粲重子Λ_c^+极化参数的研究

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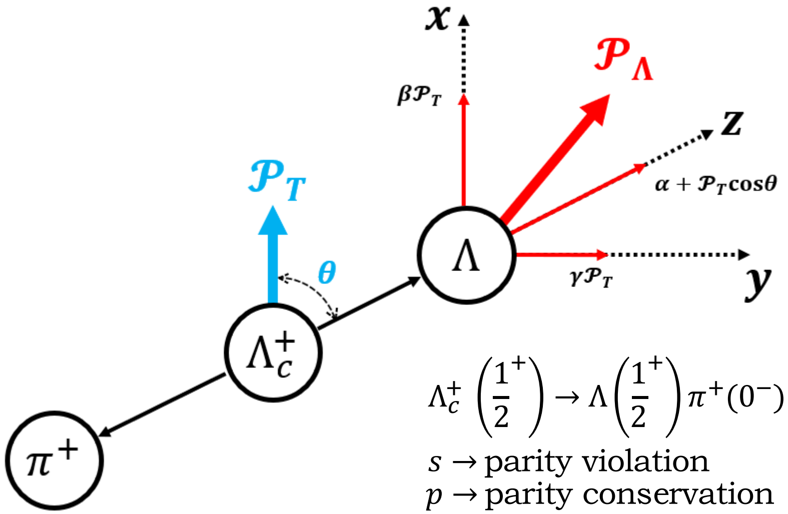
outline

- Polarization in weak decay
- Digging more information
  - Dynamic parameters? Phase shift? CPV observables?
- Experiment & Phenomenon
- Methods for measurement
  - Angular analysis? Partial wave analysis?
- New results coming soon
- BEPCII-U
- Summary

Polarization in weak decay



$\Lambda_c^+\left(\frac{1}{2}^+\right) \to \Lambda\left(\frac{1}{2}^+\right)\pi^+(0^-)$

$s \to$ parity violation
$p \to$ parity conservation

$$\mathcal{P}_\Lambda = \frac{(-\alpha - \mathcal{P}_T\cdot\hat{n}_z)\hat{n}_z + \beta(\mathcal{P}_T\times\hat{n}_z) + \gamma\hat{n}_z\times(\mathcal{P}_T\times\hat{n}_z)}{1+\alpha\mathcal{P}_T\cdot\hat{n}_z}$$

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

$$\alpha^2+\beta^2+\gamma^2 = 1$$

If party violation exists: $\boldsymbol{\alpha}$, $\boldsymbol{\beta \neq 0}$, $\boldsymbol{\gamma \neq -1}$

- **Another definition:**

$$\alpha = \frac{\left|H_{\frac{1}{2}}\right|^2 - \left|H_{-\frac{1}{2}}\right|^2}{\left|H_{\frac{1}{2}}\right|^2 + \left|H_{-\frac{1}{2}}\right|^2} \quad \beta = \sqrt{1-\alpha^2}\sin\Delta \quad \gamma = \sqrt{1-\alpha^2}\cos\Delta \quad \Delta = \delta_{-\frac{1}{2}} - \delta_{\frac{1}{2}}$$

$$\alpha^2+\beta^2+\gamma^2 = 1$$

- **Transform using a simple linear relation**

Two-body decay with extremely narrow width

$$H^{0\to 1+2}_{\lambda_1,\lambda_2} = \sum_{ls} g_{ls}\sqrt{\frac{2l+1}{2J_0+1}}\langle ls, 0\ \delta|J_0,\delta\rangle\langle J_1 J_2, \lambda_1-\lambda_2|s,\delta\rangle\left(\frac{q}{q_0}\right)^l B_l'(q,q_0,d)$$

equal to one

Digging more information

The amplitude for the two-body weak decay $B_i \to B_f + P$ can be parameterized as

$$M(B_i \to B_f + P) = i\bar{u}_f(A - B\gamma_5)u_i$$

$A \to s, B \to p/\kappa$

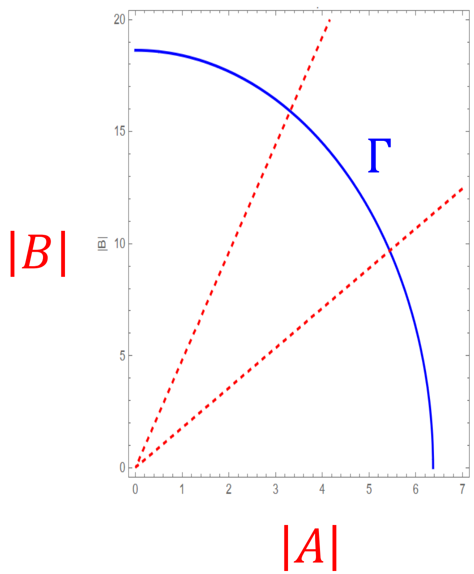
$\kappa = |\vec{p}_c|/(E_\Lambda + m_\Lambda)$

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

$$\alpha = \frac{2\kappa|A||B|\cos(\delta_p - \delta_s)}{|A|^2 + \kappa^2|B|^2}$$

$$\Delta = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2}$$

Three unknowns and three independent equations



$$\gamma = \frac{|A|^2 - \kappa^2|B|^2}{|A|^2 + \kappa^2|B|^2}$$

✓ Once $\gamma > 0$ or $\gamma < 0$, one solution will be determined.

Digging more information

➢ For CPV observables

$$s = |s|e^{i\xi_s}e^{i\phi_s} \xrightarrow[\text{transformation}]{\text{under CP}} \bar{s} = -|s|e^{i\xi_s}e^{-i\phi_s}$$

$$p = |p|e^{i\xi_p}e^{i\phi_p} \qquad \bar{p} = |p|e^{i\xi_p}e^{-i\phi_p}$$

ϕ weak phase, ξ strong phase

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

- If CP conserved:

$$s \xrightarrow{\text{CP}} -s$$

$$p \xrightarrow{\text{CP}} p$$

- Thus:

$$\alpha \xrightarrow{\text{CP}} \bar{\alpha} = -\alpha$$

$$\beta \xrightarrow{\text{CP}} \bar{\beta} = -\beta$$

$$\gamma \xrightarrow{\text{CP}} \bar{\gamma} = +\gamma$$

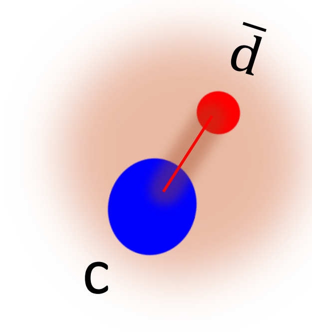
$$A_{CP}^{\alpha} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = \tan\phi_{CP}\tan\Delta_S$$

$$\tan\phi_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} = \frac{\sqrt{1-\alpha^2}\sin\Delta + \sqrt{1-\bar{\alpha}^2}\sin\bar{\Delta}}{\alpha-\bar{\alpha}}$$

$$\tan\Delta_S = \frac{\beta-\bar{\beta}}{\alpha-\bar{\alpha}} = \frac{\sqrt{1-\alpha^2}\sin\Delta - \sqrt{1-\bar{\alpha}^2}\sin\bar{\Delta}}{\alpha-\bar{\alpha}}$$

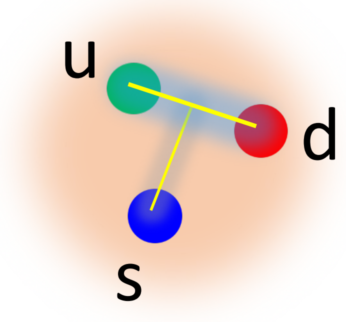
Λ_c^+: The lightest charmed baryon spectroscopy

- 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



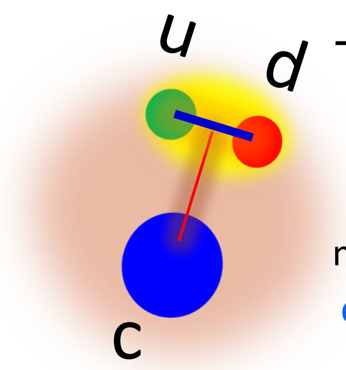
→ Charmed meson
($D^+[c\bar{d}]$)

$m_d << m_c$ →
quark + heavy quark
(q) (Q)



→ Strange baryons
(Λ[uds])

m_u, $m_d \approx m_s$ →
(qqq) uniform

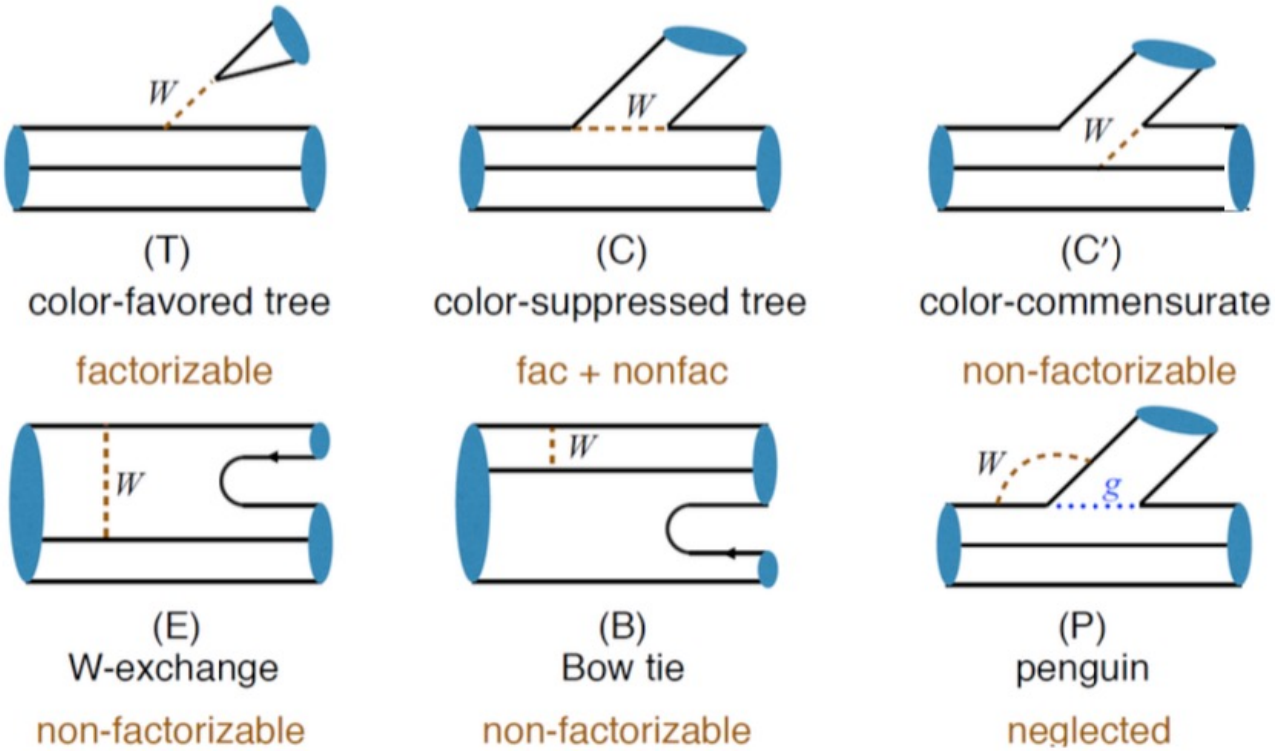


→ Charmed baryon
(Λ_c[udc])

m_u, $m_d << m_c$ →
diquark + quark
(qq) (Q)

Λ_c^+ weak decay picture in theory

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



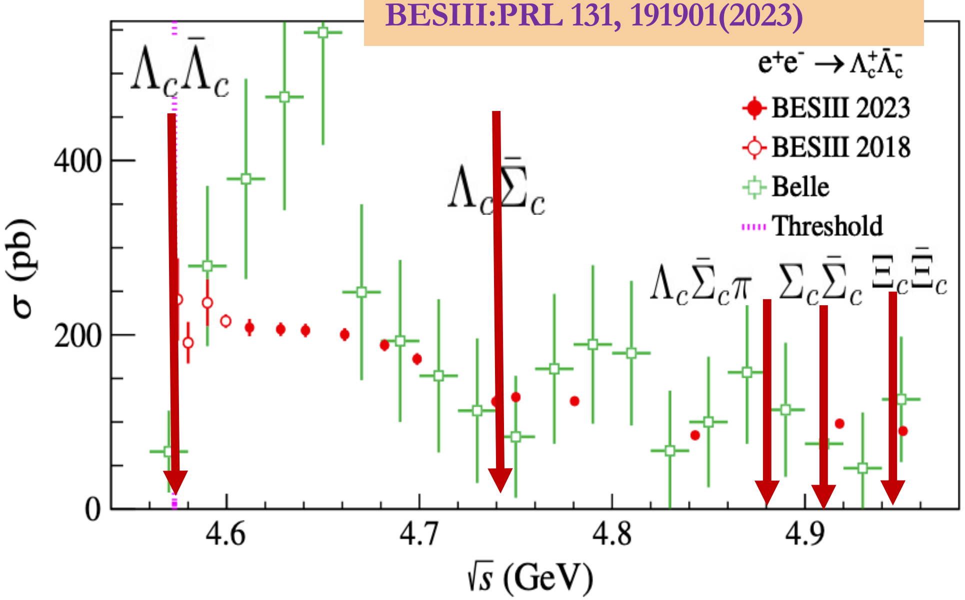
- Phenomenology aim at explain data and predict important observables.
- Calculate what they can(HQET, factorization)+parametrize what they cannot + some non-perturbations extracted from data=> explain and predict.

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%

Belle: PRL 101, 172001 (2008)
BESIII:PRL 131, 191901(2023)



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

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	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
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
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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.

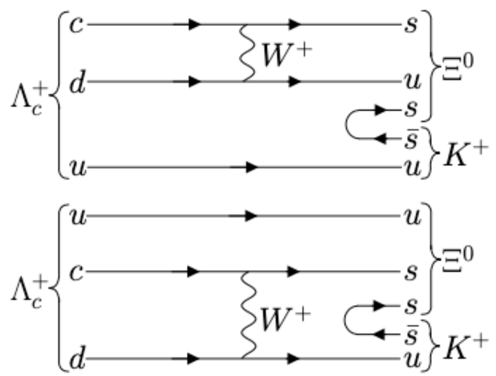

FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

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

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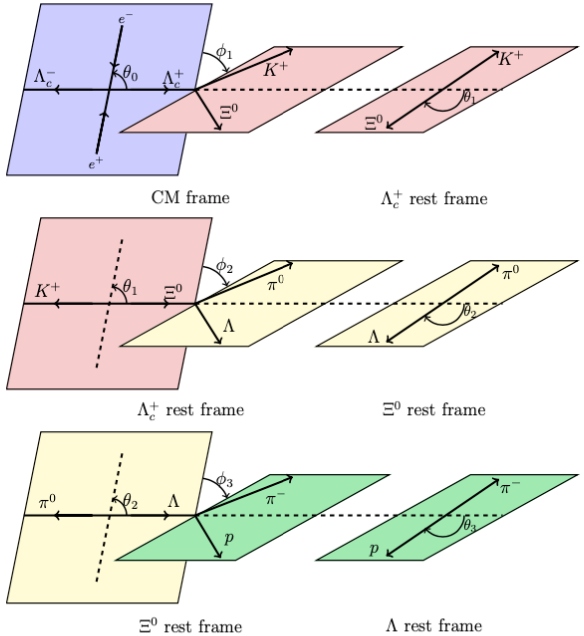
$$\alpha_{BP} = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2}, \quad \gamma_{BP} = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

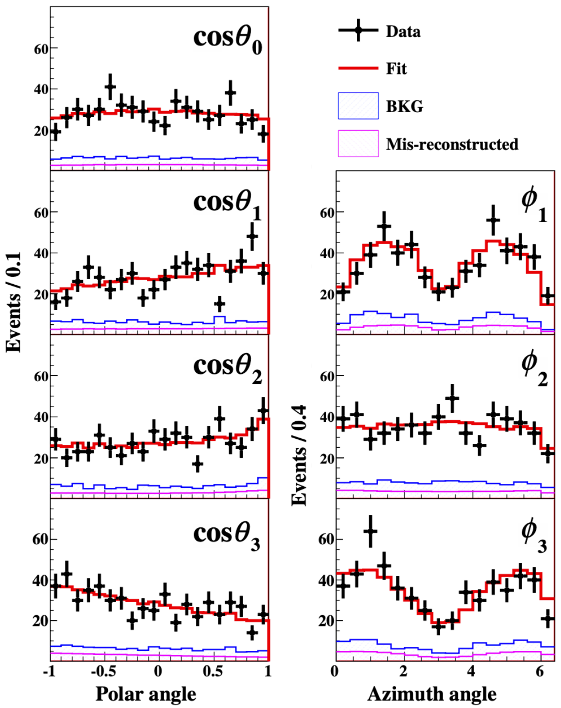
Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	D_{λ_5}

$$
\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_{\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}
$$



- 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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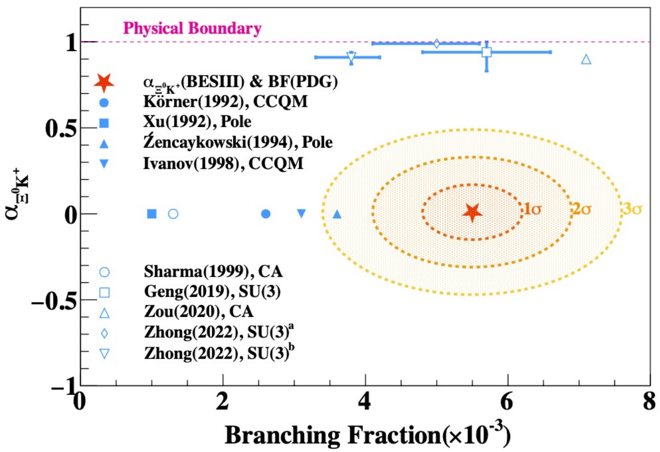
- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$

- $\alpha_{\Xi^0 K^+}$ 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	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0K^+}$
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	-
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), IR [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.92
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	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
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]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
~$587pb^{-1}$ 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	$0.91^{+0.03}_{-0.04}$
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	-

~$6.4fb^{-1}$ 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**

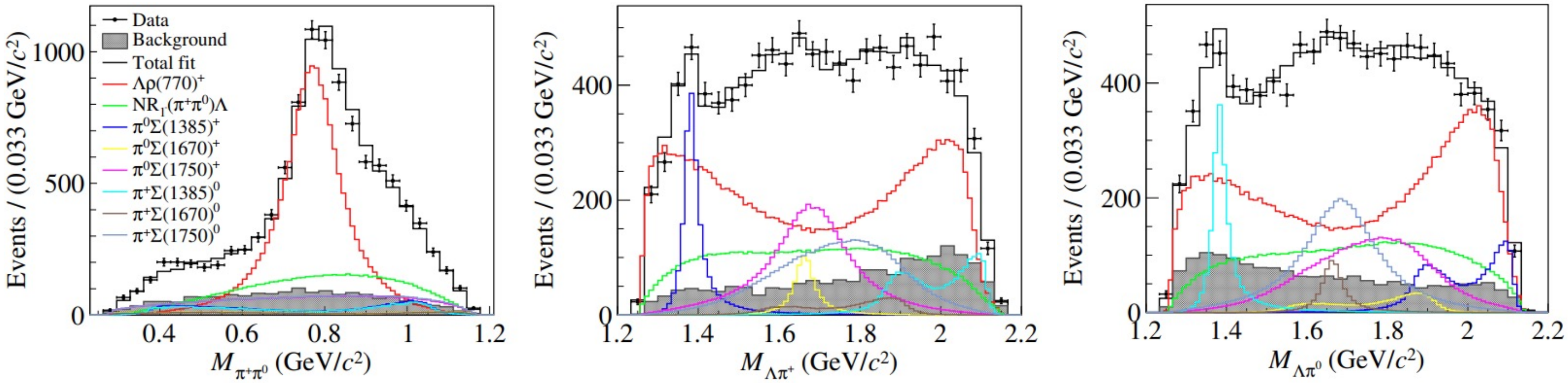
s and p of all intermediate resonance states

- ✓ 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



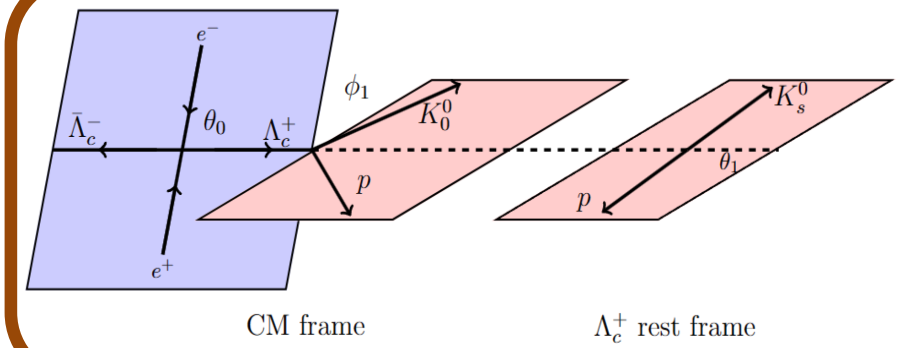
	Result
$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+\to\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.18 \pm 0.60 \pm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

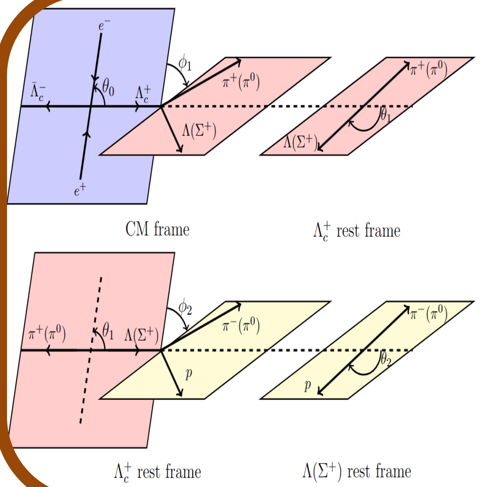
More multi-body decays are underway!

- ✓ $\Lambda_c^+ \to pK^-\pi^+$
- ✓ $\Lambda_c^+ \to \Lambda^0\pi^+\eta$
- ✓ $\Lambda_c^+ \to pK^-\pi^+\pi^0$
- ✓ $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$
- ✓ $\Lambda_c^+ \to pK_S^0\pi^0$
- ✓ $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$
- ✓ $\Lambda_c^+ \to nK_S^0\pi^+$
- ✓ …

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

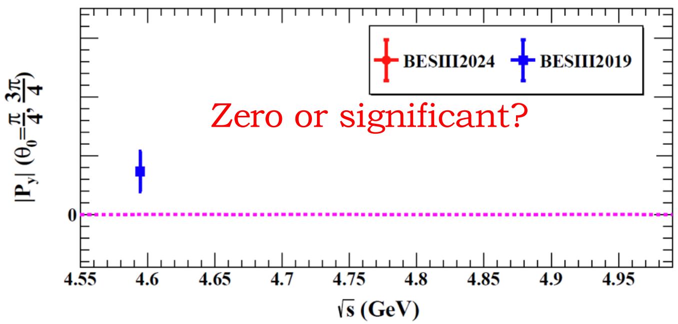
New Λ_c^+ polarization on BESIII

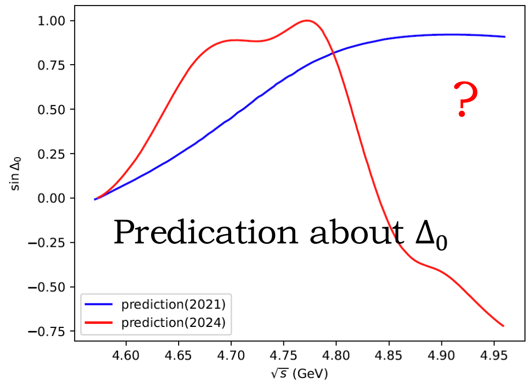
— Transverse polarization with energy from 4.60-4.95 GeV combined with $\Lambda_c^+ \to pK^-\pi^+$ channel(fixed all decay info. with LHCb input).

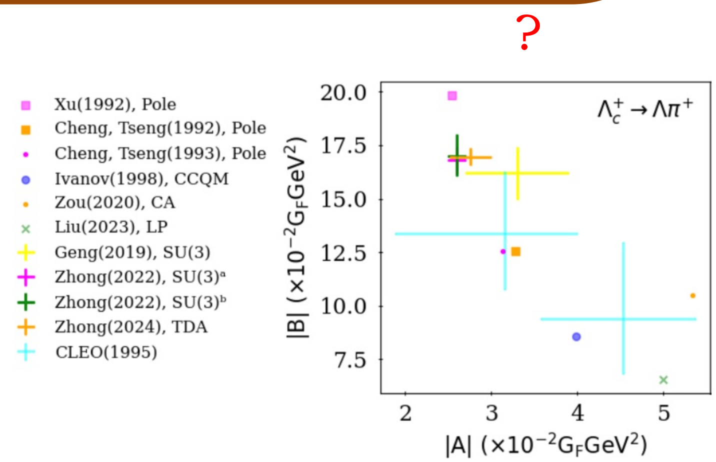
— Update 4 two-body decays polarization parameters with higher precision

— Strong/Weak phase shift

— α-induced CPV observables





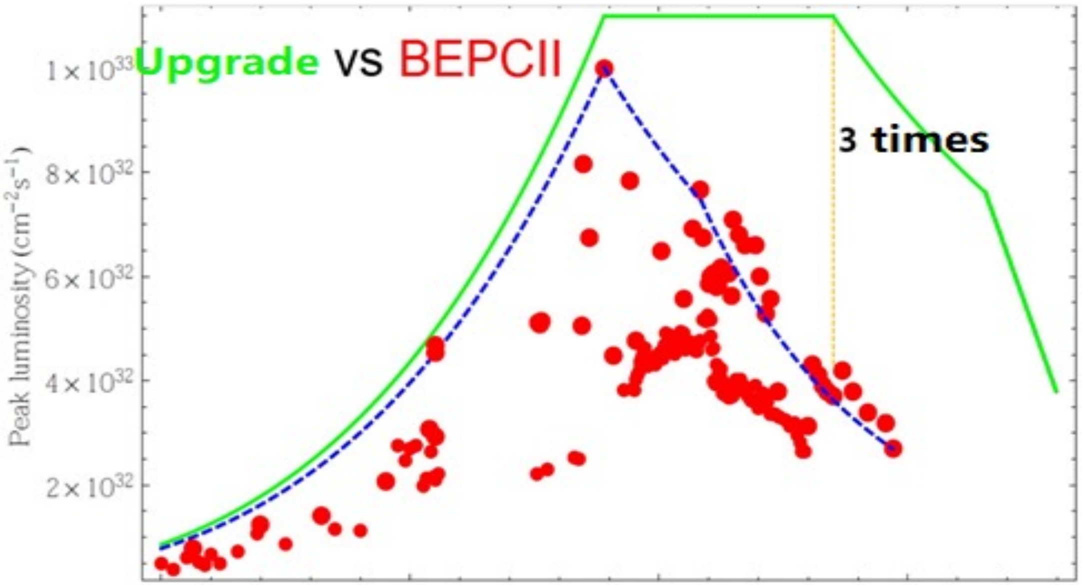


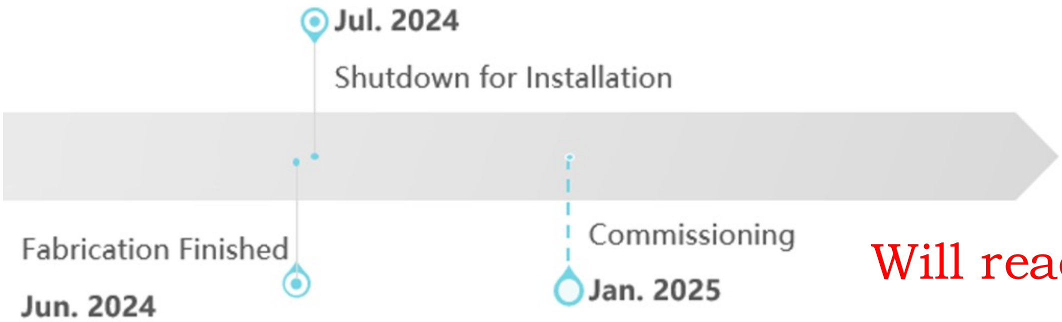
Eur. Phys. J. Plus 136, no.9, 949 (2021)
Chinese Physics Letters 41, 021302 (2024)

coming soon!

BEPCII-U

- The polarization of weak decay can bring us more information.
- More data needs to be collected.
- optimized energy at 2.35 GeV with luminosity 3 times higher than the current BEPCII.





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

Will reach the thresholds of Ξ_c^0 and Ξ_c^+.

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

- ✓ BESIII collected a large amount of Λ_c^+ data near the threshold, which enable polarization parameters to be measured.
- ✓ Polarization can help us obtain more weak decay information, such as amplitude magnitude, strong phase shift, and CPV observables.
- ✓ Especially with strong phase shift, the performance of Λ_c^+ and hyperons is completely different, which requires further verification with more data.

Summary

- ✓ Partial wave analysis is an effective tool for analyzing multibody decay, and the polarization of many two-body processes in multibody decay is measuring.
  - ✓ $\Lambda_c^+ \to pK^-\pi^+$
  - ✓ $\Lambda_c^+ \to \Lambda^0\pi^+\eta$
  - ✓ $\Lambda_c^+ \to pK^-\pi^+\pi^0$
  - ✓ $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$
  - ✓ $\Lambda_c^+ \to pK_S^0\pi^0$
  - ✓ $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$
  - ✓ $\Lambda_c^+ \to nK_S^0\pi^+$
  - ✓ …
- ✓ More measurement information about $\Lambda_c^+ \to pK_S^0/\Lambda^0\pi^+/\Sigma^0\pi^+/\Sigma^+\pi^0$ will be released soon.
- ✓ BEPCII-U will help us give more interesting information about Λ_c^+ and $\Xi_c^{0/+}$.
- ✓ More contributions from Belle(II) and LHCb are expected.

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Thanks

Polarization in weak decay

The beginning of all…

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

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(Received October 22, 1957)

THIS note is to consider the general problem of the decay of a hyperon of spin $\frac{1}{2}$ into a pion and a nucleon under the general assumption of possible violations of parity conservation, charge-conjugation invariance, and time-reversal invariance. The discussion is in essence a partial wave analysis of the decay phenomena and is independent of the dynamics of the decay.

Experimental Test of Parity Conservation in Beta Decay*

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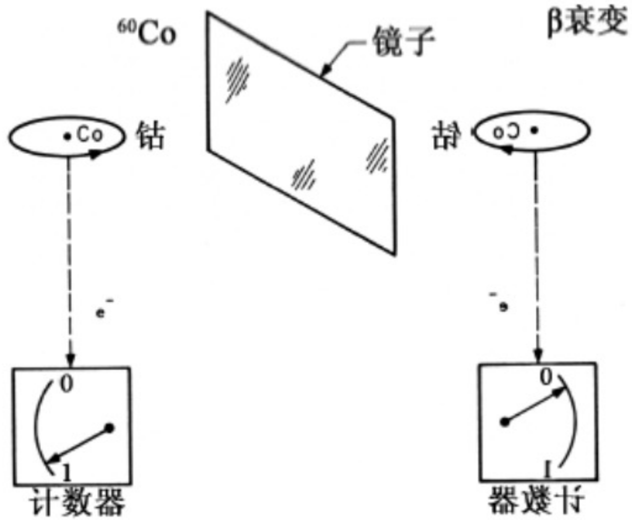
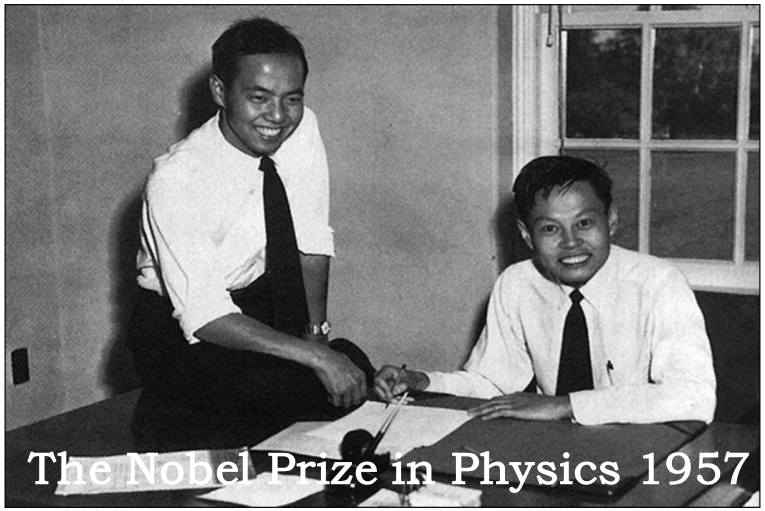
IN a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation.





The Nobel Prize in Physics 1957

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

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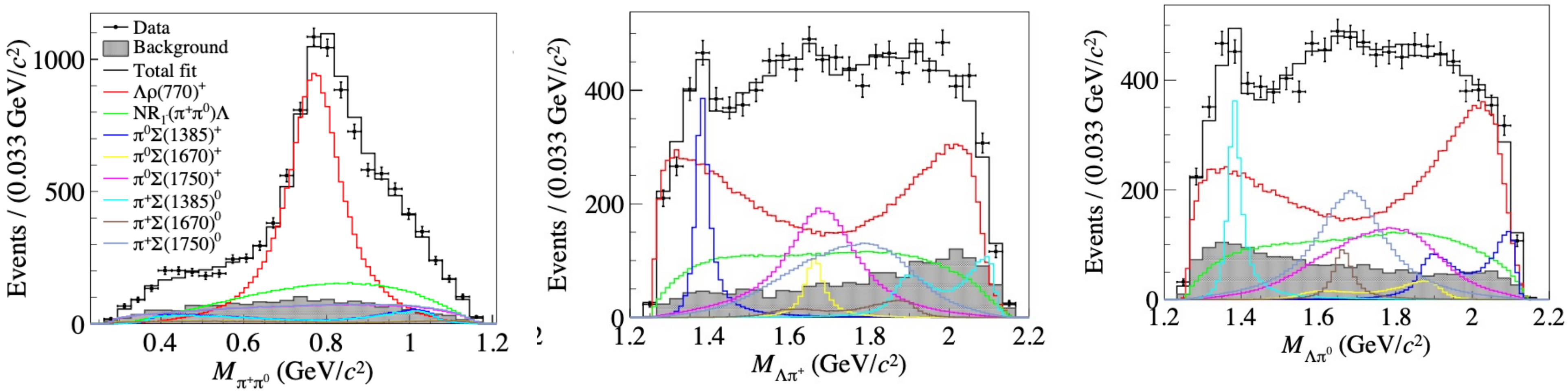

Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-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 $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

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$\frac12^+(\Lambda_c^+)\to\frac32^+(\Sigma(1385)^+)+0^-(\pi^0)$			$\frac12^+(\Lambda_c^+)\to\frac32^+(\Sigma(1385)^0)+0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1385)^+}_{1,\frac32}$	1.0 (fixed)	0.0 (fixed)	$g^{\Sigma(1385)^0}_{1,\frac32}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1385)^+}_{2,\frac32}$	1.29 ± 0.25	2.82 ± 0.18	$g^{\Sigma(1385)^0}_{2,\frac32}$	1.70 ± 0.38	2.70 ± 0.22
$\frac12^+(\Lambda_c^+)\to\frac32^-(\Sigma(1670)^+)+0^-(\pi^0)$			$\frac12^+(\Lambda_c^+)\to\frac32^-(\Sigma(1670)^0)+0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1670)^+}_{1,\frac32}$	1.0 (fixed)	0.0 (fixed)	$g^{\Sigma(1670)^0}_{1,\frac32}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1670)^+}_{2,\frac32}$	1.39 ± 0.42	0.85 ± 0.26	$g^{\Sigma(1670)^0}_{2,\frac32}$	0.74 ± 0.18	0.29 ± 0.24
$\frac12^+(\Lambda_c^+)\to\frac12^-(\Sigma(1750)^+)+0^-(\pi^0)$			$\frac12^+(\Lambda_c^+)\to\frac12^-(\Sigma(1750)^0)+0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g^{\Sigma(1750)^+}_{0,\frac12}$	1.0 (fixed)	0.0 (fixed)	$g^{\Sigma(1750)^0}_{0,\frac12}$	1.0 (fixed)	0.0 (fixed)
$g^{\Sigma(1750)^+}_{1,\frac12}$	0.45 ± 0.10	-2.28 ± 0.22	$g^{\Sigma(1750)^0}_{1,\frac12}$	0.38 ± 0.10	-2.03 ± 0.20
$\frac12^+(\Lambda_c^+)\to\frac12^+(\Lambda)+1^-(\rho(770)^+)$			$\frac12^+(\Lambda_c^+)\to\frac12^+(\Lambda)+1^-(NR_{1^-})$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g^{\rho}_{0,\frac12}$	1.0 (fixed)	0.0 (fixed)	$g^{NR}_{0,\frac12}$	1.0 (fixed)	0.0 (fixed)
$g^{\rho}_{1,\frac12}$	0.48 ± 0.12	-1.69 ± 0.12	$g^{NR}_{1,\frac12}$	0.94 ± 0.12	-0.49 ± 0.16
$g^{\rho}_{1,\frac32}$	0.90 ± 0.10	0.48 ± 0.13	$g^{NR}_{1,\frac32}$	0.21 ± 0.09	-2.84 ± 0.53
$g^{\rho}_{2,\frac32}$	0.55 ± 0.08	-0.04 ± 0.18	$g^{NR}_{2,\frac32}$	0.33 ± 0.14	-1.92 ± 0.30
$\frac12^+(\Lambda)\to\frac12^+(p)+0^-(\pi^-)$					
Amplitude	Magnitude	Phase ϕ (rad)			
$g^{\Lambda}_{0,\frac12}$	1.0 (fixed)	0.0 (fixed)			
$g^{\Lambda}_{1,\frac12}$	0.435376 (fixed)	0.0 (fixed)			

$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^\rho_{\frac12,1}|^2 - |H^\rho_{-\frac12,-1}|^2 + |H^\rho_{\frac12,0}|^2 - |H^\rho_{-\frac12,0}|^2}{|H^\rho_{\frac12,1}|^2 + |H^\rho_{-\frac12,-1}|^2 + |H^\rho_{\frac12,0}|^2 + |H^\rho_{-\frac12,0}|^2}$$
$$= \frac{\sqrt{\frac19}\cdot 2\cdot\Re\left(g^\rho_{0,\frac12}\cdot\bar g^\rho_{1,\frac12} - g^\rho_{1,\frac32}\cdot\bar g^\rho_{2,\frac32}\right) - \sqrt{\frac89}\cdot 2\cdot \Re\left(g^\rho_{0,\frac12}\cdot\bar g^\rho_{1,\frac32} + g^\rho_{1,\frac12}\cdot\bar g^\rho_{2,\frac32}\right)}{|g^\rho_{0,\frac12}|^2+|g^\rho_{1,\frac12}|^2+|g^\rho_{1,\frac32}|^2+|g^\rho_{2,\frac32}|^2}. \tag{4.28}$$

$$\alpha_{\Sigma(1385)\pi} = \frac{|H^{\Sigma(1385)}_{0,\frac12}|^2 - |H^{\Sigma(1385)}_{0,-\frac12}|^2}{|H^{\Sigma(1385)}_{0,\frac12}|^2 + |H^{\Sigma(1385)}_{0,-\frac12}|^2} = \frac{2\Re\left(g^{\Sigma(1385)}_{1,\frac32}\cdot\bar g^{\Sigma(1385)}_{2,\frac32}\right)}{|g^{\Sigma(1385)}_{1,\frac32}|^2+|g^{\Sigma(1385)}_{2,\frac32}|^2}.$$

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

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

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

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

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

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

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

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

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

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

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

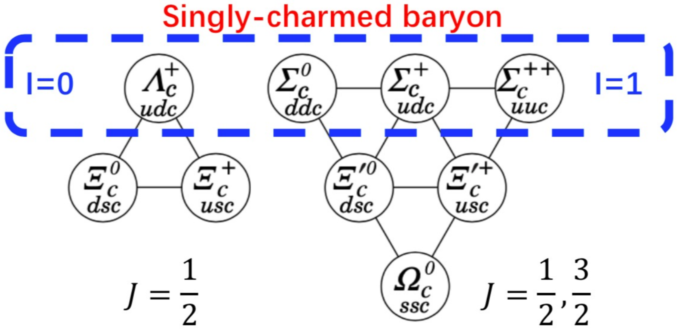
Table 9. The comparison among this work, various theoretical calculations and PDG results. Here, the uncertainties of this work are the combined uncertainties. "—" means unavailable.

	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.

Energy thresholds

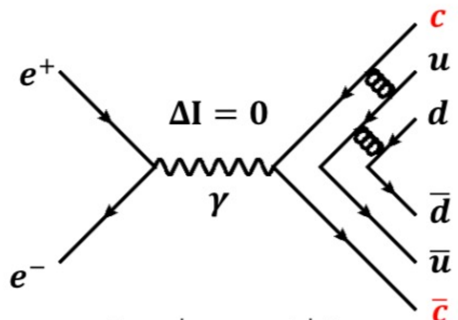
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74~4.87 GeV
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-(2595)(\bar{\Sigma}_c\ \pi)$ 4.88 GeV
- ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
- ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.95 GeV



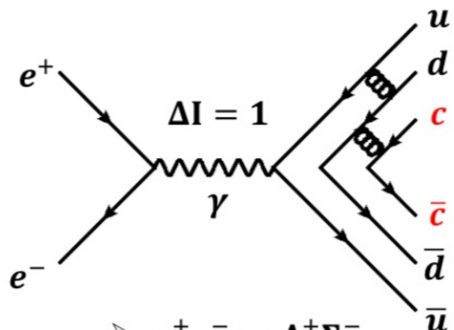
The Born cross-section **ratios** between $\Lambda_c^+\Lambda_c^- + c.c.$ and $\Lambda_c^-\Sigma_c^+ + c.c.$ at different energy points can provide more information about the production of $c\bar{c}$ or $q\bar{q}$ from vacuum.

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 $\Sigma_c^+\bar{\Sigma}_c^-$



➢ $e^+e^- \to \Lambda_c^+\Lambda_c^-$



➢ $e^+e^- \to \Lambda_c^+\Sigma_c^-$