BESIII program on charmed baryon

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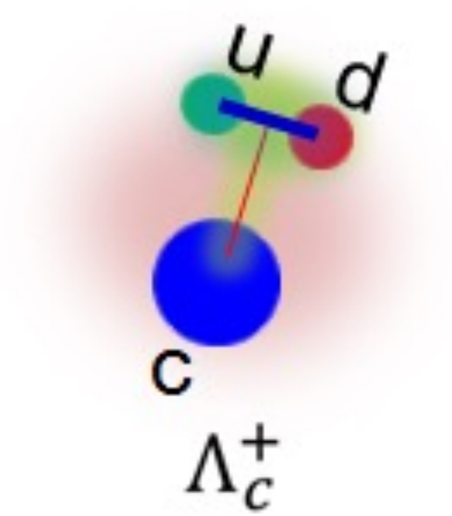
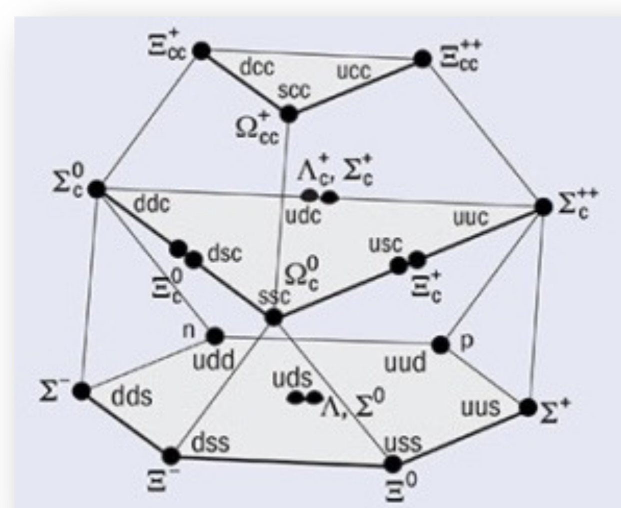
(UCAS)

On behalf the BESIII collaboration



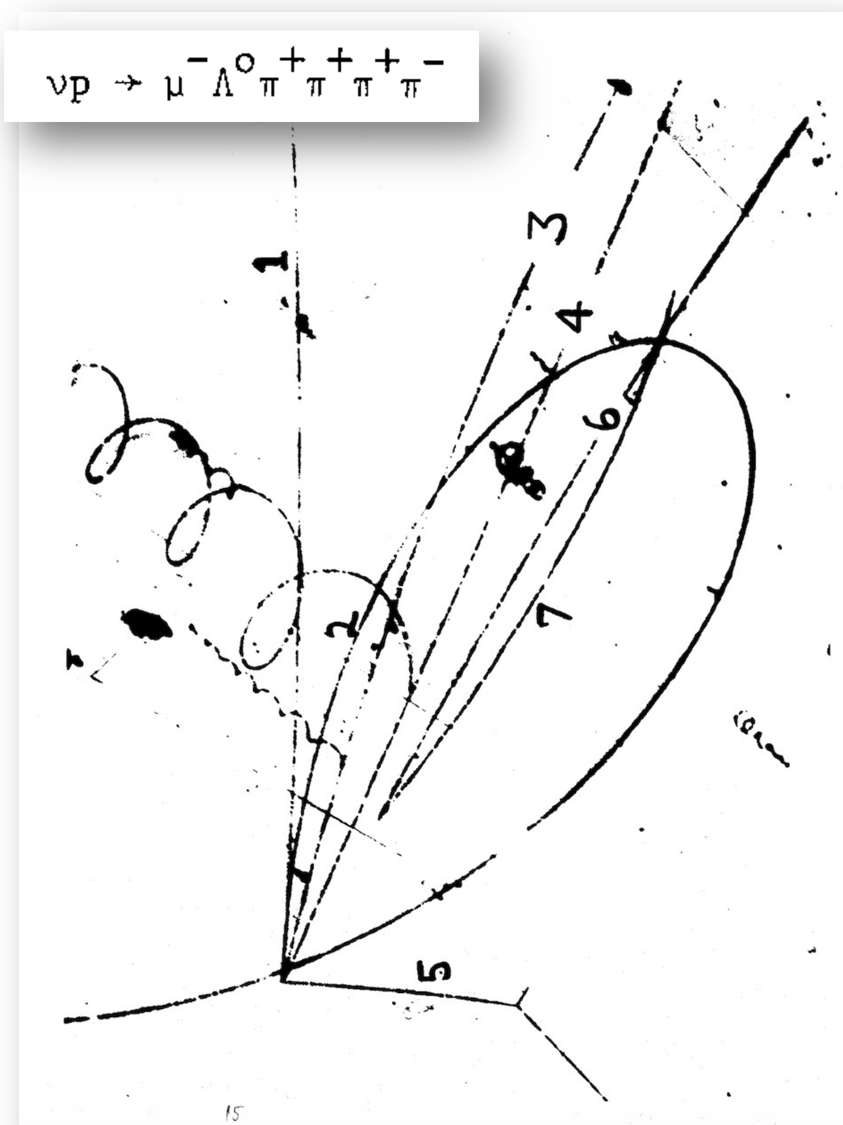


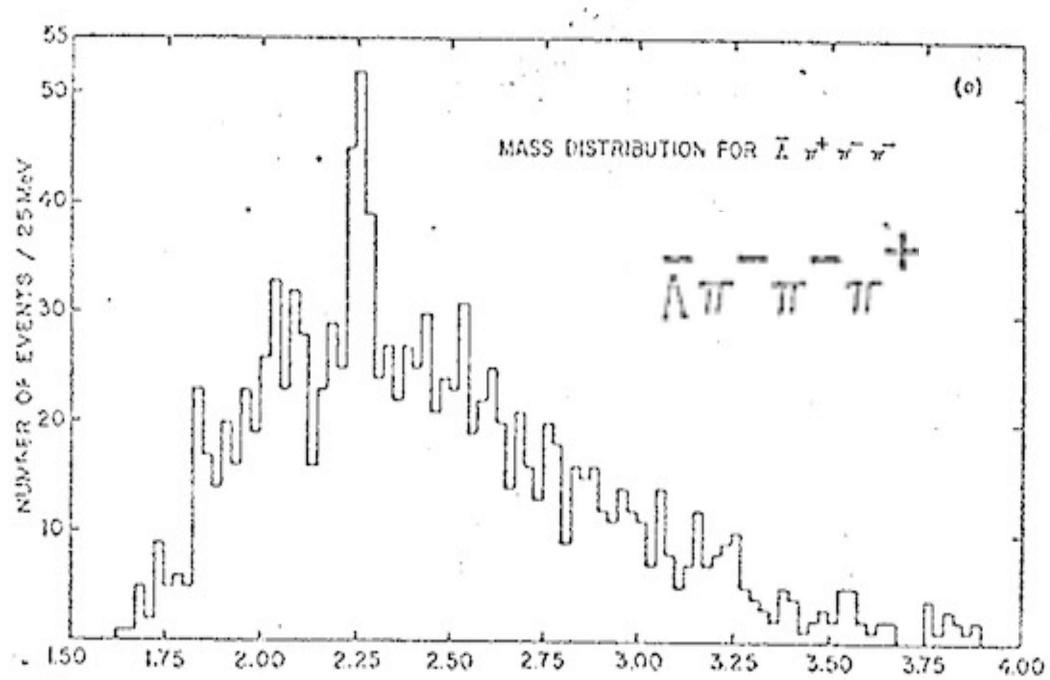
Outline

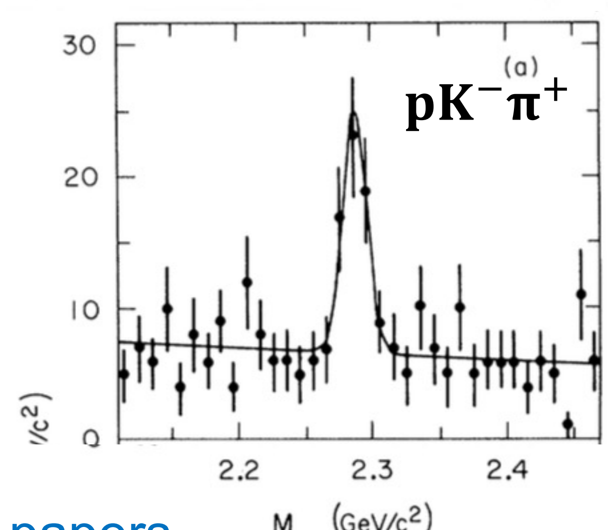
- The lightest charmed baryon Λ_c^+
- BESIII accomplishment in studying the Λ_c^+
- Ongoing progress and future plan
- Summary

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)







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

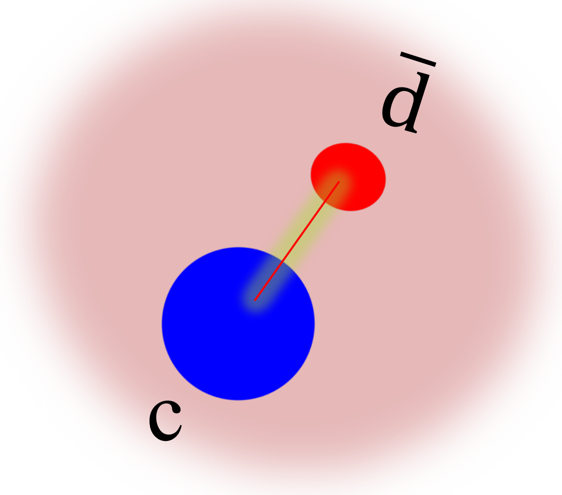
Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S=-1$ final states					
$p\overline{K}^0$		(3.21 ± 0.30) %			
$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %			
$p\overline{K}^*(892)^0$	[q]	(2.13 ± 0.30) %			
$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %			22.9%
$\Lambda(1520)\pi^+$	[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%

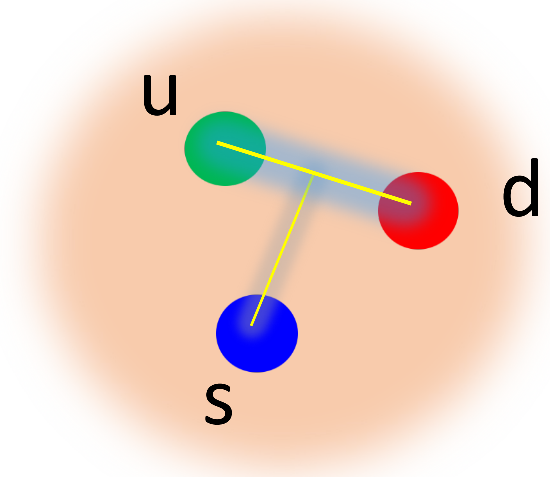
BESIII

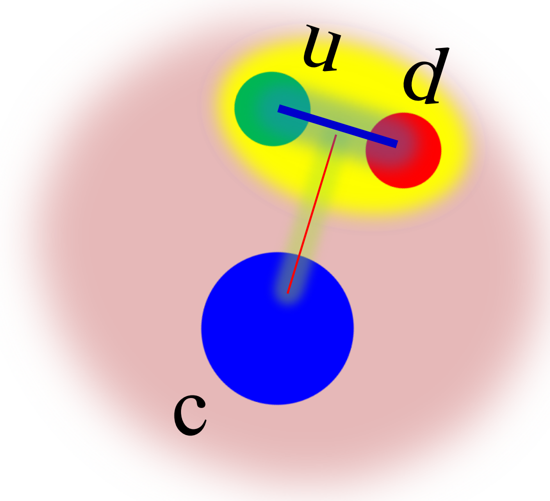
Why Λ_c^+ is interesting

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.*







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

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

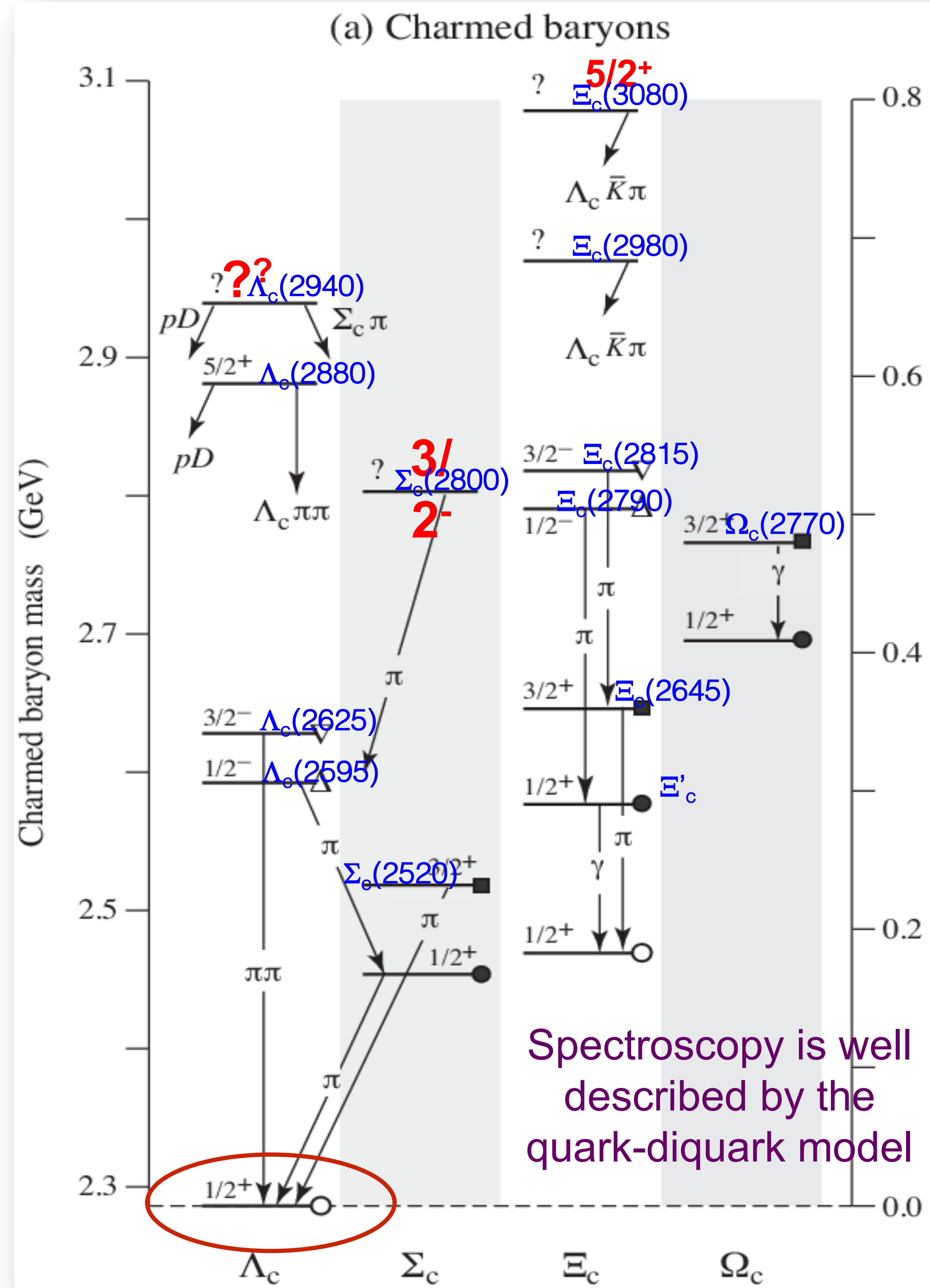
→ Charmed baryon (Λ_c[udc])
$m_u, m_d << m_c$ → **diquark + quark**
(qq) (Q)

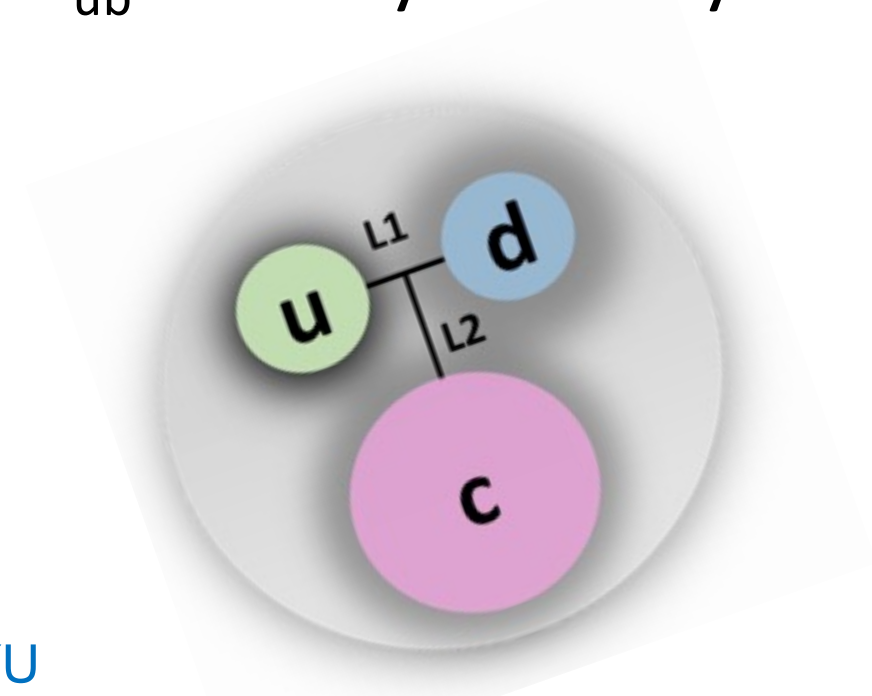
In some sense, more reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

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

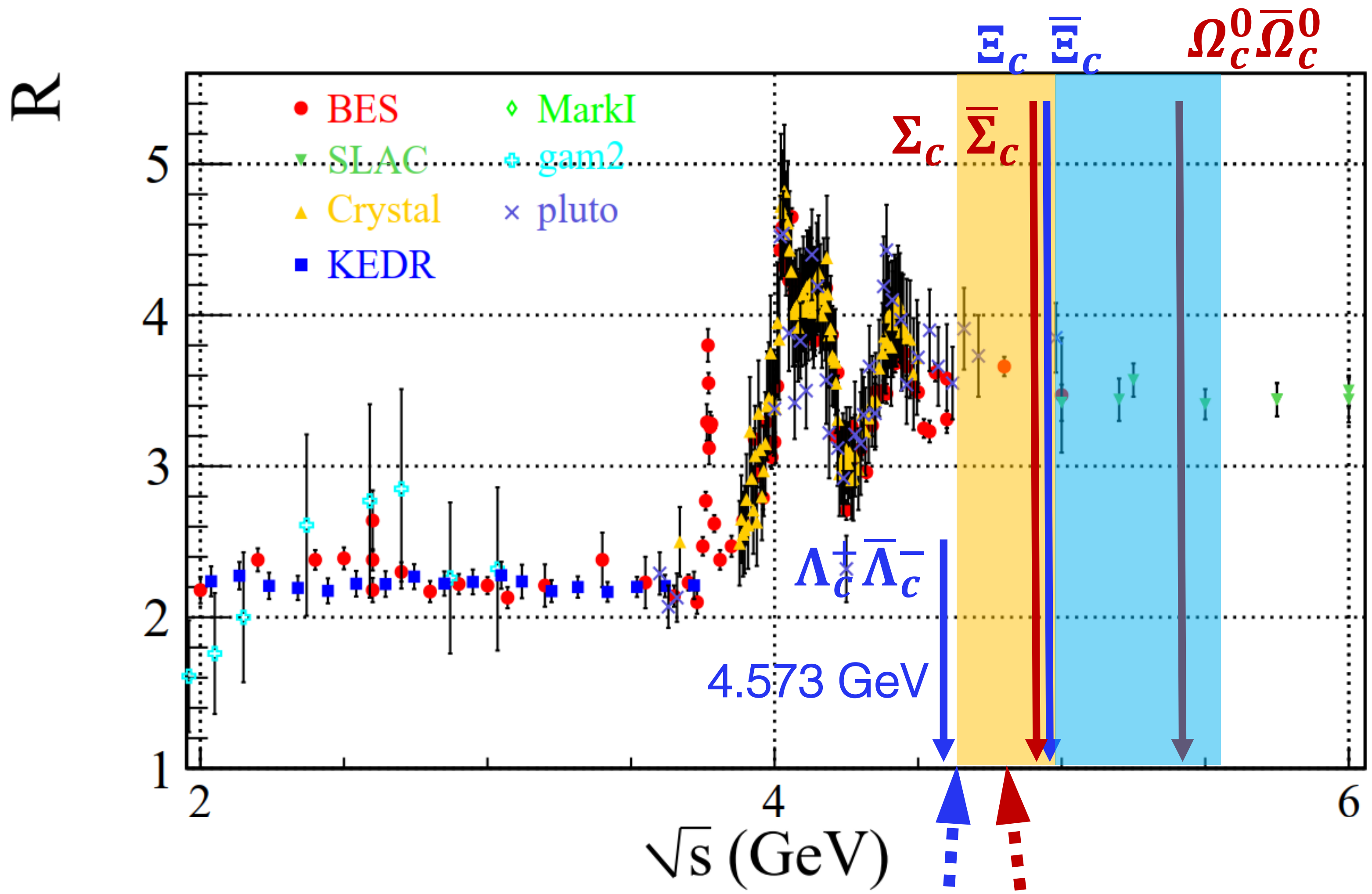
Λ_c^+ : cornerstone of charmed baryon spectroscopy

- 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





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

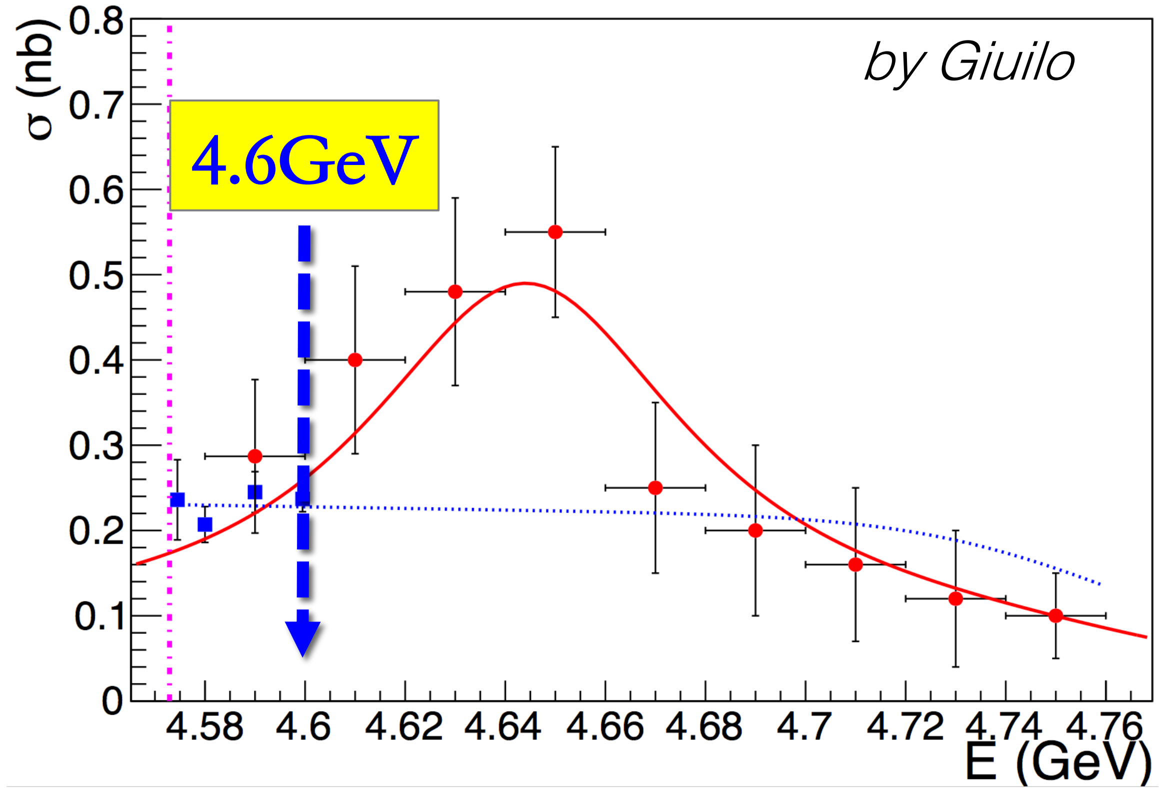
In spring of 2013, a proposal of Λ_c^+ data taking was discussed and later approved inside the collaboration.

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

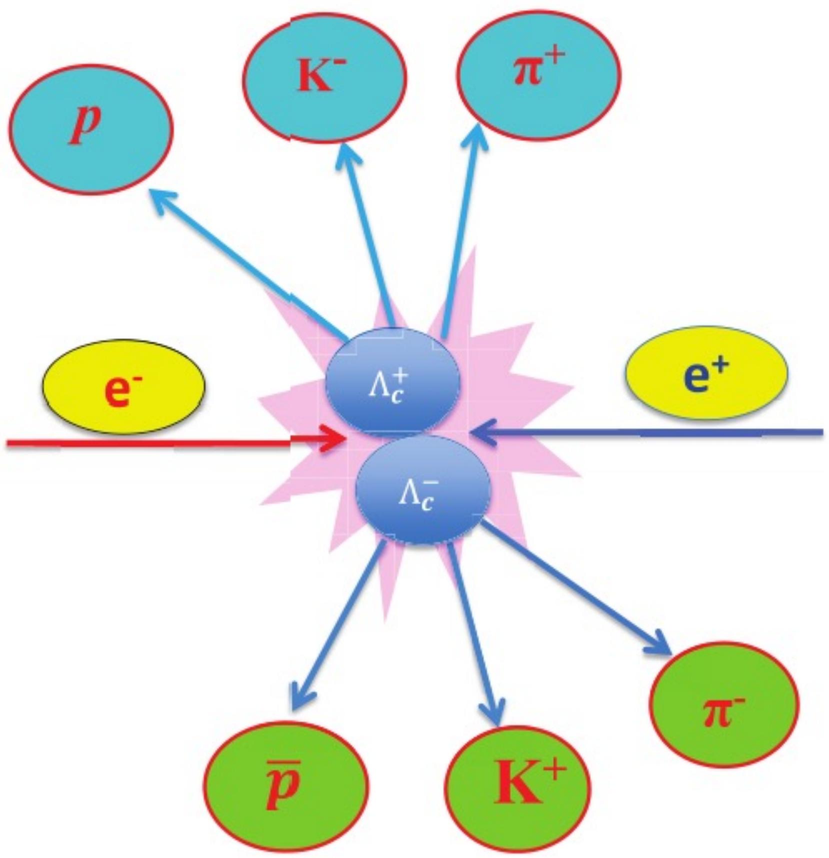


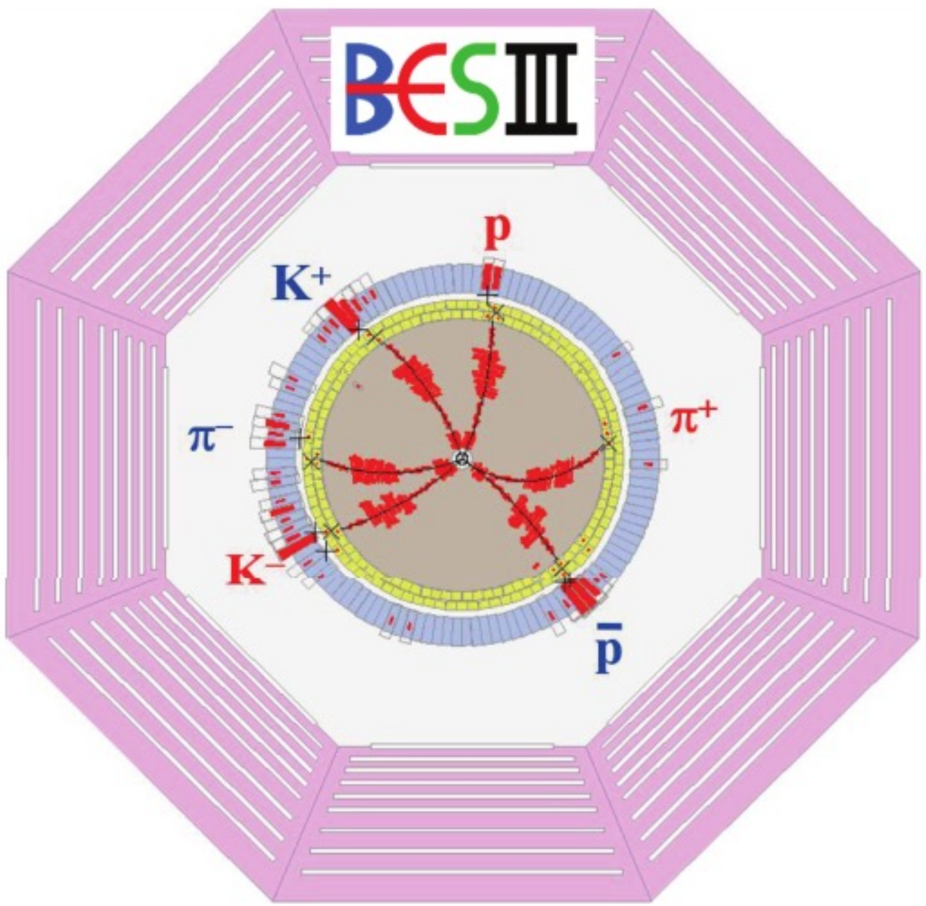
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

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

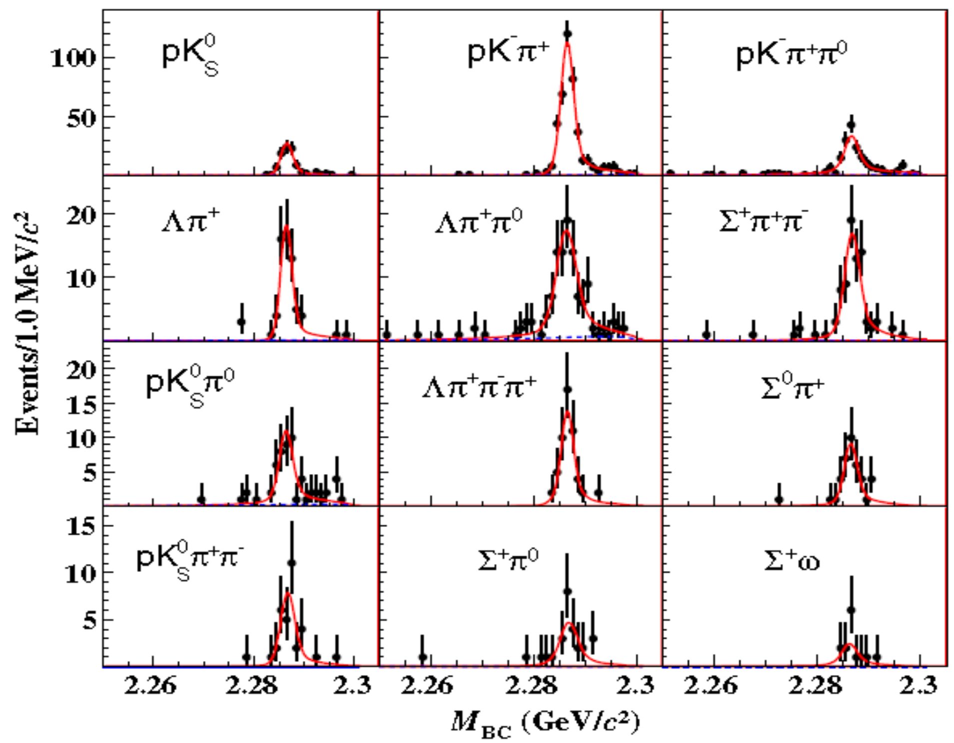
Very productive for the data set taken in 35 days!

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)**
$\Lambda_c^+ \to K_s^0X$	EPJC 80, 935 (2020)
Production	
$\Lambda_c^+\Lambda_c^-$ cross section	**PRL 120,132001(2018)**

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]

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	

- ✓ **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**

So far, the mostly cited BESIII charm paper

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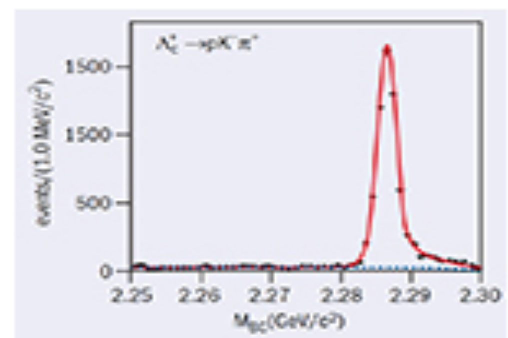
Mar 18, 2016

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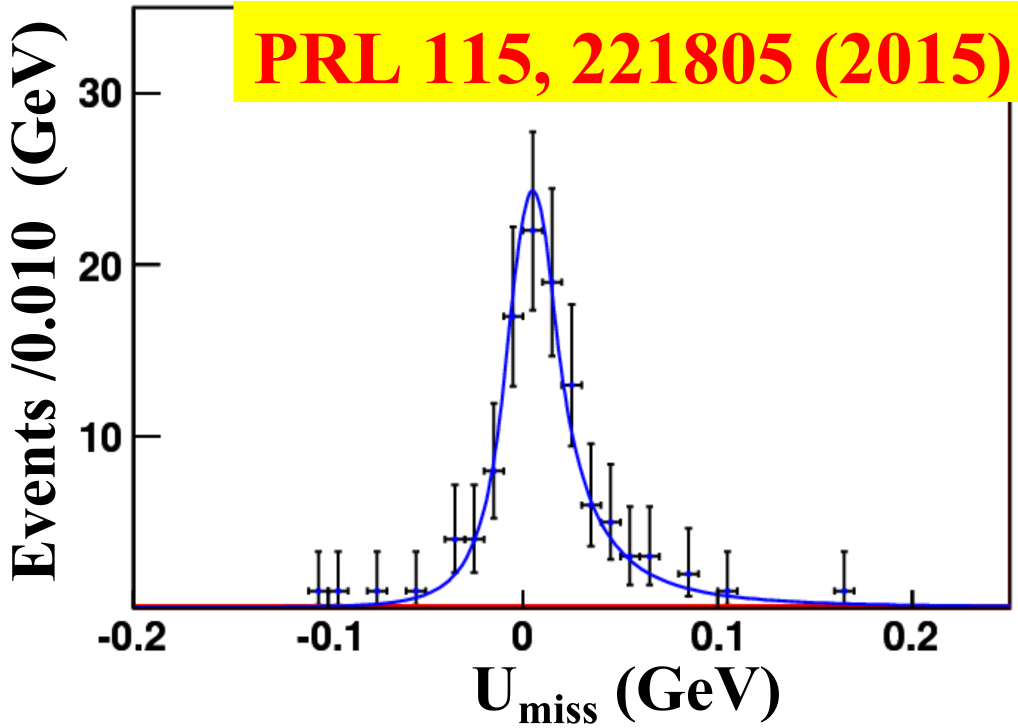
BF for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

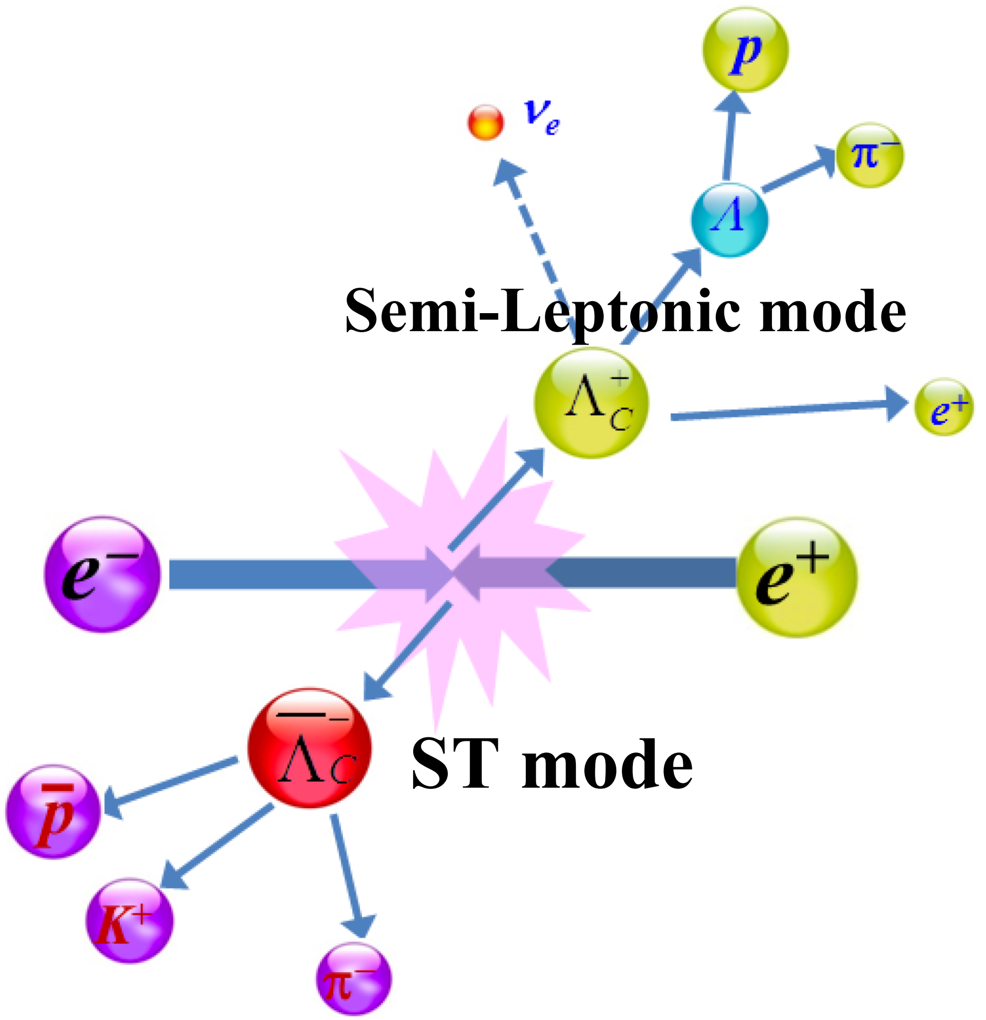
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is a $c \to s l^+ \nu_l$ dominated process.
- Urgently needed for LQCD calculations.
- No direct absolute measurement for $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ available.

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

11 hadronic single tag modes are used

PRL 115, 221805 (2015)





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

- 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)

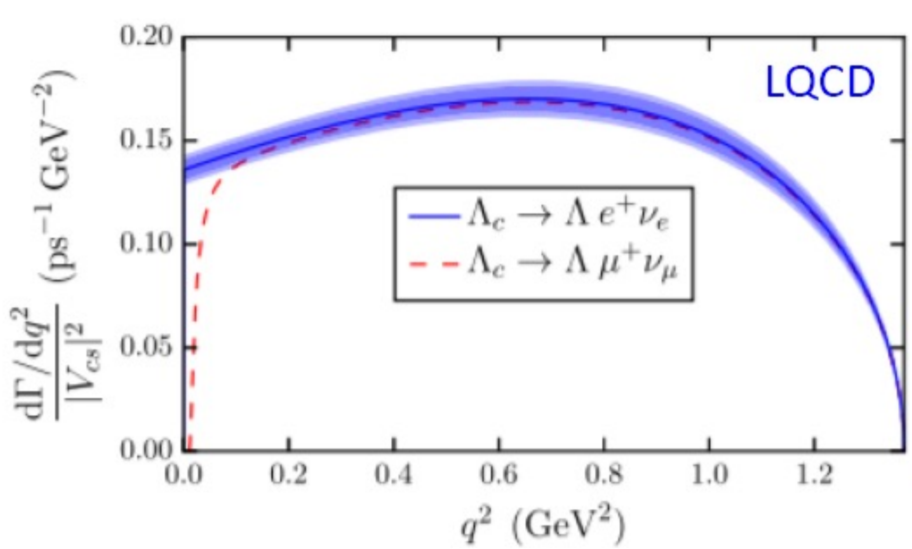
Triggered by BESIII

- Input the measured BFs from 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

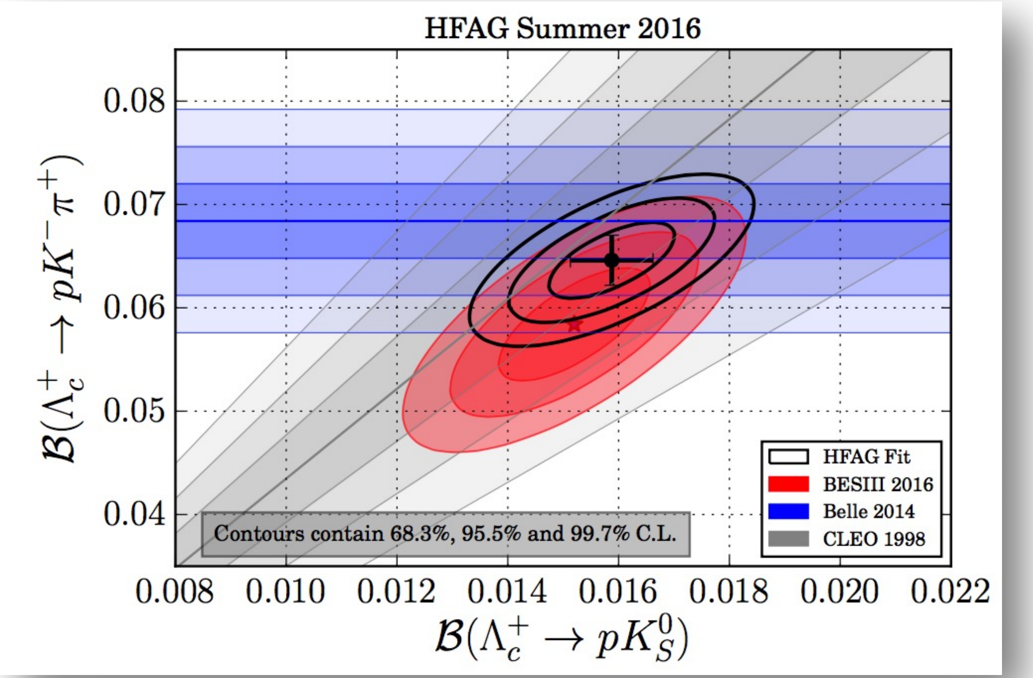
$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases}$$

✓ 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		Scale / 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) %		

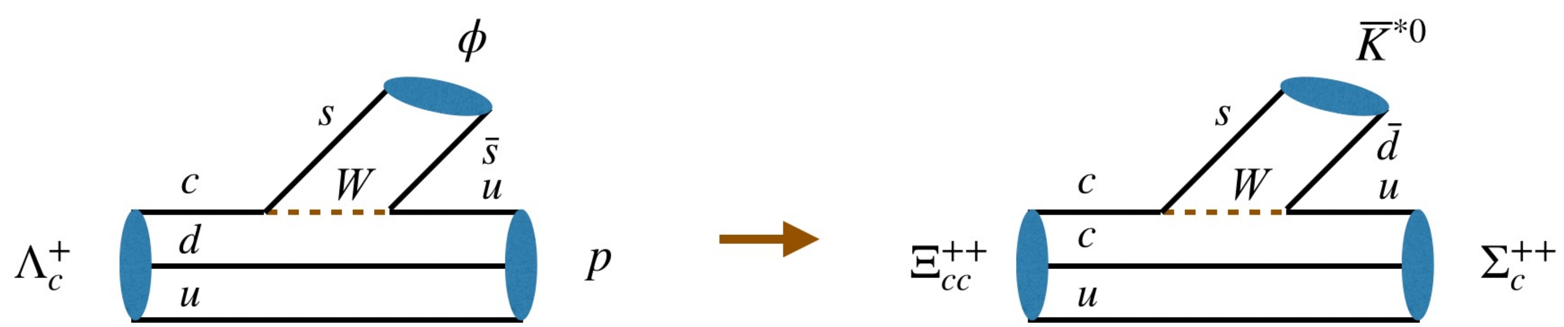
Experimental precision reaches of the charmed hadrons

	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

A theoretical Framework for Charmed Hadrons

- 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.



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

[PRL 117, 232002 (2016)]

↓

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

Large enough for observation

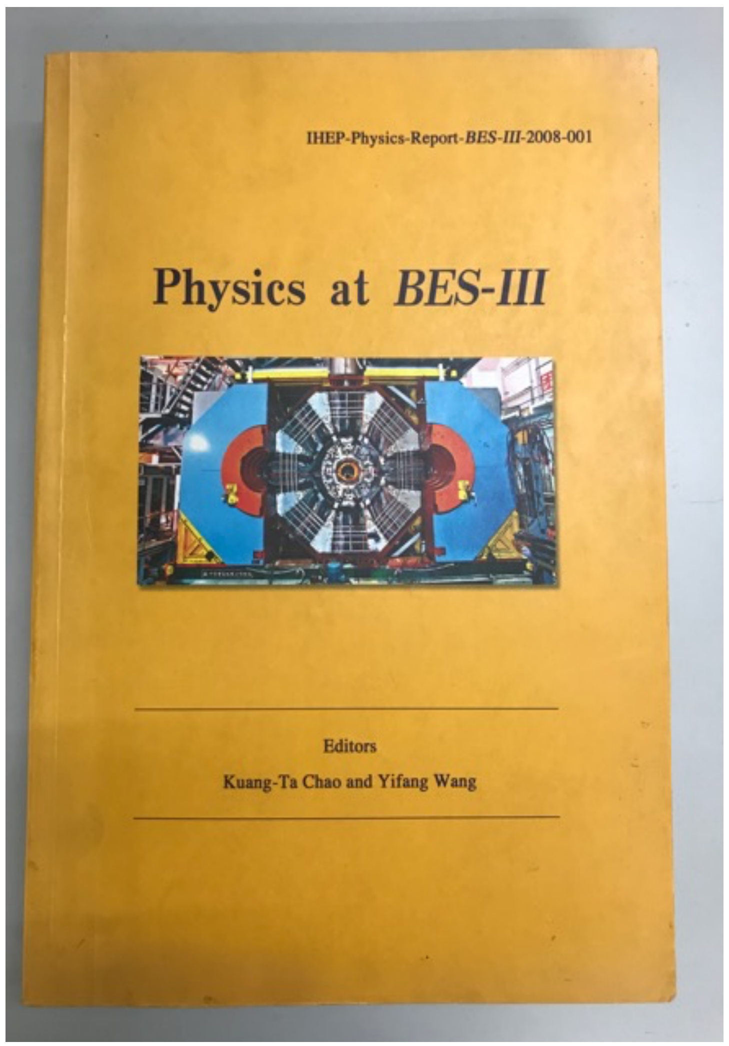
Important inputs to the Ξ_{cc}^{++} observation at LHCb

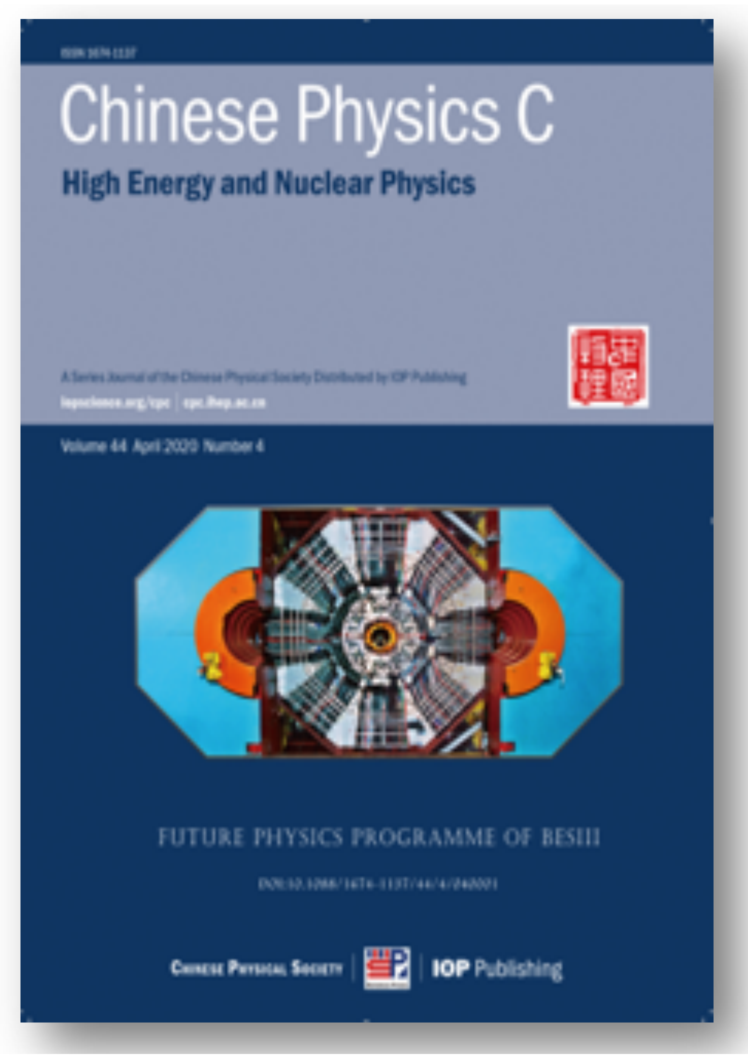
Λ_c^+ data from BESIII ➔ Stronger predictive power

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

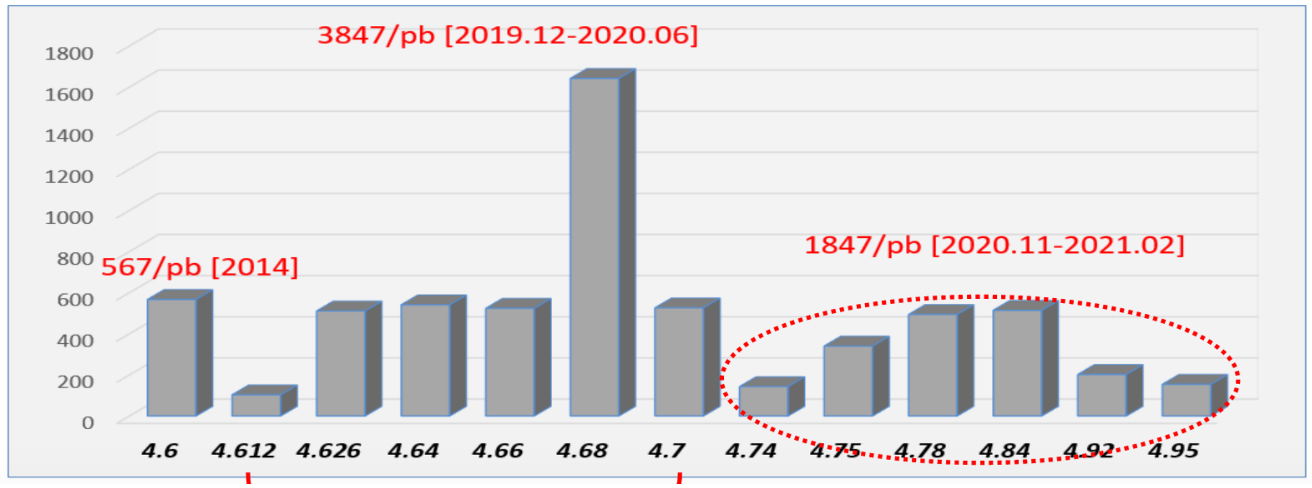
to be complete in 2022-24

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 $\Lambda_c^+ \to pK^- e^+ \nu_e$
- 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 $\Lambda_c^+ \to \gamma \Sigma^+$

More analyses will be published

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ *PRL129, 231803 (2022)*
- ✓ Observation of $\Lambda_c^+ \to pK^- e^+ \nu_e$ *PRD106, 112010 (2022)*
- ✓ Search for $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $pK_s \pi^- e^+ \nu_e$ *arXiv:2302.07529*

Neutron-involved decay

- ✓ Observation of $\Lambda_c^+ \to n\pi^+$ *PRL 128, 142001 (2022)*
- ✓ Observation of $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^+\pi^-, nK^-\pi^+\pi^+$ *CPC116, 052001 (2016) (Cover Story)*

Hadronic CS decays

- ✓ $\Lambda_c^+ \to \Sigma^+ K_s, \Sigma^0 K^+$ *PRD 106, 052003 (2022)*
- ✓ $\Lambda_c^+ \to p\eta'$ *PRD 106, 072002 (2022)*
- ✓ $\Lambda_c^+ \to \Lambda K^+$ *PRD 106, L111101 (2022)*
- ✓ $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$ *arXiv:2304.09405*

Hadronic CF decays

- ✓ PWA of $\Lambda_c^+ \to \Lambda \pi^+ \pi^0$ *JHEP12, 033(2022)*
- ✓ W-exchange-only process $\Lambda_c^+ \to \Sigma^+ K^+ K^-, \Sigma^+ \phi$

Inclusive decay

- ✓ Improved BF of $\Lambda_c^+ \to e^+ X$ *PRD107, 052005 (2023)*
- ✓ First BF of $\Lambda_c^- \to \bar{n} X$ *arXiv:2210.09561*

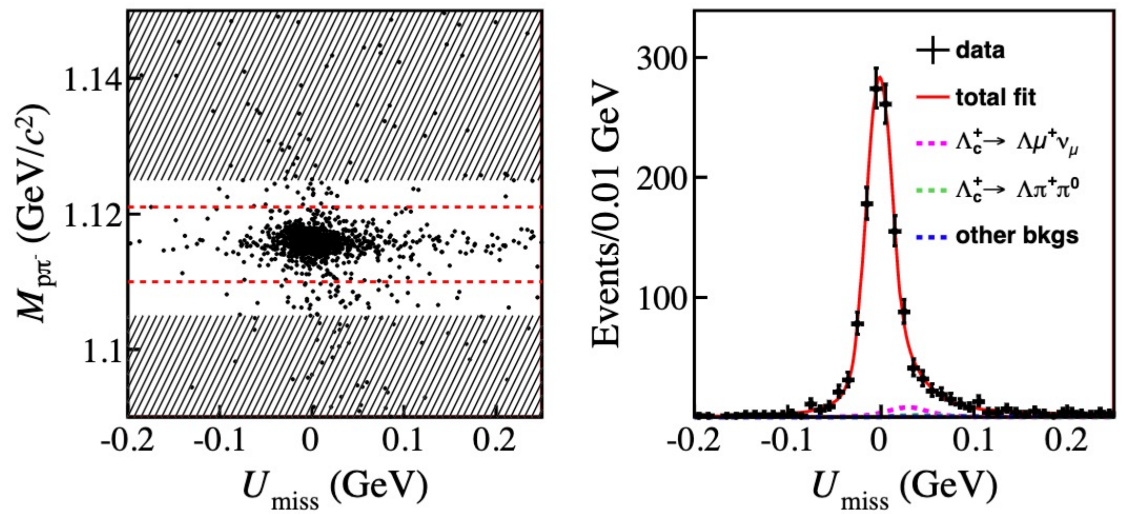
Rare decay

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

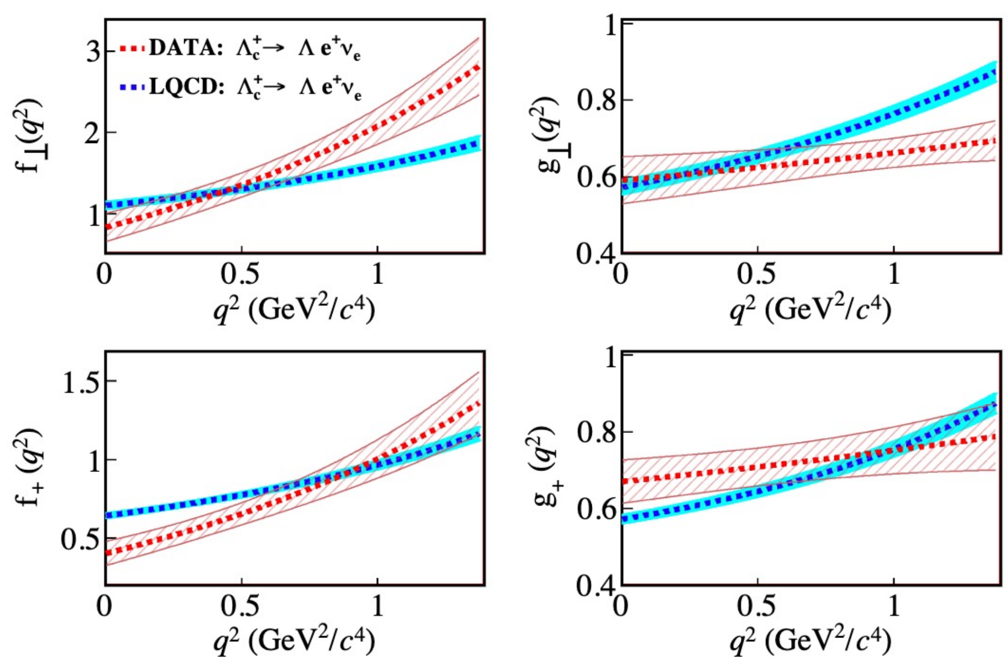
Better sensitivities on Λ_c^+ semi-leptonic decays

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

PRL129, 231803 (2022)



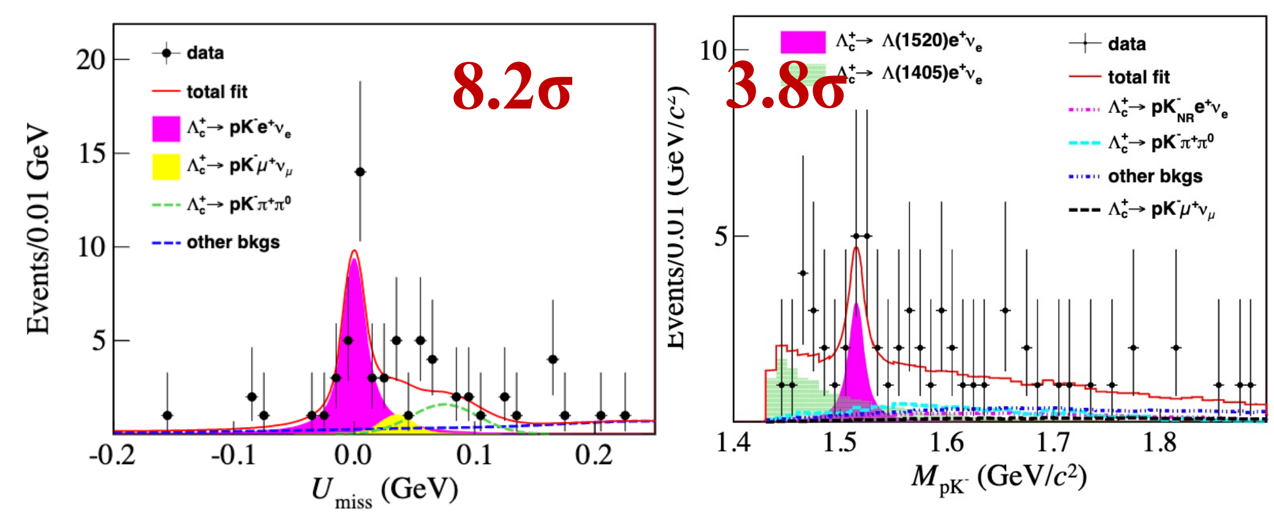
$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$



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)



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

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

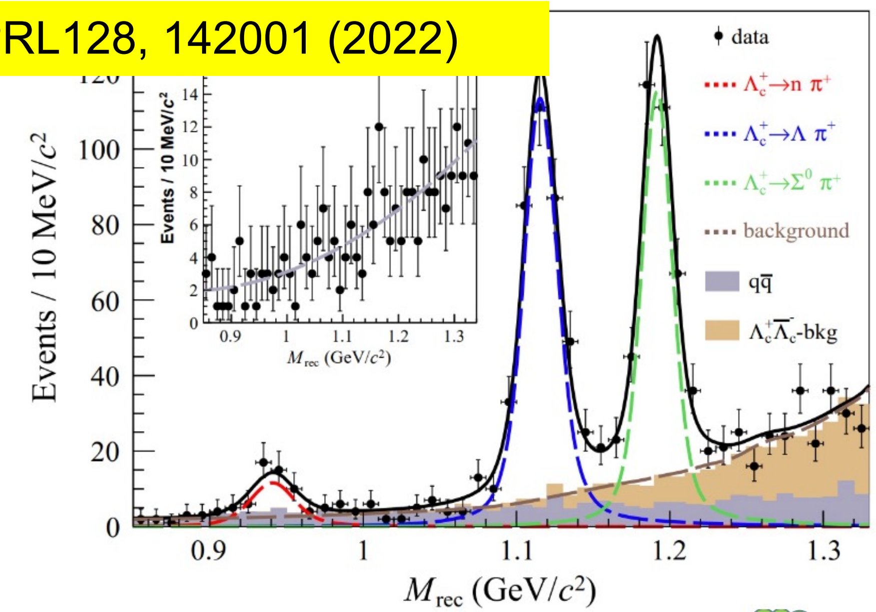
$B(\Lambda_c^+ \to \Lambda(1520) e^+ \nu) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$

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

Λ_c^+ Cabbibo-Suppressed hadronic decays

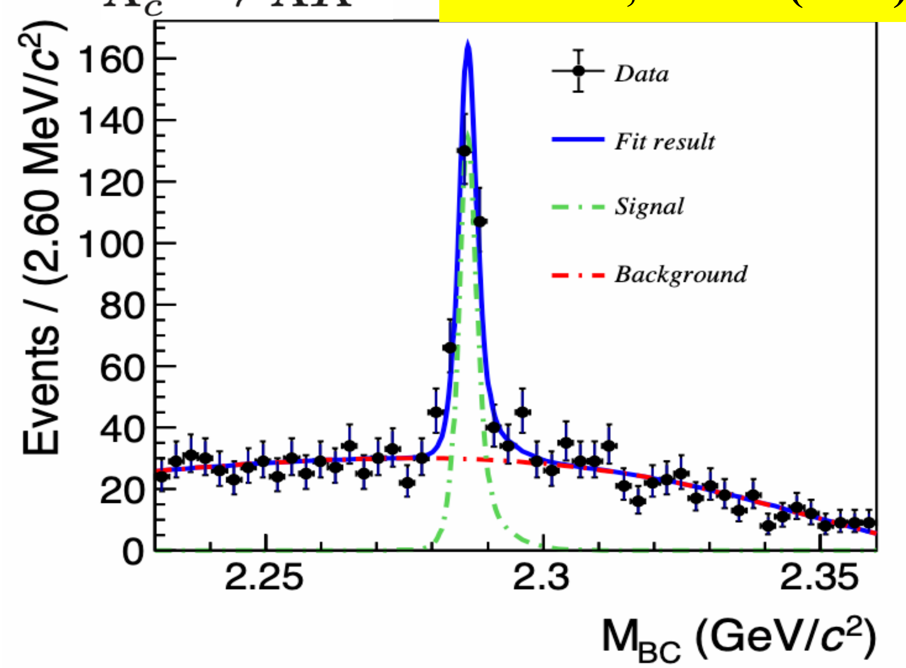
Observation of $\Lambda_c^+ \to n\pi^+$

PRL128, 142001 (2022)



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

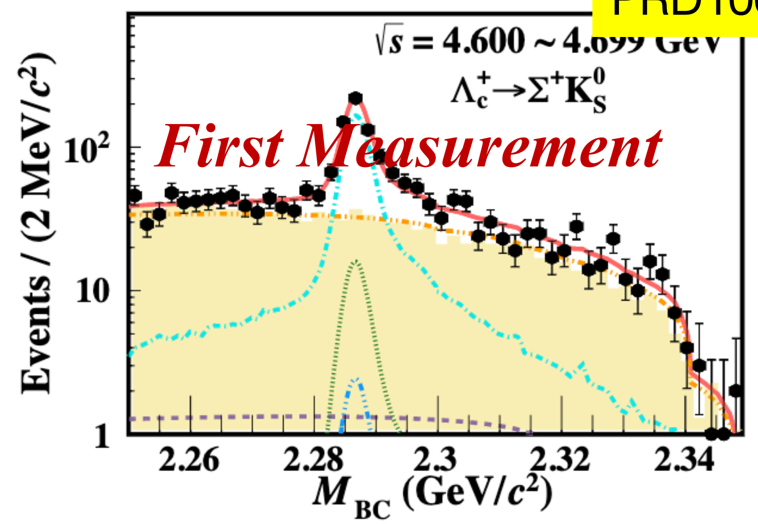
PRD106, 111101 (2022)

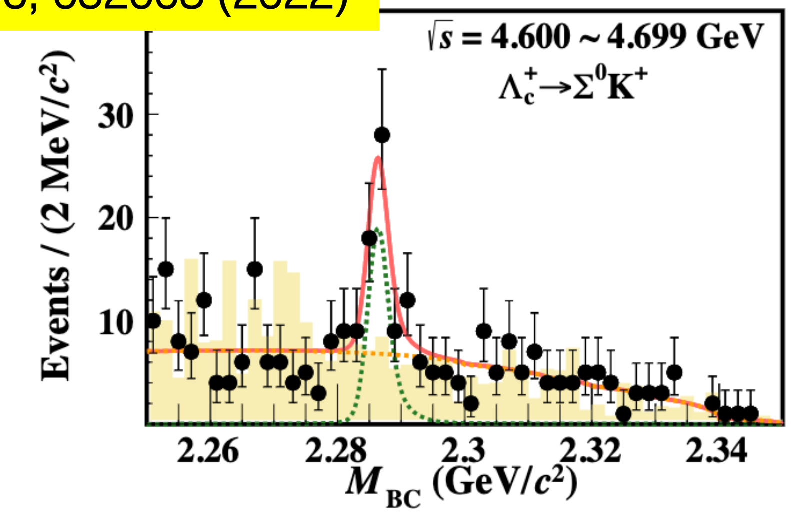


Many CS modes are measured with best precisions

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

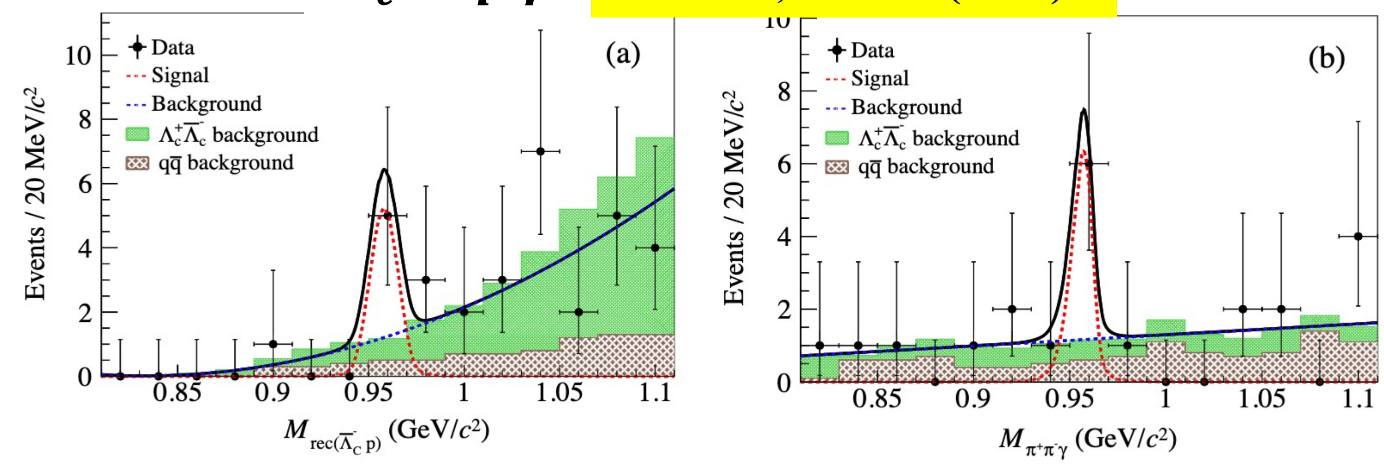
PRD106, 052003 (2022)



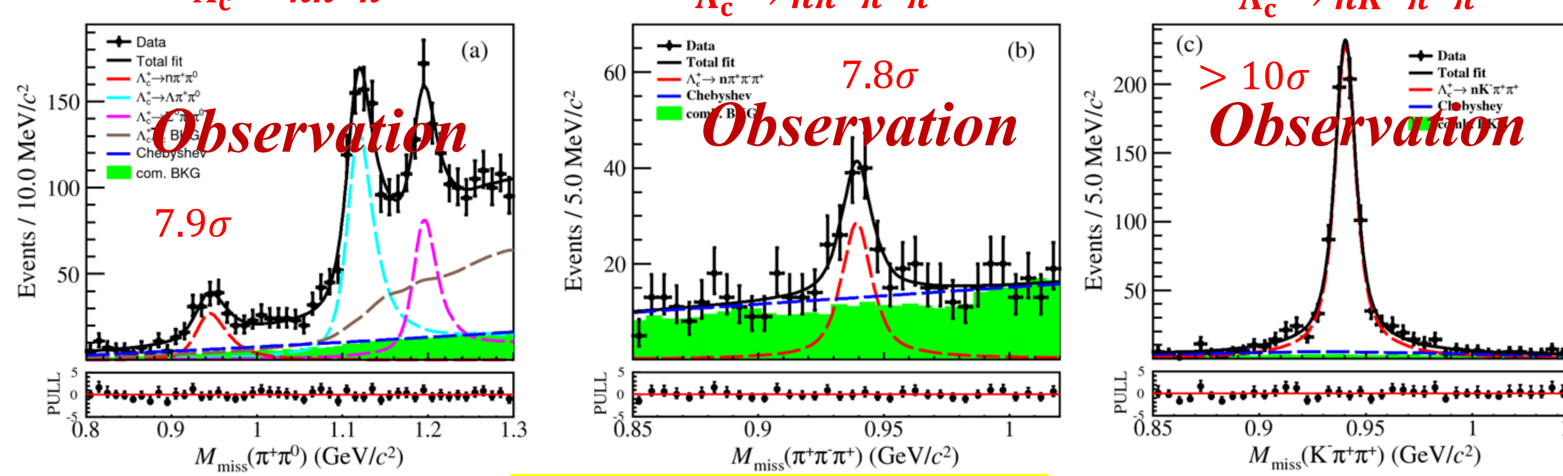


$\Lambda_c^+ \to p\eta'$

PRD106, 072002 (2022)



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

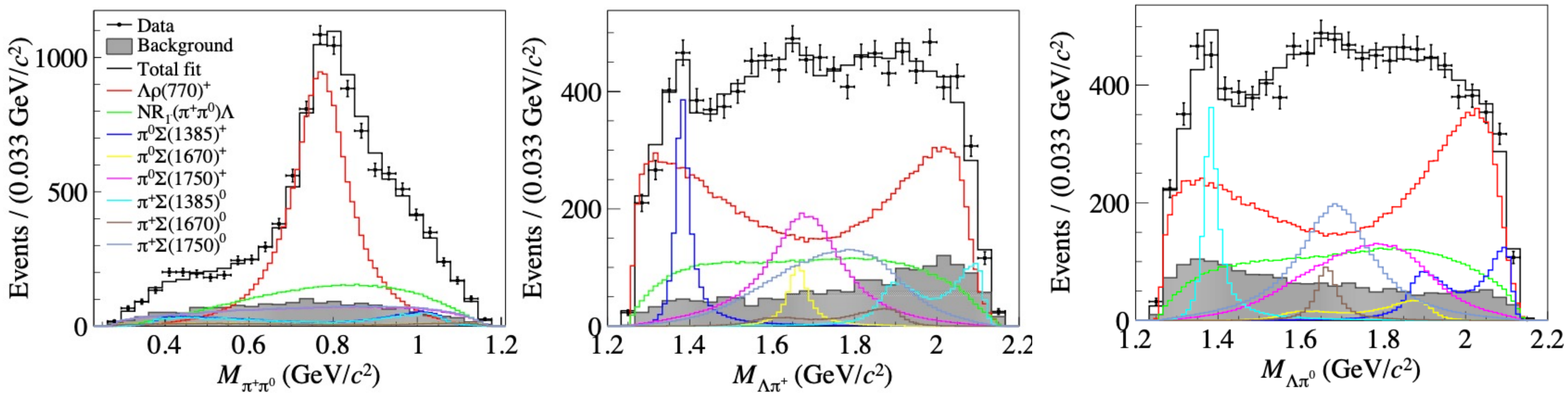


CPC47, 023001 (2023)

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!

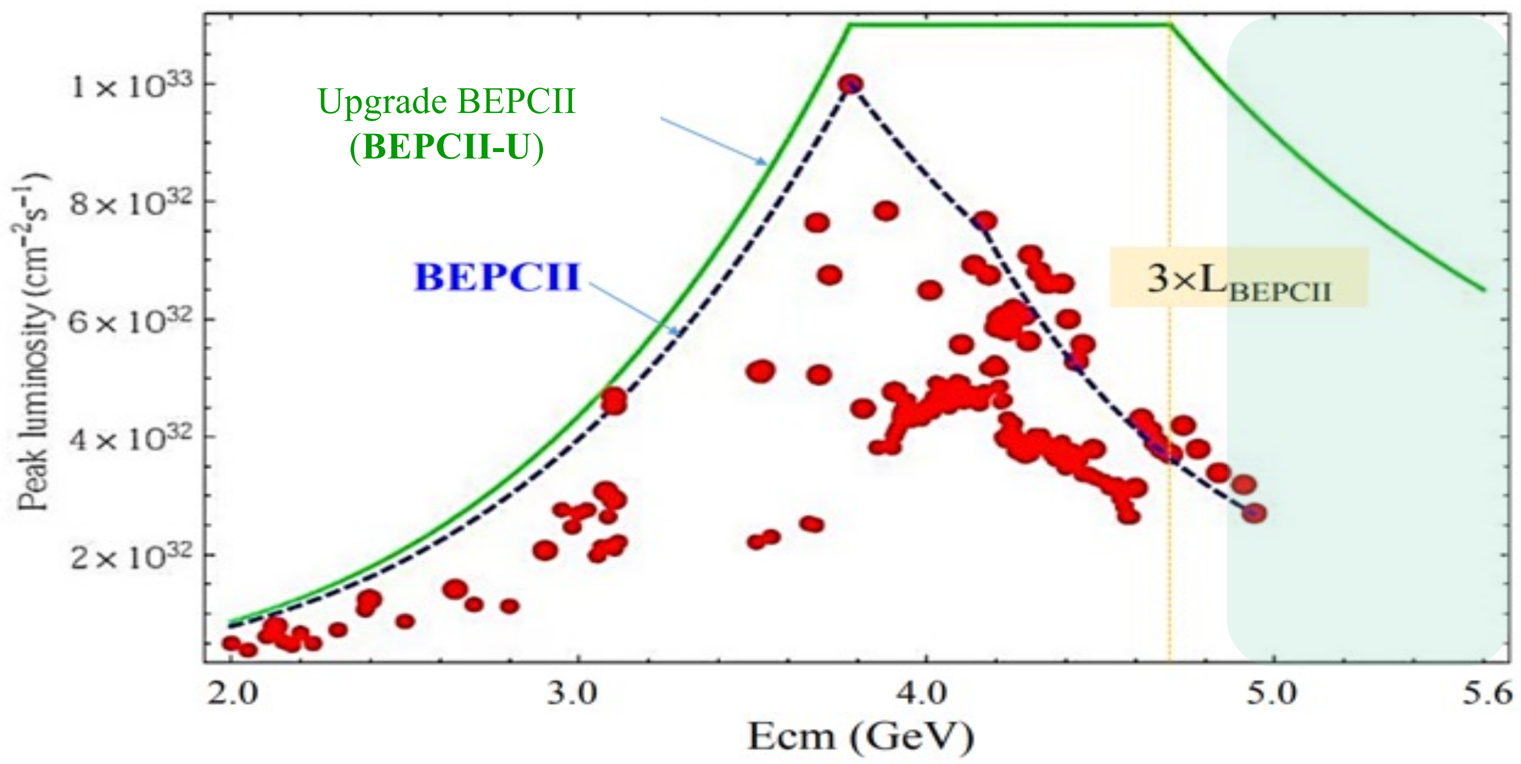
Phase III

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 in summer of 2024

- ✓ **Improve luminosity by 3 times higher than current BEPCII at 4.7 GeV**
- ✓ **Extend the maximum energy to 5.6 GeV**

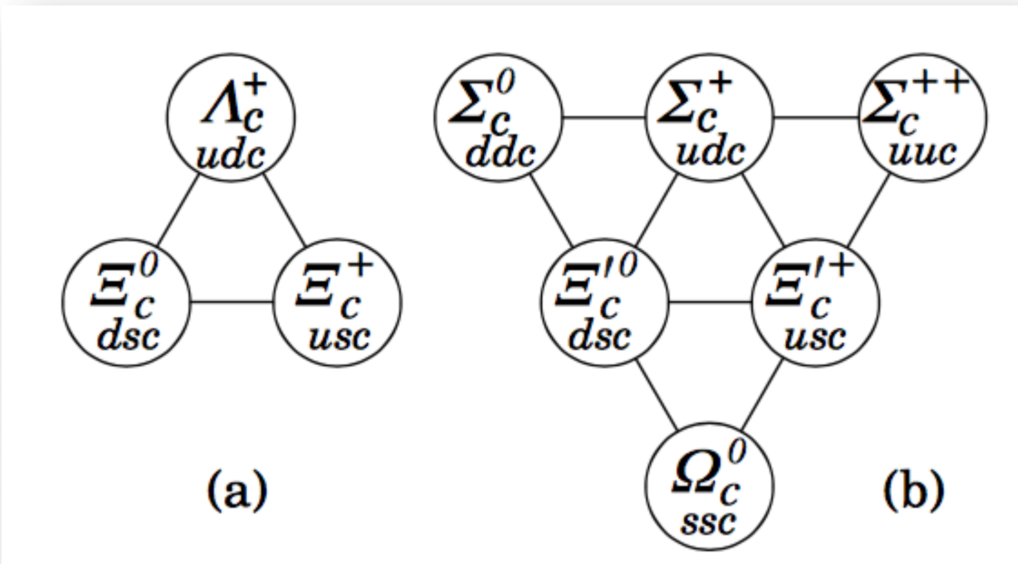


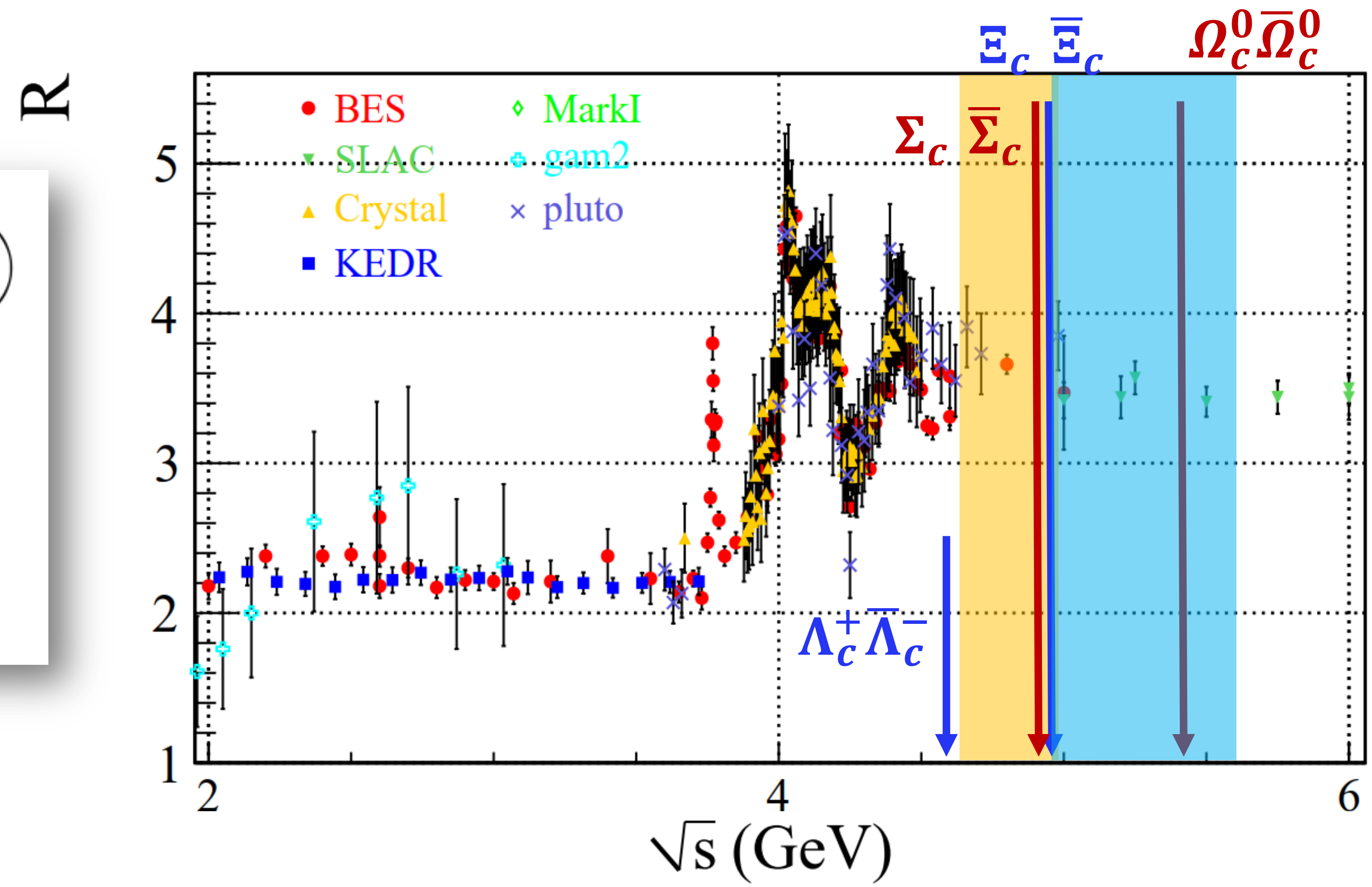
Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

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

Summary

- BEPCII/BESIII get capability to reach the energy (much) above 4.6 GeV
  - A new territory of studying charmed baryon has never been explored in direct production
- Near threshold production is unique to directly measure the Λ_c^+ decay properties
  - BESIII has published many high-impact Λ_c^+ results based on 6.4/fb data at 4.60 -4.95 GeV
  - The future larger data set for thorough exploration of Λ_c decays are unique and necessary: precision study
- BESIII's opportunity to map out the full picture of **Λ_c decay patterns, like Ds at CLEO-c**
- Opportunities to study the other charmed baryons (Σ_c, Ξ_c, Ω_c) in the BEPCII-U phase
  - To understand the QCD dynamics in the charmed baryons via threshold production

Thank you!