolute BFs are measured to be $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n}X) = (33.5 \pm 0.7_{stat} \pm 1.2_{syst})\%$, precision up to 4%.
- All known exclusive process 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.

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

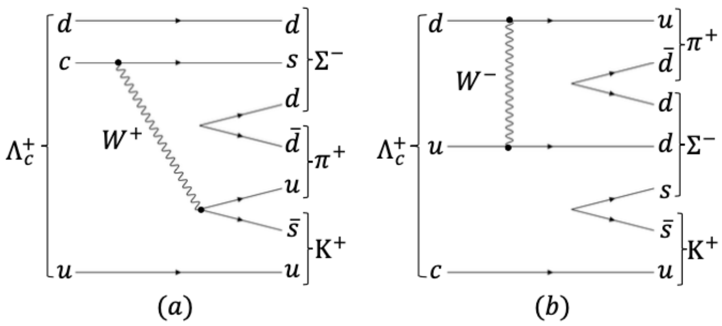
PRD 109.032003(2024).

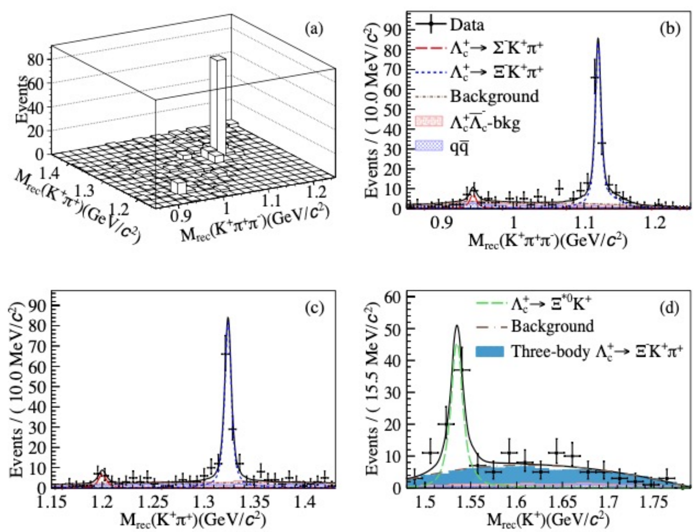


- First observation of the singly Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda K^+\pi^0$ [5.7σ]
- First evidence of the singly Cabibbo-suppressed decay $\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-$[3.1$\sigma$]
- $\frac{\mathcal{B}(\Lambda_c^+\to\Lambda K^+\pi^0)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)} = (2.09 \pm 0.39_{stat} \pm 0.07_{syst})\times10^{-2}$
- $\frac{\mathcal{B}(\Lambda_c^+\to\Lambda K^+\pi^+\pi^-)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^+\pi^-)} = (1.13 \pm 0.41_{stat} \pm 0.06_{syst})\times10^{-2}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^0) = (1.49 \pm 0.27_{stat} \pm 0.05_{syst} \pm 0.08_{ref})\times10^{-3}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-) = (4.13 \pm 1.48_{stat} \pm 0.20_{syst} \pm 0.33_{ref})\times10^{-4}$
- 3.5σ deviation with SU(3) flavor symmetry prediction.

$\Lambda_c^+ \to \Sigma^- K^+ \pi^+$

PRD(L) 109.L071103(**2024**)

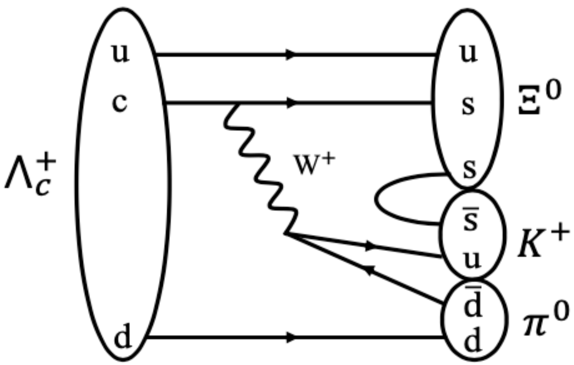


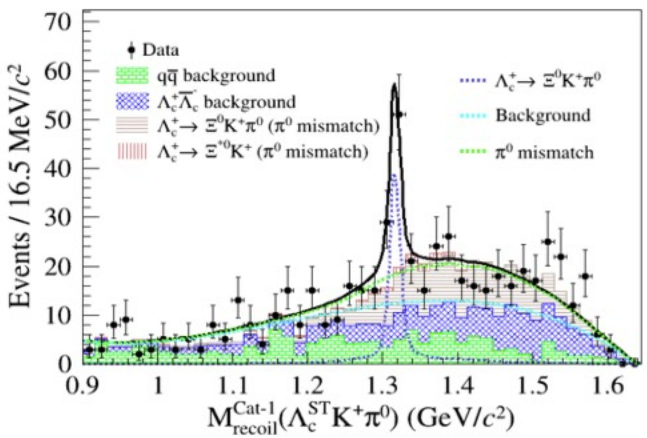


- $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ is the simplest singly Cabibbo Suppressed process with a Σ^- directly in the final state.
- BESIII firstly observe $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ with significance of 6.4σ
- The branching fraction is measured to be $(3.8 \pm 1.3_{stat} \pm 0.2_{syst}) \times 10^{-4}$
- $\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^- K^+ \pi^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+)} = (2.03 \pm 0.72) \times 10^{-2} \sim (0.4 \pm 0.1) s_c^2$ =>indicates the nonfactorization contribution is important.

$\Lambda_c^+ \to \Xi^0 K^+ \pi^0$

PRD 109.052001(**2024**).





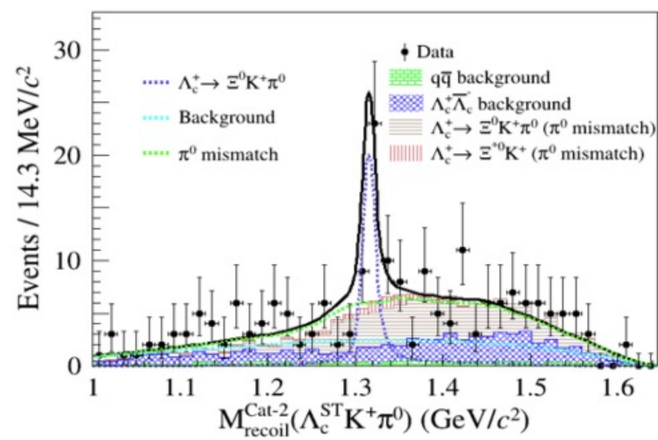


Table 9. The comparison between the measurement and theoretical predictions ($\times 10^{-3}$).

	$\Lambda_c^+ \to \Xi(1530)^0 K^+$	$\Lambda_c^+ \to \Xi^0 K^+ \pi^0$	$\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$	$\Lambda_c^+ \to \Lambda K^+ \pi^0$	$\Lambda_c^+ \to n K^+ \pi^0$
This measurement	$5.99 \pm 1.04 \pm 0.29$	$7.79 \pm 1.46 \pm 0.71$	< 1.8	< 2.0	< 0.71
K. K. Sharma *et al* . [23]	–	45 ± 8	1.2 ± 0.3	4.5 ± 0.8	0.05 ± 0.005
Jian-Yong Cen *et al* . [24]	–	32 ± 6	0.7 ± 0.2	3.5 ± 0.6	0.05 ± 0.006
$\mathcal{B}$(previous results) [48]	$5.02 \pm 0.99 \pm 0.31$	–	–	–	–

- CF $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ are observed with significance of 8.6σ
- $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+ \pi^0) = (7.79 \pm 1.46_{stat} \pm 0.71_{syst}) \times 10^{-3}$=>Smaller than theoretical predictions