BESIII上Λ_c^+强子衰变研究

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Outline

- **Introduction of the lightest charm baryon Λ_c^+**
- **BESIII data taking at Λ_c^+ pair threshold**
- **BESIII results of Λ_c^+ hadronic decay**
- **summary**

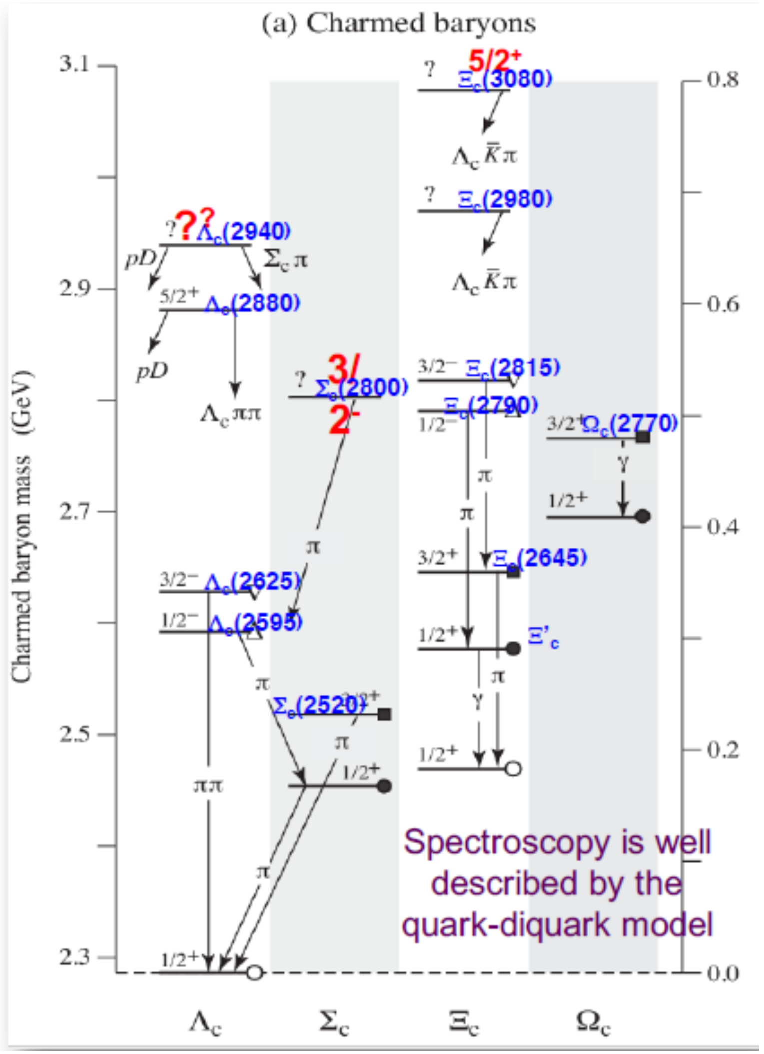
Renaissance on the charmed heavy baryon

- Before 2014, the charmed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).

- Large uncertainties in experiment=>Retarder development in theory.

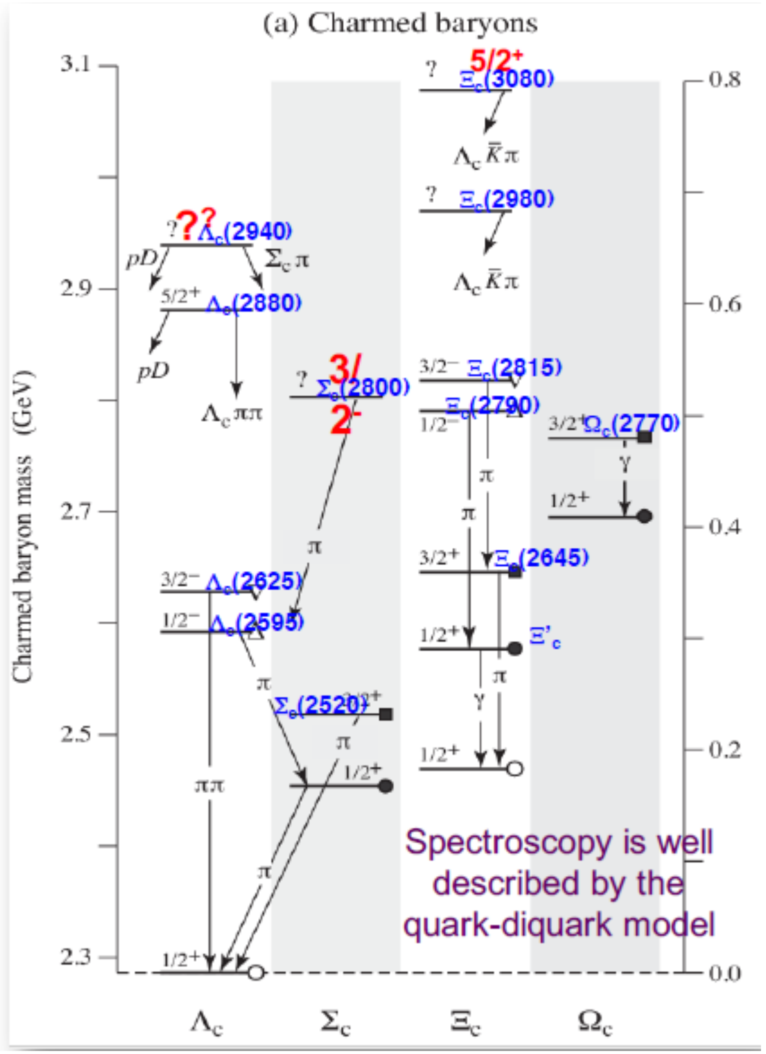
- Afterwards, more extensive measurements on charmed baryons are performed at BESIII, BELLE and LHCb.
  - The absolute BF measurements at BESIII and BELLE.
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE.
  - The observation of the doubly charmed baryon Ξ_{cc}^{++} at LHCb.

- These experimental progresses have evoked the activities in the theoretical efforts



The charmed baryon family

- Singly charmed baryons
  - Established ground states:
    Λ_c^+, Σ_c, $\Xi_c^{(\prime)}$, Ω_c
  - Excited states are being explored
- Doubly charmed baryons(Ξ_{cc}^{++}) observed recently.
- No observations of triply charmed baryons.



✓ Λ_c^+ decay only weakly, many recent experimental progress since 2014.

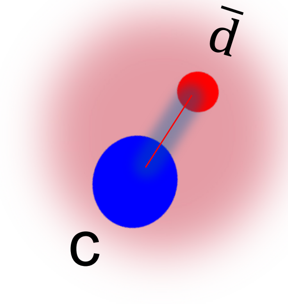
✓ Σ_c: B($\Sigma_c \to \Lambda_c^+\pi$)~100%, B($\Sigma_c \to \Lambda_c^+\gamma$)?

✓ Ξ_c : decay only weakly; no absolute BF measured, most relative to $\Xi^-\pi^+(\pi^+)$.

✓ Ω_c:decay only weakly; no absolute BF measured.

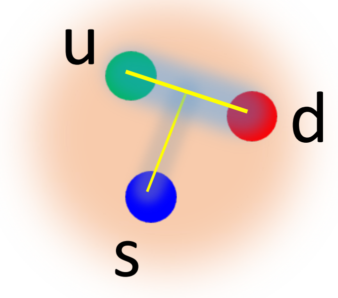
Λ_c^+: The lightest charmed baryon spectroscopy

- Most of the charmed baryons will eventually decay to $\mathbf{\Lambda_c^+}$.
- The $\mathbf{\Lambda_c^+}$ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.
- Also important input to $\mathbf{\Lambda_b}$ (including $\mathbf{\Xi_{cc}^{++}}$) physics as $\mathbf{\Lambda_b}$ decay preferentially to $\mathbf{\Lambda_c}$.
  ==>Important input to B physics and V_{ub} calculations.
- $\mathbf{\Lambda_c^+}$ may provide more powerful test on internal dynamics than D/Ds does !
- Naive 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).



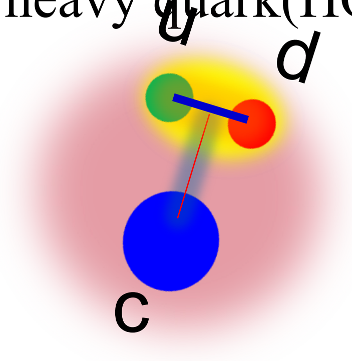
→ Charmed meson ($D^+[c\bar{d}]$)

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



→ Strange baryons (**Λ[uds]**)

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

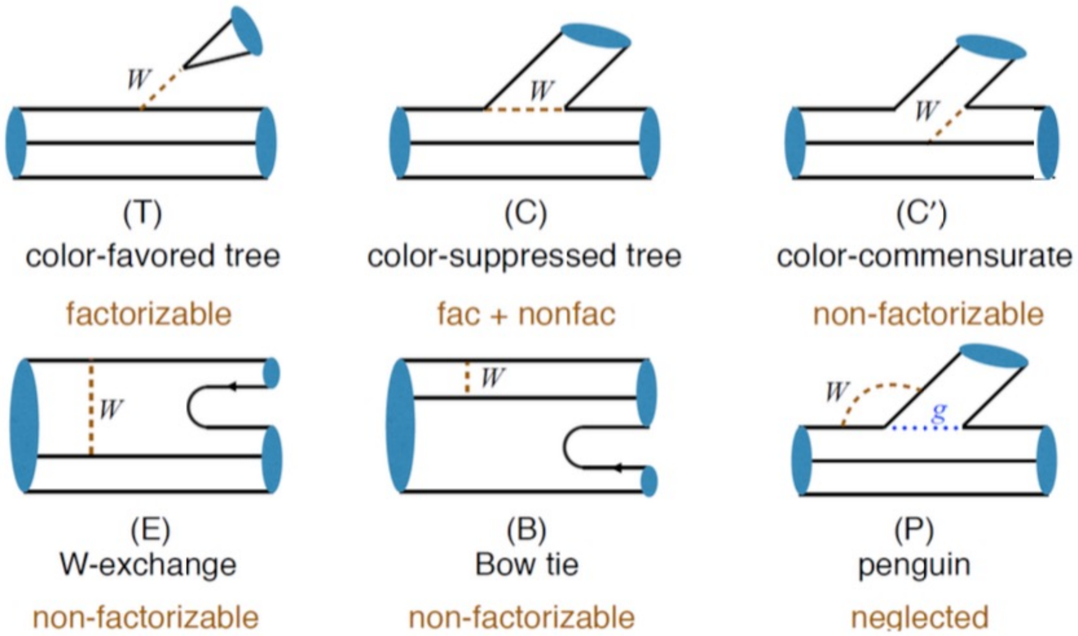


→ Charmed baryon (**Λ_c[udc]**)

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

Λ_c^+ weak decays

- 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.

BESIII data taking at Λ_c^+ pair threshold

- Measurement using the threshold pair-productions via e+e- annihilations is unique: the most simple and straightforward.
- In 2014, BESIII took data above Λ_c^+ pair threshold and run machine at 4.6GeV with excellent performance! ~106×103 $\Lambda_c^+\Lambda_c^-$ pairs make sensitivity to 10^{-3}.
- First time to systematically study Λ_c^+ at threshold.
- From December 2019 to June 2021, the BESIII experiment collected approximately 5.85 fb^{-1} of data at center-of-mass energies between 4.61 and 4.95 GeV.
- will allow to improve the precision of Λ_c^+ decay rates to a level comparable to the charmed mesons,
- Provide an opportunity to study many unexplored physics observables related to Λ_c^+ decays
- Boost our understanding of the non-perturbative effects in the charmed baryon sector.

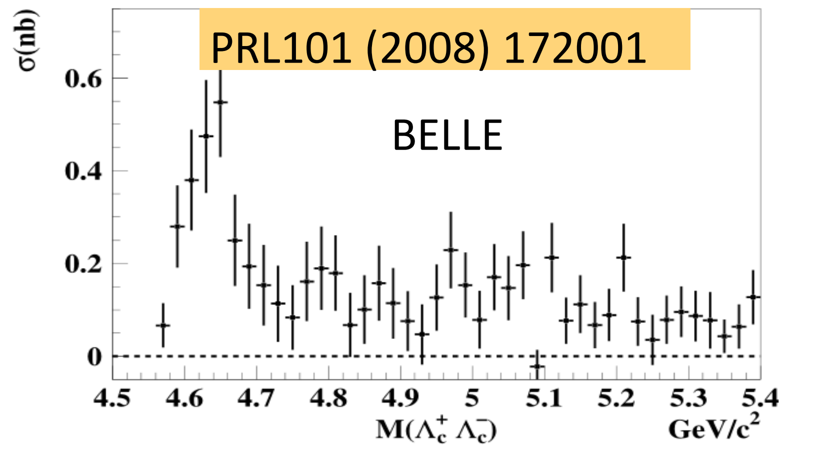
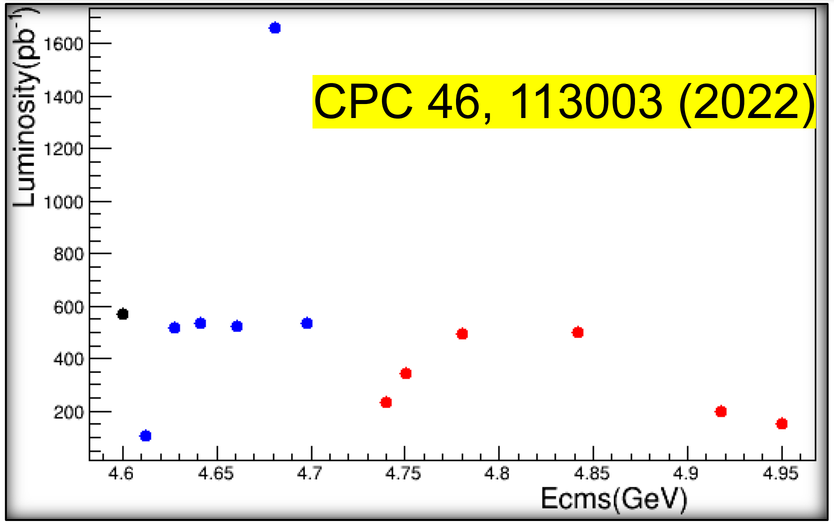


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

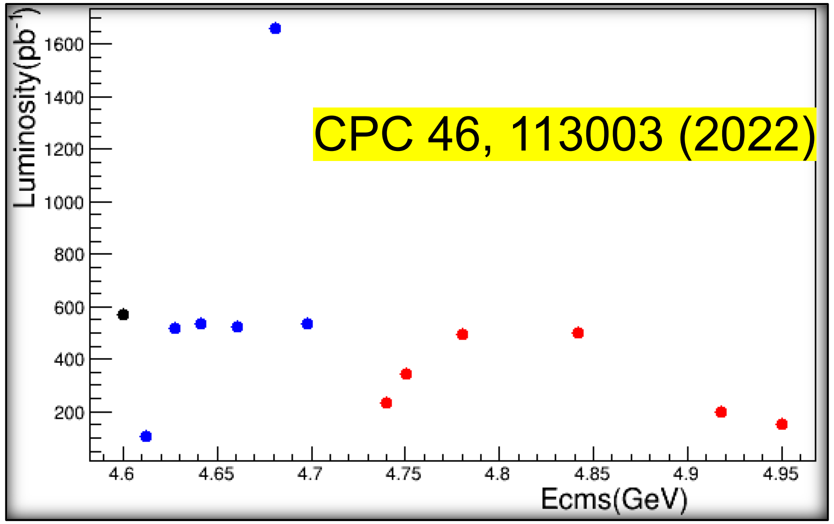


BESIII result of Λ_c^+ hadronic decay

Data 4.600 GeV

1. BF($\Lambda_c^+ \to pK^-\pi^+$) +11hadronic modes	PRL 116, 052001 (2016)(update)
2. BF($\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$) SCS	PRL 117, 232002 (2016)
3. BF($\Lambda_c^+ \to p\eta, p\pi^0$) SCS	PRD 95, 111102(2017)(update)
4. BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$)	PLB 772, 388 (2017)
5. BF($\Lambda_c^+ \to \Xi^{(*)0}K^+$) W-exchange only	PLB 783,200 (2018) (update)
6. BF($\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$)W-emission and W-exchange.	CPC 43, 083002, (2019) （update）
7. BF($\Lambda_c^+ \to \Lambda\,\eta\,\pi^+$) BF($\Lambda_c^+ \to \Sigma^{*+}\eta$)	PRD 99, 032010,(2019)
8. BF($\Lambda_c^+ \to \Lambda X$)	PRL 121, 062003(2018)(update)
9. Cross section of $\Lambda_c^+\Lambda_c^-$ pair	PRL 120,132001(2018).
10. Decay parameters measurement Λ_c^+	PRD 100, 072004 (2019) （update）

BESIII result of Λ_c^+ hadronic decay



Data 4.600 GeV

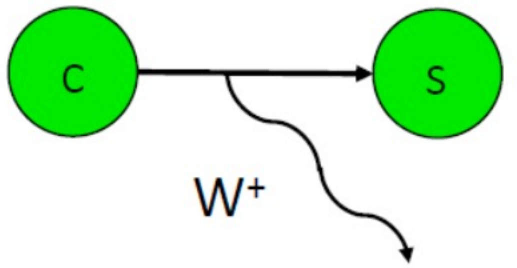
1. BF($\Lambda_c^+ \to K_S X$) EPJC 80, 935 (2020)
2. BF($\Lambda_c^+ \to p K_S^0 \eta$) PLB 817, 136327 (2021)

Data 4.600~ GeV

1. Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ JHEP 12, 033 (2022)
2. BF($\Lambda_c^+ \to \Lambda K^+$) PRD 106, L111101 (2022)
3. BF($\Lambda_c^+ \to p\eta'$) PRD 106, 072002 (2022)
4. BF($\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+$) PRD 106, 052003 (2022)

First measurement $\Lambda_c^+ \to K_S^0 X$ EPJC 80, 935 (2020)

- The Λ_c^+ Cabibbo-favored (CF) decay dominantly includes $\Lambda_c^+ \to \Lambda X$ and $\Lambda_c^+ \to KX$ $(K^{\pm}, K^0, \bar{K}^0)$.
- Measuring the BF of $\Lambda_c^+ \to K_S^0 X$ can provide an important information for understanding the missing CF decay modes.
- Comparing the BF of $\Lambda_c^+ \to K_S^0 X$ with that of the charmed mesons provides some information about the nature of these charmed particles.



Cabibbo-favored decay

Γ_{76}	e^+ anything	$(3.95 \pm 0.35)\%$
Γ_{77}	p anything	$(50 \pm 16)\%$
Γ_{78}	n anything	$(50 \pm 16)\%$
Γ_{79}	Λ anything	$(38.2^{+2.9}_{-2.4})\%$

PDG result

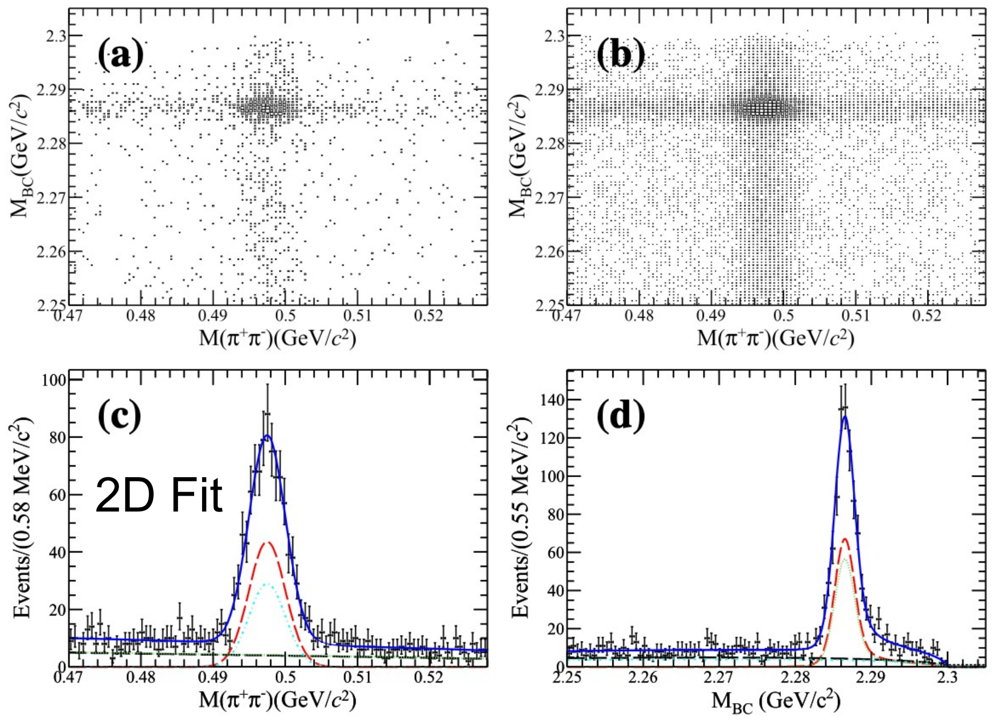
$\mathcal{B}(D^0 \to \bar{K}^0/K^0 + X) = (47 \pm 4)\%$

$\mathcal{B}(D^0 \to \bar{K}^0/K^0 + X) = (61 \pm 5)\%$

$\mathcal{B}(D_S^+ \to K_S^0 + X) = (19.0 \pm 1.1)\%$

First measurement $\Lambda_c^+ \to K_S X$

EPJC 80, 935 (2020)



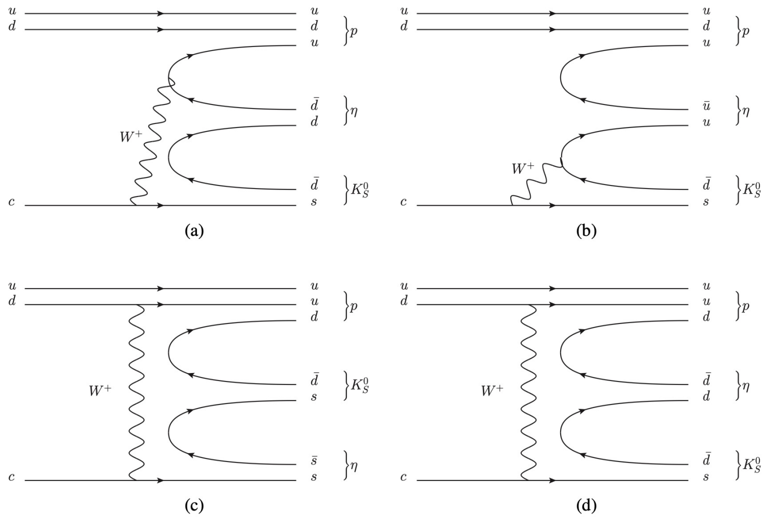
$$\mathcal{B}(\Lambda_c^+ \to K_S^0 + X) = (9.9 \pm 0.6 \pm 0.4)\%$$

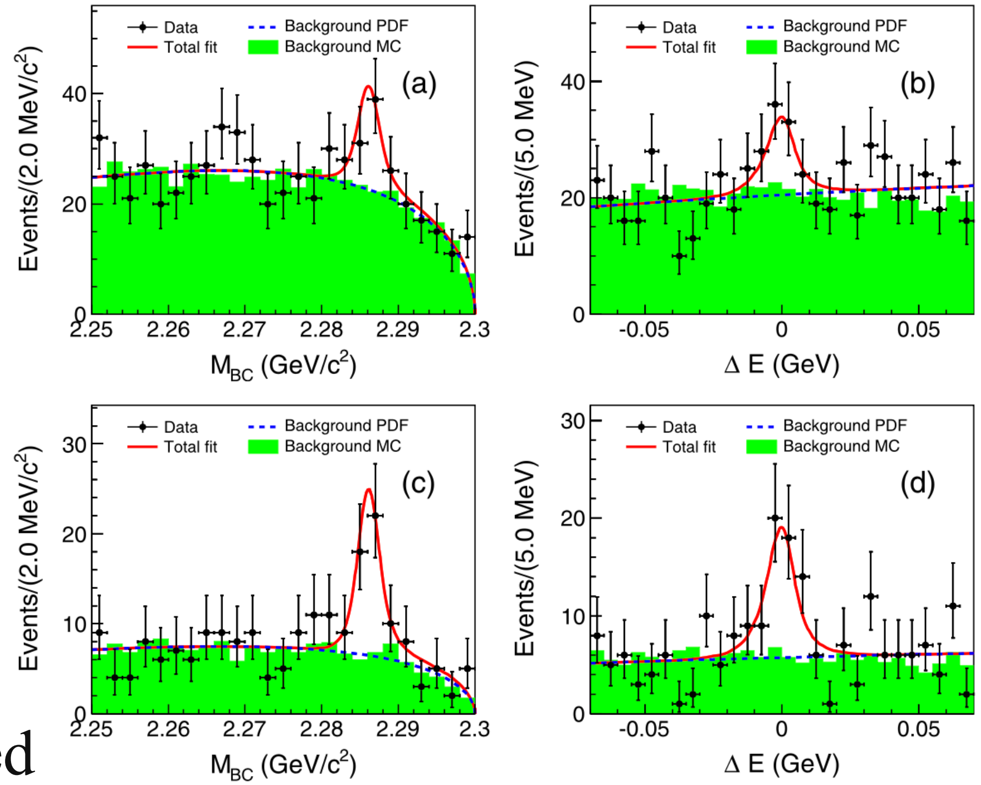
$$\mathcal{B}(\Lambda_c^+ \to \bar{K}^0/K^0 + X) = (19.8 \pm 1.2 \pm 0.8 \pm 1.0)\%$$

- The relative deviation between the branching fractions for the inclusive decay and the observed exclusive decays is $(18.7 \pm 8.3)\%$.
- There may be some unobserved decay modes with a neutron or excited baryons in the final state.

Mode	Value (%)	Mode	Value (%)
Observed BF		Extrapolated BF	
$p\bar{K}^0$	3.18±0.16	$n\bar{K}^0\pi^+\pi^0$	3.07±0.16
$p\bar{K}^0\pi^0$	3.94±0.26	$p\bar{K}^0\pi^0\pi^0$	1.36±0.07
$p\bar{K}^0\pi^+\pi^-$	3.20±0.24	$n\bar{K}^0\pi^+\pi^+\pi^-$	0.14±0.09
$n\bar{K}^0\pi^+$	3.64±0.50	$p\bar{K}^0\pi^+\pi^-\pi^0$	0.22±0.14
$p\bar{K}^0\eta$	1.60±0.40	$n\bar{K}^0\pi^+\pi^0\pi^0$	0.10±0.06
$\Lambda K^+\bar{K}^0$	0.57±0.11	$p\bar{K}^0\pi^0\pi^0\pi^0$	0.03±0.02
		$(\Sigma K)^+\bar{K}^0$	0.68±0.34
		$\Xi^0 K^0\pi^+$	0.62±0.06
Total	16.1 ± 0.8	Total	6.3 ± 0.4
Total		22.4±0.9	

Absolute BF measurement $\Lambda_c^+ \to pK_S^0\eta$





- Only relative measurement with high uncertainty.

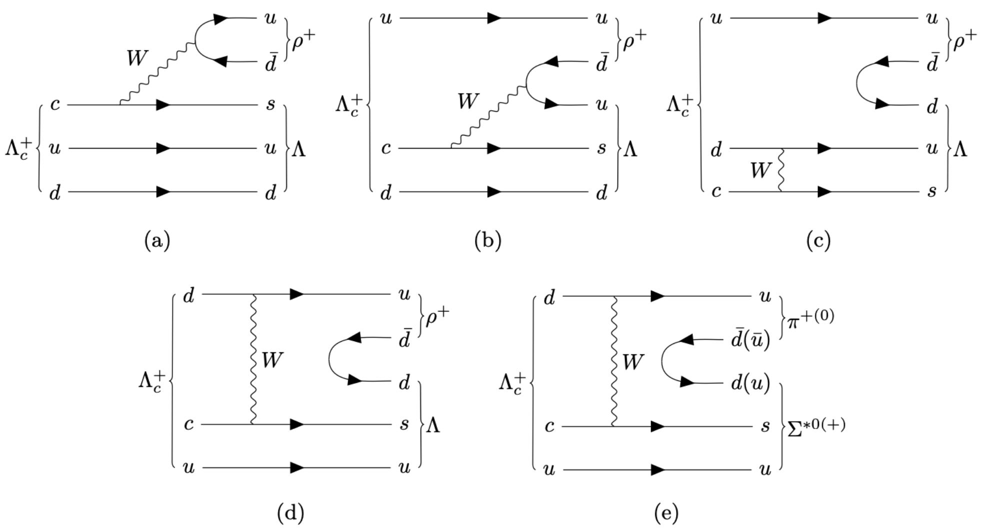
$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (0.414 \pm 0.084 \pm 0.028)\%$$

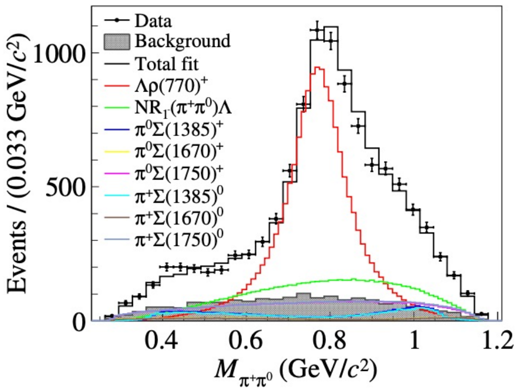
- The result is consistent with theoretical predictions based on SU(3) flavor symmetry

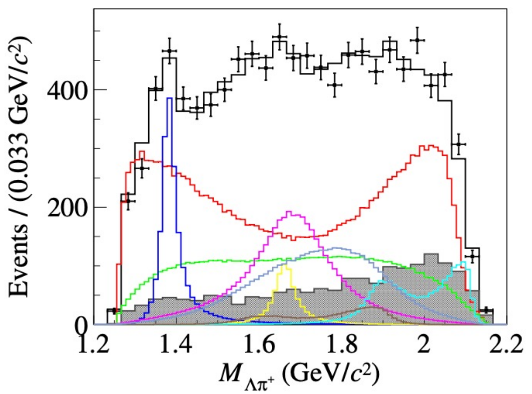
Decay mode	Current PDG(%) [4]	Theoretical prediction(%) [6]	This work(%)
$\Lambda_c^+ \to p\bar{K}^0\eta$	1.6 ± 0.4	0.9 ± 0.1	$0.83 \pm 0.17 \pm 0.06$

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

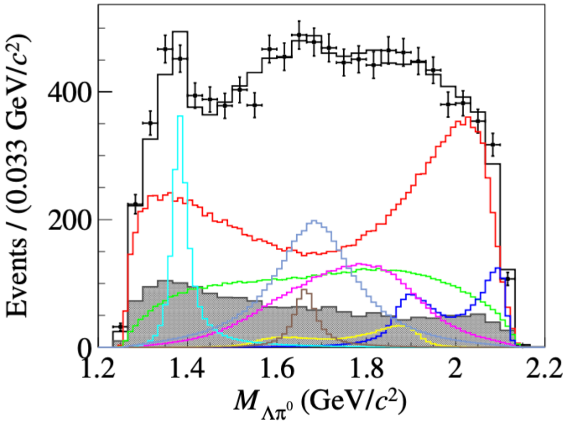
- BF of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ has been measured by BESIII with high precision, but no previous study on intermediate structure.
- Perform Partial Wave Analysis to obtain the information of intermediate resonances ρ^+、$\Sigma(1385)^+$、$\Sigma(1385)^0$.
- Measurements the decay asymmetry.







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



1. The first PWA of the charmed baryon hadronic decay at BESIII.
2. The decay asymmetry parameters for the resonant components are determined for the first time .

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

PRD 106, L111101 (2022)

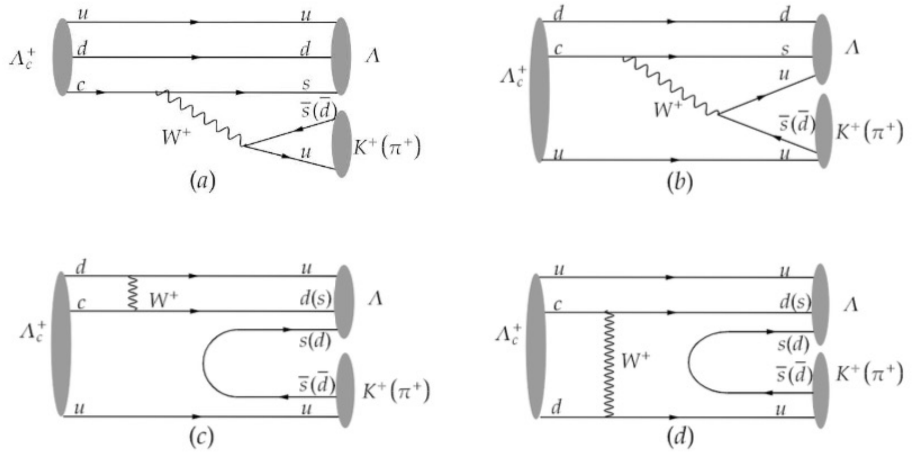
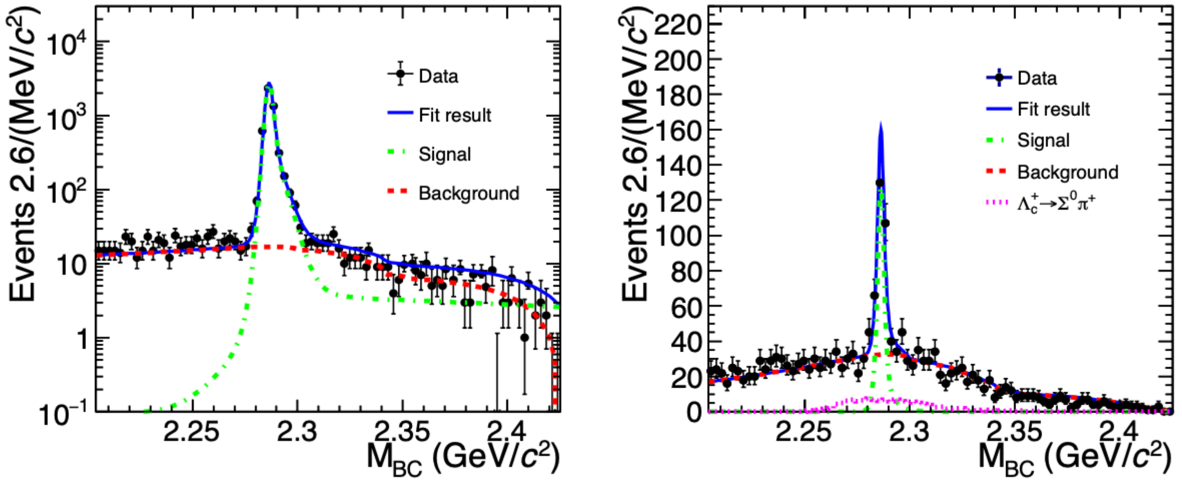


FIG. 1. The (a) external emission, (b) internal emission, and (c)(d) W-exchange Feynman diagrams for $\Lambda_c^+ \to \Lambda K^+$ and $\Lambda_c^+ \to \Lambda\pi^+$.



non-factorizable contributions are important.

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

$$R = \frac{\Lambda_c^+ \to \Lambda K^+}{\Lambda_c^+ \to \Lambda\pi^+} = (4.78 \pm 0.34 \pm 0.20)\%$$

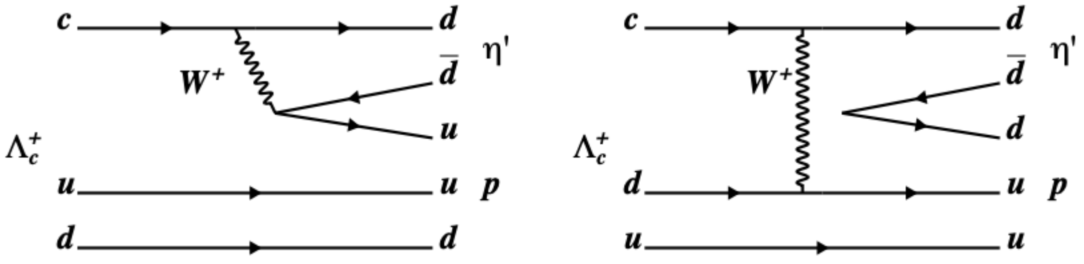
$$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.21 \pm 0.44 \pm 0.26 \pm 0.34)\times 10^{-4}$$

- More precise than previous measurements, does not agree with theoretical predictions.
- Suggests that non-factorizable contributions have been under-estimated in current models.

Singly Cabibbo suppressed decay $\Lambda_c^+ \to p\eta'$

PRD 106, 072002 (2022)

- Provide an input to understand the dynamics of charmed baryon decays
- Help to improve different theoretical models.



(a) (b)

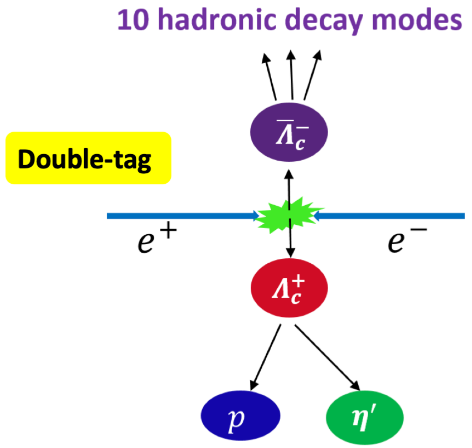
Lowest-order Feynman diagrams W -emission and W -exchange mechanisms for the singly Cabibbo suppressed decay $\Lambda_c^+ \to p\eta'$

PRD 97, 074028 (2018)

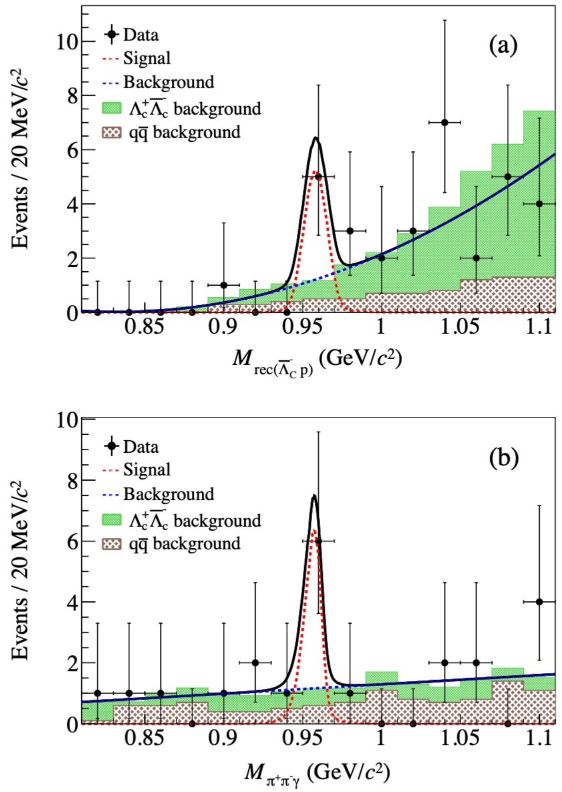
	Sharma *et al.* [24]	Uppal *et al.* [42]	Chen *et al.* [43]	Lu *et al.* [25]	Geng *et al.* [28]	This work	Experiment [7,19]
$\Lambda_c^+ \to p\pi^0$	0.2	0.1–0.2	0.11–0.36	0.48	0.57 ± 0.15	0.08	<0.27
$\Lambda_c^+ \to p\eta$	$0.2^{a}(1.7)^{b}$	0.3			1.24 ± 0.41	1.28	1.24 ± 0.29
$\Lambda_c^+ \to p\eta'$	0.4–0.6	0.04–0.2			$1.22^{+1.43}_{-0.87}$		
$\Lambda_c^+ \to n\pi^+$	0.4	0.8–0.9	0.10–0.21	0.97	1.13 ± 0.29	0.27	
$\Lambda_c^+ \to \Lambda K^+$	1.4	1.2	0.18–0.39		0.46 ± 0.09	1.06	0.61 ± 0.12
$\Lambda_c^+ \to \Sigma^0 K^+$	0.4–0.6	0.2–0.8			0.40 ± 0.08	0.72	0.52 ± 0.08
$\Lambda_c^+ \to \Sigma^+ K^0$	0.9–1.2	0.4–0.8			0.80 ± 0.16	1.44	

Singly Cabibbo suppressed decay $\Lambda_c^+ \to p\eta'$

PRD 106, 072002 (2022)



- **Category1: $\eta' \to \pi^+\pi^-$missing (η)**
- **Category2: $\eta' \to \pi^+\pi^-\gamma$**

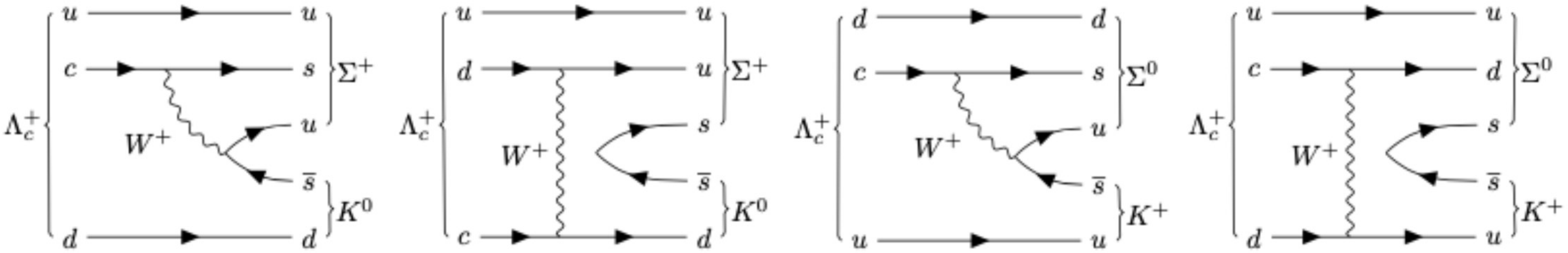


- The result is consistent with the branching fraction obtained by the Belle collaboration within the uncertainty of 1σ.
- The result from this analysis provides an input to understand the dynamics of charmed baryon decays and helps to improve different theoretical models.

$$\mathcal{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04} \pm 0.26)\times 10^{-4} \quad 3.6\sigma$$

	$\Lambda_c^+ \to p\eta'$
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]	$12.2^{+14.3}_{-8.7}$

$\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+$ PRD 106, 052003 (2022)



- Many charmed baryon decays like $\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+$ don't receive any factorizable contribution, which indicates factorization approximation don't work.
- BESIII's measurement of absolute hadronic BFs of Λ_c^+ baryon is crucial for improve theoretical treatment on the Λ_c^+ decays.
- Current PDG gives $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (5.2 \pm 0.8)\%$ and no measurement of $\Lambda_c^+ \to \Sigma^+ K_S^0$.

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

$\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+$ PRD 106, 052003 (2022)

- This is the first measurement of the $\Lambda_c^+ \to \Sigma^+ K_S^0$ branching fraction.
- The $\Lambda_c^+ \to \Sigma^0 K^+$ BF is measured with a comparable precision to the combined result from the Belle and BaBar collaborations.
- The ratio of $\Lambda_c^+ \to \Sigma^0 K^+$ and $\Lambda_c^+ \to \Sigma^+ K_S^0$ is consistent with the predictions under SU(3)F flavor symmetry and disfavors the prediction.

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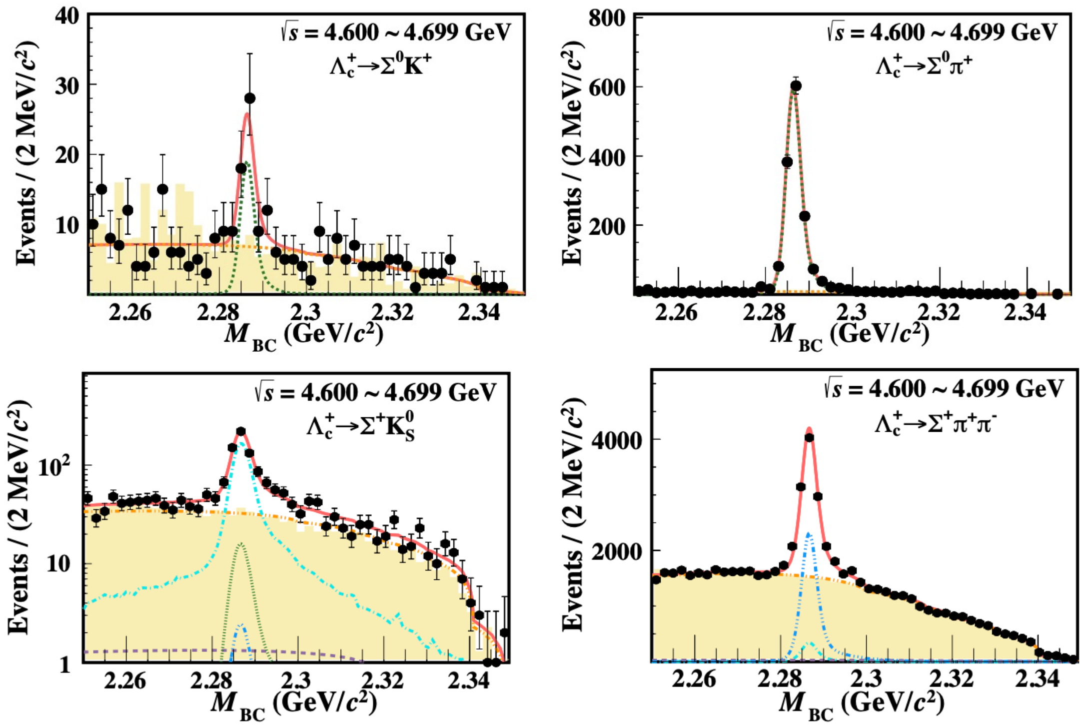


$$R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)} = (3.61 \pm 0.73 \pm 0.05)\%$$

$$R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-)} = (1.06 \pm 0.31 \pm 0.04)\%$$

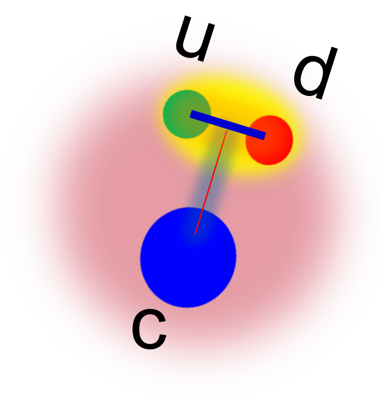
$$R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)} = (0.98 \pm 0.35 \pm 0.04 \pm 0.08)\%$$

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

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

Summary

- Studying the Λ_c^+ decays allows a deeper understanding charmed baryon.
- Threshold data at BESIII opens a new door to direct measurements of the decays : precise study of Λ_c^+ decays
- The knowledge of Λ_c^+ decays is still very limited in comparison with charmed mesons.



	Leading hadronic decay	Typical two-body decay
Λ_c^+	$\mathcal{B}(K^-p\pi^+)$ =	$\mathcal{B}(K_S^0 p)$ =
	2014: (5.0±1.3)% (26%)	2014: (1.2±0.3)% (26%)
	2017(w/ BESIII): (6.35±0.33)% (5.2%)	BESIII: (1.52±0.08)% (5.6%)
	5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%	5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%
D^0	$\mathcal{B}(K^-\pi^+)$ =(3.89±0.04)% (1.0%)	$\mathcal{B}(K_S^0\pi^0)$ =(1.19±0.04)% (3.4%)
D^+	$\mathcal{B}(K^-\pi^+\pi^+)$ =(8.98±0.28)% (3.1%)	$\mathcal{B}(K_S^0\pi^+)$ =(1.47±0.08)% (5.4%)
D_s^+	$\mathcal{B}(K^-K^+\pi^+)$ =(5.45±0.17)% (3.8%)	$\mathcal{B}(K_S^0 K^+)$ =(1.40±0.05)% (3.6%)

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Prospects in Λ_c^+ physics

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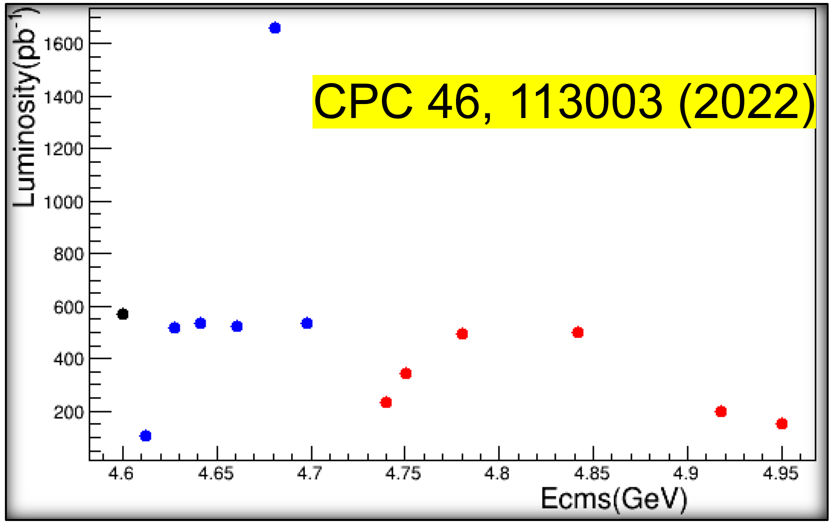
- Amplitude analyses
  - The multi-body final states. such as $\Lambda_c^+ \to pK^-\pi^+, pK_S^0\pi^0$. From these analyses, additional two-body decay patterns can be extracted.
  - Provide a good opportunity to study the light hadron spectroscopy, such as the study of $\Lambda^*$and scalar meson.
- The EM form factor of charmed baryons
- Asymmetry parameter
- CP violation



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