Charmed Baryons Decays at BESIII

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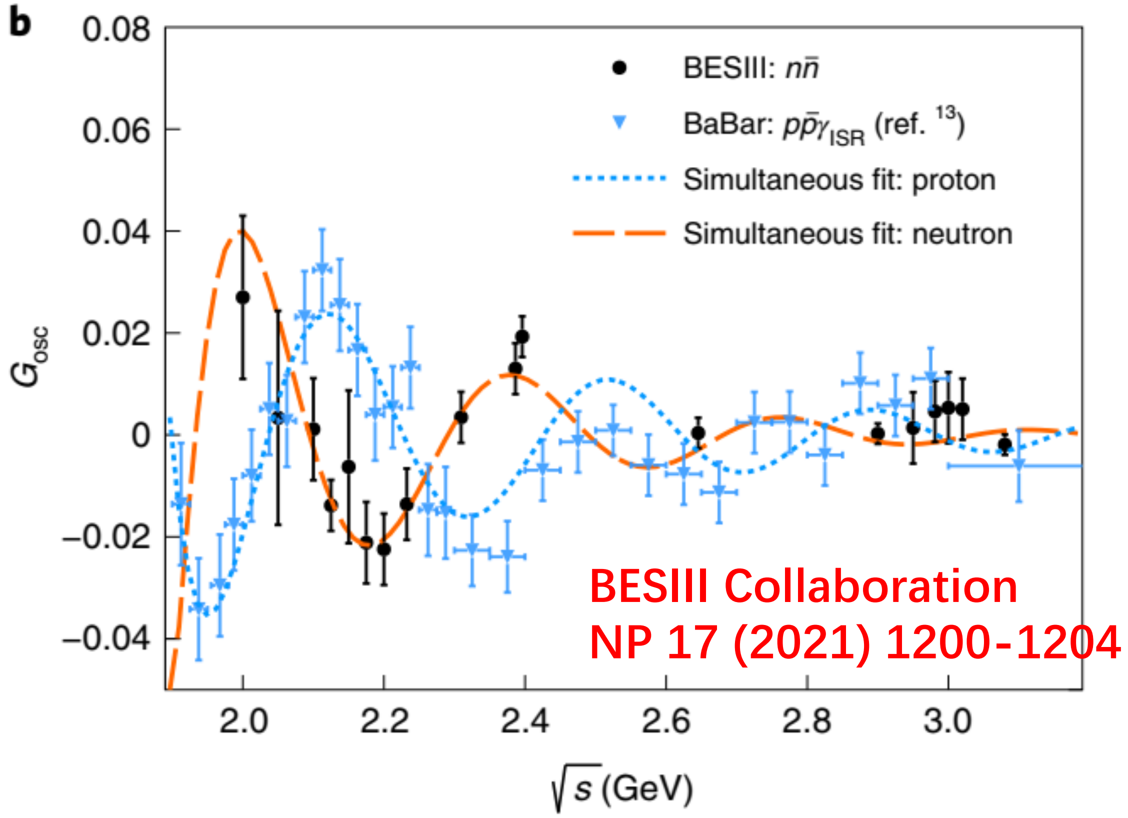
(On behalf of BESIII Collaboration)

Outline

- Charmed Baryons
- BESIII experiment
- Cabibbo favored and suppressed decays
- Inclusive decays
- Decays of excited charmed baryons
- List of the released results
- Prospect at BESIII

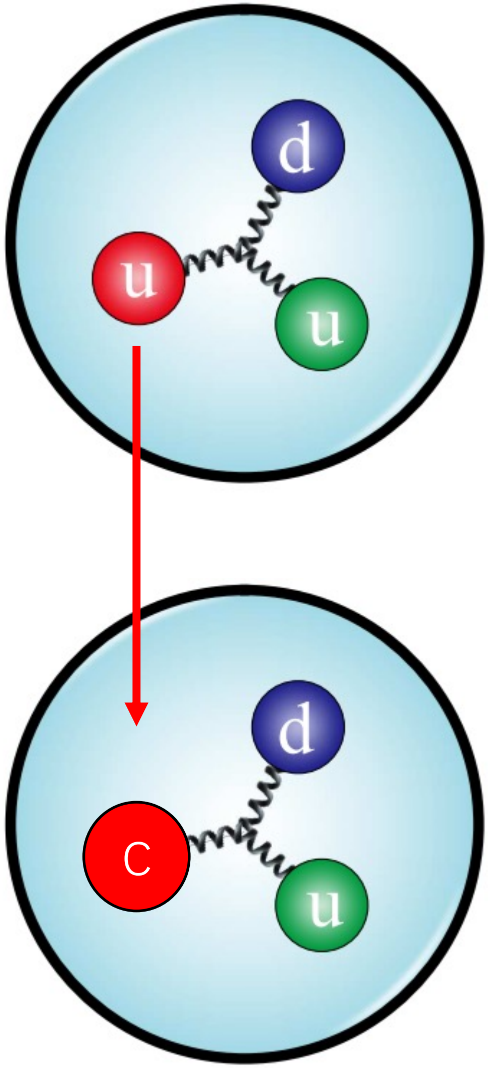
Charmed Baryons

Form factors oscillate!



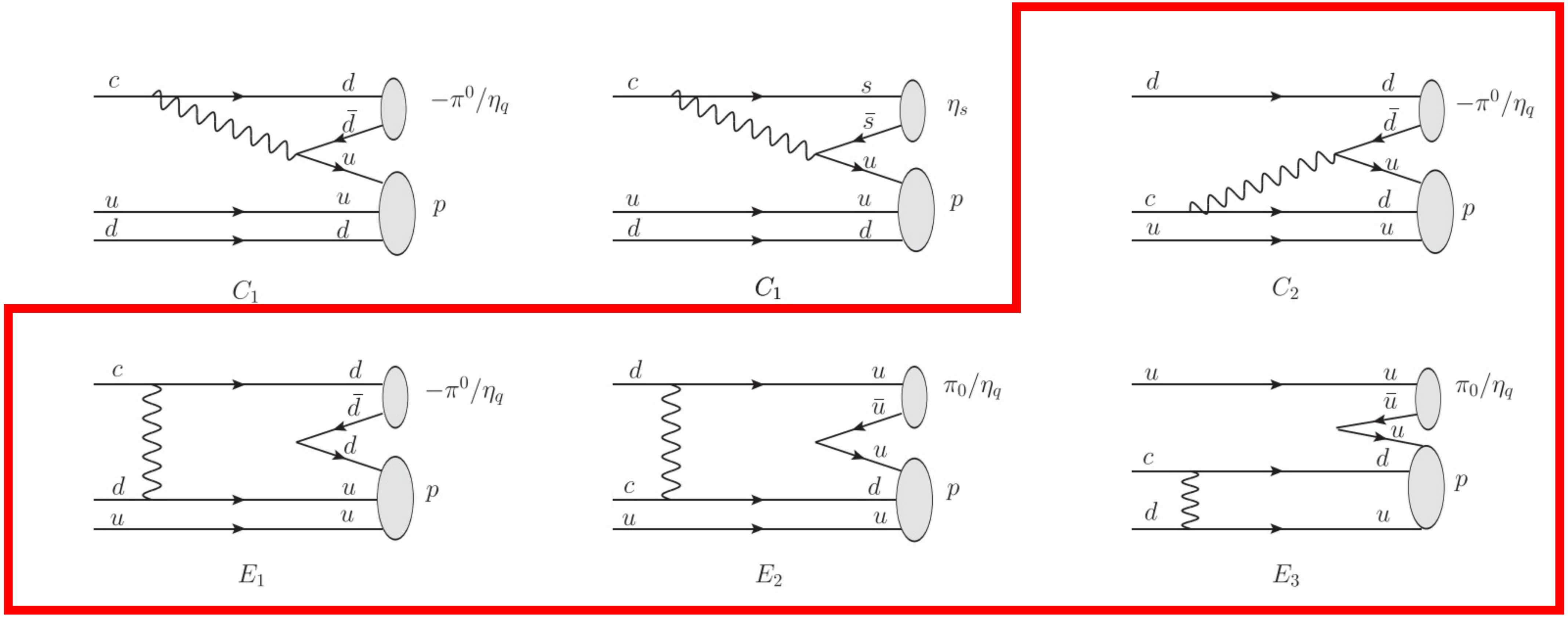
Proton

Charmed Baryon



Baryon structure is attractive !

Decays of Charmed Baryons

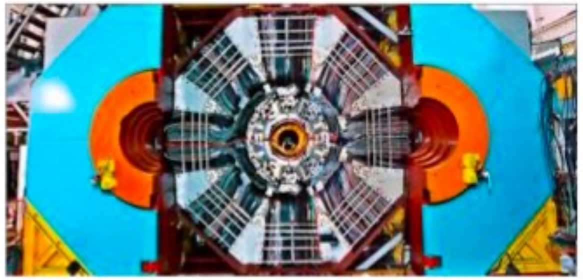


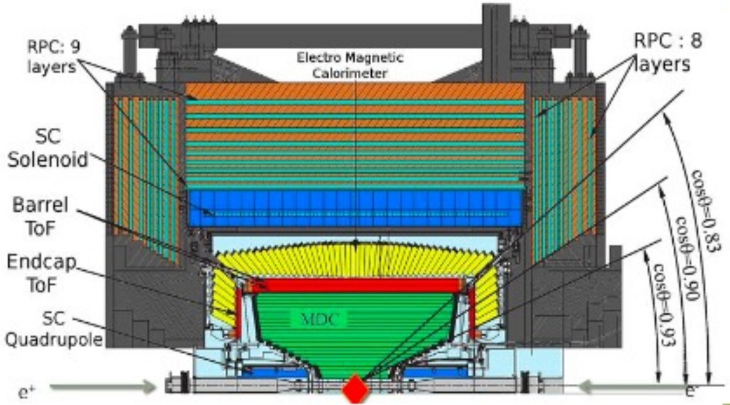
Calculation is not reliable, need exp. input

C_1 : factorization component

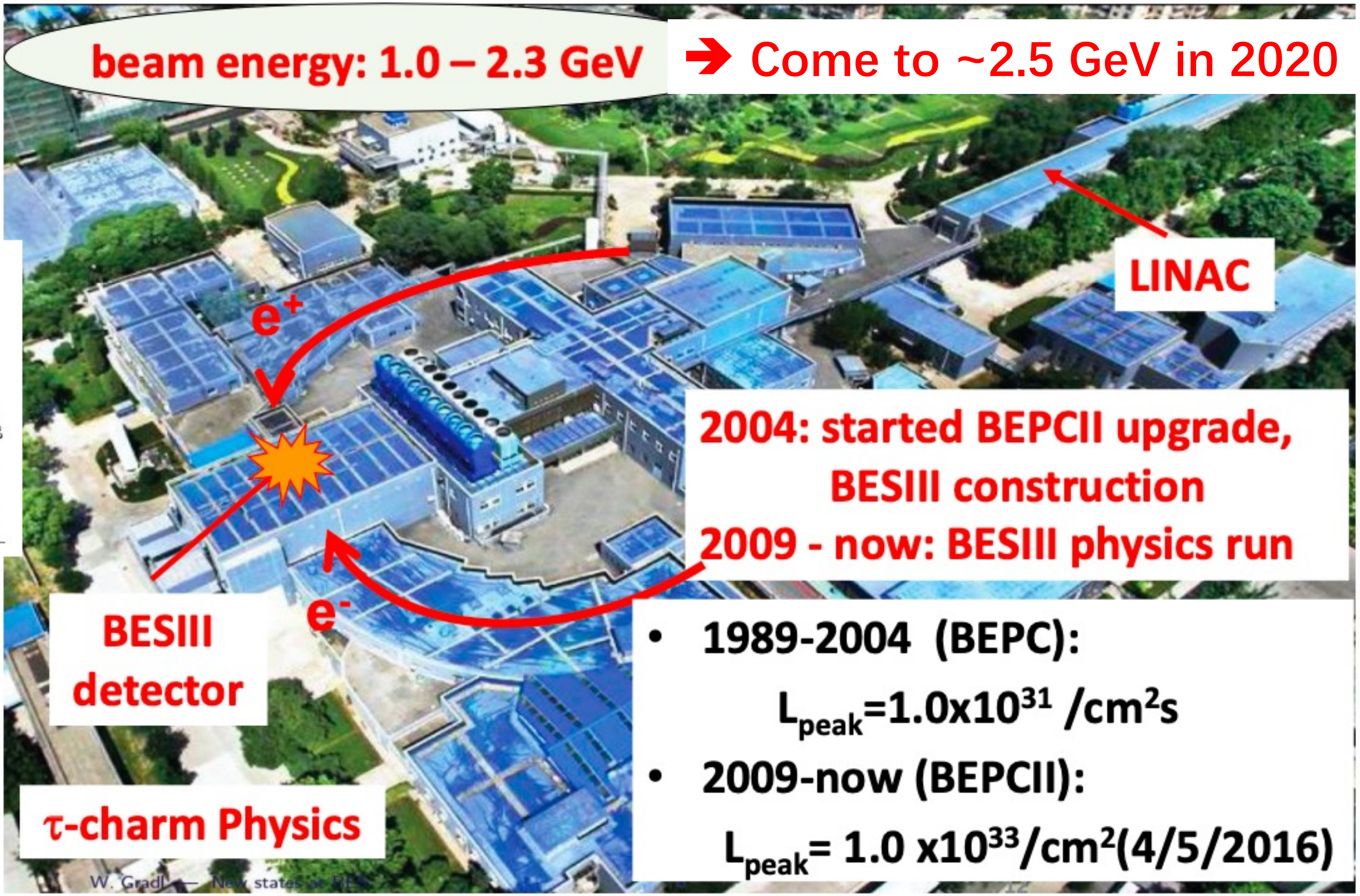
C_2,E_1,E_2,E_3: non-factorization component

BEPCII and BESIII



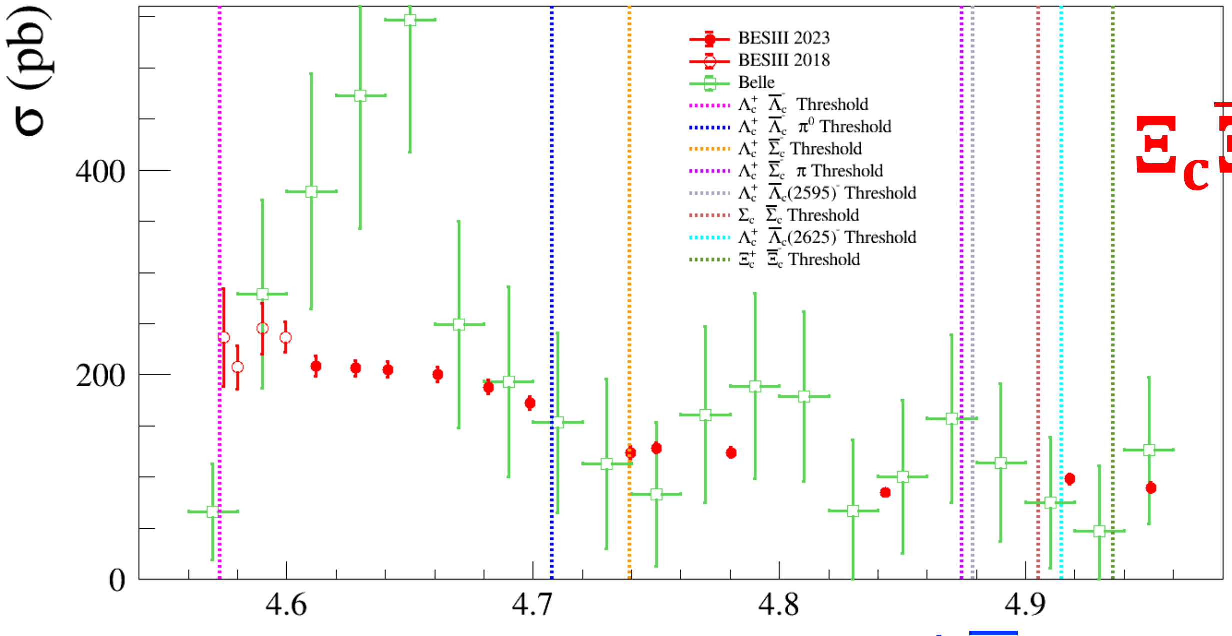


MDC: spatial reso. 115μm
dE/dx reso: 5%
EMC: energy reso.: 2.4%
BTOF: time reso.: 70 ps
ETOF: time reso.: 60 ps



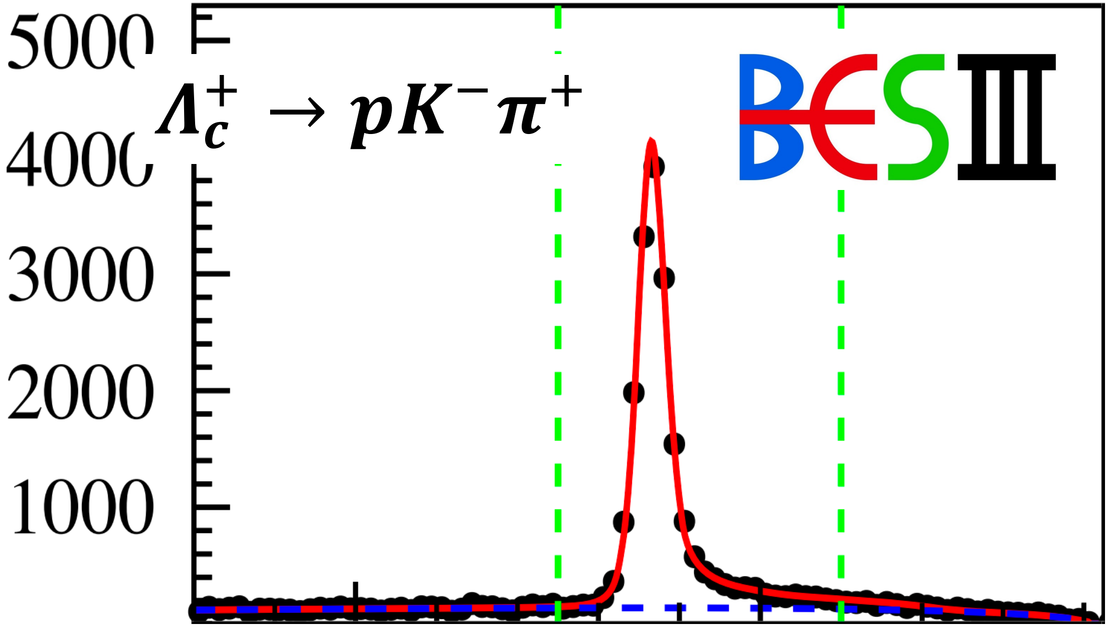
Threshold effect at BESIII

$\Lambda_c^+\bar{\Lambda}_c^-$ $\Lambda_c^+\bar{\Sigma}_c^-$ $\Sigma_c\bar{\Sigma}_c$ $\Xi_c\bar{\Xi}_c$



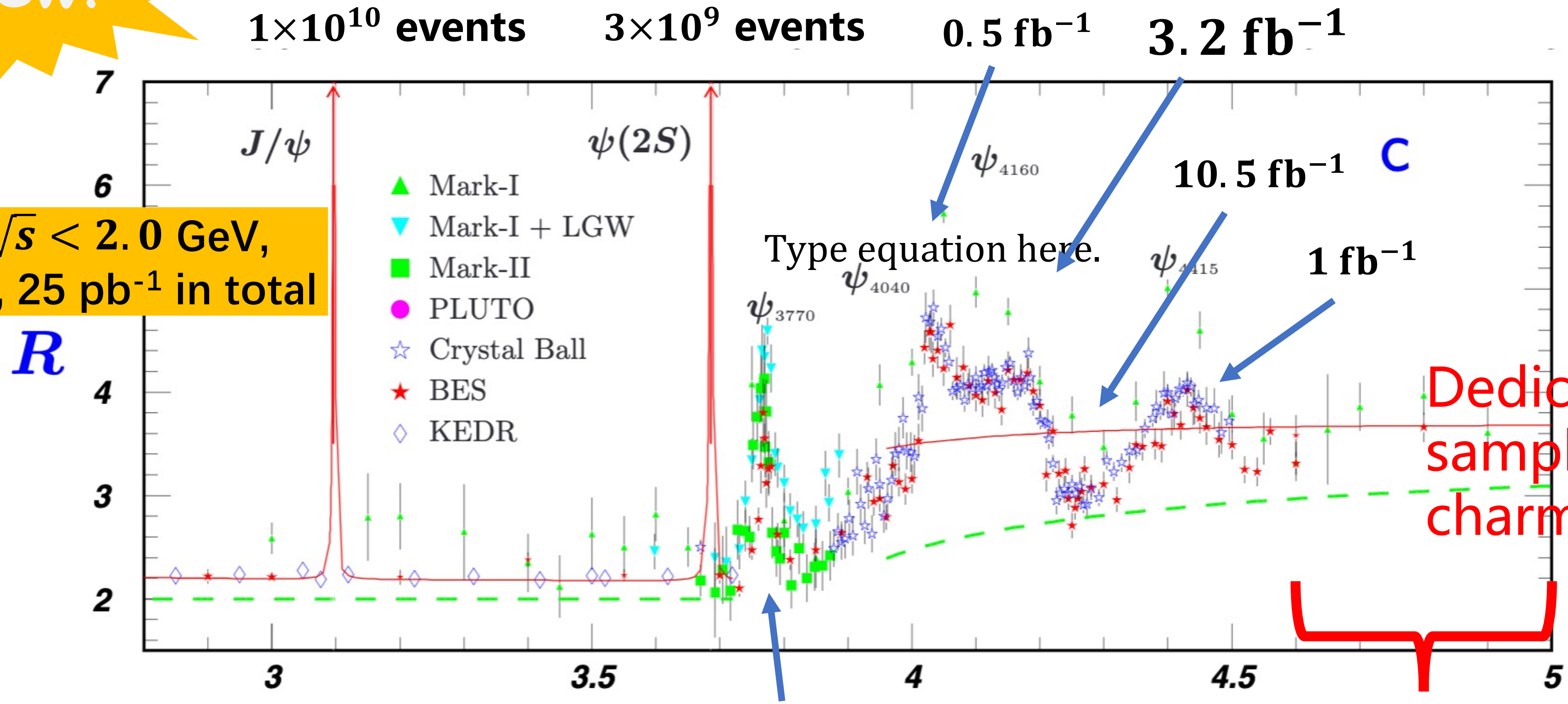
$\Lambda_c^+\bar{\Lambda}_c^-\pi^0$ $\Lambda_c^+\bar{\Lambda}_c^*$

Higher signal to bkg ratio



Data sets at BESIII

New!



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

Dedicated samples for charmed baryons

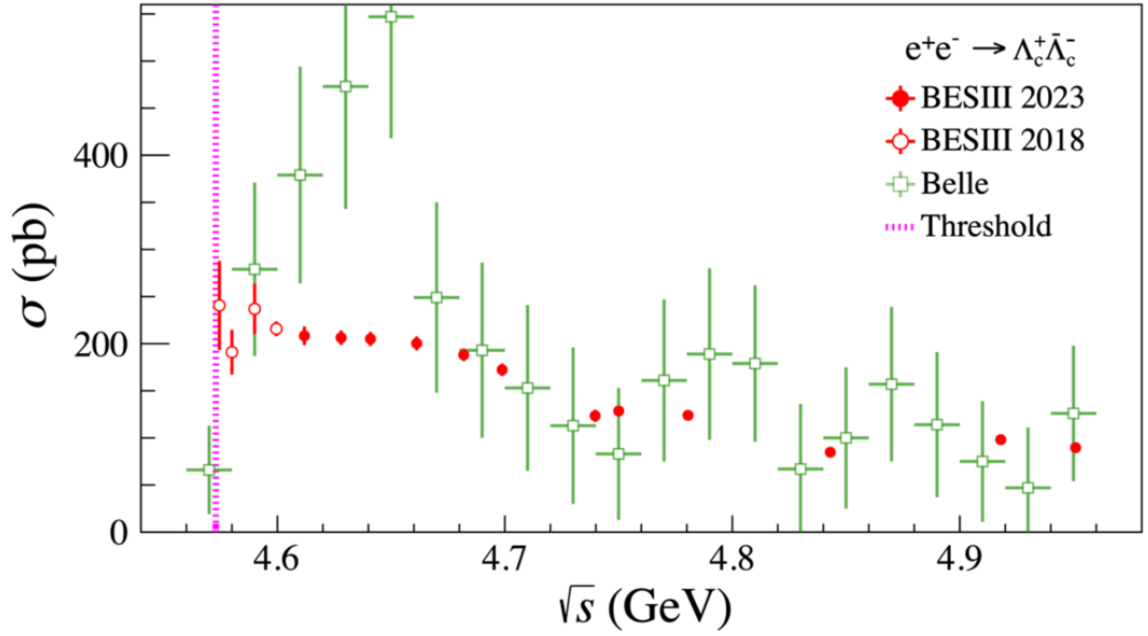
130 points, $2.0 < \sqrt{s} < 4.6$ GeV
1×10^{5} had. events each

$20\ fb^{-1}$

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

Data sets collected in 2020 and 2021

PRL 131, 191901 (2023)



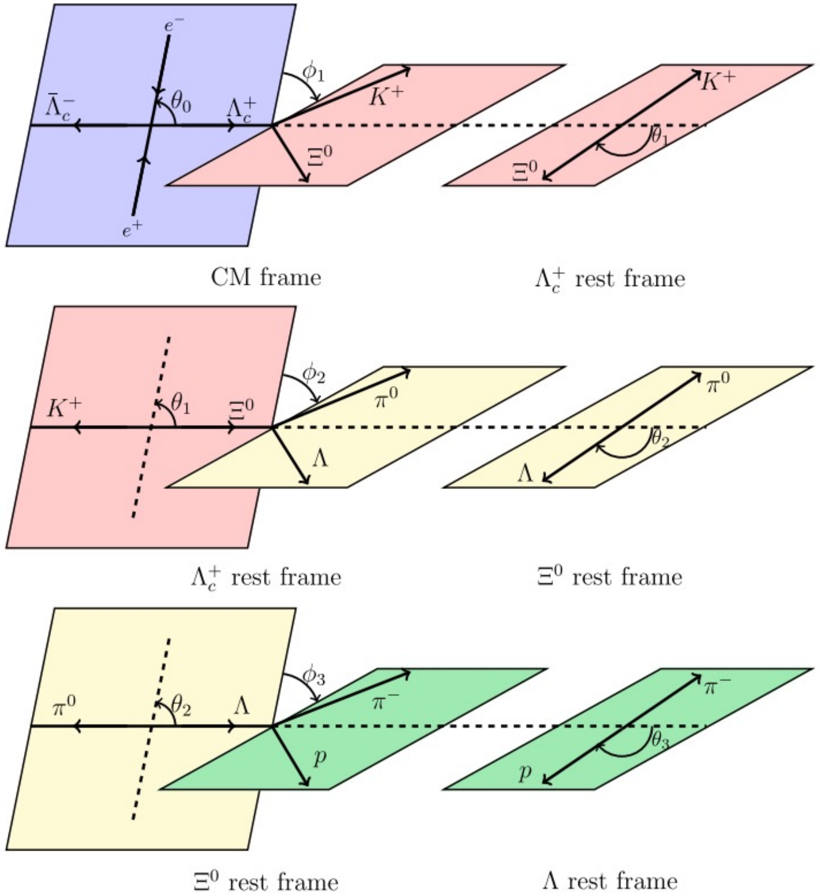
Sample	$E_{\rm cms}$/MeV	$\mathscr{L}_{\rm Bhabha}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84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

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

Only receives the non-factorization contribution

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

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

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

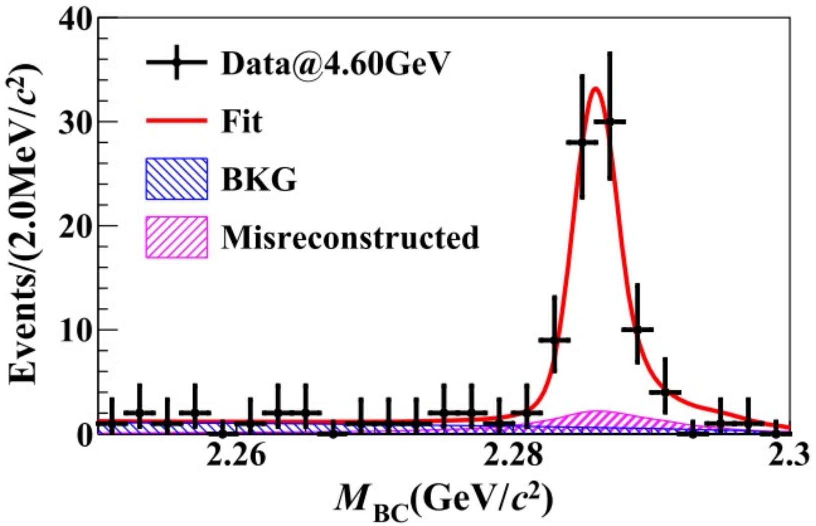
$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}$$

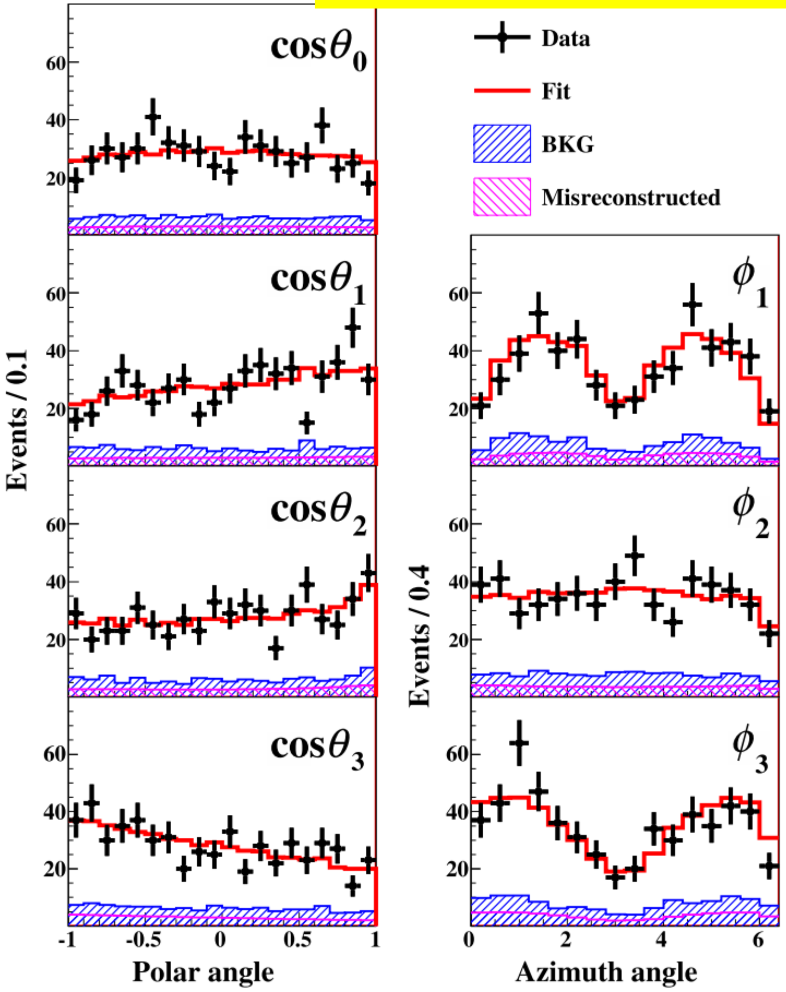
$$\beta = \sqrt{1-\alpha^2}\sin\Delta$$

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

Distributions

PRL 132, 031801 (2024)





- 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

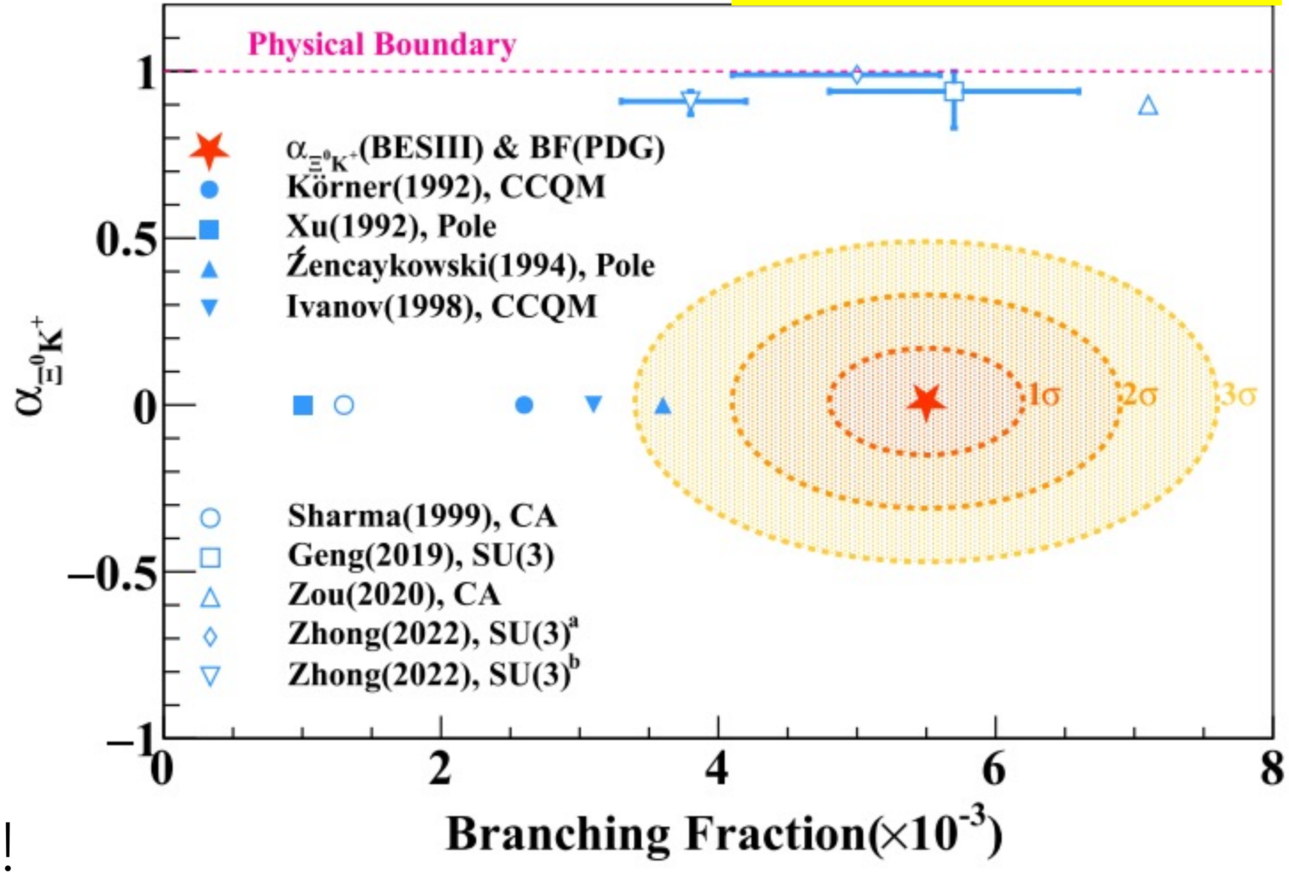
PRL 132, 031801 (2024)

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

In good agreement with zero

$\delta_p - \delta_s = -1.55 \pm 0.25 \pm 0.05$
or $1.59 \pm 0.25 \pm 0.05$

Important for understanding of charmed baryon decay mechanism!



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

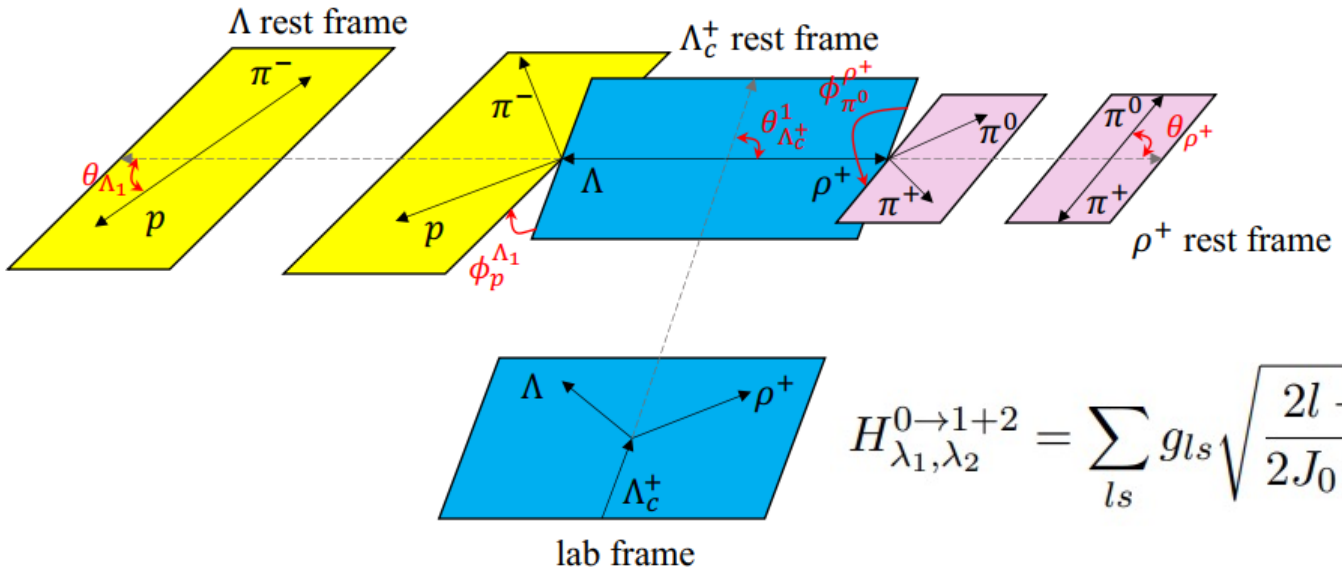
JHEP 12 (2022) 033

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

$\Lambda_c^+ \to \Lambda\rho^+$

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

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



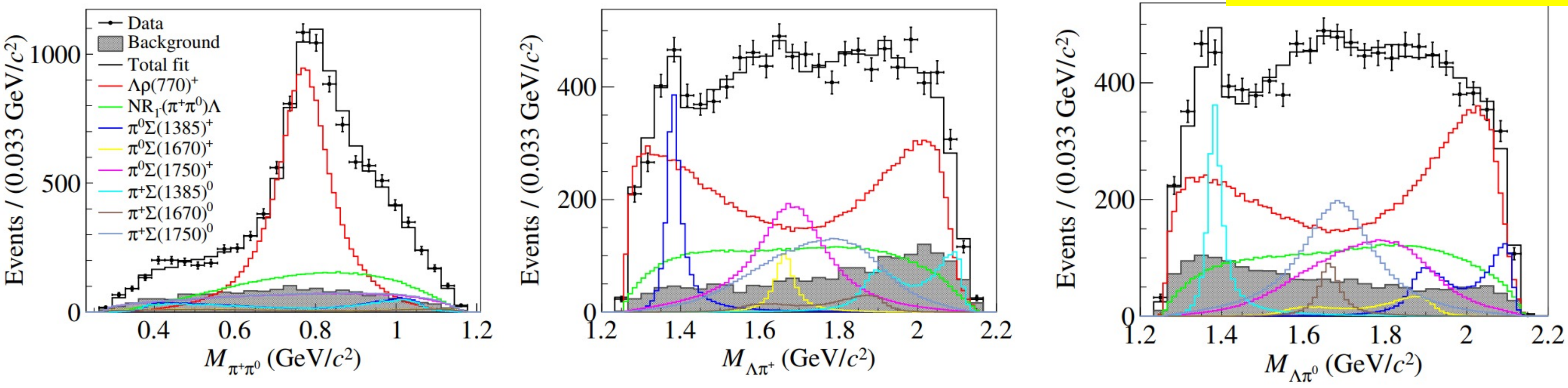
Helicity Amplitude (TF-PWA)

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

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

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

JHEP 12 (2022) 033



PWA framework is established !
Baryon decuplet can be probed !

Decay asymmetry $\Lambda_c^+ \to \Lambda\rho^+$ differs from prediction

	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

Various predictions for Cabibbo suppressed decays

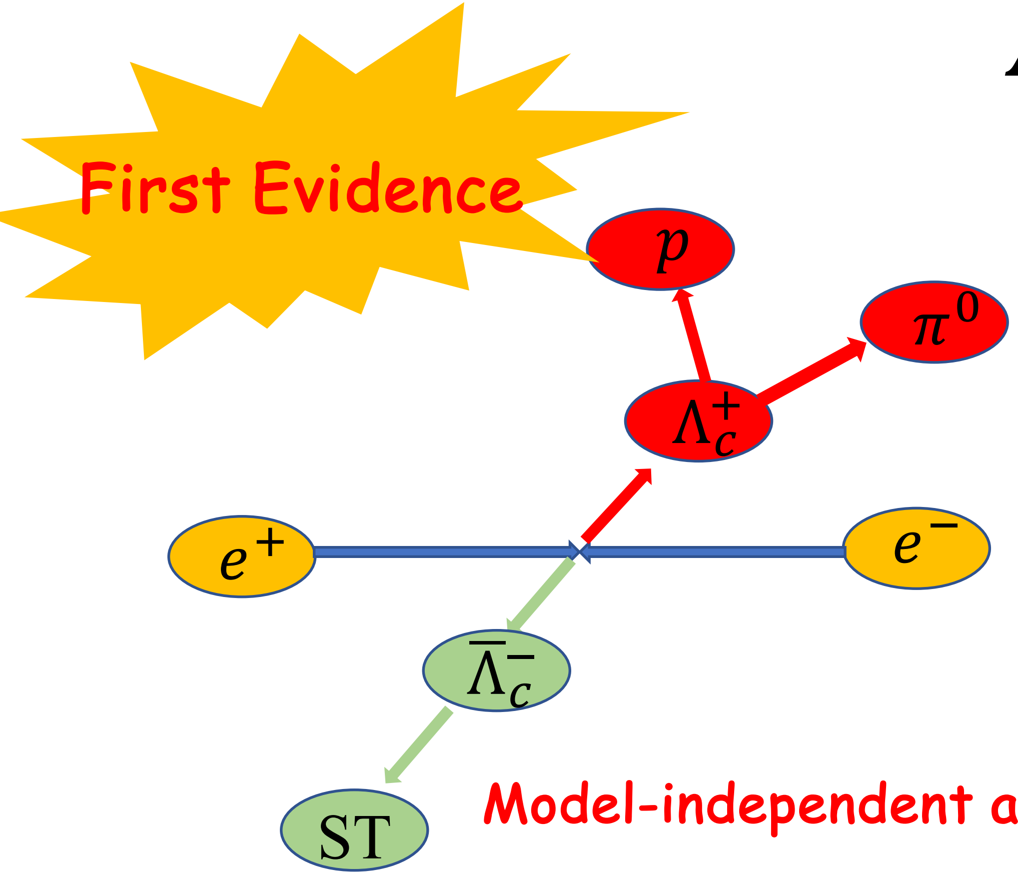
H.-Y. Cheng, et al., PRD 97, 074028 (2018)

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	?

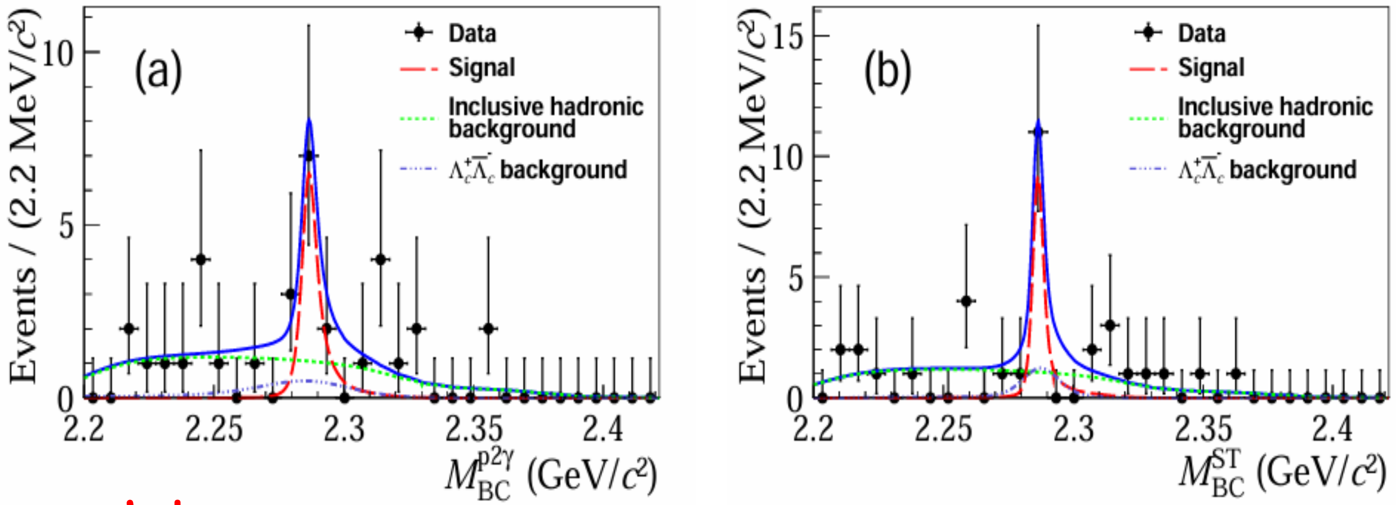
- ❖ $\Lambda_c^+ \to p\eta$: looks consistent between exp. and theo.
- ❖ The significant discrepancy in the channel $\Lambda_c^+ \to p\pi^0$
- ❖ Interference between factorization and non-factorization?

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



Model-independent approach !

PRD 109, L091101 (2024)

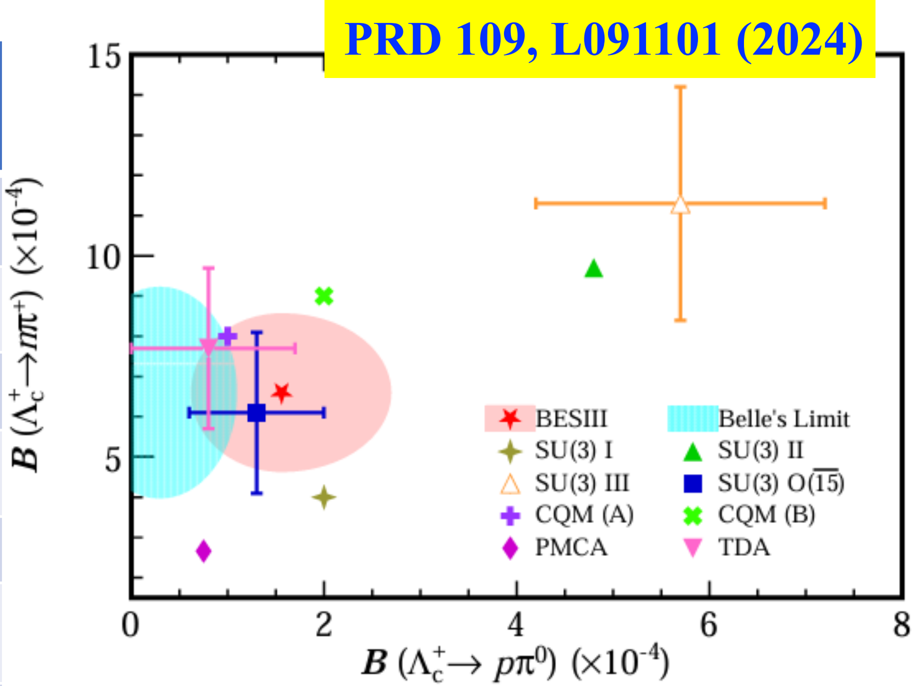


- Double tag strategy is adopted; 9 tag modes used.
- 2D fit to extract the signal yield: ST $\bar{\Lambda}_c^-$ vs. signal $\Lambda_c^+ \to p\pi^0$
- Significance 3.7σ, branching fraction $(1.56^{+0.72}_{-0.58} \pm 0.20)\times 10^{-4}$

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

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times10^{-4}$	$\mathcal{B}(\Lambda_c^+ \to p\pi^0)\times10^{-4}$	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)	$< 0.8\times10^{-4}$ (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

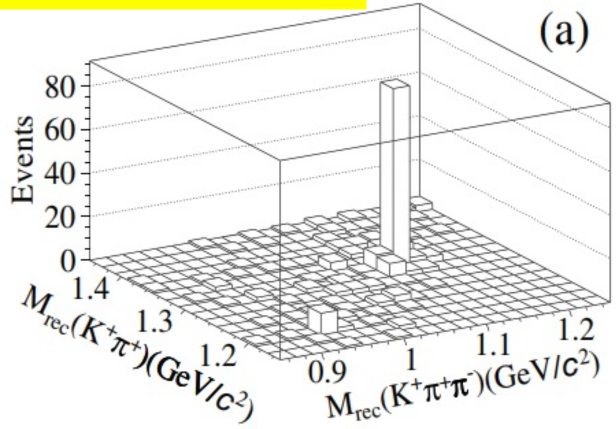
The interference between factorization and non-fac maybe is not significant !



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

$\Lambda_c^+ \to \Sigma^- K^+ \pi^+$

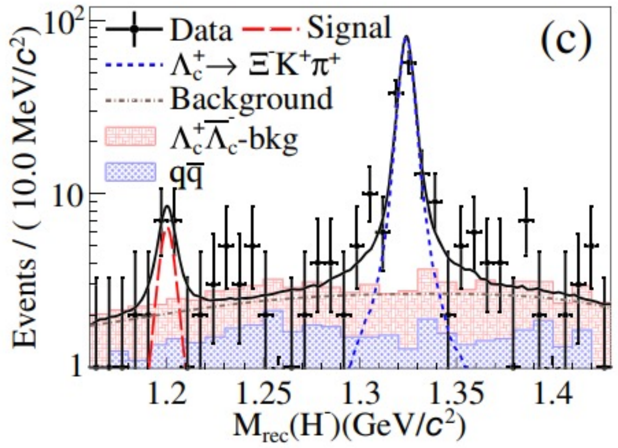
PPD 109, L071103 (2024)



- Double tag strategy
- $\Sigma^- \to n\pi^-$ (almost 100% decay rate), and n is considered to be missing.
- 2D fit to extract the signal yield: Σ^- and n signals

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^- K^+ \pi^+) = (3.8 \pm 1.2 \pm 0.2) \times 10^{-4}$$

- Consistent with SU(3) prediction $(3.3 \pm 2.3) \times 10^{-4}$
- Help constrain the parameters and improve the understanding of decay mechanism.



Measurement of inclusive $\bar{\Lambda}_c^- \to \bar{n} + X$

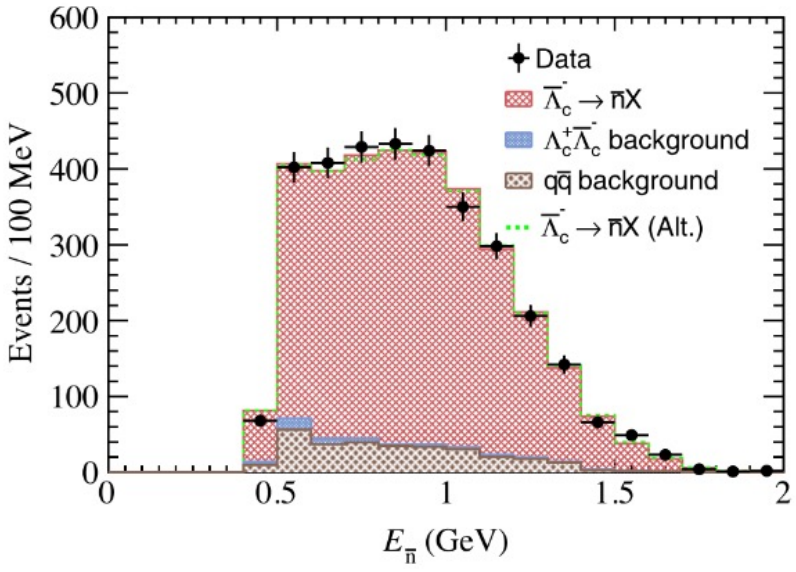
PPD 108, L031101 (2023)

PDG-2022

$\Gamma(n\ \text{anything})/\Gamma_{\text{total}}$ Γ_{78}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.08±0.14	[1] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[1] This CRAWFORD 92 value includes neutrons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.



- The rates of Λ_c^+ decays to proton and neutron ?
- Measure the inclusive decay $\bar{\Lambda}_c^- \to \bar{n} + X$
- Utilize the annihilation effect to extract the signal

Precision: 5% (previous 32%)
Asymmetry between proton and neutron in Λ_c^+ decays

★PDG-2024

$\Gamma(n\ \text{anything})/\Gamma_{\text{total}}$ Γ_{102}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
32.6±1.6 OUR AVERAGE					
32.4±0.7± 1.5	3105	[1] ABLIKIM	23AS	BES3	e^+e^- at 4.6–4.698 GeV
50 ±8 ±14		[2] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[1] ABLIKIM 23AS measures the antiparticle decay $\bar{\Lambda}_c^- \to \bar{n}X$.

[2] This CRAWFORD 92 value includes neutrons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.

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

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

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

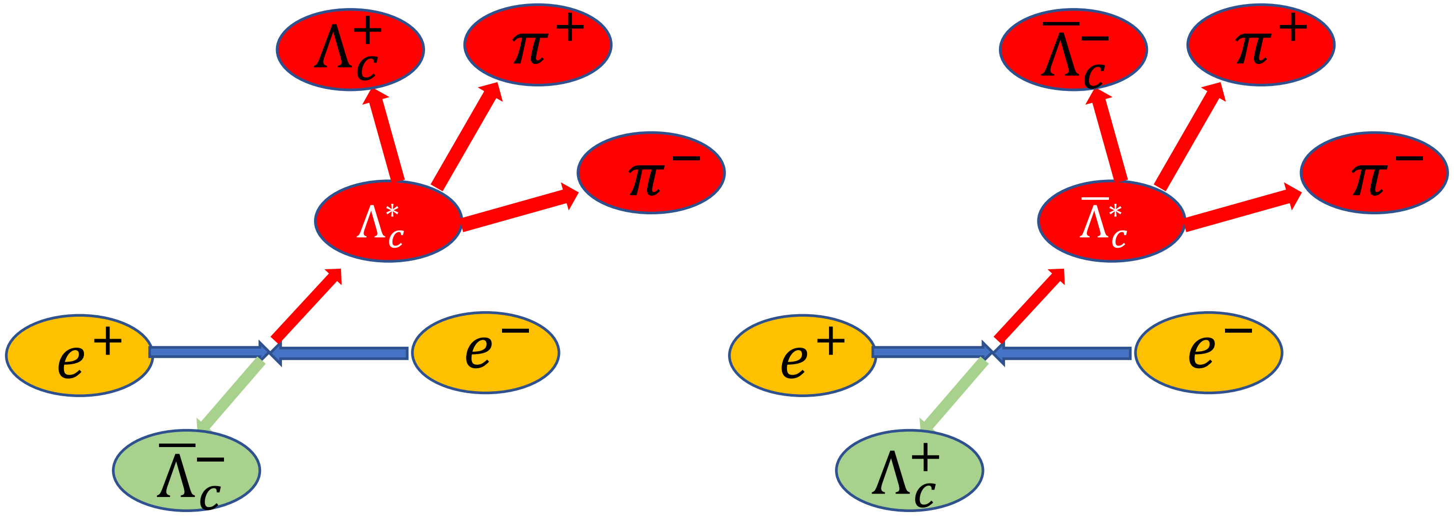
See Particle Listings for 2 decay modes that have been seen / not seen.

Measurements of strong transition

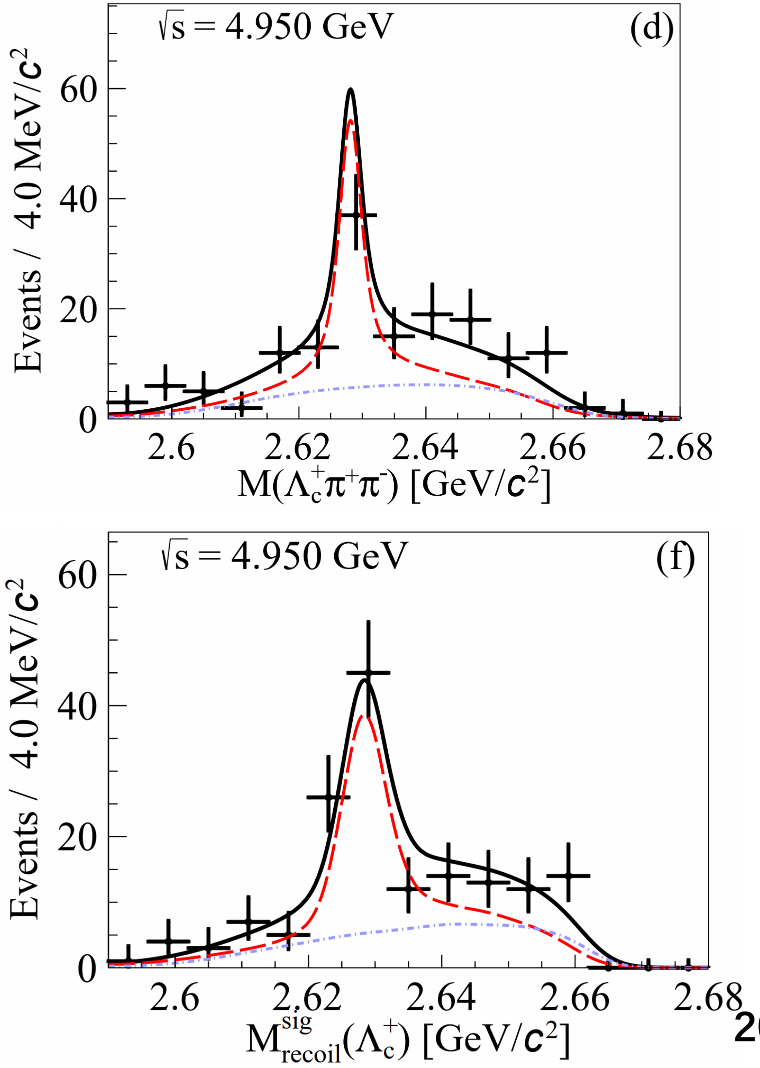
PRD 109, 112007 (2024)

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

- Select one Λ_c^+ ➔ $\bar{\Lambda}_c^*$ in the other side
- Require additional $\pi^+\pi^-$ pair
- another $\bar{\Lambda}_c^-$ as a missing particle and not reconstructed (under E-P conservation)



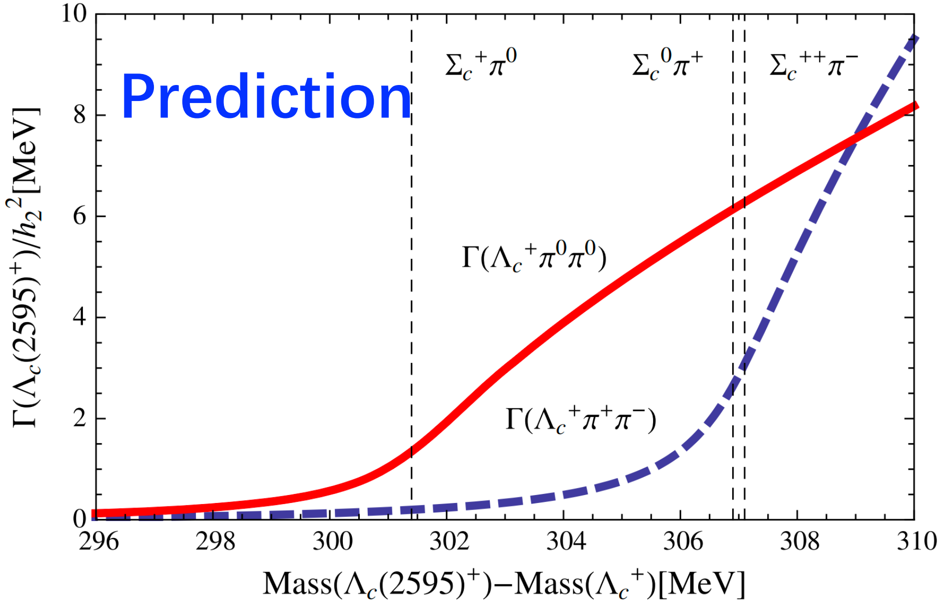
Model-independent



Results of Branching fractions

PRD 109, 112007 (2024)

Hai-Yang Cheng and Chun-Khiang 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 pions 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

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

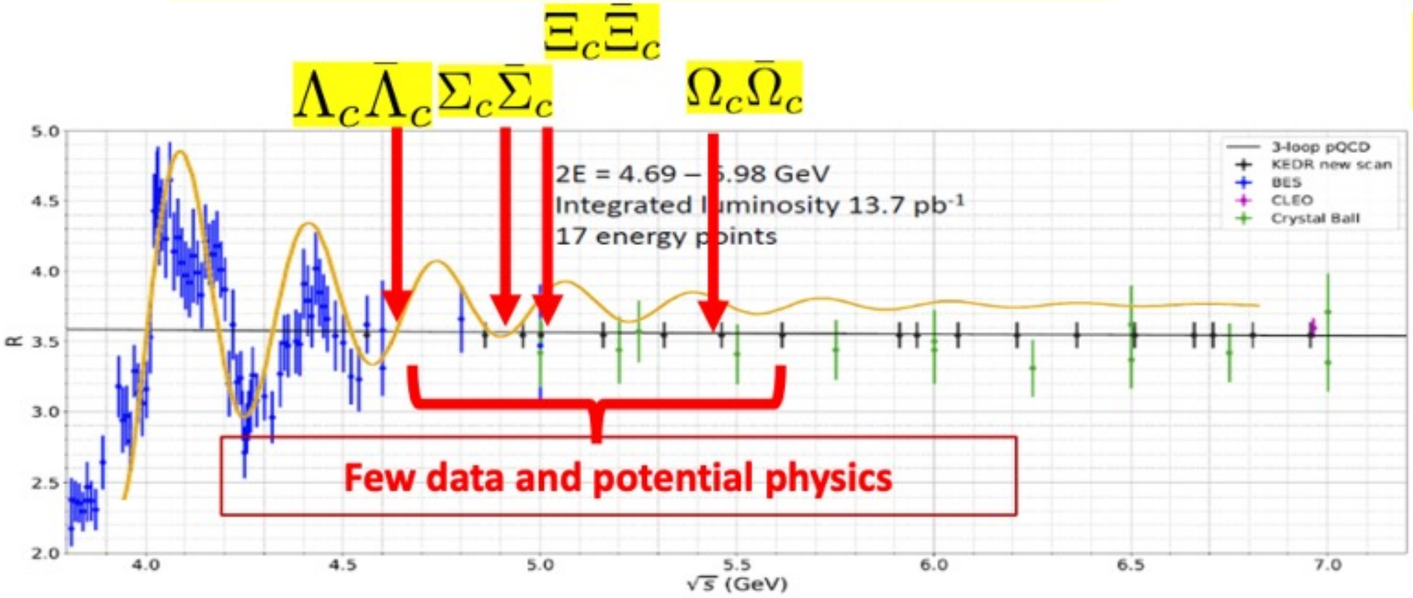
Semileptonic	
$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL 129, 231803 (2022)
$\Lambda_c^+ \to \Lambda\mu^+\nu_e$	PRD 108, 031105 (2023)
$\Lambda_c^+ \to pK^-e^+\nu_e$	PRD 106, 112010 (2022)
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ $\Lambda_c^+ \to pK_S e^+\nu_e$	PLB 843 (2023) 137993

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

✓ $\Xi_c\ \bar{\Xi}_c$ 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

❖Various decay modes of Λ_c^+ have been investigated.

❖The excited charmed baryons $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ can be probed at BESIII. Decay rates of strong transition are measured with a model independent approach 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!