Study of Λ_c^+ decays with a neutron in the final state at BESIII

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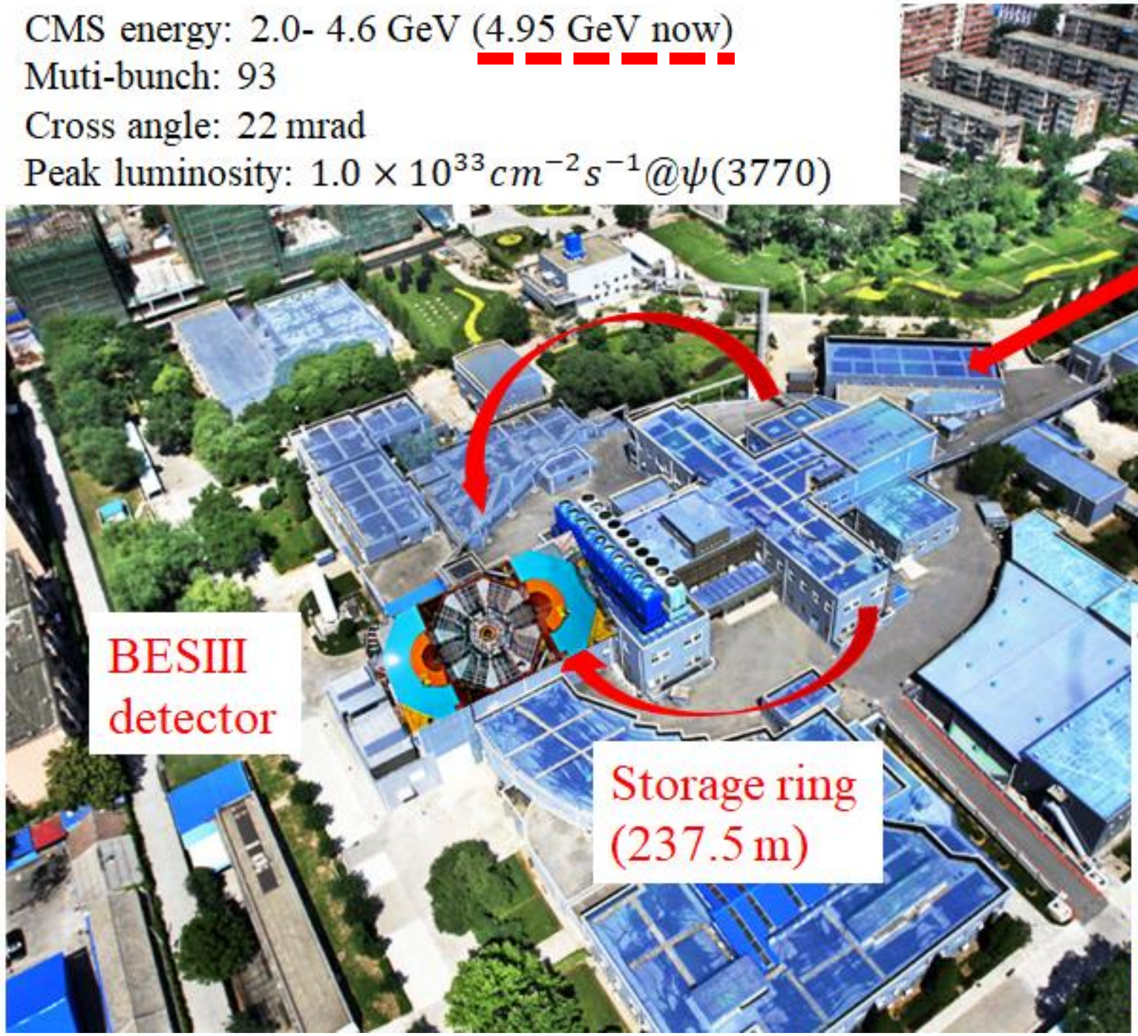
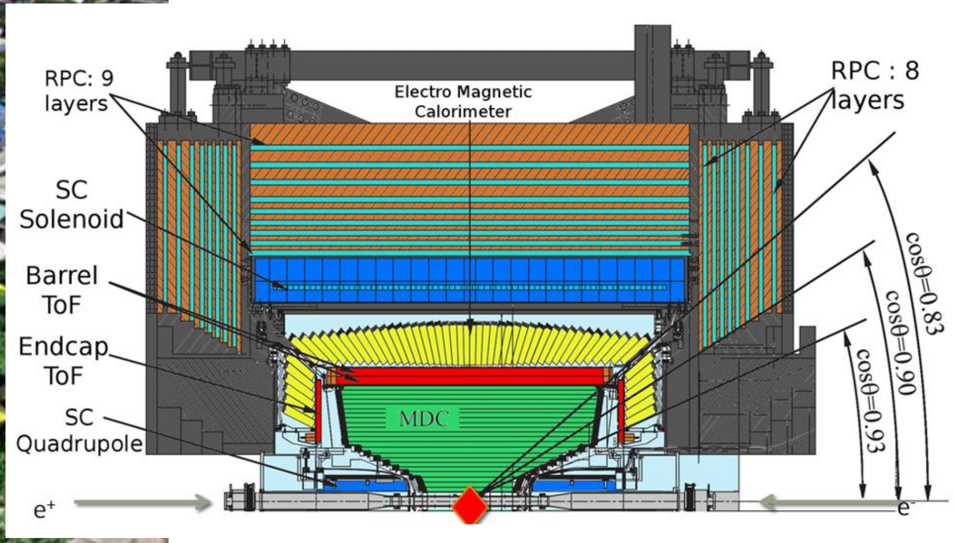
Outline

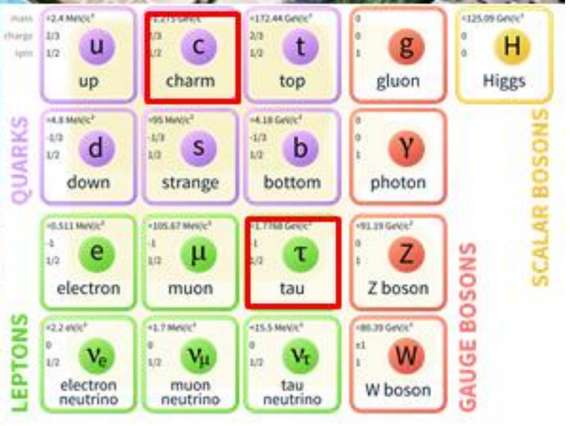
- BESIII experiment
- Λ_c^+ history at BESIII
- Λ_c^+ production at BESIII
- Study of $\Lambda_c^+ \to n\pi^+, n\pi^+\pi^0, \ldots$
- Inclusive decay of $\Lambda_c^+ \to n + X$
- Summary

BESIII Experiment

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

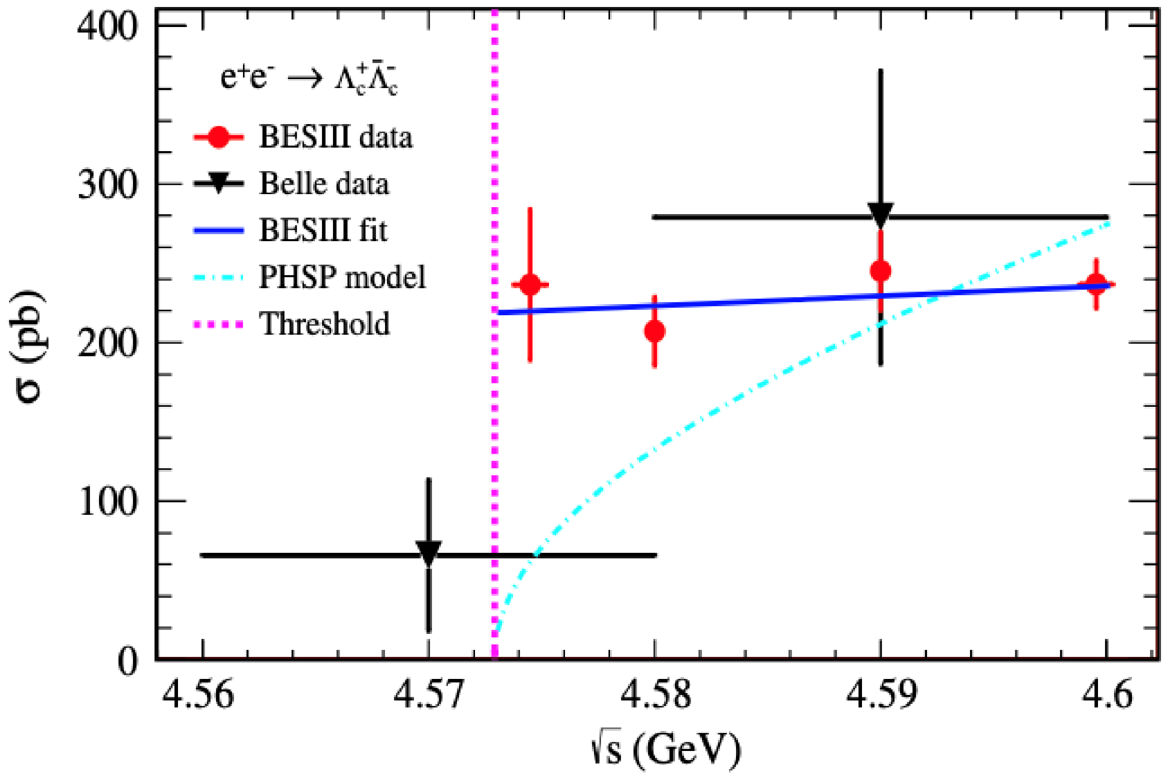






Λ_c^+ history at BESIII

In 2014, 567 pb^{-1} at 4.6 GeV



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)

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}	$pK^-\pi^+\pi^+\pi^-$		$(1.5\pm1.0)\times10^{-3}$	
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}	$p\pi^+\pi^-$		$(4.7\pm2.5)\times10^{-3}$	
Γ_{18}	$pf_0(980)$	[a]	$(3.8\pm2.5)\times10^{-3}$	
Γ_{19}	$p\pi^+\pi^+\pi^-\pi^-$		$(2.5\pm1.6)\times10^{-3}$	
Γ_{20}	pK^+K^-		$(1.1\pm0.4)\times10^{-3}$	
Γ_{21}	$p\phi$	[a]	$(1.12\pm0.23)\times10^{-3}$	
Γ_{22}	pK^+K^- non-ϕ		$(4.8\pm1.9)\times10^{-4}$	

PDG in 2020

	Mode		Fraction	Scale factor/CL	
	Hadronic modes with a p or n: $S=-1$ final states				
Γ_1	pK^0_S		(1.59 ± 0.08) %	S=1.1	↓44%
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) %	S=1.1	↓50%
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) %	S=1.1	↓28%
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	S=1.5	↓61%
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}	$pK^-2\pi^+\pi^-$		$(1.4\pm0.9)\times10^{-3}$		
Γ_{16}	$pK^-\pi^+2\pi^0$		(1.0 ± 0.5) %		
	Hadronic modes with a p: $S=0$ final states				
Γ_{17}	$p\pi^0$		$<2.7\times10^{-4}$	CL=90%	
Γ_{18}	$p\eta$		$(1.24\pm0.30)\times10^{-3}$		First
Γ_{19}	$p\omega(782)^0$		$(9\pm4)\times10^{-4}$		
Γ_{20}	$p\pi^+\pi^-$		$(4.61\pm0.28)\times10^{-3}$		First
Γ_{21}	$pf_0(980)$	[a]	$(3.5\pm2.3)\times10^{-3}$		
Γ_{22}	$p2\pi^+2\pi^-$		$(2.3\pm1.4)\times10^{-3}$		
Γ_{23}	pK^+K^-		$(1.06\pm0.06)\times10^{-3}$		
Γ_{24}	$p\phi$	[a]	$(1.06\pm0.14)\times10^{-3}$		↓36%
Γ_{25}	pK^+K^- non-ϕ		$(5.3\pm1.2)\times10^{-4}$		
Γ_{26}	$p\phi\pi^0$		$(10\pm4)\times10^{-5}$		
Γ_{27}	$pK^+K^-\pi^0$ nonresonant		$<6.3\times10^{-5}$	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}	$\Xi(1690)^0 K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$		$(1.8 \pm 0.6) \times 10^{-3}$	
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) %

PDG in 2020

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

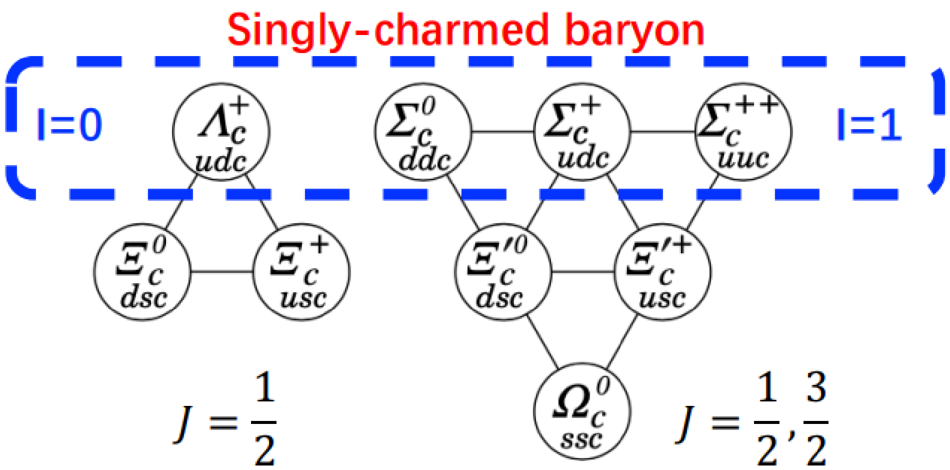
Hadronic modes with a hyperon: $S = -1$ final states

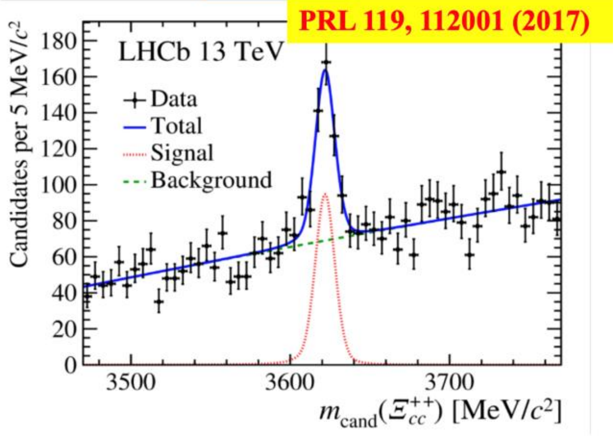
Γ_{28}	$\Lambda\pi^+$	(1.30 ± 0.07) %		S=1.1
Γ_{29}	$\Lambda\pi^+\pi^0$	(7.1 ± 0.4) %	↓78%	S=1.1
Γ_{30}	$\Lambda\rho^+$	< 6 %		CL=95%
Γ_{31}	$\Lambda\pi^-2\pi^+$	(3.64 ± 0.29) %		S=1.4
Γ_{44}	$\Sigma^0\pi^+$	(1.29 ± 0.07) %	↓45%	S=1.1
Γ_{45}	$\Sigma^+\pi^0$	(1.25 ± 0.10) %	↓33%	
Γ_{46}	$\Sigma^+\eta$	$(4.4 \pm 2.0) \times 10^{-3}$		
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) %		

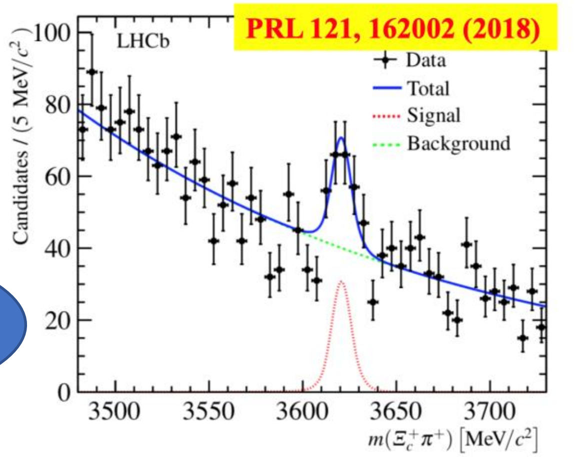
Semileptonic modes

Γ_{72}	$\Lambda e^+\nu_e$	(3.6 ± 0.4) %	↓35%
Γ_{73}	$\Lambda\mu^+\nu_\mu$	(3.5 ± 0.5) %	

Charmed baryon Λ_c^+





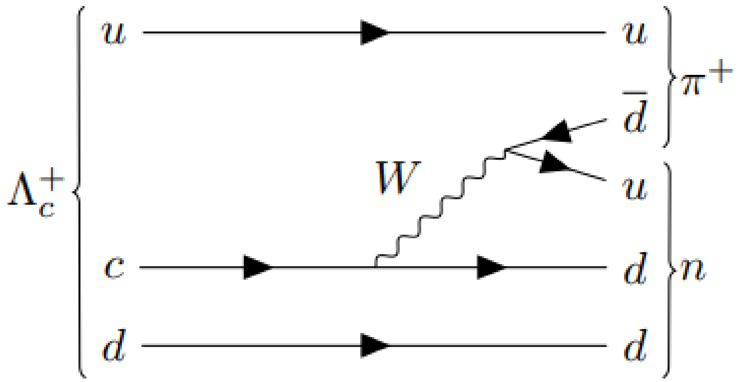


- LHCb observed doubly charm baryon Ξ_{cc}^{++} with$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays.

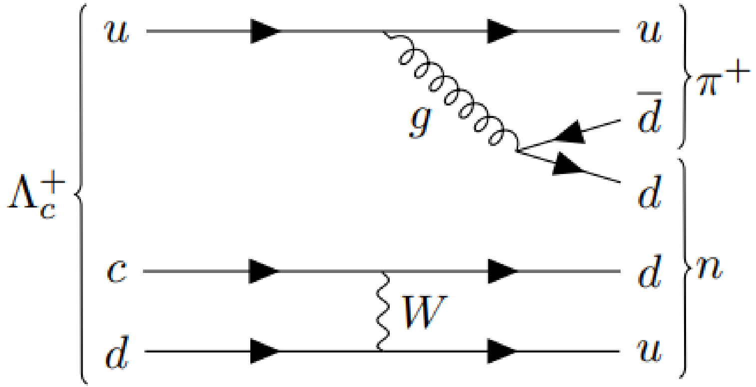
Λ_c^+ is lowest-lying charmed bayron: Important for the higher mass charmed baryon and bottomed baryon

Λ_c^+ hadronic decays

Internal W emission



W exchange



Λ_c hadronic decay amplitudes[1][2]

- Nonfactorizable components — Experimental input
- Factorizable components

[1]: L. L. Chau and H. Y. Cheng, Phys. Rev. Lett. 56, 1655 (1986).
[2]: K. Yoji, Phys. Rev. D. 44, 2799 (1991).

Singly Cabibbo suppressed decays

Λ_c^+	$SU(3)_f$	Cheng et al.	Our work	Expt.
$10^4\mathcal{B}_{\Sigma^+K^0}$	10.5 ± 1.4	14.4	19.1 ± 4.8	
$10^4\mathcal{B}_{\Sigma^0K^+}$	5.2 ± 0.7	7.2	5.5 ± 1.6	5.2 ± 0.8
$10^4\mathcal{B}_{p\pi^0}$	$1.1^{+1.3}_{-1.1}$	1.3	$0.8^{+0.9}_{-0.8}$	0.8 ± 1.4
$10^4\mathcal{B}_{p\eta}$	11.2 ± 2.8	12.8	11.4 ± 3.5	12.4 ± 3.0
$10^4\mathcal{B}_{p\eta'}$	24.5 ± 14.6		7.1 ± 1.4	
$10^4\mathcal{B}_{n\pi^+}$	7.6 ± 1.1	0.9	7.7 ± 2.0	
$10^4\mathcal{B}_{\Lambda^0K^+}$	6.6 ± 0.9	10.7	5.9 ± 1.7	6.1 ± 1.2

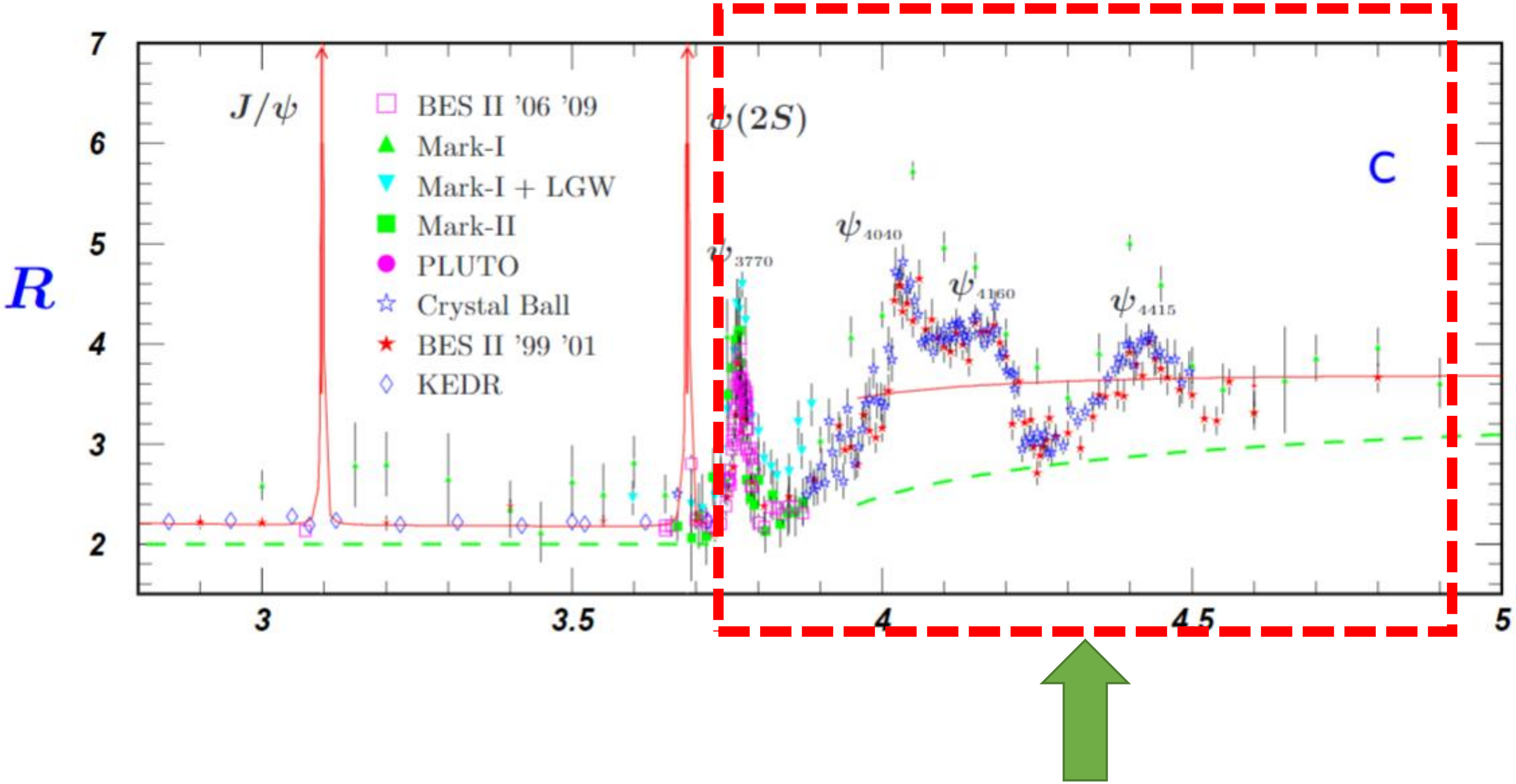
Ref: J. High Energy Phys. 02 (2020) 165

Challenge: Small branching fractions of 10^{-3} or below

Various models: SU(3) flavor symmetry, pole model and current-algebra, topological-diagram approach, etc

* $n\pi^+$,$p\eta$ and $p\eta'$ were observed in 2022.

Λ_c^+ production at BESIII

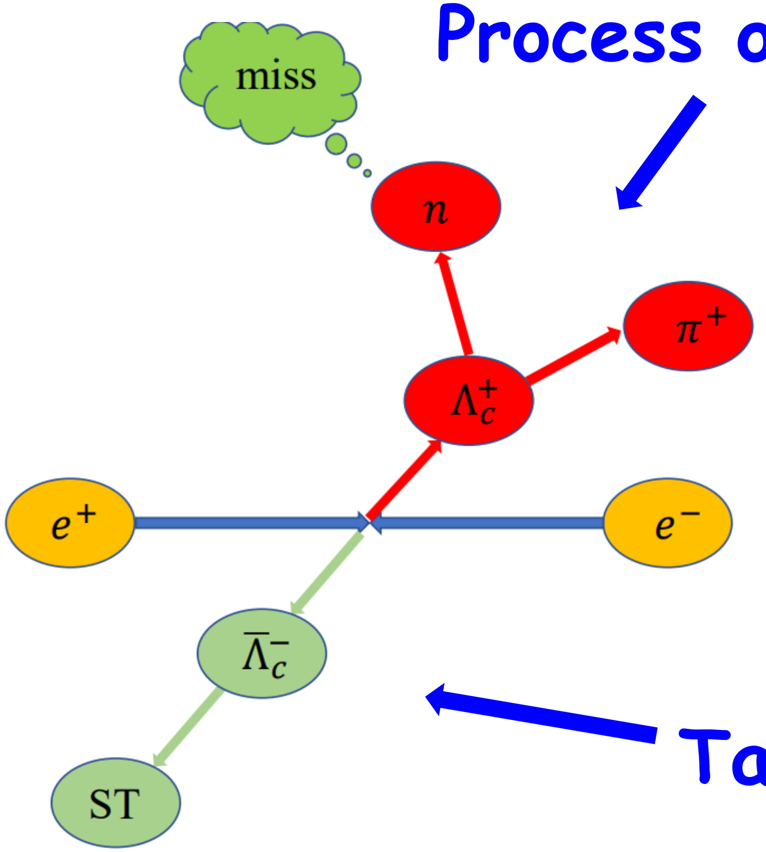


Threshold effect: pair production of charmed mesons/baryons !

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

Double-tag approach

Process of interest



Tag-side

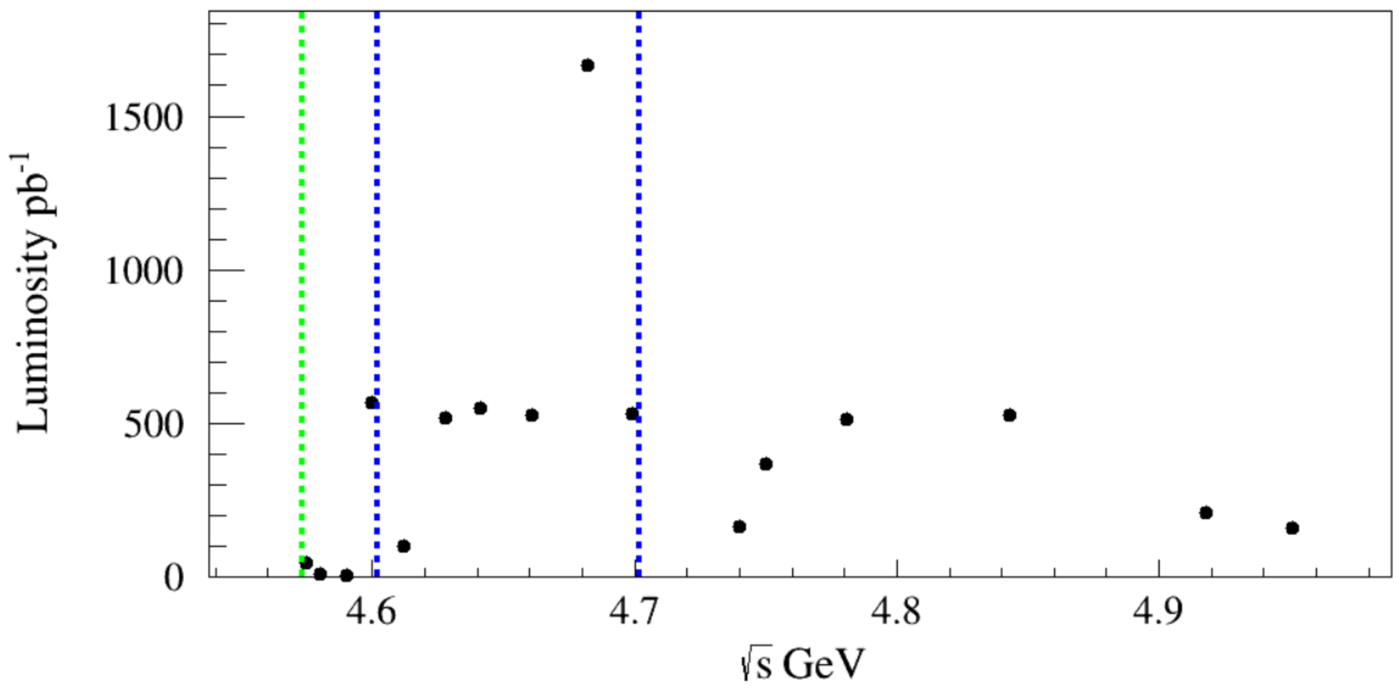
Model-independent

$$N_{i\ ST} = 2N_0 \times \mathcal{B}_i \times \varepsilon_{i\ ST}$$

$$N_{is\ DT} = 2N_0 \times \mathcal{B}_i \times \mathcal{B}_s \times \varepsilon_{is\ DT}$$

$$\mathcal{B}_s = \frac{\Sigma N_{is\ DT}}{\Sigma N_{i\ ST} \times \varepsilon_{is\ DT} / \varepsilon_{i\ ST}}$$

New data sets at BESIII

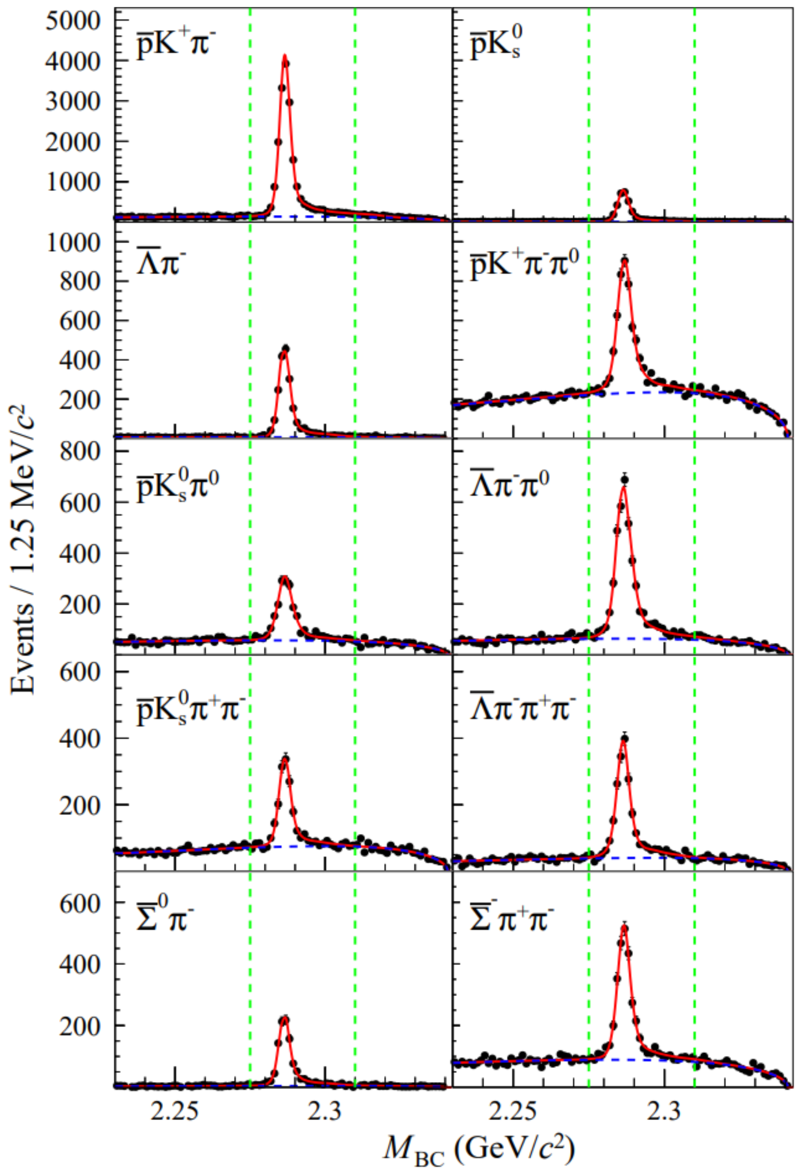


New!
Collected in 2020
and 2021

4.6 – 4.7 GeV 0.6 + 3.8 fb^{-1}

4.7 – 4.95 GeV 1.9 fb^{-1}

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



Λ_c^+ tagging

PRL 128 (2022) 142001

✓10 singly tagged modes at BESIII

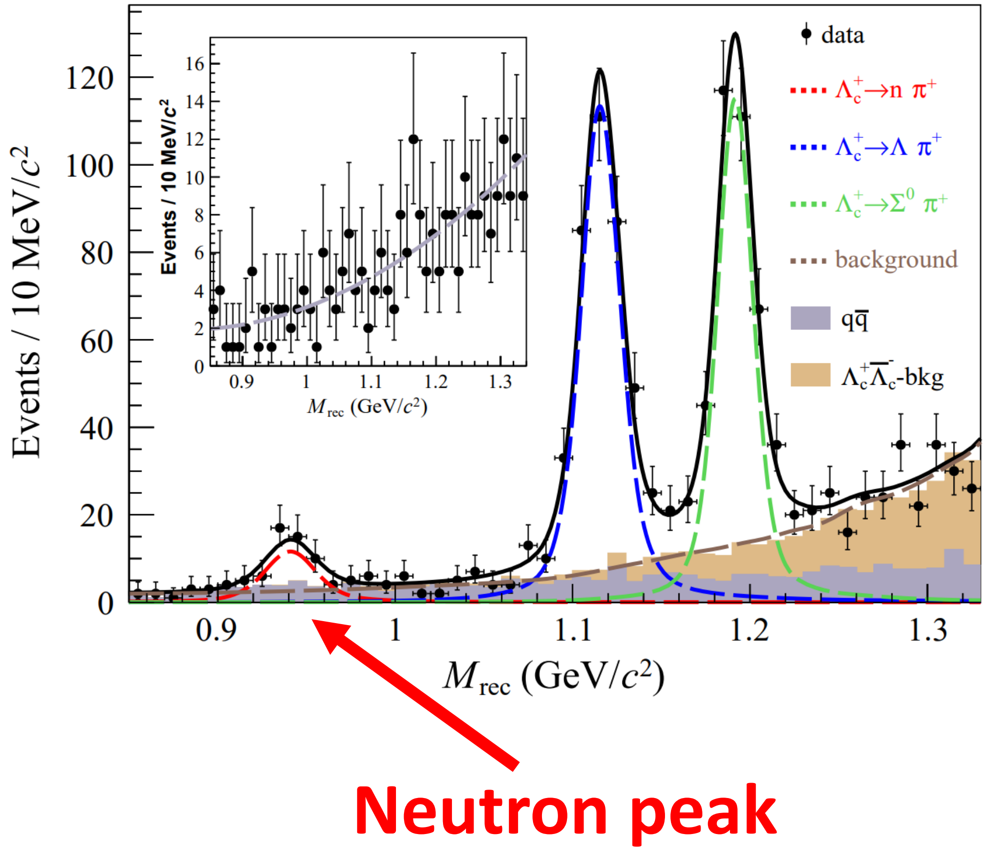
✓$N_{ST} = 90692 \pm 359$ @ 4.612-4.699 GeV

$$M_{\rm BC} = \sqrt{E_{\rm beam}^2/c^4 - |\vec{p}_{\bar{\Lambda}_c^-}|^2/c^2}$$

- $E_{\rm beam}$ is the beam energy.
- $\vec{p}_{\bar{\Lambda}_c^-}$ is the momentum of the $\bar{\Lambda}_c^-$ candidate.

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

PRL 128 (2022) 142001



$$M_{\text{rec}}^2 = (E_{\text{beam}} - E_{\pi^+})^2/c^4 - |\rho \cdot \vec{p}_0 - \vec{p}_{\pi^+}|^2/c^2$$

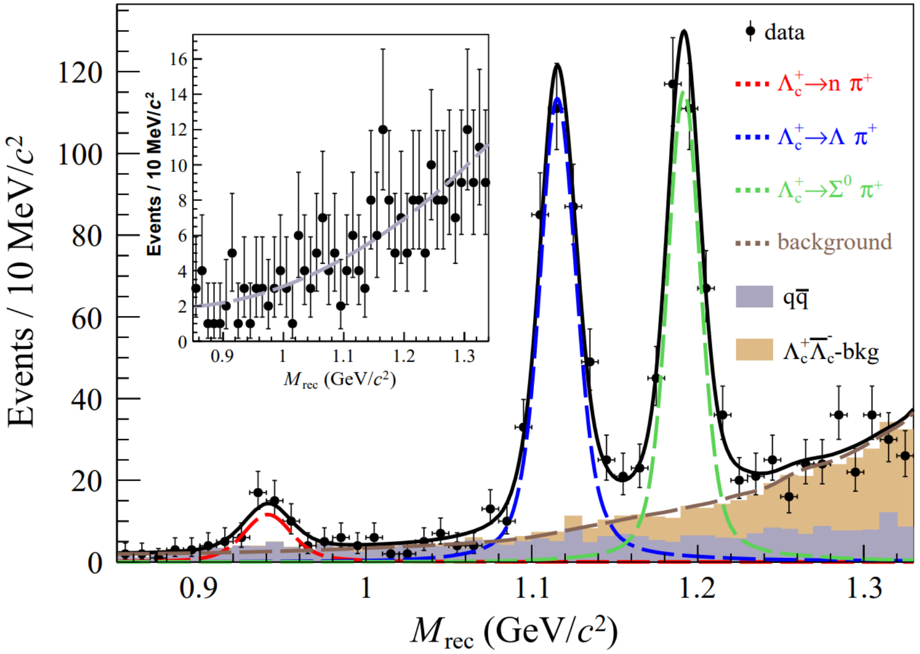
- $\rho = \sqrt{E_{\text{beam}}^2/c^2 - m_{\Lambda_c^+}^2 c^2}$
- $\vec{p}_0 = -\vec{p}_{\bar{\Lambda}_c^-}/|\vec{p}_{\bar{\Lambda}_c^-}|$ is the unit direction opposite to the ST $\bar{\Lambda}_c^-$

Energy-momentum conservation !

✓ Select the π^+ against the ST $\bar{\Lambda}_c^-$.

✓ Extract the yields from the invariant mass of the missing part ➔ **Neutron as missing particle!**

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



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

- ✓ Red peak: $\Lambda_c^+ \to n\pi^+$ 7.3σ
- ✓ Blue peak: $\Lambda_c^+ \to \Lambda\pi^+$
- ✓ Green peak: $\Lambda_c^+ \to \Sigma^0\pi^+$

} Consistent with results from PDG

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

✓ 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.**

Comparison to theory

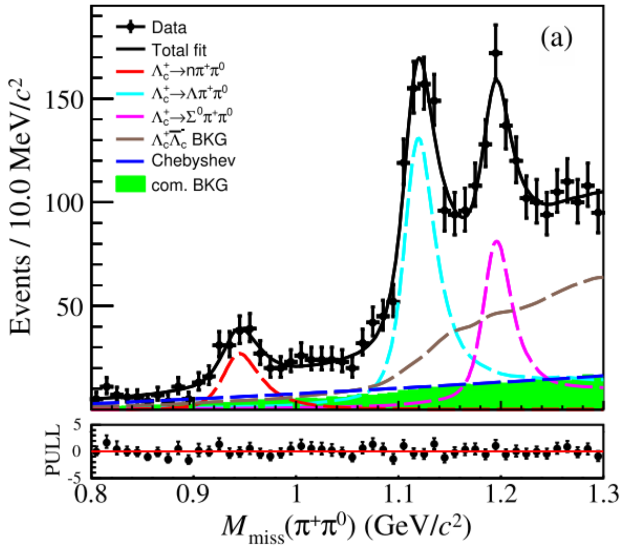
Decay	Yields	Branching fraction this work
$\Lambda_c^+ \to n\pi^+$	50 ± 9	$(6.6 \pm 1.2_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-4}$
R	**> 7.2 at 90% C.L.**	

$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	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

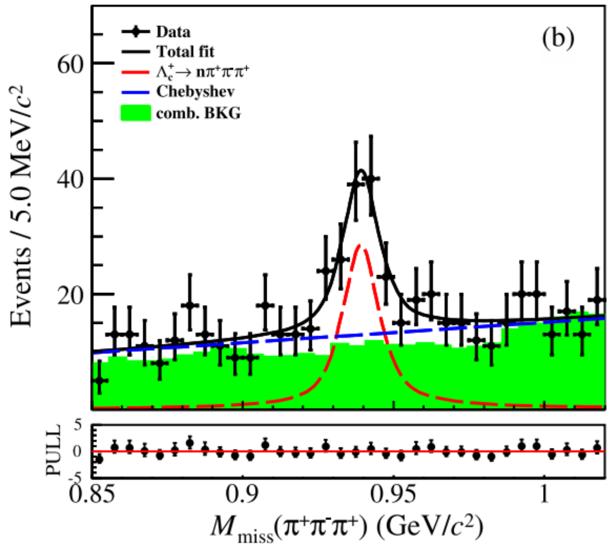
- ✓ Contradictory with most of predictions
- ✓ Revisiting the $\Lambda_c^+ \to p\pi^0$ with the larger data sets. New results will come out late this year.

Observation of $\Lambda_c^+ \to n\pi^+\pi^0$, $n3\pi$, $nK^+2\pi$

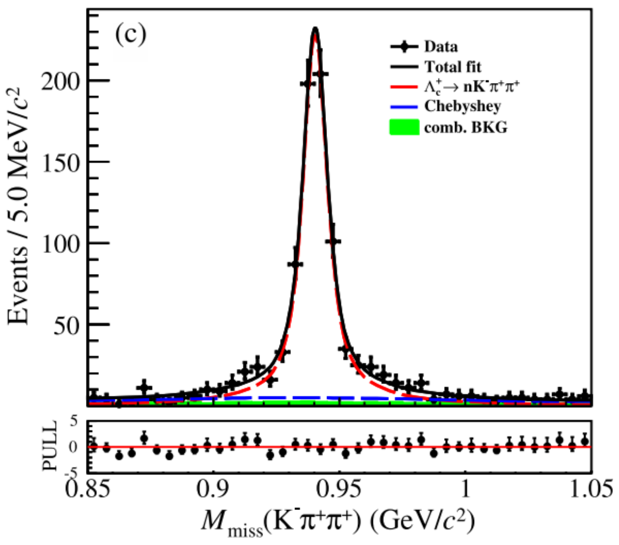
CPC 47, 023001 (2023)



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



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



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

Signal decay	$\mathcal{B}$ (%)
$\Lambda_c^+ \to n\pi^+\pi^0$	$0.64 \pm 0.09 \pm 0.02$
$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	$0.45 \pm 0.07 \pm 0.03$
$\Lambda_c^+ \to nK^-\pi^+\pi^+$	$1.90 \pm 0.08 \pm 0.09$

- ✓ Double-tag approach
- ✓ Neutron as missing particle

Results

$B(\Lambda_c^+ \to pK_S^0\pi^0)/B(\Lambda_c^+ \to pK_S^0)$ = 1.24 ± 0.10

$B(\Lambda_c^+ \to n\pi^+\pi^0)/B(\Lambda_c^+ \to n\pi^+)$	9.7 ± 2.4
$B(\Lambda_c^+ \to p\pi^+\pi^-)/B(\Lambda_c^+ \to n\pi^+\pi^0)$	0.72 ± 0.11
$B(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)/B(\Lambda_c^+ \to nK^+\pi^+\pi^-)$	0.24 ± 0.04

Consistent with CKM

$|V_{cd}|/|V_{cs}|$ = (0.224 ± 0.005)

Branching fraction of $\Lambda_c^+ \to n + X$

PDG 2022

PRD 45, 752 (1992)

Inclusive modes

e^+ anything	(3.95 ± 0.35) %
p anything	(50 ± 16) %
n anything	(50 ± 16) %
Λ anything	$(38.2\ ^{+\ 2.9}_{-\ 2.4})$ %
K_S^0 anything	(9.9 ± 0.7) %
3prongs	(24 ± 8) %

How large does Λ_c^+ decay into a neutron ?

Large uncertainty in the indirect measurement

Strategy

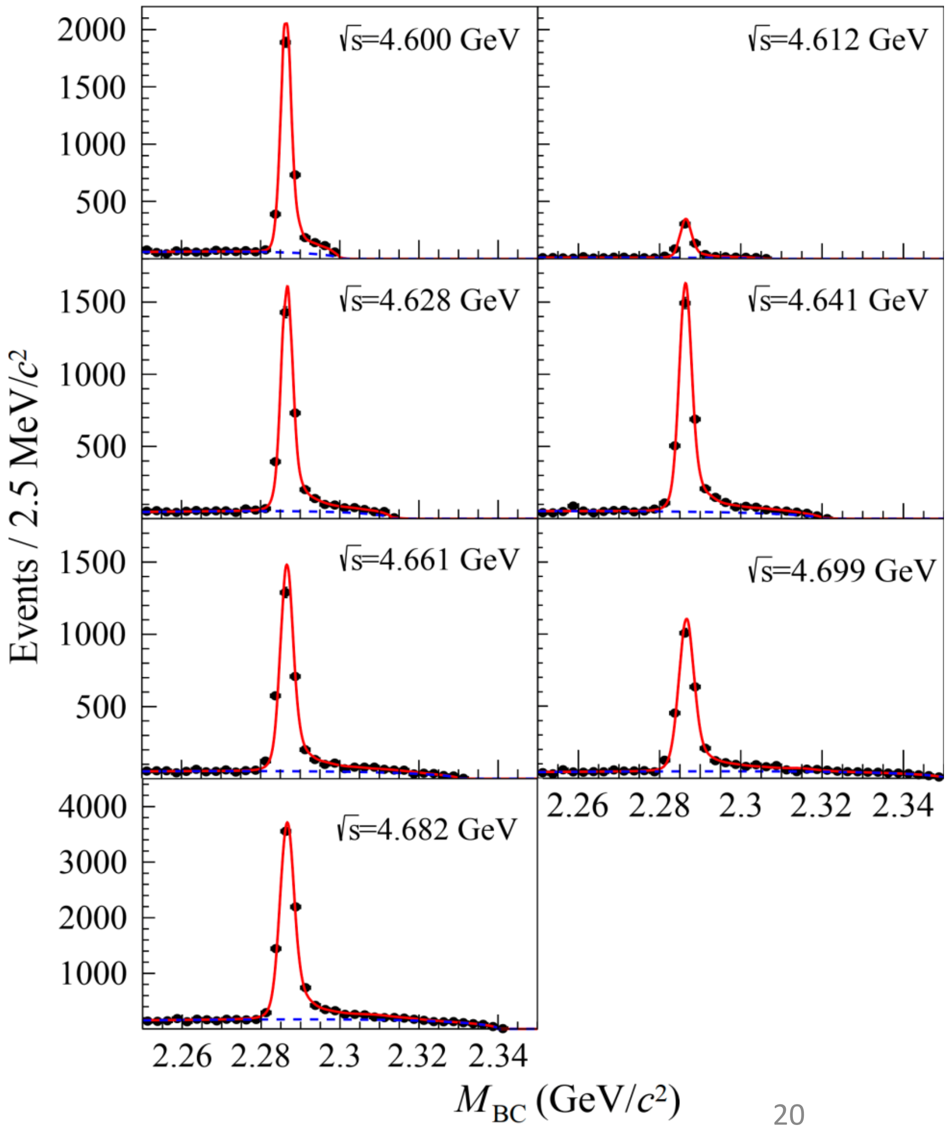
arXiv:2210.09561

Under CP symmetry :

$\bar{\Lambda}_c^- \to \bar{n} + X \quad \Leftrightarrow \quad \Lambda_c^+ \to n + X$

- $\Lambda_c^+ \to pK^-\pi^+$ as tagging, yield 24577 ± 179
- Discriminate the $\bar{n}$ from the neutral noise:

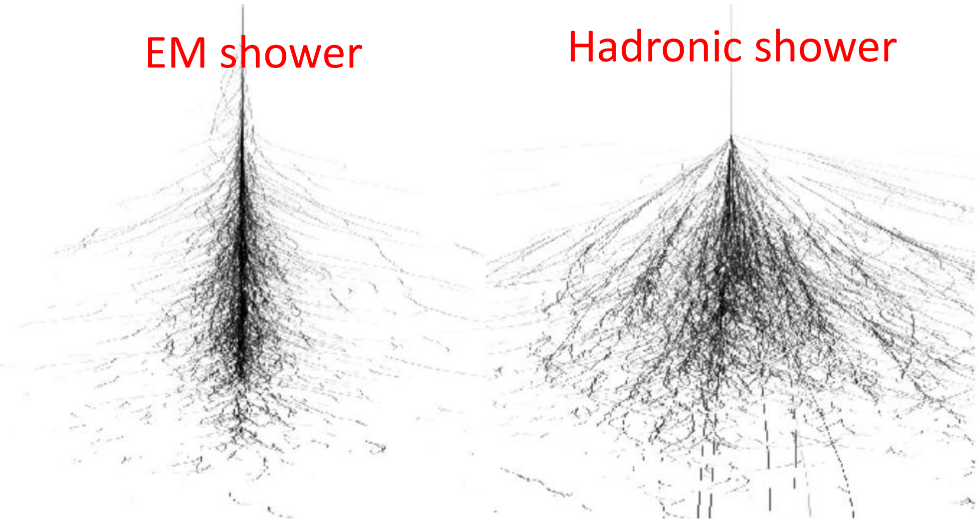
  $E_{\bar{n}} > 0.48$ GeV, $S_{\bar{n}} > 18$ cm^2, $Hits_{\bar{n}} > 20$



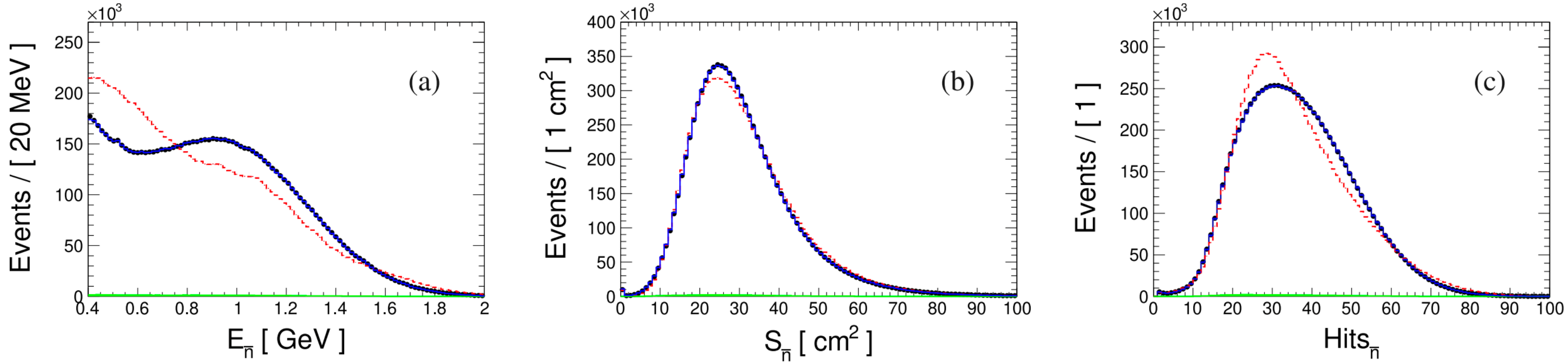
Anti-neutron signals

L. Liu, X. R. Zhou, and H. P. Peng, NIM A 1033 (2022) 166672

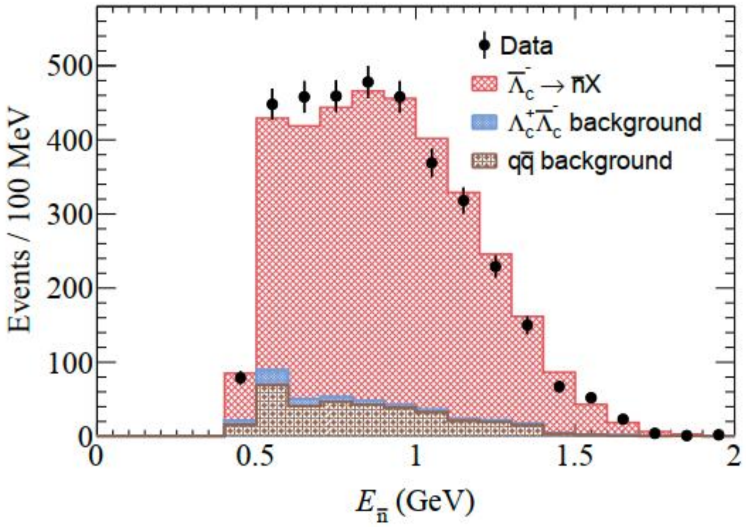
- 10 billion J/ψ events at BESIII
- $J/\psi \to p\pi\bar{n}$ as control sample

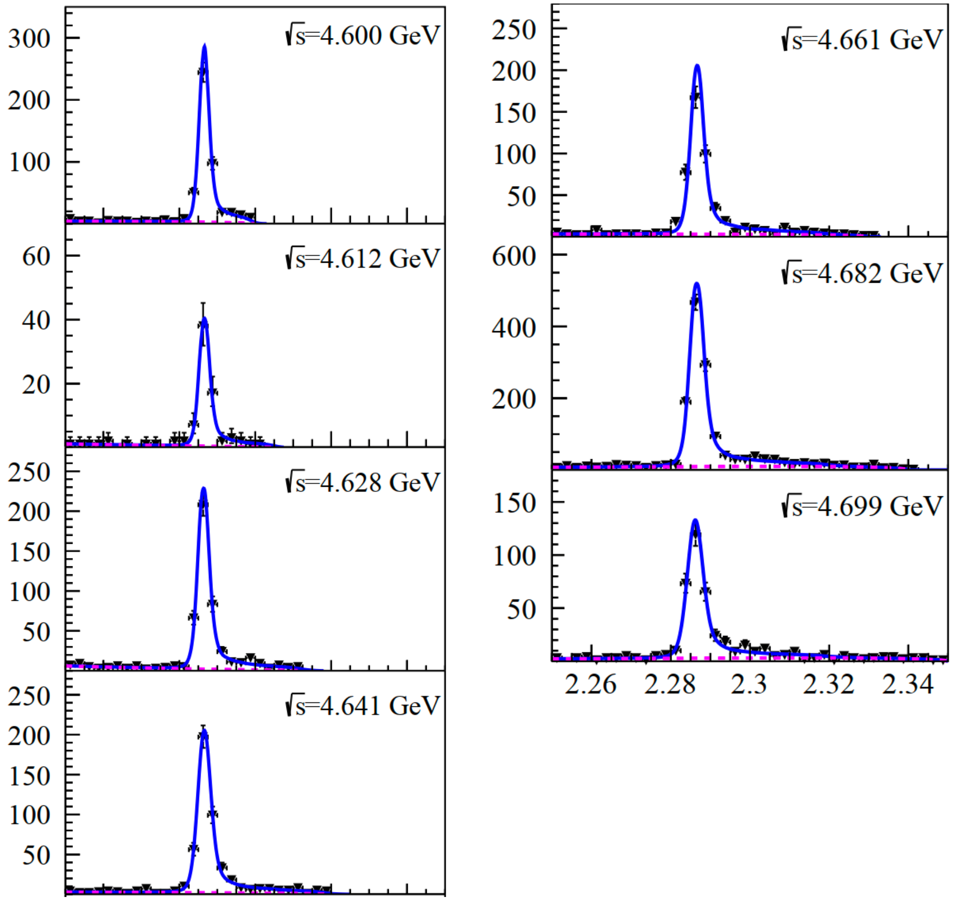


Three key variables: deposited energy ($E_{\bar{n}}$), second moment ($S_{\bar{n}}$), number of hits for each shower ($Hits_{\bar{n}}$)



25% is missing





25% of Λ_c^+ decays into a neutron haven't been observed

This work	$\Lambda_c^+ \to n + X$	$(33.5 \pm 0.7 \pm 1.2)\%$	
PDG (Exclusive)	$\Lambda_c^+ \to n_{direct} + X$	$(4.88 \pm 0.30)\%$	$(25.4 \pm 0.8)\%$
	$\Lambda_c^+ \to \Lambda + X$	$(8.03 \pm 0.41)\%$	
	$\Lambda_c^+ \to \Sigma/\Xi + X$	$(12.5 \pm 0.66)\%$	

Summary

- BESIII has collected about 6.5 fb^{-1} data between $\sqrt{s} = 4.6$ and 5.0 GeV.
- $\Lambda_c^+ \to n\pi^+$, $n\pi^+\pi^0$ … have been observed for the first time.
- $B(\Lambda_c^+ \to n + X)$ is about 33% of total Λ_c^+ decays, and one-fourth of decays into a neutron have not yet observed.
- More results of Λ_c^+ will come very soon. Stay tuned !

Thanks for your attention!

Backup

Data collected at BESIII

Data sets collected so far include,

- 10×10^9 J/ψ **events**
- 0.5×10^9 ψ' events
- Scan data [2.0, 3.08] GeV; [3.735, 4.600] GeV

  130 energy points, about 2.0 fb^{-1}
- Large data sets for XYZ study above 4.0 GeV

  about 20 fb^{-1}

Unique data sets at open charm thresholds

$$3.77\,\mathrm{GeV}\quad 2.93\,\mathrm{fb}^{-1}\quad D\bar{D}$$

$$4.008\,\mathrm{GeV}\quad 0.48\,\mathrm{fb}^{-1}\quad D_s^+D_s^-$$

$$4.18\,\mathrm{GeV}\quad 3.2\,\mathrm{fb}^{-1}\quad D_sD_s^*$$

$$4.6-4.7\,\mathrm{GeV}\quad 0.6+3.8\,\mathrm{fb}^{-1}\quad \Lambda_c^+\bar{\Lambda}_c^-$$

Totally about 33 fb^{-1} in 10 year running