Charmed Baryons at BESIII

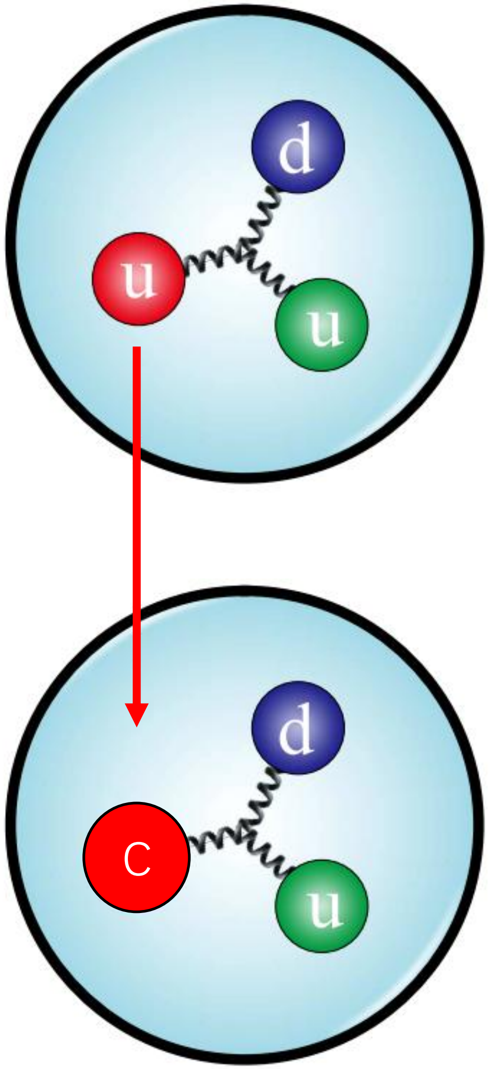
Cong GENG (耿 聪)
Sun Yat-sen University (中山大学)

Outline

- ❖ Interests in Charmed Baryons
- ❖ BESIII experiment
- ❖ Technique and strategy at BESIII
- ❖ Cabibbo suppressed decays of Λ_c^+
- ❖ Excited Charmed Baryons
- ❖ Prospect at BESIII

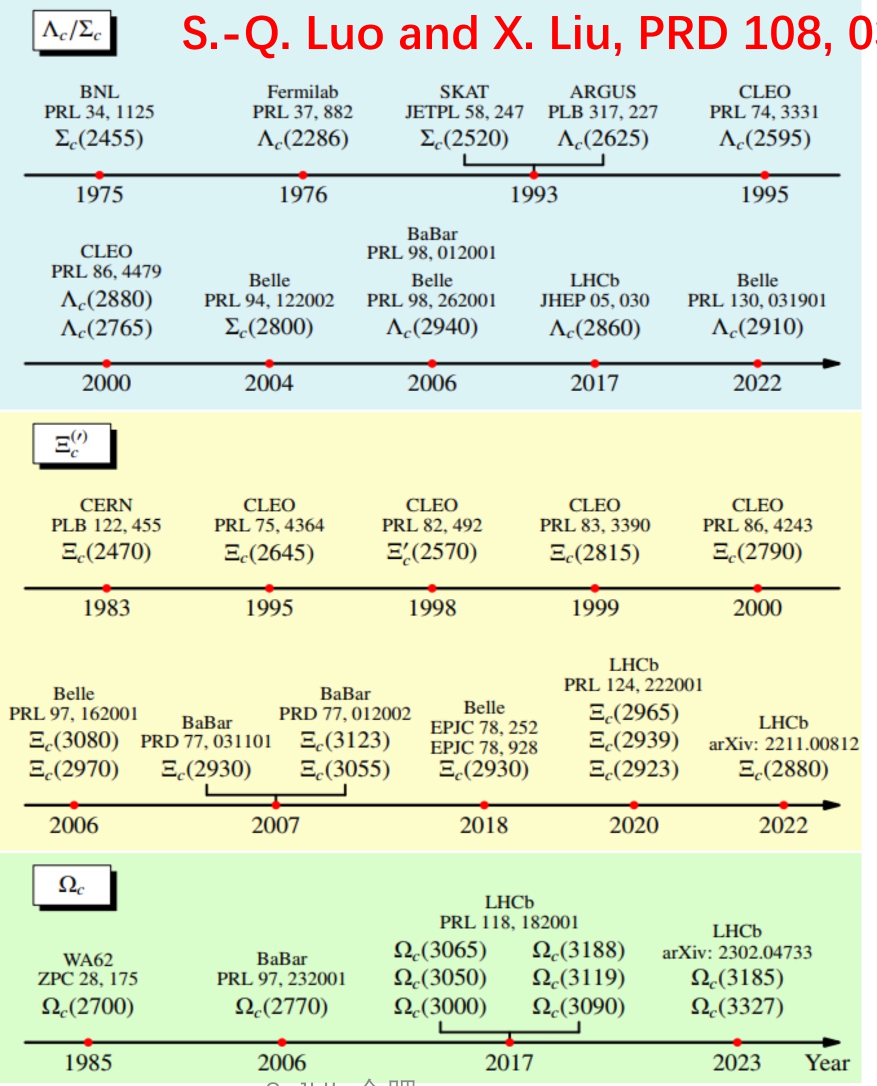
Charmed Baryon

Baryon



Charmed Baryon

S.-Q. Luo and X. Liu, PRD 108, 034002 (2023)

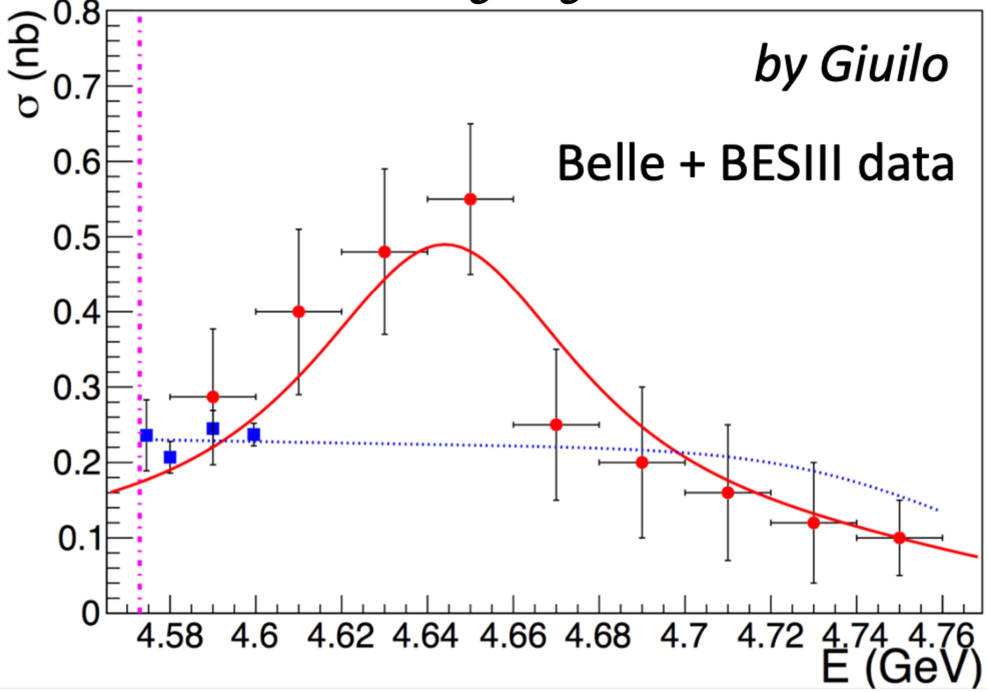


Discovered shortly after J/ψ

But, both experiment and theory develop slowly

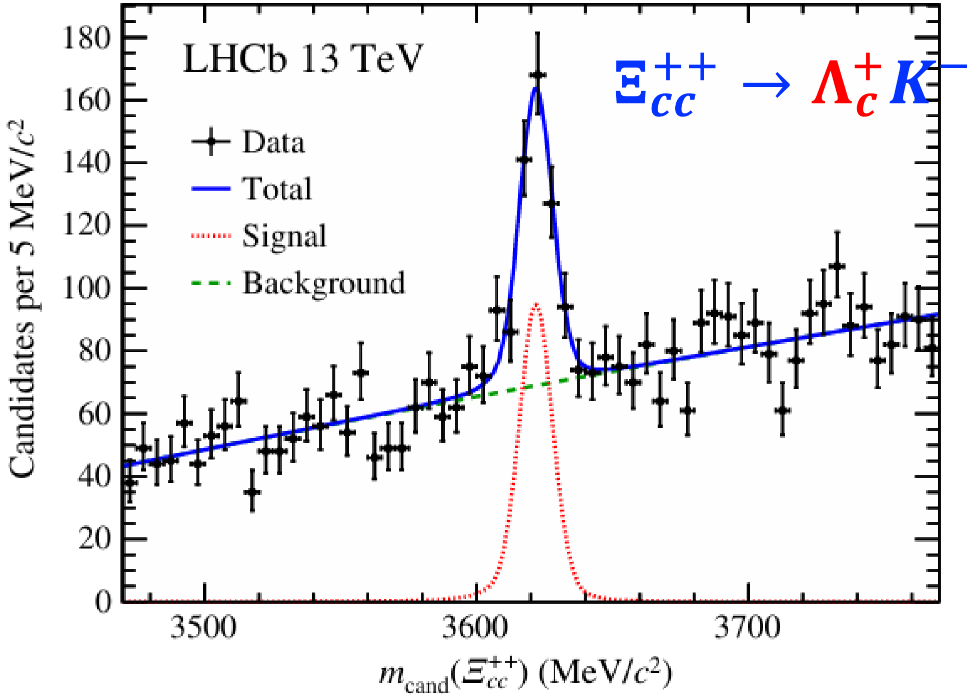
Productions and Decays

$e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$



Doubly charmed Baryons !

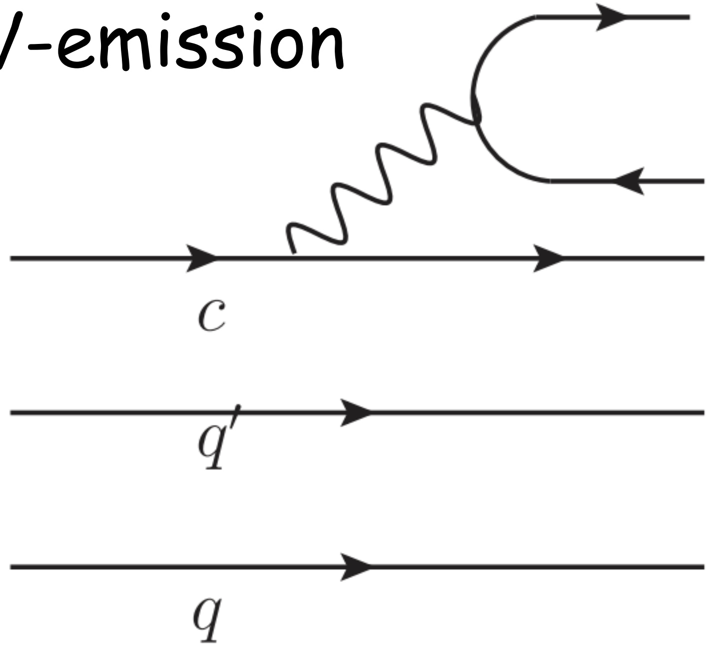
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



- ❖ Form Factors
- ❖ Spectroscopy, New states?

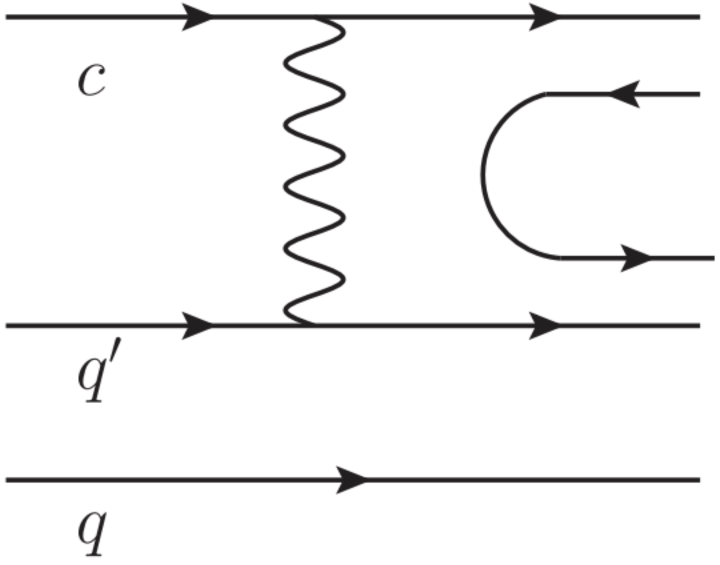
Productions and Decays

W-emission



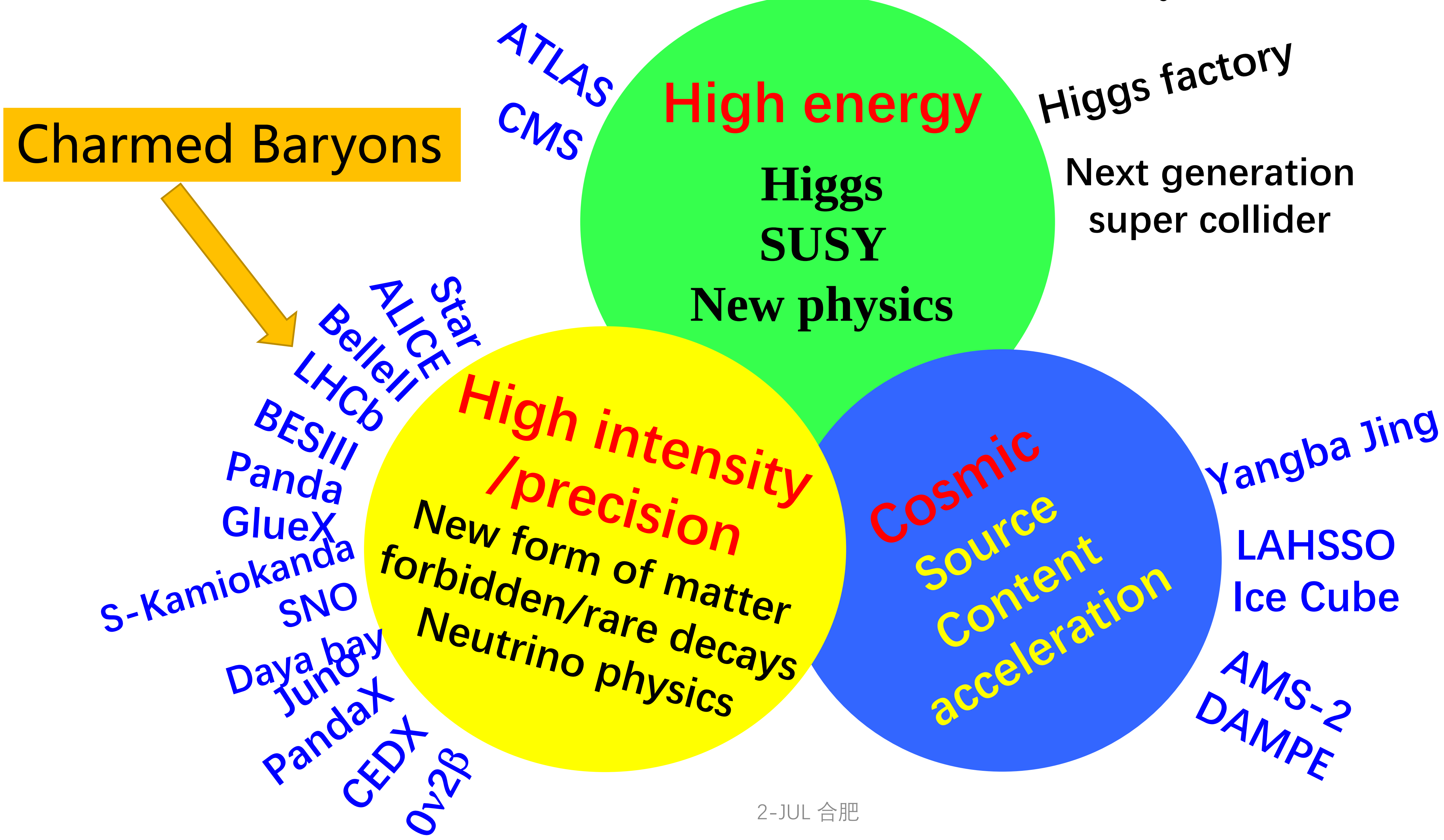
W-exchange

(suppressed in charmed meson)



- ❖W-exchange not subject to color suppression
- ❖Significant Non-factorization contribution !

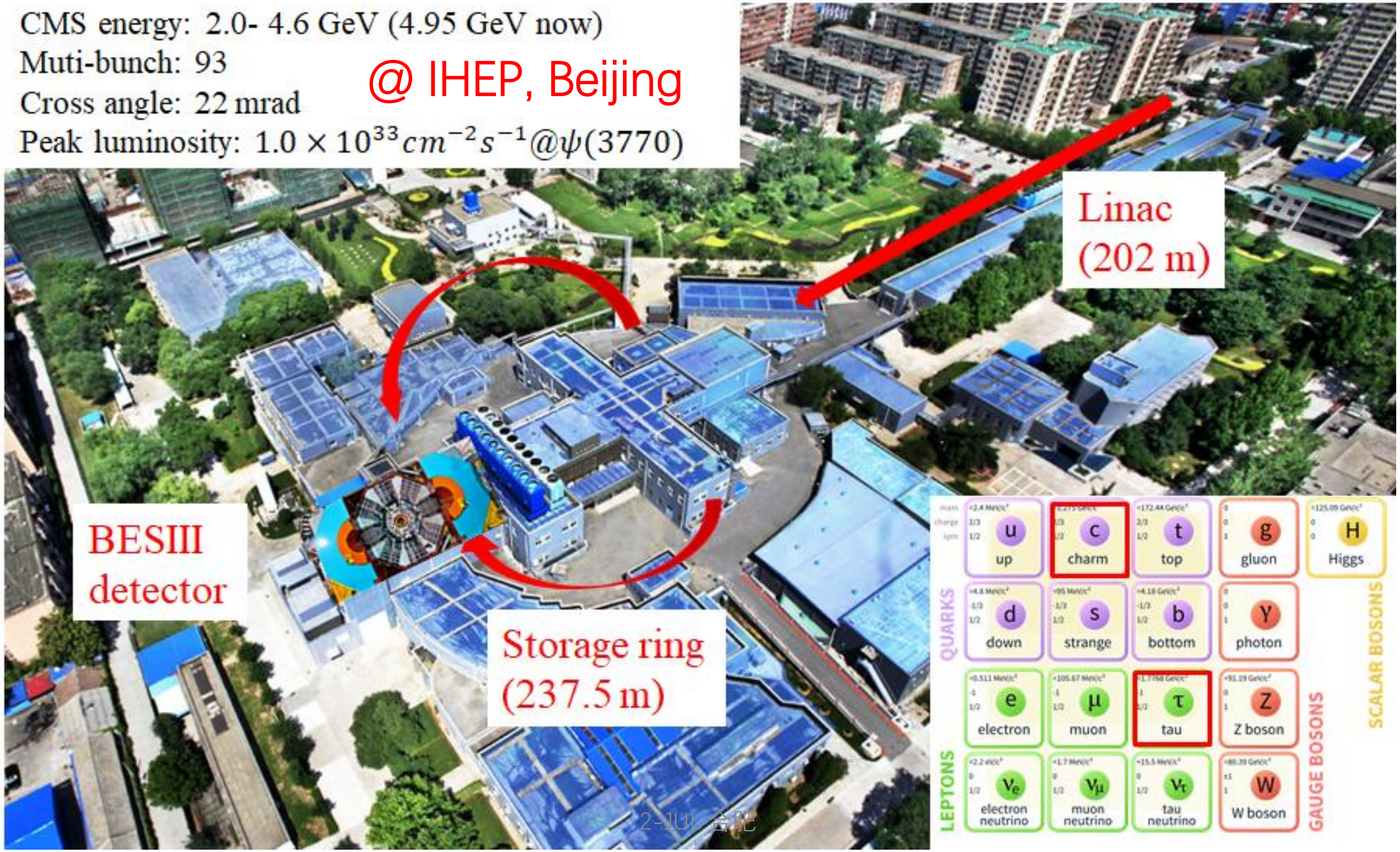
Frontier of Particle Physics



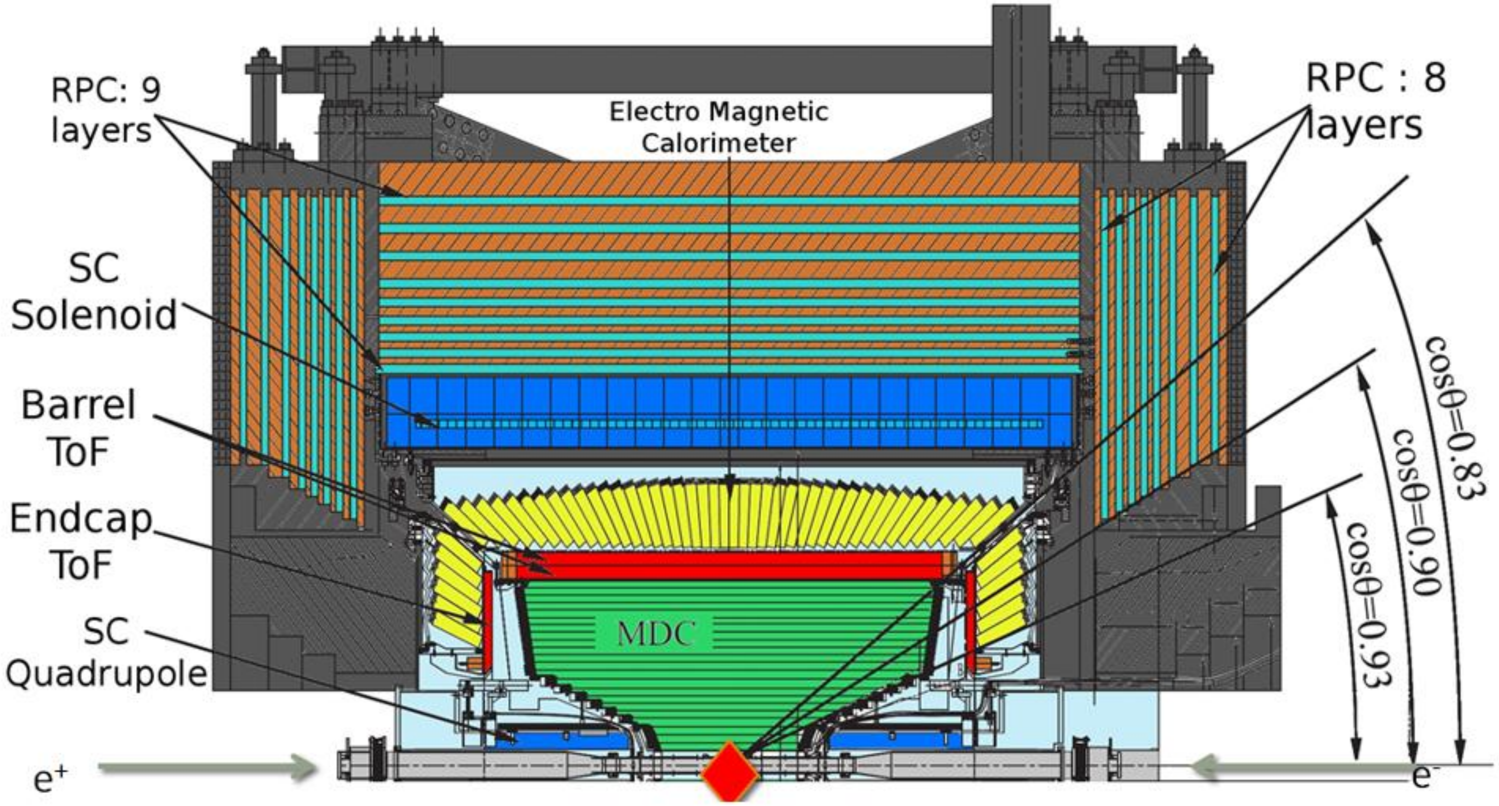
BESIII experiment

CMS energy: 2.0- 4.6 GeV (4.95 GeV now)
Muti-bunch: 93
Cross angle: 22 mrad
Peak luminosity: $1.0 \times 10^{33} cm^{-2} s^{-1} @ \psi(3770)$

@ IHEP, Beijing



BESIII experiment



MDC: charged tracks

dE/dx + TOF: PID

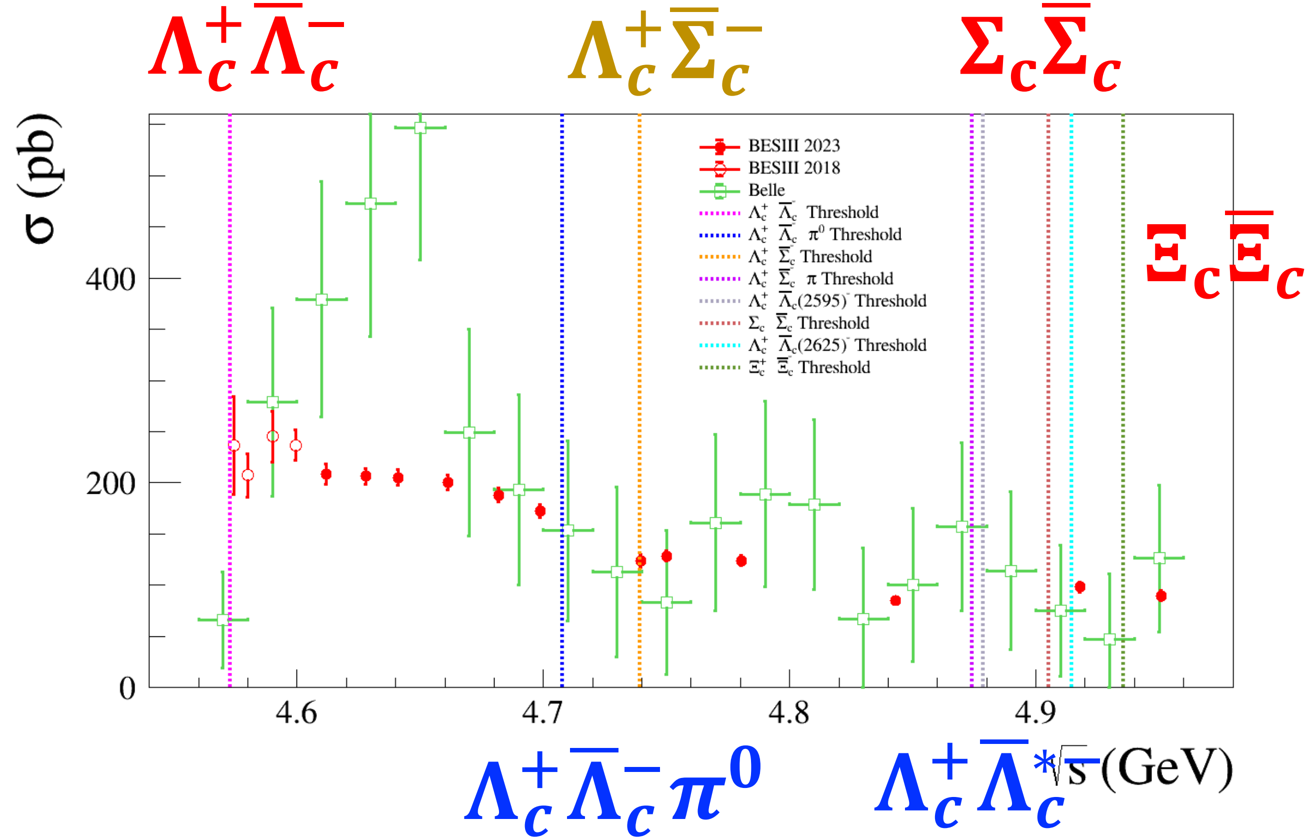
EMC: photons and electrons

RPC: muon detection

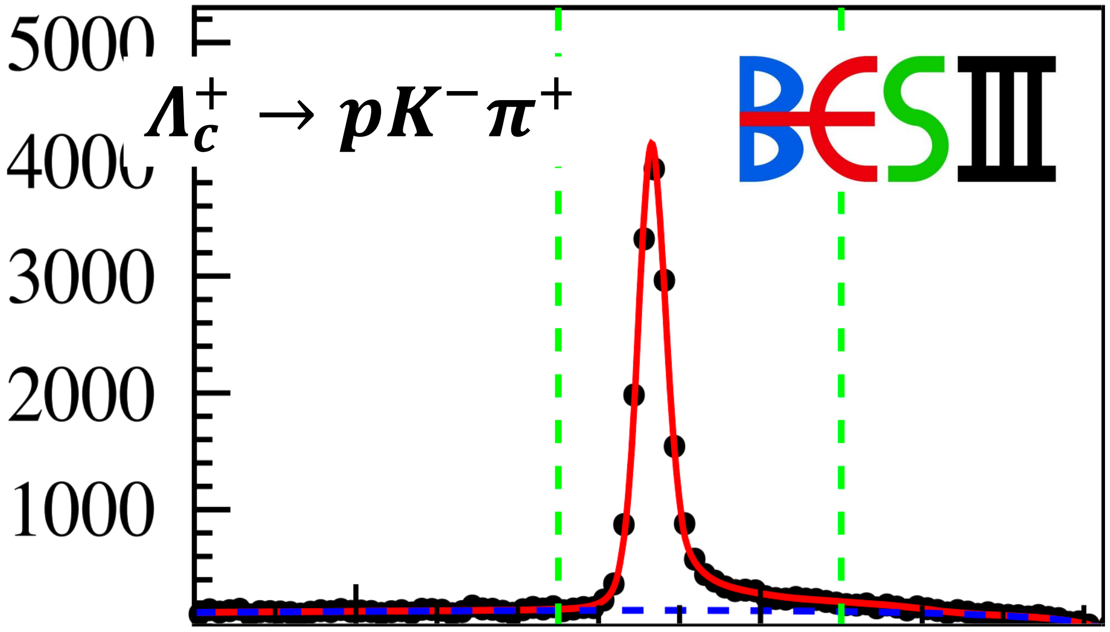
SC Solenoid: 1T magnet

Charmed Baryons at BESIII

Threshold effect for charmed hadrons



Higher signal to bkg ratio

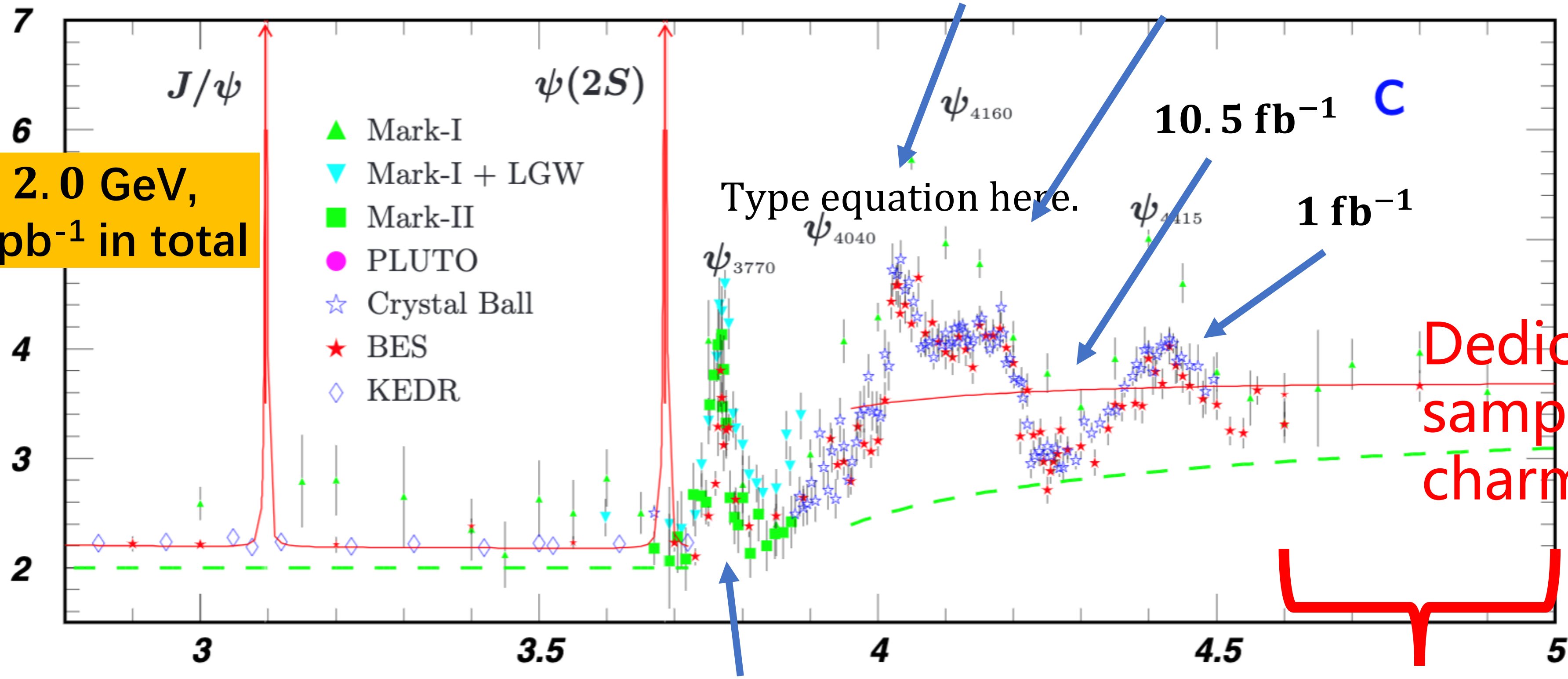


Data sets at BESIII

New!

1×10^{10} events 3×10^{9} events $0.5\ \mathrm{fb}^{-1}$ $3.2\ \mathrm{fb}^{-1}$

1.84< $\sqrt{s}$ < 2.0 GeV,
13 points, 25 pb^{-1} in total



Dedicated samples for charmed baryons

130 points, 2.0< $\sqrt{s} < 4.6$ GeV
1×10^{5} had. events each

$20\ \mathrm{fb}^{-1}$

$5.6\ \mathrm{fb}^{-1}$ at 14 points
$4.6<\sqrt{s}<5.0$ GeV

Publications related to Λ_c^+ at BESIII

The first period, with only 2014 data set

Hadronic decays	
$\Lambda_c \to pK\pi$ + 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, 112001 (2017)
$\Lambda_c \to p\eta, p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c \to \Sigma\pi^+\pi^-\pi^0$	PLB 772, 338 (2017)
$\Lambda_c \to \Xi^{0(*)}K$	PLB 783, 200 (2018)
$\Lambda_c \to \Lambda\eta\pi$	PRD 99, 032010 (2019)
$\Lambda_c \to pK_s\eta$	PLB 817 (2021) 136327

Semi-leptonic decays	
$\Lambda_c \to \Lambda e^+\nu$	PRL 115, 221805 (2015)
$\Lambda_c \to \Lambda\mu^+\nu$	PLB 767m 42 (2017)
Inclusive decays	
$\Lambda_c \to \Lambda + X$	PRL 121, 062003 (2018)
$\Lambda_c \to e^+ + X$	PRL 121, 251801 (2018)
$\Lambda_c \to K_s + X$	EPJC 80, 935 (2020)
Production	
$\Lambda_c^+\bar{\Lambda}_c^-$	PRL 120, 132001 (2018)

- **One of the highlights at BESIII !**
- **Higer stat samples in 2020 and 2021**

PDG in 2015

Λ_c^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	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		$(4.8\pm 1.9)\times 10^{-4}$	

PDG in 2020

	Mode		Fraction	Change	Scale factor
	Hadronic modes with a p or n: $S=-1$ final states				
Γ_1	pK^0_S		(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	$pK^0_S\pi^0$		(1.97 ± 0.13) %	↓ 50%	S=1.1
Γ_8	$nK^0_S\pi^+$		(1.82 ± 0.25) %	First	
Γ_9	$p\overline{K}^0\eta$		(1.6 ± 0.4) %		
Γ_{10}	$pK^0_S\pi^+\pi^-$		(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%

PDG in 2015

PDG in 2020

Improvement: Not only the central value, but also the uncertainty

Hadronic modes with a hyperon: $S = -1$ final states (PDG 2015)

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}	$\Xi(1690)^0 K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$		$(1.8 \pm 0.6) \times 10^{-3}$	
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) %	

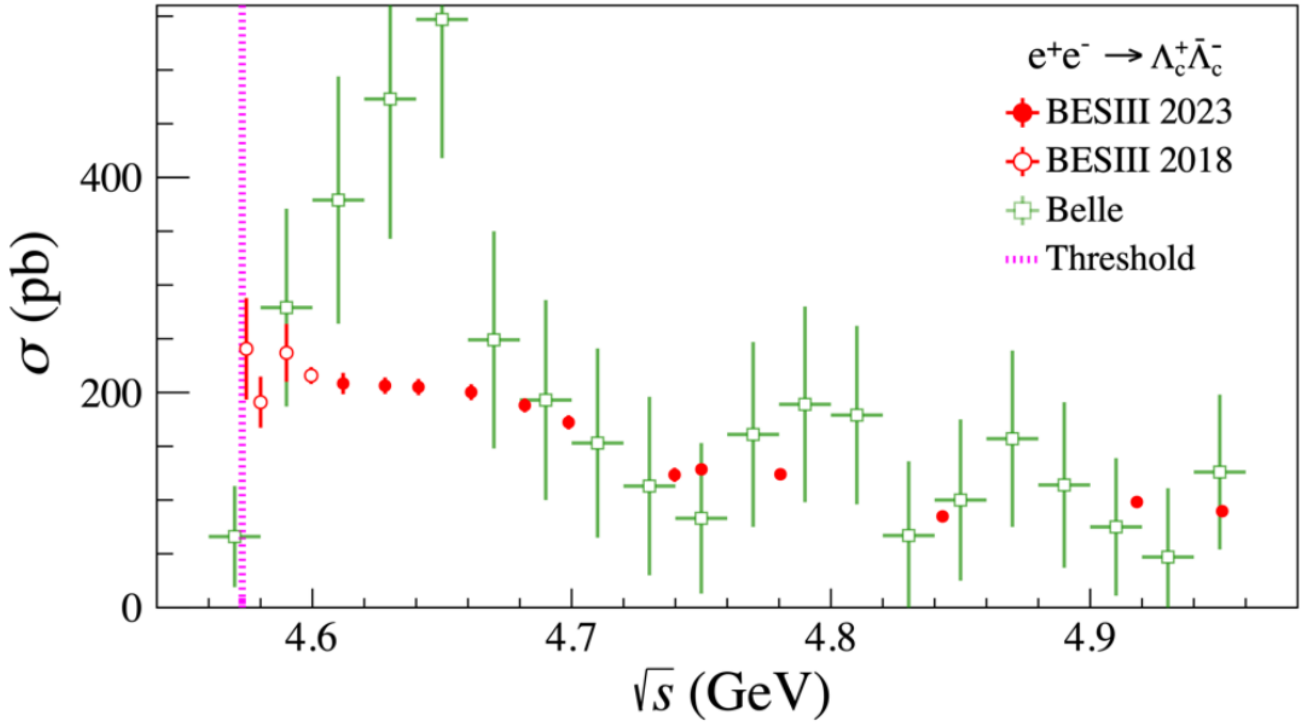
Hadronic modes with a hyperon: $S = -1$ final states (PDG 2020)

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) %	

Data sets collected in 2020 and 2021

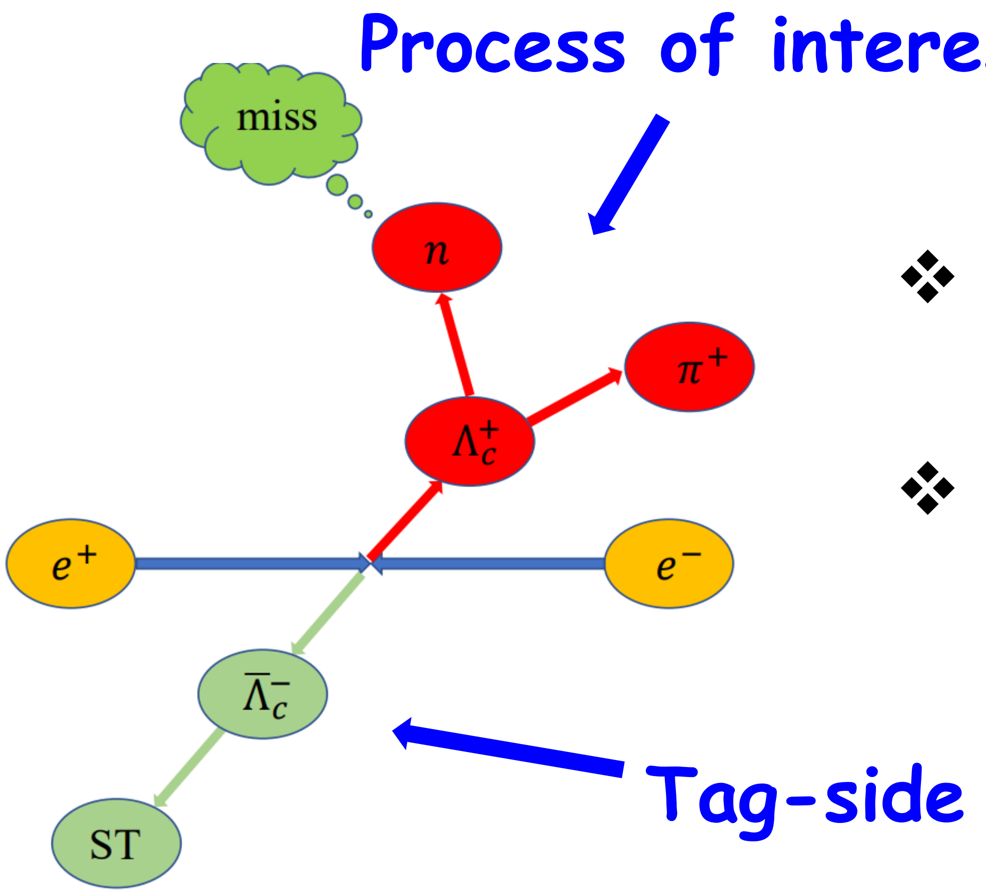


The 2nd period

Sample	E_{cms}/MeV	$\mathscr{L}_{Bhabha}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84
4740	4739.70±0.20±0.30	163.87±0.07±0.87
4750	4750.05±0.12±0.29	366.55±0.10±1.94
4780	4780.54±0.12±0.30	511.47±0.12±2.71
4840	4843.07±0.20±0.31	525.16±0.12±2.78
4920	4918.02±0.34±0.34	207.82±0.08±1.10
4950	4950.93±0.36±0.38	159.28±0.07±0.84

- **13 energy points between 4.61 ~ 4.95 GeV**
- **~5.6 fb^{-1} collision data in total**
- **about 1 million $\Lambda_c^+\bar{\Lambda}_c^-$ pair productions**

Strategies at BESIII : double-tag

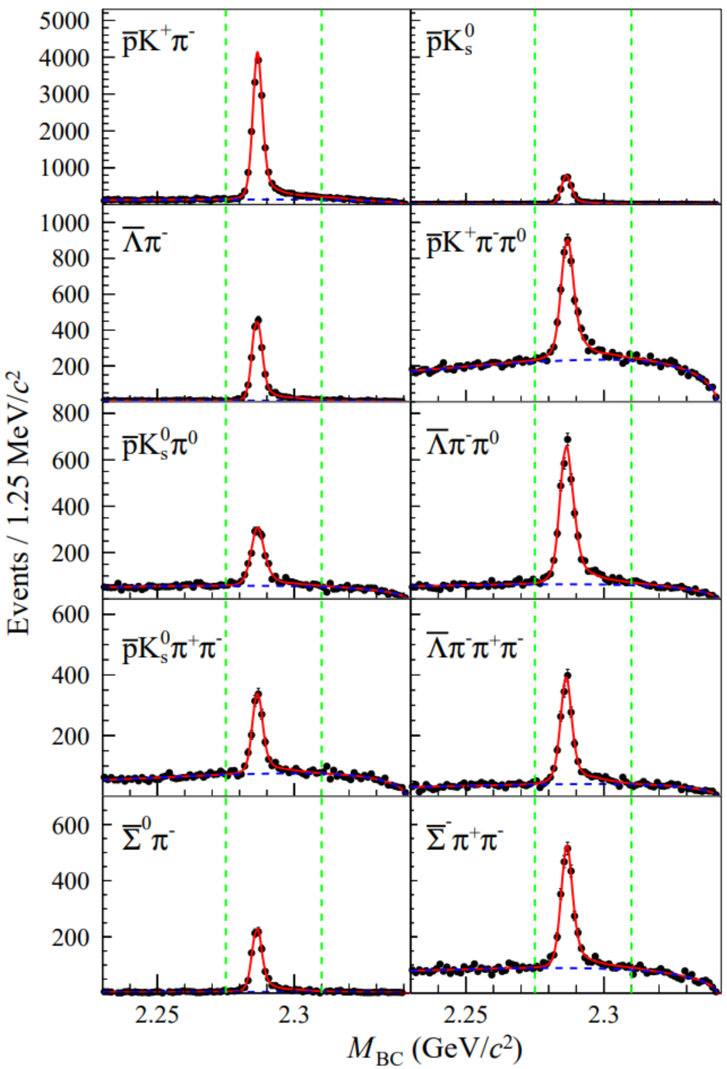


- In the center-of-mass system, Λ_c^+ is producted associated with the other $\bar{\Lambda}_c^-$.
- "Tagged" one $\bar{\Lambda}_c^-$, should exist the other Λ_c^+ in the opposite side.

Model-independent approach !

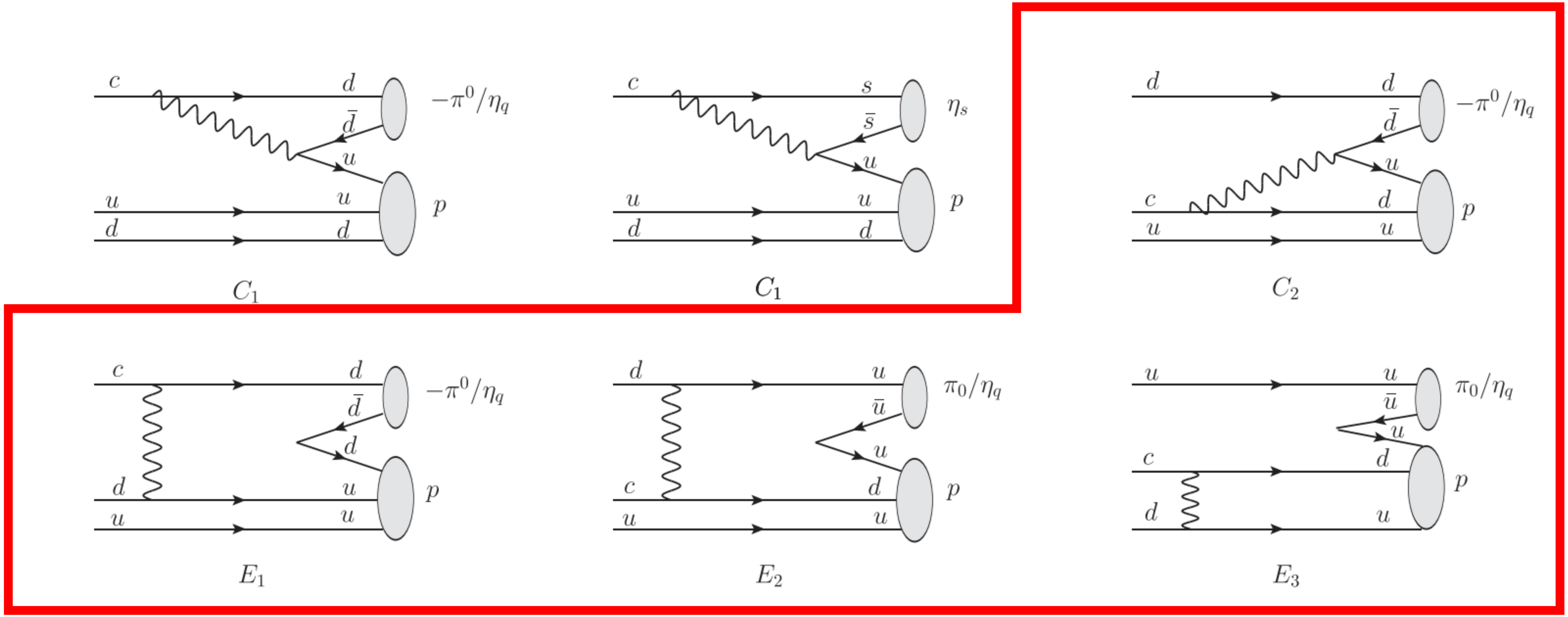
Single tag of Λ_c^+

$\sqrt{s}$ = 4.682 GeV as an example



- 10 hadronic tagged modes of Λ_c^+
- Total yield: $N_{ST} = 90692 \pm 359$ for 7 energy points @ 4.612-4.699 GeV
- The signal of interest is searched for in the opposite side of these single tagged Λ_c^+
- Charge-conjugate is included

Decays in Charmed Baryons



Calculation is not reliable, need exp. input

C_1 : factorization component

C_2,E_1,E_2,E_3: non-factorization component

Predictions

H.-Y. Cheng, et al.
PRD 97, 074028 (2018)

Before 2020

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

- ❖ $\Lambda_c^+ \to p\eta$: consistent between exp. and theo.
- ❖ The significant discrepancy in the channel $\Lambda_c^+ \to p\pi^0$
- ❖ Interference between factorization and non-factorization?

Experimental results on $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to n\pi^+$ are critical !

Cabibbo suppressed (CS) decays

- ❖Cabibbo flavored (CF) decays have been shown consistent results between experimental results and $SU(3)_f$
- ❖However, this is not applicable in CS decays

CF modes

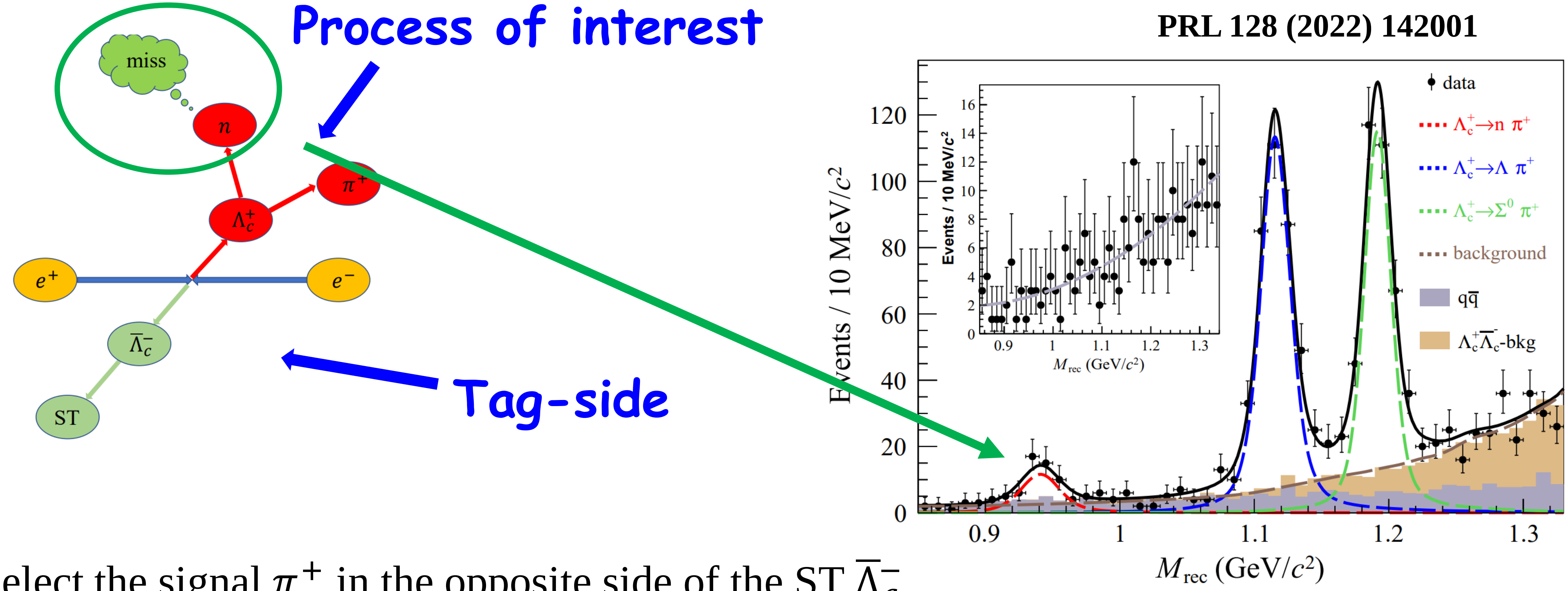
Decay branching ratio	Data	$SU(3)_F$ [22]
$10^3\mathcal{B}(\Lambda_c^+\to\Sigma^+\pi^0)$	12.4 ± 1.0	12.8 ± 2.3
$10^3\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta)$	7.0 ± 2.3	7.1 ± 3.8
$10^3\mathcal{B}(\Lambda_c^+\to\Sigma^0\pi^+)$	12.9 ± 0.7	12.8 ± 2.3
$10^3\mathcal{B}(\Lambda_c^+\to\Xi^0K^+)$	5.9 ± 0.9	5.5 ± 1.4
$10^3\mathcal{B}(\Lambda_c^+\to p\bar{K}^0)$	31.6 ± 1.6	32.7 ± 1.5
$10^3\mathcal{B}(\Lambda_c^+\to\Lambda^0\pi^+)$	13.0 ± 0.7	12.8 ± 1.7

C. Q. Geng, et al.
PRD 97, 073006 (2018)
Predicted: B($p\pi^0$):B($n\pi^+$)=1:2

CS modes

$10^4\mathcal{B}(\Lambda_c^+\to\Sigma^+K^0)$	–	8.0 ± 1.6
$10^4\mathcal{B}(\Lambda_c^+\to\Sigma^0K^+)$	5.2 ± 0.8	4.0 ± 0.8
$10^4\mathcal{B}(\Lambda_c^+\to p\pi^0)$	<2.7	5.7 ± 1.5
$10^4\mathcal{B}(\Lambda_c^+\to p\eta)$	12.4 ± 3.0	$12.5^{+3.8}_{-3.6}$
$10^4\mathcal{B}(\Lambda_c^+\to n\pi^+)$	–	11.3 ± 2.9
$10^4\mathcal{B}(\Lambda_c^+\to\Lambda^0K^+)$	6.1 ± 1.2	4.6 ± 0.9

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



- ❖ Select the signal π^+ in the opposite side of the ST $\bar{\Lambda}_c^-$.
- ❖ Extract the yields from the invariant mass of the missing part (i.e. neutron).

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

PRL 128, 142001 (2022)

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

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

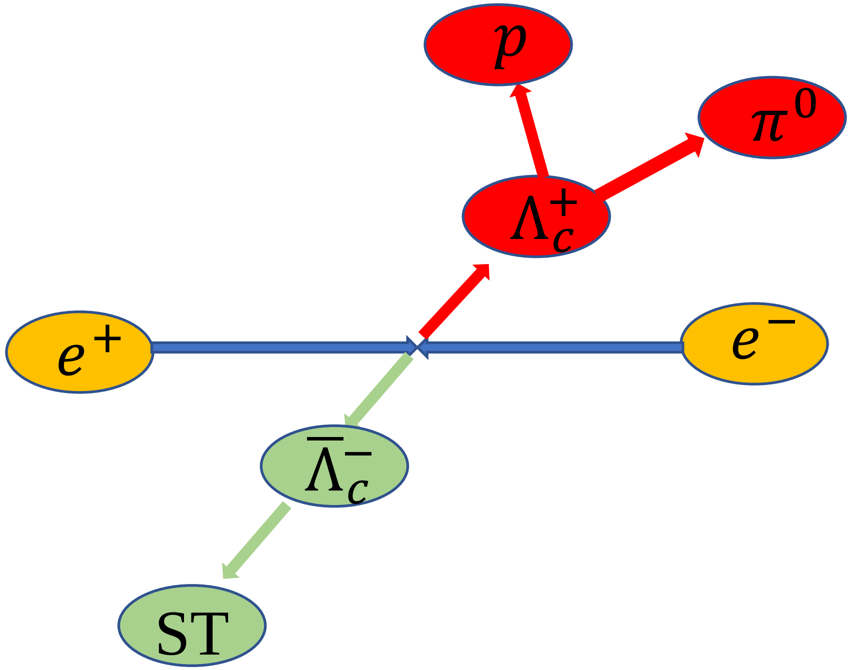
✓ Use $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ at 90% C.L. of Belle from PRD 103, 072004 (2021)

R	> 7.2 at 90% C.L.

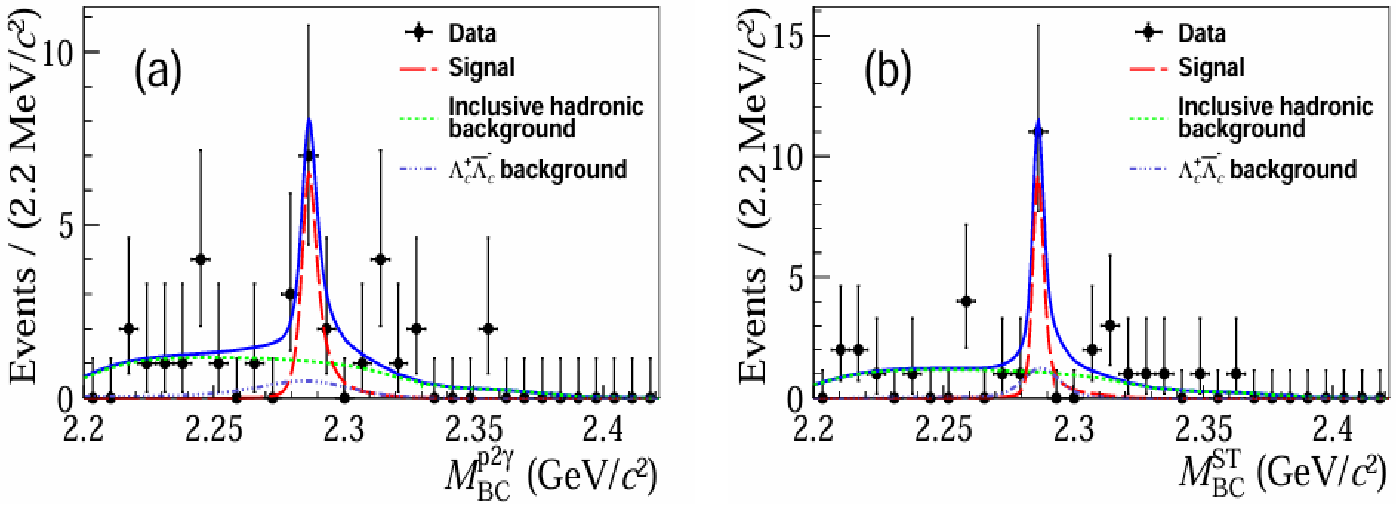
In 2022, disagree with most of predictions !?

$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	R	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165

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



PRD 109, L091101 (2024)



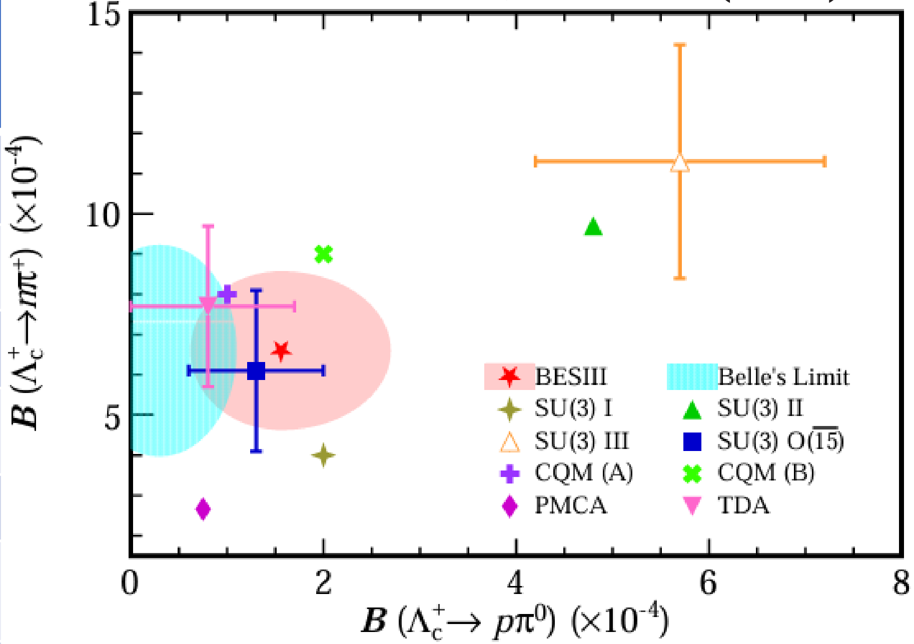
- Similar strategy as $\Lambda_c^+ \to n\pi^+$ is applied, but higher background
- 2D fit to extract the signal yield: ST $\bar{\Lambda}_c^-$ vs. signal $\Lambda_c^+ \to p\pi^0$
- Significance 3.7σ, branching fraction $(1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$

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

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times 10^{-4}$	$\mathcal{B}(\Lambda_c^+ \to p\pi^0)\times 10^{-4}$	R = $\mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0)$	Reference	models
$6.6 \pm 1.2 \pm 0.4$	$1.56^{+0.72}_{-0.58} \pm 0.20$	$3.2^{+2.2}_{-1.2}$	PRD 109, L091101 (2024)	Lastest results from BESIII
$6.6 \pm 1.2 \pm 0.4$ (BESIII)	$< 0.8 \times 10^{-4}$ (BELLE)	> 7.2 @90% C. L.		Result from BELLE
11.3 ± 2.9	5.7 ± 1.5	2	PRD 97, 073006 (2018)	SU(3)f with only H(6)
6.1 ± 2.0	1.3 ± 0.7	4.7	PLB 790, 225 (2019)	SU(3)f with both H(6) and H(15-bar)
8 or 9	1 or 2	4.5 or 8.0	PRD 49, 3417 (1994)	constituent quark model
2.66	0.75	3.5	PRD 97, 074028 (2018)	a dynamical calculation based on pole model and current-algebra
7.7 ± 2.0	$0.8^{+0.9}_{-0.8}$	9.6	JHEP 02 (2020) 165	topological-diagram approach
8.5 ± 2.0	1.2 ± 1.2	7.1 ± 7.3	PLB 794 (2019) 19–28	SU(3) flavor symmetry with O($\overline{15}$)
3.5 ± 1.1	44.5 ± 8.5	0.08	JHEP 03(2022) 143	
$6.47^{+1.33}_{-1.55}$ $8.15^{+0.69}_{-0.67}$	$0.51^{+0.59}_{-0.61}$ 0.16 ± 0.09	$12.69^{+15.4}_{-15.5}$ $50.94^{+29.0}_{-29.0}$	JHEP 02 (2023) 235	SU(3) broken SU(3) respected

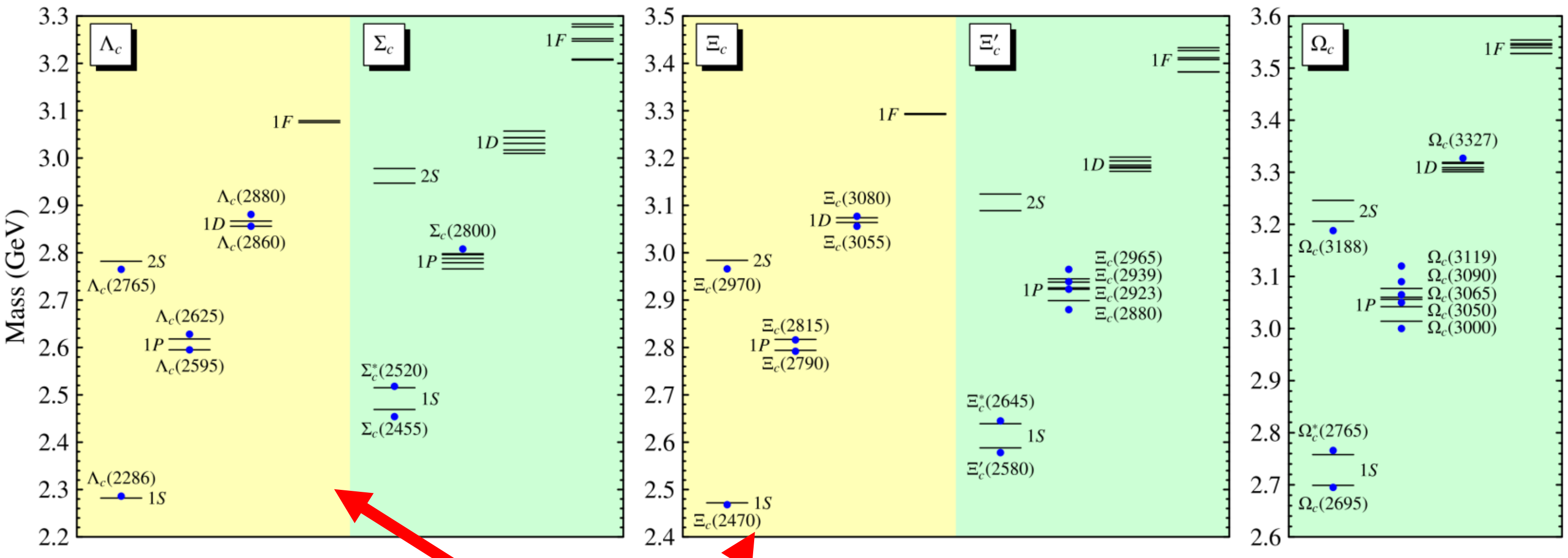
The interference between factorization and non-fac maybe is not significant !

PRD 109, L091101 (2024)



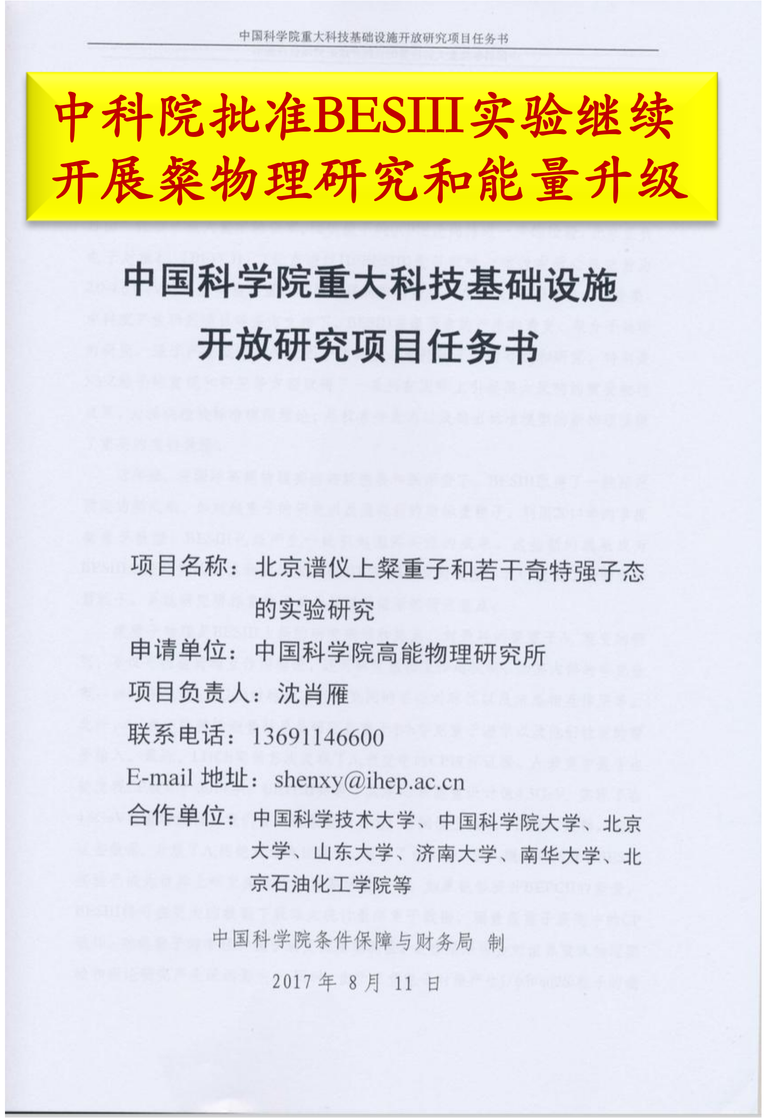
- ❖ Likely different from Belle
- ❖ consistent with SU(3) prediction with representation $H(6)$ and $H(\overline{15})$

Excited Charmed Baryons



CMS energy coverage：

Year 2019: 4.6 GeV → 4.95 GeV


中国科学院重大科技基础设施开放研究项目任务书

中科院批准BESIII实验继续开展粲物理研究和能量升级

中国科学院重大科技基础设施

开放研究项目任务书

项目名称：北京谱仪上粲重子和若干奇特强子态的实验研究

申请单位：中国科学院高能物理研究所

项目负责人：沈肖雁

联系电话：13691146600

E-mail 地址：shenxy@ihep.ac.cn

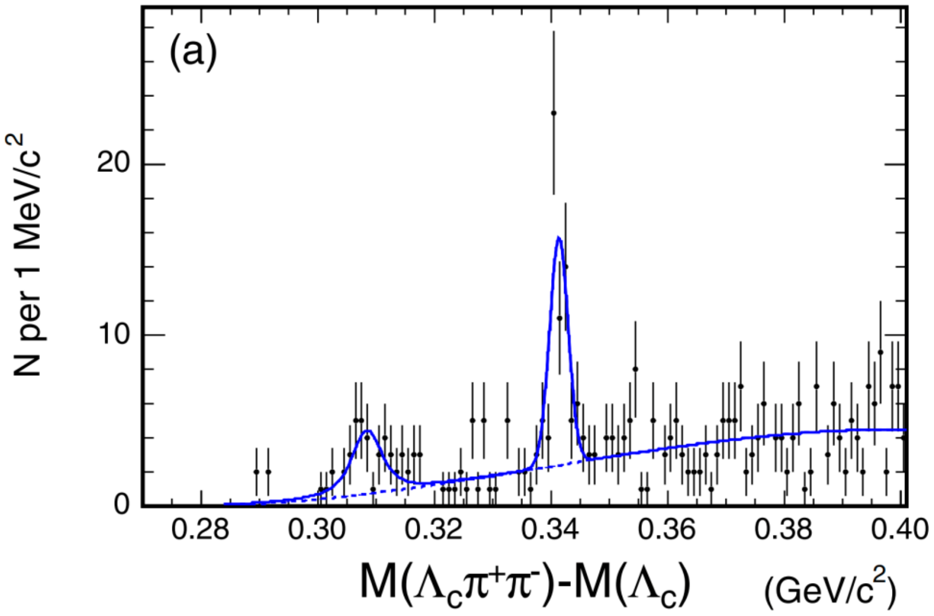
合作单位：中国科学技术大学、中国科学院大学、北京大学、山东大学、济南大学、南华大学、北京石油化工学院等

中国科学院条件保障与财务局 制

2017 年 8 月 11 日

P-wave: $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$

CDF Collaboration
PRD 79, 032001 (2009)



$$R_1 \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2595)^+ \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)} = 0.126 \pm 0.033(\text{stat}) {}^{+0.047}_{-0.038}(\text{syst}),$$

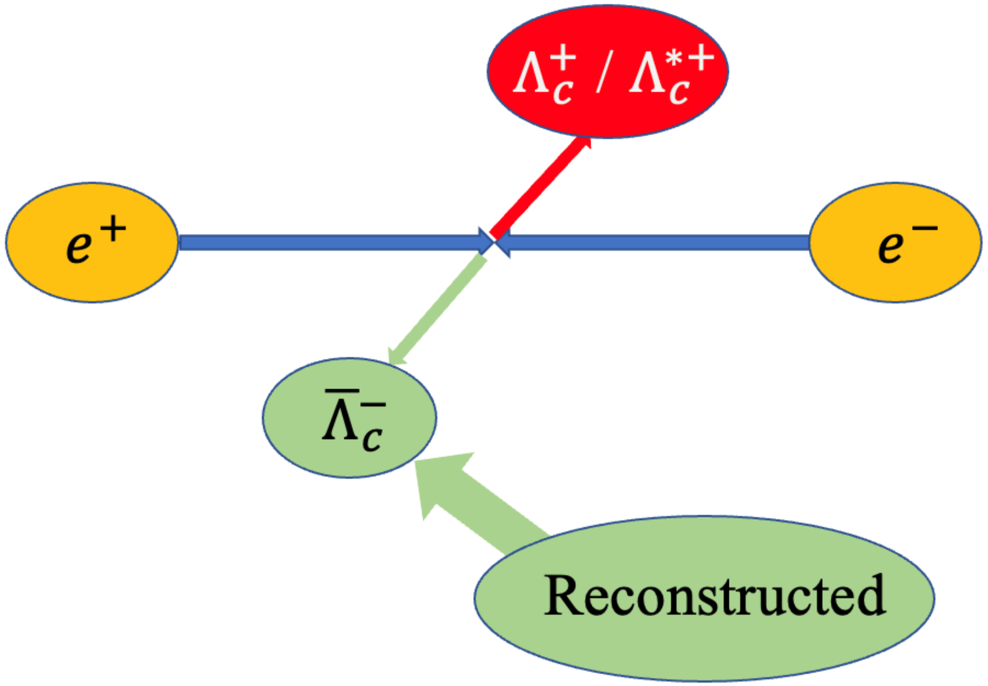
$$R_2 \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2625)^+ \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)} = 0.210 \pm 0.042(\text{stat}) {}^{+0.071}_{-0.050}(\text{syst}),$$

The production rate is different from LQCD prediction!

- $\Lambda_c(2595)^+$ is at the threshold of $\Sigma_c\pi$
- Analogous to problem of $\Lambda(1405)$ and $\Lambda(1520)$?

Exotic state?

Production measurements at BESIII

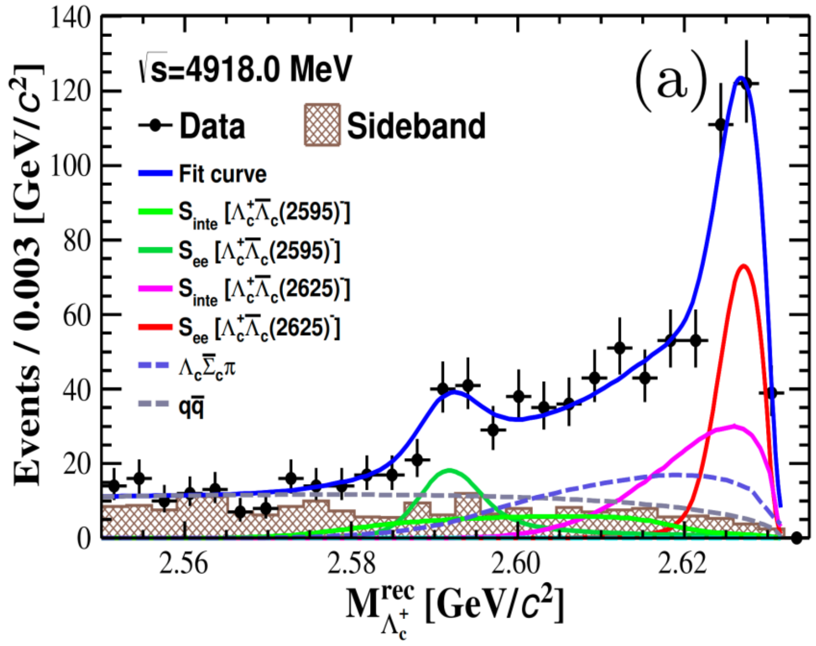


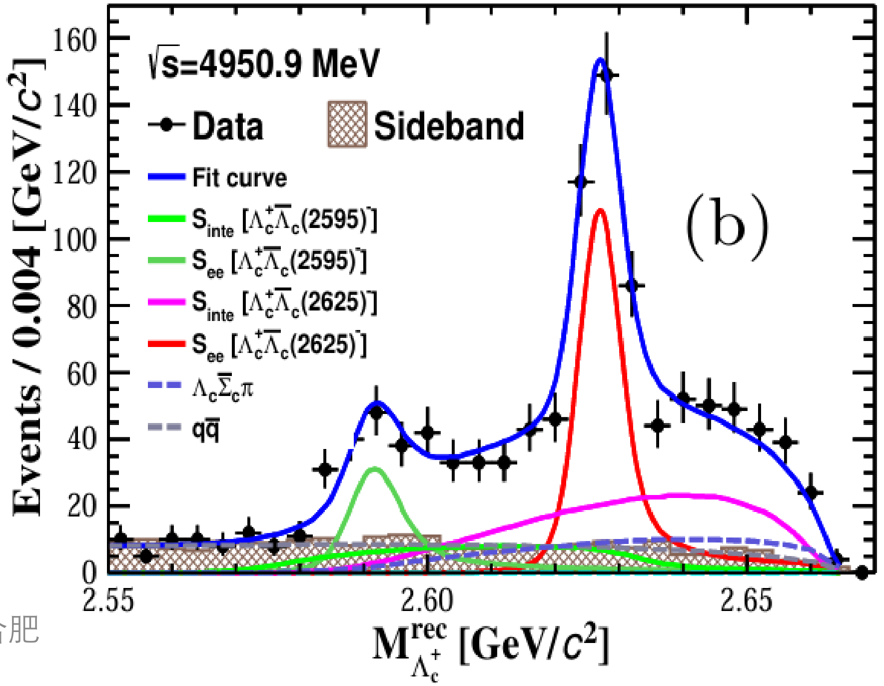
- Λ_c^+ + $\Lambda_c{}^*$ produced near the threshold
- "Tagged" one $\bar{\Lambda}_c^-$ to extract the production information

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

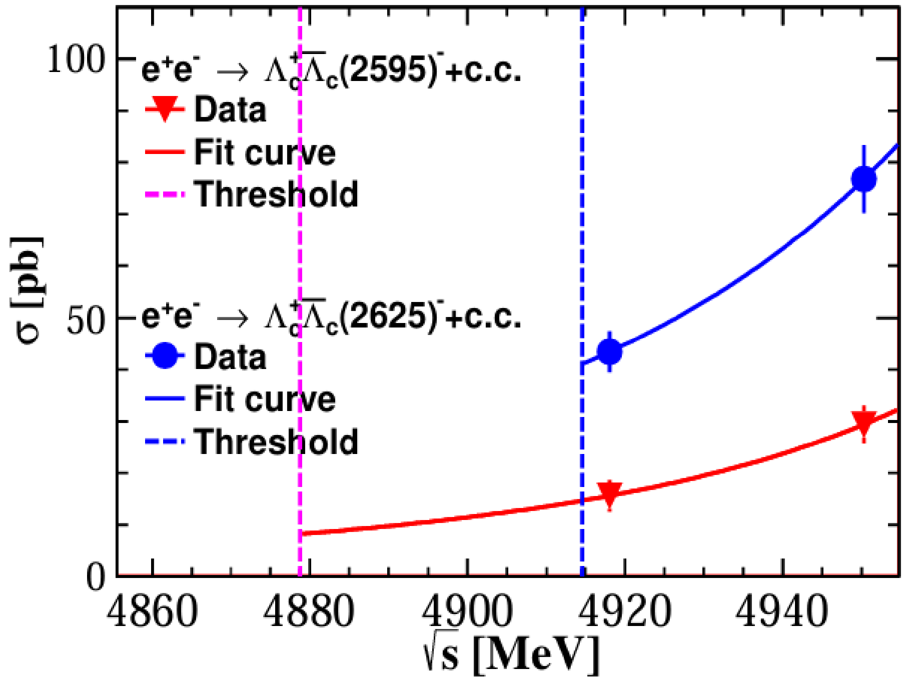
PRD 109, L071104 (2024)

- Select candidates of $\Lambda_c^+ \to pK^-\pi^+$
- Search for the excited states in the opposite side
- Applicable only at $\sqrt{s} = 4.918$ and 4.950 GeV





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



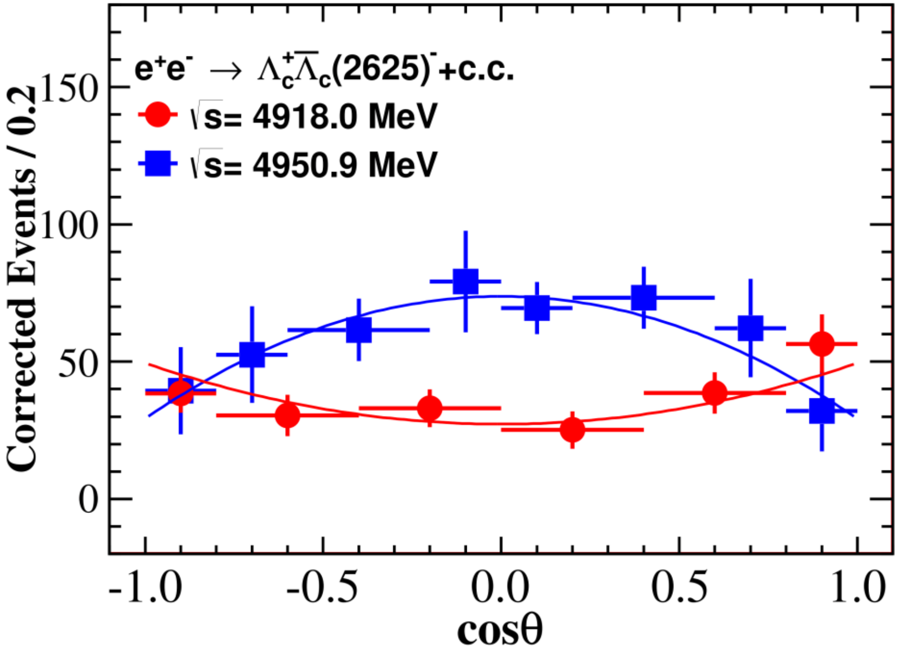
- Model dependent fit and ISR correction with

$$\sigma(s) = \frac{C\beta}{s}(1+\frac{2mm_*}{s})\frac{c_0}{(s-c_1)^4[\pi^2+\ln^2(\frac{s}{\Lambda_{\rm QCD}^2})]^2}$$

- Non-zero cross section at the threshold for $\Lambda_c(2625)^+$
- $\Lambda_c(2625)^+$ production rate is 2-3 times higher than $\Lambda_c(2595)^+$

Signal process	$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^- +$ c.c.		$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^-$+c.c.	
$\sqrt{s}$ (MeV)	4918.0	4950.9	4918.0	4950.9
$N_{\rm sig}$	148 ± 29	216 ± 27	311 ± 28	552 ± 47
ε (%)	47.0 ± 0.1	46.8 ± 0.1	46.7 ± 0.1	46.8 ± 0.1
$f_{\rm ISR}$	0.735	0.741	0.558	0.728
σ (pb)	$15.6 \pm 3.1 \pm 0.9$	$29.4 \pm 3.7 \pm 2.4$	$43.4 \pm 4.0 \pm 4.1$	$76.8 \pm 6.5 \pm 4.2$

Form factors in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^+$



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

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

$$\frac{|G_E|^2+3|G_M|^2}{|G_C|^2} = \frac{1}{\tau}\cdot\frac{1+\alpha_{\Lambda_c}}{1-\alpha_{\Lambda_c}}$$

The direction of angular curve flips in very narrow range !

- ❖ Oscillation feature as proton/neutron ?
- ❖ Need fine scan in future !

	4.918 GeV	4.951 GeV
α_{Λ_c}	0.82±0.56±0.02	−0.60±0.20±0.01
$\sqrt{\|G_E\|^2+3\|G_M\|^2}/\|G_C\|$	5.95±4.07±0.15	0.94±0.32±0.02

Decays of $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$

PDG-2022

- Strong transition is dominant.
- Relative measurements was performed w.r.t mode $\Lambda_c^+\pi^+\pi^-$
- Isospin relation is assumed: $\Lambda_c^+\pi^+\pi^-$: $\Lambda_c^+\pi^0\pi^0$ = 2:1

$\Lambda_c(2595)^+$ $\quad I(J^P) = 0(\frac{1}{2}^-)$

The spin-parity follows from the fact that $\Sigma_c(2455)\pi$ decays, with little available phase space, are dominant. This assumes that $J^P = 1/2^+$ for the $\Sigma_c(2455)$.

Mass $m = 2592.25 \pm 0.28$ MeV
$m - m_{\Lambda_c^+} = 305.79 \pm 0.24$ MeV
Full width $\Gamma = 2.6 \pm 0.6$ MeV

$\Lambda_c^+\pi\pi$ and its submode $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the submode seems to dominate.

$\Lambda_c(2595)^+$ DECAY MODES		Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	[s]	—	117
$\Sigma_c(2455)^{++}\pi^-$		24 ± 7 %	†
$\Sigma_c(2455)^0\pi^+$		24 ± 7 %	†
$\Lambda_c^+\pi^+\pi^-$ 3-body		18 ± 10 %	117

See Particle Listings for 2 decay modes that have been seen / not seen.

$\Lambda_c(2625)^+$ $\quad I(J^P) = 0(\frac{3}{2}^-)$

J^P has not been measured; $\frac{3}{2}^-$ is the quark-model prediction.

Mass $m = 2628.11 \pm 0.19$ MeV $\quad$ (S = 1.1)
$m - m_{\Lambda_c^+} = 341.65 \pm 0.13$ MeV $\quad$ (S = 1.1)
Full width $\Gamma < 0.97$ MeV, CL = 90%

$\Lambda_c^+\pi\pi$ and its submode $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

$\Lambda_c(2625)^+$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	≈ 67%		184
$\Sigma_c(2455)^{++}\pi^-$	<5	90%	102
$\Sigma_c(2455)^0\pi^+$	<5	90%	102
$\Lambda_c^+\pi^+\pi^-$ 3-body	large		184

See Particle Listings for 2 decay modes that have been seen / not seen.

Strong transition between P and S-wave

Two Couplings in heavy hadron chiral perturbation theory

$$\Gamma(\Lambda_{c1}(1/2^-) \to \Sigma_c\pi) = \frac{h_2^2}{2\pi f_\pi^2}\frac{m_{\Sigma_c}}{m_{\Lambda_{c1}}}E_\pi^2 p_\pi$$

$$\Gamma(\Lambda_{c1}(3/2^-) \to \Sigma_c\pi) = \frac{2h_8^2}{9\pi f_\pi^2}\frac{m_{\Sigma_c}}{m_{\Lambda_{c1}(3/2)}}p_\pi^5$$

- Due to the decay width of $\boldsymbol{\Lambda_c(2625)^+}$ is almost zero, the coupling h_8 is only determined to be an upper limit.
- The derivation is very sensitive to the kinematical phase space because $\boldsymbol{\Lambda_c(2595)^+}$ **and** $\boldsymbol{\Lambda_c(2625)^+}$ are close to the threshold of $\Sigma_c\pi$ ➔ Isospin violation ?

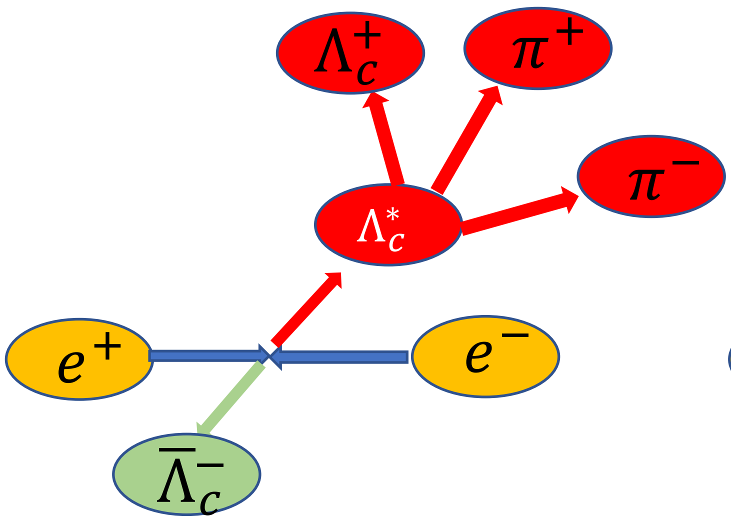
Direct measurement on the strong decays can answer this question !

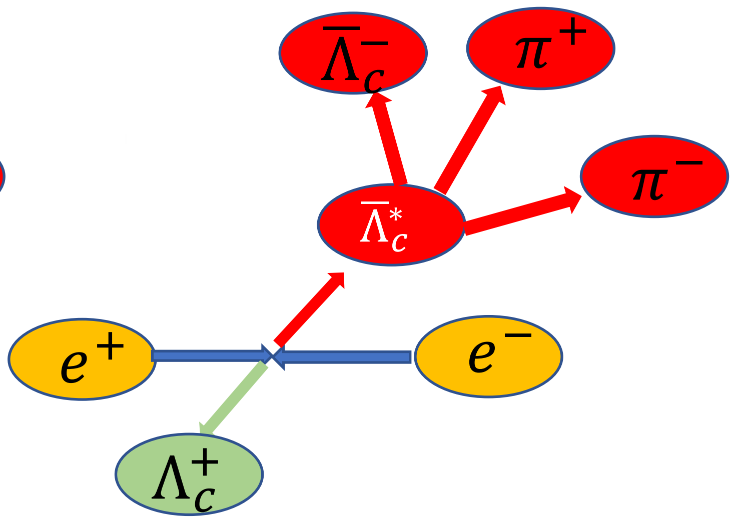
Measurements of strong transition

PRD 109, 112007 (2024)

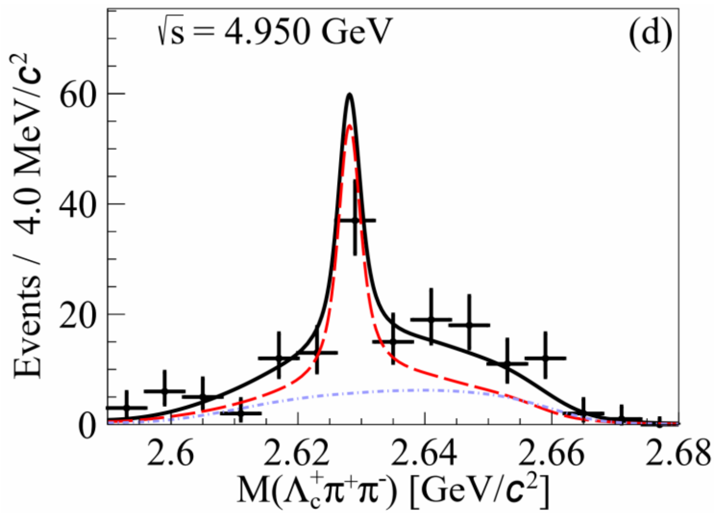
$\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$

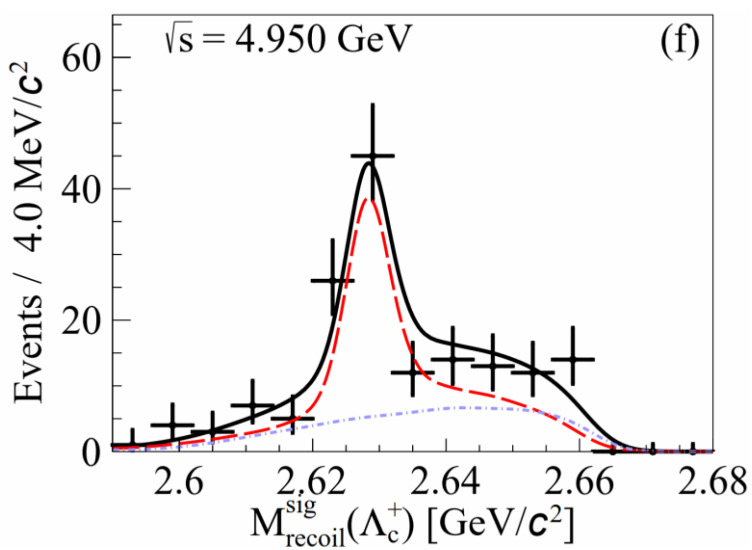
- Based on the previous cross section measurement
- After selecting Λ_c^+, require additional $\pi^+\pi^-$ pair in each event
- another $\overline{\Lambda}_c^-$ be a missing particle and not required to reconstruct (under E-P conservation)





Model-independent



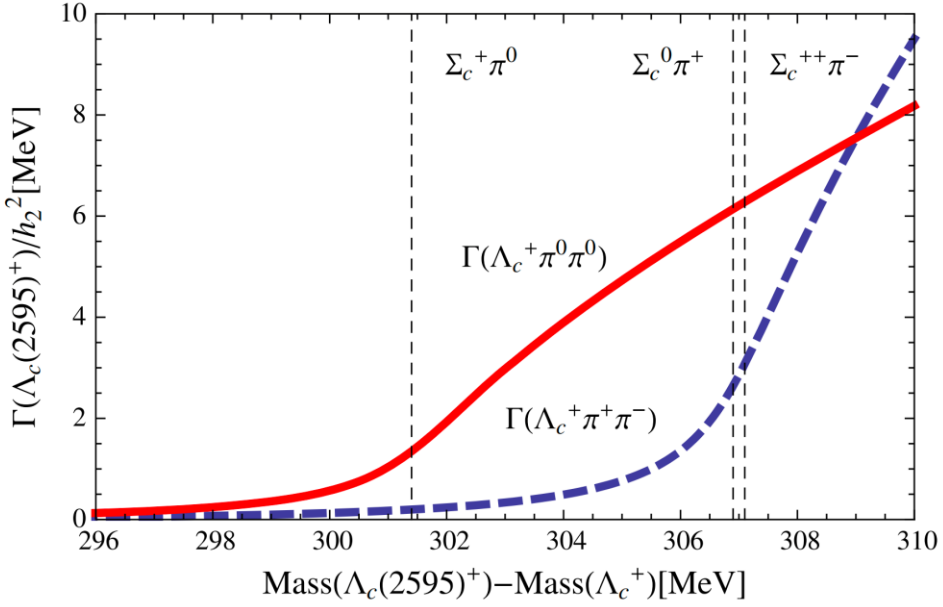


Results of Branching fractions

PRD 109, 112007 (2024)

	This result	Assumption
$\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$	50.7 ± 5.0 ± 4.9	67%
$\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$	<81% (at 90% CL)	67%

Hai-Yang Cheng and Chun-Khiang Chua, PRD 92, 074014 (2015)



- Due to low momentum in decays of $\Lambda_c(2595)^+$, the $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$ is not observed.
- Likely the threshold effect also exist in decays of $\Lambda_c(2625)^+$. $B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-) = B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^0\pi^0)$, if considering the strong decays is 100% .

Released results in the 2nd period

Cabibbo suppressed (hadronic)	
$\Lambda_c^+ \to n\pi^+$	PRL 128, 142001 (2022)
$\Lambda_c^+ \to p\eta, p\omega$	JHEP 11 (2023) 137
$\Lambda_c^+ \to p\eta'$	PRD 106, 072002 (2022)
$\Lambda_c^+ \to p\pi^0$	PRD 109, L091101 (2024)
$\Lambda_c^+ \to \Lambda K^+$	PRD 106, L111101 (2022)
$\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S$	PRD 106, 052003 (2022)
$\Lambda_c^+ \to \Sigma^- K^+ \pi^+$	PRD 109, L071103 (2024)
$\Lambda_c^+ \to nK^+\pi^0$ (DCS)	PRD 109, 052001 (2024)
$\Lambda_c^+ \to nK_S K^+, nK_S\pi^+$	arXiv: 2311.17131
$\Lambda_c^+ \to \Lambda K^+\pi^0$, $\Lambda K^+\pi^+\pi^-$	PRD 109, 032003 (2024)

Cabibbo favored (hadronic)	
$\Lambda_c^+ \to \Xi^0 K^+$	PRL 132, 031801 (2024)
$\Lambda_c^+ \to nK_s\pi^+\pi^0$	PRD 109, 053005 (2024)
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	JHEP 12 (2022) 033

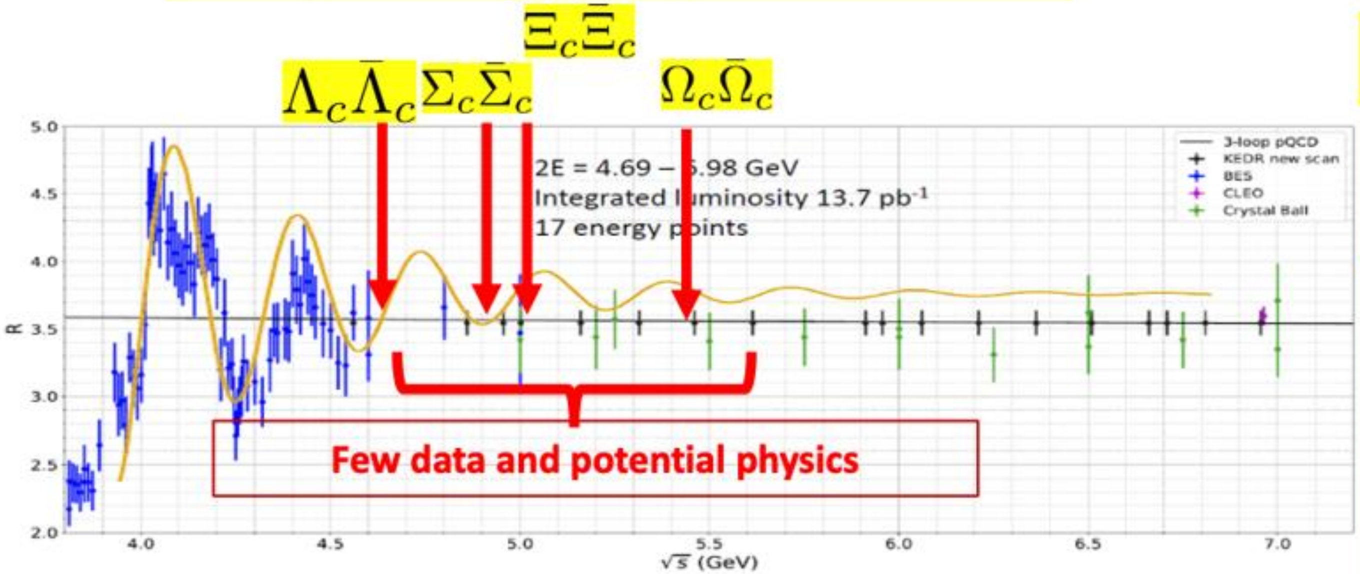
Semileptonic	
$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL 129, 231803 (2022)
$\Lambda_c^+ \to \Lambda\mu^+\nu_e$	PRD 108, 031105 (2023)
$\Lambda_c^+ \to pK^-e^+\nu_e$	PRD 106, 112010 (2022)
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ $\Lambda_c^+ \to pK_S e^+\nu_e$	PLB 843 (2023) 137993

Others	
$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$	PRL 131, 191901 (2023)
$\Lambda_c^+ \to e^+ + X$	PRD 107, 052005 (2023)
$\bar{\Lambda}_c^- \to \bar{n} + X$	PRD 108, L031101 (2023)
$\Lambda_c^+ \to \Sigma^+ + \gamma$	PRD 107, 052002 (2023)
$\Lambda_c^+ \to p + \gamma'$	PRD 106, 072008 (2022)
$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^{*-}$	PRD 109, L071104 (2024)
$\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$	PRD 109, 112007 (2024)

>10 analyses are under review inside Collaboration

Prospect at BESIII

Many charmed baryon thresholds



BEPCII upgrade: In 2024

Scan data： 65 fb^{-1}

4.01 GeV: 20 fb^{-1} DsDs

4.60 GeV: 20 fb^{-1} Λ_c Λ_c

Others

✓ Ξ_c $\bar{\Xi}_c$ 6 fb^{-1} 4.95 -4.97GeV

✓ $\Omega_c^0\bar{\Omega}_c^0$ 6 fb^{-1} 5.4 -5.5 GeV

Total： **117fb^{-1}**

Unique data samples at the thresholds for charmed baryons.

❖Hadron physics: spectroscopy, (transition-)form-factors, fragmentation ...

❖Precise test of SM: weak decays, CKM, CP violation, rare/forbidden decays ...

Summary

❖After the upgrade, the BESIII has collected dedicated data for the charmed baryons between $\sqrt{s} = 4.6 \sim 4.95$ GeV

❖The $\Lambda_c^+ \rightarrow n\pi^+$ and $\Lambda_c^+ \rightarrow p\pi^0$ have been investigated, and SU(3)f provides consistent predictions.

❖The excited charmed baryons $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ can also be probed at BESIII. Production cross sections and decay rates are measured for the first time.

❖In 2024, the BEPC-II will be upgraded again. Larger data sets covering the charmed baryons will be collected, and more interesting results will be produced.