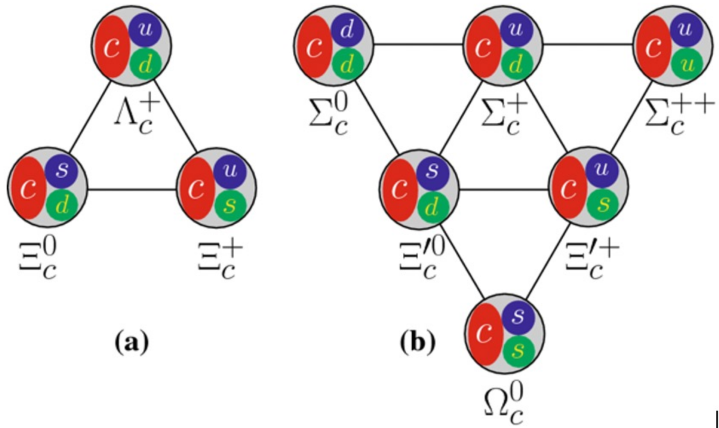

Recent results on charmed baryon at BESIII and LHCb

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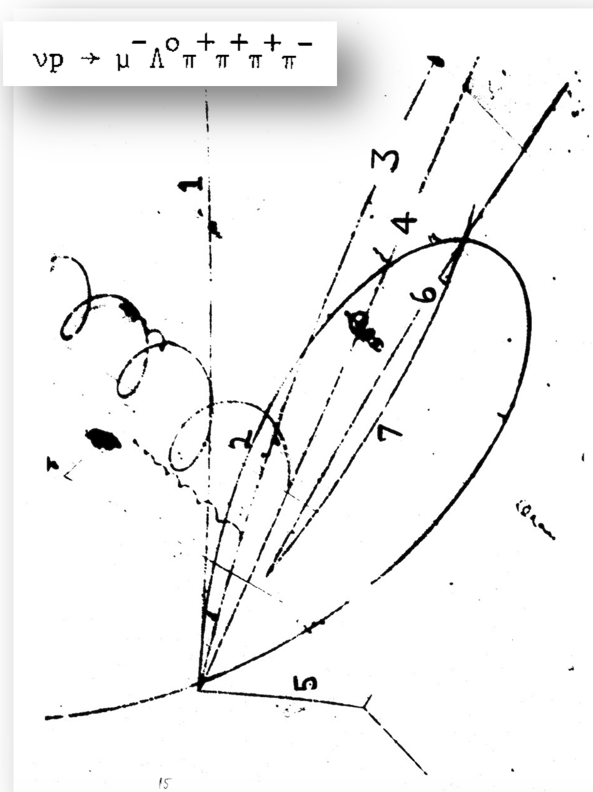
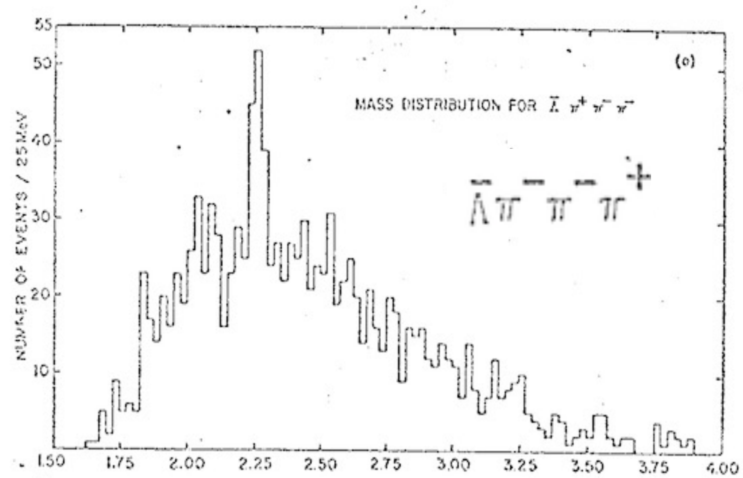
Outline

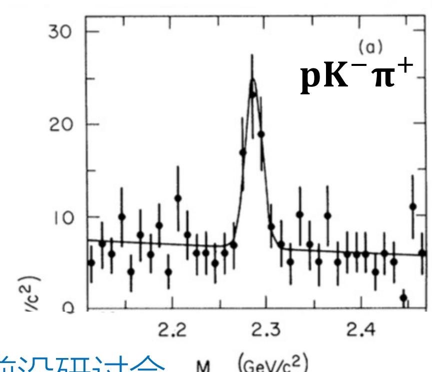
- Introduction to the charmed baryons
- BESIII progress in studying the Λ_c^+
- Recent LHCb results on charmed baryons
- Ongoing progress and future plan at BESIII
- Summary

Discovery of the charmed heavy baryon

- Not exclusively clear about the first observation
- A number of experiments which published evidence for the charmed baryons beginning in 1975
  - ✓ First hint of charmed baryon $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$ in BNL PRL34, 1125 (1975)
  - ✓ First evidence of Λ_c^+ at Fermi Lab PRL37, 882 (1976)
- The first well established state is the Λ_c^+ at MarkII PRL44, 10 (1980)



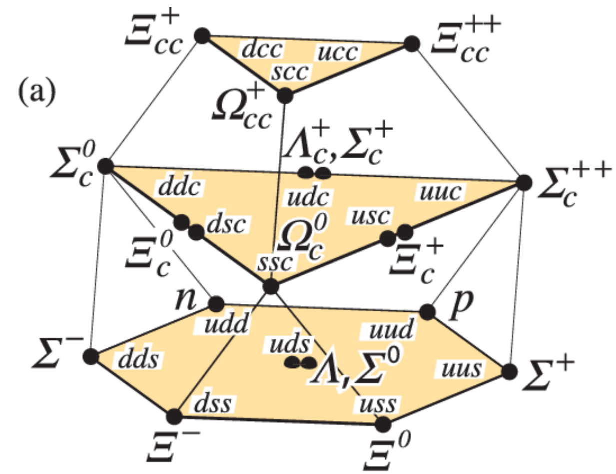




The charmed baryon family

- Singly charmed baryons
  - ✓ Established ground states:

    Λ_c^+, Σ_c , $\Xi_c^{(\prime)}$, Ω_c
  - ✓ Excited states are being explored
- Observation of other doubly charmed baryon Ξ_{cc}^{++}
- No observations of other doubly or triply charmed baryons

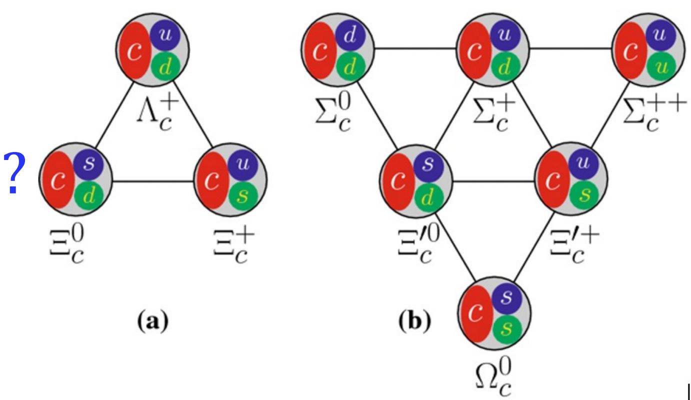


➢ Λ_c^+: decay only weakly, **many recent experimental progress since 2014**

➢ Σ_c : $B(\Sigma_c \to \Lambda_c^+ \pi) \sim 100\%$; $B(\Sigma_c \to \Lambda_c^+ \gamma)$?

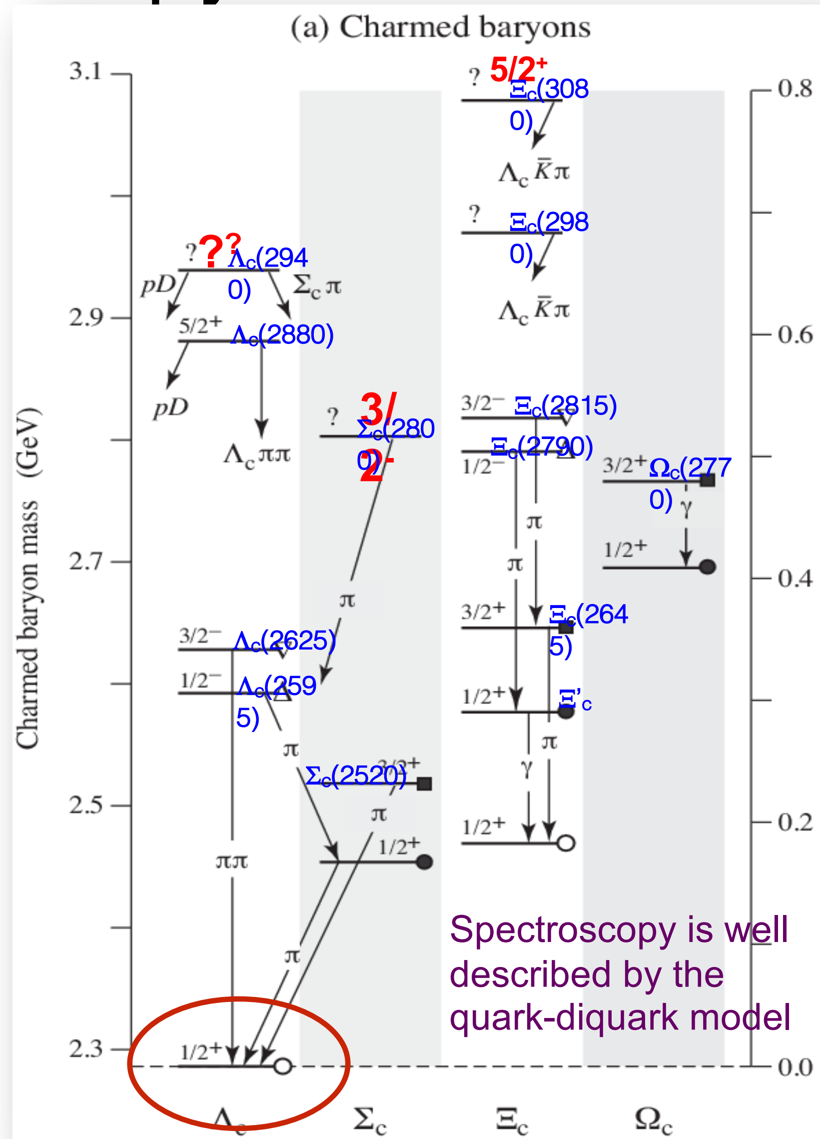
➢ Ξ_c : decay only weakly; absolute BF measured with poor precision

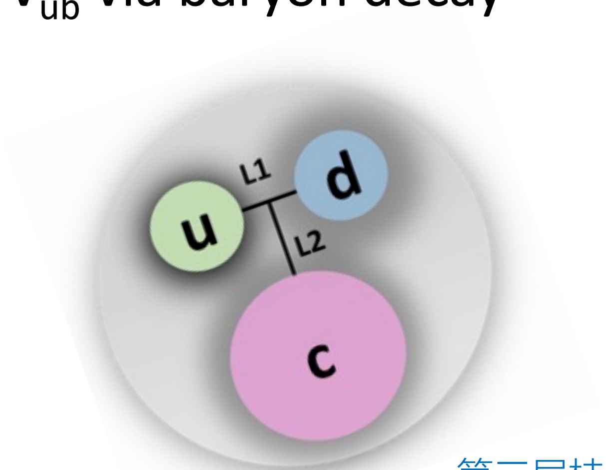
➢ Ω_c : decay only weakly; no absolute BF measured



Λ_c^+ : cornerstone of charmed baryon spectroscopy

- The lightest charmed baryon
- Most of the charmed baryons will eventually decay to Λc
- The Λc is one of important tagging hadrons in c-quark counting in the productions at high energy energies and Bottom baryon decays
- $B(\Lambda_c^+ \to pK^-\pi^+)$: dominant error for V_{ub} via baryon decay

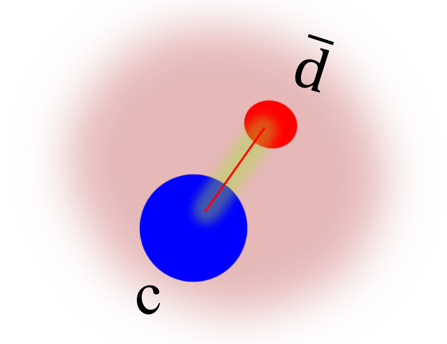


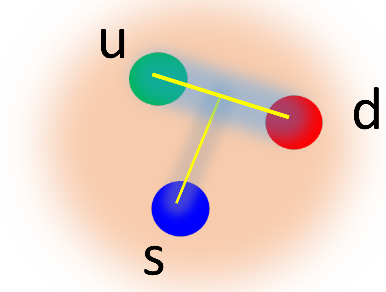


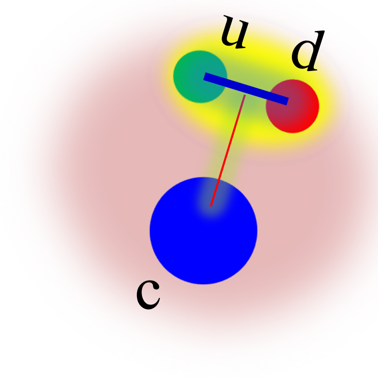
Quark model picture

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.*







→ <u>Charmed meson</u> ($D^+[c\bar{d}]$)
$m_d << m_c$ → **quark (q) + heavy quark (Q)**

→ <u>Strange baryons</u> (Λ[uds])
$m_u, m_d \approx m_s$ → **(qqq)** uniform

→ <u>Charmed baryon</u> (Λ_c[udc])
$m_u, m_d << m_c$ → **diquark (qq) + quark (Q)**

In some sense, more reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

<u>Λ_c^+ may provide complementary powerful test on internal dynamics to D/Ds does</u>

Experimental studies on Λ_c^+ until 2014

Before 2014, the *c*-ed 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).

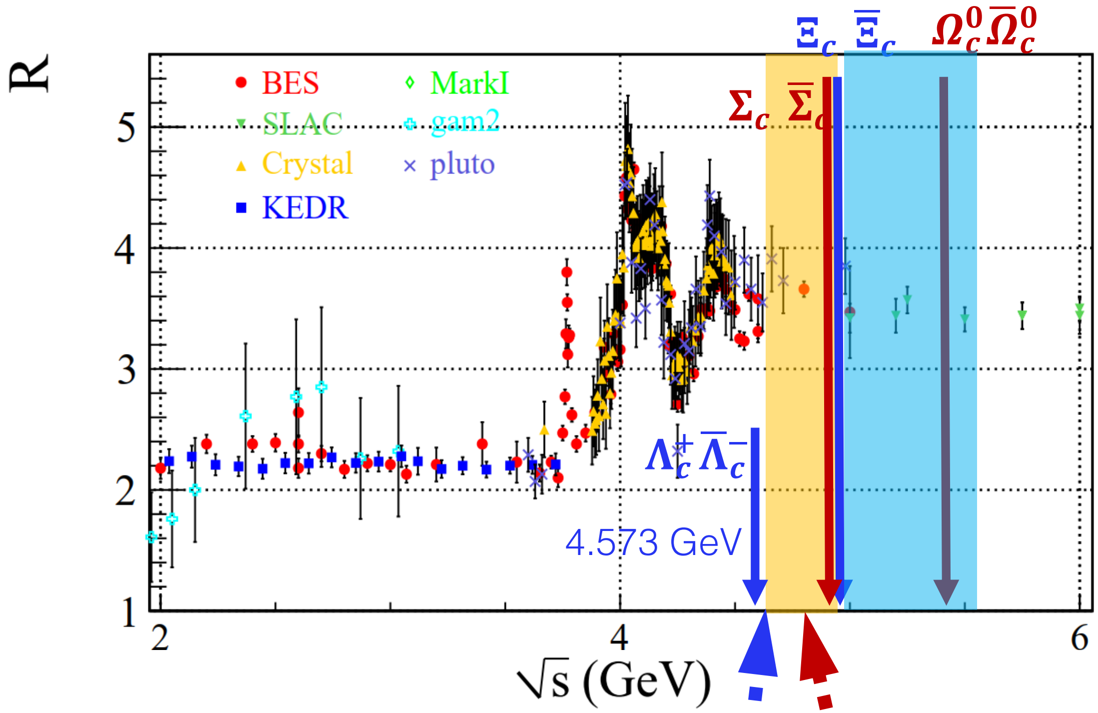
- ✓ Total branching fraction ~60%
- ✓ Lots of unknown decay channels
- ✓ Quite large uncertainties(>20%)
- ✓ Most BFs are measured relative to $\Lambda_c^+ \to pK^-\pi^+$

Large uncertainties in experiment
➔ slow development in theory

Λ_c^+ data in PDG2015

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S=-1$ final states					
$p\overline{K}^0$		(3.21 ± 0.30) %			
$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %			
$p\overline{K}^*(892)^0$	[q]	(2.13 ± 0.30) %			
$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %			22.9%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %			25.0%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %			10.5%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %			13.3%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %			23.5%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %			11.4%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %			13.0%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %			33.3%
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %			18.0%
$\Delta(1232)\overline{K}^*(892)$		seen			
$pK^-\pi^+\pi^+\pi^-$		$(1.5 \pm 1.0) \times 10^{-3}$			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S=0$ final states					
$p\pi^+\pi^-$		$(4.7 \pm 2.5) \times 10^{-3}$			45.4%
$pf_0(980)$	[q]	$(3.8 \pm 2.5) \times 10^{-3}$			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		$(2.5 \pm 1.6) \times 10^{-3}$			64.0%
pK^+K^-		$(1.1 \pm 0.4) \times 10^{-3}$			36.4%
$p\phi$	[q]	$(1.12 \pm 0.23) \times 10^{-3}$			
pK^+K^- non-ϕ		$(4.8 \pm 1.9) \times 10^{-4}$			
Hadronic modes with a hyperon: $S=-1$ final states					
$\Lambda\pi^+$		(1.46 ± 0.13) %			8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %			26.0%
$\Lambda\rho^+$		< 6 %	CL=95%		
$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		$(7.5 \pm 1.4) \times 10^{-3}$			18.7%

Charmed baryon thresholds



BESIII energy upgrades:

4.6 GeV (Phase I, 2014)

→ 4.95 GeV(Phase II, 2021)

→ 5.6 GeV (Phase III, planned in 2024)

Phase I

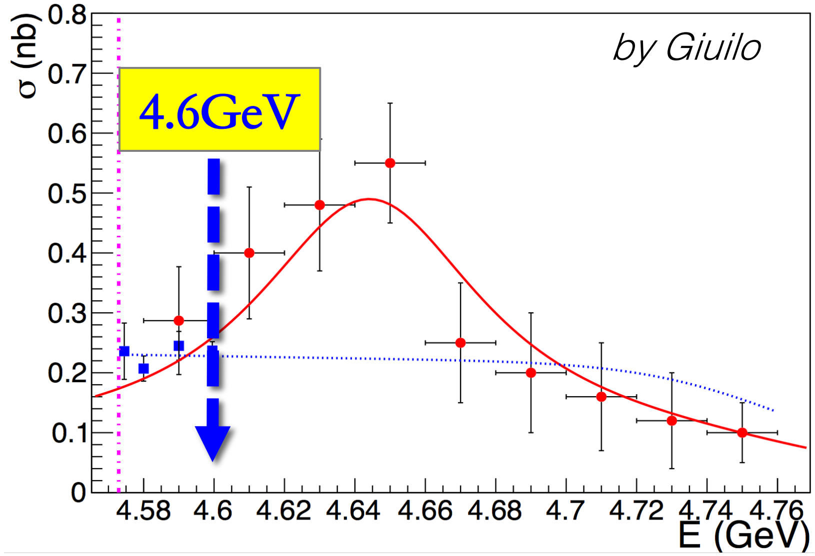
In spring of 2013, a proposal of Λ_c^+ data taking was discussed and later approved inside the collaboration.

Near threshold production at BESIII

In 2014, BESIII took (only!) 35 days to run at 4.6GeV and collected ~500/pb data.

Energy(GeV)	lum.(1/pb)
4.575	47.67
4.580	8.54
4.590	8.16
4.600	566.93

Corresponds to 0.1M Λ_c pairs

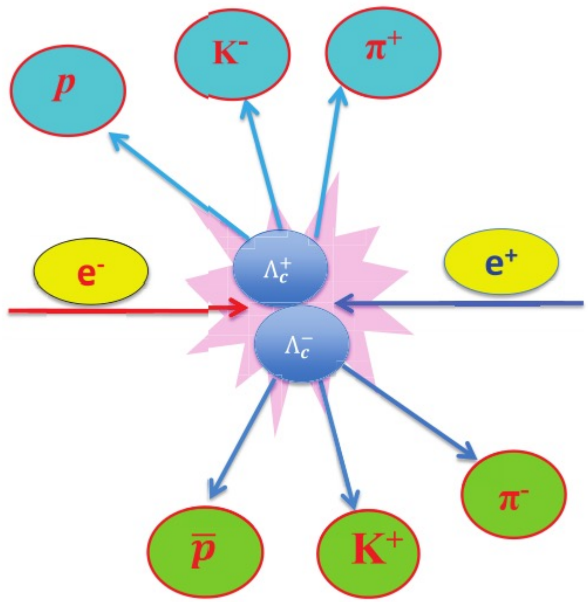


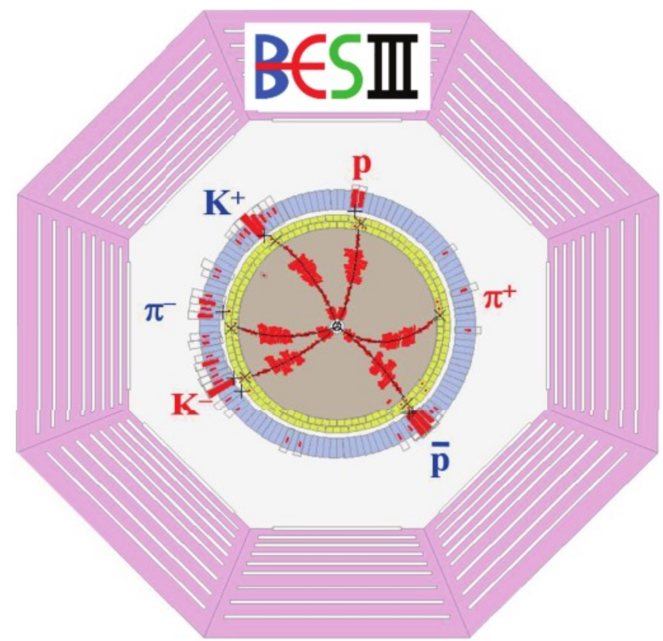
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

Single Tag (ST) and Double Tag (DT) method at Threshold

The absolute BF can be obtained by the ratio of DT yields to ST yields





- High efficiency and clean background
- Absolute measurement with many systematics cancel out
- Missing-mass technique: K_L/neutron, neutrino, …
- Good photon resolution: Σ, Ξ, π^0, …

$$\mathcal{B}_i = \frac{N_{ij}^{\mathrm{DT}}}{N_j^{\mathrm{ST}}} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

Physics publications on the Λ_c^+

Published 17 papers
(7 PRLs)

- A series of precise absolute BF measurements: hadronic, semi-leptonic and inclusive decays
- Observation of decays into neutron $\Lambda_c^+ \to nK_s\pi^+, \Sigma^-\pi^+\pi^+\pi^0$
- Observation of Cabbibo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$
- First evidence of Cabbibo-suppressed decay $\Lambda_c^+ \to p\eta$
- First measurements of many decay asymmetries
- Determination of Λ_c^+ spin
- Threshold cross section and form factors of Λ_c^+ pairs

Very productive for the data set taken in 35 days!

2014：0.567 fb^{-1} at 4.6 GeV

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	**PRL 116, 052001 (2016)**
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	**PRL 117, 232002 (2016)**
$\Lambda_c^+ \to nK_s\pi^+$	**PRL 118, 12001 (2017)**
$\Lambda_c^+ \to p\eta, p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB 783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD 99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC 43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD 100, 072004 (2019)
$\Lambda_c^+ \to pK_s\eta$	PLB 817, 136327 (2021)
Λ_c^+ spin determination	PRD 103, L091101(2021)

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$	**PRL 115, 221805(2015)**
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)

Inclusive decay

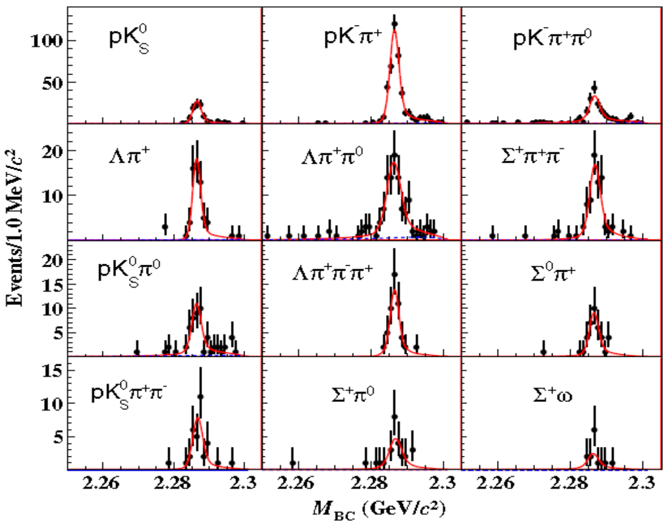
$\Lambda_c^+ \to \Lambda X$	**PRL121, 062003 (2018)**
$\Lambda_c^+ \to e^+X$	**PRL 121 251801(2018)**
$\Lambda_c^+ \to K_s^0 X$	EPJC 80, 935 (2020)

Production

$\Lambda_c^+\bar{\Lambda}_c^-$ cross section	**PRL 120,132001(2018)**

BESIII Absolute BFs of Λ_c^+ hadronic decays

- Absolute BF of Λ_c^+ decays are still not well determined since its discovery 30 years ago. PDG2014: δB/B~26%; BELLE2014: δB/B~5.3%
- Double tag technique is applied to control systematics



- a global least square fit to 12 hadronic modes [Chin. Phys. C37(2013)106201]

✓ **First direct measurement on Λc BFs at threshold**

✓ **$B(pK^-\pi^+)$: BESIII precision comparable with Belle's**

✓ **Improved precisions of the other 11 modes significantly**

PRL 116, 052001 (2016)

Mode	This work (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	

So far, the mostly cited BESIII charm paper

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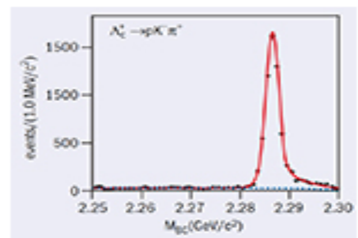
Mar 18, 2016

BESIII makes first direct measurement of the Λ_c at threshold



Beam-constrained mass distribution

The charmed baryon, Λ_c, was first observed at Fermilab in 1976. Now, 40 years later, the Beijing Spectrometer (BESIII) experiment at the Beijing Electron-Positron Collider II (BEPCII) has measured the absolute branching fraction of $\Lambda^+_c \to pK^-\pi^+$ at threshold for the first time.

Because the decays of the Λ^+_c to hadrons proceed only through the weak interaction, their branching fractions are key probes for understanding weak interactions inside of a baryon. In particular, precise measurements of the decays of the Λ^+_c will provide important information on the final-state strong interaction in the charm sector, thereby improving the understanding of quantum chromodynamics in the non-perturbative energy region. In addition, because most of the

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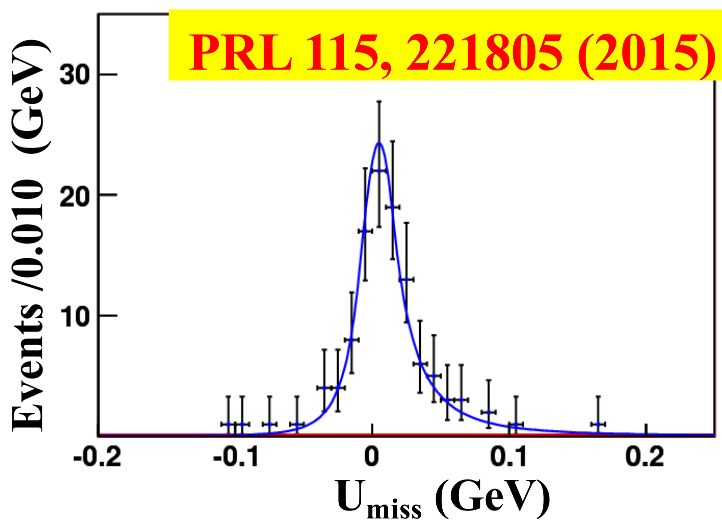
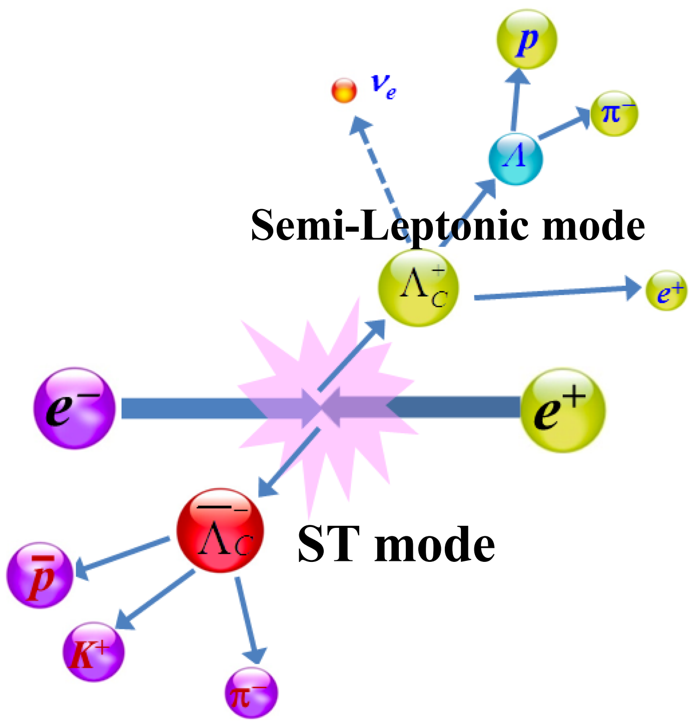
BF for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is a $c \to s l^+ \nu_l$ dominated process.
- Urgently needed for LQCD calculations.
- No direct absolute measurement for $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ available.

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (2.1 \pm 0.6)\% \qquad \text{PDG 2014}$$

11 hadronic single tag modes are used





$$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

- First absolute measurement of the semi-leptonic decay
- Statistics limited
- Best precision to date: twofold improvement

First Lattice calculation on charmed baryon SL decays

PRL 118, 082001 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

$\Lambda_c \to \Lambda l^+ \nu_l$ Form Factors and Decay Rates from Lattice QCD with Physical Quark Masses

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(Received 1 December 2016; published 21 February 2017)

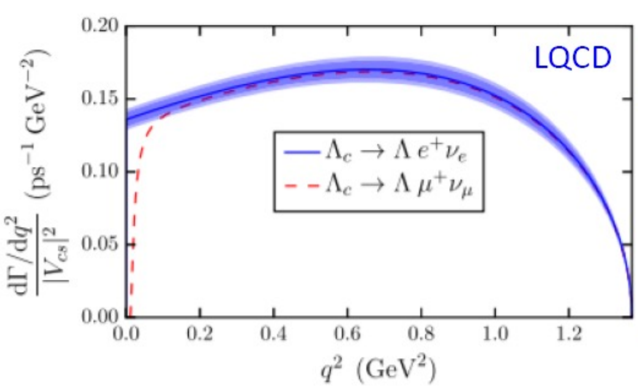
- Input the measured BFs from BESIII

Triggered by BESIII

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

- The first LQCD calculations on BFs and form factors

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = \mu, \end{cases}$$



✓ The first determination of $|V_{cs}|$ based on BFs of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ measured by BESIII

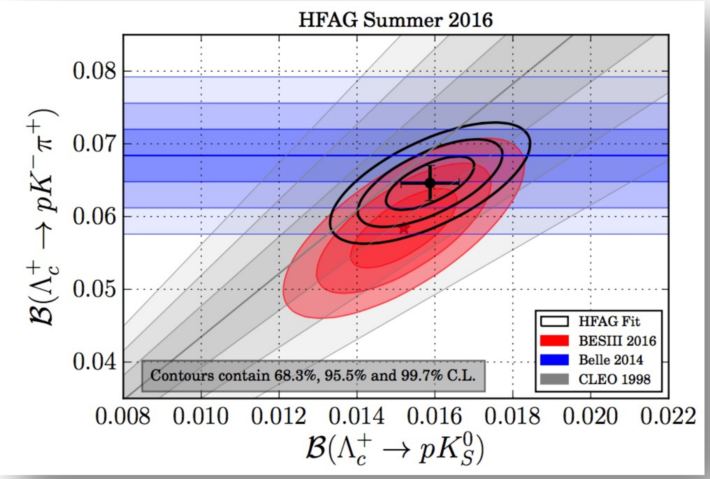
$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases}$$

✓ More data on Λ_c^+ will be collected at BESIII

HFLAV Fit to world BF data

- A fitter to constrain the 12 hadronic BFs and 1 SL BF, based on all the existing experimental data
- Correlated systematics are fully taken into account

Mode	HFAG 2016 (%)	BESIII (%)	PDG 2014 (%)	BELLE (%)
pK_S^0	1.59 ± 0.07	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	6.46 ± 0.24	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	1.69 ± 0.11	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	5.05 ± 0.29	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	1.28 ± 0.06	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	7.09 ± 0.36	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.73 ± 0.21	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.31 ± 0.07	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	1.25 ± 0.09	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	4.64 ± 0.24	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	1.77 ± 0.21	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	
$\Lambda e^+\nu_e$	3.18 ± 0.32	$3.63 \pm 0.38 \pm 0.20$	2.1 ± 0.6	



The least overall χ^2/ndf=30.0/23=1.3

Precise $B(pK^-\pi^+)$ is useful for constrain V_{ub} determined via baryonic mode

PDG2015

Λ_c^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Sc Confi
	Hadronic modes with a p: $S = -1$ final states			
Γ_1	$p\overline{K}^0$		(3.21 ± 0.30) %	
Γ_2	$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %	
Γ_3	$p\overline{K}^*(892)^0$	[a]	(2.13 ± 0.30) %	
Γ_4	$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %	
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.4 ± 0.6) %	
Γ_6	$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %	
Γ_7	$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %	
Γ_8	$p\overline{K}^0\eta$		(1.7 ± 0.4) %	
Γ_9	$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %	
Γ_{10}	$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %	
Γ_{11}	$pK^*(892)^-\pi^+$	[a]	(1.5 ± 0.5) %	
Γ_{12}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %	
Γ_{13}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{14}	$pK^-\pi^+\pi^+\pi^-$		$(1.5 \pm 1.0) \times 10^{-3}$	
Γ_{15}	$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %	
Γ_{16}	$pK^-\pi^+3\pi^0$			
	Hadronic modes with a p: $S = 0$ final states			
Γ_{17}	$p\pi^+\pi^-$		$(4.7 \pm 2.5) \times 10^{-3}$	
Γ_{18}	$pf_0(980)$	[a]	$(3.8 \pm 2.5) \times 10^{-3}$	
Γ_{19}	$p\pi^+\pi^+\pi^-\pi^-$		$(2.5 \pm 1.6) \times 10^{-3}$	
Γ_{20}	pK^+K^-		$(1.1 \pm 0.4) \times 10^{-3}$	
Γ_{21}	$p\phi$	[a]	$(1.12 \pm 0.23) \times 10^{-3}$	
Γ_{22}	pK^+K^- non-ϕ		$(4.8 \pm 1.9) \times 10^{-4}$	
	Hadronic modes with a hyperon: $S = -1$ final states			
Γ_{23}	$\Lambda\pi^+$		(1.46 ± 0.13) %	
Γ_{24}	$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %	
Γ_{25}	$\Lambda\rho^+$		< 6 %	CL=95%
Γ_{26}	$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %	
Γ_{27}	$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(1.0 ± 0.5) %	
Γ_{28}	$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		$(7.5 \pm 1.4) \times 10^{-3}$	
Γ_{29}	$\Lambda\pi^+\rho^0$		(1.4 ± 0.6) %	
Γ_{30}	$\Sigma(1385)^+\rho^0$, $\Sigma^{*+} \to \Lambda\pi^+$		$(5 \pm 4) \times 10^{-3}$	
Γ_{31}	$\Lambda\pi^+\pi^+\pi^-$ nonresonant		< 1.1 %	CL=90%
Γ_{32}	$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(2.5 ± 0.9) %	
Γ_{33}	$\Lambda\pi^+\eta$	[a]	(2.4 ± 0.5) %	
Γ_{34}	$\Sigma(1385)^+\eta$	[a]	(1.16 ± 0.35) %	
Γ_{35}	$\Lambda\pi^+\omega$	[a]	(1.6 ± 0.6) %	
Γ_{36}	$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		$< 9 \times 10^{-3}$	CL=90%
Γ_{37}	$\Lambda K^+\overline{K}^0$		$(6.4 \pm 1.3) \times 10^{-3}$	S=1.6
Γ_{38}	$\Xi(1690)^0K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$		$(1.8 \pm 0.6) \times 10^{-3}$	
Γ_{39}	$\Sigma^0\pi^+$		(1.43 ± 0.14) %	
Γ_{40}	$\Sigma^+\pi^0$		(1.37 ± 0.30) %	
Γ_{41}	$\Sigma^+\eta$		$(7.5 \pm 2.5) \times 10^{-3}$	
Γ_{42}	$\Sigma^+\pi^+\pi^-$		(4.9 ± 0.5) %	
Γ_{43}	$\Sigma^+\rho^0$		< 1.8 %	CL=95%
Γ_{44}	$\Sigma^-\pi^+\pi^+$		(2.3 ± 0.4) %	
Γ_{45}	$\Sigma^0\pi^+\pi^0$		(2.5 ± 0.9) %	
	Semileptonic modes			
Γ_{64}	$\Lambda\ell^+\nu_\ell$	[b]	(2.8 ± 0.4) %	
Γ_{65}	$\Lambda e^+\nu_e$		(2.9 ± 0.5) %	
Γ_{66}	$\Lambda\mu^+\nu_\mu$		(2.7 ± 0.6) %	

PDG2020

	Mode		Fraction	Change	S / CL
	Hadronic modes with a p or n: $S = -1$ final states				
Γ_1	pK_S^0		(1.59 ± 0.08) %	↓44%	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) %	↓50%	S=1.1
Γ_8	$nK_S^0\pi^+$		(1.82 ± 0.25) %	First	
Γ_9	$p\overline{K}^0\eta$		(1.6 ± 0.4) %		
Γ_{10}	$pK_S^0\pi^+\pi^-$		(1.60 ± 0.12) %	↓28%	S=1.1
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	↓61%	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) %		
	Hadronic modes with a p: $S = 0$ final states				
Γ_{17}	$p\pi^0$		$< 2.7 \times 10^{-4}$		CL=90%
Γ_{18}	$p\eta$		$(1.24 \pm 0.30) \times 10^{-3}$	First	
Γ_{19}	$p\omega(782)^0$		$(9 \pm 4) \times 10^{-4}$		
Γ_{20}	$p\pi^+\pi^-$		$(4.61 \pm 0.28) \times 10^{-3}$	First	
Γ_{21}	$pf_0(980)$	[a]	$(3.5 \pm 2.3) \times 10^{-3}$		
Γ_{22}	$p2\pi^+2\pi^-$		$(2.3 \pm 1.4) \times 10^{-3}$		
Γ_{23}	pK^+K^-		$(1.06 \pm 0.06) \times 10^{-3}$		
Γ_{24}	$p\phi$	[a]	$(1.06 \pm 0.14) \times 10^{-3}$	↓36%	
Γ_{25}	pK^+K^- non-ϕ		$(5.3 \pm 1.2) \times 10^{-4}$		
Γ_{26}	$p\phi\pi^0$		$(10 \pm 4) \times 10^{-5}$		
Γ_{27}	$pK^+K^-\pi^0$ nonresonant		$< 6.3 \times 10^{-5}$		CL=90%
	Hadronic modes with a hyperon: $S = -1$ final states				
Γ_{28}	$\Lambda\pi^+$		(1.30 ± 0.07) %		S=1.1
Γ_{29}	$\Lambda\pi^+\pi^0$		(7.1 ± 0.4) %	↓78%	S=1.1
Γ_{30}	$\Lambda\rho^+$		< 6 %		CL=95%
Γ_{31}	$\Lambda\pi^-2\pi^+$		(3.64 ± 0.29) %		S=1.4
Γ_{44}	$\Sigma^0\pi^+$		(1.29 ± 0.07) %	↓45%	S=1.1
Γ_{45}	$\Sigma^+\pi^0$		(1.25 ± 0.10) %	↓33%	
Γ_{46}	$\Sigma^+\eta$		$(4.4 \pm 2.0) \times 10^{-3}$		
Γ_{47}	$\Sigma^+\eta'$		(1.5 ± 0.6) %		
Γ_{48}	$\Sigma^+\pi^+\pi^-$		(4.50 ± 0.25) %	↓46%	S=1.3
Γ_{49}	$\Sigma^+\rho^0$		< 1.7 %		CL=95%
Γ_{50}	$\Sigma^-2\pi^+$		(1.87 ± 0.18) %		
Γ_{51}	$\Sigma^0\pi^+\pi^0$		(3.5 ± 0.4) %		
Γ_{52}	$\Sigma^+\pi^0\pi^0$		(1.55 ± 0.15) %		
Γ_{53}	$\Sigma^0\pi^-2\pi^+$		(1.11 ± 0.30) %		
	Semileptonic modes				
Γ_{72}	$\Lambda e^+\nu_e$		(3.6 ± 0.4) %	↓35%	
Γ_{73}	$\Lambda\mu^+\nu_\mu$		(3.5 ± 0.5) %		

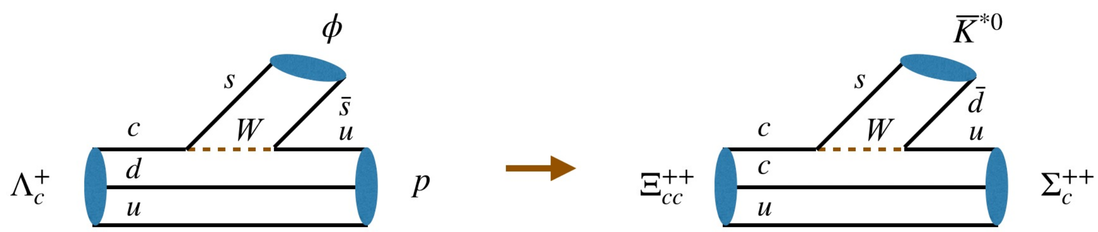
Experimental precision reaches of the charmed hadrons

	Golden hadronic mode	δB/B	Golden SL mode	δB/B
D^0	B(Kπ)=(3.88±0.05)%	1.3%	B(Keν)=(3.55±0.05)%	1.4%
D^+	B(Kππ)=(9.13±0.19)%	2.1%	B(K^0eν)=(8.83±0.22)%	2.5%
D_s	B(KKpi)=(5.39±0.21)%	3.9%	B(φeν)=(2.49±0.14)%	5.6%
Λc	B(pKπ)=(5.0±1.3)%(PDG2014) =(6.8±0.36)% (BELLE) =(5.84±0.35)% (BESIII) =(6.46±0.24)% (HFLAV)	26% 5.3% 6.0% 3.7%	B(Λeν)=(2.1±0.6)%(PDG2014) =(3.63±0.43)% (BESIII) =(3.18±0.32)% (HFLAV)	29% 12% 10%

- The precisions of Λc decay rates reaches to the level of charmed mesons!
- However, search for more unknown modes, especially Cabbibo-suppressed mode, are important

- Topological diagrams + Symmetries + Experimental inputs $\Rightarrow$ to understand the decaying dynamics, predicting double-charm baryon decays, CPV, etc. (predictive power)
  - Λ_c^+ branching fractions used for global analysis

    $\Rightarrow$ $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are large enough for observation.



$Br(\Lambda_c^+ \to p\phi)/|V_{us}|^2$ = 2 % $\Rightarrow$ $Br\left(\Xi_{cc}^{++} \to \Sigma_c^{++} \bar{K}^{*0}\right)$ = O(%)

[PRL 117, 232002 (2016)]

$\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+ K^- \pi^+$

Large enough for observation

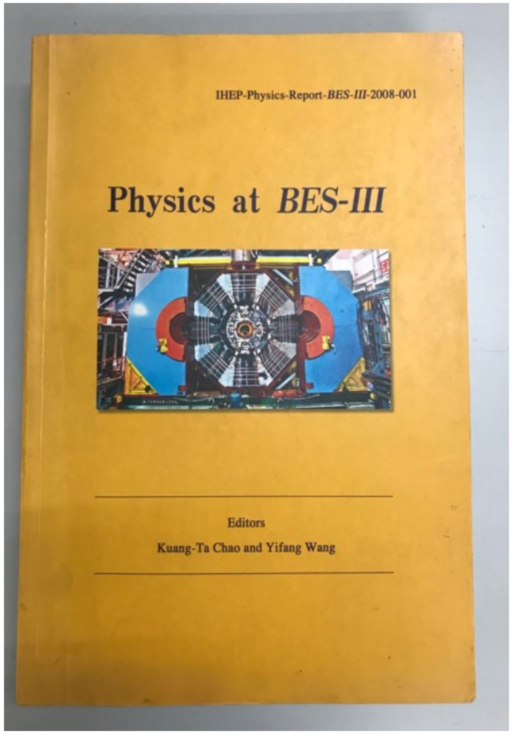
Important inputs to the Ξ_{cc}^{++} observation at LHCb

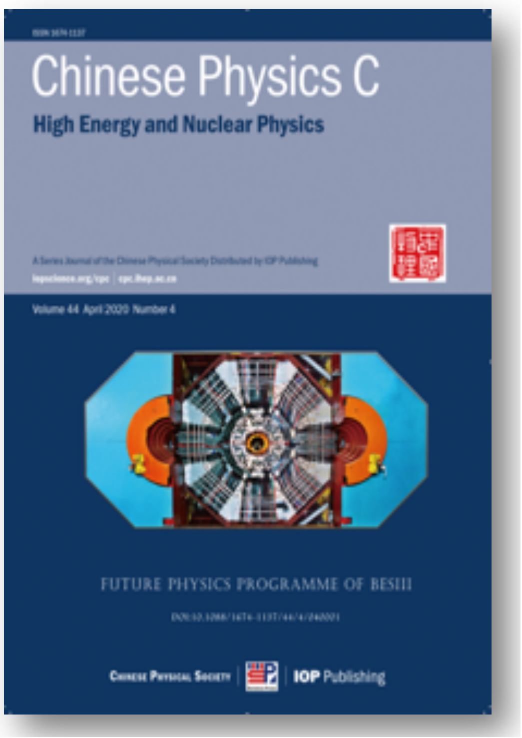
Λ_c^+ data from BESIII → Stronger predictive power

Phase II

After success of the first Λ_c^+ data set, an energy upgrade on the BEPCII, 4.6 GeV ➔ 4.95 GeV, has been implemented to study Λ_c^+ with more statistics

BESIII Physics Reports





Int. J. Mod. Phys. A 24, S1-794 (2009) [arXiv:0809.1869 [hep-ex]].

Chin. Phys. C 44, 040001 (2020) doi:10.1088/1674-1137/44/4/040001 [arXiv:1912.05983 [hep-ex]].

Planned future data set

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 most right column shows the number of required data taking days in current (T_C) or 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

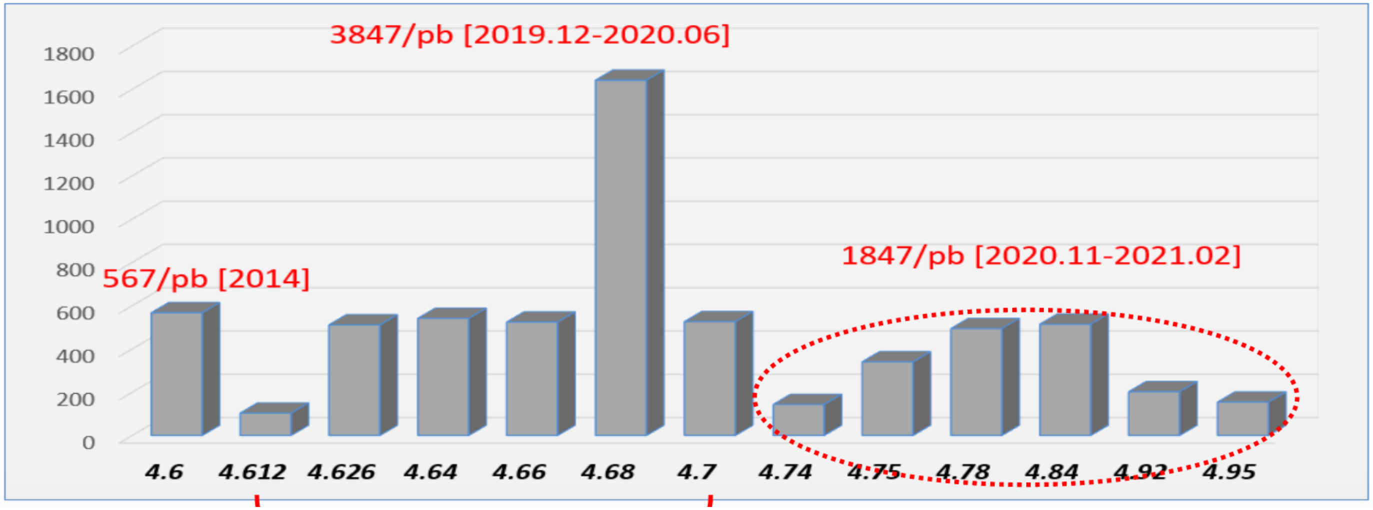
to be complete in 2022-24

18 fb^{-1} Λ_c^+ data

in 2020-2021, 5.8 fb^{-1} is taken

[Chin. Phys. C 46, 113003 (2022)]

New Λ_c^+ data in 2020-2021



in total, 6.4 fb^{-1} data above Λ_c^+ threshold (~8x times more Λ_c^+ statistics)

- First measurement of absolute form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$
- Observation of second SL decay $\Lambda_c^+ \to p K^- e^+ \nu_e$
- Many observations and improved precisions of Cabbibo-Suppressed modes
- First partial wave analysis of Λ_c^+ decays
- More studies of neutron-involved decay modes
- Search for rare decay $\Lambda_c^+ \to \gamma \Sigma^+$

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ — PRL129, 231803 (2022)
- ✓ $\Lambda_c^+ \to p K^- e^+ \nu_e$ — PRD106, 112010 (2022)
- ✓ *LFU test of* $\Lambda_c^+ \to \Lambda l^+ \nu_l$, — PRD108, L031105 (2023)
- ✓ Search for $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $p K_s \pi^- e^+ \nu_e$ — PLB843, 137993 (2023)

Neutron-involved decay

- ✓ $\Lambda_c^+ \to n \pi^+$ — PRL 128, 142001 (2022)
- ✓ $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^+\pi^-, nK^-\pi^+\pi^+$ — CPC 47, 023001 (2023) (Cover Story)
- ✓ $\Lambda_c^+ \to n K_s K^+$ — arXiv:2311.17131
- ✓ $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ — arXiv:2309.05484
- ✓ $\Lambda_c^+ \to n K_s \pi^+ \pi^0$ — arXiv:2401.06813

Hadronic CS decays

- ✓ $\Lambda_c^+ \to p\pi^0, p\eta, p\eta', p\omega$ — PRD106, 072002 (2022); JHEP11, 137 (2023); arXiv:2311.06883
- ✓ $\Lambda_c^+ \to \Lambda K^+, \Lambda K^+ \pi^0$ — PRD106, L111101 (2022); PRD109, 032003 (2024)
- ✓ $\Lambda_c^+ \to \Sigma^+ K_s, \Sigma^0 K^+$ — PRD106, 052003 (2022)
- ✓ $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$ — JHEP09, 125 (2023);

24 papers are published

Hadronic CF decays

- ✓ PWA of $\Lambda_c^+ \to \Lambda \pi^+ \pi^0$ — JHEP 12, 033(2022)
- ✓ W-exchange-only process $\Xi^0 K^+$ — PRL132, 031801 (2024)
- ✓ $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ — PRD109, 052001 (2024)

Inclusive decay

- ✓ Improved BF of $\Lambda_c^+ \to e^+ X$ — PRD107, 052005 (2023)
- ✓ First BF of $\bar{\Lambda}_c^- \to \bar{n} X$ — PRD108, L031101 (2023)

Rare decay

- ✓ $\Lambda_c^+ \to \gamma \Sigma^+$ — PRD107, 052002 (2023)

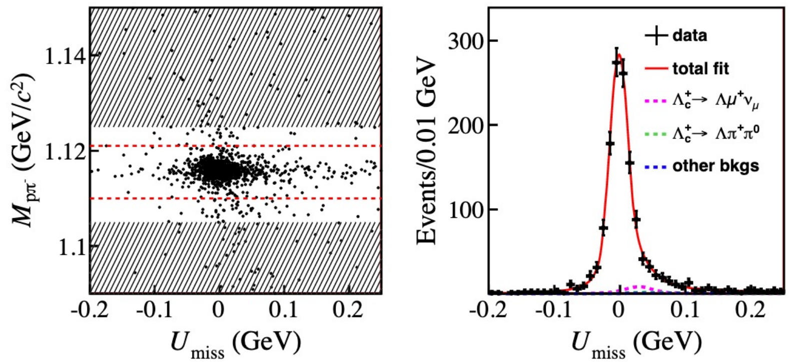
Production

- ✓ $\Lambda_c^+ \bar{\Lambda}_c^-$ *lineshape and form factor* — PRL107, 052002 (2023)
- ✓ $\Lambda_c^+ \bar{\Lambda}_c(2595)^-$ *and* $\Lambda_c^+ \bar{\Lambda}_c(2625)^-$ *cross section* — arXiv:2312.08414

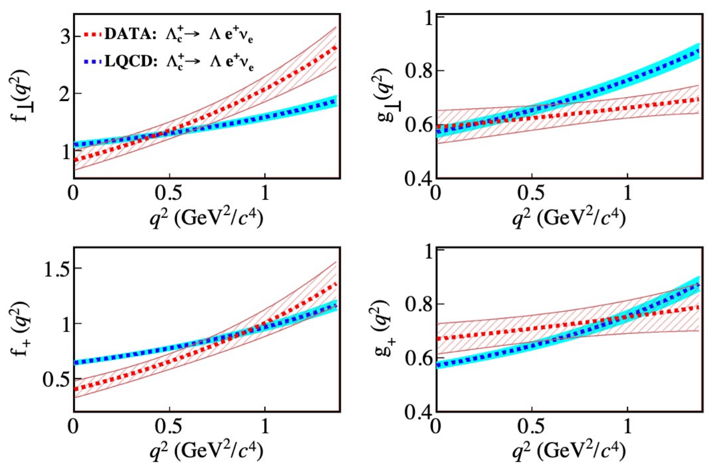
Recent results on Λ_c^+ leptonic decays

Determination of form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

PRL129, 231803 (2022)



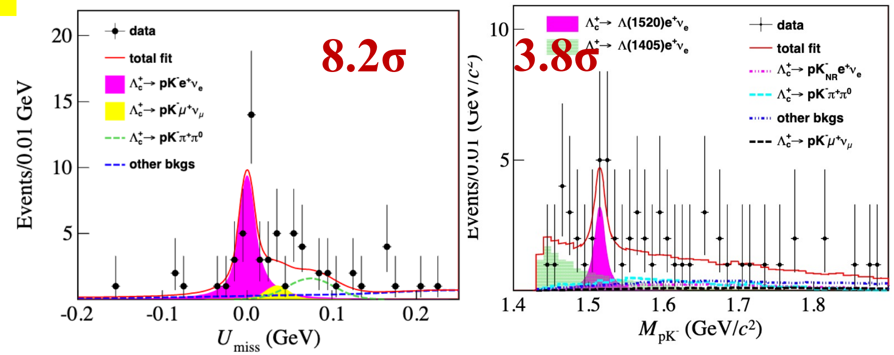
$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$



First direct comparisons on the differential decay rates and form factors with LQCD calculations

Observation of $\Lambda_c^+ \to pK^- e^+ \nu$

PRD106, 112010 (2022)



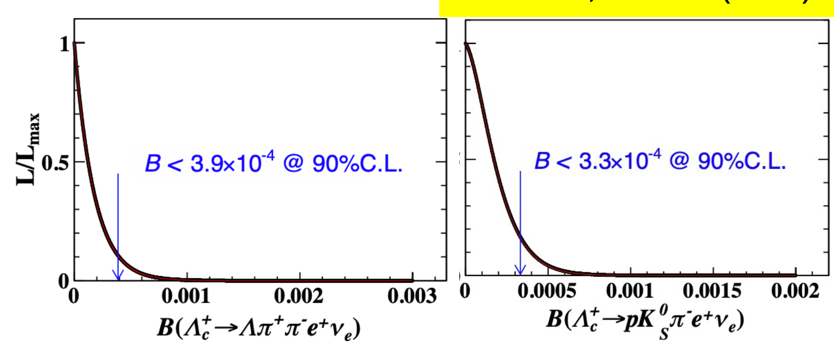
$B(\Lambda_c^+ \to pK^- e^+ \nu) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$

$B(\Lambda_c^+ \to \Lambda(1405) e^+ \nu) = (1.69 \pm 0.76 \pm 0.16) \times 10^{-3}$

$B(\Lambda_c^+ \to \Lambda(1520) e^+ \nu) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$

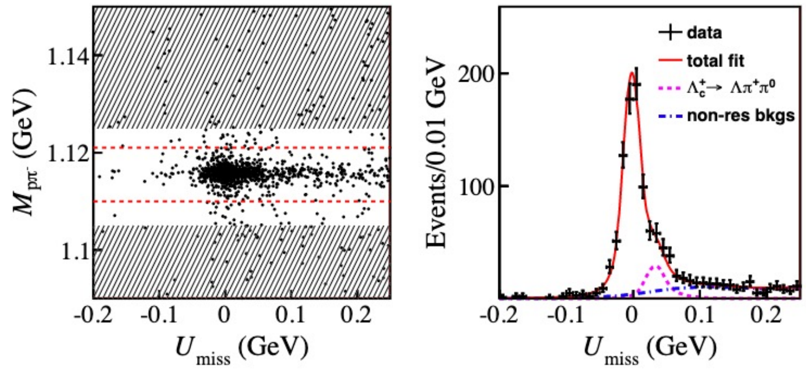
- Second leptonic decay of Λ_c^+ is observed!
- Good channel to study Λ excited states, such as $\Lambda(1405)$ and $\Lambda(1520)$

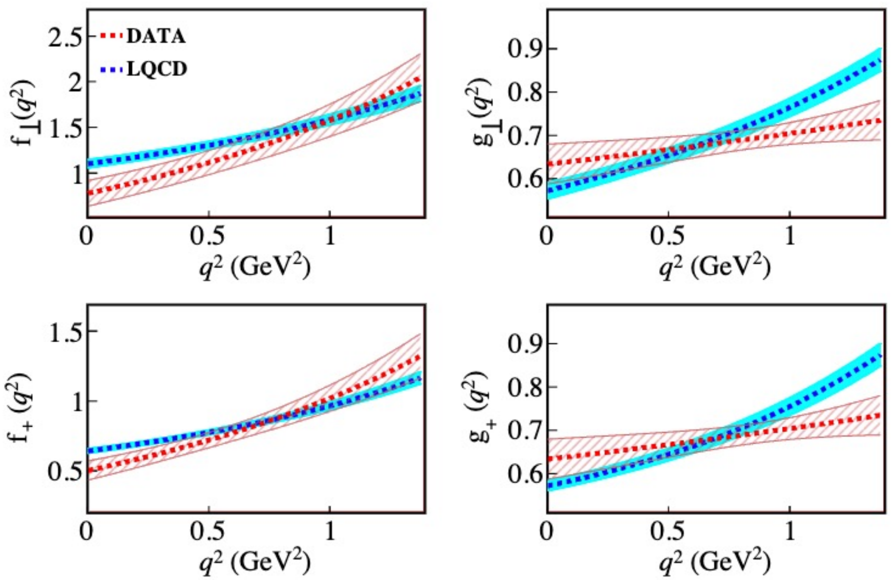
PLB 843, 137993 (2023)

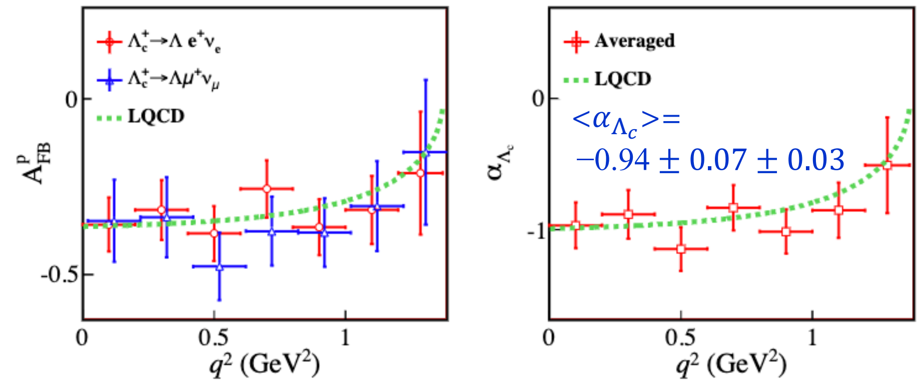


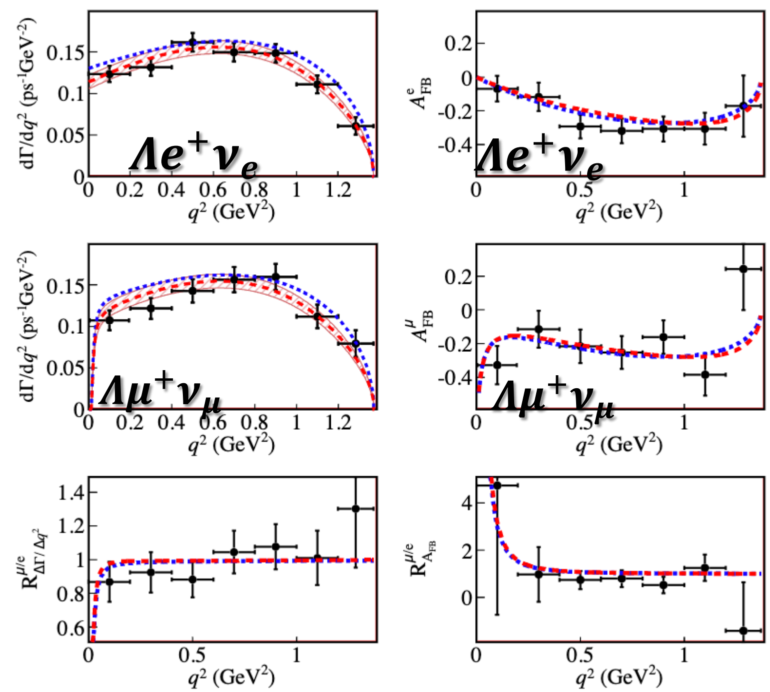
BESIII Combined form factor fits to $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ and $\Lambda e^+\nu_e$

PRD 108, L031105 (2023)





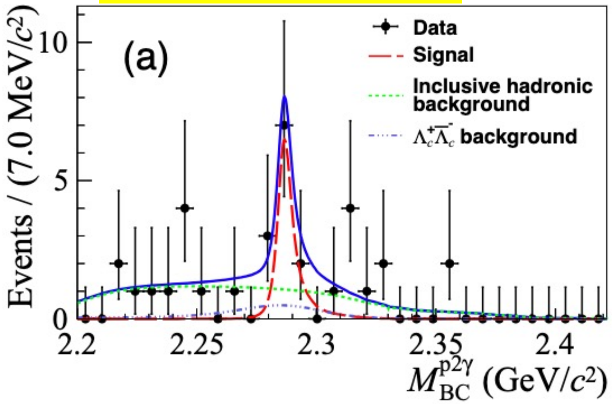


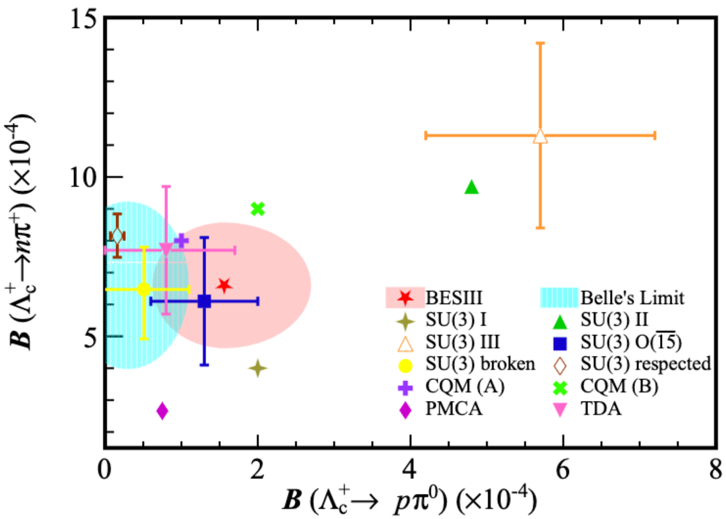


SCS decays of $\Lambda_c^+ \to p\pi^0$ and $p\eta$

First evidence of $\Lambda_c^+ \to p\pi^0$

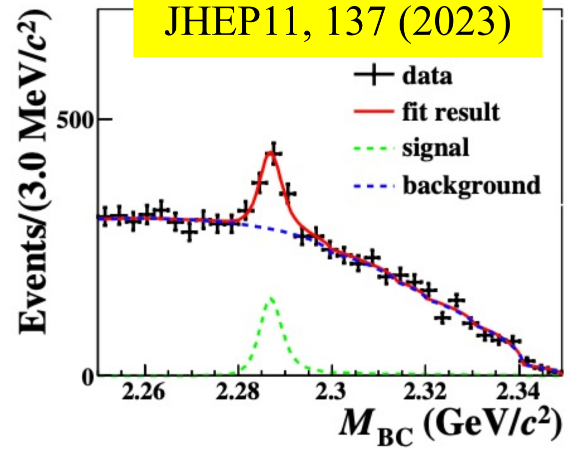
arXiv:2311.06883





Most precise measurement of $\Lambda_c^+ \to p\eta$

JHEP11, 137 (2023)

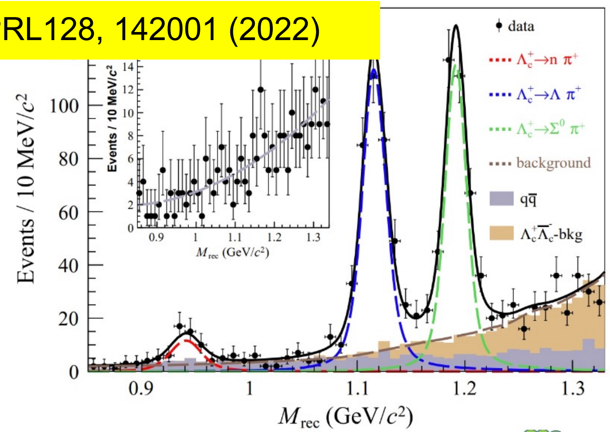


		$\mathcal{B}(\Lambda_c^+ \to p\eta)$	$\mathcal{B}(\Lambda_c^+ \to p\omega)$
BESIII		$1.24 \pm 0.28 \pm 0.10$ [22]	—
LHCb		—	$0.94 \pm 0.32 \pm 0.22$ [23]
Belle		$1.42 \pm 0.05 \pm 0.11$ [24]	$0.827 \pm 0.075 \pm 0.075$ [25]
This paper		$1.57 \pm 0.11 \pm 0.04$	$1.11 \pm 0.20 \pm 0.07$
Current algebra	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

Recent results on Λ_c hadronic decays

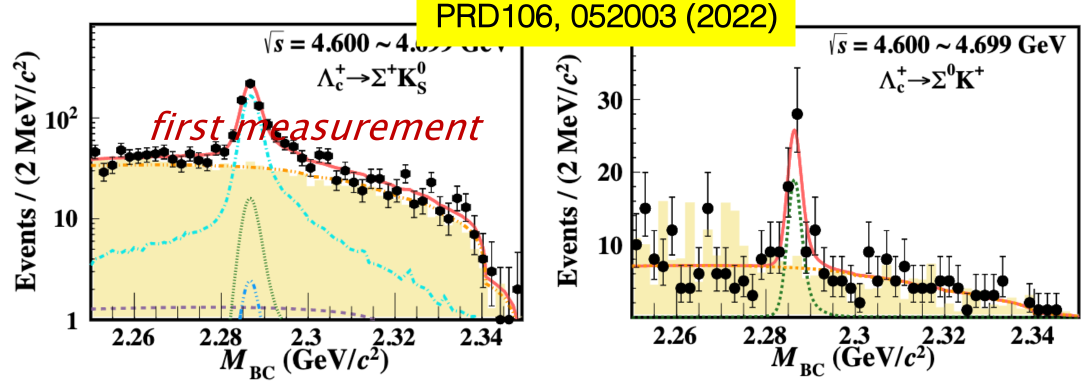
Observation of $\Lambda_c^+ \to n\pi^+$

PRL128, 142001 (2022)



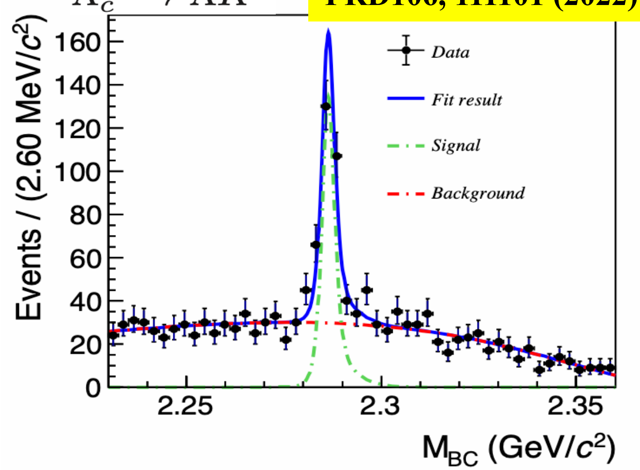
Determination of the BF for $\Lambda_c^+ \to \Sigma^+ K_S$ and $\Sigma^0 K^+$

PRD106, 052003 (2022)



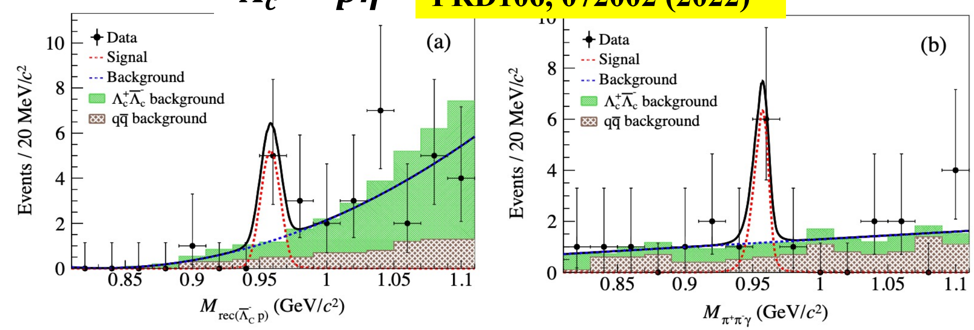
$\Lambda_c^+ \to \Lambda K^+$

PRD106, 111101 (2022)

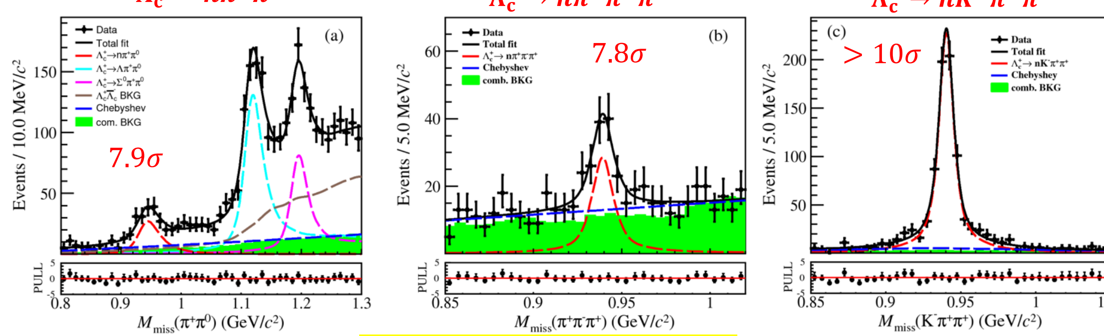


$\Lambda_c^+ \to p\eta'$

PRD106, 072002 (2022)



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



CPC47, 023001 (2023)

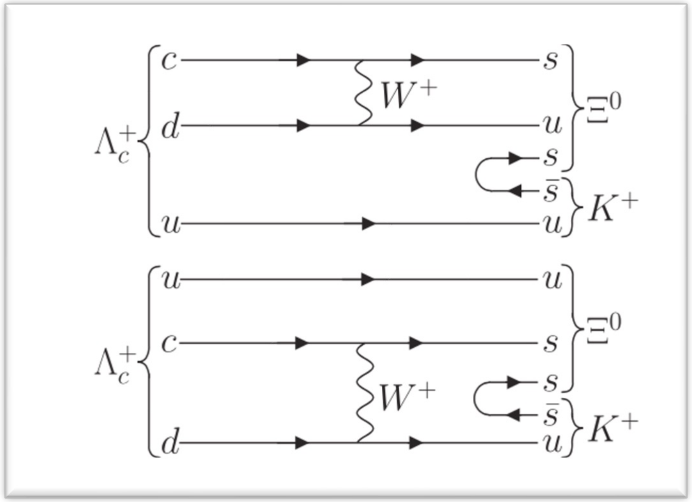
Many CS modes are explored.

Decay asymmetry in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

- Previous theoretical calculation on the BF lower than exp. measurement, which all predicted zero decay asymmetry
- BESIII confirmed the exp. result of BF in 2018 [PLB 783, 200 (2018)]
- In theory, BF is enhanced by enhancing the decay asymmetry close to 1

$$\alpha_{\Xi^0 K^+} = 2\mathrm{Re}(s^* p)/(|s|^2 + |p|^2),$$

$$\delta_p - \delta_s = \arctan\left(\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sin\Delta_{\Xi^0 K^+}/\alpha_{\Xi^0 K^+}\right)$$



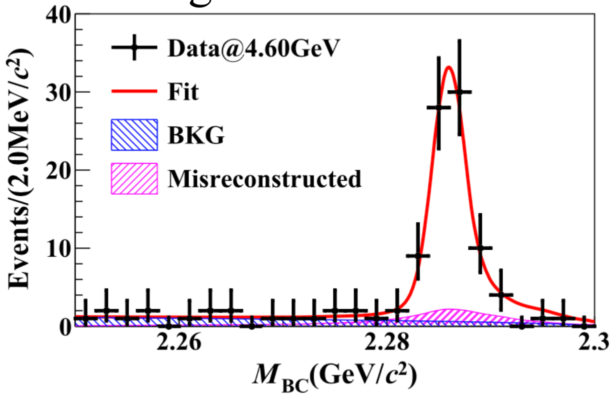
Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ ($\times 10^{-3}$)	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\lvert B\rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	...	...	...
Xu (1992), Pole [8]	1.0	0	0	7.94	...
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 [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	...
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	...
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

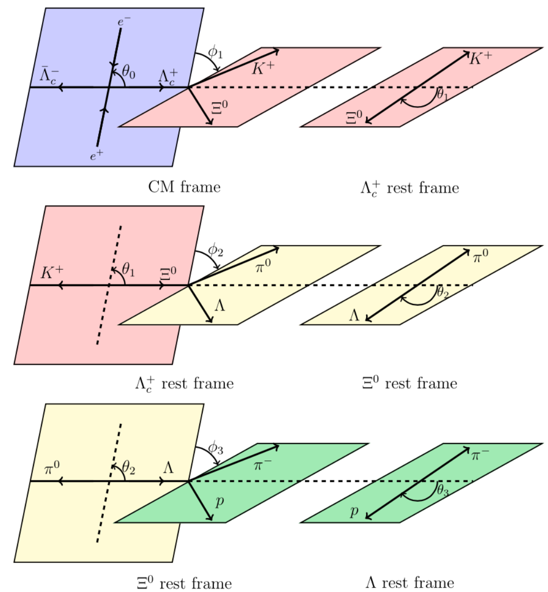
Decay asymmetry in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

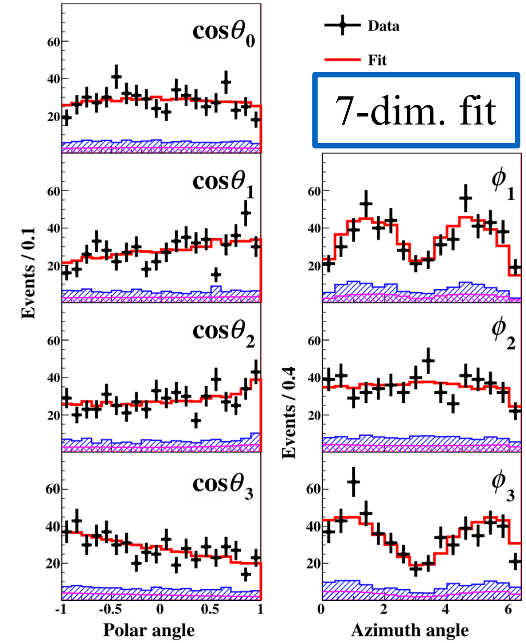
three-level cascade decay $\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$

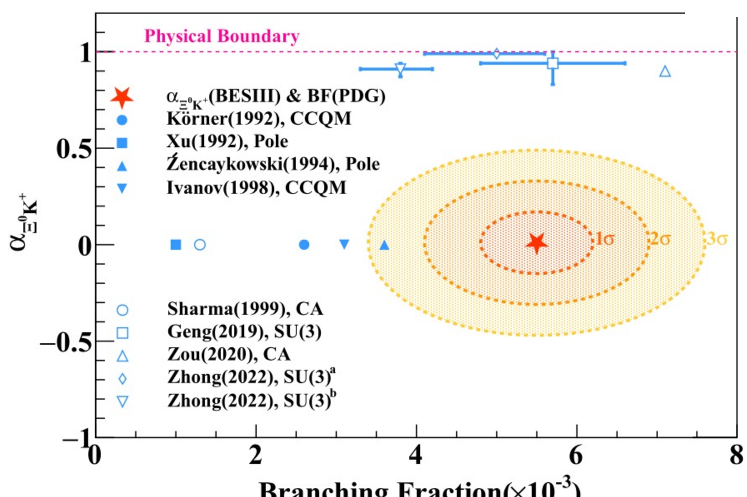
PRL132, 031801(2024)

~378 signals reconstructed







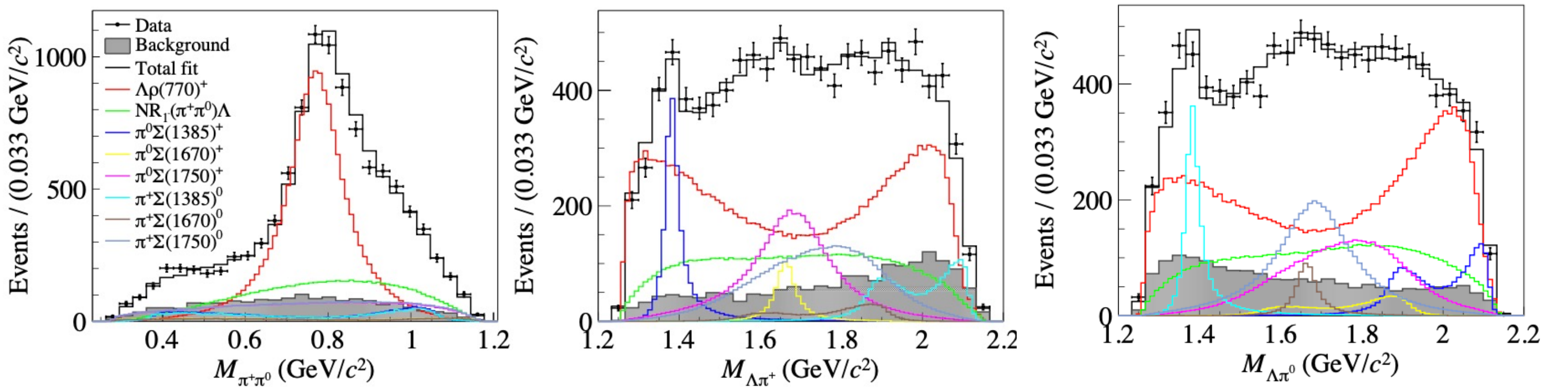


- First determination of decay asymmetry $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$, consistent with zero
- No theoretical model explains the current results
- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$

Amplitude analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP12, 033 (2022)

- First Amplitude analysis of charmed baryon multi-hadronic decays
- Based on **TF-PWA** package: ***https://gitlab.com/jiangyi15/tf-pwa***

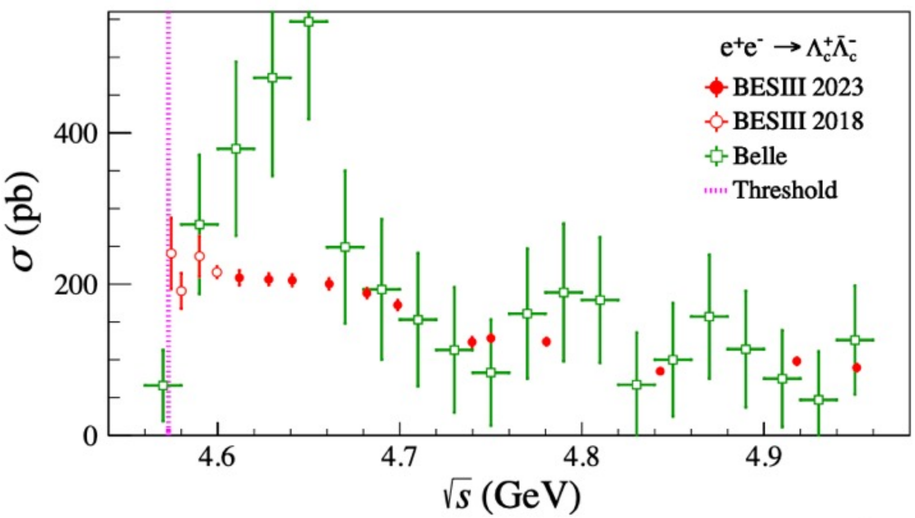


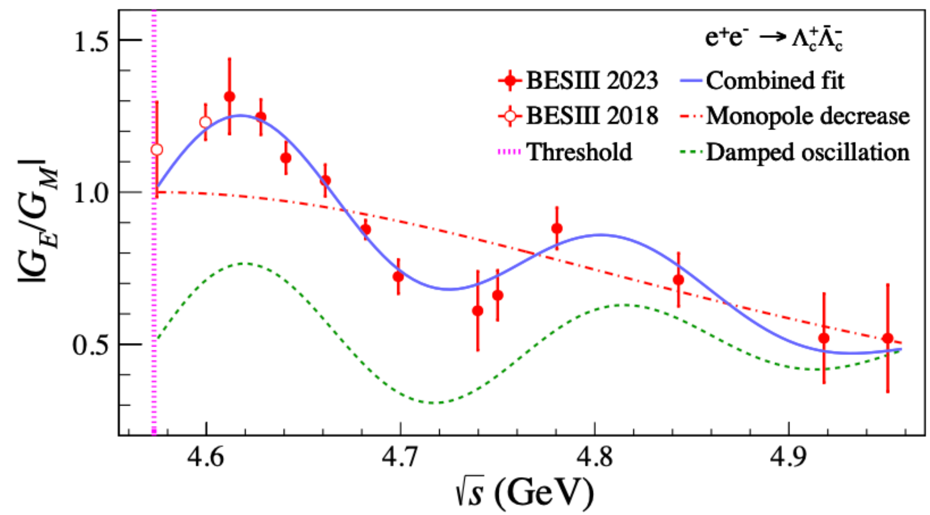
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	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	—

Many first measurements of intermediate states!

BESIII Cross sections of $e^+e^- \to \Lambda_c^+\Lambda_c^-$

PRL131, 191901 (2023)



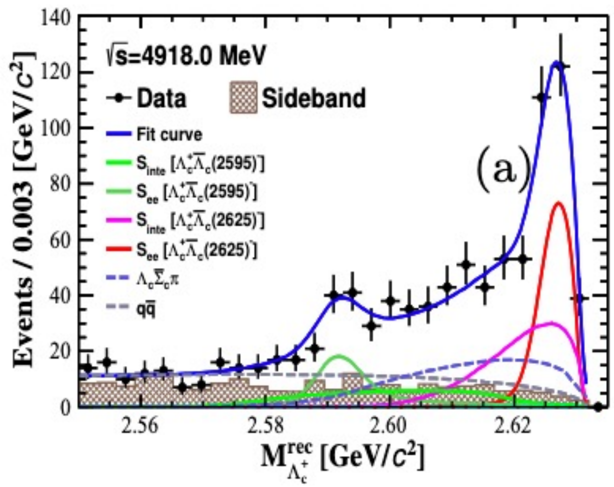


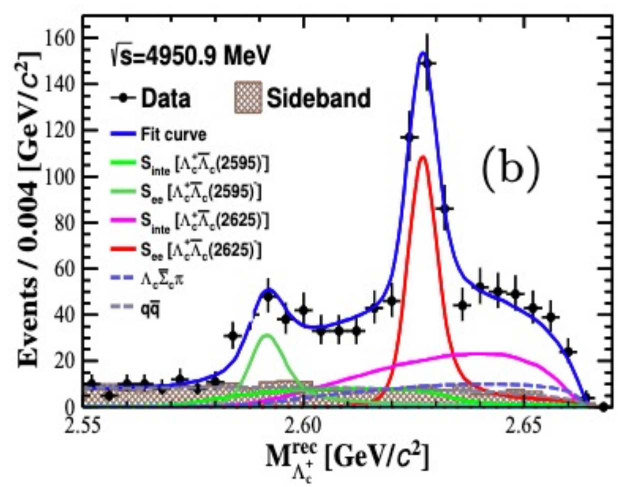
- Negate the $Y(4630)$ in decaying into $\Lambda_c^+\Lambda_c^-$ reported by BELLE
- Energy-dependence of $|G_E/G_M|$ reveals an oscillation feature, which may imply a non-trivial structure of the lightest charmed baryon.

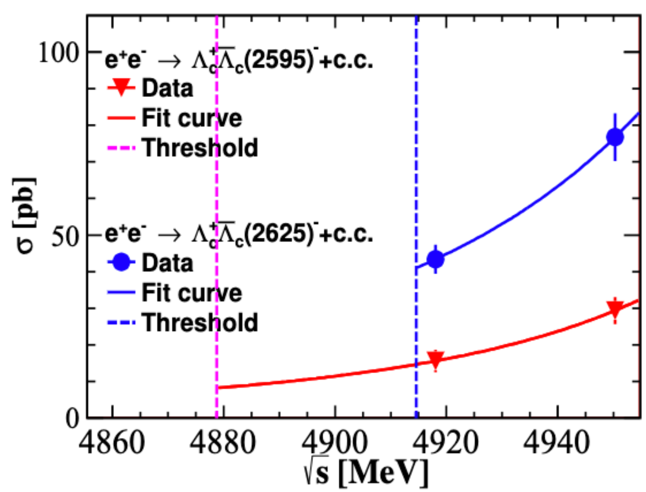
Observation of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^-$ and $\Lambda_c^+\bar{\Lambda}_c(2625)^-$

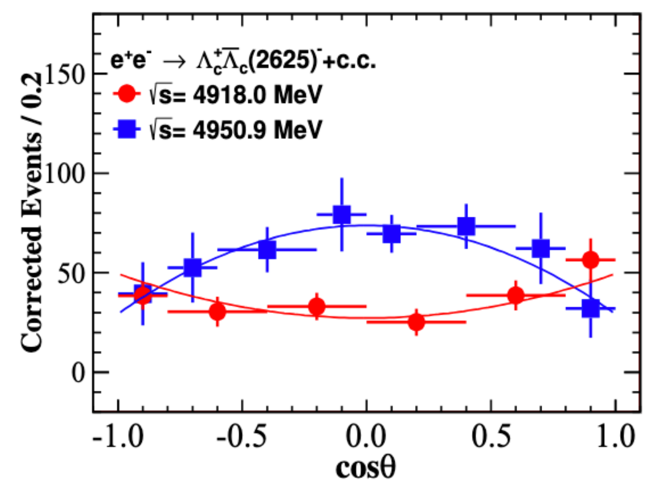
arXiv:2312.08414

Datasets of 208/pb at 4.92 GeV and 159/pb at 4.95 GeV









$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta)(|G_E|^2+3|G_M|^2)+\frac{1}{\tau}|G_C|^2\sin^2\theta$$

Phase III

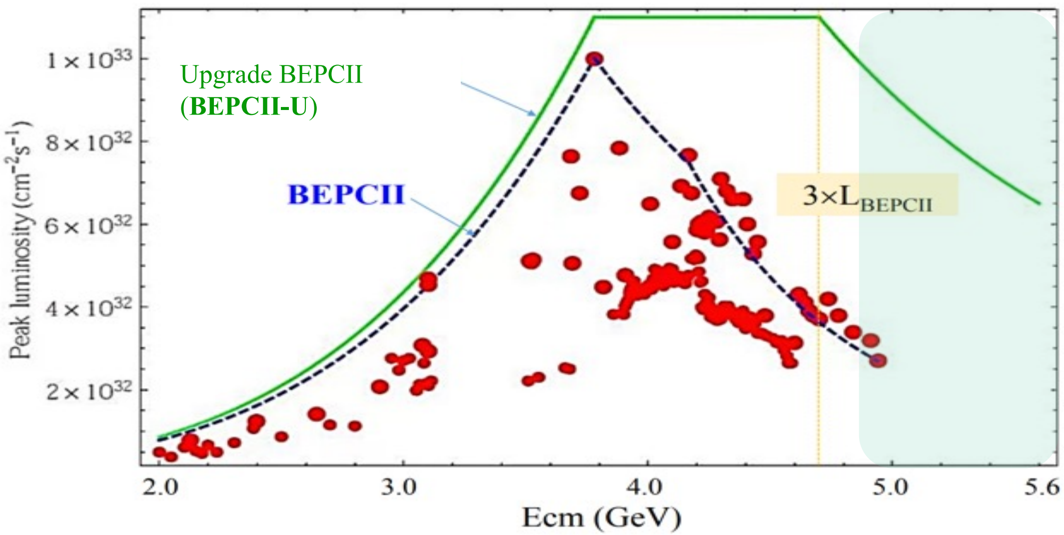
To better accomplish the physics potentials in the white paper, an upgrade plan of BEPCII is being implemented

Proposal of the upgrade BEPCII

An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021 and planned to be completed by the end of 2024

✓ **Improve luminosity by 3 times higher than current BEPCII at 4.7 GeV**

✓ **Extend the maximum energy to 5.6 GeV**

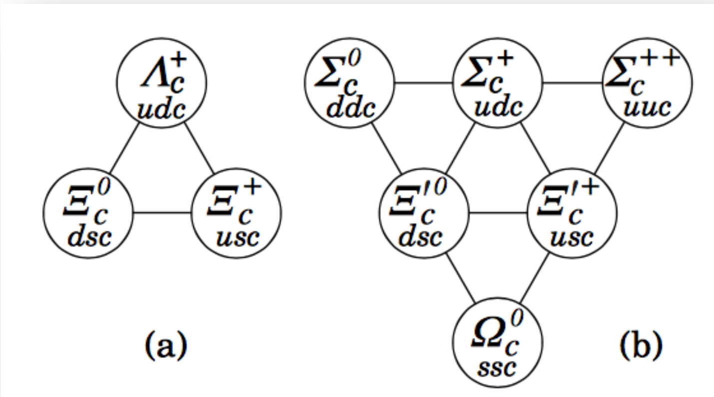


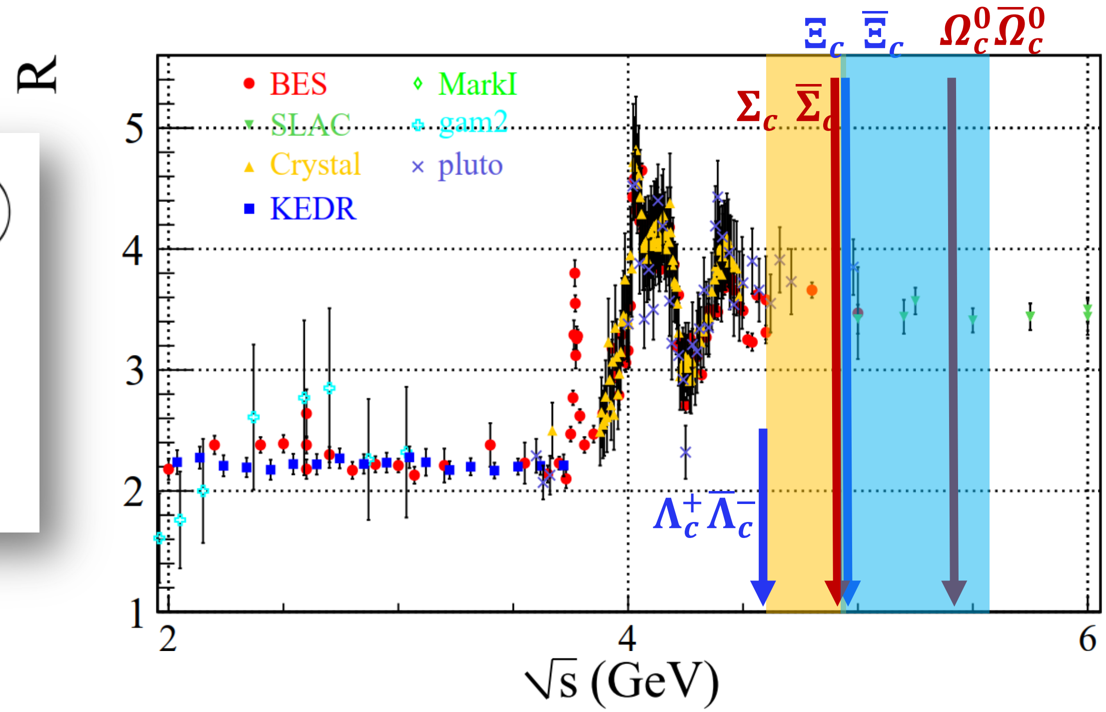
Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

1490 → 600 days

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
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

Heavier charmed baryons





- Energy thresholds
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ 4.88 GeV
  - ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
  - ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.94 GeV
  - ✓ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$ 5.40 GeV

- Cover all the ground-state charmed baryons: studies on their production & decays, CPV search, to help developing more reliable QCD-derived models in charm sector
- Studies on the production and decays of excited charmed baryons

Yet-to-be-Explored $\Xi_c^{+,0}$/ Ω_c^0 Decays

- We (will) have precise Λ_c^+ data after BESIII efforts
- However, $\Xi_c^{+,0}$/ Ω_c^0 has insufficient data
- A new territory for BESIII!

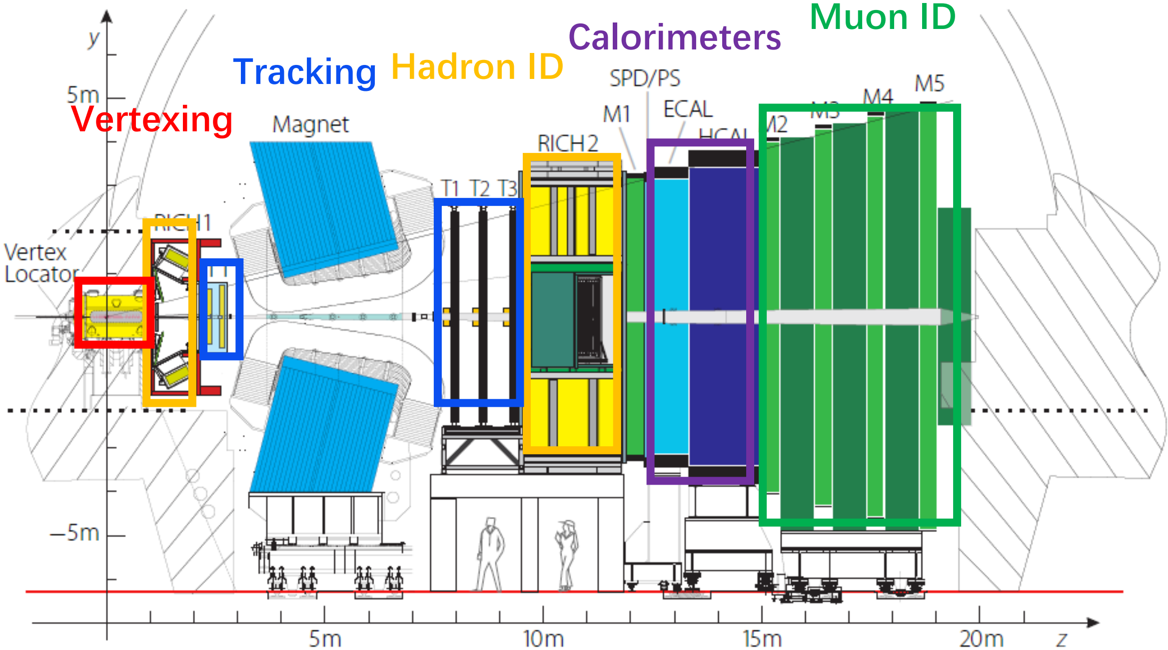
	Mode		Fraction (Γ_i/Γ)
	Cabibbo-favored ($S=-2$) decays		
Γ_1	$p2K_S^0$		$(2.5\pm1.3)\times10^{-3}$
Γ_2	$\Lambda\overline{K}^0\pi^+$		
Γ_3	$\Sigma(1385)^+\overline{K}^0$	[1]	$(2.9\pm2.0)\%$
Γ_4	$\Lambda K^-2\pi^+$		$(9\pm4)\times10^{-3}$
Γ_5	$\Lambda\overline{K}^*(892)^0\pi^+$	[1]	$<5\times10^{-3}$
Γ_6	$\Sigma(1385)^+K^-\pi^+$	[1]	$<6\times10^{-3}$
Γ_7	$\Sigma^+K^-\pi^+$		$(2.7\pm1.2)\%$
Γ_8	$\Sigma^+\overline{K}^*(892)^0$	[1]	$(2.3\pm1.1)\%$
Γ_9	$\Sigma^0K^-2\pi^+$		$(8\pm5)\times10^{-3}$
Γ_{10}	$\Xi^0\pi^+$		$(1.6\pm0.8)\%$
Γ_{11}	$\Xi^-2\pi^+$		$(2.9\pm1.3)\%$
Γ_{12}	$\Xi(1530)^0\pi^+$	[1]	$<2.9\times10^{-3}$
Γ_{13}	$\Xi(1620)^0\pi^+$		seen
Γ_{14}	$\Xi(1690)^0\pi^+$		seen
Γ_{15}	$\Xi^0\pi^+\pi^0$		$(6.7\pm3.5)\%$
Γ_{16}	$\Xi^0\pi^-2\pi^+$		$(5.0\pm2.6)\%$
Γ_{17}	$\Xi^0e^+\nu_e$		$(7\pm4)\%$
Γ_{18}	$\Omega^-K^+\pi^+$		$(2.0\pm1.5)\times10^{-3}$

Ξ_c^+ PDG2023

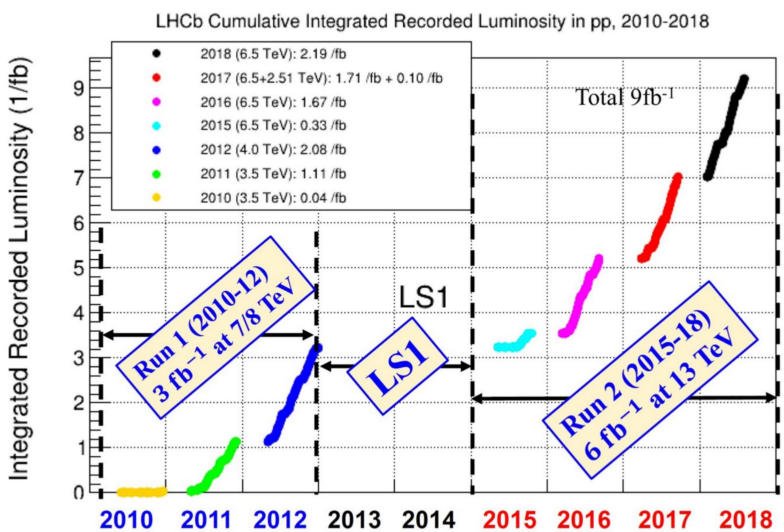
	Mode	Fraction (Γ_i/Γ)
	Cabibbo-favored ($S=-3$) decays — relative to $\Omega^-\pi^+$	
Γ_6	$\Xi^0\overline{K}^0$	1.64 ± 0.29
Γ_7	$\Xi^0K^-\pi^+$	1.20 ± 0.18
Γ_8	$\Xi^0\overline{K}^{*0}$, $\overline{K}^{*0}\to K^-\pi^+$	0.68 ± 0.16
Γ_9	$\Omega(2012)^-\pi^+$, $\Omega(2012)^-\to\Xi^0K^-$	0.12 ± 0.05
Γ_{10}	$\Xi^-\overline{K}^0\pi^+$	2.12 ± 0.28
Γ_{11}	$\Omega(2012)^-\pi^+$, $\Omega(2012)^-\to\Xi^-\overline{K}^0$	0.12 ± 0.06
Γ_{12}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{13}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0}\to\Xi^-\pi^+$	0.21 ± 0.06
Γ_{14}	$\Xi^-\overline{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{15}	$pK^-K^-\pi^+$	seen
Γ_{16}	$\Sigma^+K^-K^-\pi^+$	<0.32
Γ_{17}	$\Lambda\overline{K}^0\overline{K}^0$	1.72 ± 0.35

Ω_c^0 PDG2023

LHCb



Tracking
Hadron ID
Calorimeters
Muon ID
Vertexing
Magnet
SPD/PS
M1
ECAL
M4
M5
RICH2
T1 T2 T3
Vertex Locator
5m
−5m
5m
10m
15m
20m
z
y



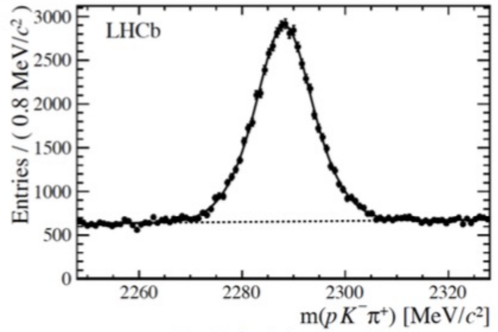
LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Total 9fb-1
Integrated Recorded Luminosity (1/fb)
Run 1 (2010-12) 3 fb−1 at 7/8 TeV
LS1
LS1
Run 2 (2015-18) 6 fb−1 at 13 TeV
2010
2011
2012
2013
2014
2015
2016
2017
2018

my talk in Charm2016

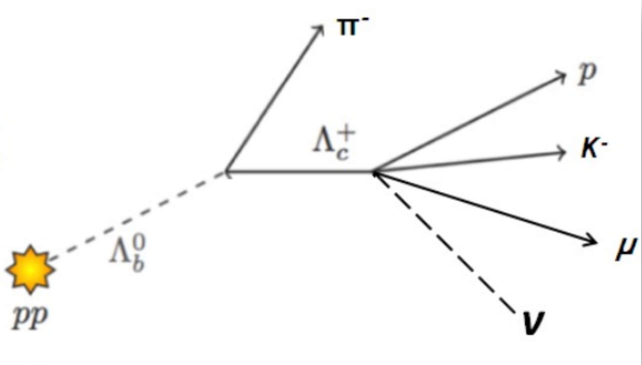
BESIII

Potentials @LHCb

- Huge Λc production at LHCb: ~100μb
- Prompt charm: using exclusive reconstruction
- Secondary charm from *b*-hadron decays with inclusive *b* triggers
- $\Lambda_c^+ \to pK^-\pi^+$ CF yields: 0.8M in 0.65/fb (~20% of Run I data)
- CS samples O(10^5) in Run I: BF measurement and CPV
- DCS $\Lambda_c^+ \to pK^+\pi^-$ can be measured with best precision
- Potential to set up the SL modes $pK^-\mu^+\nu$ and $p\pi^-\mu^+\nu$
  ➔ size of this BF is critical to understand the internal dynamics of Λc
- Search for CS SL mode: $p\pi^-\mu^+\nu$
- amplitude analysis of $\Lambda c \to \Lambda\mu^+\nu$, to extract form factors
  ➔ input to theoretical calculation
- Rare decays: $p\mu^+\mu^-$, 3μ, $p\mu^+\mu^+$, …



30 pb^{-1} of $\Lambda_c^+ \to pK\pi$
~5% of the 2011 data sample
JHEP **1312** 90 (2013)



tag in secondary Λ_b/Σ_c decays

Charm 2016, Bologna

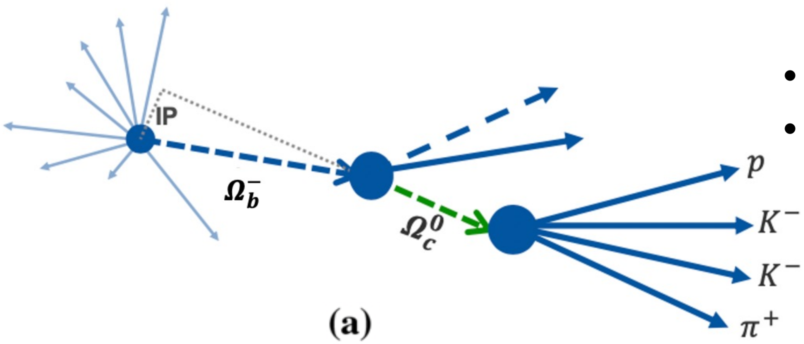
23

Charmed baryon results at LHCb

- Singly charmed baryon
  - ✓ Ξ_c^+ mass [Phys. Rev. Lett. 113, 032001 (2014)]
  - ✓ BF for $\Lambda_c^+ \to pK^+\pi^-$, pK^+K^-, $p\pi^+\pi^-$ [JHEP 03, 043 (2018)]
  - ✓ CPV search in $\Lambda_c^+ \to pK^+K^-$, $p\pi^+\pi^-$[JHEP 03, 182 (2018)]
  - ✓ Rare decay of $\Lambda_c^+ \to p\mu^+\mu^-$ [Phys. Rev. D 97, 091101 (2018)]
  - ✓ Lifetime of Ω_c^0 [Phys. Rev. Lett. 121, 092003 (2018)]
  - ✓ Lifetimes of Λ_c^+, Ξ_c^+ and Ξ_c^0 [Phys. Rev. D 100, 032001 (2019)]
  - ✓ CPV search in $\Xi_c^+ \to pK^-\pi^+$ [Eur. Phys. J. C 80, 986 (2020)]
  - ✓ Suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$ [Phys. Rev. D 102, 071101 (2020)]
  - ✓ Lifetime of Ω_c^0 and Ξ_c^0 [Sci. Bull. 67, 479 (2022)]
  - ✓ $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis [Phys. Rev. D 108, 012023 (2023)]
  - ✓ Λ_c^+ polarimetry [JHEP 07, 228 (2023)]
  - ✓ $\Omega_c^0 \to \Omega^-K^+$, $\Xi^-\pi^+$ and Ω_c^0 mass [Phys. Rev. Lett.132.081802 (2024)]
- Doubly charmed baryon: Ξ_{cc}^{++} discovery and other searches
- Charmed baryon spectroscopy
  - ✓ Λ_c^{**+} in $\Xi_c^+K^-$ via $\Lambda_b^0 \to D^0p\pi^-$ [JHEP 05, 030 (2017)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ via prompt production [Phys. Rev. Lett. 118,182001 (2017)]
  - ✓ Ξ_c^{**0} in $\Lambda_c^+K^-$ final states [Phys. Rev. Lett. 124, 222001 (2020)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ from $\Omega_b^- \to \Xi_c^+K^-\pi^-$ [Phys. Rev. D 104, L091102 (2021)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ via prompt production [Phys. Rev. Lett. 131, 131902 (2023)]

Lifetimes of charmed baryons

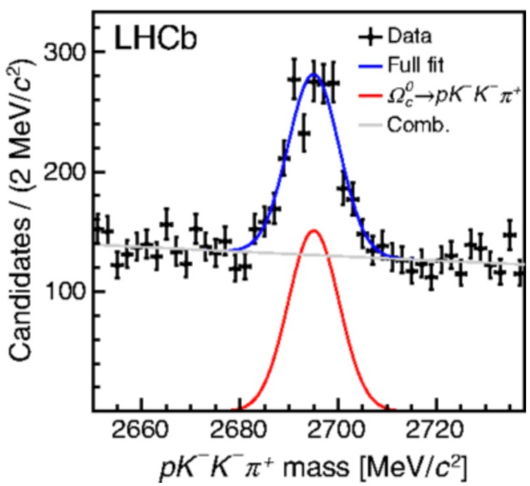
arXiv:2111.09566 unit: fs	$\tau(\Xi_c^+)$	$\tau(\Lambda_c^+)$	$\tau(\Xi_c^0)$	$\tau(\Omega_c^0)$
PDG (2004-2018) [10]	442 ± 26	200 ± 6	112^{+13}_{-10}	69 ± 12
LHCb (2018) [12]				268 ± 26
LHCb (2019) [14]	457 ± 6	203.5 ± 2.2	154.5 ± 2.6	
PDG (2020) [11]	456 ± 5	202.4 ± 3.1	153 ± 6	268 ± 26

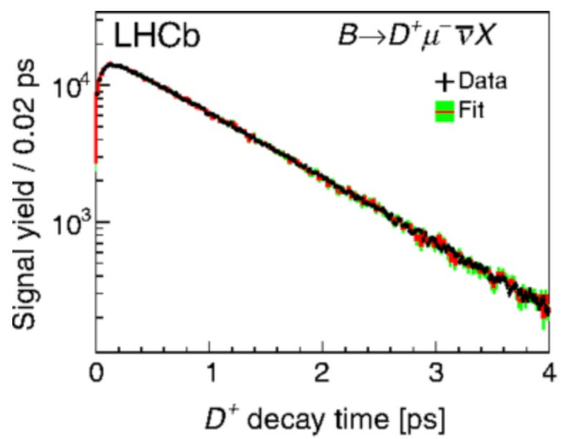


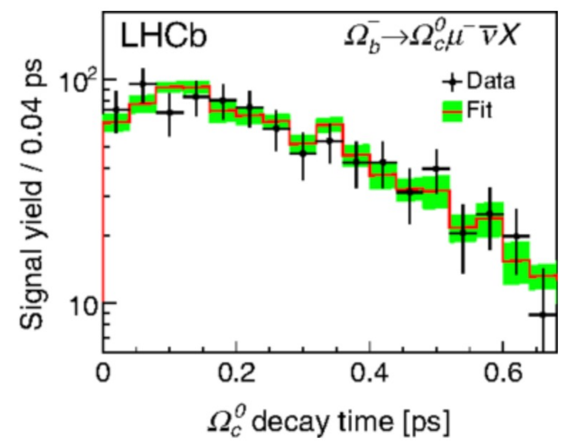
- Lifetime of Ω_c^0 [Phys. Rev. Lett. 121, 092003 (2018)]
- Lifetimes of Λ_c^+, Ξ_c^+ and Ξ_c^0 [Phys. Rev. D 100, 032001 (2019)]

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

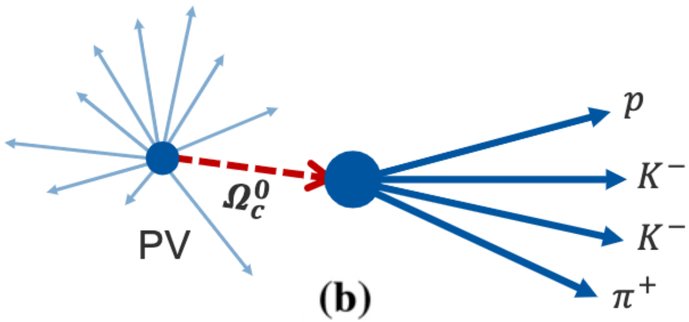
$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0).$$



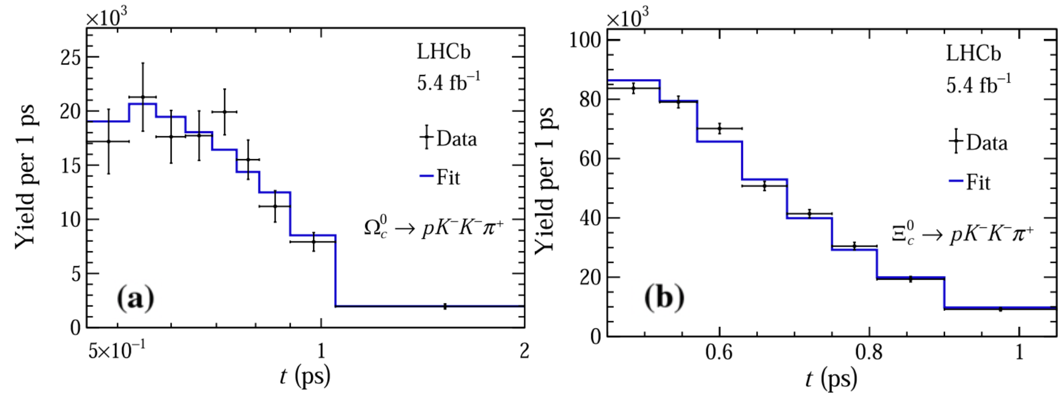




Lifetimes of charmed baryons

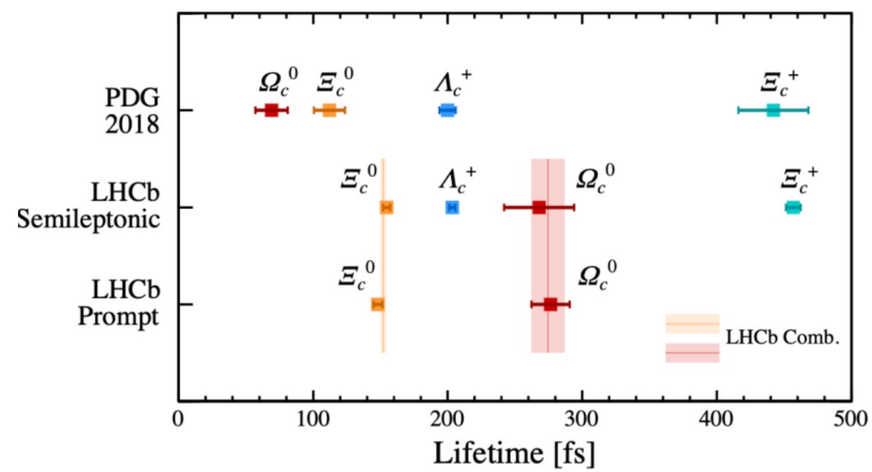


Lifetime of Ω_c^0 and Ξ_c^0 [Sci. Bull. 67, 479 (2022)]



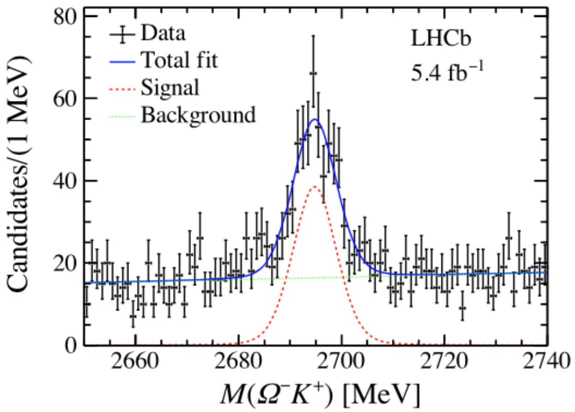
arXiv:2305.00665

unit: fs	$\tau(\Xi_c^+)$	$\tau(\Lambda_c^+)$	$\tau(\Xi_c^0)$	$\tau(\Omega_c^0)$
PDG (2004-2018) [3]	442 ± 26	200 ± 6	112^{+13}_{-10}	69 ± 12
LHCb (2018) [4]				268 ± 26
LHCb (2019) [6]	457 ± 6	203.5 ± 2.2	154.5 ± 2.6	
PDG (2020) [8]	456 ± 5	202.4 ± 3.1	153 ± 6	268 ± 26
LHCb (2021) [7]			148.0 ± 3.2	276.5 ± 14.1
PDG (2022) [1]	453 ± 5	201.5 ± 2.7	151.9 ± 2.4	268 ± 26
Belle II (2022) [9, 10]		203.20 ± 1.18		243 ± 49
WA values (2023)	453 ± 5	202.9 ± 1.1	150.5 ± 1.9	273 ± 12

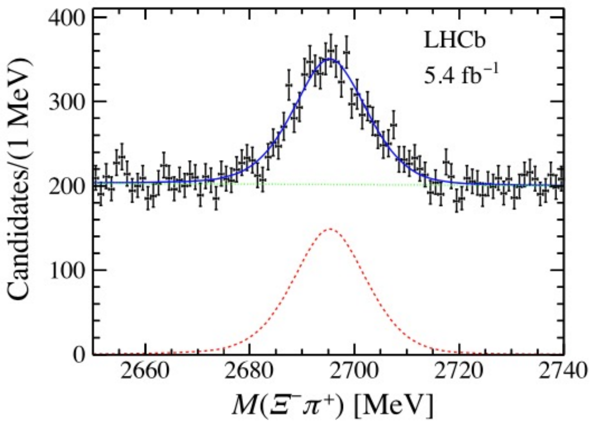


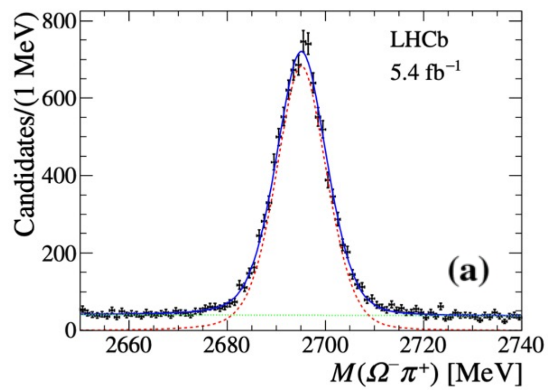
Observation of $\Omega_c^0 \to \Omega^- K^+$, $\Xi^-\pi^+$ and Ω_c^0 mass

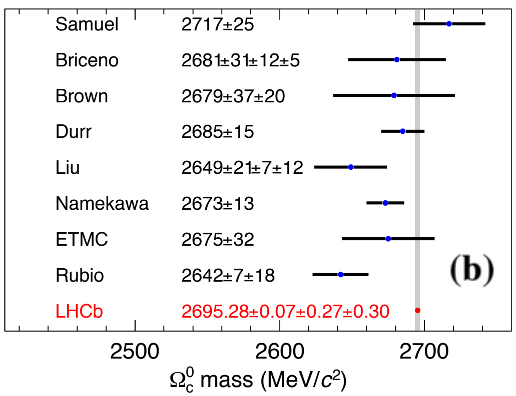
Phys. Rev. Lett.132.081802 (2024)



BF ratios	This work	CA model	LFQM	Naive estimation
$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}$	0.0608 ± 0.0064	-	-	0.0467
$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}$	0.1581 ± 0.0099	0.1038	0.0345	-







unit: MeV	$m_{\Lambda_c^+}$	$m_{\Xi_c^+}$	$m_{\Xi_c^0}$	$m_{\Omega_c^0}$
之前国际平均值	2286.46 ± 0.14	$2467.93^{+0.28}_{-0.40}$	2470.44 ± 0.28	2695.2 ± 1.7
LHCb 2014		$2467.97 \pm 0.14 \pm 0.17$		
LHCb 2023				$2695.28 \pm 0.07 \pm 0.40$
当前国际平均值	2286.46 ± 0.14	2467.95 ± 0.19	2470.44 ± 0.28	2695.28 ± 0.40

$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

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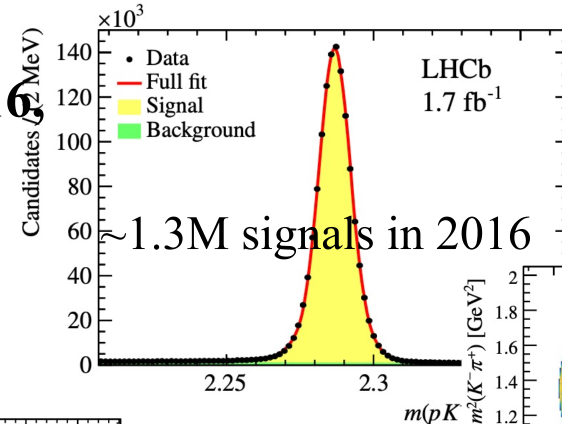
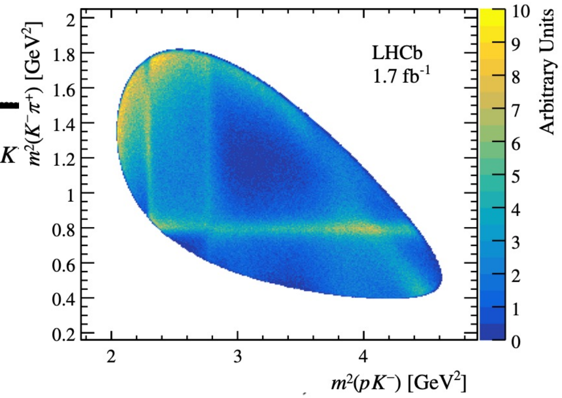
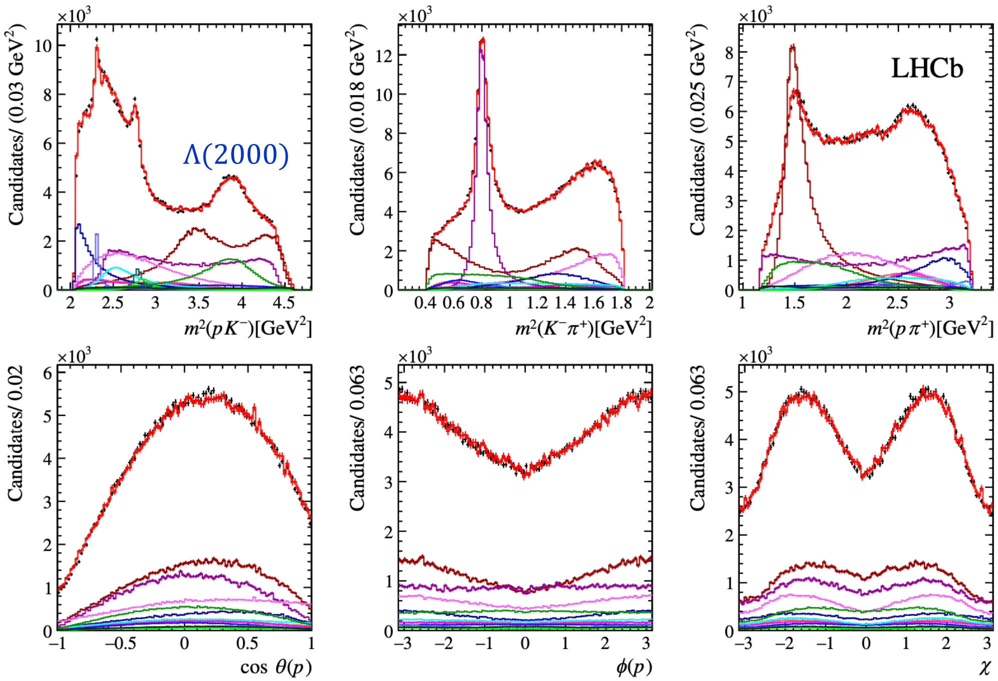
Λ_c^+ signals are selected via $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$ from dataset taken in 2016, where only a subset of 0.4 M signals are employed



~1.3M signals in 2016



5-dim fit



Resonance	Fit fraction (%)
$\Lambda(1405)$	7.7
$\Lambda(1520)$	1.86
$\Lambda(1600)$	5.2
$\Lambda(1670)$	1.18
$\Lambda(1690)$	1.19
$\Lambda(2000)$	9.58
$\Delta(1232)^{++}$	28.60
$\Delta(1600)^{++}$	4.5
$\Delta(1700)^{++}$	3.90
$K_0^*(700)$	3.02
$K^*(892)$	22.14
$K_0^*(1430)$	14.7

Resonance	α
Model $\sqrt{3}S$	0.662
$K^*(892)$ $\sqrt{3}S$	0.873
$\Lambda(1405)$	−0.58
$\Lambda(1520)$	−0.925
$\Lambda(1600)$	−0.20
$\Lambda(1670)$	−0.817
$\Lambda(1690)$	−0.958
$\Lambda(2000)$	−0.57
$\Delta(1232)^{++}$	−0.548
$\Delta(1600)^{++}$	−0.50
$\Delta(1700)^{++}$	−0.216
$K_0^*(700)$	−0.06
$K_0^*(1430)$	−0.34

Λ_c^+ polarization and $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

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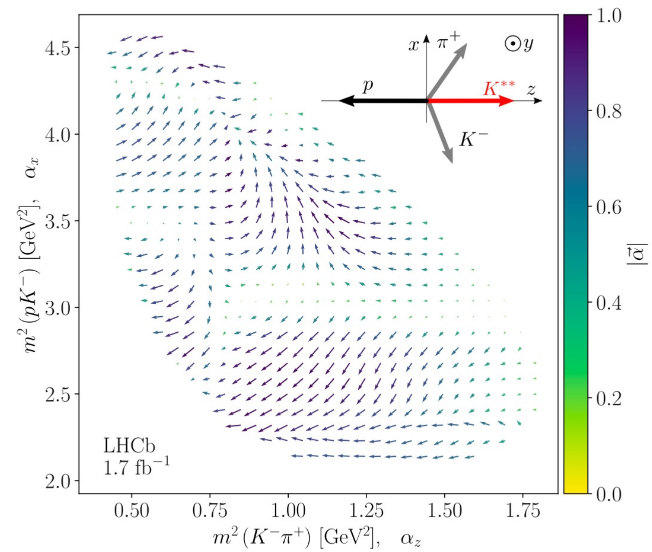
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x ($\tilde{B}$)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y ($\tilde{B}$)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z ($\tilde{B}$)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

A large Λ_c^+ polarization is found in *b* semi-leptonic decays $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$

JHEP 07, 228 (2023)

The amplitude model is used to produce the distribution of the kinematic-dependent polarimeter vector in the space of Mandelstam variables to express the polarized decay rate in a model-independent way.

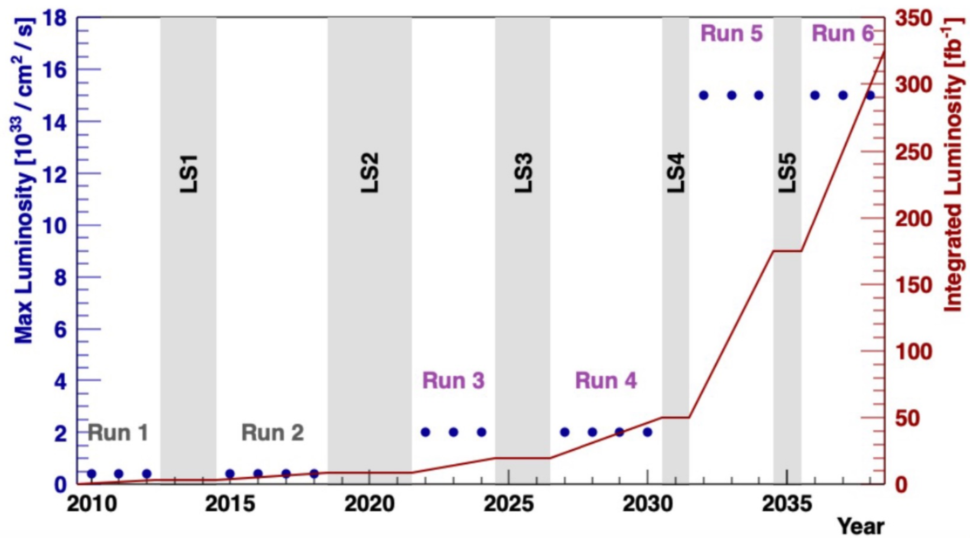


- The obtained representation can facilitate polarization measurements of the Λ_c^+ baryon and eases inclusion of the $\Lambda_c^+ \to pK^-\pi^+$ decay mode in hadronic amplitude analyses.
- At BESIII, the transverse polarization of Λ_c^+ can be obtained via $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

Future opportunity at LHCb

- RUN1&2: 9 fb^{-1}
- RUN3&4: 50 fb^{-1}

➔ x10 more statistics



- Further improvement on mass and lifetime measurement
- SCS and DCS hadronic decays
  - e.g. $\Xi_c^0 \to pK^-$、$\Xi_c^+ \to pK_S$、$\Omega_c^0 \to \Lambda K_S$、$pK^-$
- Semi-leptonic decays via b-baryon four-body decays
  - e.g. $\Lambda_c^+ \to pK^-\mu^+\nu, p\pi^-\mu^+\nu; \Xi_c^0 \to \Xi^-\mu^+\nu; \Xi_c^+ \to \Lambda\mu^+\nu; \Omega_c^0 \to \Omega^-\mu^+\nu$
- Decay asymmetries and CPV search via prompt production or b-baryon decays
  - e.g. $\Lambda_c^+ \to pK_S,\ \Lambda\pi^+,\ \Lambda K^+; \Xi_c^0 \to \Lambda K_S,\ \Xi^-\pi^+,\ \Xi^-K^+; \Omega_c^0 \to \Omega^-\pi^+, \Omega^-K^+,\ \Xi^-\pi^+$
- Amplitude analysis of multi-body hadronic decays

Summary

- In recent years, experimental activities on charmed baryons are reviving, esp. at BESIII, LHCb and Belle (II)
- Threshold data at BESIII opens a new door to direct measurements of the decays ➔comprehensive and systematic studies of charmed baryon decays
  - BESIII has published several world-leading results based on ~80 M Λc samples
  - More efforts on hadronic decays w/ $n/\Sigma/\Xi$ particles & semi-leptonic decays
  - Plan to take data up to 5.6 GeV to cover all the ground-state charmed baryons
- LHCb has largest charmed baryon yields ➔ large potential of best precisions
  - Search for more semi-leptonic decays
  - Precise determination of decay rate and amplitude analysis
  - Decay asymmetry and CPV test
  - Rare decays: LFV, FCNC, …
- BESIII and LHCb will be complementary in charmed baryon decays

Backup

Contribution to PDG

PDG2014

$\Gamma(p\overline{K}^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.66±0.05±0.07	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_8/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.06 OUR AVERAGE					
0.52±0.04±0.05	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.43±0.12±0.04	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.98±0.36±0.08	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.67±0.04±0.11	2606	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK^*(892)^-\pi^+)/\Gamma(p\overline{K}^0\pi^+\pi^-)$ — Γ_{11}/Γ_9

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.14	17	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(p(K^-\pi^+)_{\text{nonresonant}}\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{12}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.73±0.12±0.05	67	BOZEK	93	NA32	π^- Cu 230 GeV

PDG2019

$\Gamma(pK^0_S\pi^0)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.96±0.13 OUR FIT Error includes scale factor of 1.1.					
1.87±0.13±0.05	558	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^0_S\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K^0_S ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.314±0.018 OUR FIT					
0.33 ±0.03 ±0.04	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(nK^0_S\pi^+)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.82±0.23±0.11	83	ABLIKIM	17H	BES3	e^+e^- at 4.6 GeV

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK^0_S\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.12 OUR FIT Error includes scale factor of 1.2.					
1.53±0.11±0.09	485	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^0_S\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K^0_S ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.255±0.015 OUR FIT Error includes scale factor of 1.1.					
0.257±0.031 OUR AVERAGE					
0.26 ±0.02 ±0.03	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.22 ±0.06 ±0.02	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.49 ±0.18 ±0.04	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

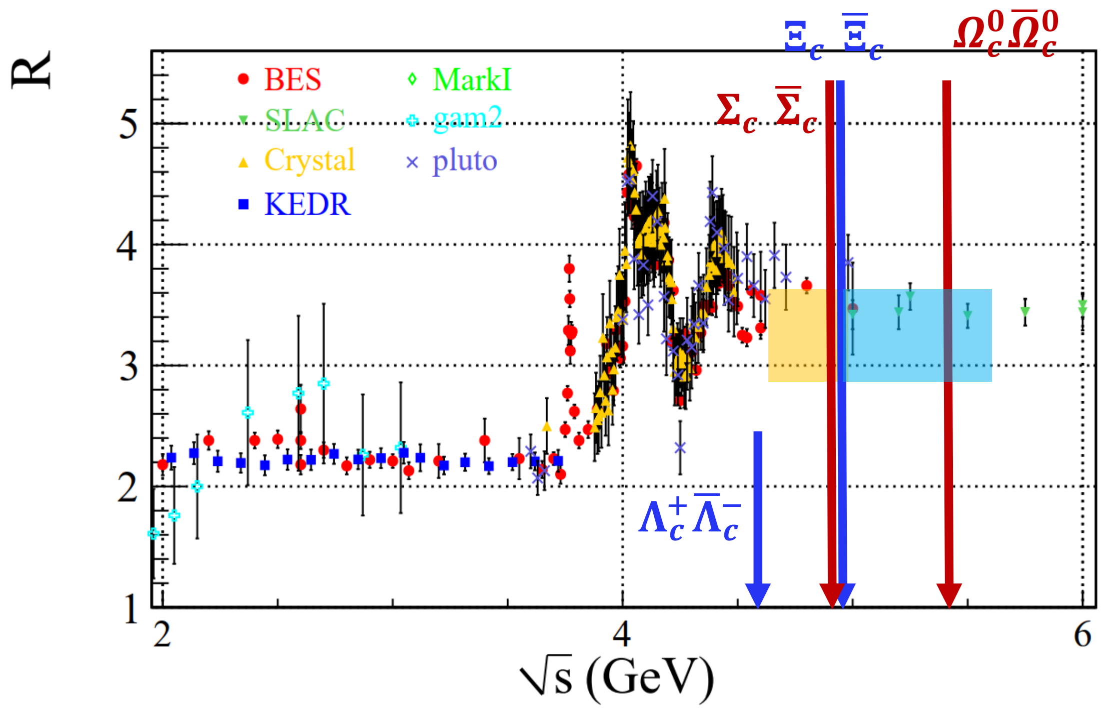
VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.42±0.31 OUR FIT Error includes scale factor of 1.5.					
4.53±0.23±0.30	1849	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT

- ✦ BESIII的贡献使得多数分支比结果由相对测量改为绝对测量。
- ✦ BESIII对黄金道$\Lambda_c^+ \to pK\pi$的测量 ⇒ “模型依赖”变为“模型无关”。
- ✦ BESIII贡献发现了更多以前没发现的衰变道(比如含中子末态的衰变)。

- Energy thresholds
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\,\pi$ 4.88 GeV
  - ✓ $e^+e^- \to \Sigma_c\,\bar{\Sigma}_c$ 4.91 GeV
  - ✓ $e^+e^- \to \Xi_c\,\bar{\Xi}_c$ 4.94 GeV
  - ✓ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$ 5.40 GeV



Charmed Baryons

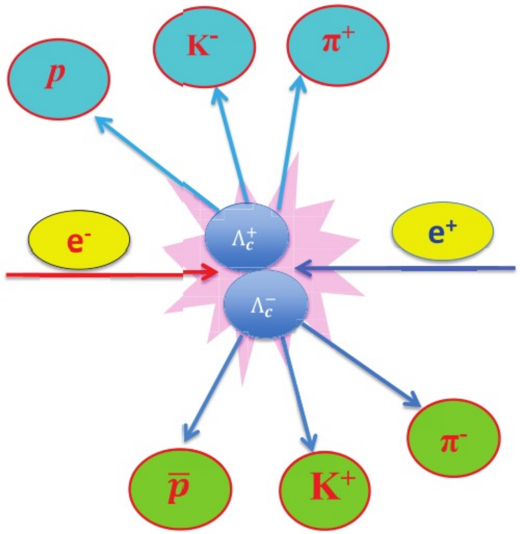
	Structure	J^P	Mass, MeV	Width,MeV	Decay
Λ_c^+	udc	$(1/2)^+$	2286.46 ± 0.14	(200 ± 6) fs	weak
Ξ_c^+	usc	$(1/2)^+$	$2467.8^{+0.4}_{-0.6}$	(442 ± 26) fs	weak
Ξ_c^0	dsc	$(1/2)^+$	$2470.88^{+0.34}_{-0.8}$	112^{+13}_{-10} fs	weak
Σ_c^{++}	uuc	$(1/2)^+$	2454.02 ± 0.18	2.23 ± 0.30	$\Lambda_c^+\pi^+$
Σ_c^+	udc	$(1/2)^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c^+\pi^0$
Σ_c^0	ddc	$(1/2)^+$	2453.76 ± 0.18	2.2 ± 0.4	$\Lambda_c^+\pi^-$
$\Xi_c^{\prime +}$	usc	$(1/2)^+$	2575.6 ± 3.1	—	$\Xi_c^+\gamma$
$\Xi_c^{\prime 0}$	dsc	$(1/2)^+$	2577.9 ± 2.9	—	$\Xi_c^0\gamma$
Ω_c^0	ssc	$(1/2)^+$	2695.2 ± 1.7	(69 ± 12) fs	weak
Σ_c^{*++}	uuc	$(3/2)^+$	2518.4 ± 0.6	14.9 ± 1.9	$\Lambda_c^+\pi^+$
Σ_c^{*+}	udc	$(3/2)^+$	2517.5 ± 2.3	< 17	$\Lambda_c^+\pi^0$
Σ_c^{*0}	ddc	$(3/2)^+$	2518.0 ± 0.5	16.1 ± 2.1	$\Lambda_c^+\pi^-$
Ξ_c^{*+}	usc	$(3/2)^+$	$2645.9^{+0.5}_{-0.6}$	< 3.1	$\Xi_c\pi$
Ξ_c^{*0}	dsc	$(3/2)^+$	2645.9 ± 0.5	< 5.5	$\Xi_c\pi$
Ω_c^{*0}	ssc	$(3/2)^+$	2765.9 ± 2.0	—	$\Omega_c^0\gamma$

Production near threshold and tag technique

E_{cms}=4600MeV

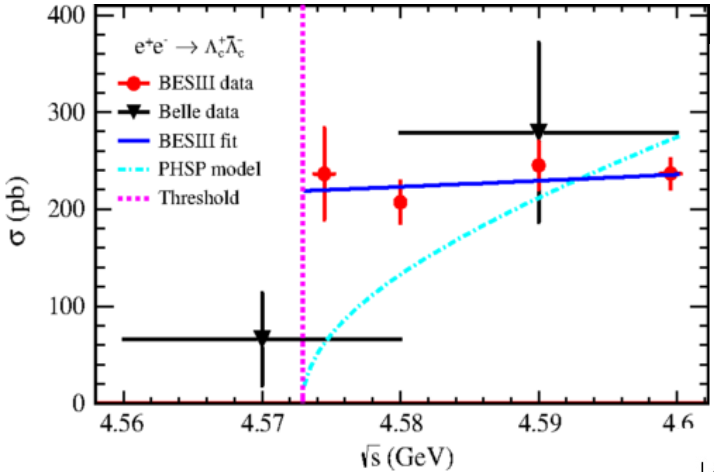
- E_{cms}-$2M_{\Lambda c}$=26MeV only!
- $\Lambda_c^+\Lambda_c^-$ produced in pairs with no additional accompany hadrons.
  - $e^+e^-\to\gamma^*\to\Lambda_c^+\Lambda_c^-$
- Clean backgrounds and well constrained kinematics.

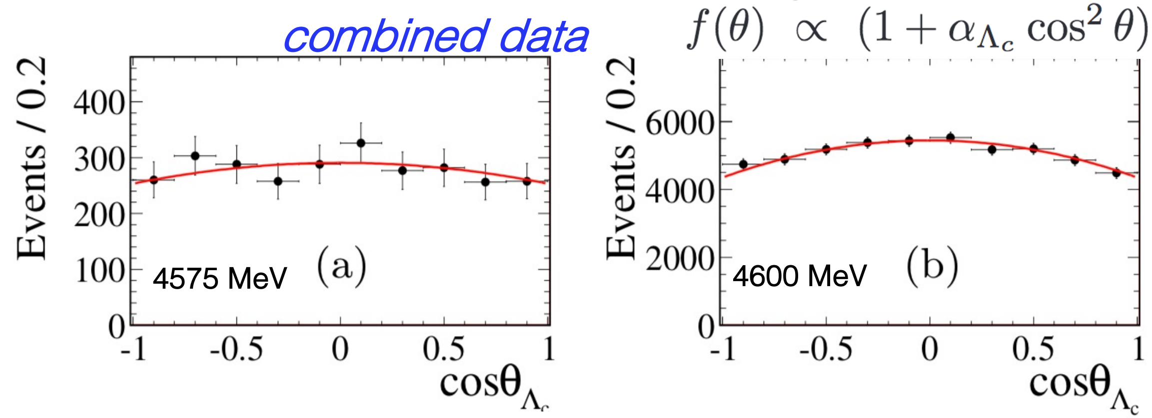
- Typically, two ways to study Λ_c^+ decays:
  - **Single Tag (ST): detect only one of the $\Lambda_c^+\Lambda_c^-$**
    - **=> Relative higher backgrounds**
    - **=> Higher efficiencies**
    - **=> Full reconstruction**
  - **Double Tag (DT): detect both of $\Lambda_c^+\Lambda_c^-$**
    - **=> Smaller backgrounds**
    - **=> Missing mass technique**
    - **=> Lower efficiencies**
    - **=> Systematic in tag side are mostly cancelled**



Angular dependence analysis of $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ near threshold

PRL 120, 132001 (2018)





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

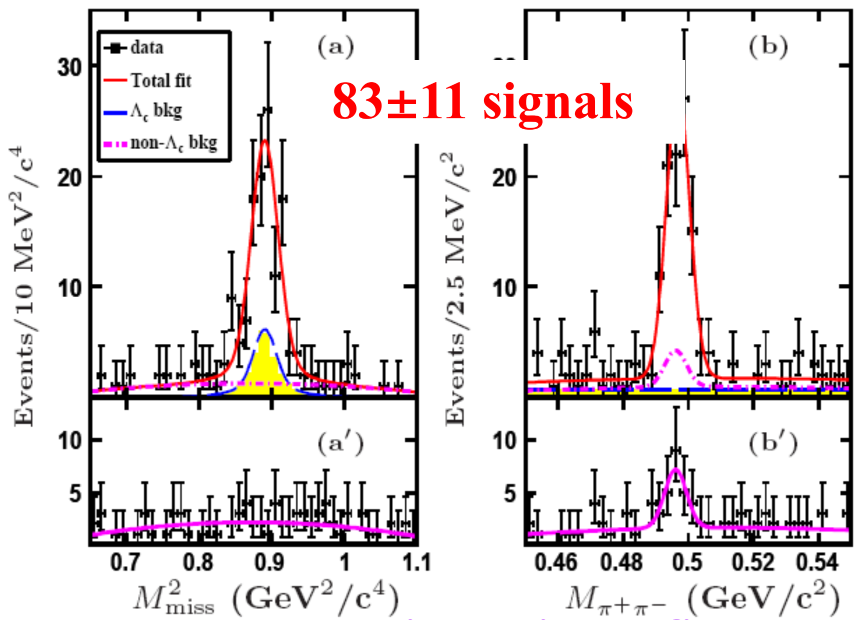
$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c}).$$

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

- One of the most basic observables that intimately related to the internal structure of the nucleon.
- One of the most challenging questions in contemporary physics is why and how quarks are confined into hadrons.
- The electromagnetic form factors (EMFFs) have been a powerful tool in understanding the structure of nucleons.
- First measurements of the EMFFs of the Λ_c^+

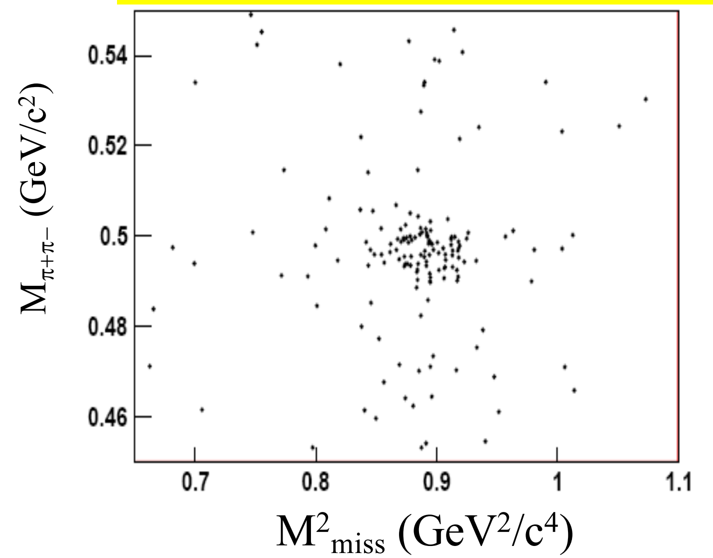
Observation of $\Lambda_c^+ \to nK_S\pi^+$

- ✓ No measurements for Λ_c^+ decay into a neutron yet.
- ✓ To confer the missing neutron, we define the variable M^2_{miss} , which considers the beam energy constrain to improve resolution



two-dimensional fit

567/pb data @ 4.6 GeV

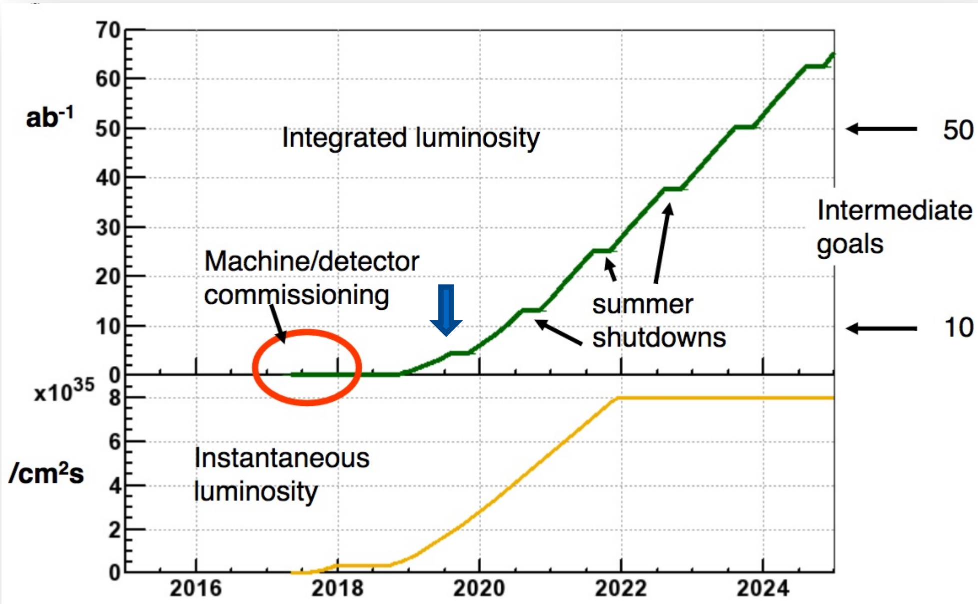


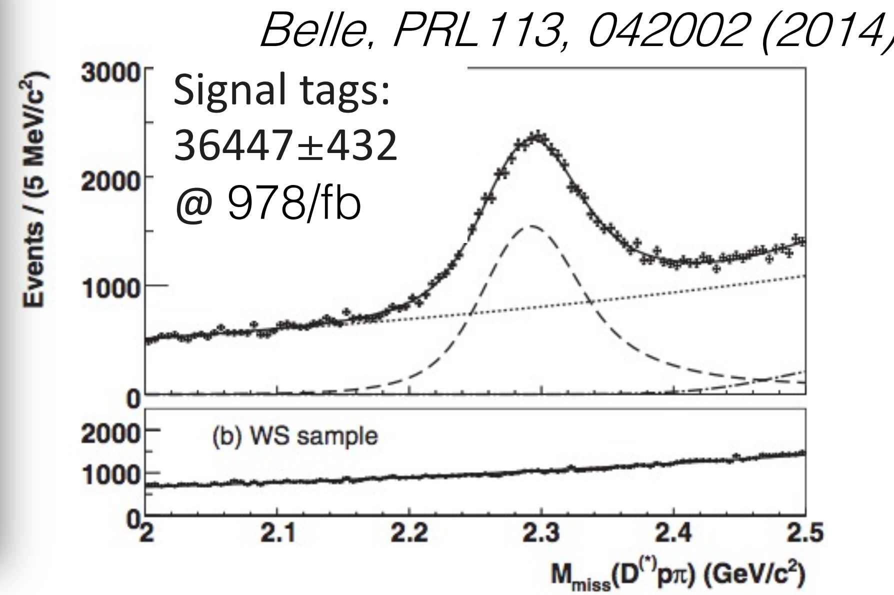
scatter plots $M_{\pi+\pi-}$ versus M^2_{miss}

BESIII Preliminary results: $B[\Lambda_c^+ \to nK_S\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$

First observation of Λ_C^+ decays to final states involving the neutron

Competition from Belle & BelleII





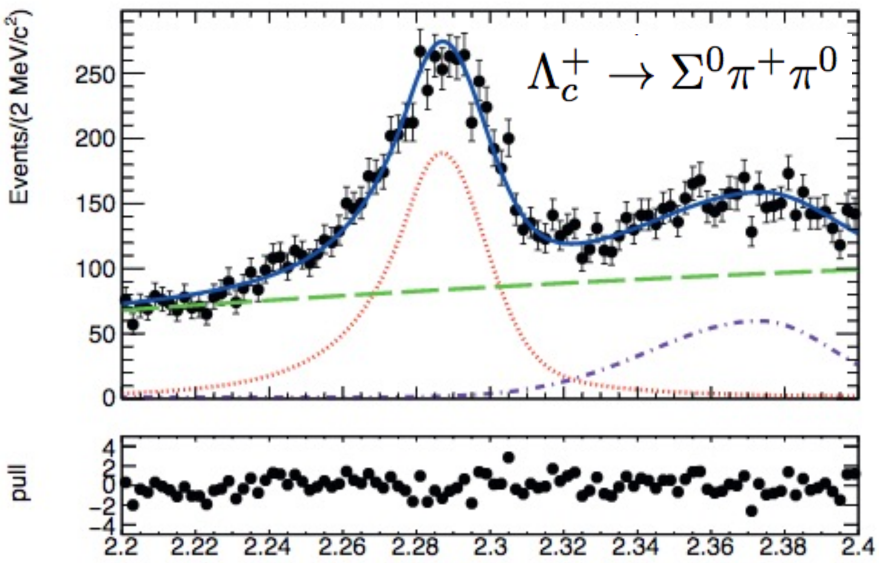
- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, BELLEII will have 5/ab data, 5x of BELLE data;
  ➔ 180K tagged Λ_c^+;
- We will have 150K tagged Λ_c^+, however, BESIII is very clean
- Many precise measurements at BESIII will reach to the level of systematic dominated
  ➔ BESIII has advantages on backgrounds and systematics

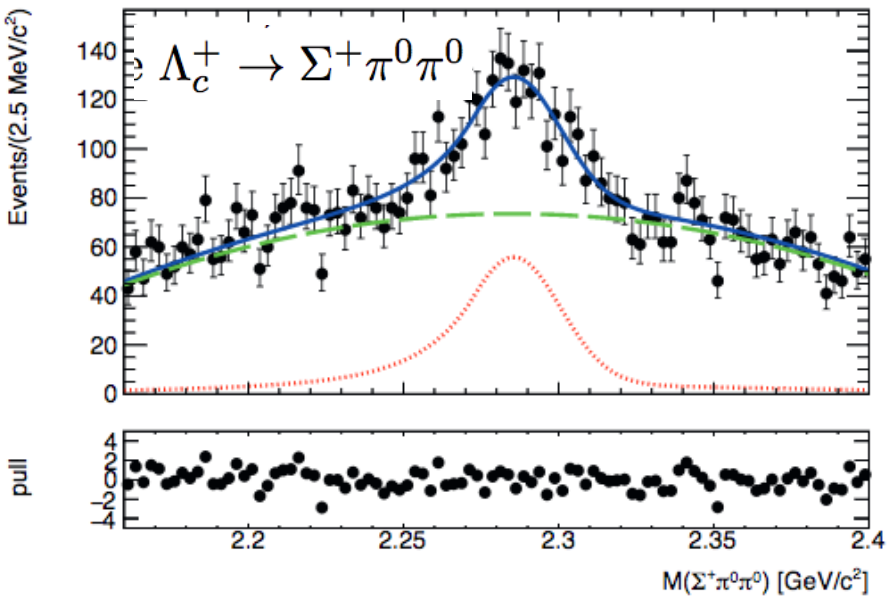
World campaign on the Λ_c^+

	BESIII	Belle(-II)	LHCb
Λ_c^+ total yields	★ ★ ★	★ ★ ★ ★	★ ★ ★ ★ ★
S/B ratio	★ ★ ★ ★ ★	★ ★	★ ★
Systematic error	★ ★ ★ ★ ★	★ ★ ★	★ ★
Systematic research	★ ★ ★ ★ ★	★ ★ ★	★
Semi-leptonic mode	★ ★ ★ ★ ★	★ ★ ★	★
n/K_L-involved mode	★ ★ ★ ★ ★	★ ★	☆
Photon final state	★ ★ ★ ★ ★	★ ★ ★ ★	☆
Absolute measurement	★ ★ ★ ★ ★	★ ★ ★	☆

- The threshold data at BESIII have systematic advantage over Belle(-II) and LHCb in the Λ_c^+ studies.
- This proposal holds an optimal time window to maximize the visibility of BESIII physics.

Measurement of the Decays $\Lambda_c \to \Sigma\pi\pi$ at Belle





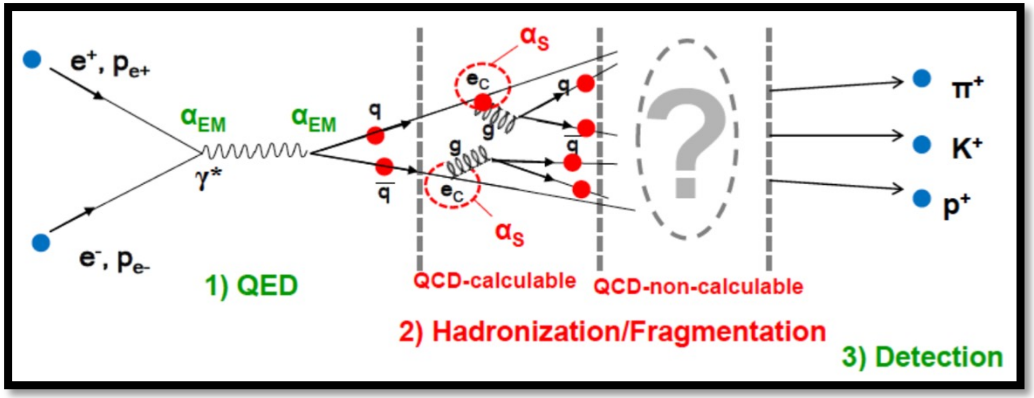
Important Input for b physics

- stringent Fragmentation Function of b/c quark to baryon
  - [Eur. Phys. J. C12, 225 (2000); Eur. Phys. J. C 16, 597 (2000); Phys. Rev. D 85, 032008 (2012), Phys. Rev.D 66, 091101 (2002).]
  - Fragmentation Function (FF) is an important probe in experiment to test and calibrate QCD theory.

PhysRevD.85.032008

TABLE IV. Systematic uncertainties on the absolute scale of $f_{\Lambda_b}/(f_u + f_d)$.

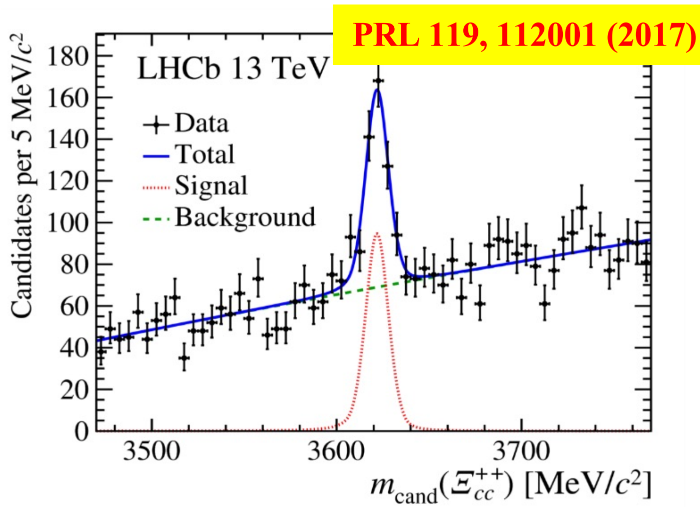
Source	Error (%)
Bin-dependent errors	2.2
$\mathcal{B}(\Lambda_b^0 \to D^0 p X \mu^- \bar{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
Γ_{sl}	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	26.0
Total	26.8

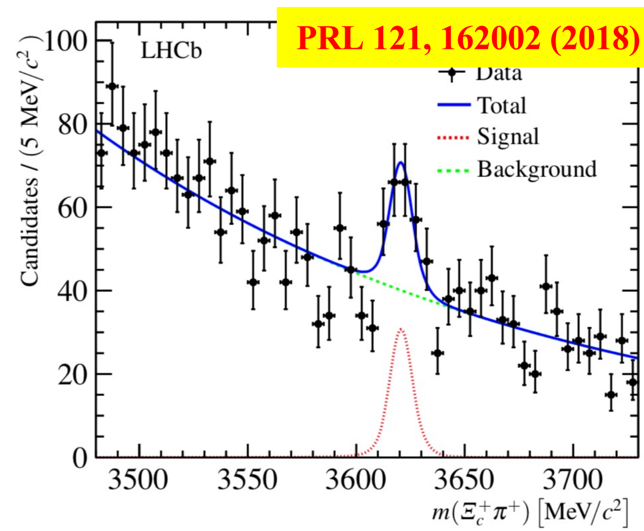


- Now B($pK^-\pi^+$) are still dominated (6%)
- 20x data=> small than 2%

Contributions to Ξ_{cc}^{++} observation

- LHCb observed Ξ_{cc}^{++} from $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays
- Credits from theorists
  - $\tau(\Xi_{cc}^{++}) \approx 3\,\tau(\Xi_{cc}^{+})$ (Chang, Li, Wang, Karliner, et al.)
  - "Discovery channels of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ was predicted benefited from BESIII Λ_c^+ measurements" (Fu-Sheng Yu, et al, '17)





First Measurements of absolute BFs for Ξ_c

$$\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+) = (1.17 \pm 0.37 \pm 0.09)\%,$$
$$\mathcal{B}(\Xi_c^0 \to p K^- K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.21 \pm 0.38)\%,$$
$$\mathcal{B}(\Xi_c^+ \to p K^- \pi^+) = (0.45 \pm 0.21 \pm 0.07)\%.$$

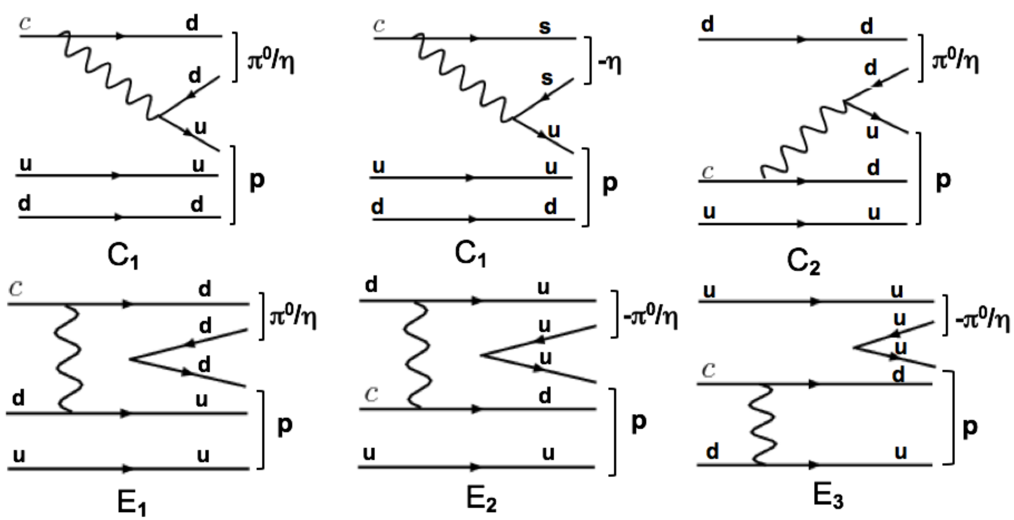
- Large errors
- Belle II will improve these to ~10%
- BESIII has potential to improve these to be <5%

Λ_c^+ hadronic decay

- Study of SCS channels: $\Lambda_c^+ \to \Lambda K^+, p\pi^0, p\eta, n\pi^+, \Sigma^0 K^+, \Sigma^+ K^0$ etc.

From Prof. Hai-Yang Cheng's report.

Singly Cabibbo-suppressed modes: $\Lambda_c^+ \to p\pi^0, p\eta$



$\pi^0 = (d\bar{d} - u\bar{u})/\sqrt{2}$, $\eta = (d\bar{d} + u\bar{u} - s\bar{s})/\sqrt{3}$ for $\eta - \eta'$ mixing angle = 19.5°

$A(\Lambda_c^+ \to p\pi^0) = (C_1 + C_2 + E_1 - E_2 - E_3)/\sqrt{2}$

$A(\Lambda_c^+ \to p\eta) = (2C_1 + C_2 + E_1 + E_2 + E_3)/\sqrt{3}$

It is most likely that

$\Gamma(\Lambda_c^+ \to p\eta) >> \Gamma(\Lambda_c^+ \to p\pi^0)$

30

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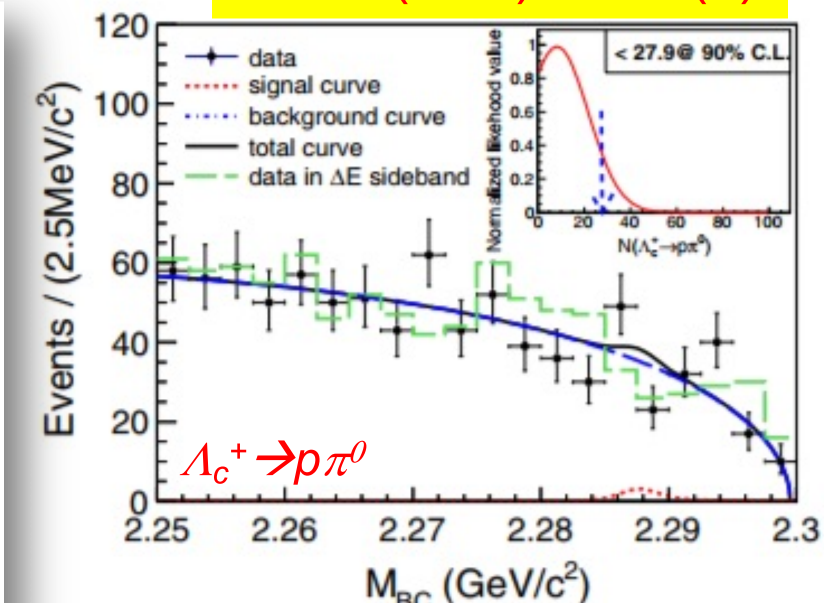


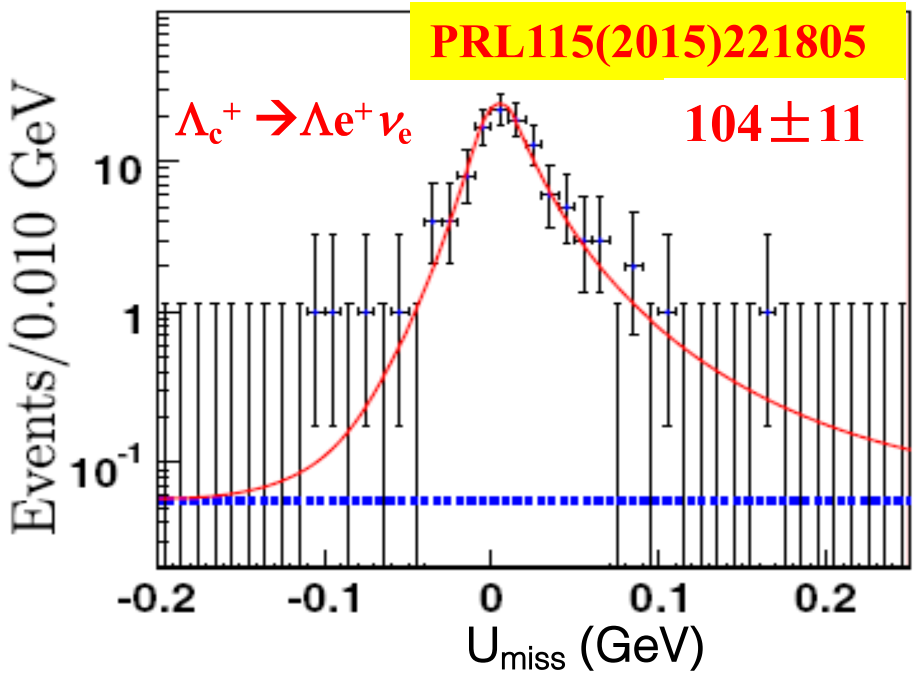
BESIII: $B[\Lambda_c^+ \to p\pi^0] < 2.7 \times 10^{-4}$

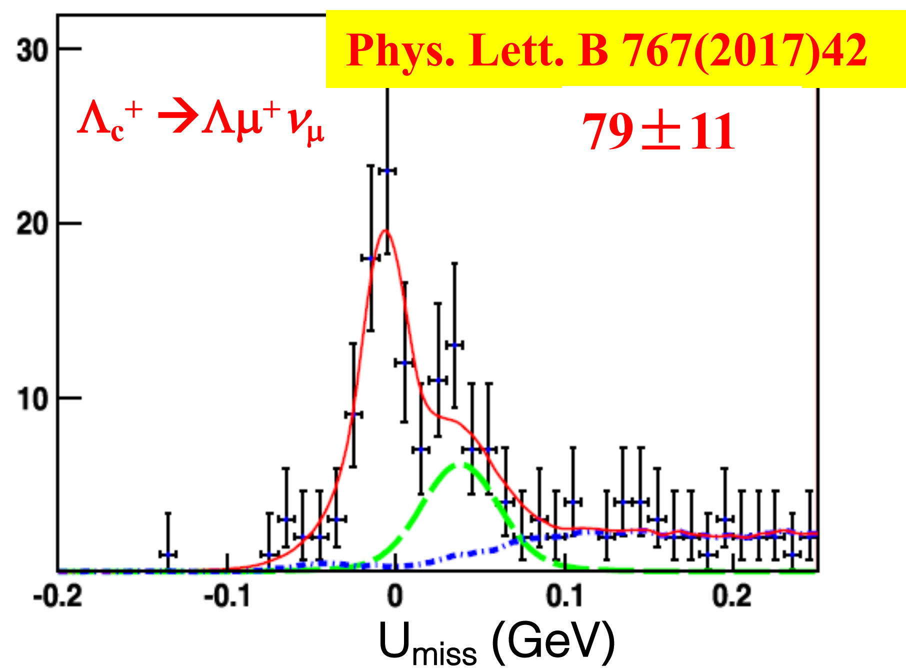
$$M(\Lambda_c^+ \to n\pi^+) = \sqrt{2} M(\Lambda_c^+ \to p\pi^0),$$

- More precise comparison of the two BFs are desired to explore the interference of different non-factorizable diagrams and BESIII result support the theoretic prediction. It is predicted that $Br[\Lambda_c^+ \to n\pi^+] \sim 3.5 \times Br[\Lambda_c^+ \to p\pi^0]$ [Hai-Yang Cheng, arXiv: 1801.08625]

$\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$ decays

- Theoretical calculations on the BF ranges from 1.4% to
- BESIII performed the first absolute BF measurements.
- The BFs provide complementary information on determining





$B[\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e] = (3.63 \pm 0.38 \pm 0.20)\%$

$B[\Lambda_c^+ \rightarrow \Lambda \mu^+ \nu_\mu] = (3.49 \pm 0.46 \pm 0.26)\%$

$\Gamma[\Lambda_c^+ \rightarrow \Lambda \mu^+ \nu_\mu] / \Gamma[\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e] = 0.96 \pm 0.16 \pm 0.04$

Provides important input for calibrating the LQCD calculations.

Λ_c^+ data in PDG2015

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S = -1$ final states					
$p\overline{K}^0$		(3.21± 0.30) %			
$pK^-\pi^+$		($6.84^{+0.32}_{-0.40}$) %			
$p\overline{K}^*(892)^0$	[q]	(2.13± 0.30) %			
$\Delta(1232)^{++}K^-$		(1.18± 0.27) %			22.9%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %			25.0%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %			10.5%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %			13.3%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %			23.5%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %			11.4%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %			13.0%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %			33.3%
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %			18.0%
$\Delta(1232)\overline{K}^*(892)$		seen			
$pK^-\pi^+\pi^+\pi^-$		(1.5 ± 1.0) × 10^{-3}			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S = 0$ final states					
$p\pi^+\pi^-$		(4.7 ± 2.5) × 10^{-3}			45.4%
$pf_0(980)$	[q]	(3.8 ± 2.5) × 10^{-3}			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		(2.5 ± 1.6) × 10^{-3}			64.0%
pK^+K^-		(1.1 ± 0.4) × 10^{-3}			36.4%
$p\phi$	[q]	(1.12± 0.23) × 10^{-3}			
pK^+K^- non-ϕ		(4.8 ± 1.9) × 10^{-4}			
Hadronic modes with a hyperon: $S = -1$ final states					
$\Lambda\pi^+$		(1.46± 0.13) %			8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %			26.0%
$\Lambda\rho^+$		< 6 %	CL=95%		
$\Lambda\pi^+\pi^+\pi^-$		(3.59± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+}\to\Lambda\pi^+$		(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-}\to\Lambda\pi^-$		(7.5 ± 1.4) × 10^{-3}			18.7%
$\Lambda\pi^+\rho^0$		(1.4 ± 0.6) %			42.8%
$\Sigma(1385)^+\rho^0$, $\Sigma^{*+}\to\Lambda\pi^+$		(5 ± 4) × 10^{-3}			80.0%
$\Lambda\pi^+\pi^+\pi^-$ nonresonant		< 1.1 %	CL=90%		
$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(2.5 ± 0.9) %			36.0%
$\Lambda\pi^+\eta$	[q]	(2.4 ± 0.5) %			20.8%
$\Sigma(1385)^+\eta$	[q]	(1.16± 0.35) %			30.2%
$\Lambda\pi^+\omega$	[q]	(1.6 ± 0.6) %			37.5%
$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		< 9 × 10^{-3}	CL=90%		
$\Lambda K^+\overline{K}^0$		(6.4 ± 1.3) × 10^{-3}	S=1.6		20.3%
$\Xi(1690)^0K^+$, $\Xi^{*0}\to\Lambda\overline{K}^0$		(1.8 ± 0.6) × 10^{-3}			33.3%
$\Sigma^0\pi^+$		(1.43± 0.14) %			10.0%
$\Sigma^+\pi^0$		(1.37± 0.30) %			21.9%
$\Sigma^+\eta$		(7.5 ± 2.5) × 10^{-3}			33.3%
$\Sigma^+\pi^+\pi^-$		(4.9 ± 0.5) %			10.2%
$\Sigma^+\rho^0$		< 1.8 %	CL=95%		
$\Sigma^-\pi^+\pi^+$		(2.3 ± 0.4) %			17.4%
$\Sigma^0\pi^+\pi^0$		(2.5 ± 0.9) %			36.0%
$\Sigma^0\pi^+\pi^+\pi^-$		(1.13± 0.31) %			27.4%
$\Sigma^+\pi^+\pi^-\pi^0$		—			
$\Sigma^+\omega$	[q]	(3.7 ± 1.0) %			27.1%
$\Sigma^+K^+K^-$		(3.8 ± 0.6) × 10^{-3}			15.8%
$\Sigma^+\phi$	[q]	(4.3 ± 0.7) × 10^{-3}			16.3%
$\Xi(1690)^0K^+$, $\Xi^{*0}\to\Sigma^+K^-$		(1.11± 0.29) × 10^{-3}			26.2%
$\Sigma^+K^+K^-$ nonresonant		< 9 × 10^{-4}	CL=90%		
Ξ^0K^+		(5.3 ± 1.3) × 10^{-3}			24.5%
$\Xi^-K^+\pi^+$		(7.0 ± 0.8) × 10^{-3}	S=1.1		11.4%
$\Xi(1530)^0K^+$	[q]	(3.5 ± 1.0) × 10^{-3}			28.6%
Hadronic modes with a hyperon: $S = 0$ final states					
ΛK^+		(6.9 ± 1.4) × 10^{-4}			20.3%
$\Lambda K^+\pi^+\pi^-$		< 6 × 10^{-4}	CL=90%		
Σ^0K^+		(5.7 ± 1.0) × 10^{-4}			17.5%
$\Sigma^0K^+\pi^+\pi^-$		< 2.9 × 10^{-4}	CL=90%		
$\Sigma^+K^+\pi^-$		(2.3 ± 0.7) × 10^{-3}			30.4%
$\Sigma^+K^*(892)^0$	[q]	(3.8 ± 1.2) × 10^{-3}			31.6%
$\Sigma^-K^+\pi^+$		< 1.3 × 10^{-3}	CL=90%		
Doubly Cabibbo-suppressed modes					
$pK^+\pi^-$		< 3.1 × 10^{-4}	CL=90%		
Semileptonic modes					
$\Lambda\ell^+\nu_\ell$	[r]	(2.8 ± 0.4) %			
$\Lambda e^+\nu_e$		(2.9 ± 0.5) %			17.2%
$\Lambda\mu^+\nu_\mu$		(2.7 ± 0.6) %			22.2%

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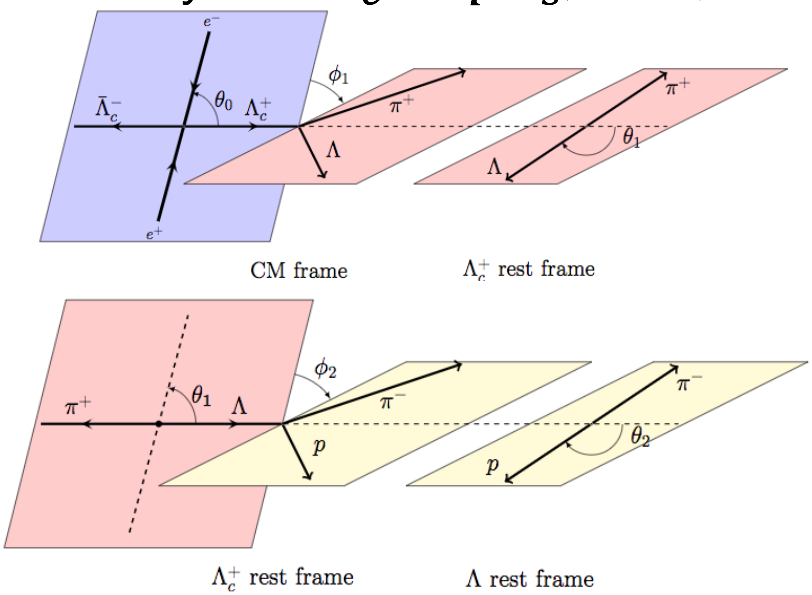
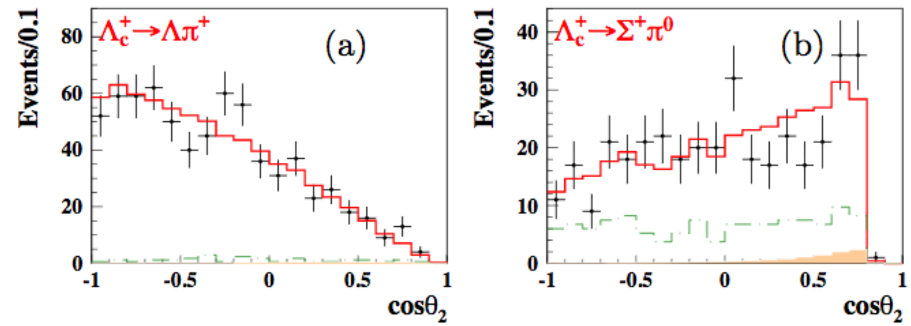
- ✓ Total branching fraction ~60%
- ✓ Lots of unknown decay channels
- ✓ Quite large uncertainties(>20%)
- ✓ Most BFs are measured relative to $\Lambda_c^+ \to pK^-\pi^+$

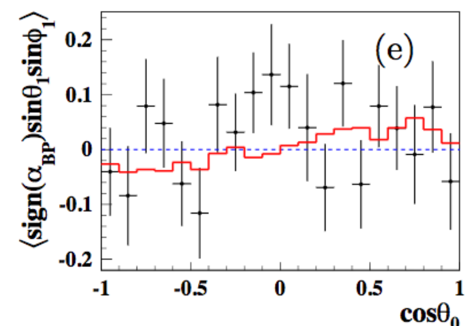
Λ_c decay asymmetries

4(6)-fold angular analysis of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$

PRD 100, 072004 (2019)







$\Lambda_c^+ \to$		pK_S^0	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
$\alpha_{BP}^{\Lambda_c^+}$	Predicted	−1.0 [16], 0.51 [11] −0.49 [10], −0.90 [10] −0.49 [17], −0.97 [18] −0.66 [19], −0.90 [30] −0.99 [20], −0.91 [31]	−0.70 [16], −0.67 [11] −0.95 [10], −0.99 [10] −0.96 [17], −0.95 [18] −0.99 [19], −0.86 [30] −0.99 [20], −0.94 [31]	0.71 [16], 0.92 [11] 0.79 [10], −0.49 [10] 0.83 [17], 0.43 [18] 0.39 [19], −0.76 [30] −0.31 [20], −0.47 [31]	0.70 [16], 0.92 [11] 0.78 [10], −0.49 [10] 0.83 [17], 0.43 [18] 0.39 [19], −0.76 [30] −0.31 [20], −0.47 [31]
	PDG [2]		-0.91 ± 0.15	-0.45 ± 0.32	
	This work	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

$\sin \Delta_0 = -0.28 \pm 0.13 \pm 0.03$

- Best precisions on the hadronic weak decay asymmetries
- The transverse polarization is firstly studied and found to be non-zero with 2.1σ