Recent Progress on Charmed Baryons at BESIII

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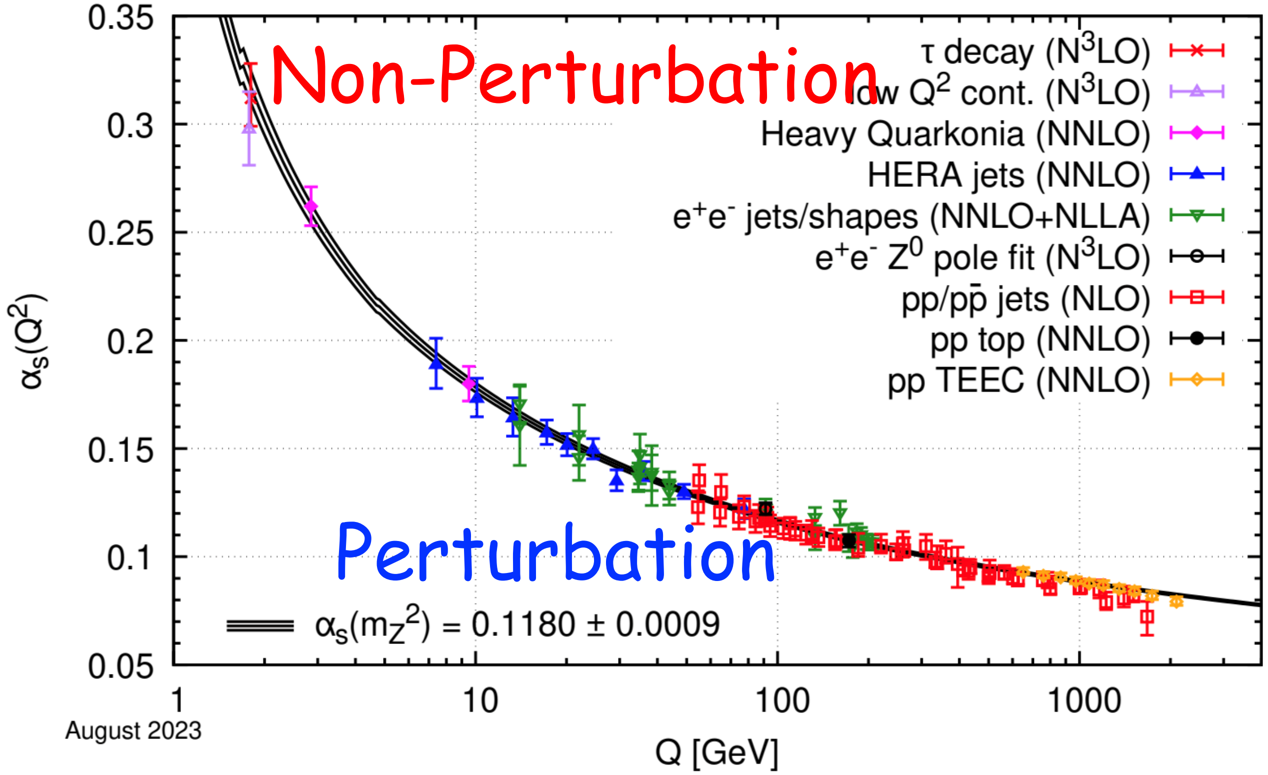
第一届超子物理研讨会-惠州

Outline

- ❖ Interests in Charmed Baryons
- ❖ BESIII experiment
- ❖ Productions and Decays
- ❖ List of the released results
- ❖ Prospect at BESIII

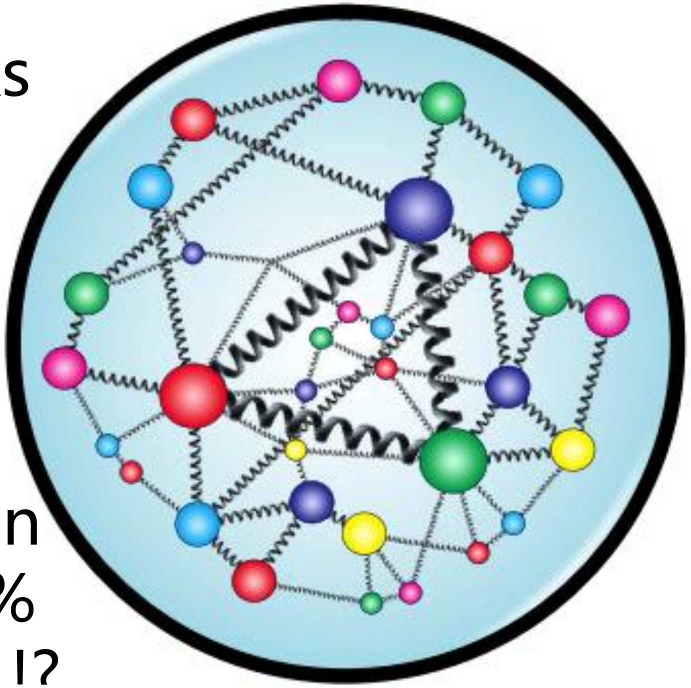
Quantum Chromodynamics



In 2011， I asked David Gross:
“Can we **really** see the free quarks?”

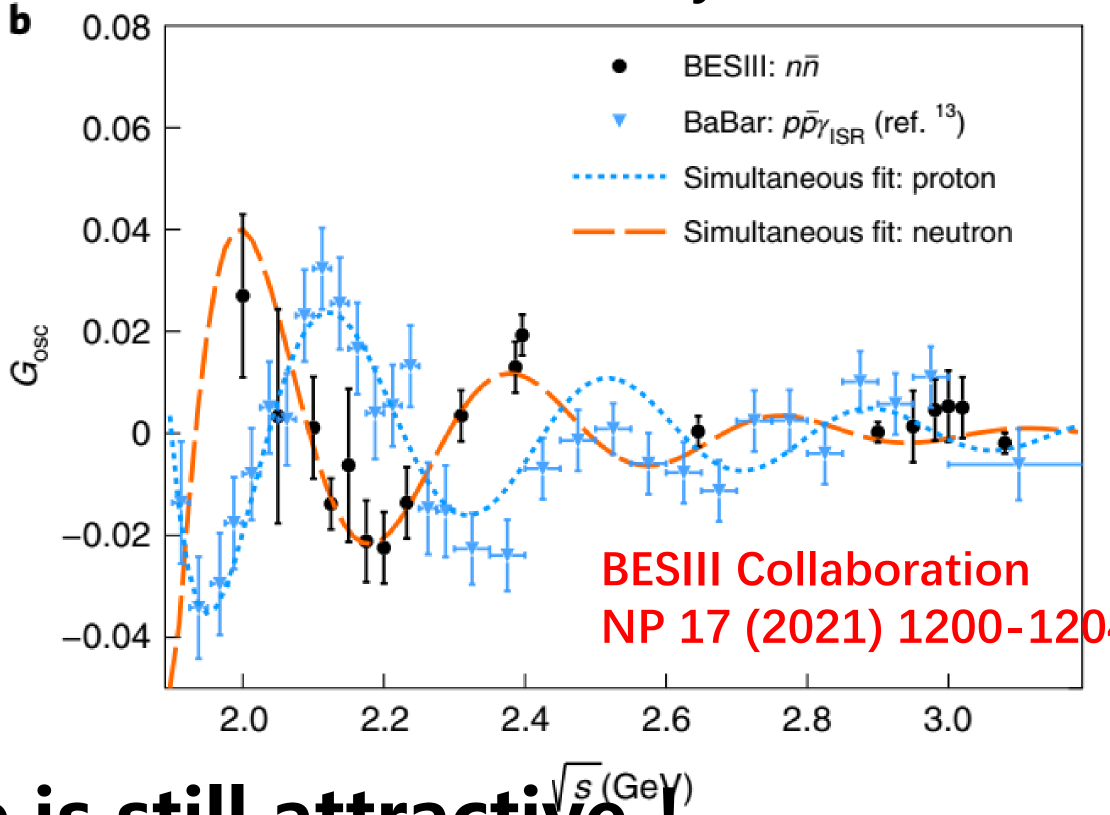
Mystery in Baryons

sea quarks
gluons



Strong interaction contributes >90% mass of baryons !?

Form factors oscillate as center-of-mass system (CMS)

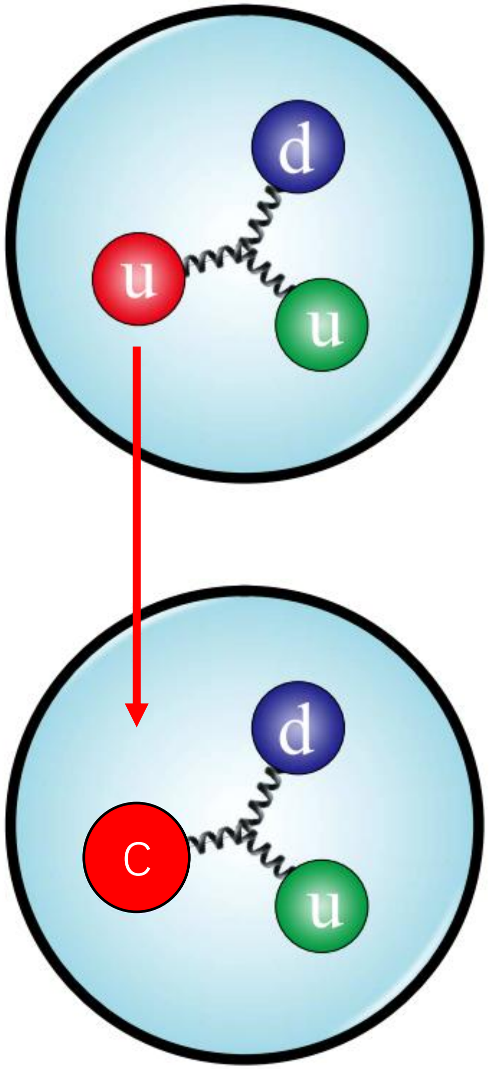


BESIII Collaboration
NP 17 (2021) 1200-1204

Neucleon structure is still attractive !

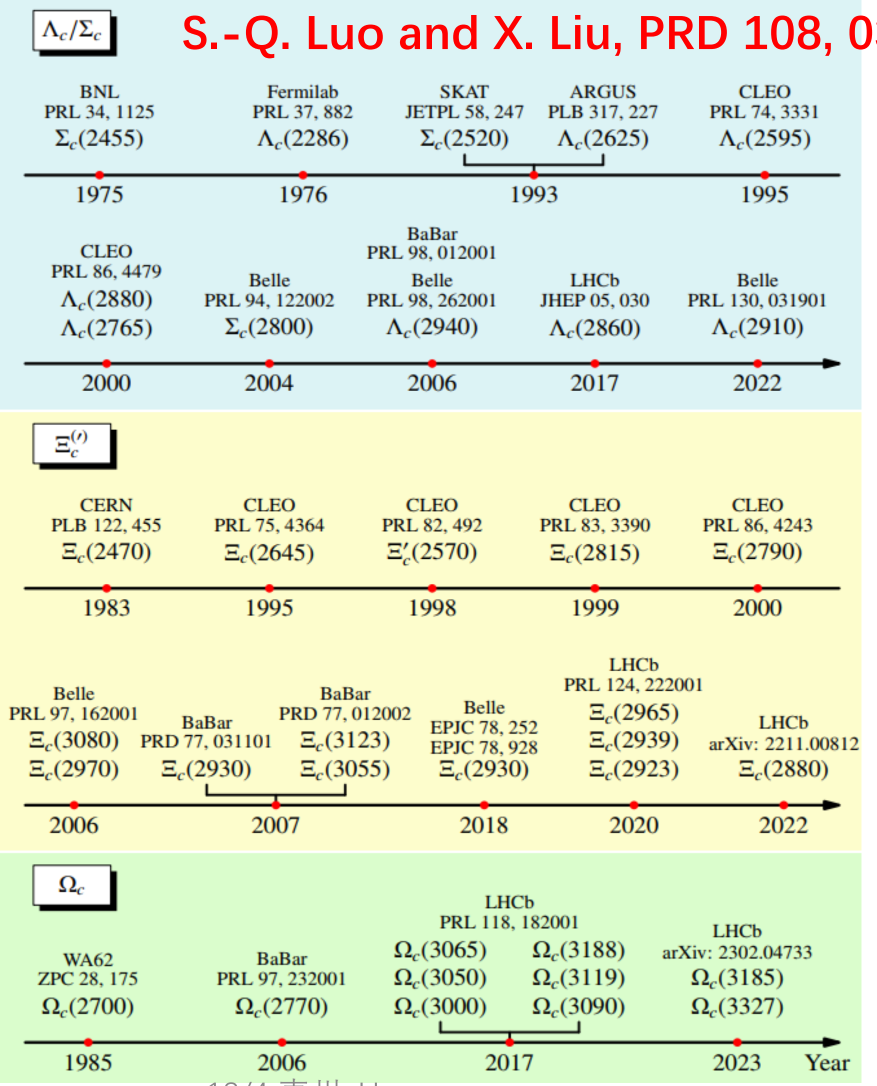
Charmed Baryons

Baryon



Charmed Baryon

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

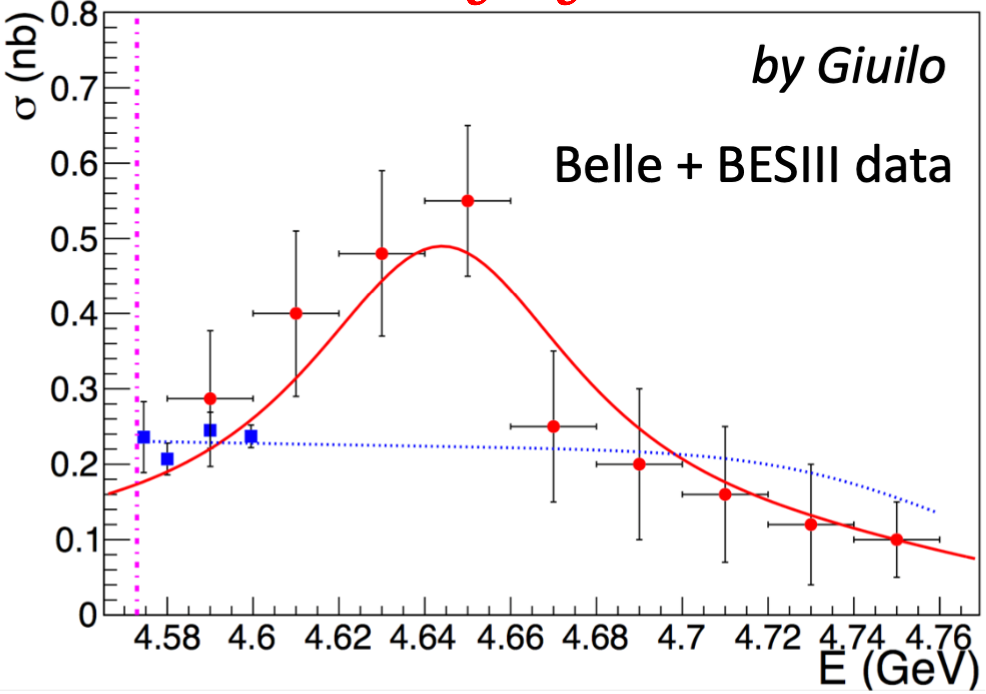


Discovered shortly after J/ψ

But, both experiment and theory develop slowly

Productions and Decays

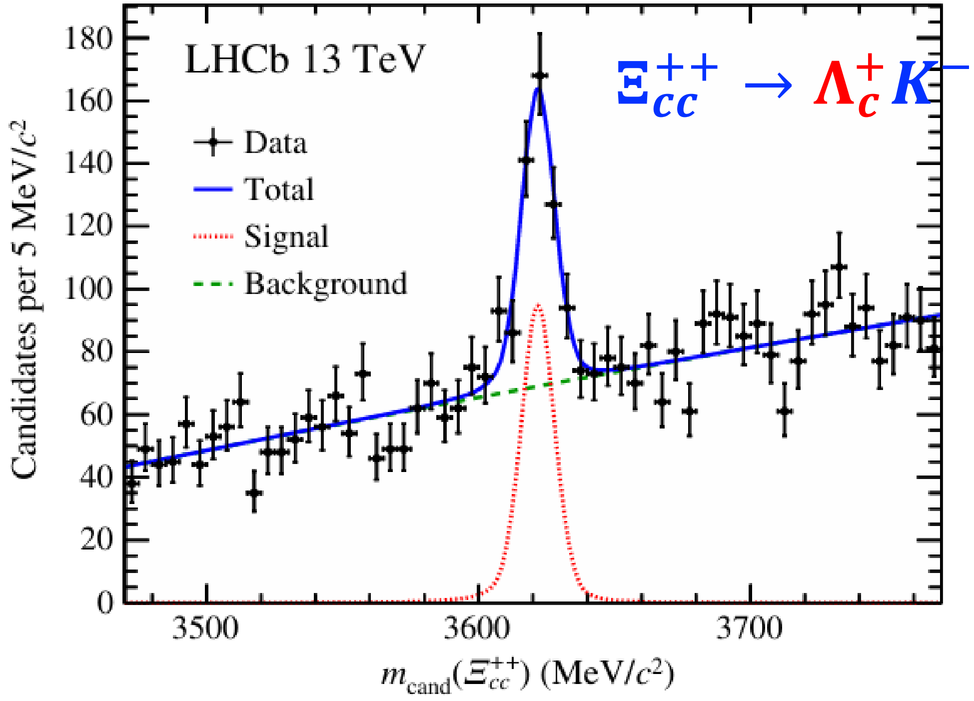
$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$



BESIII Collaboration, PRL 120, 132001 (2018)
Belle Collaboration, PRL 101, 172001 (2008)

Doubly charmed Baryons !

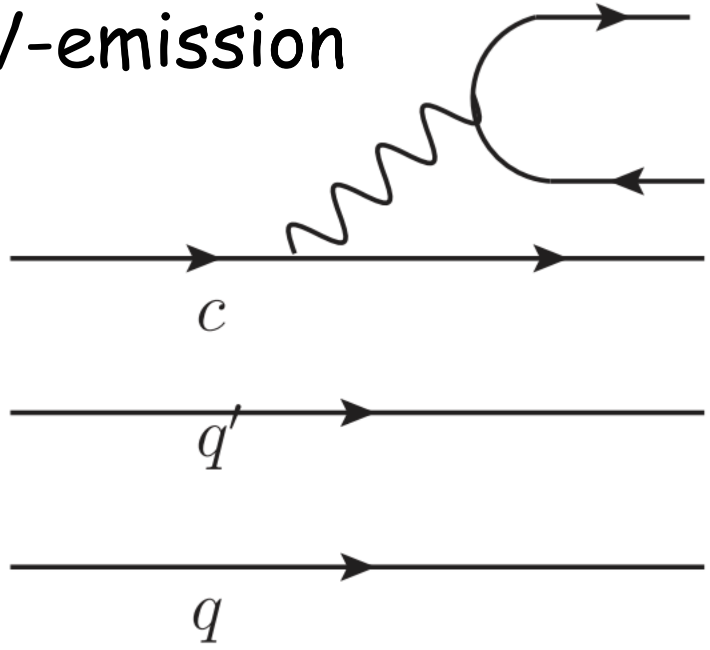
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



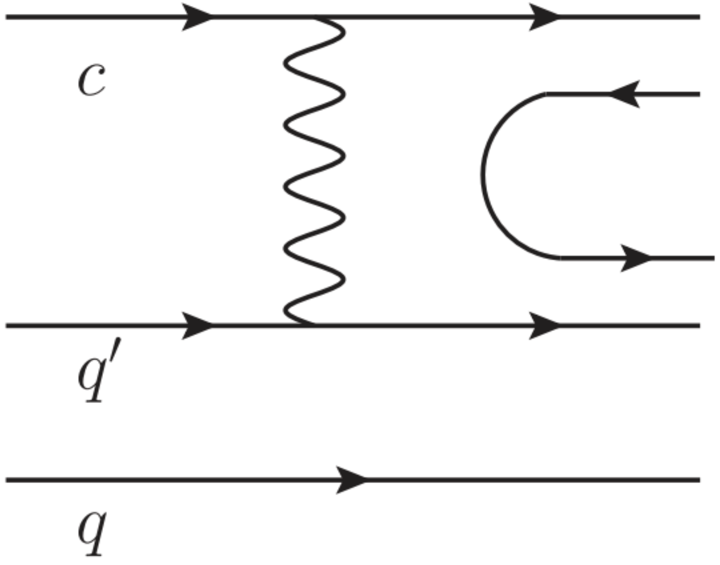
LHCb Collaboration, PRL 119, 112001 (2017)
F. S. Yu et al. , CPC 42, 051001 (2018)

Productions and Decays

W-emission



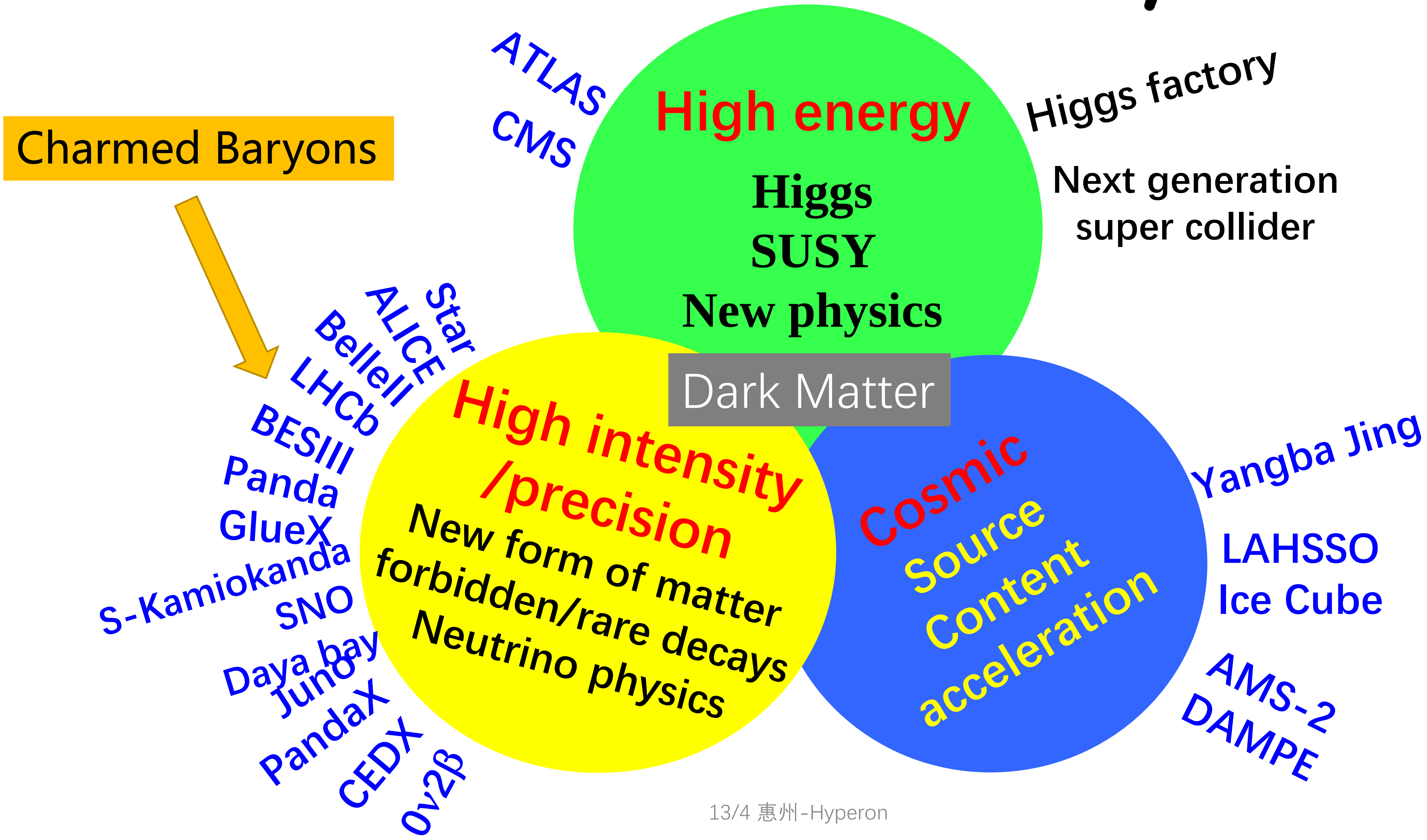
W-exchange
(suppressed in charmed mesons)



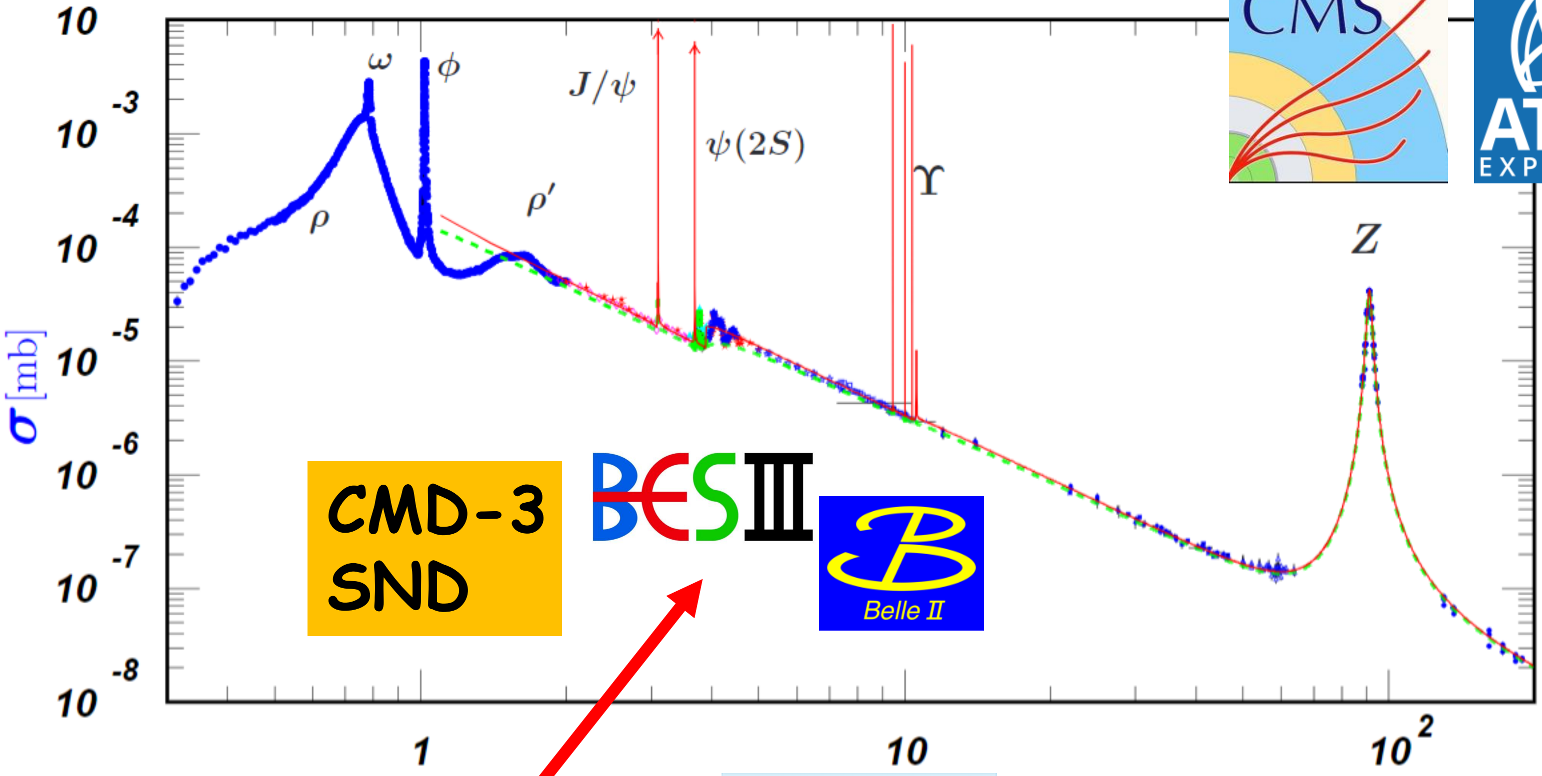
L.-L. Chau and H.-Y. Cheng, PRL 56, 1655 (1986)

- ❖ W-exchange in baryon decays is not subject to color suppression
- ❖ Non-factorization contribution is significant !

Frontier of Particle Physics



Experiments in the world

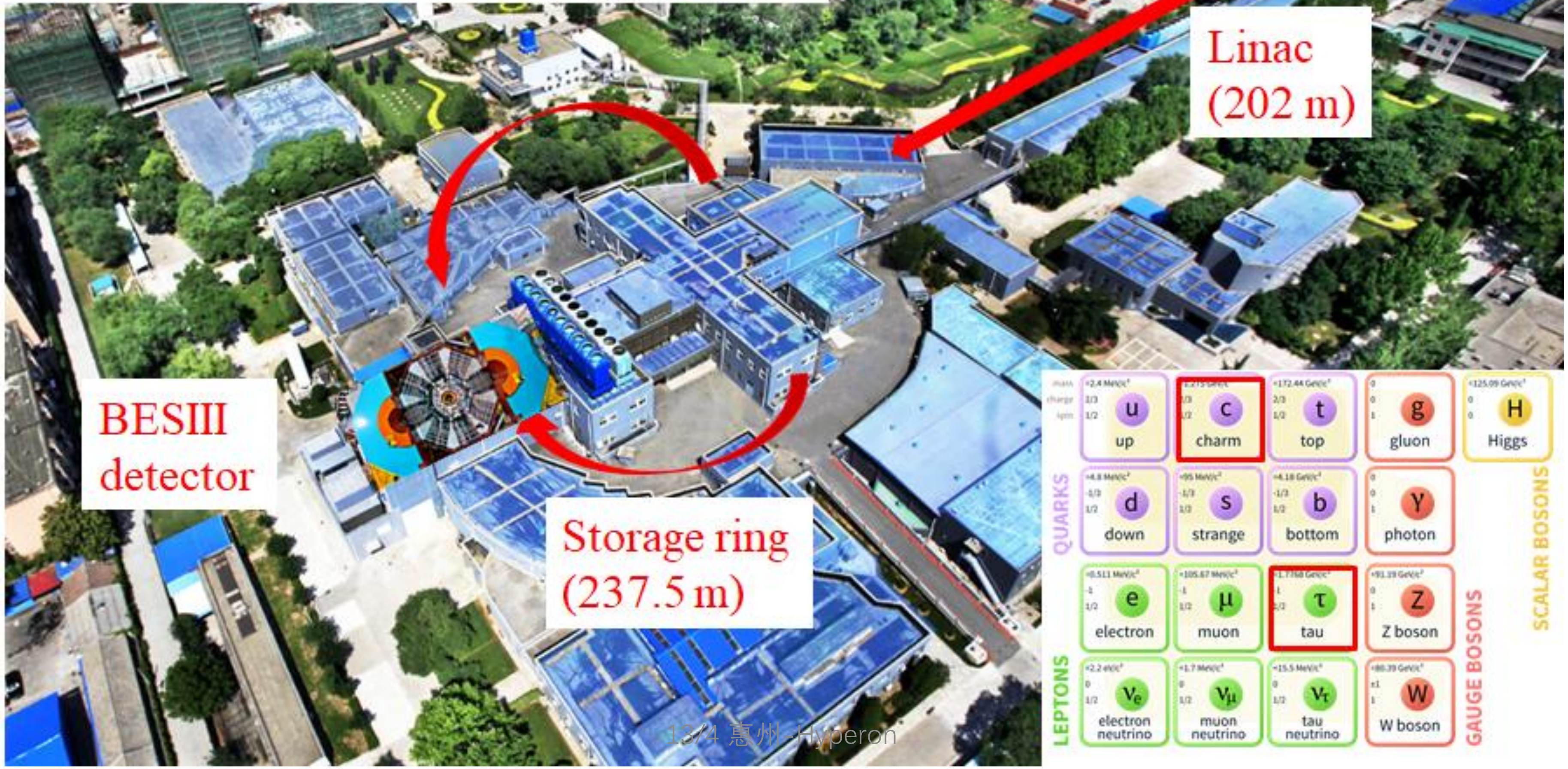


The only experiment running at thresholds of charmed hadrons in the word!

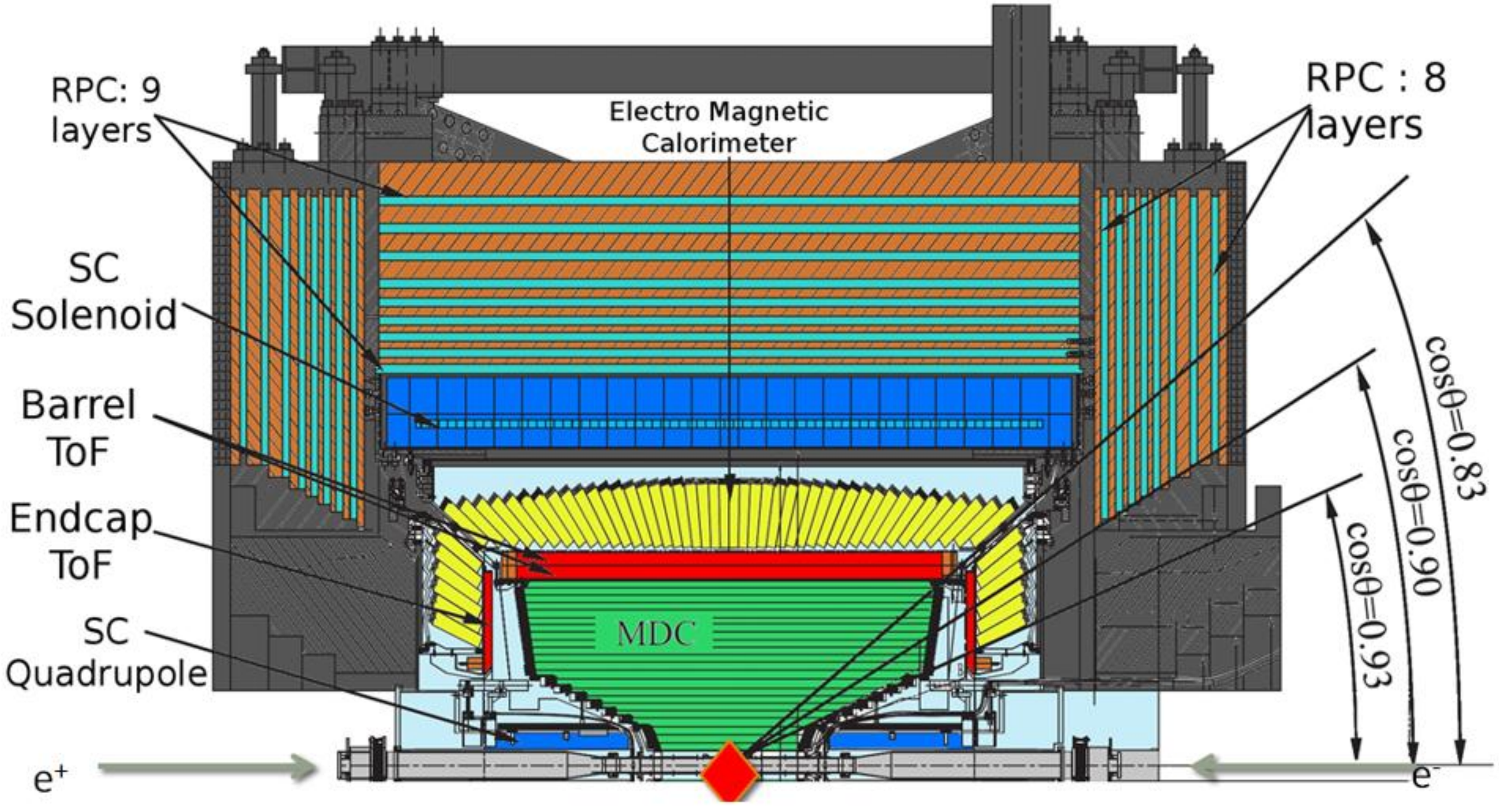
BESIII experiment

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

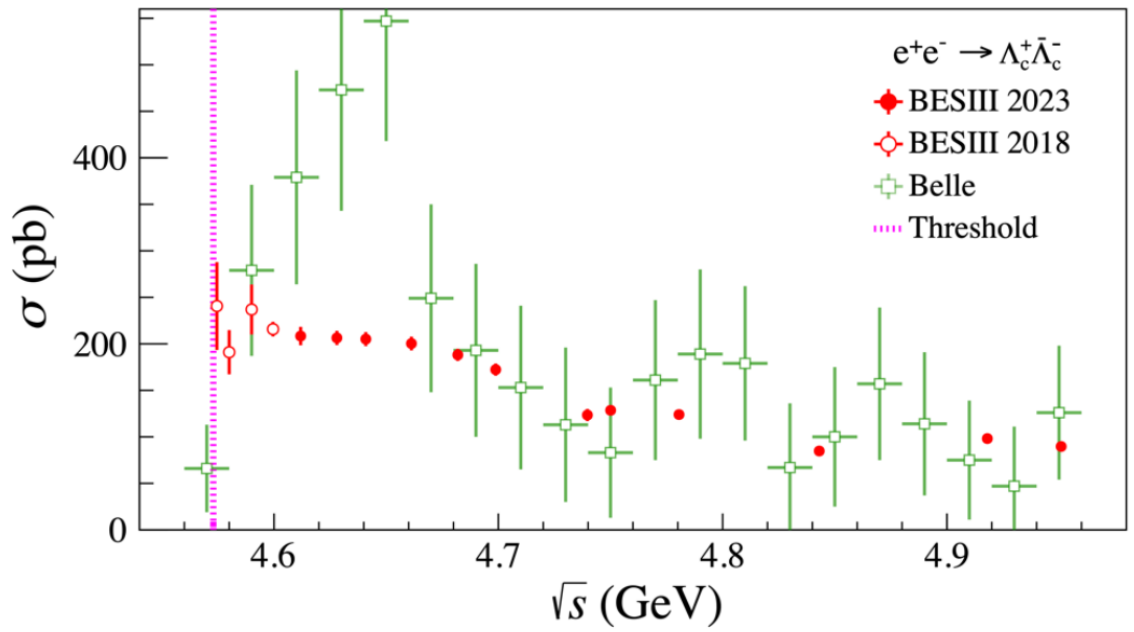
EMC: photons and electrons

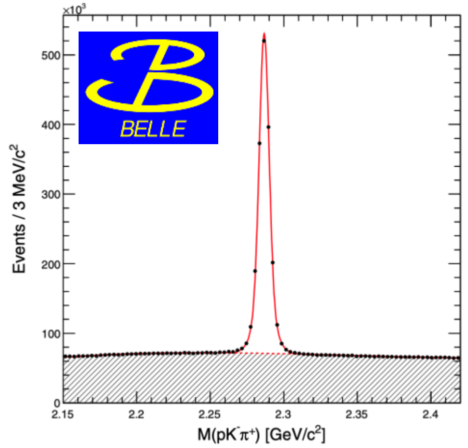
RPC: muon detection

SC Solenoid: 1T magnet

Charmed Baryons at BESIII

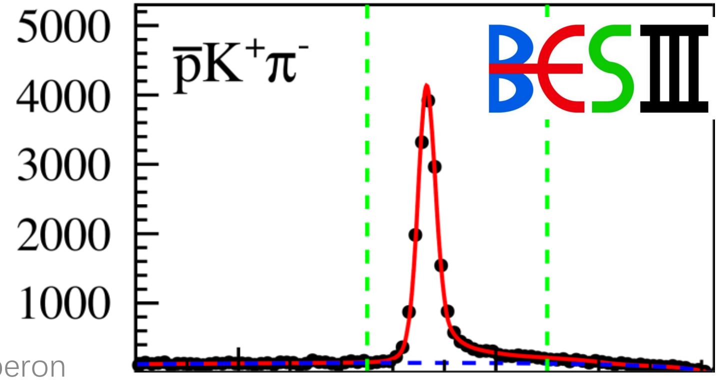
Unique: threshold effect for charmed hadrons





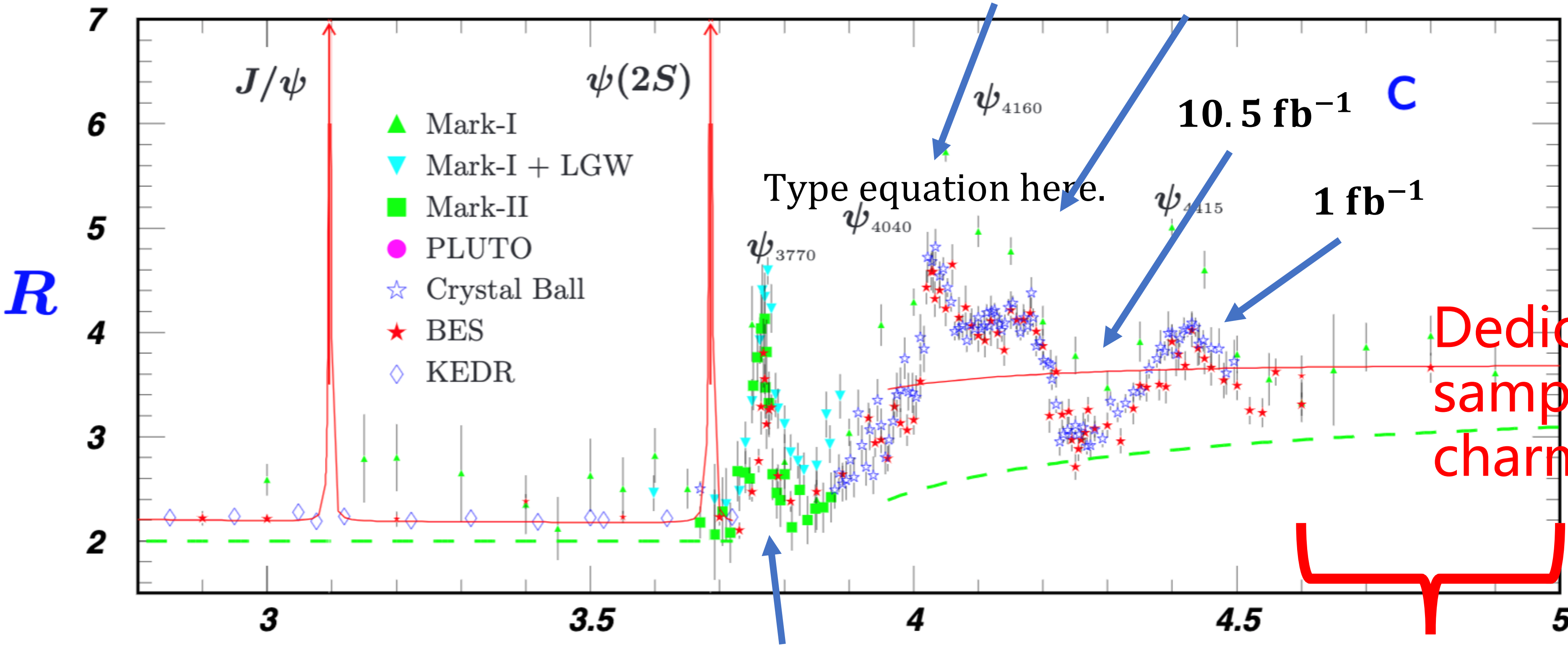
BELLE: larger stat, but higher bkg

BESIII: lower stat, but higher signal to bkg ratio



Data sets at BESIII

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



$10.5\ \mathrm{fb}^{-1}$

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

Dedicated samples for charmed baryons

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

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

$\sim 6\ \mathrm{fb}^{-1}$ at 16 points
$4.6 < \sqrt{s} < 5.0$ GeV

Publications related to Λ_c^+ at BESIII

The 1st 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 !**
- ❖ **Higher stat samples in 2020 and 2021**

PDG in 2015

PDG in 2020

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 ± 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 ± 2.5) $\times 10^{-3}$	
Γ_{18}	$pf_0(980)$	[a]	(3.8 ± 2.5) $\times 10^{-3}$	
Γ_{19}	$p\pi^+\pi^+\pi^-\pi^-$		(2.5 ± 1.6) $\times 10^{-3}$	
Γ_{20}	pK^+K^-		(1.1 ± 0.4) $\times 10^{-3}$	
Γ_{21}	$p\phi$	[a]	(1.12± 0.23) $\times 10^{-3}$	
Γ_{22}	pK^+K^- non-ϕ		(4.8 ± 1.9) $\times 10^{-4}$	

	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 ± 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± 0.30) $\times 10^{-3}$	First	
Γ_{19}	$p\omega(782)^0$		(9 ± 4) $\times 10^{-4}$		
Γ_{20}	$p\pi^+\pi^-$		(4.61± 0.28) $\times 10^{-3}$	First	
Γ_{21}	$pf_0(980)$	[a]	(3.5 ± 2.3) $\times 10^{-3}$		
Γ_{22}	$p2\pi^+2\pi^-$		(2.3 ± 1.4) $\times 10^{-3}$		
Γ_{23}	pK^+K^-		(1.06± 0.06) $\times 10^{-3}$		
Γ_{24}	$p\phi$	[a]	(1.06± 0.14) $\times 10^{-3}$	↓36%	
Γ_{25}	pK^+K^- non-ϕ		(5.3 ± 1.2) $\times 10^{-4}$		
Γ_{26}	$p\phi\pi^0$		(10 ± 4) $\times 10^{-5}$		
Γ_{27}	$pK^+K^-\pi^0$ nonresonant		< 6.3 $\times 10^{-5}$		CL=90%

PDG in 2015

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) %

PDG in 2020

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

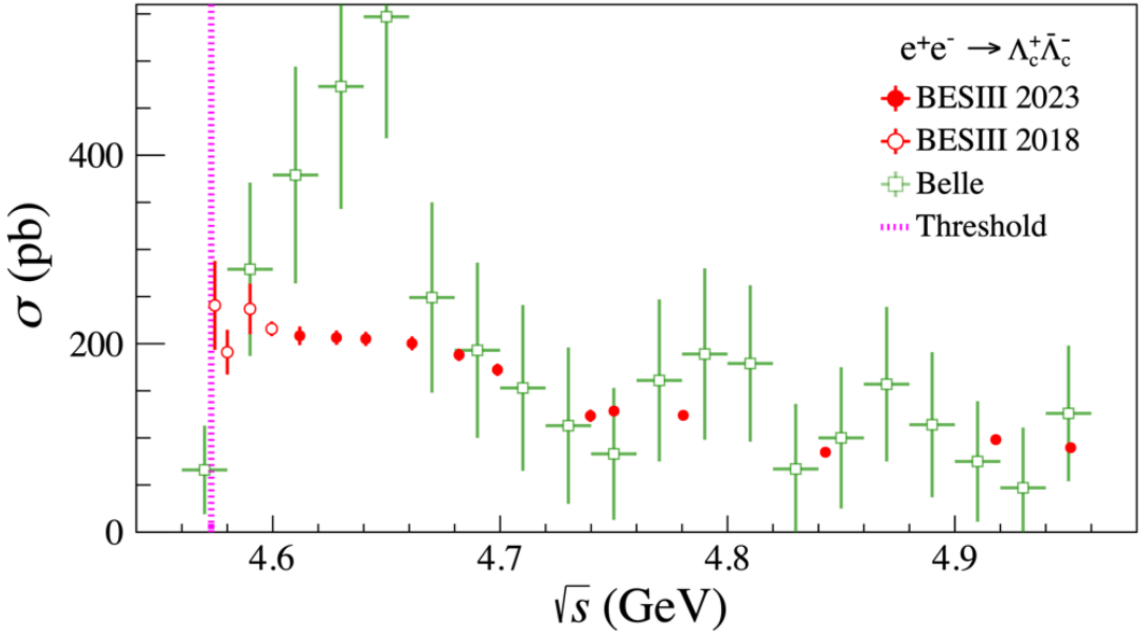
Hadronic modes with a hyperon: $S=-1$ final states

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) %	

Data sets collected in 2020 and 2021

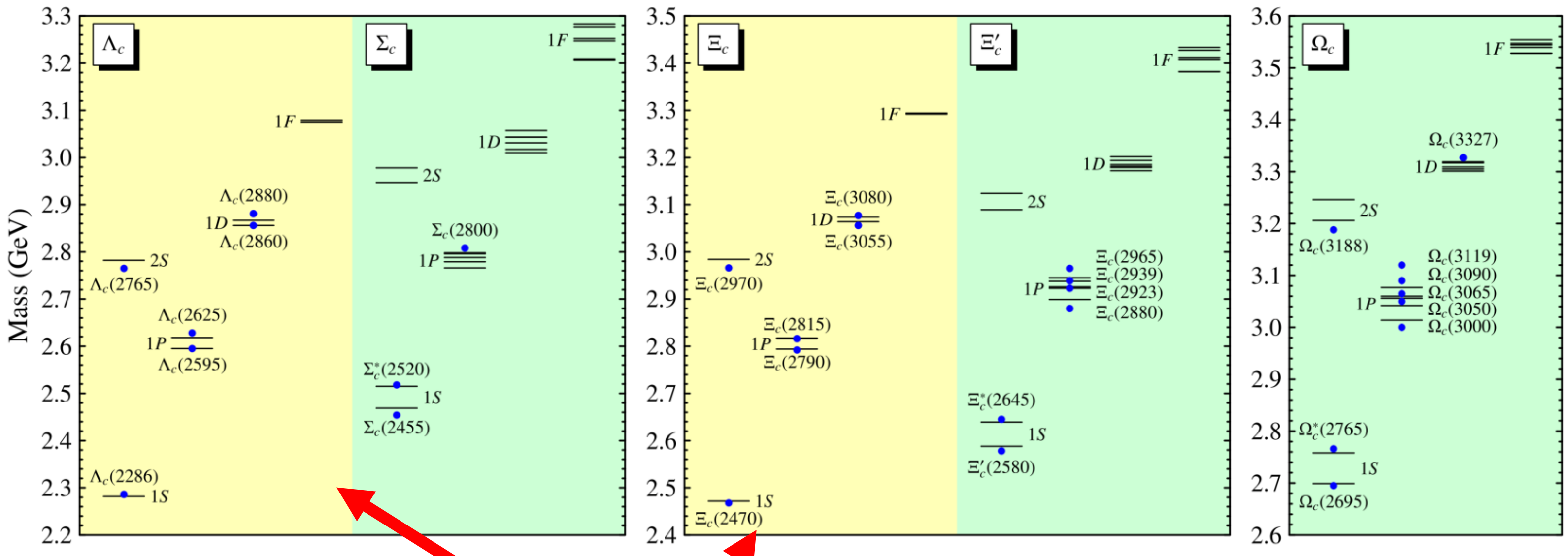


Sample	E_{cms}/MeV	$\mathscr{L}_{Bhabha}/pb^{-1}$
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84
4740	4739.70±0.20±0.30	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

- 12 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

Productions

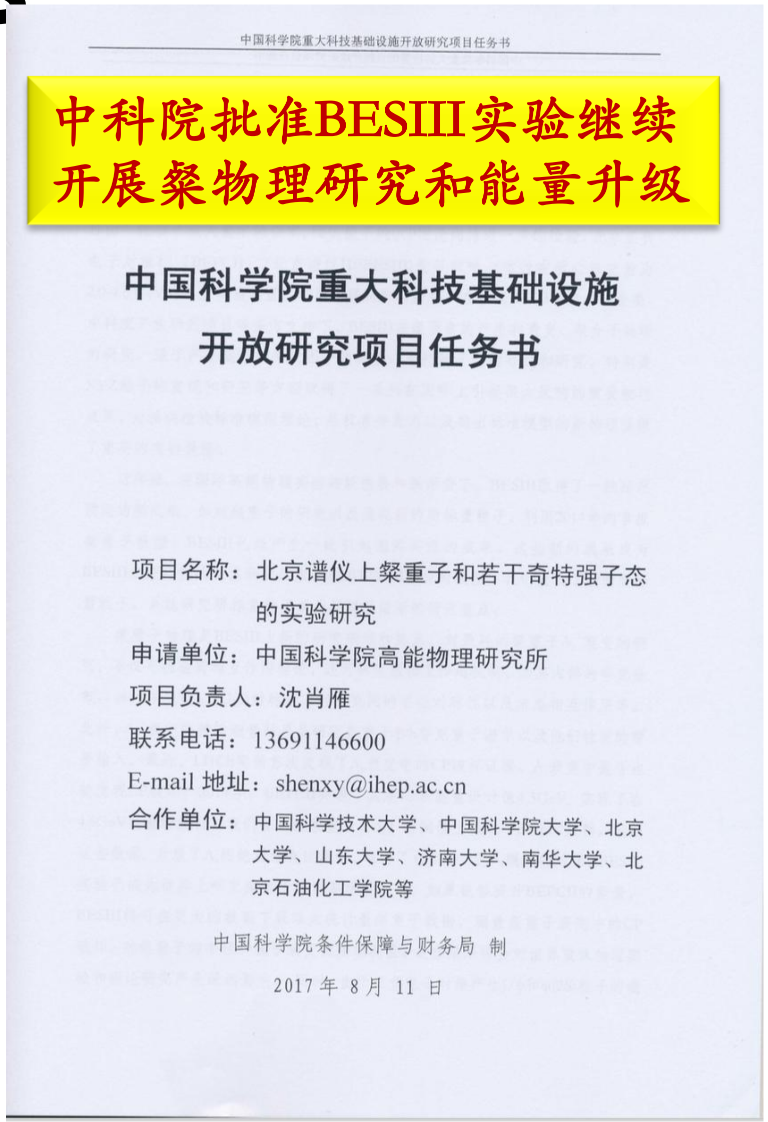
(Excited) Charmed Baryons



CMS energy coverage：

Year 2019: 4.6 GeV → 4.95 GeV

Year 2024: → 5.5 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

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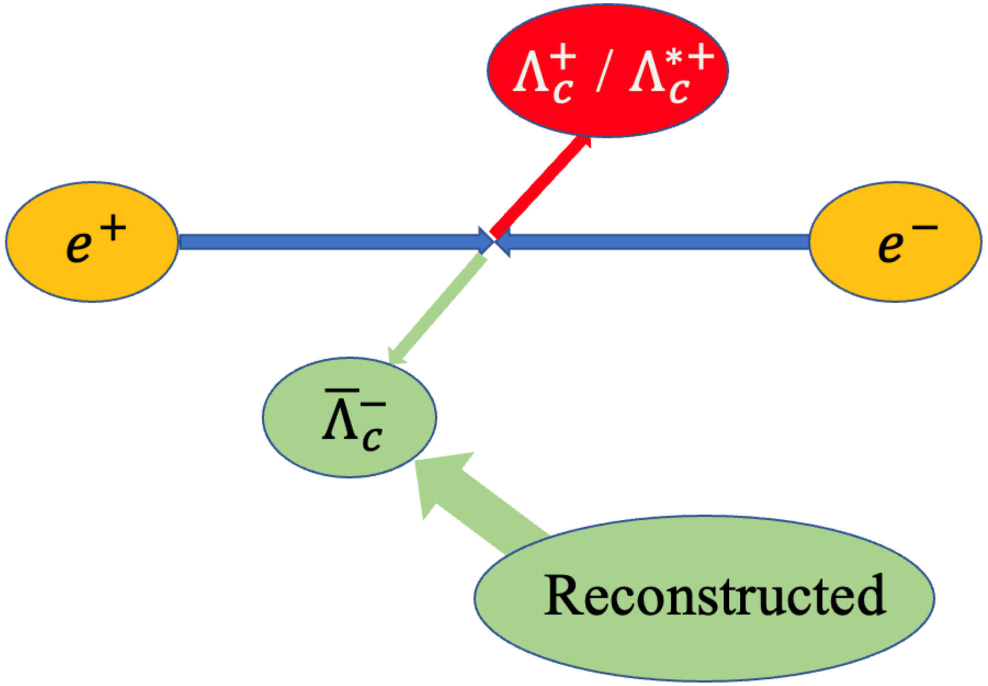
合作单位：中国科学技术大学、中国科学院大学、北京大学、山东大学、济南大学、南华大学、北京石油化工学院等

中国科学院条件保障与财务局 制

2017 年 8 月 11 日

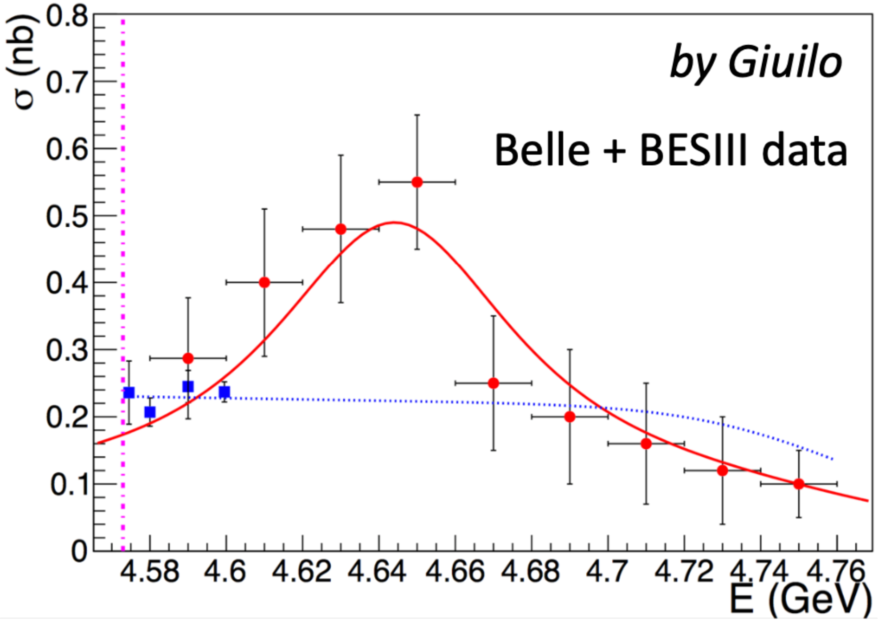
Production measurements



- Λ_c^+ pair production near the threshold
- "Tagged" one $\bar{\Lambda}_c^-$ is sufficient to extract the production information

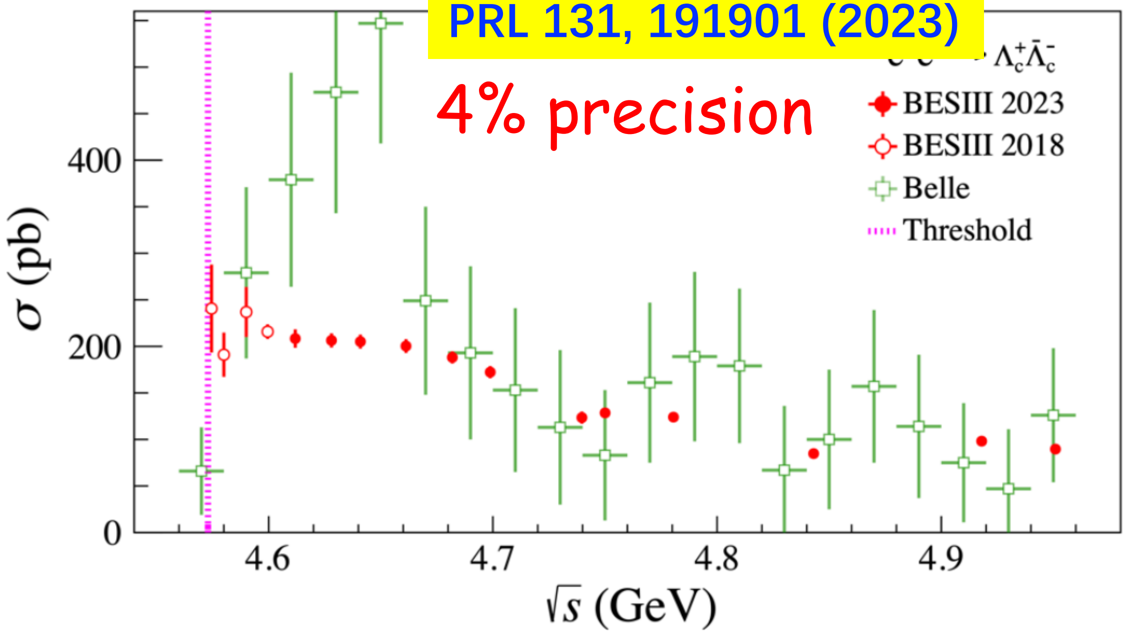
Single-tag (ST) strategy

Pair production of ground-state Λ_c^+



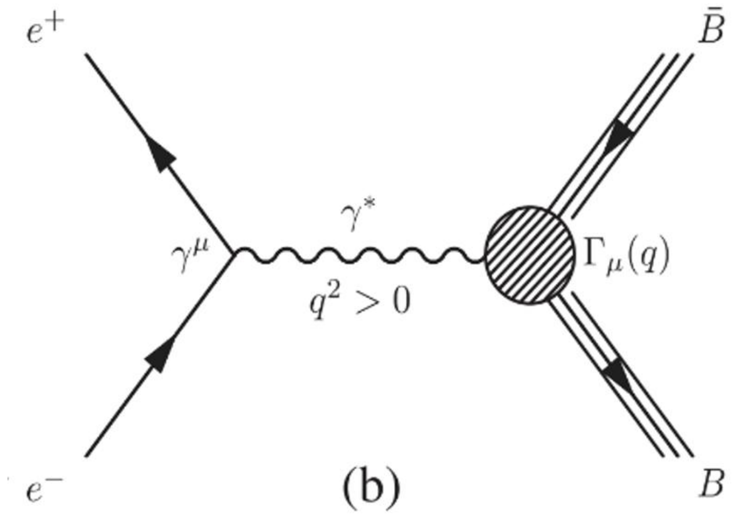
BESIII Collaboration, PRL 131, 191901 (2023)

4% precision

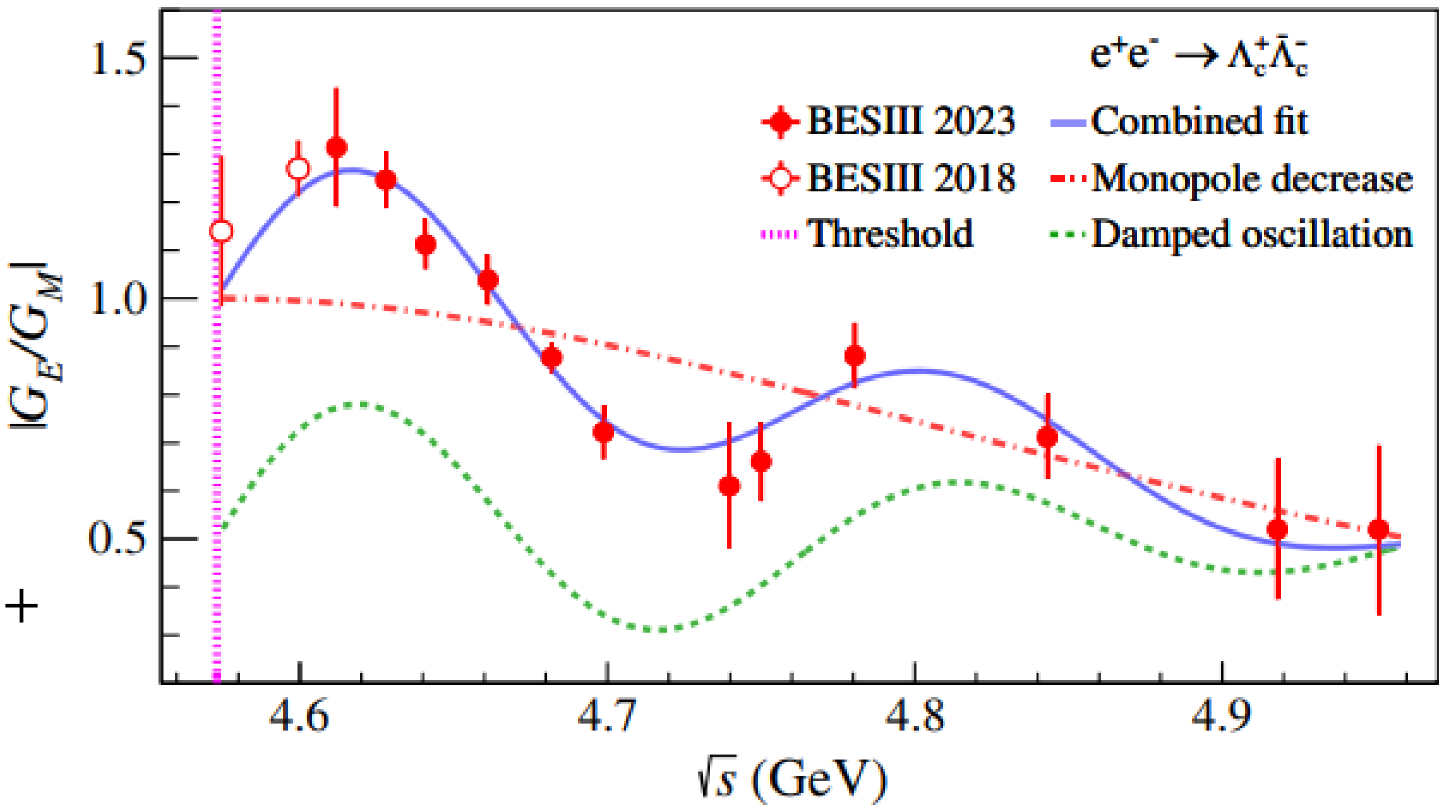


- $\Lambda_c^+ \to pK^-\pi^+$ to reconstruct the signals
- Beam constraint mass $M_{BC} = \sqrt{E_{beam}^2 - P_{\Lambda_c}^2}$ to extract the signal yields
- Not observed the structure around 4.66 GeV as BELLE's result

Oscillation in Form Factors

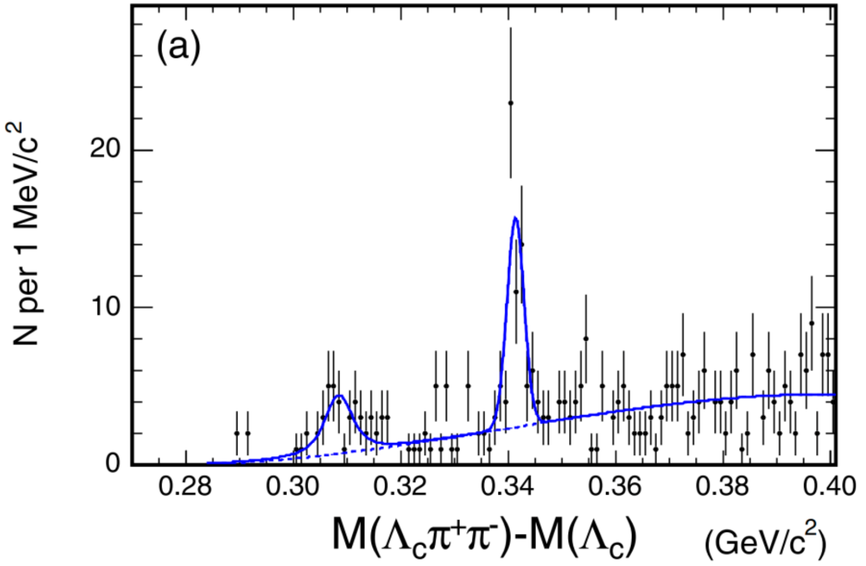


$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha^2\beta C}{4s}\left[|G_M|^2(1+\cos^2\theta) + \frac{4m_B^2}{s}|G_E|^2\sin^2\theta\right]$$



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

CDF Collaboration,
PRD 79, 032001 (2009)



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

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

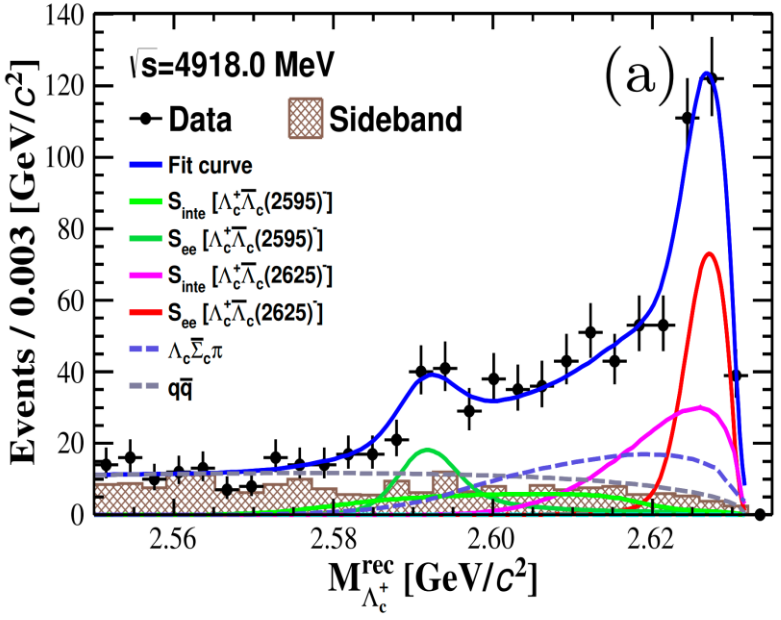
The production rate is reversed, comparing to the mass of the two excited states !?

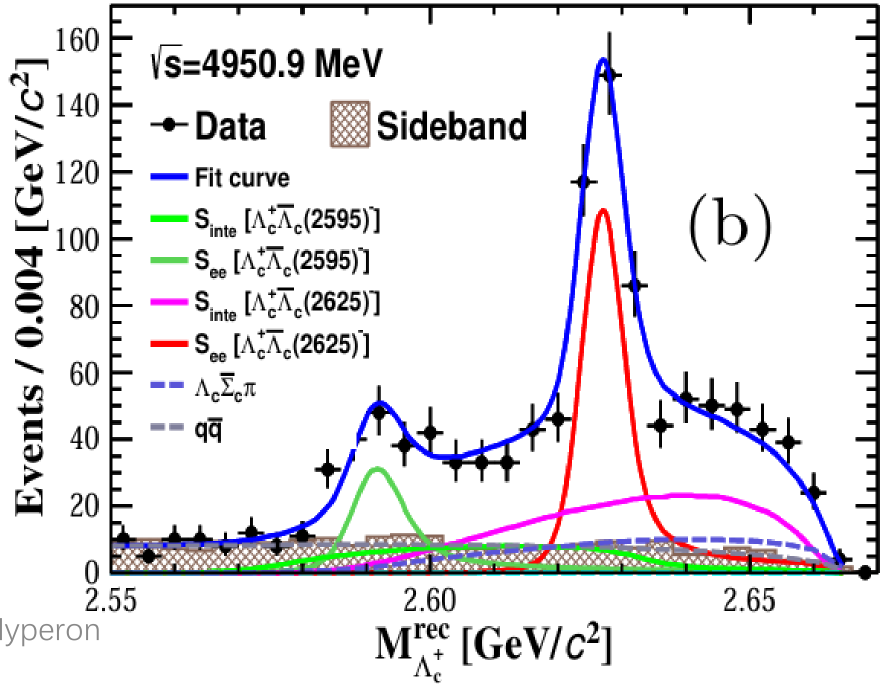
$\boldsymbol{\Lambda_c(2595)^+}$ is at the threshold of $\Sigma_c\pi$ ➔ Exotic state?

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

arXiv:2312.08414

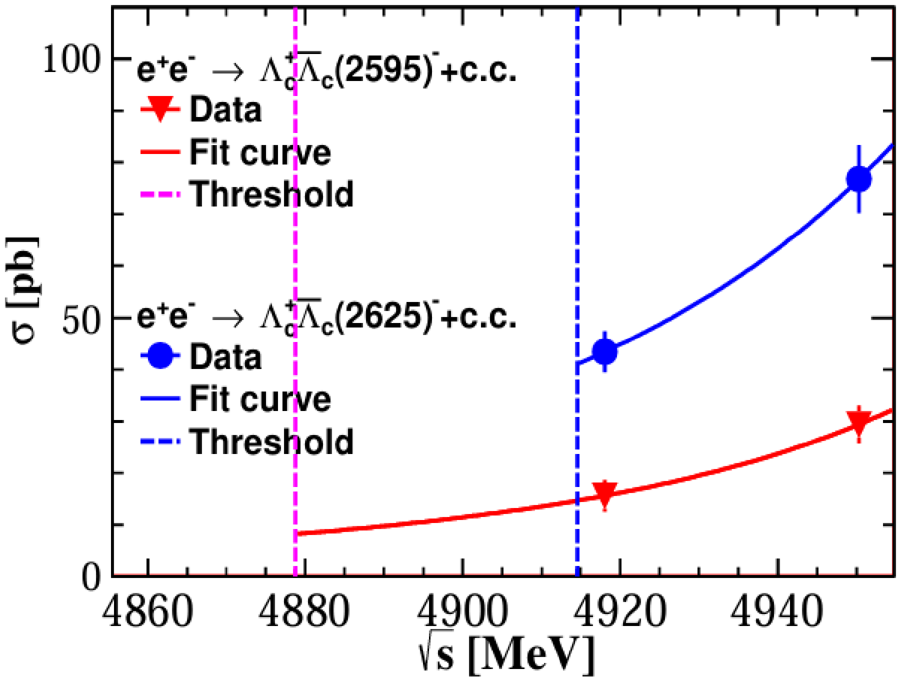
- ❖ Select one Λ_c^+ and search for the excited states in the opposite side
- ❖ Applicable only at $\sqrt{s}$ = 4.918 and 4.950 GeV





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

arXiv:2312.08414



❖ Model dependent fit and ISR correction with

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

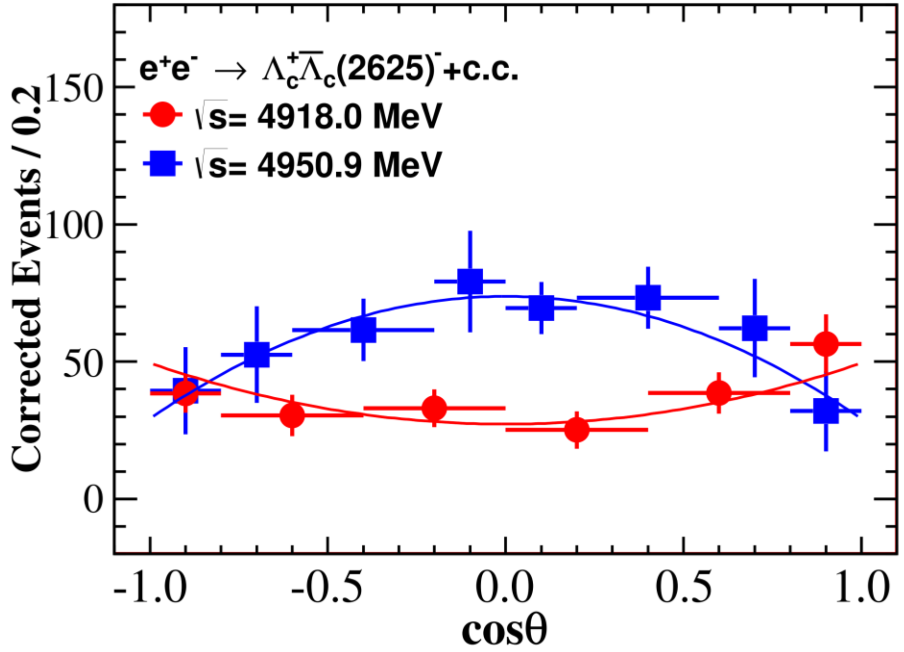
❖ Non-zero cross section is observed at the threshold for $\Lambda_c(2625)^+$

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

arXiv:2312.08414



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

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

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

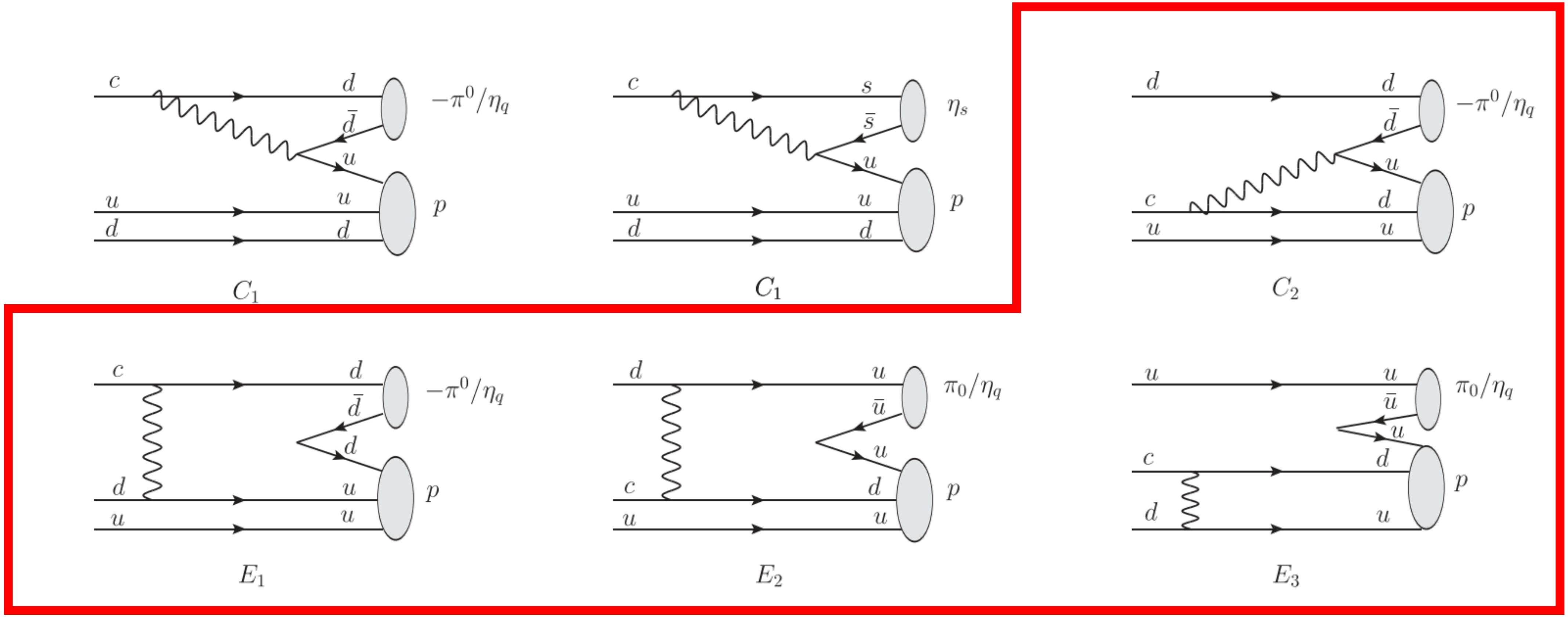
The direction of angular curve flips in very narrow range !

- Oscillation feature as Λ_c^+?
- 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

Decays in Charmed Baryons



Calculation is not reliable, need exp. input

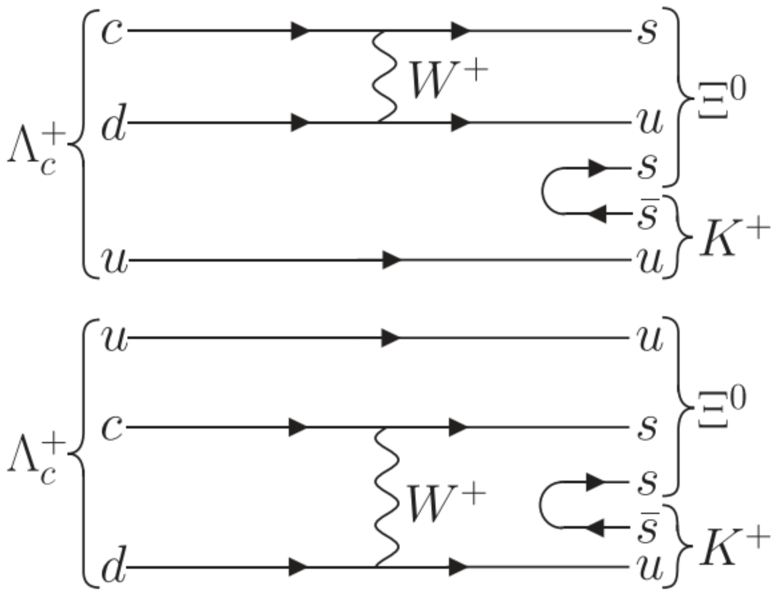
C_1 : factorization component

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

$\Lambda_c^+ \to \Xi^0 K^+$

Only receives the non-factorization contribution

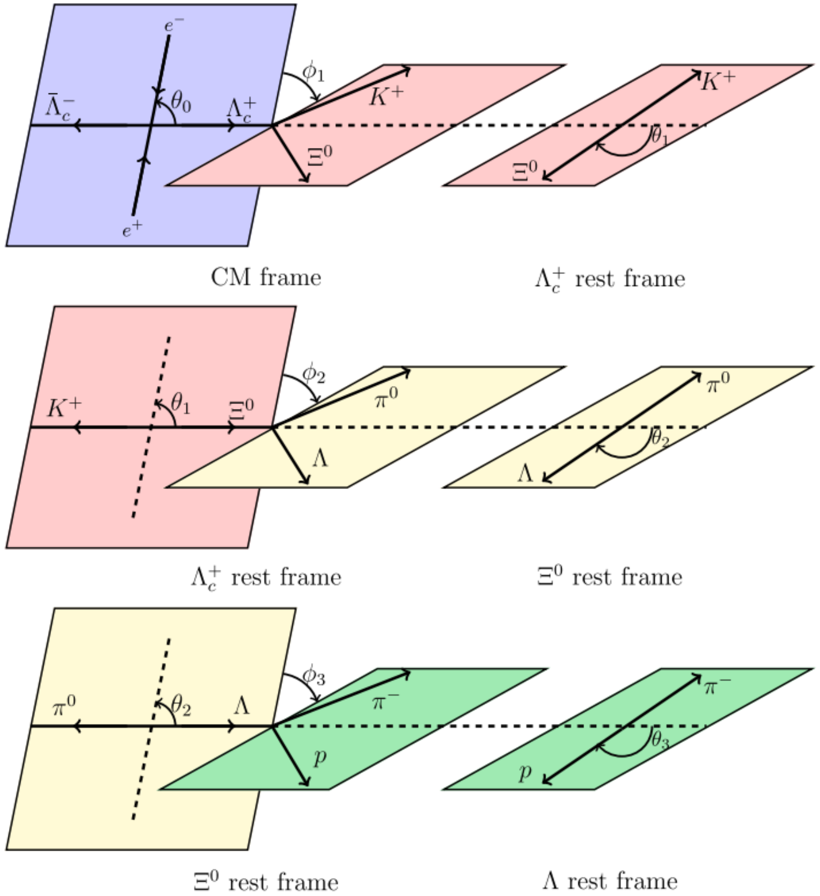
Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$
Körner (1992), CCQM [7]	2.6	0
Xu (1992), Pole [8]	1.0	0
Źencaykowski (1994), Pole [9]	3.6	0
Ivanov (1998), CCQM [10]	3.1	0
Sharma (1999), CA [11]	1.3	0
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$
Zou (2020), CA [6]	7.1	0.90
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...
PDG fit (2022) [2]	5.5 ± 0.7	...



The decay asymmetry parameter $\alpha_{\Xi^0 K^+}$ has never been measured.

$\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$

BESIII Collaboration,
PRL 132, 031801 (2024)



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

Two individual helicity $H_{\frac{1}{2},\frac{1}{2}}$ and $H_{\frac{1}{2},-\frac{1}{2}}$

$$\alpha_0 = \frac{\left|H_{\frac{1}{2},-\frac{1}{2}}\right|^2 - 2\left|H_{\frac{1}{2},\frac{1}{2}}\right|^2}{\left|H_{\frac{1}{2},-\frac{1}{2}}\right|^2 + 2\left|H_{\frac{1}{2},\frac{1}{2}}\right|^2}$$

Δ_0 is phase shift between them

$\Lambda_c^+ \to \Xi^0 K^+$

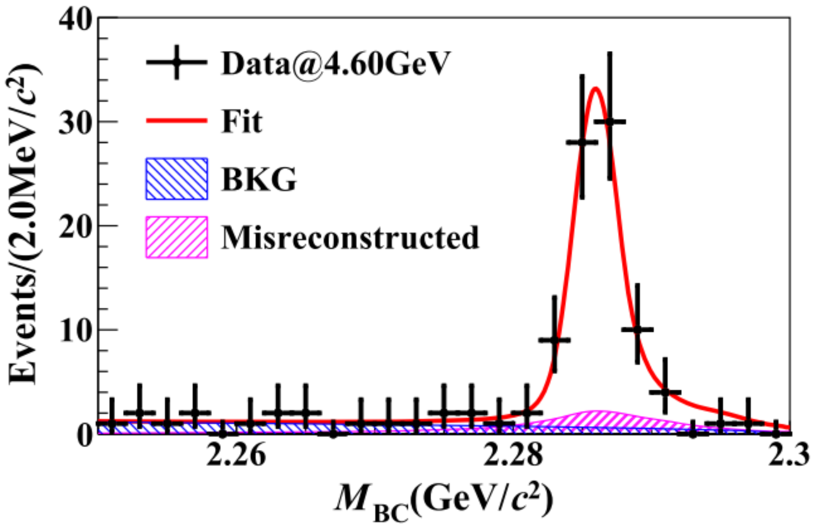
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

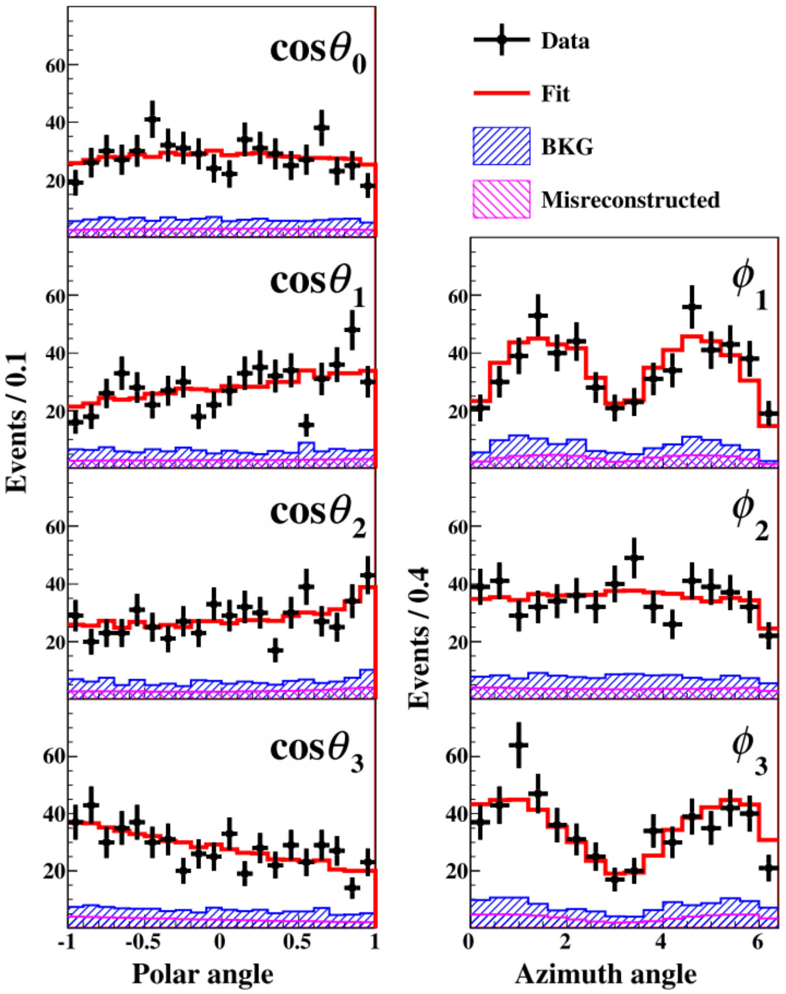
$$\beta = \sqrt{1-\alpha^2}\sin\Delta$$

$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}$$

$$\gamma = \sqrt{1-\alpha^2}\cos\Delta$$

Distributions





- Fixed the parameters in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and Ξ^0 and Λ decays
- Free parameters of $\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$
- Six data sets between 4.6 and 4.7 GeV

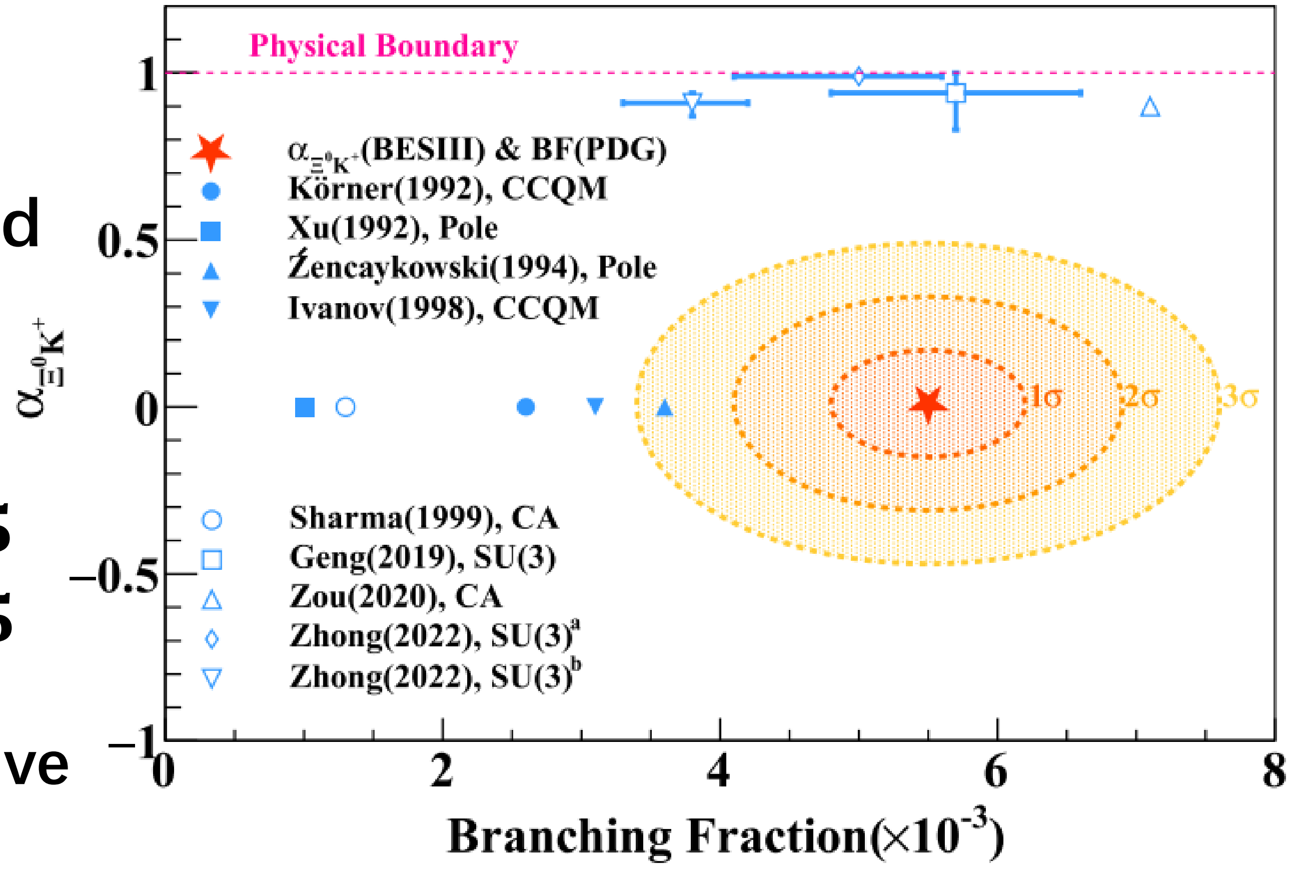
Phase difference

$$\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$$
$$\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90 \pm 0.17 \text{ rad}$$

In good agreement with zero

$$\delta_p - \delta_s = -1.55 \pm 0.25 \pm 0.05$$
$$\text{or} \quad 1.59 \pm 0.25 \pm 0.05$$

Phase difference between s and p-wave



Cabibbo suppressed (CS) decays

$$\mathcal{H}_{eff} = \sum_{i=+,-} \frac{G_F}{\sqrt{2}} c_i \left(V_{cs} V_{ud} O_i^{ds} + V_{cd} V_{ud} O_i^{qq} + V_{cd} V_{us} O_i^{sd} \right)$$

❖Cabibbo flavored (CF) decays have been shown consistent results between experimental results and SU(3)$_f$

❖Seems not applicable in CS decays

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

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
$10^3\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$	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

CS modes

$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^0)$	–	8.0 ± 1.6
$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	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
$10^4\mathcal{B}(\Lambda_c^+ \to \Lambda^0 K^+)$	6.1 ± 1.2	4.6 ± 0.9

Various predictions

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

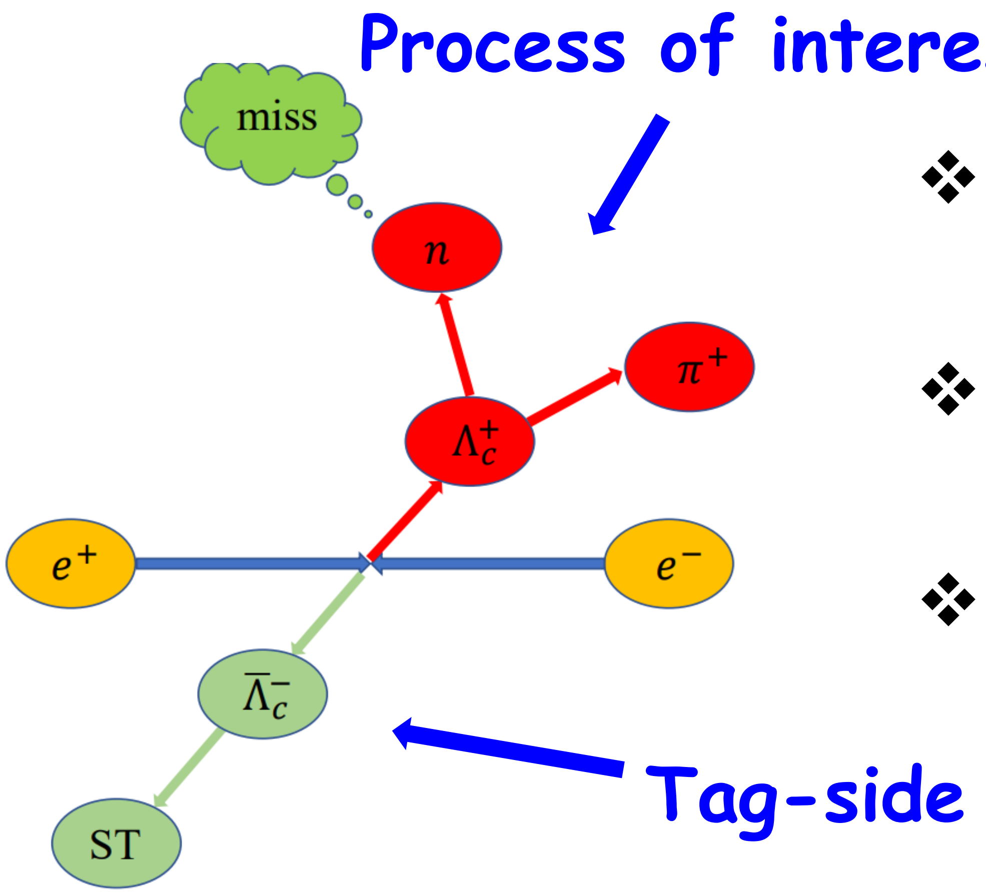
Before 2020

	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	?

- $\Lambda_c^+ \to p\eta$: looks consistent between exp. and theo.
- The significant discrepancy exists in the channel $\Lambda_c^+ \to p\pi^0$: with H(6) only in $SU(3)_f$ prediction
- Interference between factorization and non-factorization is proposed !

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

Strategies at BESIII : double-tag

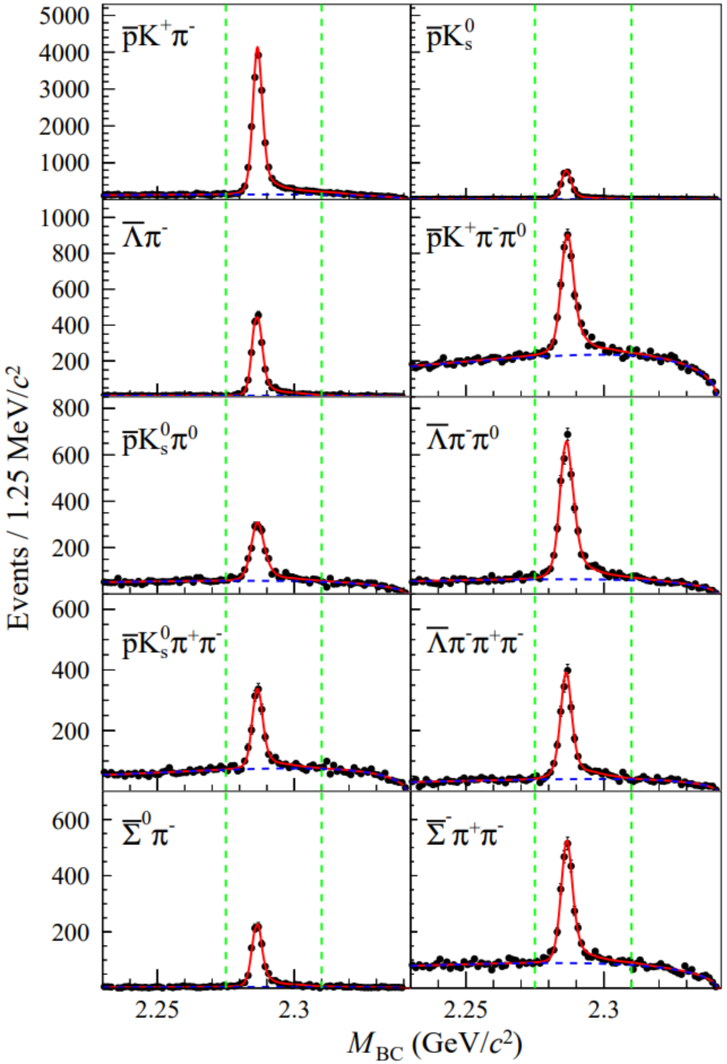


- In the center-of-mass system, Λ_c^+ is producted associated with the other $\bar{\Lambda}_c^-$.
- "Tagged" one $\bar{\Lambda}_c^-$, there should exist the other Λ_c^+ in the opposite side.
- If measuring the branching fraction, the yield of tagged $\bar{\Lambda}_c^-$ is denominator.

Model-independent approach !

Single tag of Λ_c^+

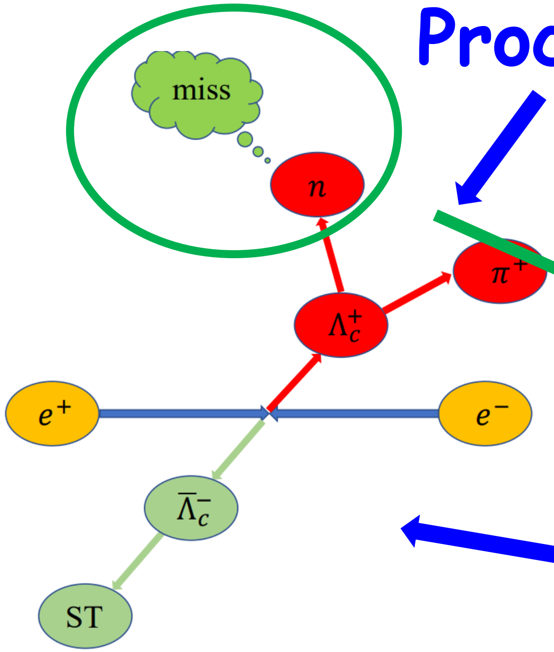
$\sqrt{s} = 4.682$ GeV as an example



- 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

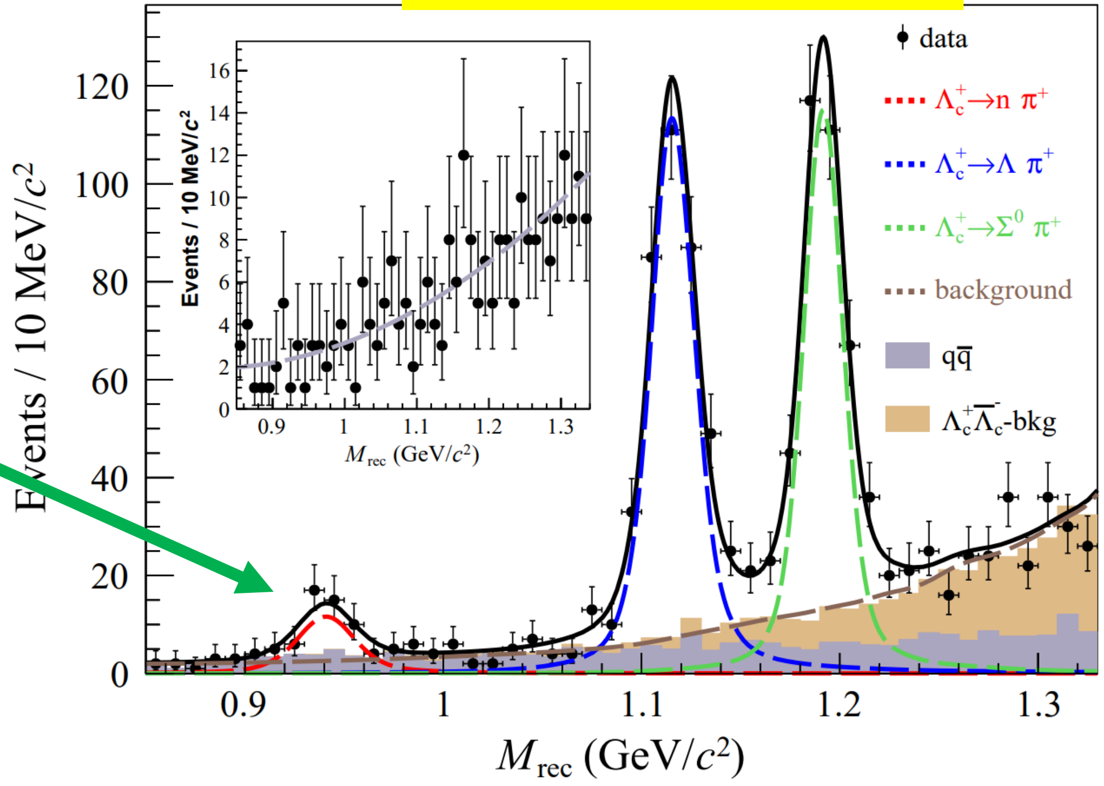
$\Lambda_c^+ \to n\pi^+$ and $\Lambda_c^+ \to p\pi^0$

Process of interest



Tag-side

BESIII Collaboration,
PRL 128 (2022) 142001



- 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 $\Lambda_c^+ \to p\pi^0$

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

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)

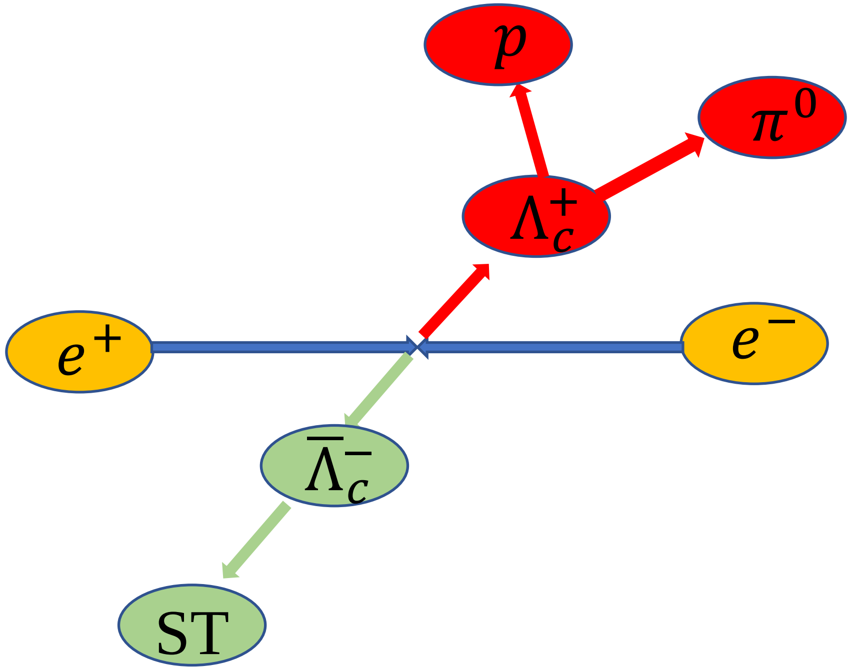
R	> 7.2 at 90% C.L.

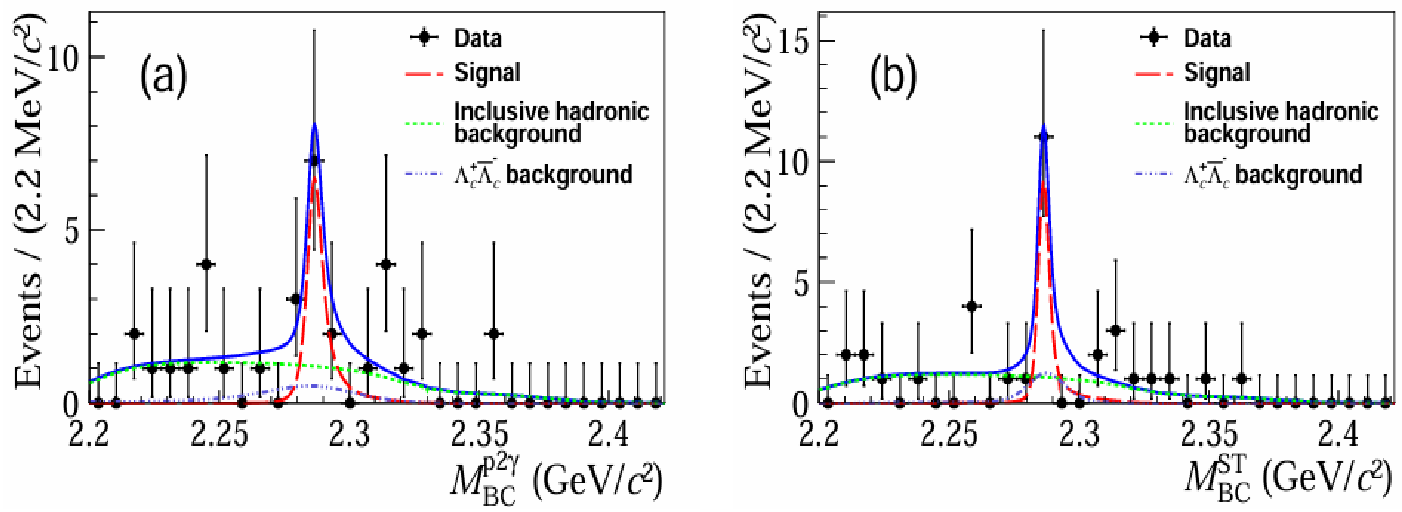
$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	R	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165

In 2022, disagree with most of predictions !?

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

arXiv:2311.06883



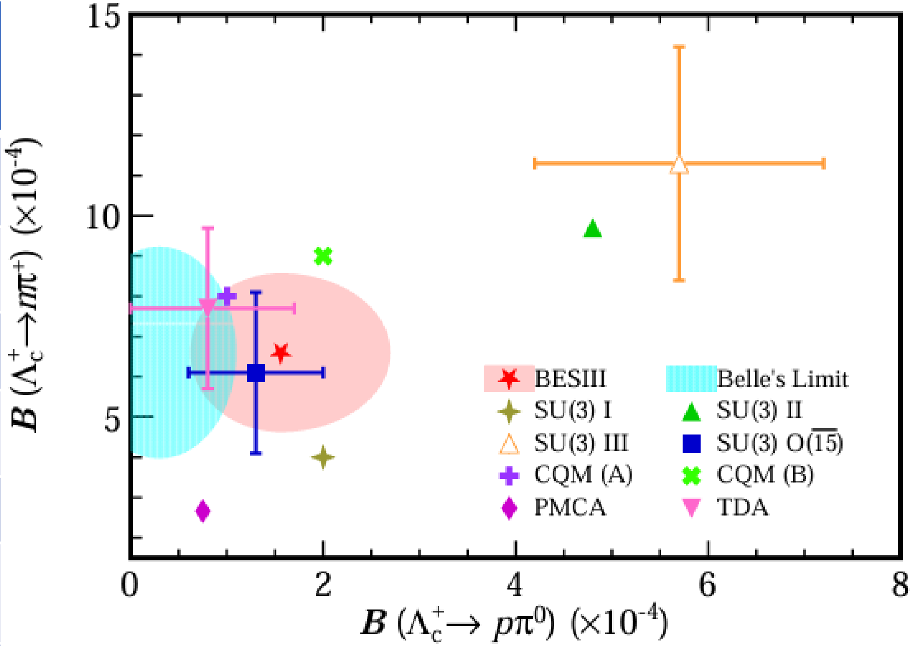


- ❖Similar strategy as $\Lambda_c^+ \to n\pi^+$ is applied, but higher background
- ❖2D fit to extract the signal yield: ST $\bar{\Lambda}_c^-$ vs. signal $\Lambda_c^+ \to p\pi^0$
- ❖Significance 3.7σ, branching fraction $(1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$

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

arXiv:2311.06883

$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	$\mathcal{B}(\Lambda_c^+ \to p\pi^0) \times 10^{-4}$	R = $\mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0)$	Reference	models
$6.6 \pm 1.2 \pm 0.4$	$1.56^{+0.72}_{-0.58} \pm 0.20$	$3.2^{+2.2}_{-1.2}$		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

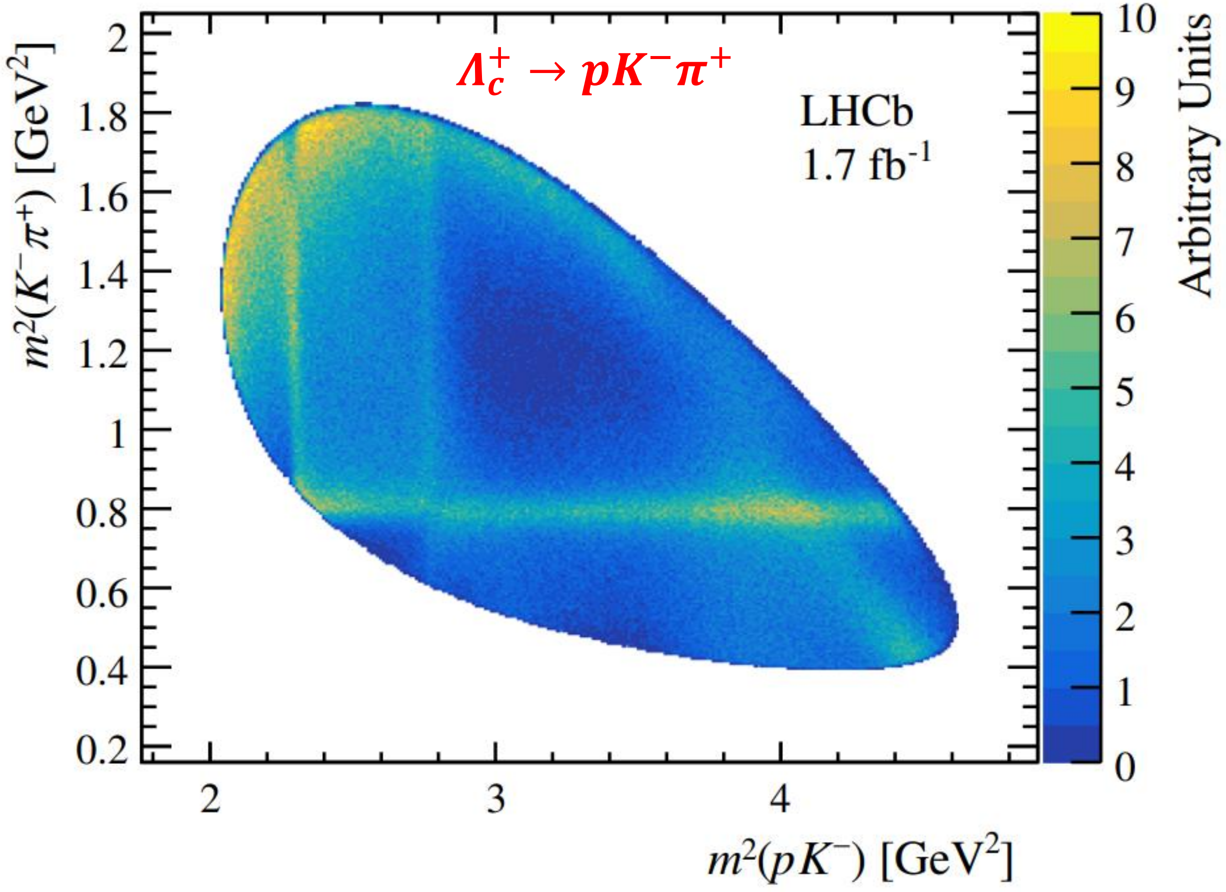


- Likely different from Belle
- consistent with SU(3) prediction with representation $H(6)$ and $H(\overline{15})$

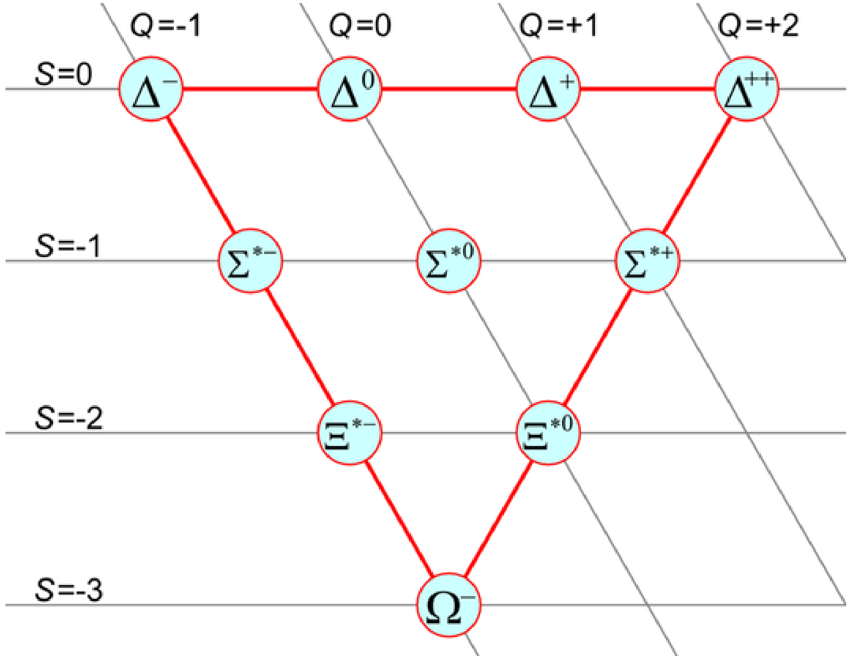
The interference between factorization and non-fac maybe is not significant !

Partial Wave Analysis in Λ_c^+

LHCb Collaboration, PRD 108, 012023 (2023)



Abundant excited baryon states

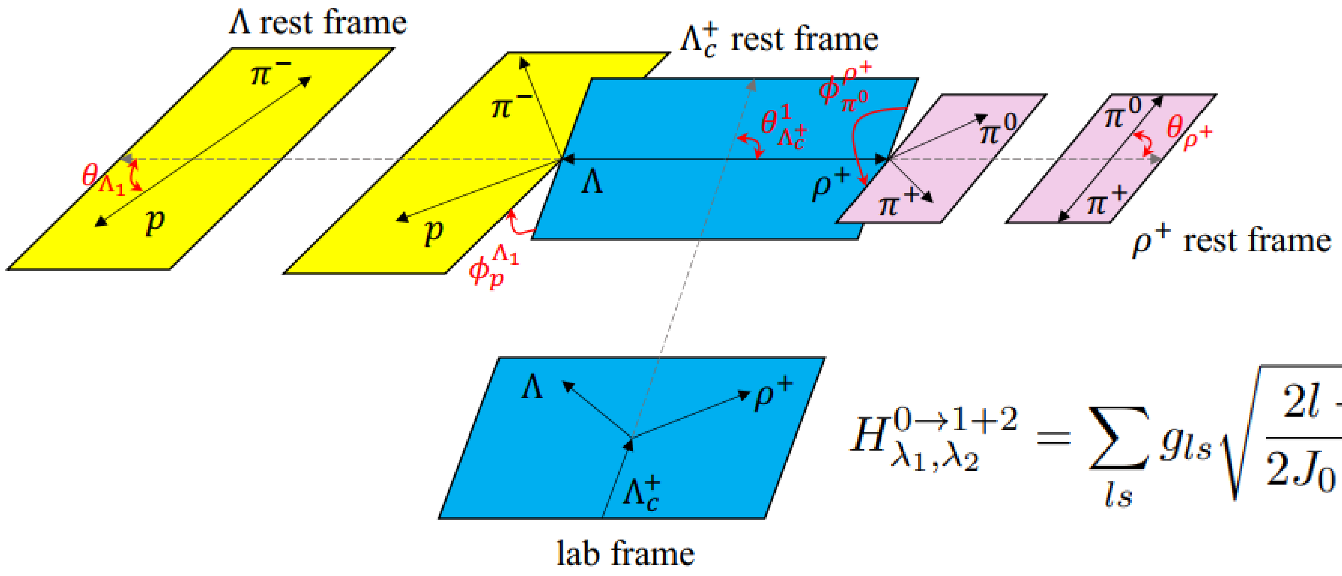


PWA in hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

BESIII Collaboration, JHEP 12 (2022) 033

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

- $\Lambda_c^+ \to \Lambda\rho^+$
- $\Lambda_c^+ \to \Sigma(1385)^+\pi^0$
- $\Lambda_c^+ \to \Sigma(1385)^0\pi^+$

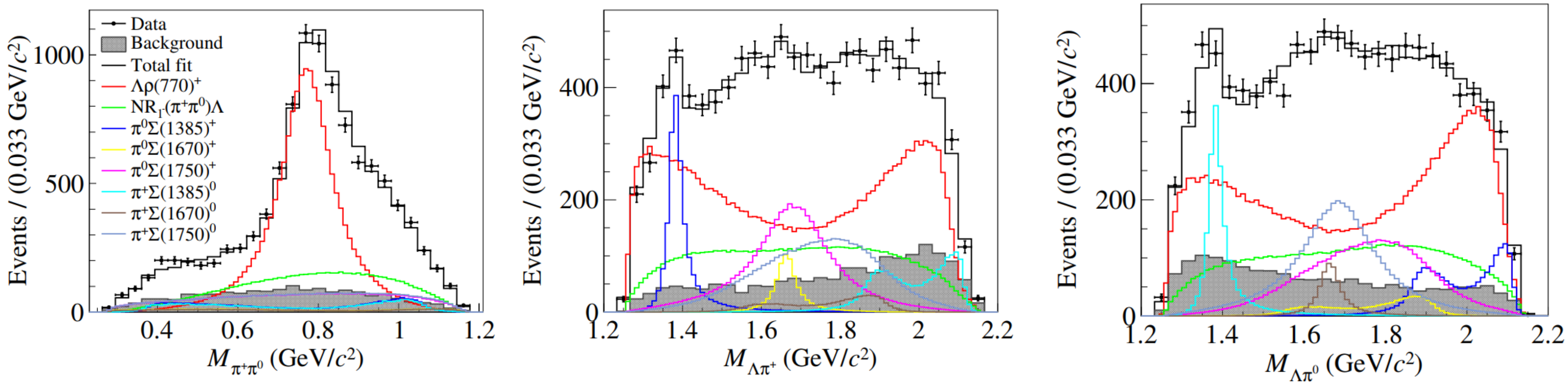


Helicity Amplitude (TF-PWA)

$$A^{0\to1+2}_{\lambda_0,\lambda_1,\lambda_2} = H^{0\to1+2}_{\lambda_1,\lambda_2} D^{J_0*}_{\lambda_0,\lambda_1-\lambda_2}(\phi,\theta,0)$$

$$H^{0\to1+2}_{\lambda_1,\lambda_2} = \sum_{ls} g_{ls}\sqrt{\frac{2l+1}{2J_0+1}}\langle l0, s\delta|J_0,\delta\rangle\langle J_1J_2,\lambda_1 \; -\lambda_2|s,\delta\rangle\left(\frac{q}{q_0}\right)^l B_l'(q,q_0,d)$$

PWA in hadronic decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$



	Theoretical calculation		This work
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	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 ± 0.070
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.089
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11

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

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

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

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.

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

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

Mass $m = 2628.11 \pm 0.19$ MeV (S = 1.1)
$m - m_{\Lambda_c^+} = 341.65 \pm 0.13$ MeV (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-wave 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 $\Lambda_c(2625)^+$ 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 $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ are close to the threshold of $\Sigma_c\pi$ ➔ Isospin violation ?

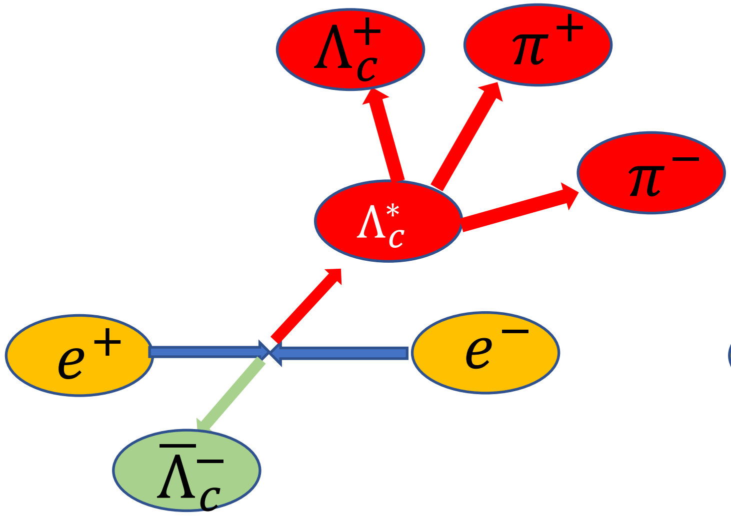
Direct measurement on the strong decays can answer this question !

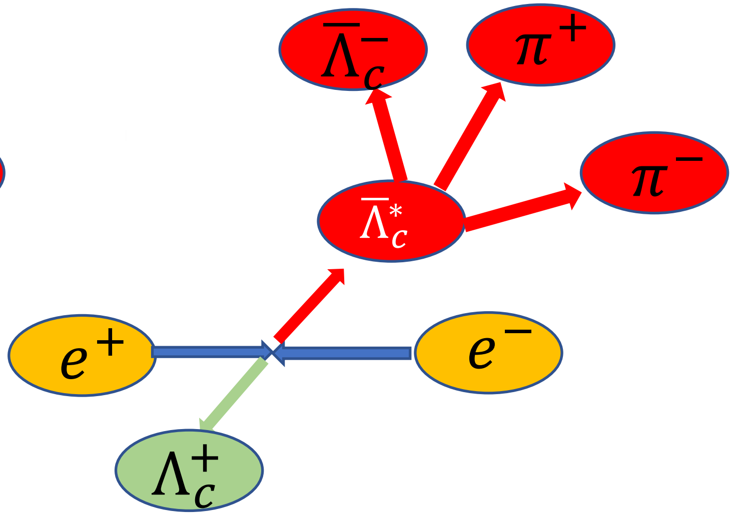
Measurements of strong transition

arXiv:2401.09225

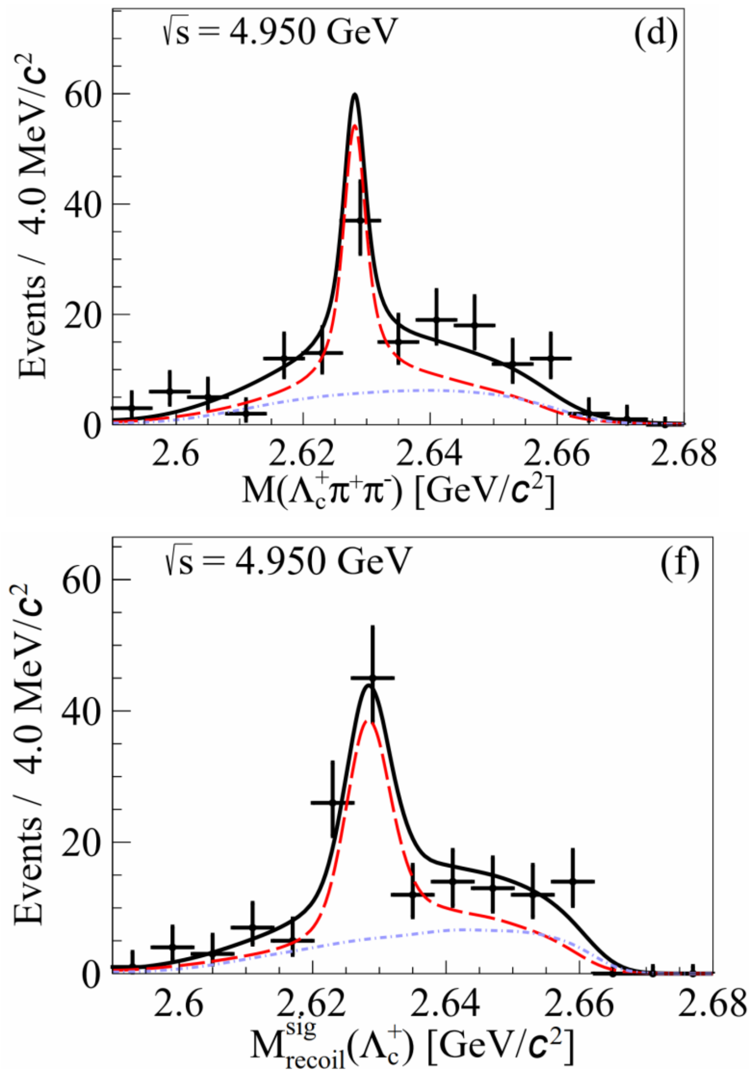
$\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$

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





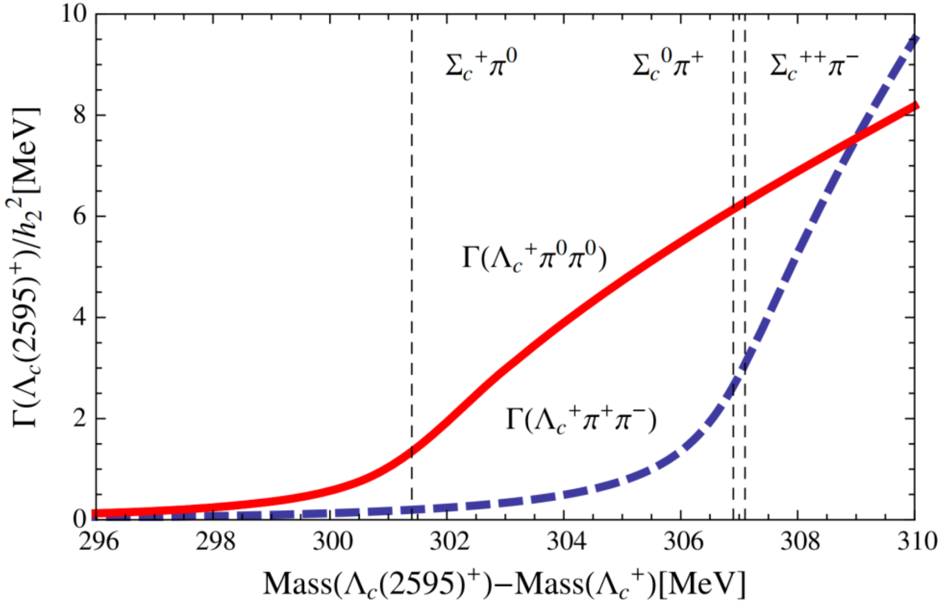
The same branching fraction in Charge-Congiugate



Results of Branching fractions

arXiv:2401.09225

H.-Y. Cheng and C.-K. Chua,
PRD 92, 074014 (2015)



	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%

- 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)
$\Lambda_c^+ \to p\pi^0$	arXiv: 2311.06883
$\Lambda_c^+ \to \Lambda K^+$	PRD 106, L111101 (2022)
$\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S$	PRD 106, 052003 (2022)
$\Lambda_c^+ \to \Sigma^- K^+ \pi^+$	arXiv: 2309.05484
$\Lambda_c^+ \to nK^+\pi^0$ (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

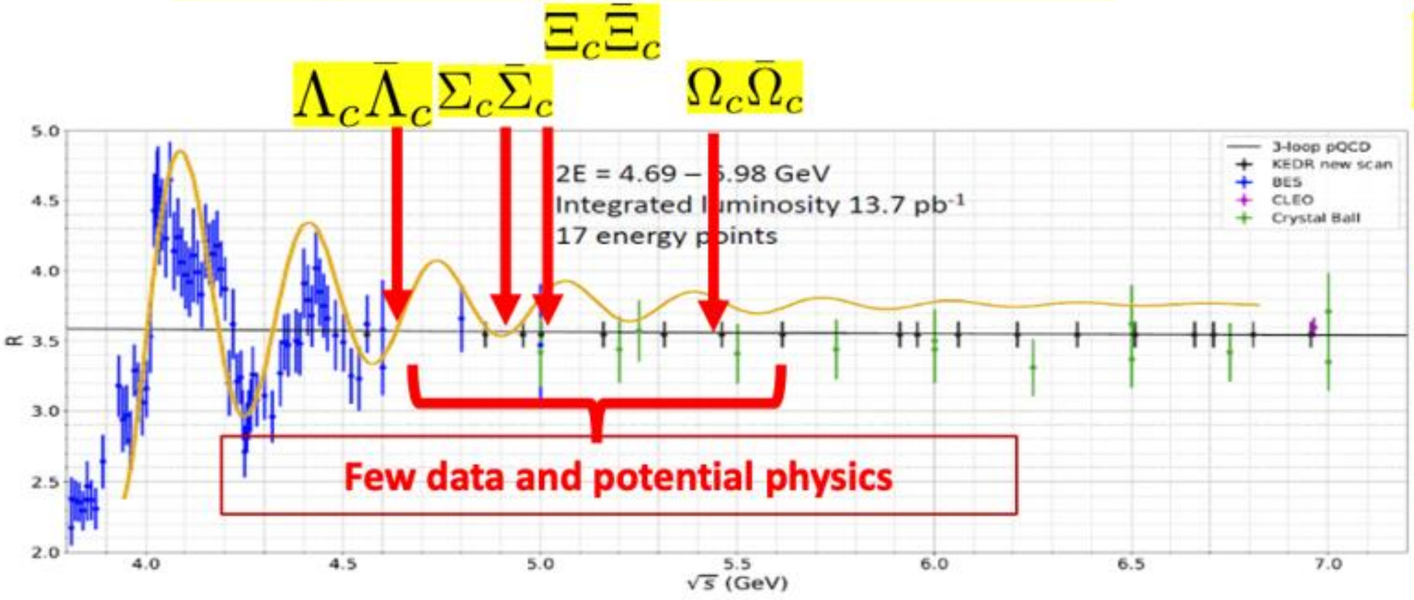
Semileptonic	
$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL 129, 231803 (2022)
$\Lambda_c^+ \to \Lambda\mu^+\nu_e$	PRD 108, 031105 (2023)
$\Lambda_c^+ \to pK^- e^+\nu_e$	PRD 106, 112010 (2022)
$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$ $\Lambda_c^+ \to pK_S e^+\nu_e$	PLB 843 (2023) 137993

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)
$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^{*-}$	arXiv:2312.08414
$\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$	arXiv:2401.09225

>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} $\Lambda_c\ \Lambda_c$

Others

✓ $\Xi_c\ \bar{\Xi}_c$ 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

- ❖BESIII has collected dedicated data for the charmed baryons between $\sqrt{s} = 4.6 \sim 4.95$ GeV
- ❖Productions and decays of ground-state Λ_c^+ have been investigated.
- ❖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.

Thank you!