Hadronic Decays of Charmed Baryon Λ_c^+ at BESIII

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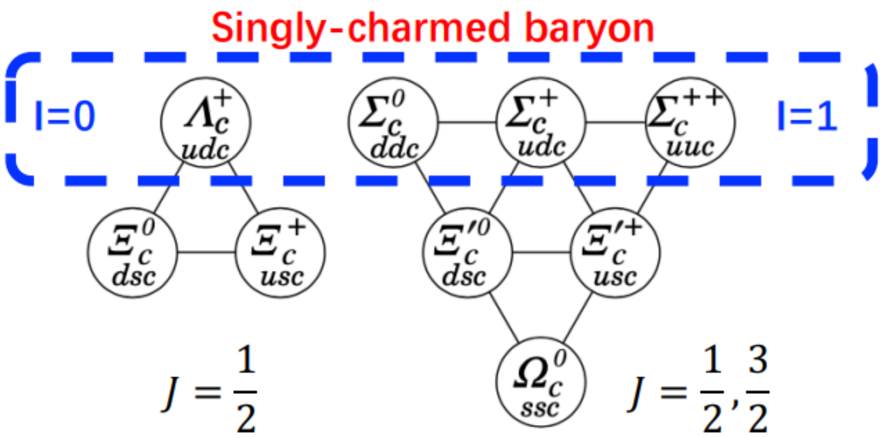
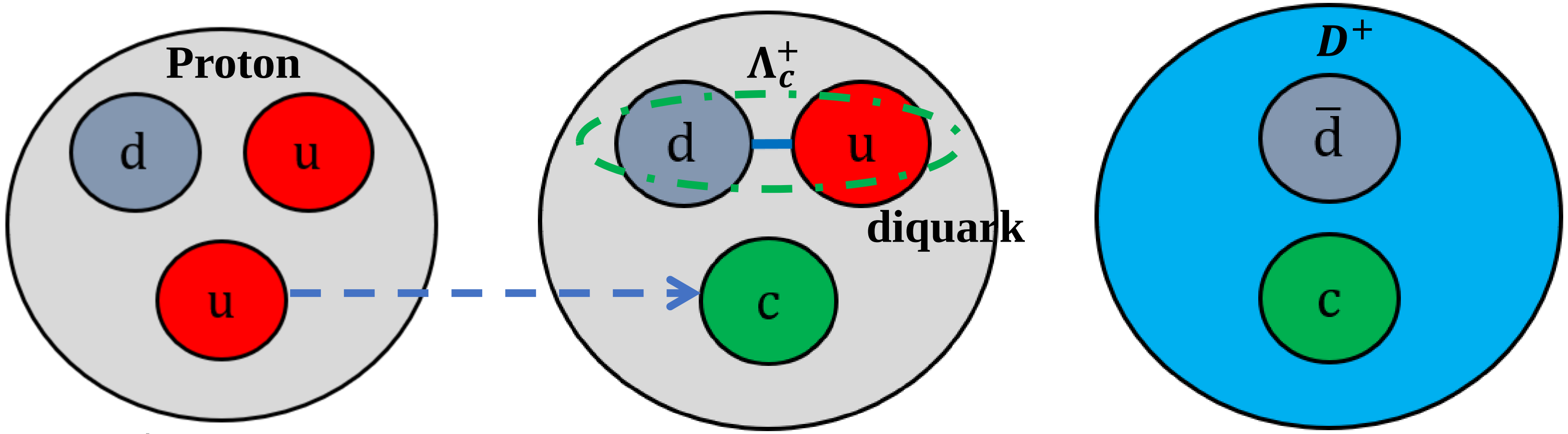
Outline

- Introduction
- Decays involve neutron
  - $\Lambda_c^+ \to n\pi^+$
  - $\Lambda_c^+ \to n\pi^+\pi^0$, $n\pi^+\pi^-\pi^+$ and $nK^-\pi^+\pi^+$
- Decays involve proton
  - $\Lambda_c^+ \to pK_S^0\eta$
  - $\Lambda_c^+ \to p\eta'$
- Decays involve Λ
  - $\Lambda_c^+ \to \Lambda K^+$
  - Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$
- Decays involve Σ
  - $\Lambda_c^+ \to \Sigma^0 K^+$ and $\Lambda_c^+ \to \Sigma^+ K_S^0$
  - $\Lambda_c^+ \to \Sigma^+ K^+ K^-$, $\Sigma^+ K^+\pi^-$ and $\Sigma^+ K^+\pi^-\pi^0$
- Summary

Introduction



- Most of the charmed baryons will eventually decay to Λ_c^+.
- Many b-baryons decay to Λ_c^+.
- Λ_c^+ decays reveal information of strong- and weak-interactions in charm region, complementary to charmed mesons.



- Charmed meson: $m_d \ll m_c \rightarrow$ quark(q) + heavy quark(Q).
- Charmed baryon: $m_u, m_d \ll m_c \rightarrow$ diquark(qq) + heavy quark(Q).

- The Λ_c^+ baryon is composed of a heavy quark (c) and two light quarks(u, d).
- According to the HQET, the u-d quarks can be treated as a diquark that has zero spin and isospin.
- Λ_c^+ can provide more powerful test on internal dynamics than mesons D^+/D_s^+.

Introduction

From the PDG we can find that:

- The golden mode of Λ_c^+ decays is $\Lambda_c^+ \rightarrow pK^-\pi^+(6.28\% \pm 0.32\%)$.
- Only one neutron mode has been measured ($\Lambda_c^+ \rightarrow nK_S^0\pi^+$: $1.82\% \pm 0.25\%$) but the branching fraction of inclusive decay $\Lambda_c^+ \rightarrow n + X$ is $50\% \pm 16\%$ from PDG2022.
- From PDG, the uncertainties of many Λ_c^+ decays are still very large.

Hadronic modes with a p or n: $S = -1$ final states

Γ_1	pK_S^0		(1.59 ± 0.08) %	S=1.1
Γ_2	$pK^-\pi^+$		(6.28 ± 0.32) %	S=1.4
Γ_3	$p\overline{K}^*(892)^0$	[a]	(1.96 ± 0.27) %	
Γ_4	$\Delta(1232)^{++}K^-$		(1.08 ± 0.25) %	
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.2 ± 0.5) %	
Γ_6	$pK^-\pi^+$ nonresonant		(3.5 ± 0.4) %	
Γ_7	$pK_S^0\pi^0$		(1.97 ± 0.13) %	S=1.1
Γ_8	$nK_S^0\pi^+$		(1.82 ± 0.25) %	
Γ_9	$p\overline{K}^0\eta$		$(8.3 \pm 1.8) \times 10^{-3}$	
Γ_{10}	$pK_S^0\pi^+\pi^-$		(1.60 ± 0.12) %	S=1.1
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	S=1.5
Γ_{12}	$pK^*(892)^-\pi^+$	[a]	(1.4 ± 0.5) %	
Γ_{13}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(4.6 ± 0.8) %	
Γ_{14}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{15}	$pK^-2\pi^+\pi^-$		$(1.4 \pm 0.9) \times 10^{-3}$	
Γ_{16}	$pK^-\pi^+2\pi^0$		(1.0 ± 0.5) %	

Inclusive modes

Γ_{76}	e^+ anything	(3.95 ± 0.35) %
Γ_{77}	p anything	(50 ± 16) %
Γ_{78}	n anything	(50 ± 16) %
Γ_{79}	Λ anything	$(38.2 {}^{+2.9}_{-2.4})$ %
Γ_{80}	K_S^0 anything	(9.9 ± 0.7) %
Γ_{81}	3prongs	(24 ± 8) %

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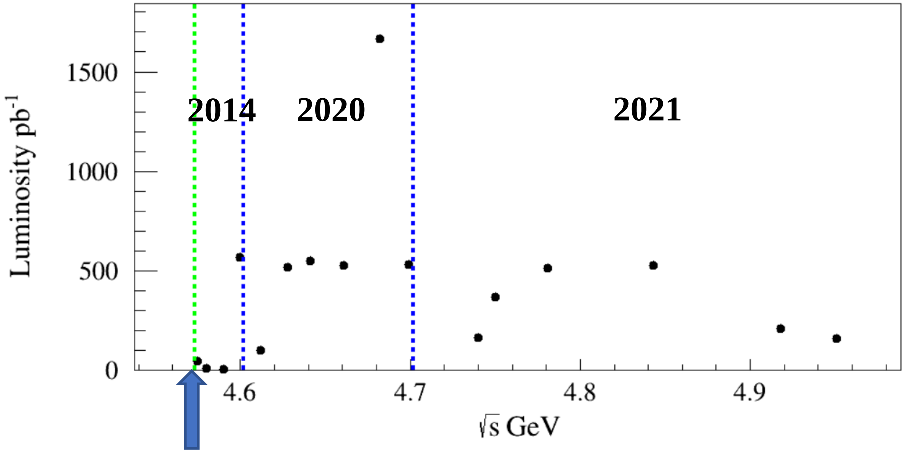
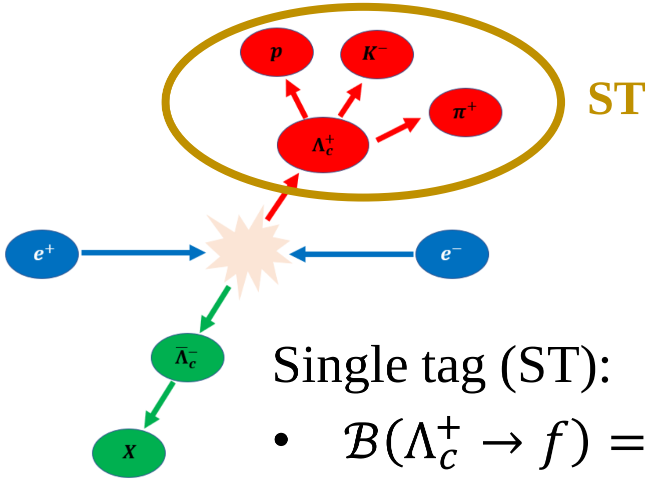
Data Samples and analysis method

$6.4\ \mathrm{fb}^{-1}$ collision data from 4.600 GeV to 4.951GeV

- The largest data samples collected near the $\Lambda_c^+\bar{\Lambda}_c^-$ production threshold



$\Lambda_c^+\bar{\Lambda}_c^-$ production threshold

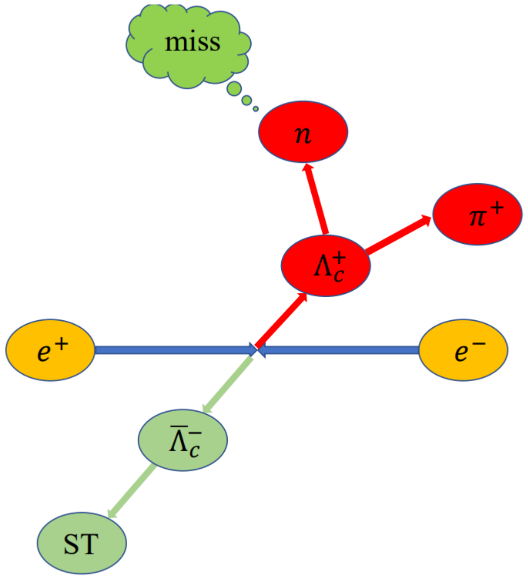


Single tag (ST):

- $\mathcal{B}(\Lambda_c^+ \to f) = \dfrac{N_{ST}}{2\times N_{pair}^{tot}\times\epsilon_{ST}}$

ϵ_{ST}: ST detection efficiency

- Only reconstruct one of the pair.
- Higher backgrounds.
- Higher efficiencies.



Double tag (DT):

- $\mathcal{B}(\Lambda_c^+ \to f) = \dfrac{N_{DT}}{N_{ST}\times\epsilon_{DT}}$

$\epsilon_{DT} = \dfrac{\sum N_{ST}^i\times\epsilon_{DT}^i/\epsilon_{ST}^i}{\sum N_{ST}^i}$: Averaged DT efficiency

- Clean background in DT method
- Can extract missing particle

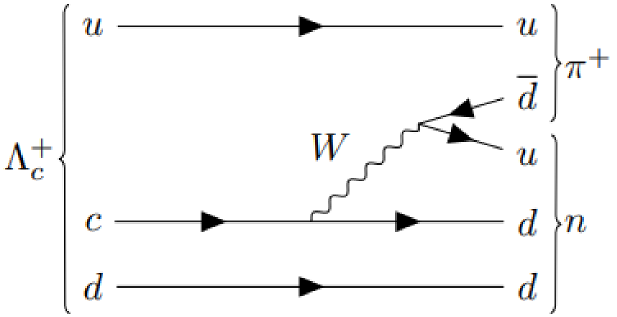
$E_{\mathrm{miss}} = E_{\mathrm{beam}} - \sum_f E_f \qquad \vec{\boldsymbol{p}}_{\mathrm{miss}} = \vec{\boldsymbol{p}}_{\Lambda_c} - \sum_f \vec{\boldsymbol{p}}_f$

$M_{\mathrm{miss}}^2 = E_{\mathrm{miss}}^2 - p_{\mathrm{miss}}^2 \qquad U_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{\boldsymbol{p}}_{\mathrm{miss}}|$

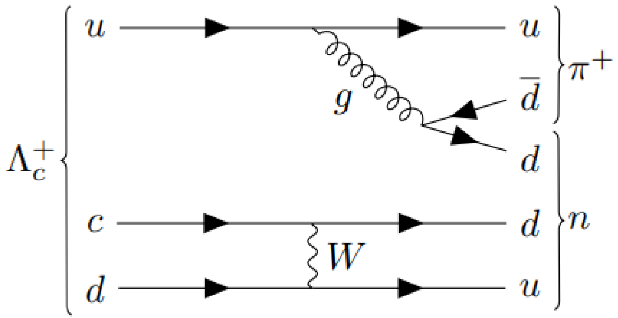
First observation of $\Lambda_c^+ \to n\pi^+$

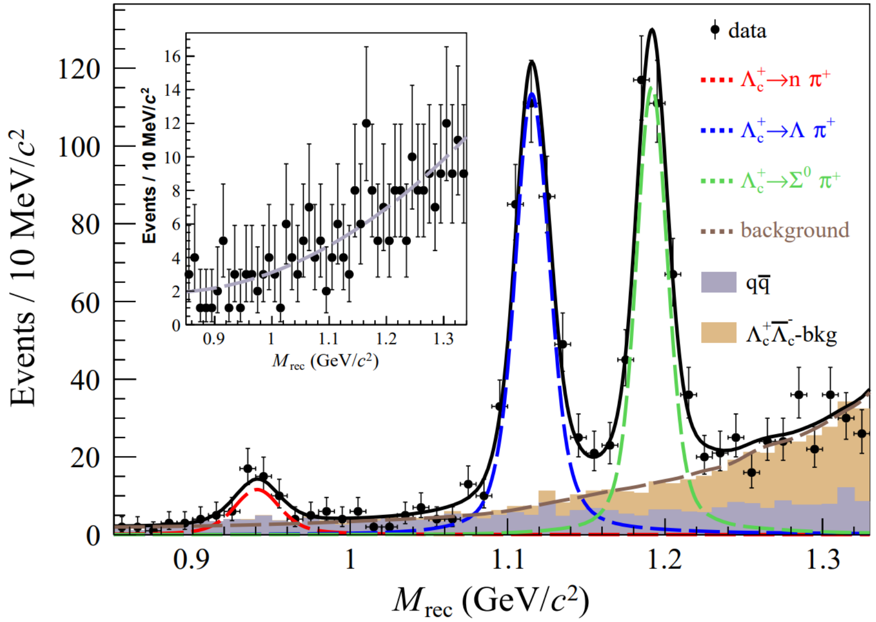
- $\Lambda_c^+ \to n\pi^+$ is Singly-Cabbibo-Suppressed decay, which can't ignore non-factorizable contributions.

Internal W emission



W exchange

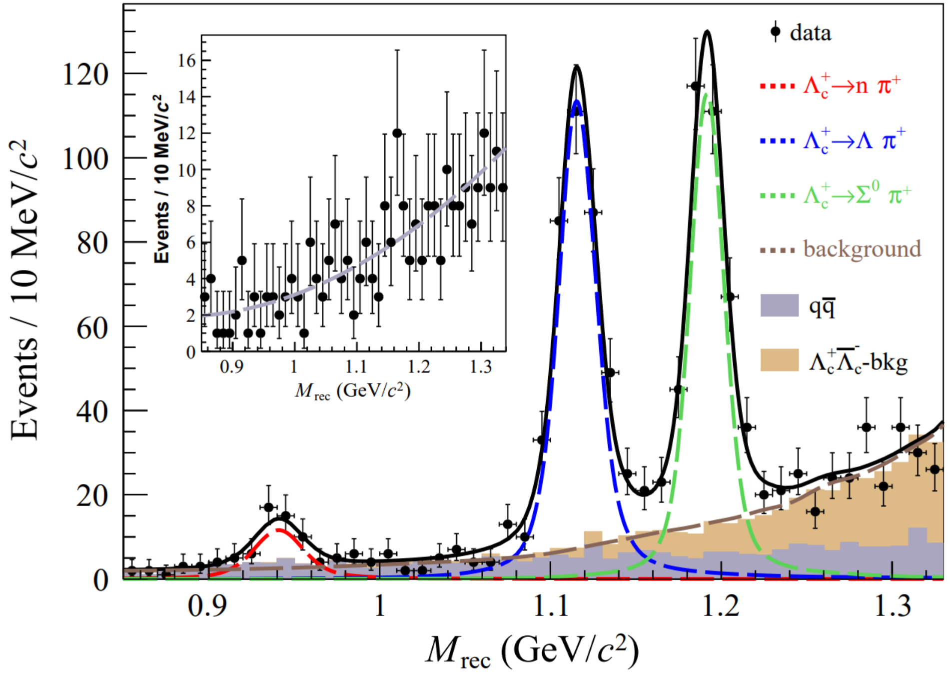




$$M_{\text{rec}}^2 = (E_{\text{beam}} - E_{\pi^+})^2/c^4 - |\rho \cdot \vec{p}_0 - \vec{p}_{\pi^+}|^2/c^2$$

- E_{π^+} and $\vec{p}_{\pi^+}$ are the energy and momentum of π^+ candidate.
- $\rho = \sqrt{E_{\text{beam}}^2/c^2 - m_{\Lambda_c^+}^2 c^2}$.
- $\vec{p}_0 = -\vec{p}_{\bar{\Lambda}_c^-}/|\vec{p}_{\bar{\Lambda}_c^-}|$ is the unit direction opposite to the ST $\bar{\Lambda}_c^-$.

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



Decay	Yields	Branching fraction
$\Lambda_c^+ \to n\pi^+$	50 ± 9	$(6.6 \pm 1.2_{\rm stat} \pm 0.4_{\rm syst}) \times 10^{-4}$
$\Lambda_c^+ \to \Lambda\pi^+$	376 ± 22	$(1.31 \pm 0.08_{\rm stat} \pm 0.05_{\rm syst}) \times 10^{-2}$
$\Lambda_c^+ \to \Sigma^0\pi^+$	343 ± 22	$(1.22 \pm 0.08_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-2}$

✓ Define $R = \mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0)$

- Use $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ at 90% C.L. of Belle from Phys. Rev. D 103, 072004 (2021)

R	> 7.2 at 90% C.L.

✓ Red peak: $\Lambda_c^+ \to n\pi^+$ **7.3σ**

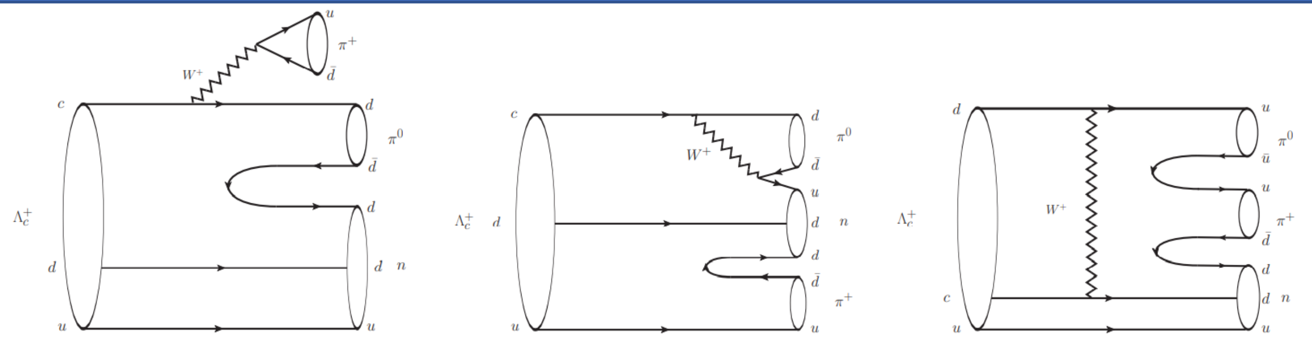
✓ Blue peak: $\Lambda_c^+ \to \Lambda\pi^+$

✓ Green peak: $\Lambda_c^+ \to \Sigma^0\pi^+$

Consistent with results from PDG

- Disagree with most theoretical predictions by phenomenological models.

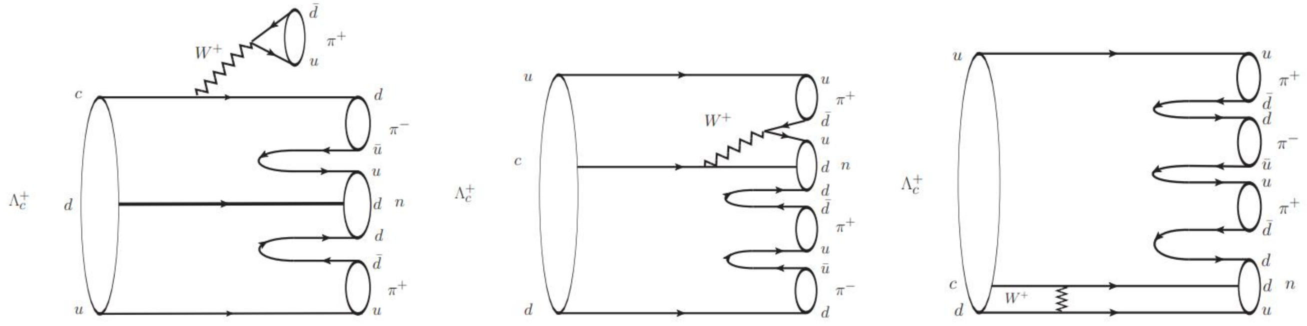
Measurement of $\Lambda_c^+ \to n\pi^+\pi^0$, $n\pi^+\pi^-\pi^+$ and $nK^-\pi^+\pi^+$



(a) External W-emission (b) Internal W-emission (c) W-exchange

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

Cabibbo-Suppressed



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$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$

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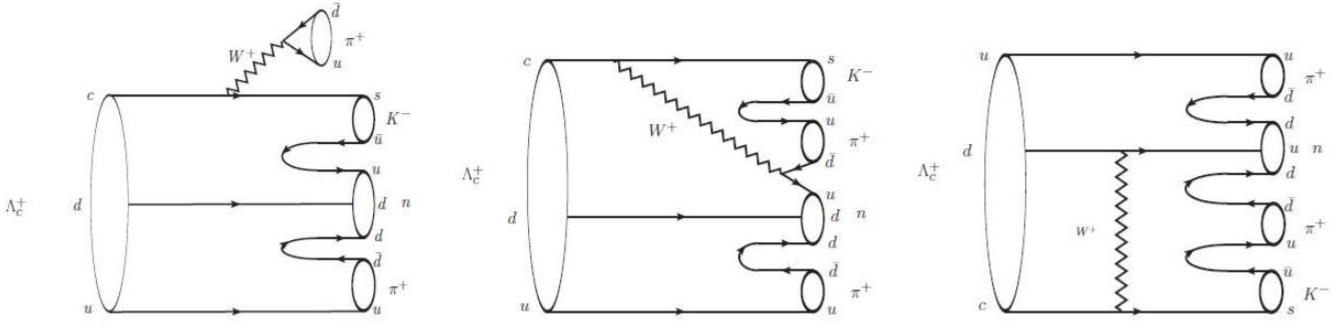


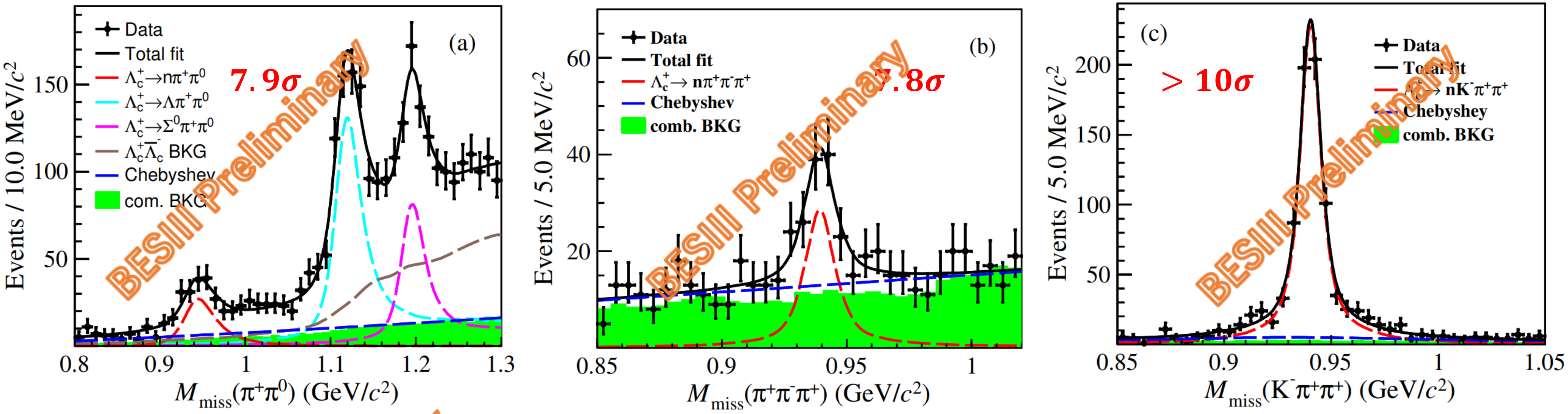
(a) External W-emission (b) Internal W-emission (c) W-exchange

$\Lambda_c^+ \to nK^-\pi^+\pi^+$

Cabibbo-favored

- Precise measurements of more neutron-involved final states are crucial to testify the isospin and SU(3) symmetries in the charmed baryon decays.

Measurement of $\Lambda_c^+ \to n\pi^+\pi^0$, $n\pi^+\pi^-\pi^+$ and $nK^-\pi^+\pi^+$



- Firstly measured, no previous theoretical calculation

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0) = (0.64 \pm 0.09 \pm 0.02)\%$$
$$\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+) = (0.45 \pm 0.07 \pm 0.03)\%$$
$$\mathcal{B}(\Lambda_c^+ \to nK^-\pi^+\pi^+) = (1.90 \pm 0.08 \pm 0.09)\%$$

- Provide significant input for future theoretical calculations of Λ_c^+ decays involving neutron!

Significantly larger than one, reveals possible abundant intermediates in $n\pi^+\pi^0$ final states.

- Relative BFs results:

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0)/\mathcal{B}(\Lambda_c^+ \to n\pi^+) = 9.7 \pm 2.2$$
$$\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)/\mathcal{B}(\Lambda_c^+ \to nK^-\pi^+\pi^+) = 0.24 \pm 0.04$$

PDG $\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)/\mathcal{B}(\Lambda_c^+ \to n\pi^+\pi^0) = 0.72 \pm 0.13$

Summary of decays involving neutron

Modes	BF(%)
$\Lambda_c^+ \to n\pi^+$	$0.066 \pm 0.012 \pm 0.004$
$\Lambda_c^+ \to n\pi^+\pi^0$	$0.64 \pm 0.09 \pm 0.02$
$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	$0.45 \pm 0.07 \pm 0.03$
$\Lambda_c^+ \to nK^-\pi^+\pi^+$	$1.90 \pm 0.08 \pm 0.09$
$\Lambda_c^+ \to n\bar{K}^0\pi^+$	$3.640 \pm 0.460 \pm 0.022$
Sum	$6.696 \pm 0.48 \pm 0.10$

- BESIII have measured about 6.7% Λ_c^+ decays involve neutron(from IP directly.)
- These measurements provide more input for phenomenological models.

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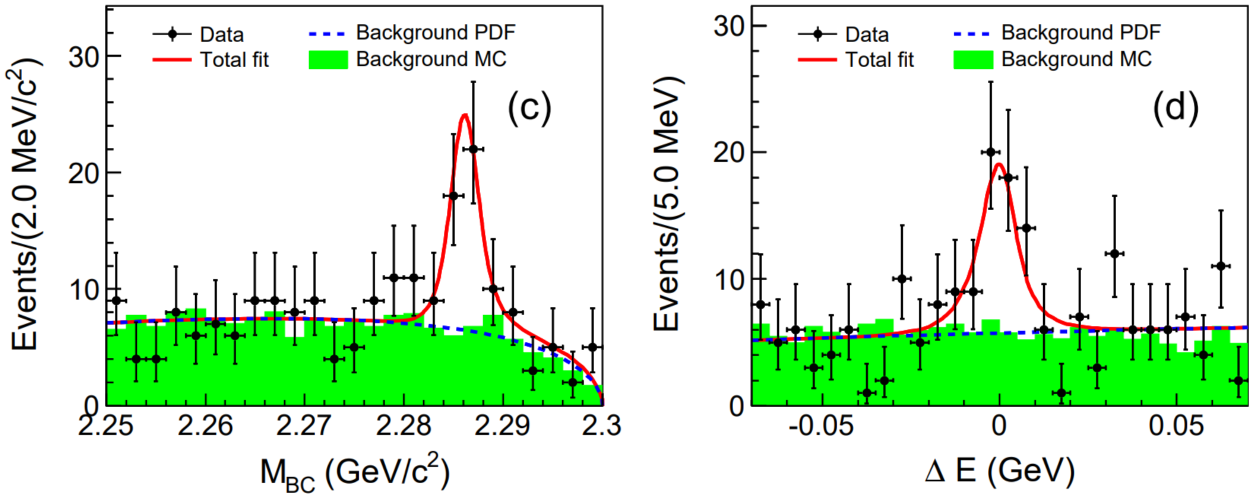
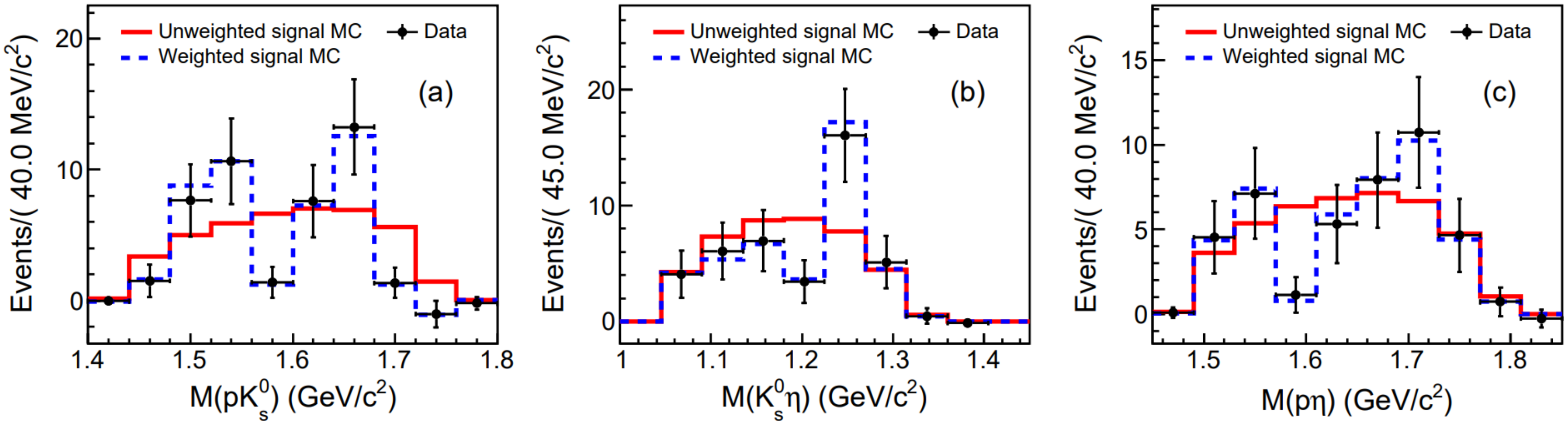
Measurement of $\Lambda_c^+ \to pK_S^0\eta$

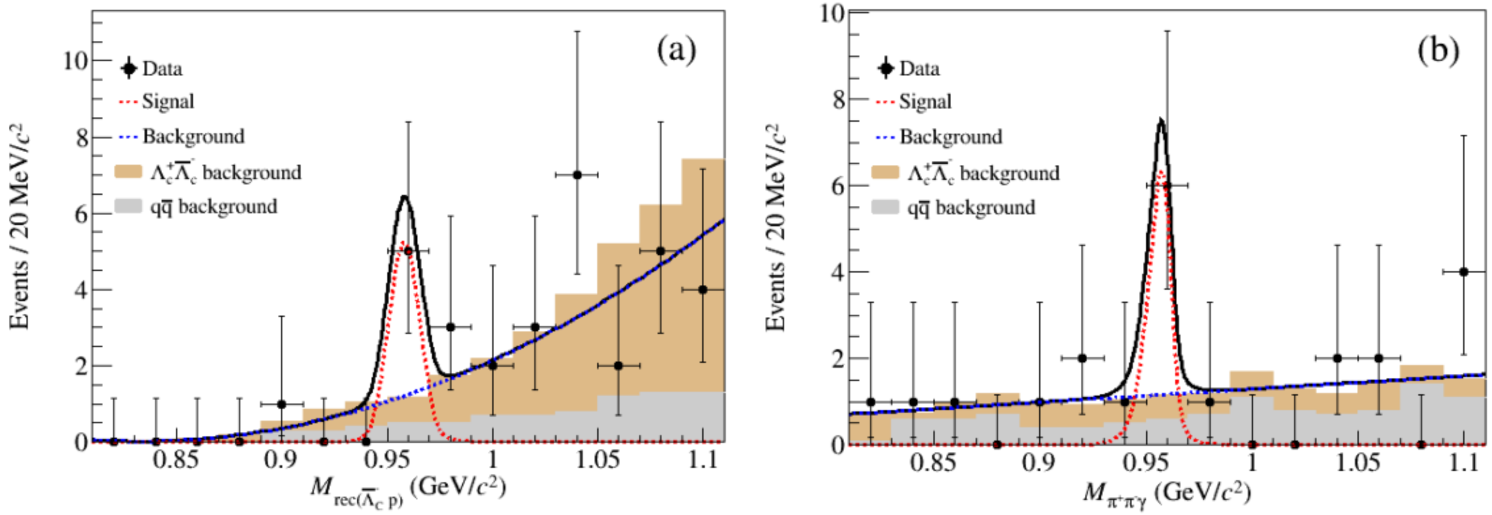


- Use data sample at 4.600 GeV.

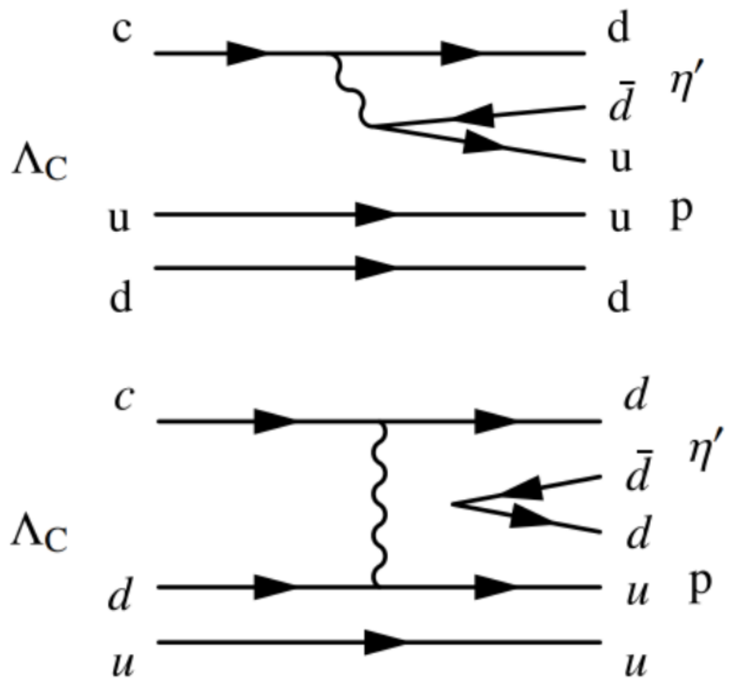
	BF%
This Work	$0.414 \pm 0.084 \pm 0.028$
PRD 99, 073003 (2019)	0.45 ± 0.05
EPJC 79, 946 (2019)	0.35 ± 0.05



Measurement of $\Lambda_c^+ \to p\eta'$



$M_{rec(\bar{\Lambda}_c^- p)}$ in $\eta' \to \pi^+\pi^-\eta$ $\quad$ $M_{\pi^+\pi^-\gamma}$ in $\eta' \to \pi^+\pi^-\gamma$



	$\Lambda_c^+ \to p\eta' \times 10^{-4}$
3.6σ This work	**$5.62^{+2.46}_{-2.04} \pm 0.26$**
[a]JHEP 03, 090 (2022)(Belle)	4.73 ± 0.97
[b]Phys. Rev. D 55, 7067 (1997)	$4-6$
[c]Phys. Rev. D 49, 3417 (1994)	$0.4-2$
[d]Phys. Lett. B 790, 225 (2019)	$12.2^{+14.3}_{-8.7}$

- The branching fraction of SCS decay $\Lambda_c^+ \to p\eta'$ is consistent the Belle result and the predictions in Ref [b][d].
- The result is significantly higher than that in Ref [c].

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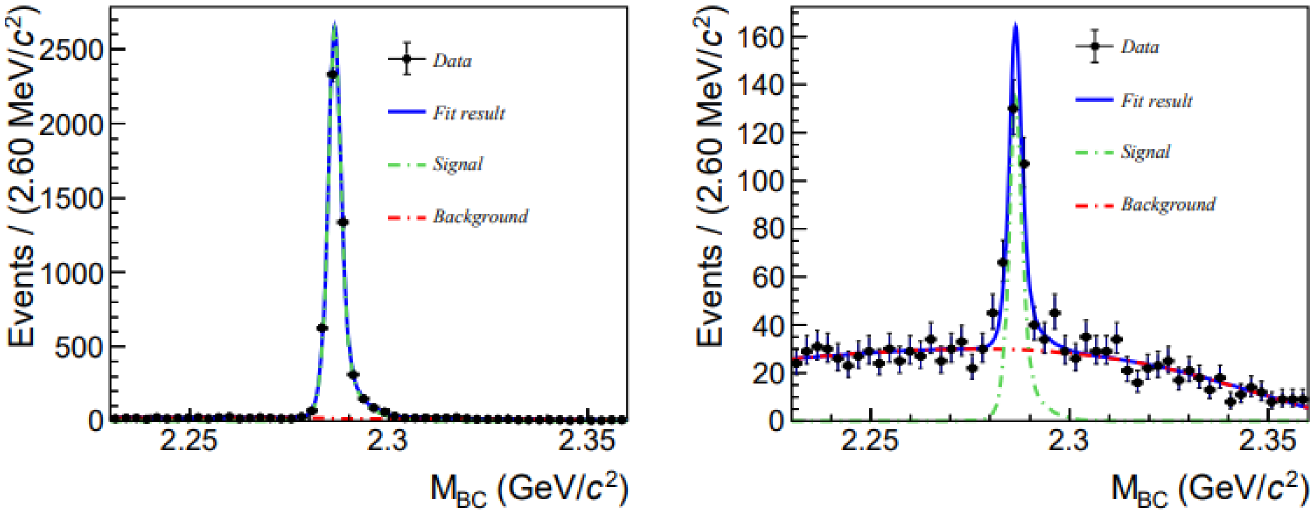
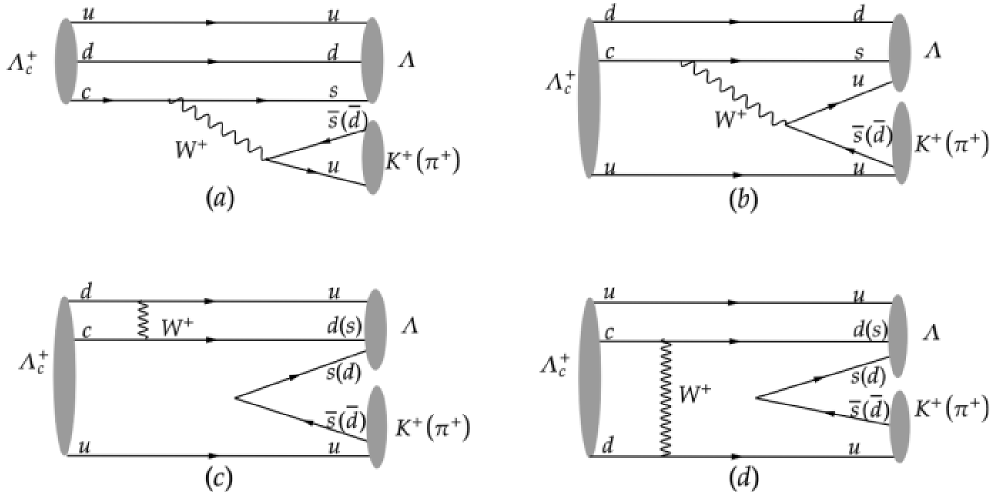
Measurement of $\Lambda_c^+ \to \Lambda K^+$





SCS Decay

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+)} = (4.66 \pm 0.34 \pm 0.15)\%$$

- Consistent with the BaBar measurement.
- Improve the precision of the world average value by ~ 3 times.

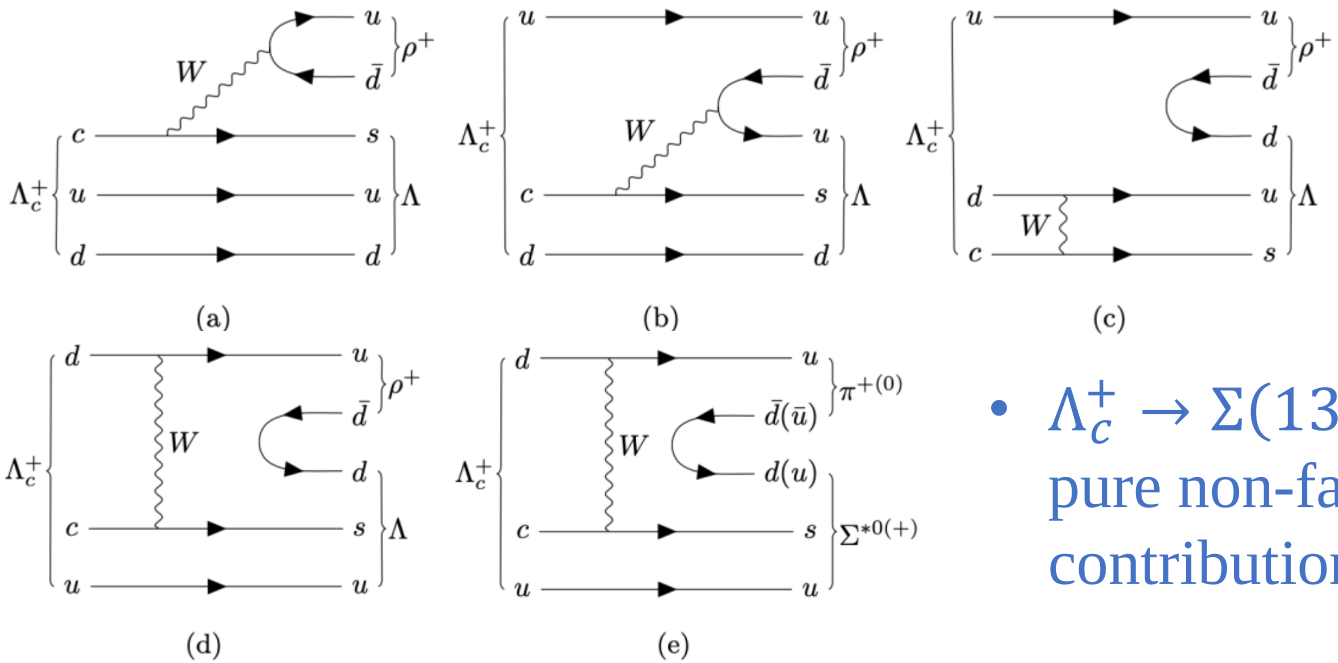
$$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.06 \pm 0.53 \pm 0.19) \times 10^{-4}$$

- As pure factorizable contribution is reliably calculated:
- $\mathcal{R}_{fac} = (7.43 \pm 0.14)\%$ (calculated)
- $\mathcal{R}_{non-fac} = \mathcal{R} - \mathcal{R}_{fac} = -(2.77 \pm 0.42)\%$
- The non-factorizable effect in Λ_c^+ decay is important and has been seriously under-estimated in current theoretical modes.

	Results
BaBar experiment	$(4.4 \pm 0.4 \pm 0.3)\%$
Belle collaboration	$(7.4 \pm 1.0 \pm 1.2)\%$
PDG	$(4.7 \pm 0.9)\%$
This work	$(4.66 \pm 0.34 \pm 0.15)\%$

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

- First charmed baryon decays PWA at BESIII.
- Intermediate processes in $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ are interesting in theoretical calculations.



- $\Lambda_c^+ \to \Lambda\rho^+$ consists of both factorizable and non-factorizable contributions.
- $\Lambda_c^+ \to \Sigma(1385)\pi$ regarded as pure non-factorizable contributions.

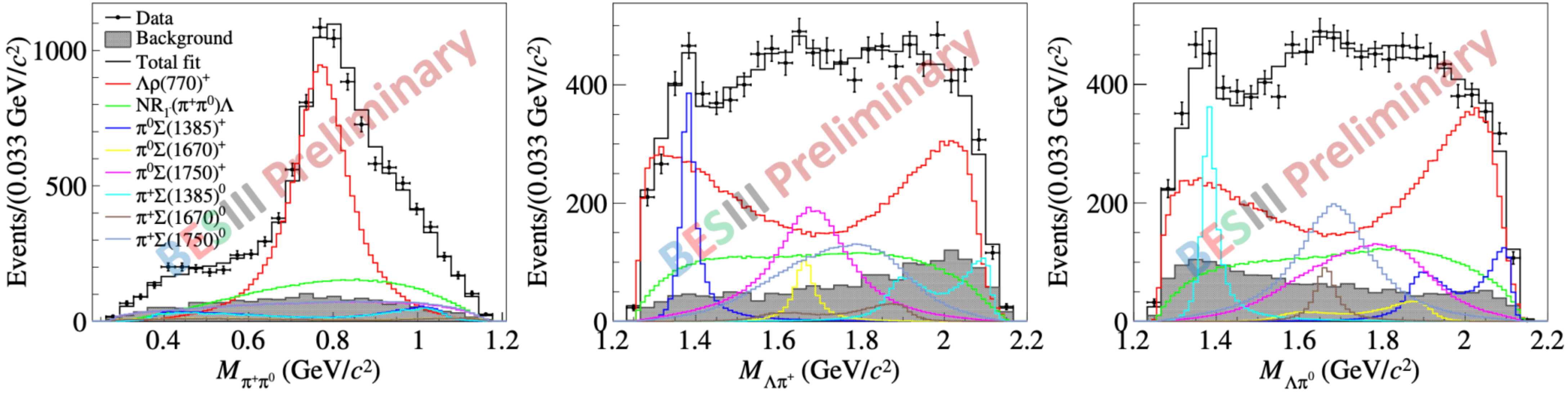
Alignment angles correctly considered

$$\mathcal{A}_{\lambda_{\Lambda_c^+},\lambda_p} = (A^{\rho}_{\lambda_{\Lambda_c^+},\lambda_p} + A^{NR}_{\lambda_{\Lambda_c^+},\lambda_p}) + \sum_{\lambda'_p}(\sum A^{\Sigma^{*+}}_{\lambda_{\Lambda_c^+},\lambda'_p}) D^{1/2}_{\lambda'_p,\lambda_p}(\alpha_p,\beta_p,\gamma_p) + \sum_{\lambda'_p}(\sum A^{\Sigma^{*0}}_{\lambda_{\Lambda_c^+},\lambda'_p}) D^{1/2}_{\lambda'_p,\lambda_p}(\alpha'_p,\beta'_p,\gamma'_p)$$

- Use new-developed TensorFlow based package TF-PWA* to perform the PWA fit. (*https://github.com/jiangyi15/tf-pwa)
- Use helicity formalism to construct the full decay amplitude.
- PWA is able to extract the intermediate processes explicitly.

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

- Use single tag method, extract around 10K signal candidates with purities $> 80\%$
- Fit results on invariant mass spectra:



	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	—

Ref. [13]: Phys. Rev. D 101 (2020) 053002.
Ref. [14,15]: Phys. Rev. D 46 (1992) 1042; Phys. Rev. D 55 (1997) 1697.
Ref. [16]: Eur. Phys. J. C 80 (2020) 1067.
Ref. [17]: Phys. Rev. D 99 (2019) 114022.

First measurements

- α extracted through results of internal partial wave amplitudes.

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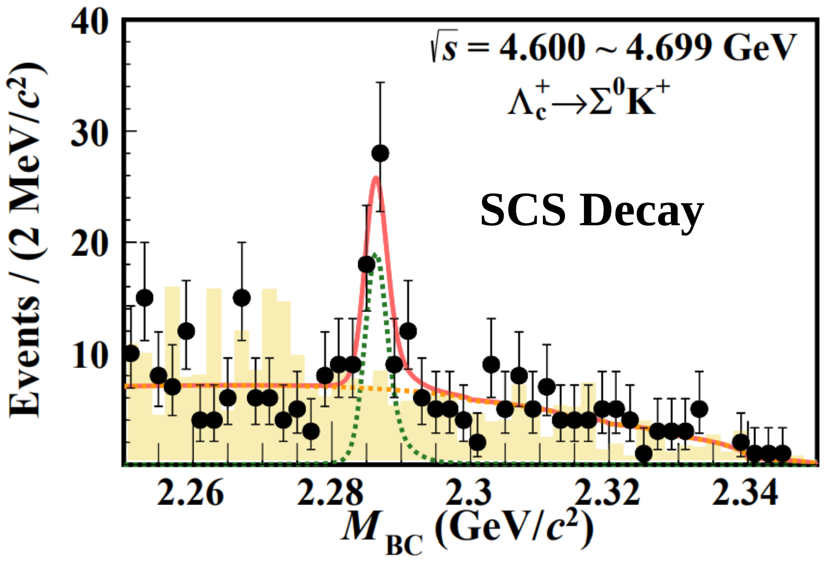
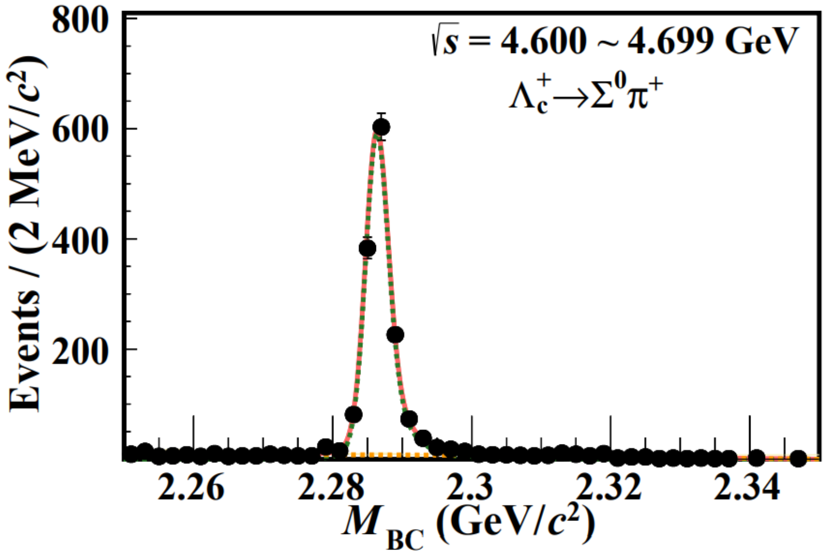




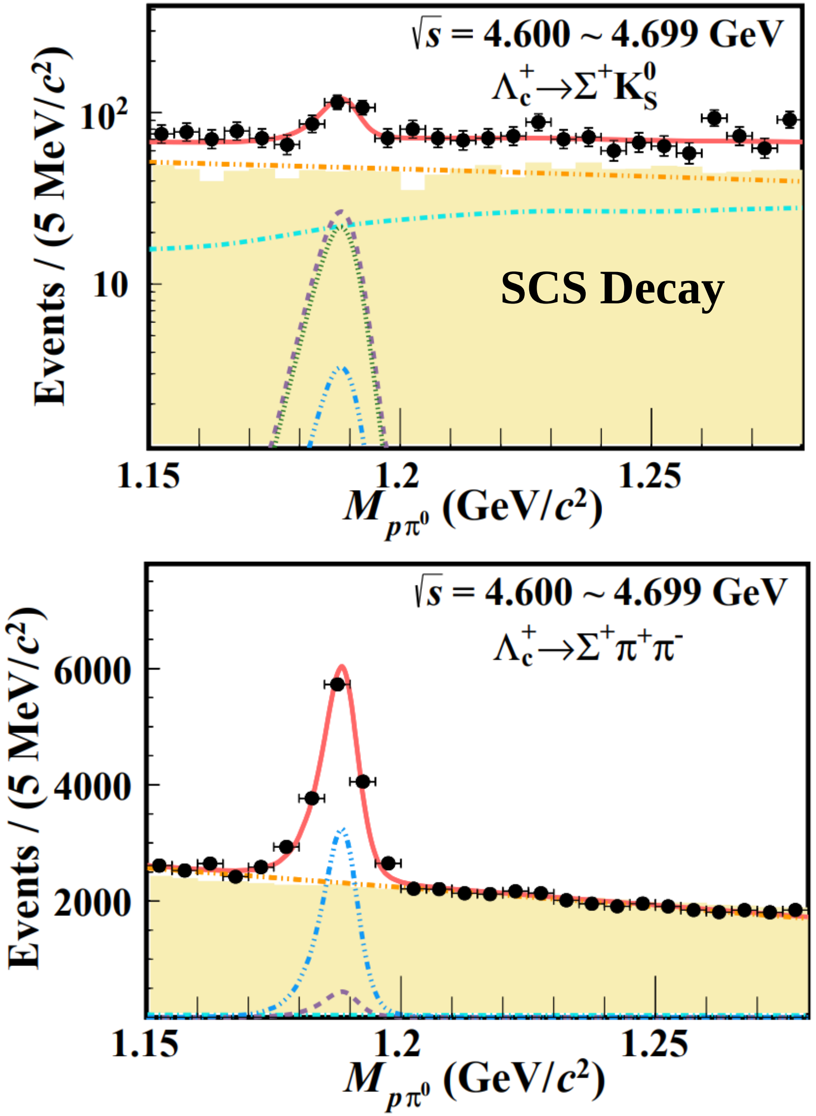
Mode	Result(%)
$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)/\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)$	$3.61 \pm 0.73 \pm 0.05$
$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$0.047 \pm 0.009 \pm 0.001 \pm 0.003$

Source	Result(%)
Theoretical prediction	0.054 ± 0.007
Current PDG	0.052 ± 0.008

Source	Result(%)
Belle	$5.6 \pm 1.4 \pm 0.8$
BaBar	$3.8 \pm 0.5 \pm 0.3$

- Compared with BESIII result, both from Belle and BaBar suffer from relatively large systematic uncertainties.

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



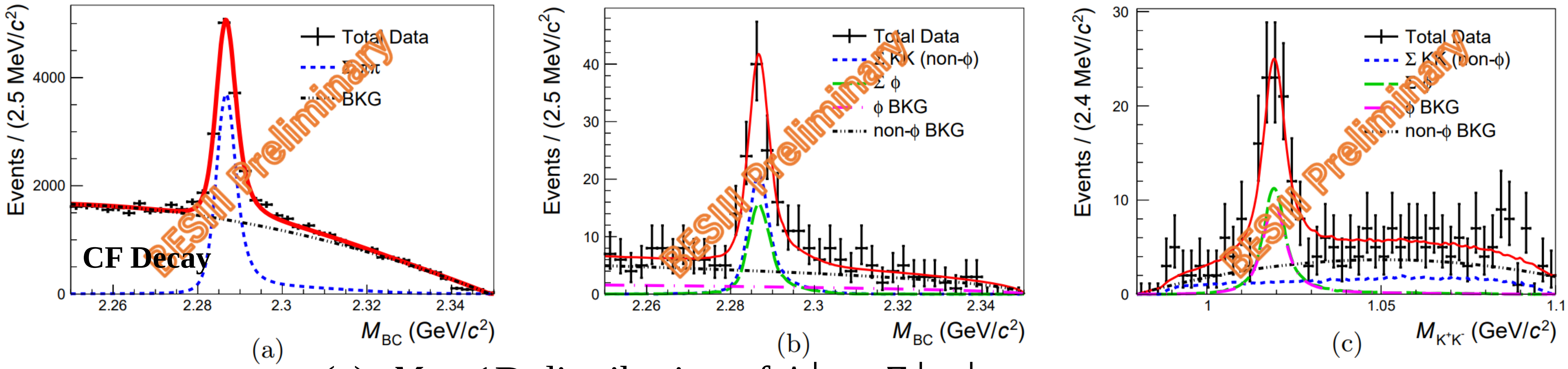
Mode	Result(%)
$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)/\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-)$	$1.06 \pm 0.31 \pm 0.04$
$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$	$0.048 \pm 0.014 \pm 0.002 \pm 0.003$

Source	Result(%)
Theoretical prediction	0.054 ± 0.007
Current PDG	$---$

- The newly measured branching fraction $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$ and improved measurement of $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$ which combines BESIII results and PDG value, can better constrain and exclude theoretical models involving charmed baryon decays.

Measurement of branching fractions for $\Lambda_c^+ \to \Sigma^+ K^+ K^-$, $\Sigma^+\phi$ and $\Sigma^+ K^+ \pi^- (\pi^0)$

- $\Lambda_c^+ \to \Sigma^+ K^+ K^-$ final states also containing $\Sigma^+\phi$ contributions.
- Relative BFs extracted, $\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-$ as reference.

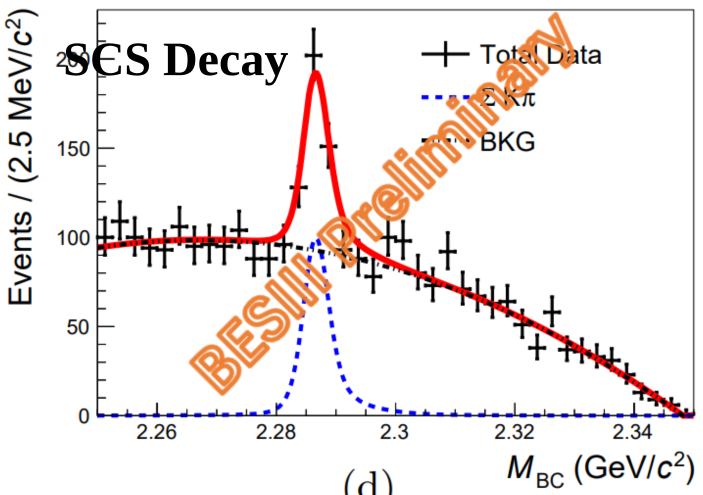


- (a): M_{BC} 1D distribution of $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$
- (b)(c): 2D fitting of $\Lambda_c^+ \to \Sigma^+ K^+ K^-$ (non-ϕ) and $\Lambda_c^+ \to \Sigma^+\phi$

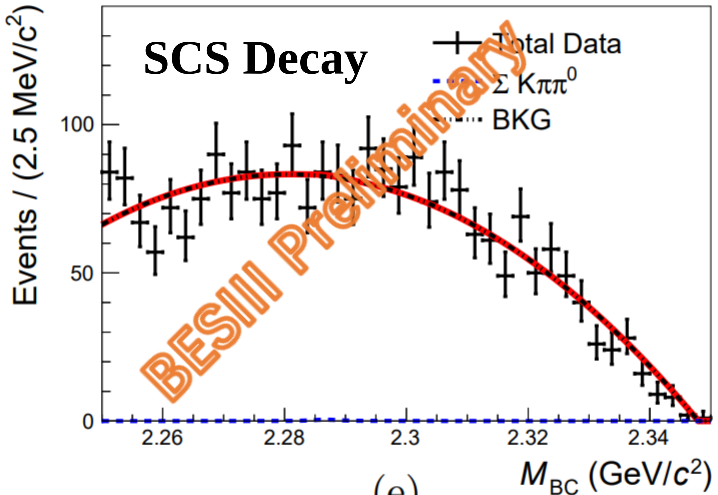
CF Decay

Mode	RBF(This work)%	RBF(Belle)%	BF(This work)%	BF(PDG)%
$\Lambda_c^+ \to \Sigma^+\phi$	$9.2 \pm 1.8 \pm 0.6$	$8.5 \pm 1.2 \pm 1.2$	$0.414 \pm 0.080 \pm 0.027 \pm 0.023$	0.39 ± 0.06
$\Lambda_c^+ \to \Sigma^+ K^+ K^- (\mathrm{non}-\phi)$	$4.38 \pm 0.79 \pm 0.16$	$---$	$0.197 \pm 0.036 \pm 0.007 \pm 0.011$	$---$

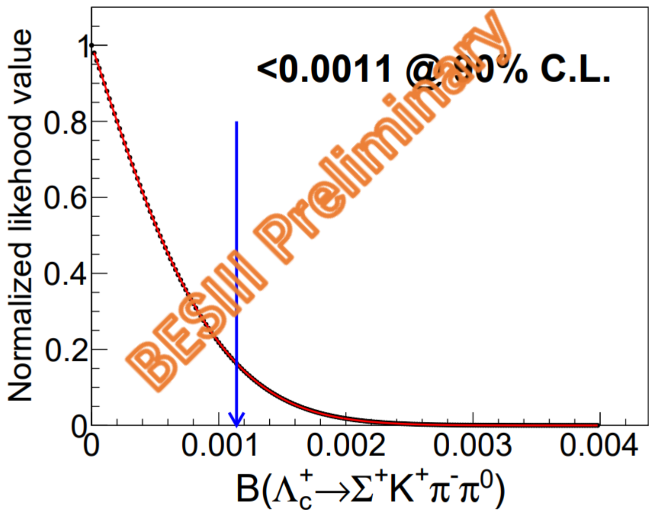
Measurement of branching fractions for $\Lambda_c^+ \to \Sigma^+ K^+ K^-$, $\Sigma^+\phi$ and $\Sigma^+ K^+ \pi^-(\pi^0)$



(d)



(e)



- (d): M_{BC} 1D distribution of $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$
- (e): M_{BC} 1D distribution of $\Lambda_c^+ \to \Sigma^+ K^+ \pi^- \pi^0$

Mode	RBF(This work)%	RBF(Belle)%	BF(This work)%	BF(PDG)%
$\Lambda_c^+ \to \Sigma^+\phi$	$9.2 \pm 1.8 \pm 0.6$	$8.5 \pm 1.2 \pm 1.2$	$0.414 \pm 0.080 \pm 0.027 \pm 0.023$	0.39 ± 0.06
$\Lambda_c^+ \to \Sigma^+ K^+ K^-(\text{non}-\phi)$	$4.38 \pm 0.79 \pm 0.16$	$---$	$0.197 \pm 0.036 \pm 0.007 \pm 0.011$	$---$
$\Lambda_c^+ \to \Sigma^+ K^+ K^-$	$7.33 \pm 0.80 \pm 0.31$	$7.6 \pm 0.7 \pm 0.9$	$0.330 \pm 0.036 \pm 0.014 \pm 0.018$	0.35 ± 0.04
$\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$	$4.51 \pm 0.52 \pm 0.23$	$4.7 \pm 1.1 \pm 0.8$	$0.202 \pm 0.023 \pm 0.011 \pm 0.011$	0.21 ± 0.06
$\Lambda_c^+ \to \Sigma^+ K^+ \pi^- \pi^0$	< 2.4	$---$	< 0.11	$---$

Summary

- BESIII have collected the largest data samples with 6.4 fb^{-1} integrated luminosity from 4.600 GeV to 4.951 GeV near the $\Lambda_c^+\overline{\Lambda}_c^-$ production threshold.
- $\Lambda_c^+ \to n\pi^+(\pi^0), n\pi^+\pi^-\pi^+$ and $nK^-\pi^+\pi^+$ are **firstly** measured.
- BESIII have measured about 6.7% Λ_c^+ decays involve neutron(from IP directly.)
- $\Lambda_c^+ \to p\eta'$ is searched with $\mathbf{3.6\sigma}$ significance.
- $\Lambda_c^+ \to \Lambda K^+$ is measured and is **consistent** with BaBar's result.
- **First** PWA of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ at BESIII performed.
- SCS decays $\Lambda_c^+ \to \Sigma^0 K^+$ with **improved** measurement, and $\Lambda_c^+ \to \Sigma^+ K_S^0$ **firstly** measured.
- $\Lambda_c^+ \to \Sigma^+ h^+ h^-(\pi^0)$ decays measured, **consistent** with PDG results.
- BESIII has made great progress on the exploration of the charmed baryon Λ_c^+ hadronic decay.
- More results ($\Lambda_c^+ \to p\pi^0, p\eta, p\omega, \bar{n}X, nK_S^0\pi^+, nK_S^0K^+, \Xi^-K^+\pi^+$ ... ...) will be released in the future.

Thanks for your attention!