Charmed baryons from 4.6 to 5.6 GeV

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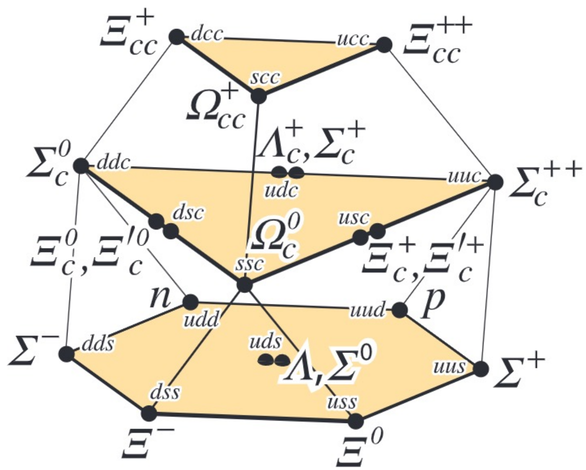
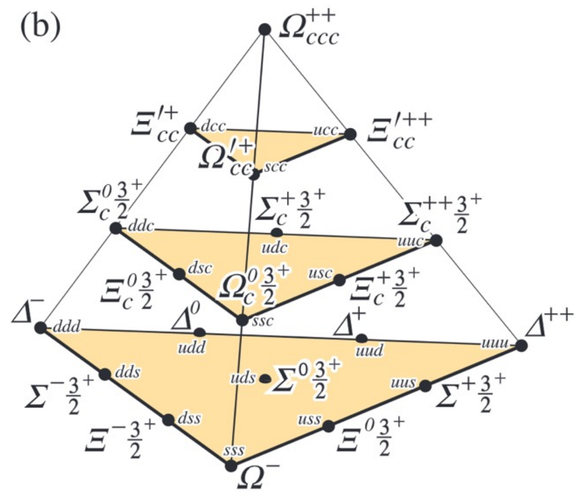
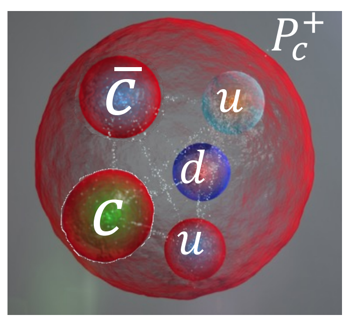
Outline

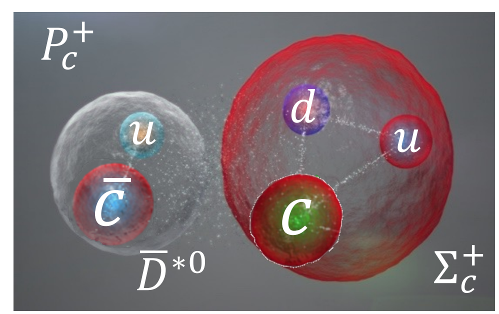
- **Open charm baryon**





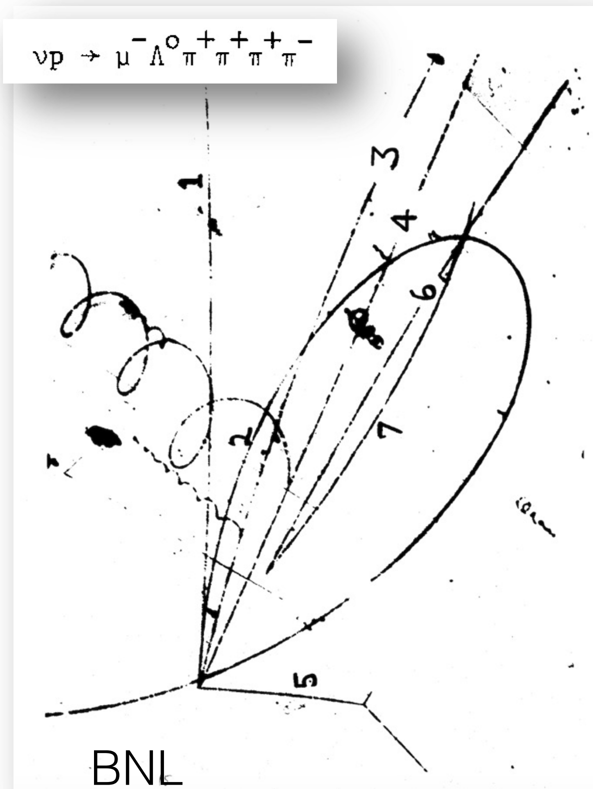
- **Hidden charm baryon**

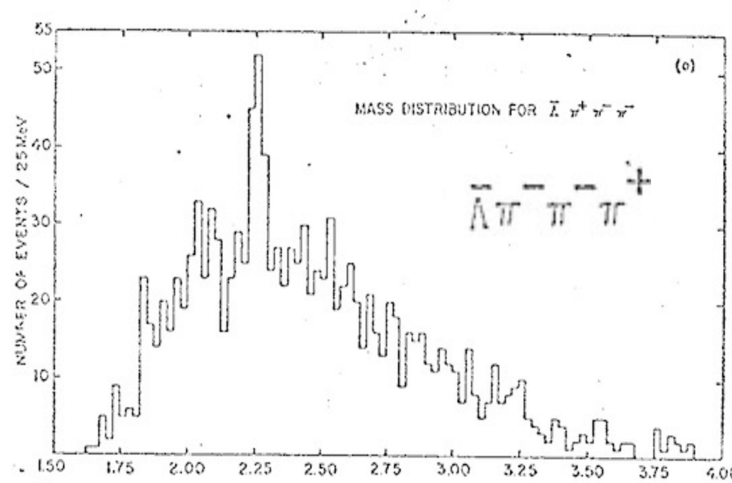


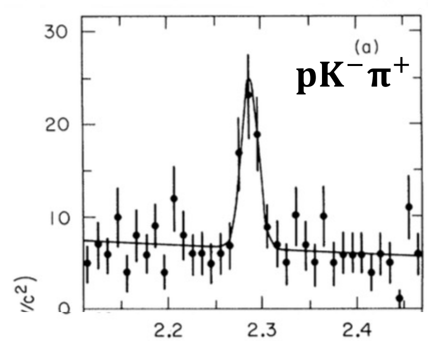


Discovery of the charmed heavy baryon

- Not exclusively clear about the first observation
- A number of experiments which published evidence for the charmed baryons beginning in 1975
  - ✓ Hint of *c*-ed baryon $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$ from neutrino 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

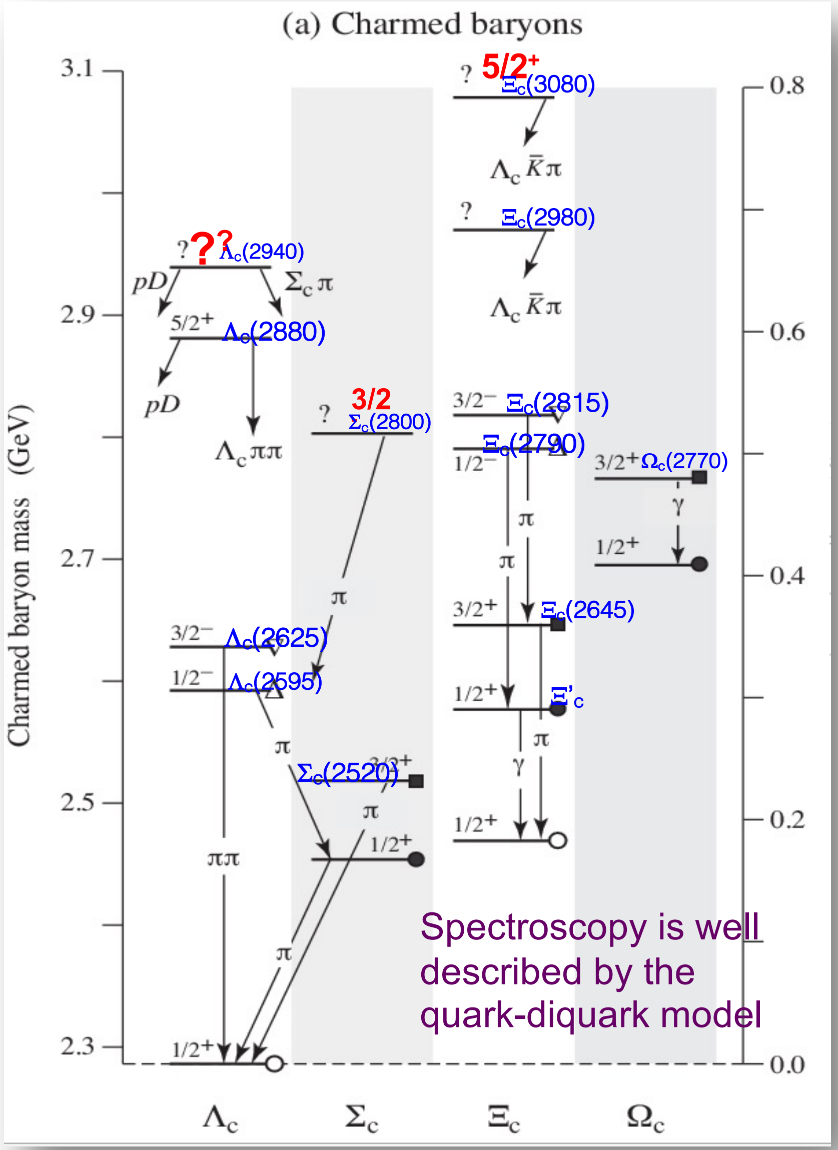
- Singly charmed baryons
  - ✓ Established ground states: Λ_c^+, Σ_c , $\Xi_c^{(\prime)}$, Ω_c
  - ✓ Excited states are being explored
- No observations of doubly or triply charmed baryons, except Ξ_{cc}^{++} in 2017 by LHCb

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

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

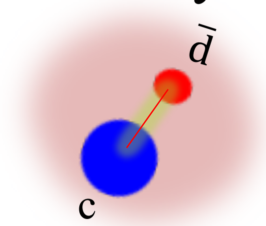
➢ Ξ_c : decay only weakly; first absolute BF measurement while large errors; most BFs were measured relative to $\Xi^-\pi^+(\pi^+)$

➢ Ω_c : decay only weakly; no absolute BF measured

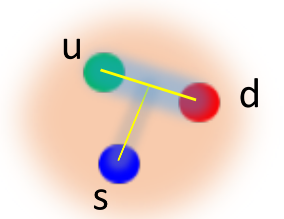


Why Λ_c^+ is interesting

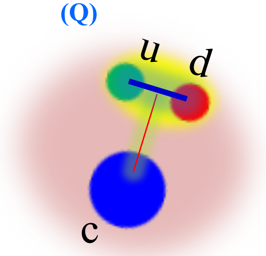
- An important intermediate particle:
  - corner stone of the charmed baryon spectra
  - many b-baryon decays to Λ_c
- Its decays reveal information of strong- and weak-interactions in charm region, complementary to D/Ds



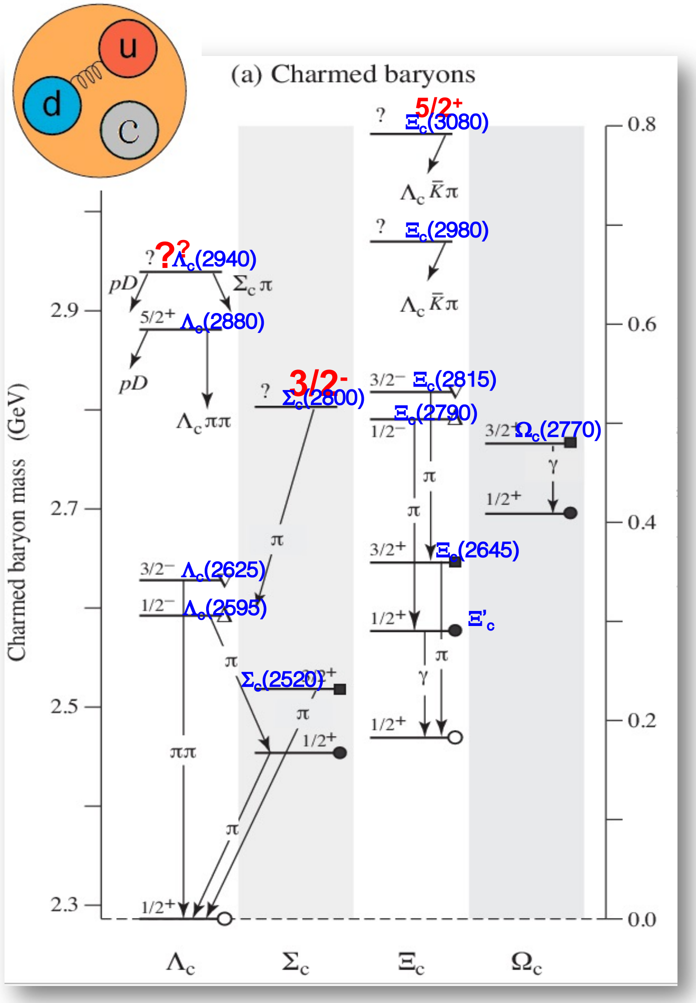
→ Charmed meson ($D^+[c\bar{d}]$)
$m_d \ll m_c$ → **quark + heavy quark**
(q) (Q)



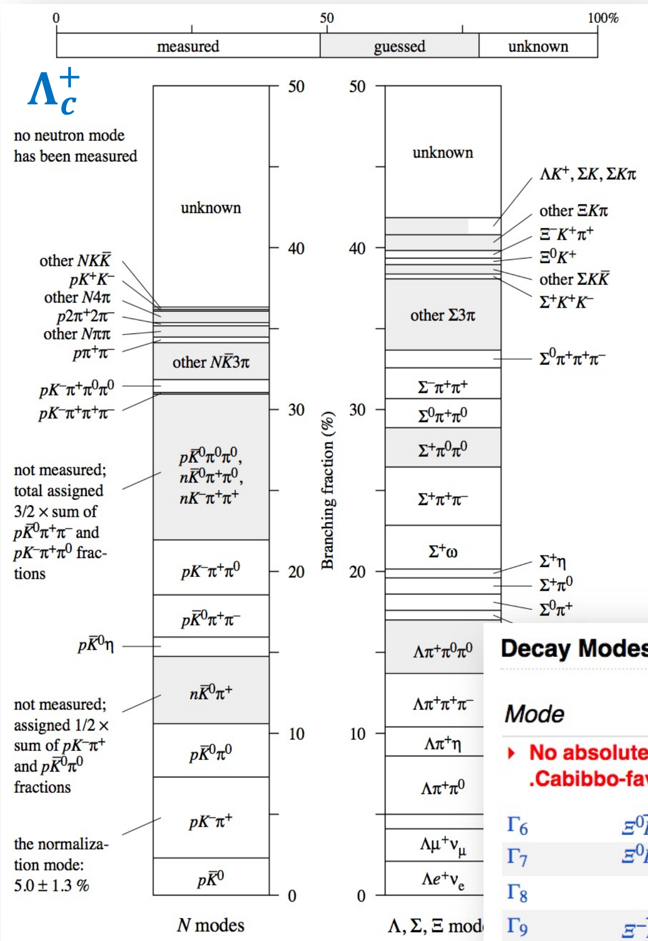
→ Strange baryons ($\Lambda[uds]$)
m_u, $m_d \approx m_s$ → **(qqq)** uniform



→ Charmed baryon ($\Lambda_c[udc]$)
m_u, $m_d \ll m_c$ → **diquark + quark**
(qq) (Q)



2015年之前的粲重子衰变信息



Ξ_c^+: relative to the decay of $\Xi^-2\pi^+$

	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured. The following are branching to $\Xi^-\pi^+$. Cabibbo-favored ($S=-2$) decays – relative to $\Xi^-\pi^+$		
Γ_1	$p2K_S^0$	0.087 ± 0.021
Γ_2	$\Lambda\bar{K}^0\pi^+$	
Γ_3	$\Sigma(1385)^+\bar{K}^0$	1.0 ± 0.5
Γ_4	$\Lambda K^-2\pi^+$	0.323 ± 0.033
Γ_5	$\Lambda\bar{K}^*(892)^0\pi^+$	< 0.16
Γ_6	$\Sigma(1385)^+K^-\pi^+$	< 0.23
Γ_7	$\Sigma^+K^-\pi^+$	0.94 ± 0.10
Γ_8	$\Sigma^+\bar{K}^*(892)^0$	0.81 ± 0.15
Γ_9	$\Sigma^0K^-2\pi^+$	0.27 ± 0.12
Γ_{10}	$\Xi^0\pi^+$	0.55 ± 0.16
Γ_{11}	$\Xi^-2\pi^+$	DEFINEDAS1
		< 0.10
		2.3 ± 0.7
		1.7 ± 0.5
		$2.3^{+0.7}_{-0.8}$
		0.07 ± 0.04
...ative to $\Xi^-\pi^+$		
		0.21 ± 0.04
		0.116 ± 0.030
		0.48 ± 0.20
		0.18 ± 0.09
		0.15 ± 0.06

Decay Modes Ω_c^0

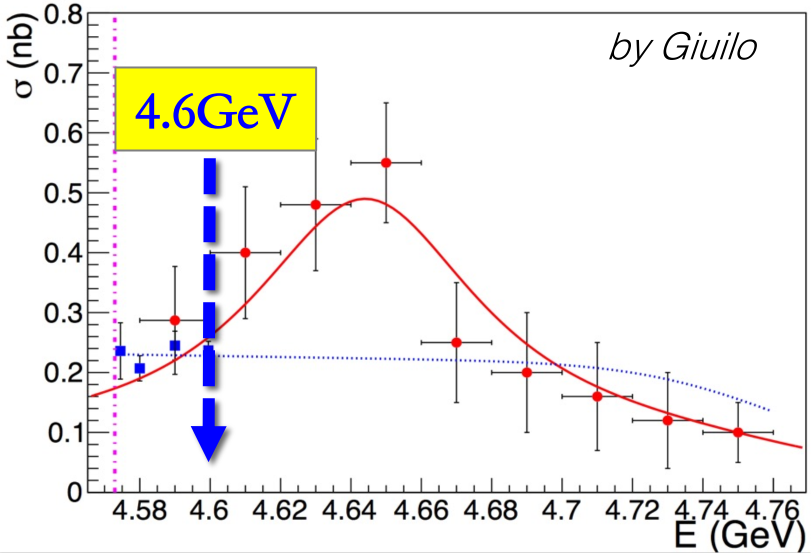
	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured. The following are branching ra... .Cabibbo-favored ($S=-3$) decays – relative to $\Omega^-\pi^+$		
Γ_6	$\Xi^0\bar{K}^0$	1.64 ± 0.29
Γ_7	$\Xi^0K^-\pi^+$	1.20 ± 0.18
Γ_8	$\Xi^0\bar{K}^{*0}$, $\bar{K}^{*0}\to K^-\pi^+$	0.68 ± 0.16
Γ_9	$\Xi^-\bar{K}^0\pi^+$	2.12 ± 0.28
Γ_{10}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{11}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0}\to\Xi^-\pi^+$	0.21 ± 0.06
Γ_{12}	$\Xi^-\bar{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{13}	$\Sigma^+K^-K^-\pi^+$	< 0.32
Γ_{14}	$\Lambda\bar{K}^0\bar{K}^0$	1.72 ± 0.35

Near threshold production at BESIII

In 2014, BESIII took (only!) 35 days to run at 4.6GeV and collected 567/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



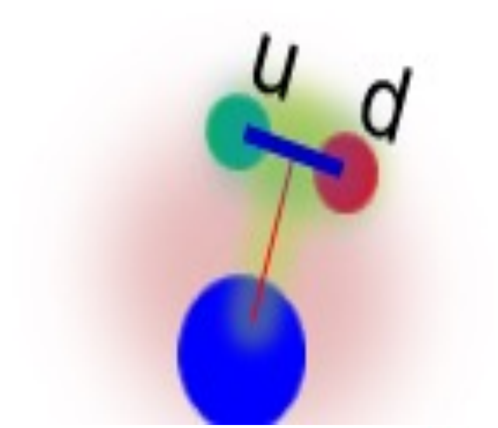
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

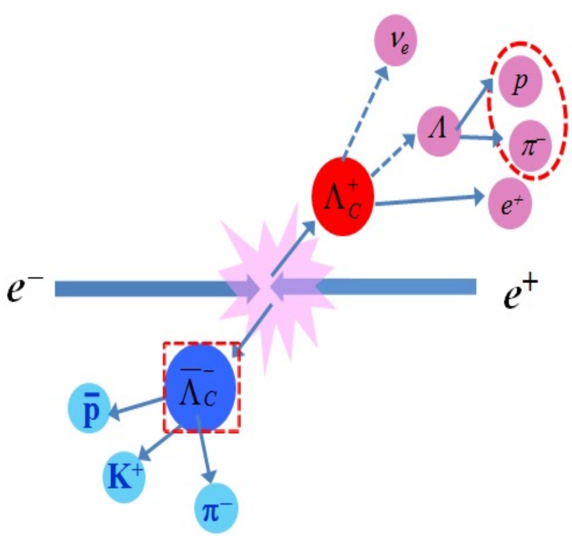
First time to systematically study charmed baryon at threshold!

The Λ_c^+ decays

16 publications (7 PRL)

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)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD100, 072004 (2019)
$\Lambda_c^+ \to pK_S\eta$	arXiv: 2012.11106

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

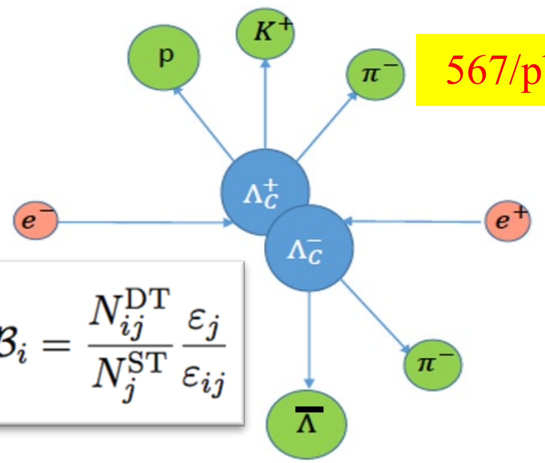
$\Lambda_c^+ \to \Lambda X$	PRL121, 062003 (2018)
$\Lambda_c^+ \to e^+X$	PRL 121 251801(2018)
$\Lambda_c^+ \to K_S^0X$	EPJC 80, 935 (2020)

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 ~25%; BELLE2014: δB/B ~4.7%
- Tagging technique @BESIII will provide *the most simple and straightforward measurement*



567/pb @ 4.6 GeV

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

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	

- The absolute BF can be obtained by the ratio of double tag yields to single tag yields.
- a global least square fit to 12 hadronic modes [Chinese 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

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

567/pb @ 4.6 GeV

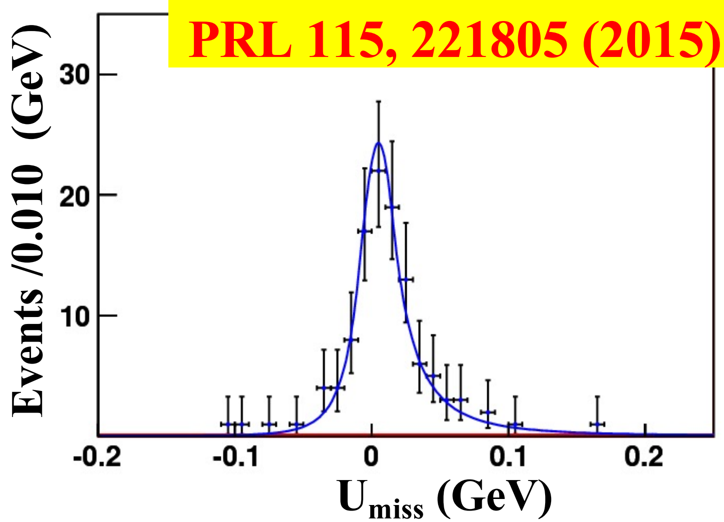
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is a $c \to s l^+ \nu_l$ dominated process.
- Urgently needed for LQCD calculations.
- No direct absolute measurement for $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ available.

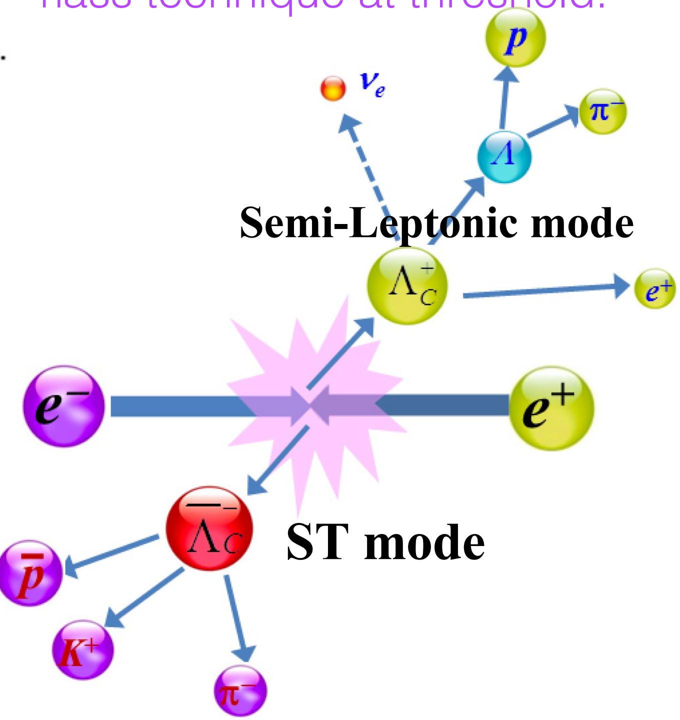
$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (2.1 \pm 0.6)\% \qquad \text{PDG 2014}$$

The tagging method and missing-mass technique at threshold.

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
- ➢ We also measure the muonic mode: stay tuned

The first Lattice calculation on Λ_c^+ 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)

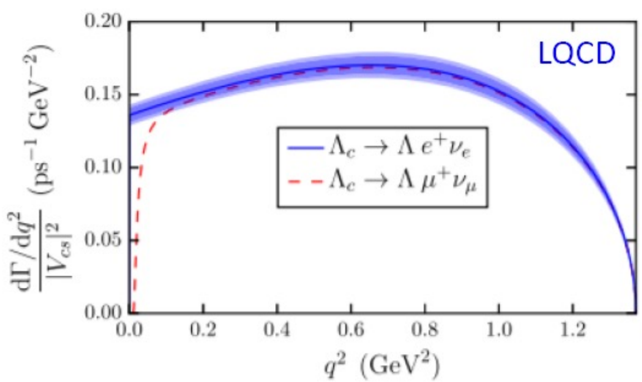
Triggered by BESIII

- 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

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

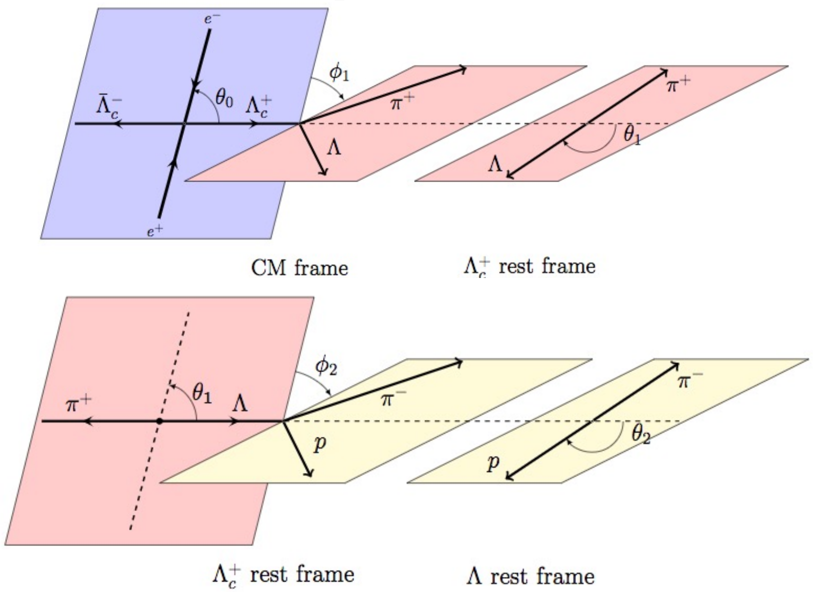
✓ More data on Λ_c^+ will be collected at BESIII

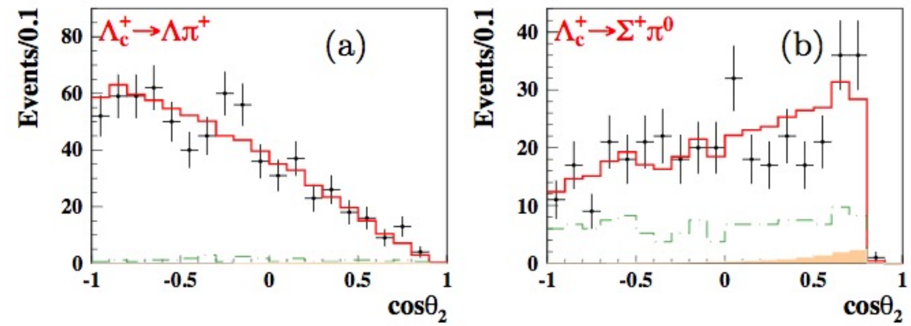
Λ_c decay asymmetries

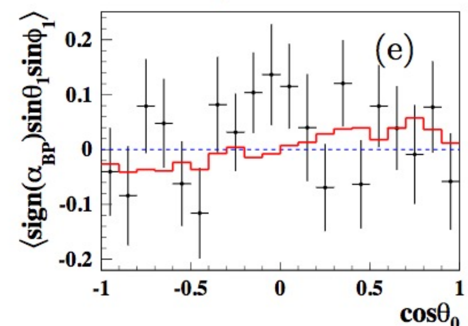
single tag method

PRD100, 072004 (2019)

- 4(6)-fold angular analysis of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ based on 567/pb data







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

$\sin\Delta\phi = -0.28 \pm 0.13 \pm 0.03$

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

Impacts on Λ_c decay data

D_s^+ BRANCHING RATIOS

A number of older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(e^+\text{semileptonic})/\Gamma_{total}$ Γ_1/Γ

This is the purely e^+ semileptonic branching fraction: the e^+ fraction from τ^+ decays has been subtracted off. The sum of our (non-τ) e^+ exclusive fractions — an $e^+\nu_e$ with an η, η', ϕ, K^0, or K^{*0} — is 5.99 ± 0.32 %.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
6.52±0.39±0.15	536 ± 29	[1] ASNER	10	CLEO	e^+e^- at 3774 MeV

[1] Using the D_s^+ and D^0 lifetimes, ASNER 10 finds that the ratio of the D_s^+ and D^0 semileptonic widths is 0.828 ± 0.051 ± 0.025.

$\Gamma(\pi^+\text{anything})/\Gamma_{total}$ Γ_2/Γ

Events with two π^+'s count twice, etc. But π^+'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
119.3±1.2±0.7	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^-\text{anything})/\Gamma_{total}$ Γ_3/Γ

Events with two π^-'s count twice, etc. But π^-'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
43.2±0.9±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^0\text{ anything})/\Gamma_{total}$ Γ_4/Γ

Events with two π^0's count twice, etc. But π^0's from $K_S^0 \to \pi^0\pi^0$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
123.4±3.8±5.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^-\text{anything})/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
18.7±0.5±0.2	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^+\text{anything})/\Gamma_{total}$ Γ_6/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
28.9±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K_S^0\text{ anything})/\Gamma_{total}$ Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
19.0±1.0±0.4	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta\text{ anything})/\Gamma_{total}$ Γ_8/Γ

This ratio includes η particles from η' decays.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
29.9±2.2±1.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
23.5±3.1±2.0	674 ± 91	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(\omega\text{ anything})/\Gamma_{total}$ Γ_9/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
6.1±1.4±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta'\text{ anything})/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
10.3±1.4 OUR AVERAGE	Error includes scale factor of 1.1.				
8.8±1.8±0.5	68	ABLIKIM	15Z	BES3	482 pb^{-1}, 4009 MeV
11.7±1.7±0.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.7±1.9±0.8	68	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(f_0(980)\text{ anything}, f_0 \to \pi^+\pi^-)/\Gamma_{total}$ Γ_{11}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\phi\text{ anything})/\Gamma_{total}$ Γ_{12}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
15.7±0.8±0.6		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
16.1±1.2±1.1	398 ± 27	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(K^+K^-\text{anything})/\Gamma_{total}$ Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
15.8±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

CLEOc dominants the D_s Branching Fraction measurements. (Sys. Err. Dominates CF modes. Many SCS&DCS modes observed.)

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1992 edition (Physical Review **D45**, 1 June, Part II) or in earlier editions.

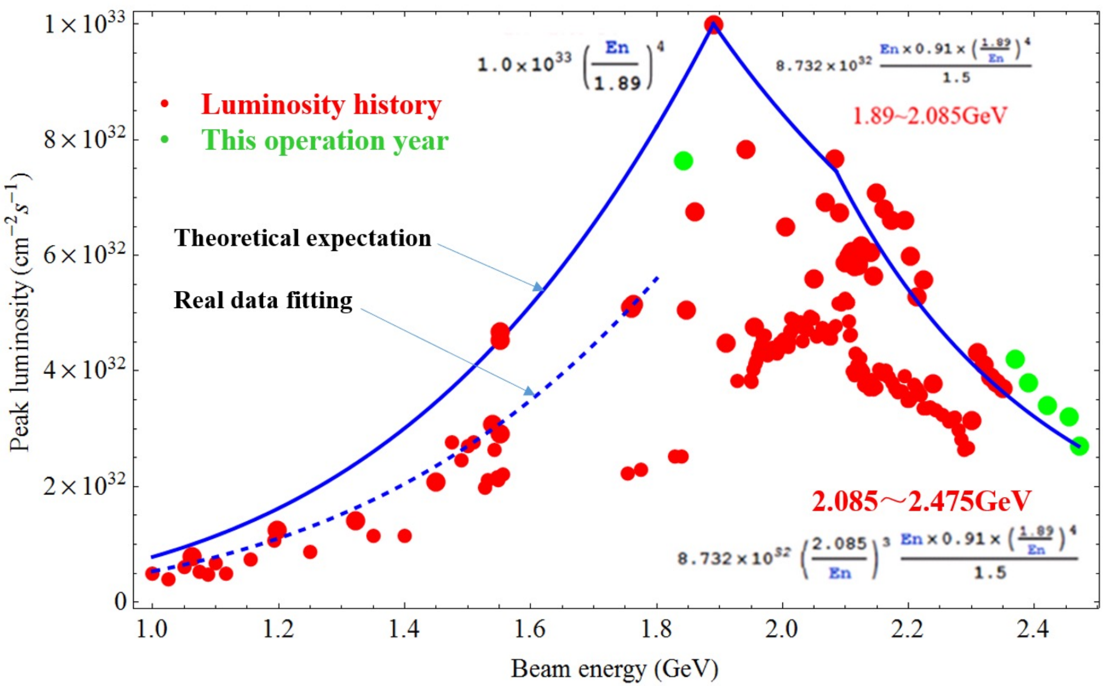
AAIJ	19AG	PR D100 032001	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	19AX	PR D100 072004	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19X	CP C43 083002	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19Y	PR D99 032010	M. Ablikim *et al.*	(BESIII Collab.) ★
AAIJ	18N	PR D97 091101	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18R	JHEP 1803 182	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18V	JHEP 1803 043	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	18AF	PRL 121 251801	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18E	PRL 121 062003	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18Y	PL B783 200	M. Ablikim *et al.*	(BESIII Collab.) ★
BERGER	18	PR D98 112006	M. Berger *et al.*	(BELLE Collab.)
ABLIKIM	17D	PL B767 42	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17H	PRL 118 112001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Q	PR D95 111102	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Y	PL B772 388	M. Ablikim *et al.*	(BESIII Collab.) ★
PAL	17	PR D96 051102	B. Pal *et al.*	(BELLE Collab.)
ABLIKIM	16	PRL 116 052001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	16U	PRL 117 232002	M. Ablikim *et al.*	(BESIII Collab.) ★
YANG	16	PRL 117 011801	S.B. Yang *et al.*	(BELLE Collab.)
ABLIKIM	15Y	PRL 115 221805	M. Ablikim *et al.*	(BESIII Collab.) ★
ZUPANC	14	PRL 113 042002	A. Zupanc *et al.*	(BELLE Collab.)
LEES	11G	PR D84 072006	J.P. Lees *et al.*	(BABAR Collab.)

Yet unknowns

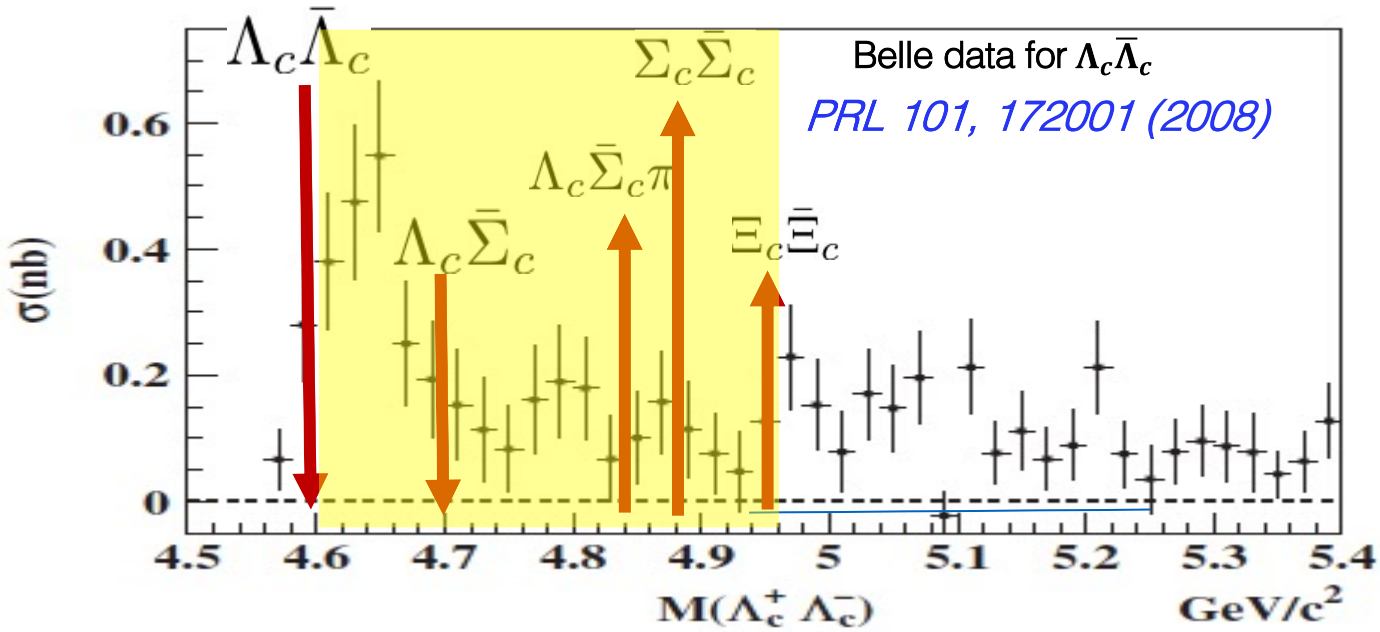
- Many of the following modes are not measured (~40%)
  - most of the semileptonic (SL) modes
  - the singly Cabibbo-Suppressed (CS) and doubly CS hadronic modes
  - the neutron- and K_L-involved channels
- Amplitude analysis of the three- and four-body decays
  - important to study the excited hyperons
  - to study the decay types of $B\left(\frac{1}{2}^+\right)V$ and $B(\frac{3}{2}^+)P$
  - not much have been done yet
- Accessible information via the energy-dependence production of Λ_c^+
  - cross section, form factor
  - polarization
  - decay asymmetry, CPV search

BEPCII upgrade

- Increase of beam energy 2.30→2.35(2018)→2.45 GeV(2020')
  - → 2.35 GeV in 2018 summer (done)
  - → 2.45 GeV in 2020 summer (done, → 2.475 GeV)
    change ISPB (Interaction region SePtum Bending) magnet
- Top-up injection (done)
  - Data taking efficiency increases by 20~30%



Data samples



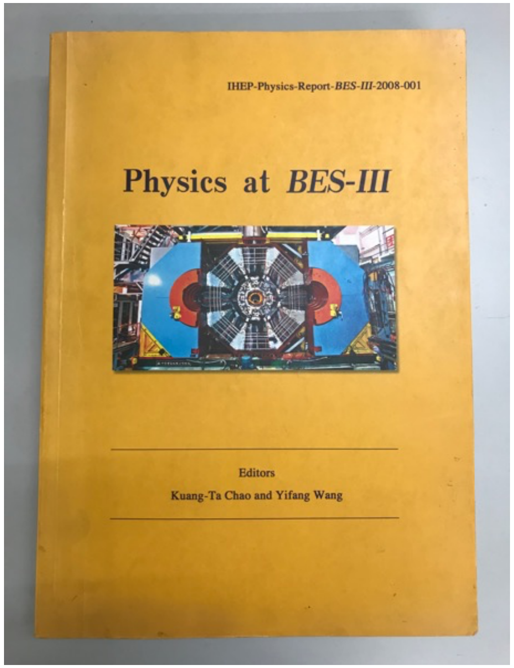
Available data for charmed baryon

- ✓ 0.567 fb^{-1} at 4.6 GeV (35 days in 2014)
- ✓ 3.8 fb^{-1} scan at 4.61, 4.63, 4.64, 4.66, 4.68, 4.7 GeV (186 days in 2020)
- ✓ 2 fb^{-1} scan at 4.74, 4.78, 4.84, 4.91, 4.95 GeV (99 days in 2021)

~ 10x Λ_c data that those at 4.6 GeV

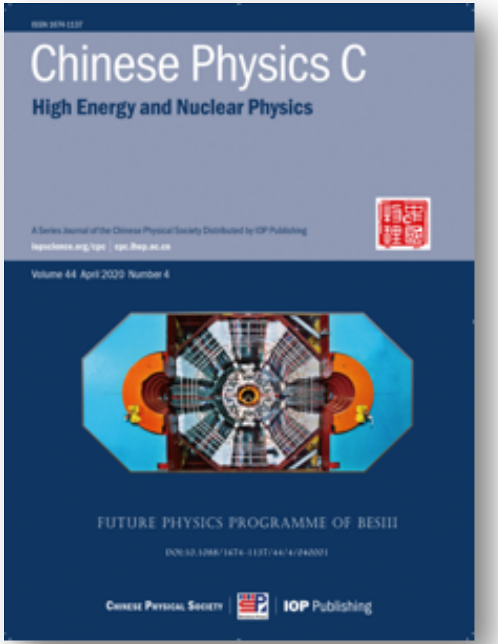
BESIII Physics

2009年: BESIII物理黄皮书



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

2020年: BESIII 物理白皮书



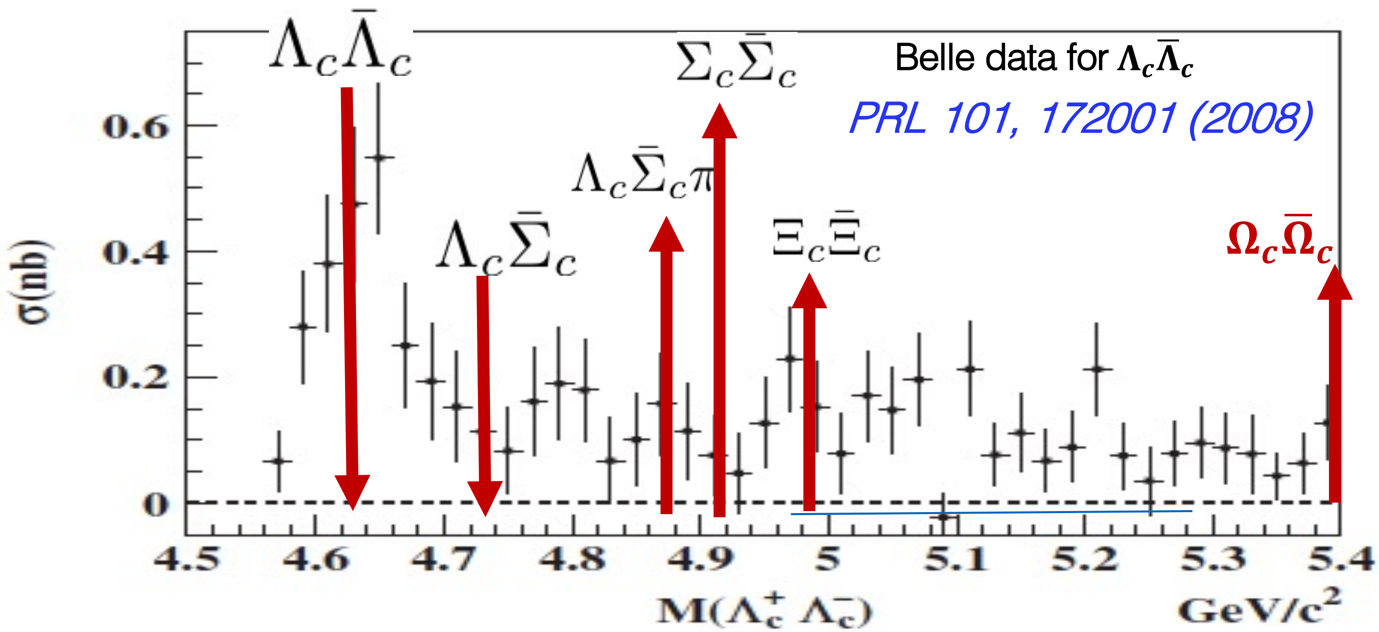
Chin. Phys. C 44, 040001 (2020)
doi:10.1088/1674-1137/44/4/040001
[arXiv:1912.05983 [hep-ex]].

Future data taking proposals

a reference table (need to be modified according to future machine status, especially for Ξ_c and Ω_c stuides)

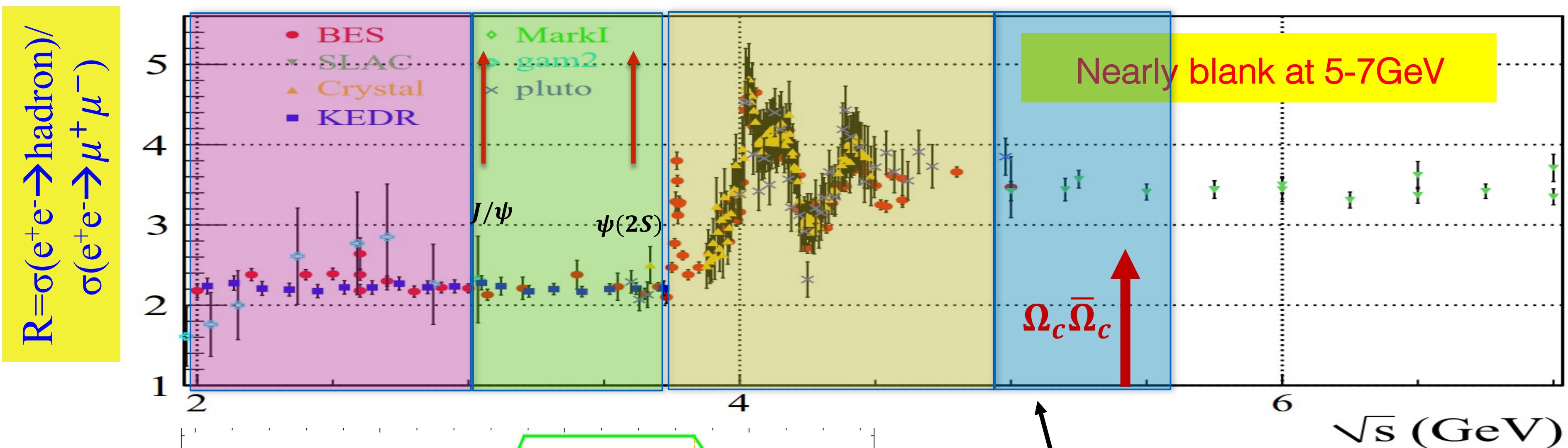
Energy	Physics motivations	Current data	Expected final data	T_C / T_U
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ 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

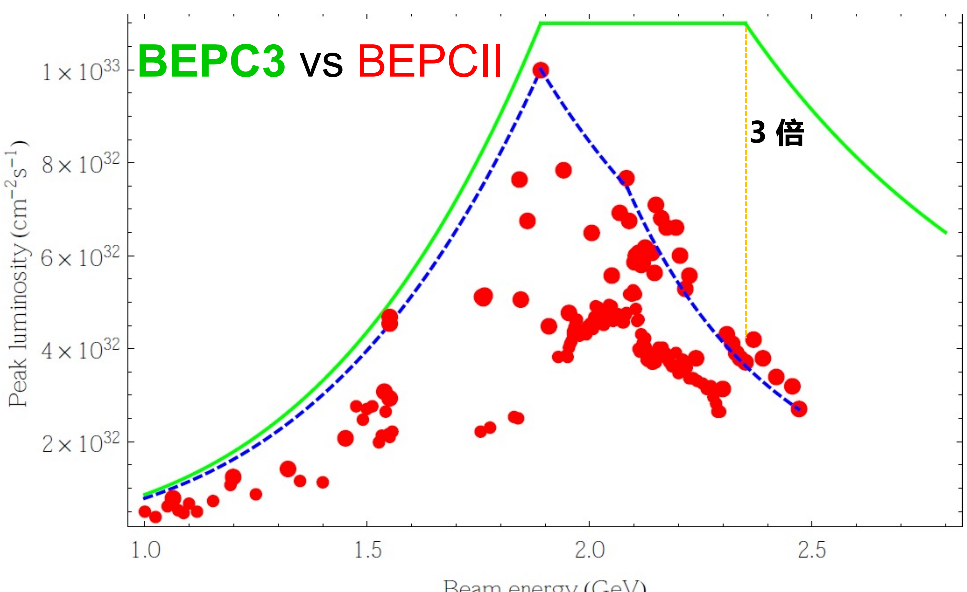
in total 18 /fb: now we have 6.3 /fb (days)



Proposal of the BEPC3

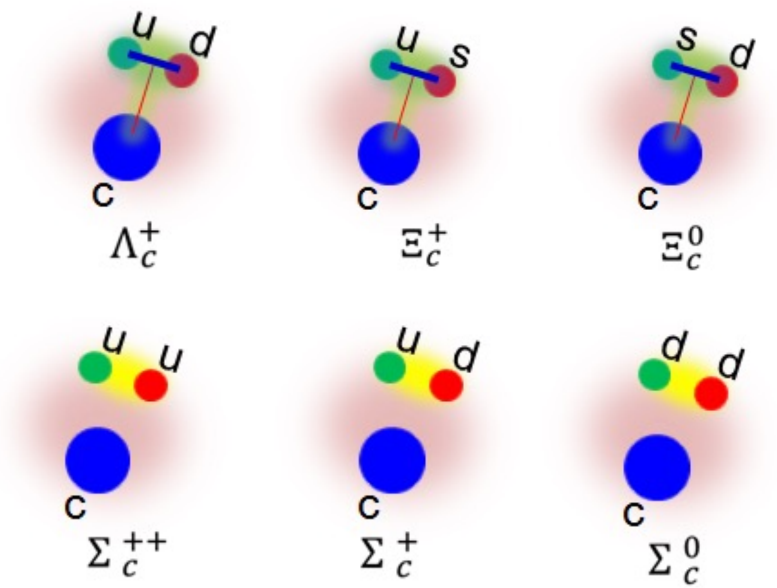
- Planning the next generation of BEPC3: the optimized energy is 2.35 GeV with luminosity 3 times higher than BEPCII.

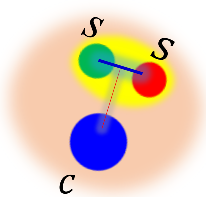




4.95 ~ 5.6 GeV: new energy coverage of BEPC3

Heavier charmed baryons





Ω_c^+

	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	—	$\Omega_c^0\gamma$

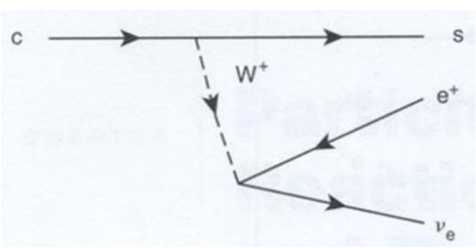
Energy thresholds

- ✓ $\Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
- ✓ $\Lambda_c^+\bar{\Sigma}_c\ \pi$ 4.88 GeV
- ✓ $\Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
- ✓ $\Xi_c\ \bar{\Xi}_c$ 4.95 GeV
- ✓ $\Omega_c^0\bar{\Omega}_c^0$ 5.4 GeV

Prospects on the Λ_c results

4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$

	Leading hadronic decay	Typical two-body decay	Leading SL decay
Λ_c^+	$\mathcal{B}(K^-p\pi^+) =$ 2014: $(5.0 \pm 1.3)\%$ (26%) 2017(w/ BESIII): $(6.35 \pm 0.33)\%$ (5.2%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}} < 2\%$	$\mathcal{B}(K_S^0 p) =$ 2014: $(1.2 \pm 0.3)\%$ (26%) BESIII: $(1.52 \pm 0.08)\%$(5.6%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}} < 2\%$	$\mathcal{B}(\Lambda e^+\nu_e) =$ 2014: $(2.1 \pm 0.6)\%$ (29%) BESIII: $(3.63 \pm 0.43)\%$ (12%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}} \sim 3.3\%$
D^0	$\mathcal{B}(K^-\pi^+) = (3.89 \pm 0.04)\%$ (1.0%)	$\mathcal{B}(K_S^0\pi^0) = (1.19 \pm 0.04)\%$ (3.4%)	$\mathcal{B}(K^-e^+\nu_e) = (3.53 \pm 0.03)\%$ (0.8%)
D^+	$\mathcal{B}(K^-\pi^+\pi^+) = (8.98 \pm 0.28)\%$ (3.1%)	$\mathcal{B}(K_S^0\pi^+) = (1.47 \pm 0.08)\%$ (5.4%)	$\mathcal{B}(K_S^0 e^+\nu_e) = (4.41 \pm 0.07)\%$ (1.5%)
D_s^+	$\mathcal{B}(K^-K^+\pi^+) = (5.45 \pm 0.17)\%$ (3.8%)	$\mathcal{B}(K_S^0 K^+) = (1.40 \pm 0.05)\%$ (3.6%)	$\mathcal{B}(\phi e^+\nu_e) = (2.39 \pm 0.23)\%$ (9.6%)



Mode	Expected rate (%)	Relative uncertainty (%)
$\Lambda_c^+ \to \Lambda l^+\nu$	3.6 [94, 95]	3.3
$\Lambda_c^+ \to \Lambda^* l^+\nu$	0.7 [96, 97]	10
$\Lambda_c^+ \to NKe^+\nu_e$	0.7 [96]	10
$\Lambda_c^+ \to \Sigma\pi l^+\nu$	0.7 [96]	10
$\Lambda_c^+ \to ne^+\nu_e$	0.2 [94, 98, 99]	17

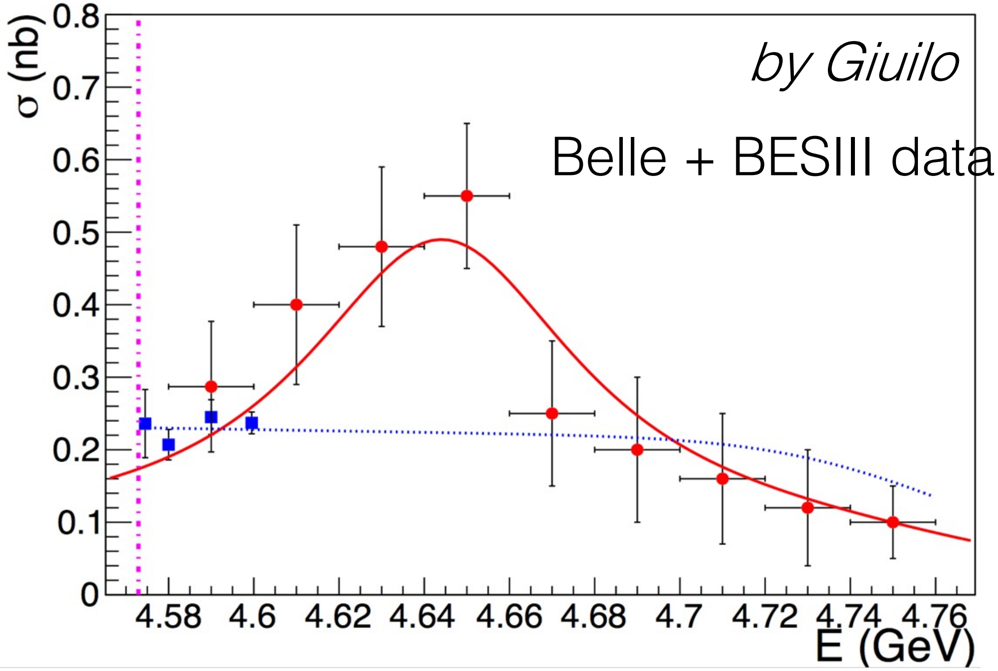
first measurement (for the modes with relative uncertainty 10, 10, 10, 17)

Precision study of the *c*-ed baryon decay

Precision study of the charmed baryon (Λ_c, Ξ_c and Ω_c) decays to help developing more reliable QCD-derived models in charm sector

- Hadronic decays:
  to explore as-yet-unmeasured channels and understand full picture of intermediate structures in B_c decays, esp., those with neutron/Σ/Ξ particles
- Semi-leptonic decays:
  to test LQCD calculations and LFU
- CPV in charmed baryon: BP and BV two-body decay asymmetry, charge-dependent rate of SCS
- Charmed Baryons Spectroscopy : (63 P-wave states from QM, less than 20 are observed!)
- Rare decays: LFV, BNV, FCNC

Lineshape of the Λ_c pairs and it's form factor



- Some tension between BELLE and BESIII data
- BESIII data above 4.6 GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold
- Accessible to the form factor and polarization of the Λ_c at higher Q^2

BESIII

Studies on the Σ_c

- Production via $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ above 4.88 GeV (or $\Sigma_c\ \bar{\Sigma}_c$ above 4.91 GeV)

Decay (MeV)	Expt. [3]	HHChPT [10]	Tawfiq et al. [25]	Ivanov et al. [26]	Huang et al. [27]	Albertus et al. [28]
$\Sigma_c^{++} \to \Lambda_c^+\pi^+$	$1.89^{+0.09}_{-0.18}$	input	1.51 ± 0.17	2.85 ± 0.19	2.5	2.41 ± 0.07
$\Sigma_c^{+} \to \Lambda_c^+\pi^0$	< 4.6	$2.3^{+0.1}_{-0.2}$	1.56 ± 0.17	3.63 ± 0.27	3.2	2.79 ± 0.08
$\Sigma_c^{0} \to \Lambda_c^+\pi^-$	$1.83^{+0.11}_{-0.19}$	$1.9^{+0.1}_{-0.2}$	1.44 ± 0.16	2.65 ± 0.19	2.4	2.37 ± 0.07

- Precise determination of $\Gamma(\Sigma_c^+ \to \Lambda_c^+\pi^0)$ can be used for for testing heavy quark symmetry and chiral symmetry
  Wise; Yan et al.; Burdman, Donoghue ('92)
- Search for radiative decay $\Sigma_c^+ \to \Lambda_c^+\gamma$

Decay	HHChPT +QM	Ivanov et al.	Bañuls et al.	Tawfiq et al.	Dey et al.	Majethiya et al.	Fayyazuddin et al.	Aliev et al.
$\Sigma_c^+ \to \Lambda_c^+\gamma$	88	60.7 ± 1.5		87	98.7	$60.1 - 85.6$	89.0	

(keV)

Cross sections for $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ and $\Sigma_c\ \bar{\Sigma}_c$

- **$e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ above 4.74 GeV:** An interesting isospin violating process to understand the QCD dynamics at charm sector
  - ✓ A cross section scan around 4.74 GeV will be useful for comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and $\Sigma_c^+\bar{\Sigma}_c^-$
  - ✓ $\sigma(\Lambda_c^+\bar{\Sigma}_c^-)/\sigma(\Lambda_c^+\bar{\Lambda}_c^-)$ v.s. $\sigma(\Lambda\bar{\Sigma})/\sigma(\Lambda\bar{\Lambda})$
    ➔ vaccum pol. to $c\bar{c}$ v.s. $s\bar{s}$
  - ✓ If observed, study the polarizations and form factors

- **$e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ above 4.91 GeV:**
  - ✓ Cross section comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
    ➔ good diquark v.s. bad diquark
  - ✓ Study the polarizations and form factors in $e^+e^- \to \Sigma_c^0\bar{\Sigma}_c^0$ and $\Sigma_c^+\bar{\Sigma}_c^-$

BESIII Ξ_c (usc/dsc): decay information is limited

- *No absolute BFs have been measured/calculated until 2019*
- *Belle measured abs. BFs in 2019, but uncertainties are large: δB ~30%*

Ξ_c^+: relative to the decay of $\Xi^- 2\pi^+$

	Mode	Fraction (Γ_i/Γ)
	No absolute branching fractions have been measured.The following are branching to $\Xi^- \pi^+$ .Cabibbo-favored ($S=-2$) decays — relative to $\Xi^- \pi^+$	
Γ_1	$p 2 K_S^0$	0.087 ± 0.021
Γ_2	$\Lambda \overline{K}^0 \pi^+$	
Γ_3	$\Sigma(1385)^+ \overline{K}^0$	1.0 ± 0.5
Γ_4	$\Lambda K^- 2\pi^+$	0.323 ± 0.033
Γ_5	$\Lambda \overline{K}^*(892)^0 \pi^+$	< 0.16
Γ_6	$\Sigma(1385)^+ K^- \pi^+$	< 0.23
Γ_7	$\Sigma^+ K^- \pi^+$	0.94 ± 0.10
Γ_8	$\Sigma^+ \overline{K}^*(892)^0$	0.81 ± 0.15
Γ_9	$\Sigma^0 K^- 2\pi^+$	0.27 ± 0.12
Γ_{10}	$\Xi^0 \pi^+$	0.55 ± 0.16
Γ_{11}	$\Xi^- 2\pi^+$	DEFINEDAS1
Γ_{12}	$\Xi(1530)^0 \pi^+$	< 0.10
Γ_{13}	$\Xi^0 \pi^+ \pi^0$	2.3 ± 0.7
Γ_{14}	$\Xi^0 \pi^- 2\pi^+$	1.7 ± 0.5
Γ_{15}	$\Xi^0 e^+ \nu_e$	$2.3^{+0.7}_{-0.8}$
Γ_{16}	$\Omega^- K^+ \pi^+$	0.07 ± 0.04
	Cabibbo-suppressed decays — relative to $\Xi^- \pi^+$	
Γ_{17}	$p K^- \pi^+$	
Γ_{18}	$p \overline{K}^*$(8	
Γ_{19}	$\Sigma^+ \pi^+ \pi^-$	
Γ_{20}	$\Sigma^- 2\pi^+$	
Γ_{21}	$\Sigma^+ K^+ K^-$	0.15 ± 0.06

Decay Modes Ξ_c^0

	Mode	*Fraction* (Γ_i/Γ)
	Cabibbo-favored (S = −2) decays	
Γ_1	$p K^- K^- \pi^+$	$(4.8 \pm 1.2) \times 10^{-3}$
Γ_2	$p K^- \overline{K}^*(892)^0$, $\overline{K}^{*0} \to K^- \pi^+$	$(2.0 \pm 0.6) \times 10^{-3}$
Γ_3	$p K^- K^- \pi^+$ (no $\overline{K}^{*0}$)	$(3.0 \pm 0.9) \times 10^{-3}$
Γ_4	ΛK_S^0	$(3.0 \pm 0.8) \times 10^{-3}$
Γ_5	$\Lambda K^- \pi^+$	$(1.45 \pm 0.33)\%$
Γ_6	$\Lambda \overline{K}^0 \pi^+ \pi^-$	seen
Γ_7	$\Lambda K^- \pi^+ \pi^+ \pi^-$	seen
Γ_8	$\Xi^- \pi^+$	$(1.43 \pm 0.32)\%$
Γ_9	$\Xi^- \pi^+ \pi^+ \pi^-$	$(4.8 \pm 2.3)\%$
Γ_{10}	$\Omega^- K^+$	$(4.2 \pm 1.0) \times 10^{-3}$
Γ_{11}	$\Xi^- e^+ \nu_e$	$(1.8 \pm 1.2)\%$
	Cabibbo-suppressed decays	
Γ_{12}	$\Xi^- K^+$	$(3.9 \pm 1.2) \times 10^{-4}$
Γ_{13}	$\Lambda K^+ K^-$ (no ϕ)	$(4.1 \pm 1.4) \times 10^{-4}$
Γ_{14}	$\Lambda \phi$	$(4.9 \pm 1.5) \times 10^{-4}$

Very limited knowledge on their decays
We have opportunity to systematic study more decays

Studies on the Ω_c^0

Mode		Fraction (Γ_i/Γ)
No absolute branching fractions have been measured. The following are branching *rati*		
Cabibbo-favored ($S = -3$) decays – relative to $\Omega^-\pi^+$		
Γ_1	$\Omega^-\pi^+$	**DEFINED AS 1**
Γ_2	$\Omega^-\pi^+\pi^0$	1.80 ± 0.33
Γ_3	$\Omega^-\rho^+$	> 1.3
Γ_4	$\Omega^-\pi^-2\pi^+$	0.31 ± 0.05
Γ_5	$\Omega^-e^+\nu_e$	2.4 ± 1.2
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	$\Xi^-\overline{K}^0\pi^+$	2.12 ± 0.28
Γ_{10}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{11}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0} \to \Xi^-\pi^+$	0.21 ± 0.06
Γ_{12}	$\Xi^-\overline{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{13}	$\Sigma^+K^-K^-\pi^+$	< 0.32
Γ_{14}	$\Lambda\overline{K}^0\overline{K}^0$	1.72 ± 0.35

BESIII

Studies on most of the Ξ_c / Ω_c weak decays are missing in experiment (I)

BFs of CF decays

RQM Pole Pole RQM Pole Pole (in units of %)

Decay	Körner, Krämer ('92)	Xu, Kamal ('92)	Cheng, Tseng ('93)	Ivanov et al. ('98)	Żenczykowski ('94)	Sharma, Verma ('99)	Expt.
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	6.45	0.44	0.84	3.08	1.56	0.04	
$\Xi_c^+ \to \Xi^0 \pi^+$	3.54	3.36	3.93	4.40	1.59	0.53	0.55 ± 0.16^a
$\Xi_c^0 \to \Lambda \bar{K}^0$	0.12	0.37	0.27	0.42	0.35	0.54	seen
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	1.18	0.11	0.13	0.20	0.11	0.07	
$\Xi_c^0 \to \Sigma^+ K^-$	0.12	0.12		0.27	0.36	0.12	
$\Xi_c^0 \to \Xi^0 \pi^0$	0.03	0.56	0.28	0.04	0.69	0.87	
$\Xi_c^0 \to \Xi^0 \eta$	0.24			0.28	0.01	0.22	
$\Xi_c^0 \to \Xi^0 \eta'$	0.85			0.31	0.09	0.06	
$\Xi_c^0 \to \Xi^- \pi^+$	1.04	1.74	1.25	1.22	0.61	2.46	seen
$\Omega_c^0 \to \Xi^0 \bar{K}^0$	1.21		0.09	0.02			

Studies on most of the Ξ_c / Ω_c^0 weak decays are missing in experiment (II)

Decay asymmetry α for CF decays

Longitudinal pol. of daughter baryon from unpol. parent baryon

⇒ information on the relative sign between s- and p-waves

Decay	Körner, Krämer ('92)	Xu, Kamal ('92)	Cheng, Tseng ('93)	Ivanov et al. ('98)	Żenczykowski ('94)	Sharma, Verma ('99)	Expt.
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	-1.0	0.24	-0.09	-0.99	1.00	0.54	
$\Xi_c^+ \to \Xi^0 \pi^+$	-0.78	-0.81	-0.77	-1.0	1.00	-0.27	
$\Xi_c^0 \to \Lambda \bar{K}^0$	-0.76	1.0	-0.73	-0.75	-0.29	-0.79	
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	-0.96	-0.99	-0.59	-0.55	-0.50	0.48	
$\Xi_c^0 \to \Sigma^+ K^-$	0	0		0	0	0	
$\Xi_c^0 \to \Xi^0 \pi^0$	0.92	0.92	-0.54	0.94	0.21	-0.80	
$\Xi_c^0 \to \Xi^0 \eta$	-0.92			-1.0	-0.04	0.21	
$\Xi_c^0 \to \Xi^0 \eta'$	-0.38			-0.32	-1.00	0.80	
$\Xi_c^0 \to \Xi^- \pi^+$	-0.38	-0.38	-0.99	-0.84	-0.79	-0.97	-0.6 ± 0.4
$\Omega_c^0 \to \Xi^0 \bar{K}^0$	0.51		-0.93	-0.81			

Studies on most of the Ξ_c / Ω_c^0 weak decays are missing in experiment (III)

Charm-flavor-conserving weak decays

- Light quarks undergo weak transitions, while c quark behaves as a "spectator" e.g. $\Xi_c \to \Lambda_c \pi$ ($s \to W^- u$). Can be studied using HHChPT.

$Br(\Xi_c^0 \to \Lambda_c^+ \pi^-) = 2.9\times10^{-4}$

$Br(\Xi_c^+ \to \Lambda_c^+ \pi^0) = 6.7\times10^{-4}$

Cheng, Cheung, Lin, Lin, Yan, Yu ('92)

$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+)$ $(0.55 \pm 0.02 \pm 0.18)\%$

[LHCb, PRD 102, 071101 (2020)]

Larger than theoretical predictions

These can be further tested at BESIII

Semileptonic decays

|→ NRQM ←| RQM LFQM QSR QSR

Process	Pérez-Marcial et al. [85]	Singleton [86]	Cheng, Tseng [81]	Ivanov et al. [87]	Luo [88]	Marques de Carvalho et al. [89]	Huang, Wang [90]	Expt. [3]
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	18.1 (12.5)	8.5	7.4	8.16	9.7			seen
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	18.4 (12.7)	8.5	7.4	8.16	9.7			seen

in units of 10^{10} s^{-1}

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.72 \pm 0.10 \pm 0.12 \pm 0.50)\%$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.71 \pm 0.17 \pm 0.13 \pm 0.50)\%$$

[Belle, arXiv:2103.06496]

$$\mathcal{B}_{\rm exp}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 2.43(0.25)(0.35)(0.72)\%$$

[ALICE, PoS ICHEP 2020, 524(2021)]

The first Lattice calculation on Ξ_c SL decays

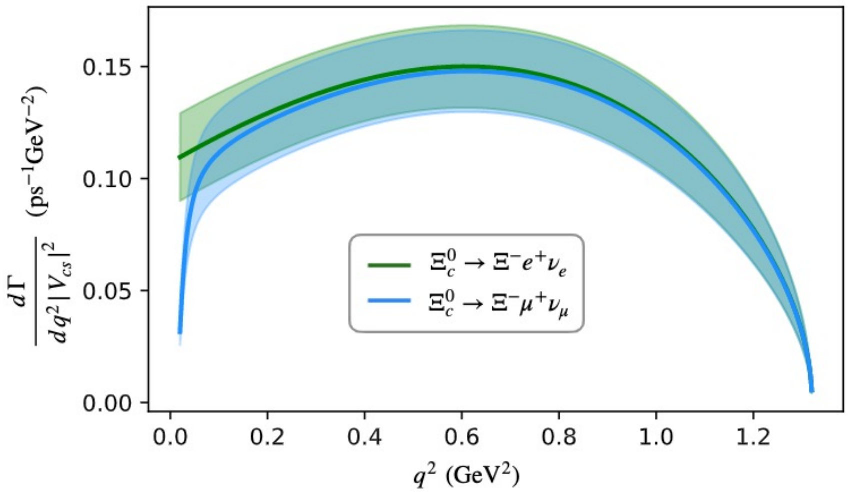
$\Xi_c \to \Xi$ Form Factors and $\Xi_c \to \Xi \ell^+ \nu_\ell$ Decay Rates From Lattice QCD

Qi-An Zhang,[1] Jun Hua,[2] Fei Huang,[2] Renbo Li,[3] Yuanyuan Li,[3]
Cai-Dian Lü,[4,5] Peng Sun,[3,*] Wei Sun,[4] Wei Wang,[2,†] and Yi-Bo Yang[6,7,8,‡]
[1] Key Laboratory for Particle Astrophysics and Cosmology (MOE)

arXiv: 2103.07064

$$\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = 2.38(0.30)(0.33)\%,$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = 2.29(0.29)(0.31)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e) = 7.18(0.90)(0.98)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu) = 6.91(0.87)(0.93)\%.$$

$$R_{\mu/e} = \frac{\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu)}{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)} = \frac{\mathcal{B}(\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu)}{\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e)} = 0.962 \pm 0.003 \pm 0.002,$$



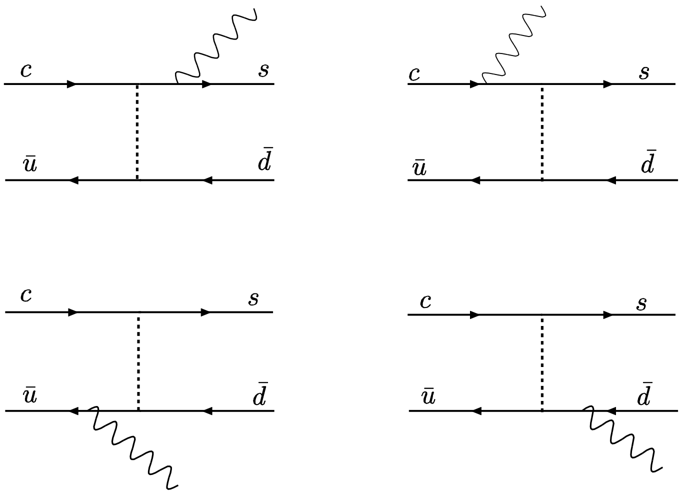
Weak radiative decay

- Charm-flavor-changing

  $\Lambda_c^+ \to \Sigma^+\gamma$, $\Xi_c^0 \to \Xi^0\gamma$

- Charm-flavor-conserving

  $\Xi_c \to \Lambda_c\gamma$, $\Omega_c \to \Xi_c\gamma$



i) e.m. penguin $c \to u\gamma$, very suppressed

ii) γ emission from external quark in W-exchange

γ emission from W boson in W-exchange

$$Br(\Lambda_c^+ \to \Sigma^+\gamma) = 4.9\times10^{-5}, \qquad \alpha = -0.86$$

$$Br(\Xi_c^0 \to \Xi^0\gamma) = 3.6\times10^{-5}, \qquad \alpha = -0.86$$

Cheng, Cheung, Lin, Lin, Yan, Yu ('95)

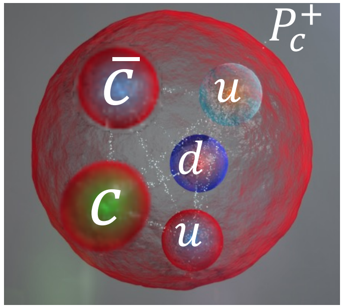
Charmed baryon spectroscopy

	Ξ_c^+	$\frac{1}{2}^+$	0	0	0^+	$2467.6^{+0.4}_{-0.6}$		weak
	Ξ_c^0	$\frac{1}{2}^+$	0	0	0^+	$2470.88^{+0.34}_{-0.80}$		weak
	$\Xi_c'^+$	$\frac{1}{2}^+$	1	0	1^+	2575.6 ± 3.1		$\Xi_c\gamma$
	$\Xi_c'^0$	$\frac{1}{2}^+$	1	0	1^+	2577.9 ± 2.9		$\Xi_c\gamma$
	$\Xi_c(2645)^+$	$\frac{3}{2}^+$	1	0	1^+	$2645.9^{+0.5}_{-0.6}$	2.6 ± 0.5	$\Xi_c\pi$
	$\Xi_c(2645)^0$	$\frac{3}{2}^+$	1	0	1^+	2645.9 ± 0.9	< 5.5	$\Xi_c\pi$
	$\Xi_c(2790)^+$	$\frac{1}{2}^-$	0	1	1^-	2789.9 ± 3.2	< 15	$\Xi_c'\pi$
	$\Xi_c(2790)^0$	$\frac{1}{2}^-$	0	1	1^-	2791.8 ± 3.3	< 12	$\Xi_c'\pi$
	$\Xi_c(2815)^+$	$\frac{3}{2}^-$	0	1	1^-	2816.6 ± 0.9	< 3.5	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
	$\Xi_c(2815)^0$	$\frac{3}{2}^-$	0	1	1^-	2819.6 ± 1.2	< 6.5	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
2S 1/2+ →	$\Xi_c(2980)^+$	$?^?$	?	?	?	2971.4 ± 3.3	26 ± 7	$\Sigma_c K, \Lambda_c K\pi, \Xi_c\pi$
	$\Xi_c(2980)^0$	$?^?$	?	?	?	2968.0 ± 2.6	20 ± 7	$\Sigma_c K, \Lambda_c K\pi, \Xi_c\pi$
1D 3/2+ →	$\Xi_c(3055)^+$	$?^?$	?	?	?	$3055.1 \pm$		
	$\Xi_c(3055)^0$	$?^?$	?	?	?	$3059.7 \pm$		
1D 5/2+ →	$\Xi_c(3080)^+$	$?^?$	?	?	?	$3074.6 \pm$		
	$\Xi_c(3080)^0$	$?^?$	?	?	?	$3079.9 \pm$		
2S ½+ →	Ω_c^0	$\frac{1}{2}^+$	1	0	1	$2695.2 \pm$		
	$\Omega_c(2770)^0$	$\frac{3}{2}^+$	1	0	1^+	$2765.9 \pm$		

(in units of MeV)

	State	J^P	S_ℓ	L_ℓ	$J_\ell^{P_\ell}$	Mass	Width	Decay modes
	Λ_c^+	$\frac{1}{2}^+$	0	0	0^+	2286.46 ± 0.14		weak
	$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	0	1	1^-	2592.25 ± 0.28	2.6 ± 0.6	$\Sigma_c\pi, \Lambda_c\pi\pi$
	$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	0	1	1^-	2628.11 ± 0.19	0.97	$\Lambda_c\pi\pi, \Sigma_c\pi$
	$\Lambda_c(2765)^+$	$?^?$	?	?	?	2766.6 ± 2.4	50	$\Sigma_c\pi, \Lambda_c\pi\pi$
	$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	?	?	?	2881.53 ± 0.35	5.8 ± 1.1	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
	$\Lambda_c(2940)^+$	$?^?$	?	?	?	$2939.3^{+1.4}_{-1.5}$	17^{+8}_{-6}	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
	$\Sigma_c(2455)^{++}$	$\frac{1}{2}^+$	1	0	1^+	2453.98 ± 0.16	$1.94^{+0.08}_{-0.16}$	$\Lambda_c\pi$
	$\Sigma_c(2455)^+$	$\frac{1}{2}^+$	1	0	1^+	2452.9 ± 0.4	< 4.6	$\Lambda_c\pi$
	$\Sigma_c(2455)^0$	$\frac{1}{2}^+$	1	0	1^+	2453.74 ± 0.16	$1.87^{+0.09}_{-0.17}$	$\Lambda_c\pi$
	$\Sigma_c(2520)^{++}$	$\frac{3}{2}^+$	1	0	1^+	2517.9 ± 0.6	$14.8^{+0.3}_{-0.4}$	$\Lambda_c\pi$
	$\Sigma_c(2520)^+$	$\frac{3}{2}^+$	1	0	1^+	2517.5 ± 2.3	< 17	$\Lambda_c\pi$
	$\Sigma_c(2520)^0$	$\frac{3}{2}^+$	1	0	1^+	2518.8 ± 0.6	$15.3^{+0.3}_{-0.4}$	$\Lambda_c\pi$
3/2- →	$\Sigma_c(2800)^{++}$	$\frac{3}{2}^-?$	1	1	2^-	2801^{+4}_{-6}	75^{+22}_{-17}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
3/2- →	$\Sigma_c(2800)^+$	$\frac{3}{2}^-?$	1	1	2^-	2792^{+14}_{-5}	62^{+60}_{-40}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
3/2- →	$\Sigma_c(2800)^0$	$\frac{3}{2}^-?$	1	1	2^-	2806^{+5}_{-7}	72^{+22}_{-15}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$

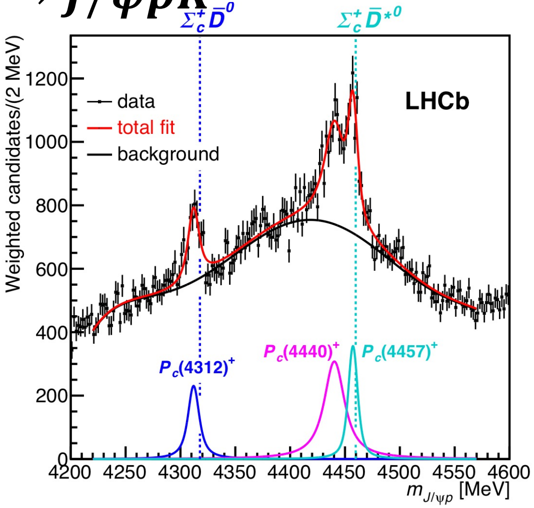
Hidden charm baryon



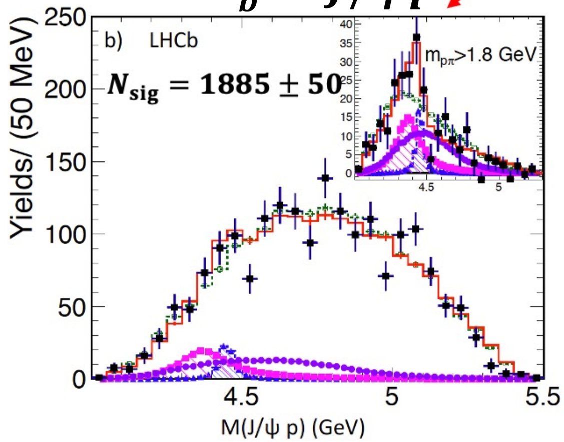
BESIII Observation of pentaquark at LHCb

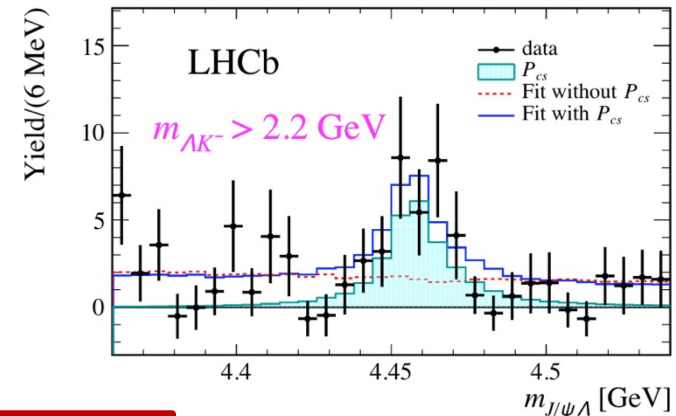
PRL 115 (2015) 072001
PRL 122 (2019) 222001
PRL 117 (2016) 082003
arXiv: 2012.10380

$\Lambda_b^0 \to J/\psi p K^-$



$\Lambda_b^0 \to J/\psi p \pi^-$





State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

System	$[\Xi_c \bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c \bar{D}^*]_{\frac{3}{2}}$
ΔE	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

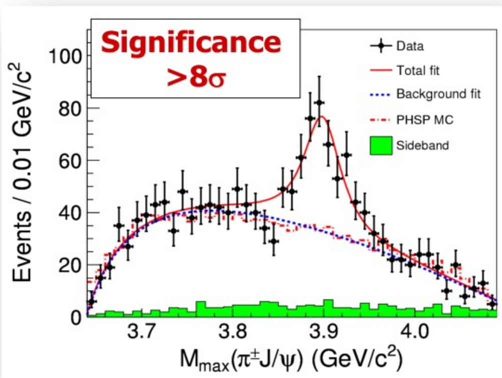
- BEPC3 could reach the mass of P_c up to 4.6 GeV in $e^+e^- \to \bar{p}P_c$, and that of P_{cs} up to 4.5 GeV in $e^+e^- \to \overline{\Lambda}(\overline{\Sigma})P_{cs}$

Pentaquark states
in e^+e^- annihilations and *b-hadron* decays

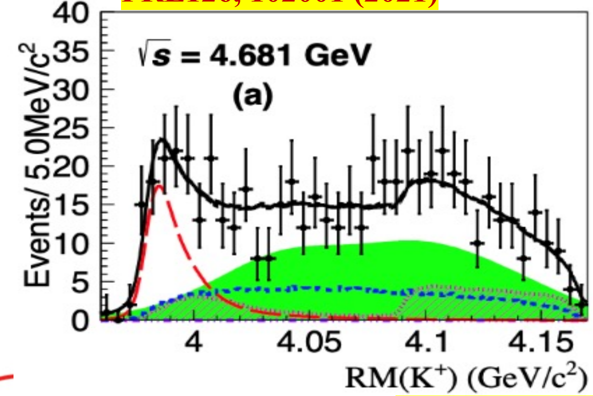
$Z_{c(s)}$ from e^+e^- annihilations and $Z_{c(s)}$ from B decays

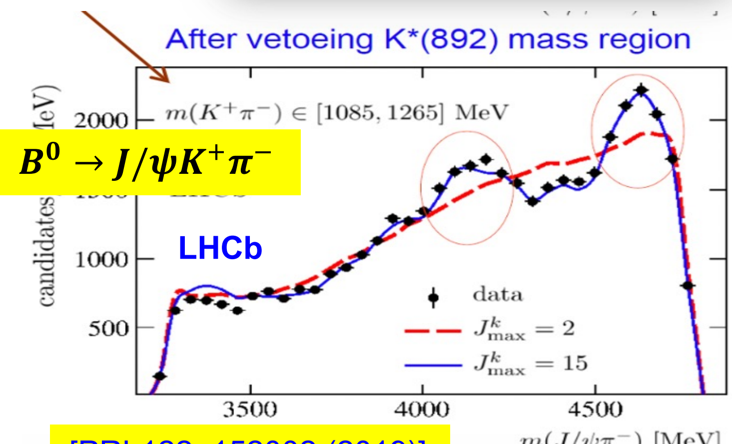
- Zcs(3985) vs Zcs(4000): masses are close, but widths are different. Same state or not?
- Zc(3900) vs Zc(4200) : much more different

How about pentaquark states?

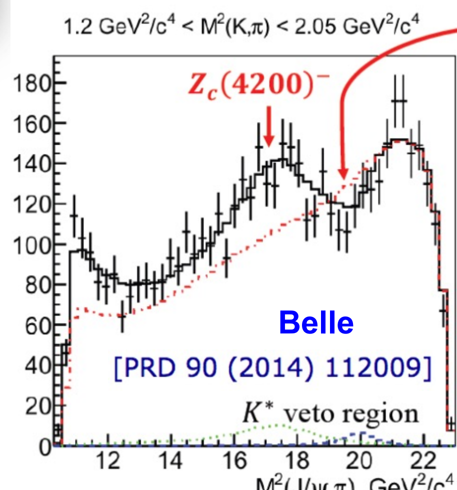


PRL126, 102001 (2021)

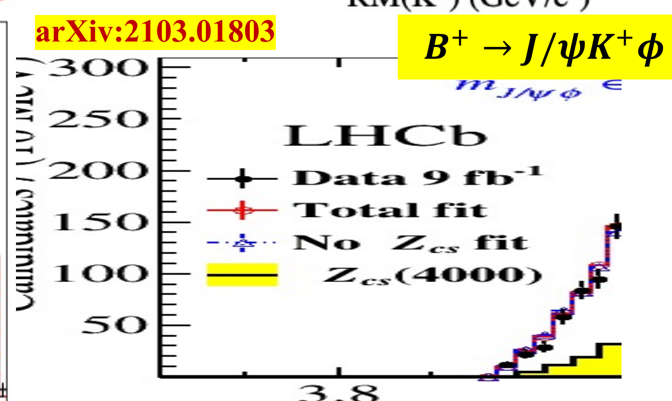




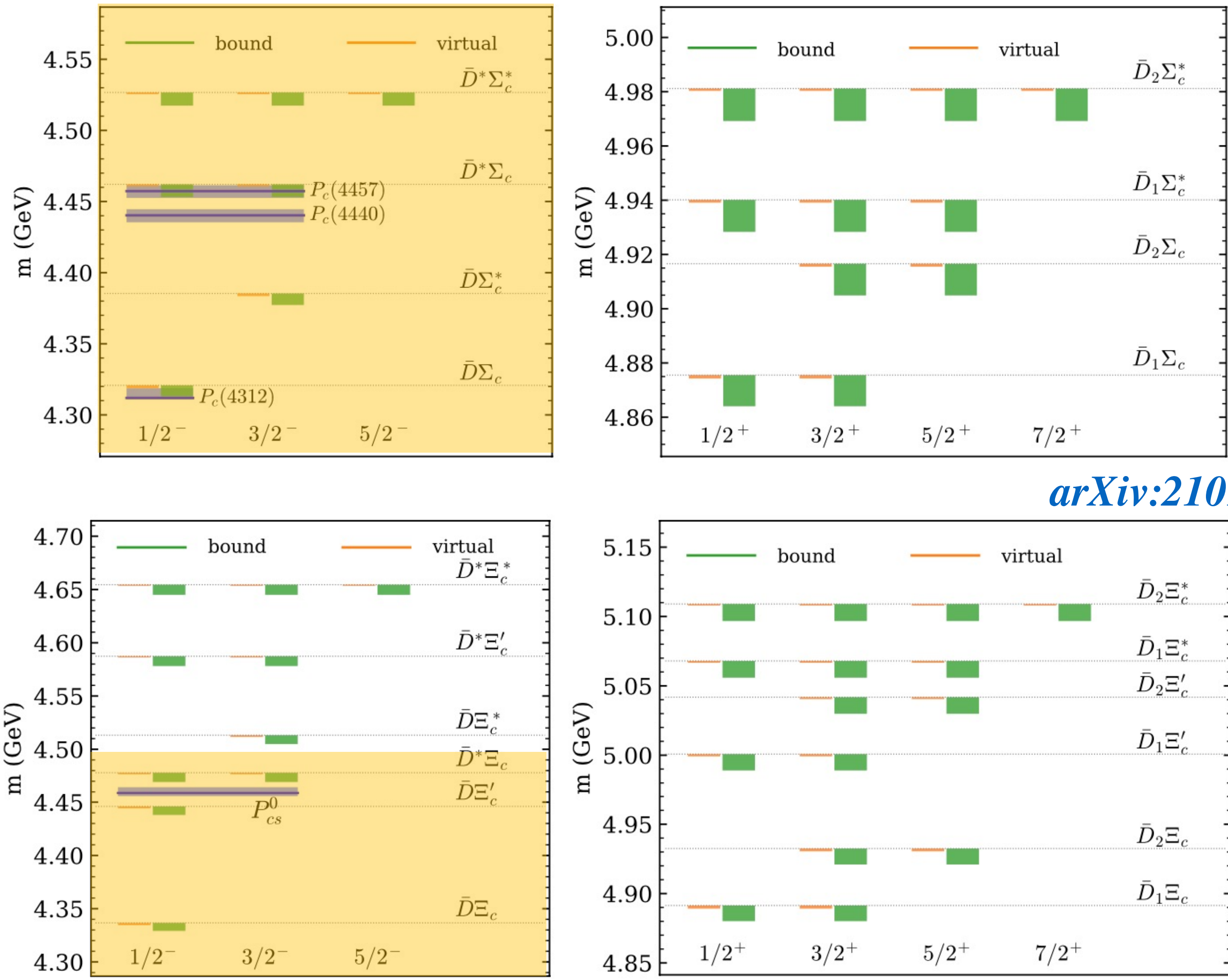
[PRL122, 152002 (2019)]



arXiv:2103.01803



Threshold for pentaquark states



arXiv:2101.01021

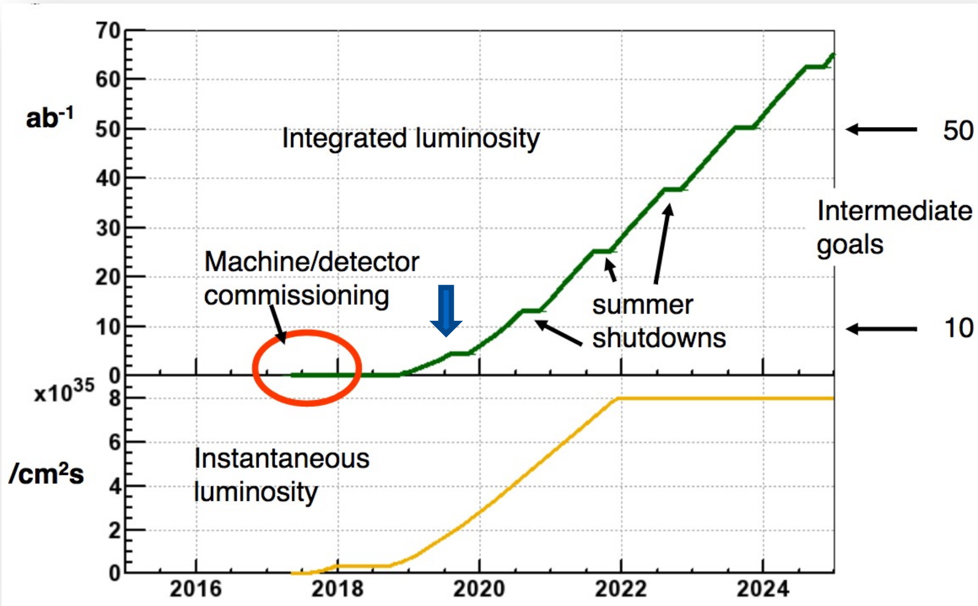
However, we don't know the production …

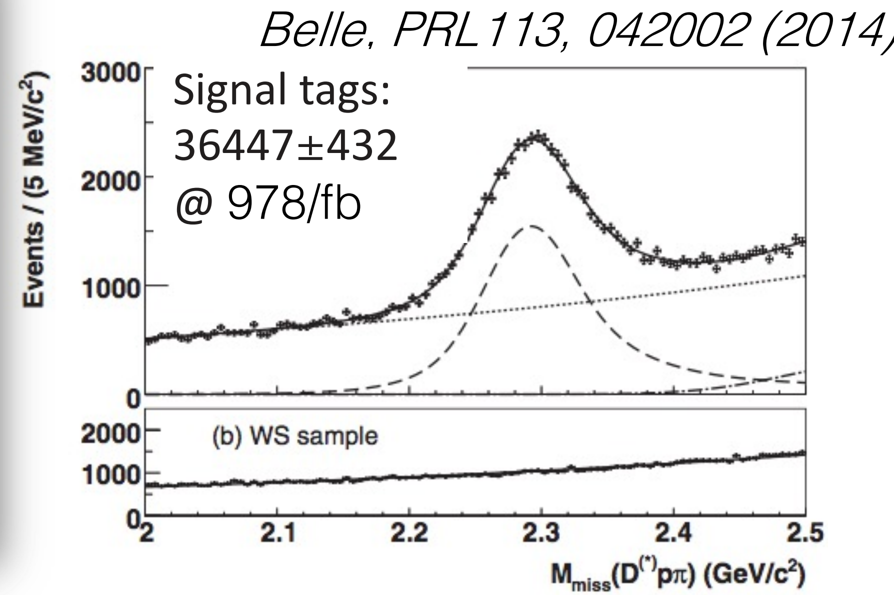
Summary

- BESIII has been playing significant role in renaissance of Λ_c decays
- BEPCII energy upgrade during 2020-2021 has improved the BESIII capability in Λ_c physics by accumulating more statistics at different energy points
- Proposal BEPC3 (3x luminosity and energy up to 5.6 GeV) will greatly extend the physics opportunities in baryon sector
  - ✓ systematic studies on decays of ground charmed baryons: Λ_c, Σ_c, Ξ_c, Ω_c
  - ✓ spectroscopy of charmed baryons
  - ✓ pentaquark states

Backup

Competition from Belle & BelleII





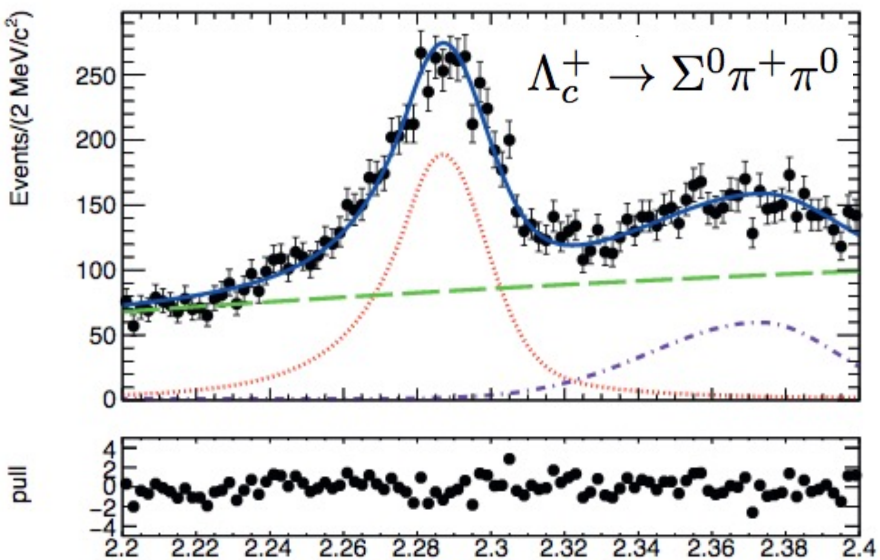
- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, BELLEII will have 5/ab data, 5x of BELLE data;
  ➔ 180K tagged Λ_c^+;
- We will have 150K tagged Λ_c^+, however, BESIII is very clean
- Many precise measurements at BESIII will reach to the level of systematic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

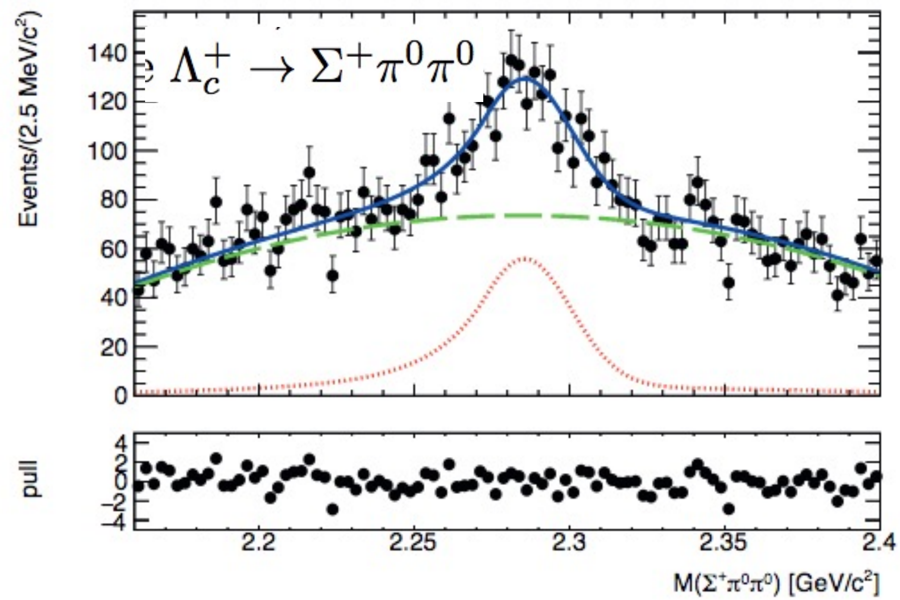
World campaign on the charmed baryon

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

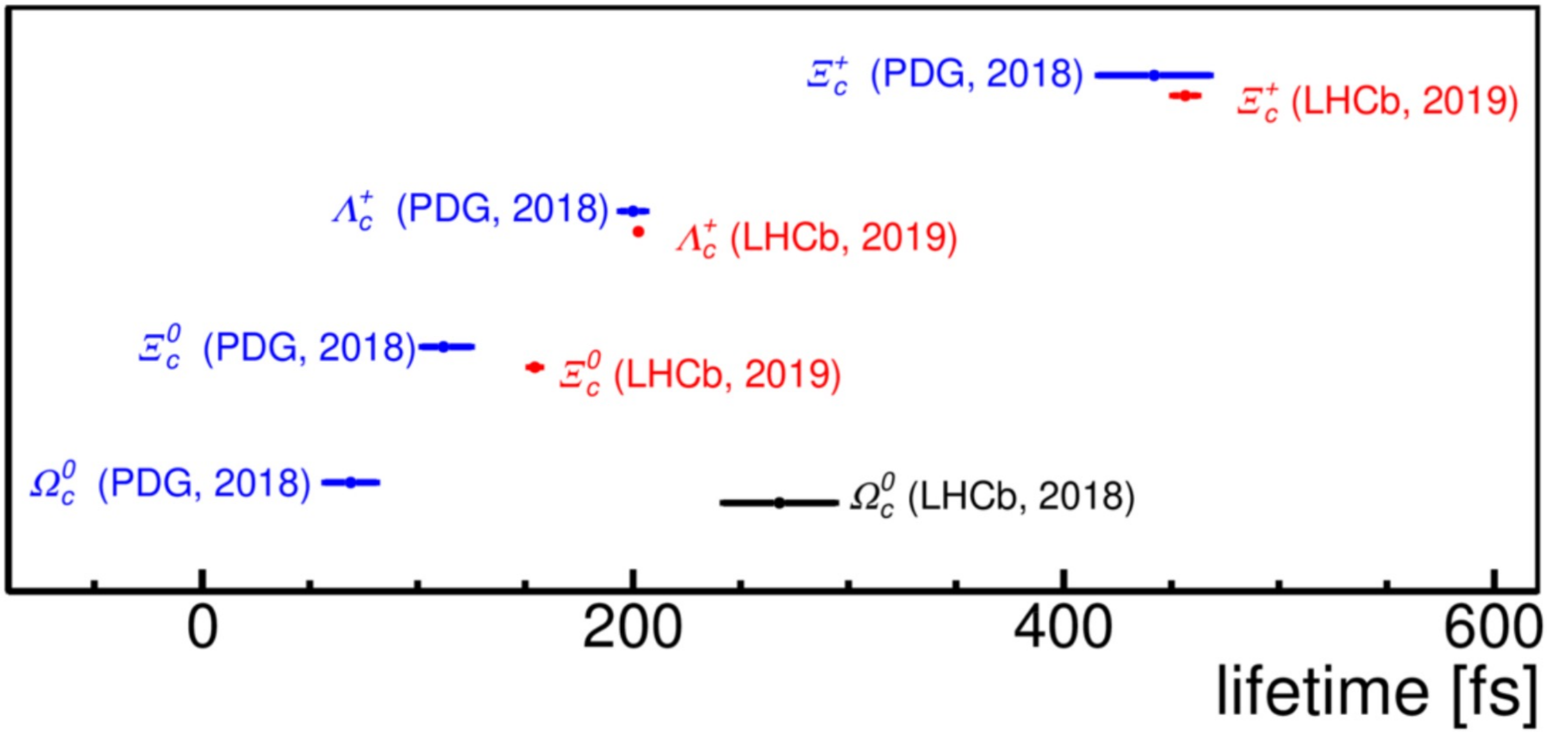
- The threshold data at BESIII have systematic advantage over Belle(-II) and LHCb

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





arXiv: 1802.03421



– Changes lifetime hierarchy

- Previous world averages

  $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \boldsymbol{\tau_{\Omega_c^0}}$

- Using LHCb measurements

  $\tau_{\Xi_c^+} > \boldsymbol{\tau_{\Omega_c^0}} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$

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.

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

[PRL 117, 232002 (2016)]

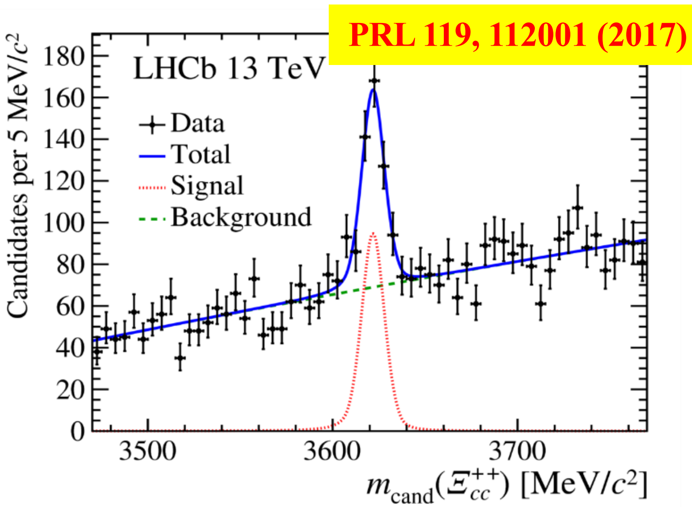
$\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+ K^- \pi^+$

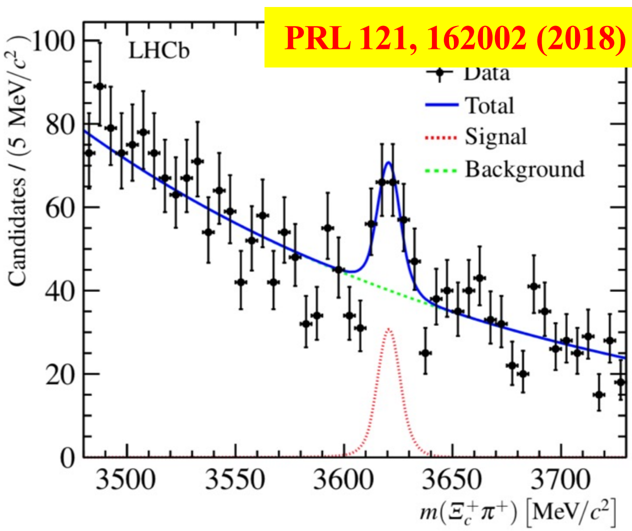
Large enough for observation

Λ_c^+ BFs from BESIII → Stronger predictive power

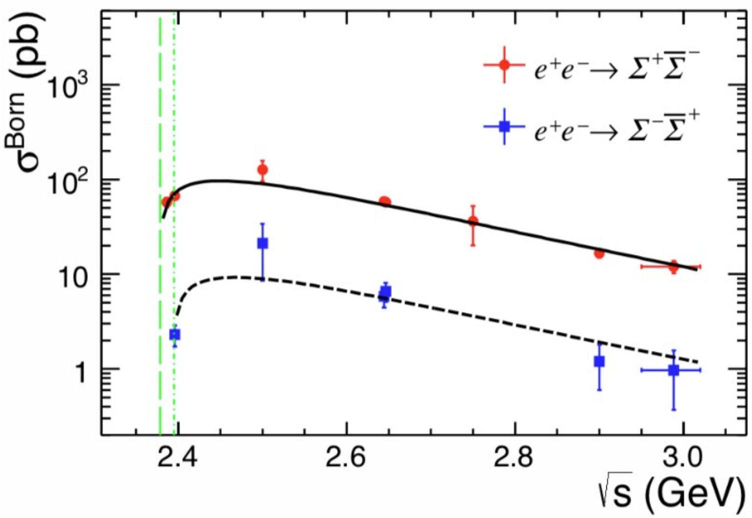
Contributions to Ξ_{cc}^{++} observation

- 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)





arXiv:2009.01404



Energy (GeV)	$\lvert G_E/G_M \rvert$
2.3960	1.83±0.26±0.24
2.6454	0.66±0.15±0.11
2.9000	1.06±0.36±0.09

well described by pQCD motivated model

Ξ_c tagging efficiencies

Ξ_c^+ Mode	Br %	eff_sub %
$\Lambda K^- \pi^+ \pi^+$	0.92	11.4
$\Sigma^+ K^- \pi^+$	2.69	12.1
$\Sigma^0 K^- \pi^+ \pi^+$	0.77	6.9
$\Xi^0 \pi^+$	1.57	12.4
$\Xi^- \pi^+ \pi^+$	2.86	9.2
$\Xi^0 \pi^+ \pi^0$	6.58	6.3
$\Xi^0 \pi^+ \pi^+ \pi^-$	4.86	6.2
$\Omega^- K^+ \pi^+$	0.20	1.9
$pK^- \pi^+$	0.01	58.6
Total ($\sum B_i * \varepsilon_i$)	1.67%	

Ξ_c^0 Mode	Br %	eff_sub %
$pK^- K^- \pi^+$	4.8	22.6
ΛK_S	3	16.8
$\Lambda K^- \pi^+$	1.45	20.3
$\Xi^- \pi^+$	1.43	11.6
$\Xi^- \pi^+ \pi^+ \pi^-$	4.8	6.5
$\Omega^- K^+$	4.2	6.1
Total ($\sum B_i * \varepsilon_i$)	2.62%	

$e^+e^- \to \Xi_c^+ \bar{\Xi}_c^- / \Xi_c^0 \bar{\Xi}_c^0$ at 4.946 GeV

Signal MC simulations

Charmed baryons productions

from Marek Karliner

In the charmed baryon system, the light quarks are more like di-quarks

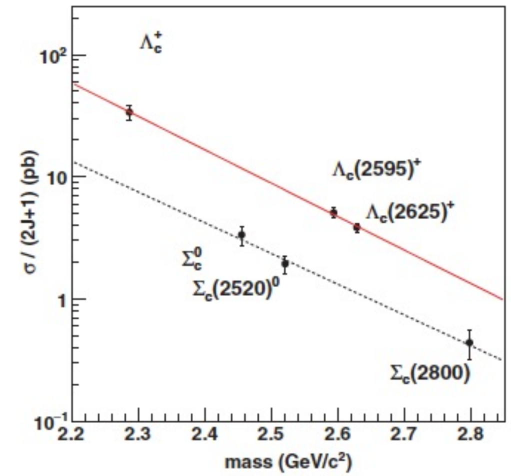
$$\Lambda_c^+(c[ud]_{spin=0}),\ \Sigma_c(c[ud]_{spin=1})$$

The spin-0 diquarks: "good" diquarks

The spin-1 one : "bad" diquarks.

The bad diquarks are heavier. So if the hadronization from the initial (ccbar) proceeds in one step, by attaching diquarks, it will provide a simple and natural explanation for the fact that the $\boldsymbol{\Lambda_c}$ cross section is much bigger than that of $\boldsymbol{\Sigma_c}$.

Belle, arXiv:1706.06791



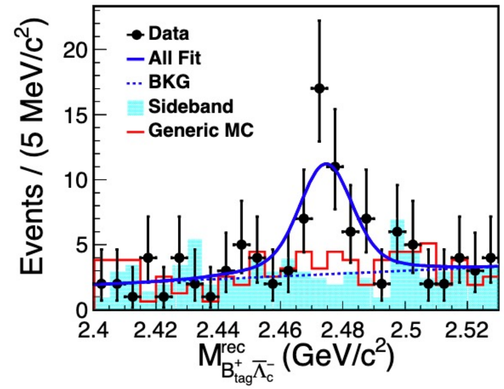
Then how about the behaves at the threshold, and to test it at BESIII will be very interesting!

First Measurements of absolute BFs for Ξ_c

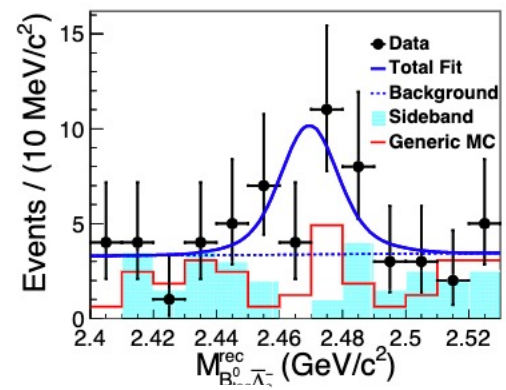
Belle, Phys.Rev.Lett. 122, 082001 (2019)
Belle, Phys. Rev. D 100, 031101 (2019)

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

- Large errors
- Belle II will improve these to ~10%
- BESIII has potential to improve them



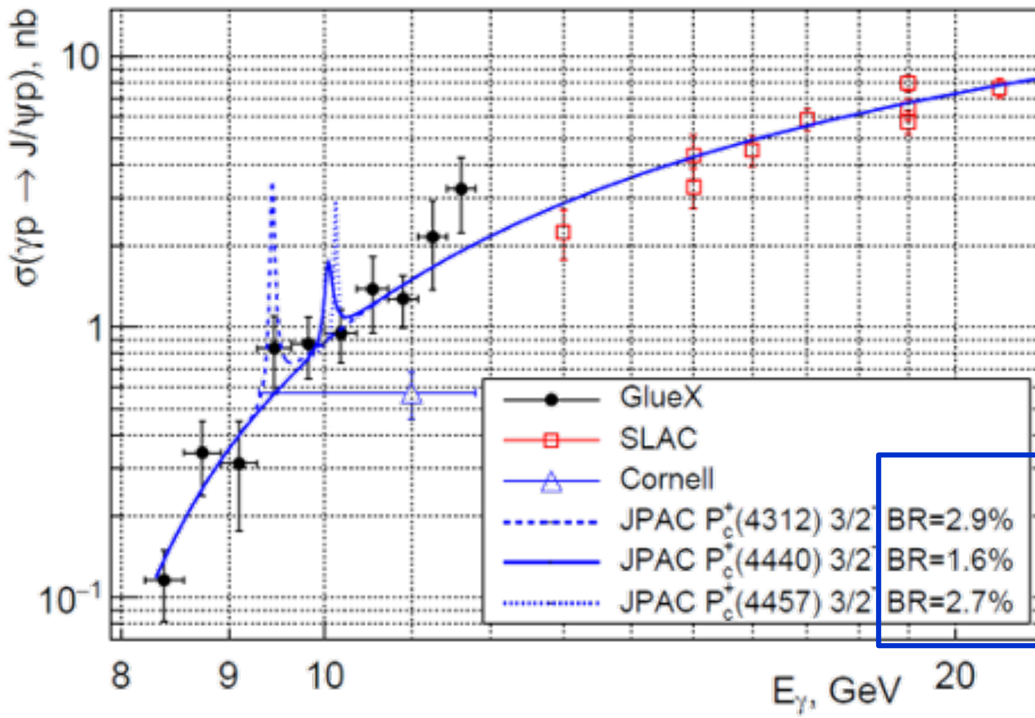
$$N_{\Xi_c^0} = 40.9 \pm 9.0$$



$$N_{\Xi_c^+} = 18.8 \pm 6.8.$$

GlueX results

"First measurement of near-threshold J/ψ exclusive photoproduction off the proton"
GlueX Collaboration, **May 26, 2019**, PRL 123 (2019) 072001



"GlueX Physics" on 18/8 (Sun.) at S1 by M. SHEPHERD

Model-dependent upper limits at 90% C.L. from JPAC model [PRD 94 (2016) 034002]

A less model-dependent limit at 90% C.L.:

$\sigma_{\max}(\gamma p \to P_c^+)\times\mathcal{B}(P_c^+ \to J/\psi p) < 4.6, 1.8, 3.9$ nb for $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$, respectively.

→ at the resonance maximum