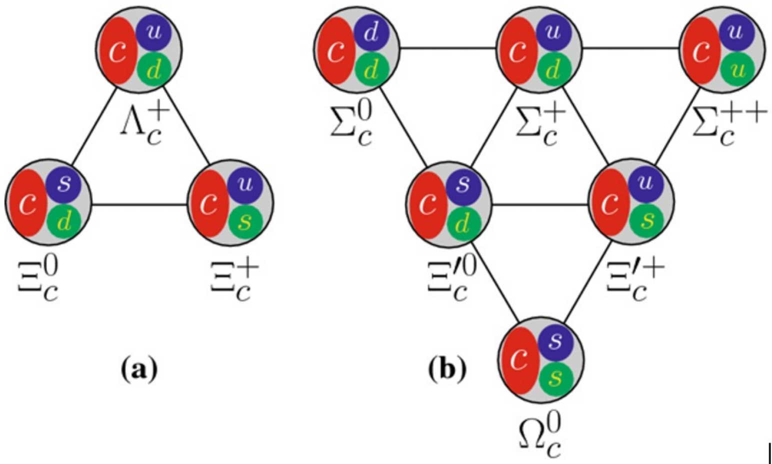

Recent progress on charmed baryon at BESIII

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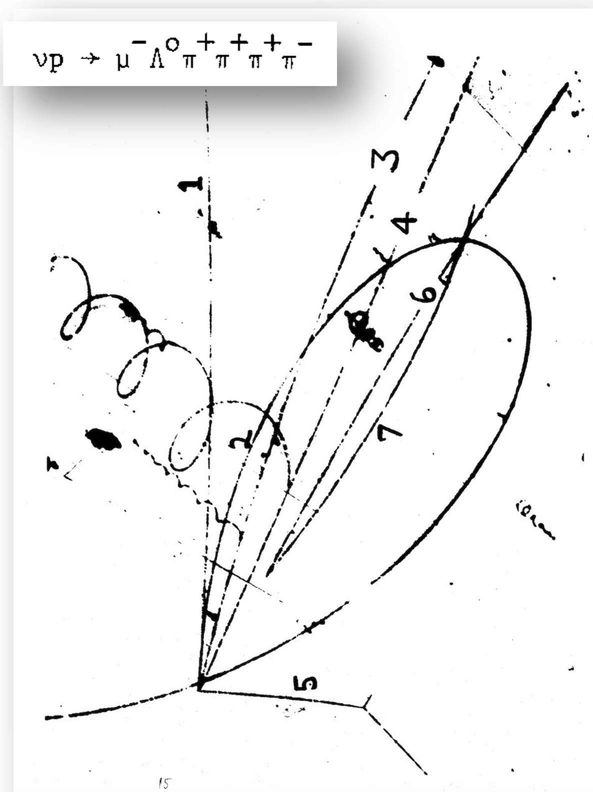
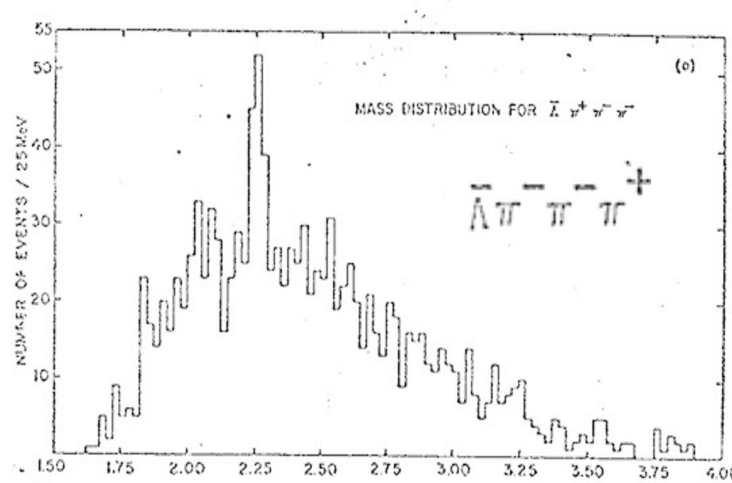
Outline

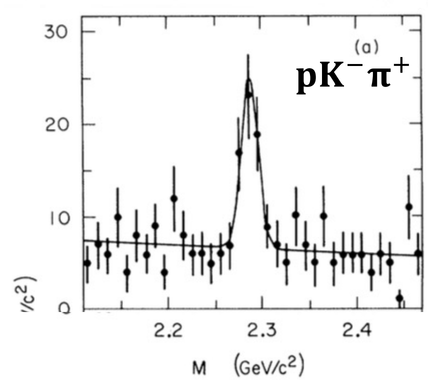
- Introduction to the charmed baryons
- BESIII progress in studying the Λ_c^+
- Future plan
- Summary

Discovery of the charmed heavy baryon

- Not exclusively clear about the first observation
- A number of experiments which published evidence for the charmed baryons beginning in 1975
  - ✓ First hint of charmed baryon $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$ in BNL PRL34, 1125 (1975)
  - ✓ First evidence of Λ_c^+ at Fermi Lab PRL37, 882 (1976)
- The first well established state is the Λ_c^+ at MarkII PRL44, 10 (1980)



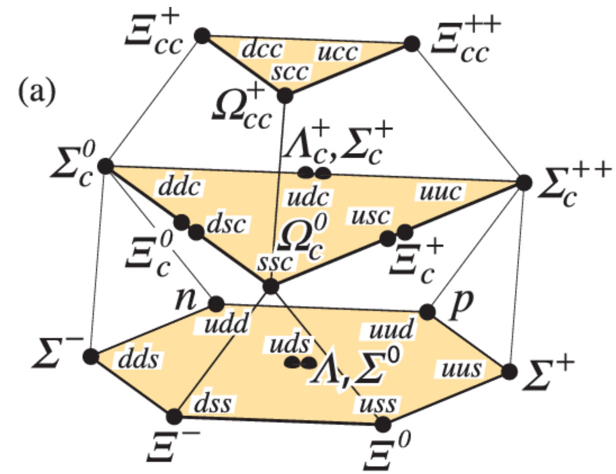




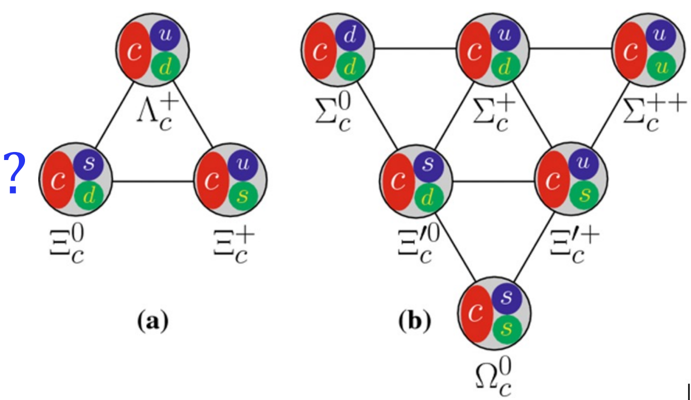
The charmed baryon family

- Singly charmed baryons
  - ✓ Established ground states:

    Λ_c^+, Σ_c , $\Xi_c^{(\prime)}$, Ω_c
  - ✓ Excited states are being explored
- Observation of other doubly charmed baryon Ξ_{cc}^{++}
- No observations of other doubly or triply charmed baryons

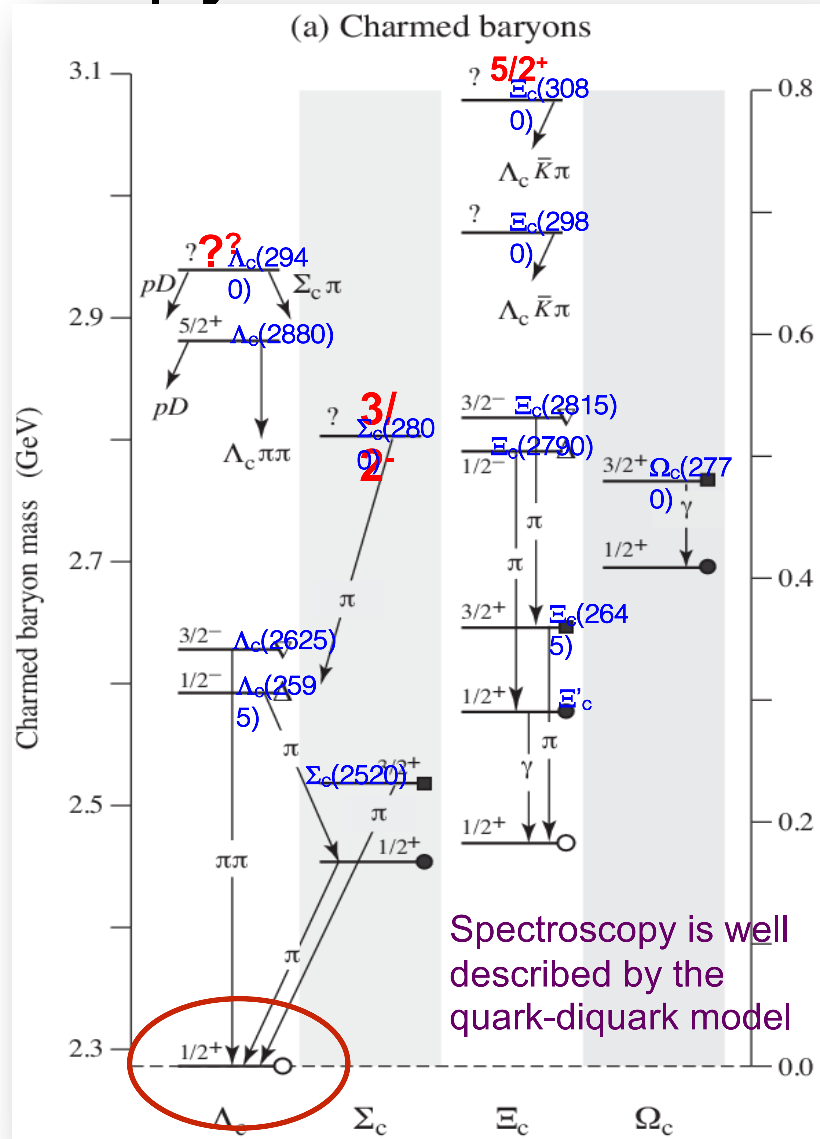


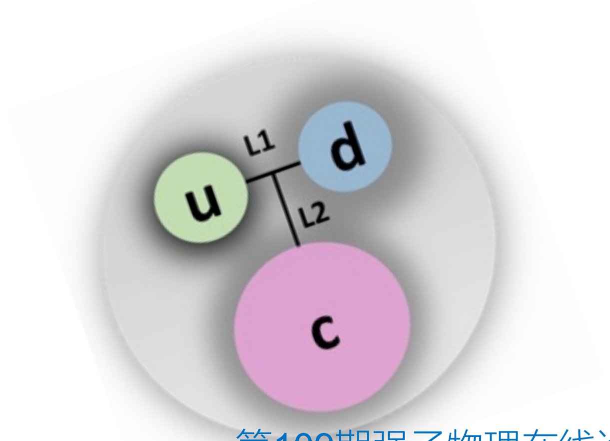
- ➤ Λ_c^+: decay only weakly, **many experimental progress since 2014**
- ➤ Σ_c : $B(\Sigma_c \to \Lambda_c^+ \pi)$~100%; $B(\Sigma_c \to \Lambda_c^+ \gamma)$?
- ➤ Ξ_c : decay only weakly; absolute BF measured with poor precision
- ➤ Ω_c : decay only weakly; no absolute BF measured



Λ_c^+ : cornerstone of charmed baryon spectroscopy

- The lightest charmed baryon
- Most of the charmed baryons will eventually decay to Λc
- The Λc is one of important tagging hadrons in c-quark counting in the productions at high energy energies and Bottom baryon decays
- $B(\Lambda_c^+ \to pK^-\pi^+)$: dominant error for V_{ub} via baryon decay

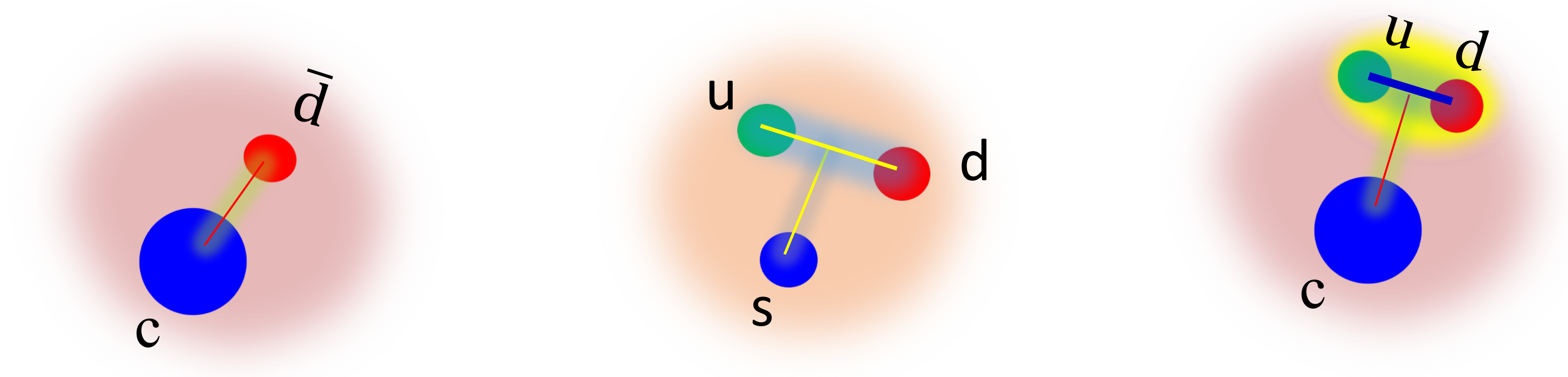




Quark model picture

a heavy quark (*c*) with an unexcited spin-zero diquark (*u*-*d*)

→ *diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark.*



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

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

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

In some sense, more reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

Λ_c^+ may provide complementary powerful test on internal dynamics to D/Ds does

Experimental studies on Λ_c^+ until 2014

Before 2014, the *c*-ed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).

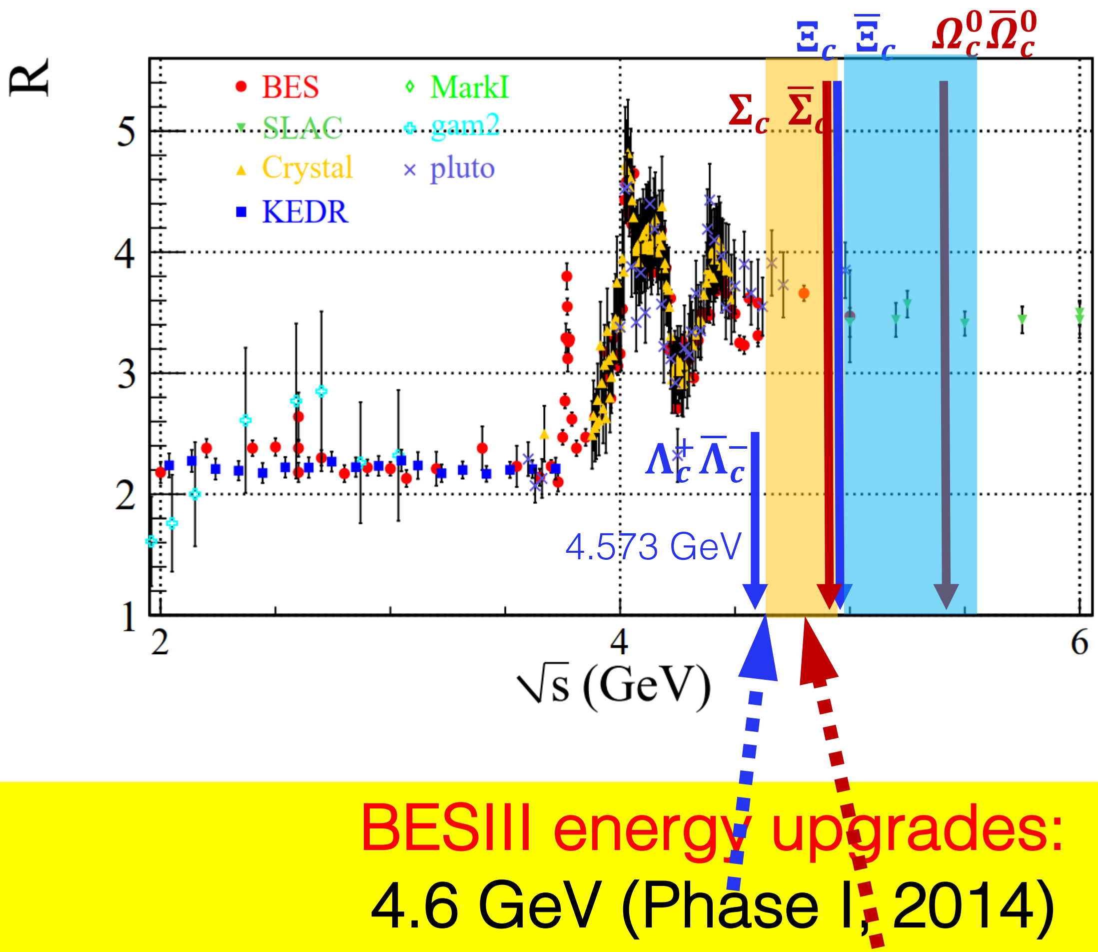
- ✓ Total branching fraction ~60%
- ✓ Lots of unknown decay channels
- ✓ Quite large uncertainties(>20%)
- ✓ Most BFs are measured relative to $\Lambda_c^+ \to pK^-\pi^+$

Λ_c^+ data in PDG2015

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)	
Hadronic modes with a p: $S=-1$ final states					
$p\overline{K}^0$		(3.21± 0.30) %			
$pK^-\pi^+$		($6.84^{+0.32}_{-0.40}$) %			
$p\overline{K}^*(892)^0$	[q]	(2.13± 0.30) %			
$\Delta(1232)^{++}K^-$		(1.18± 0.27) %			22.9%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %			25.0%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %			10.5%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %			13.3%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %			23.5%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %			11.4%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %			13.0%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %			33.3%
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %			18.0%
$\Delta(1232)\overline{K}^*(892)$		seen			
$pK^-\pi^+\pi^+\pi^-$		(1.5 ± 1.0) $\times 10^{-3}$			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S=0$ final states					
$p\pi^+\pi^-$		(4.7 ± 2.5) $\times 10^{-3}$			45.4%
$pf_0(980)$	[q]	(3.8 ± 2.5) $\times 10^{-3}$			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		(2.5 ± 1.6) $\times 10^{-3}$			64.0%
pK^+K^-		(1.1 ± 0.4) $\times 10^{-3}$			36.4%
$p\phi$	[q]	(1.12± 0.23) $\times 10^{-3}$			
pK^+K^- non-ϕ		(4.8 ± 1.9) $\times 10^{-4}$			
Hadronic modes with a hyperon: $S=-1$ final states					
$\Lambda\pi^+$		(1.46± 0.13) %			8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %			26.0%
$\Lambda\rho^+$		< 6 %	CL=95%		
$\Lambda\pi^+\pi^+\pi^-$		(3.59± 0.28) %			7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+}\to\Lambda\pi^+$		(1.0 ± 0.5) %			20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-}\to\Lambda\pi^-$		(7.5 ± 1.4) $\times 10^{-3}$			18.7%

Large uncertainties in experiment
➔ slow development in theory

Charmed baryon thresholds



BESIII energy upgrades:

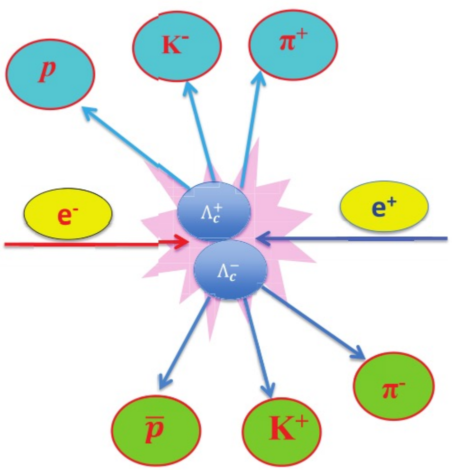
4.6 GeV (Phase I, 2014)

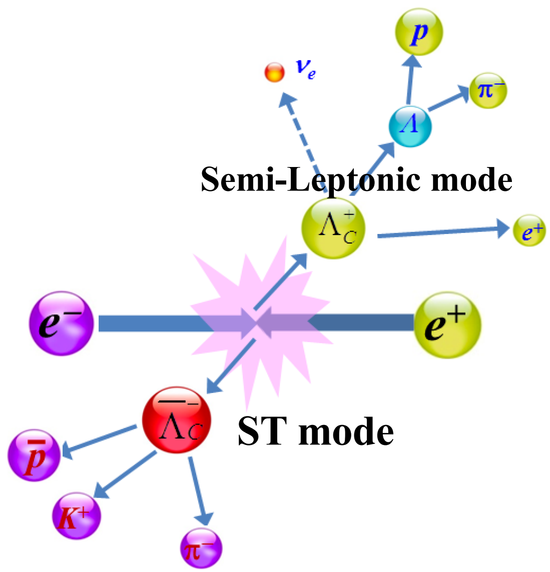
→ 4.95 GeV(Phase II, 2021)

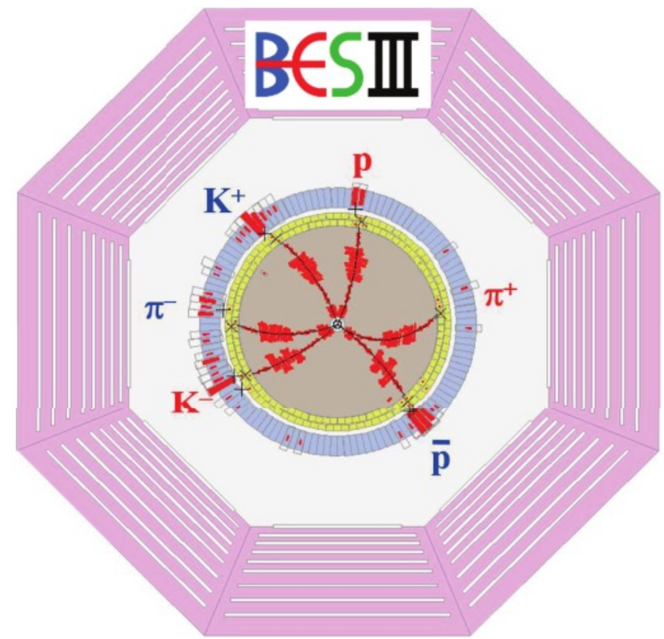
→ 5.6 GeV (Phase III, planned in 2024)

Single Tag (ST) and Double Tag (DT) method at Threshold

The absolute BF can be obtained by the ratio of DT yields to ST yields.







- High efficiency and clean background
- Absolute measurement with many systematics cancel out
- Missing-mass technique: K_L/neutron, neutrino, …
- Good photon resolution: Σ, Ξ, π^0, …

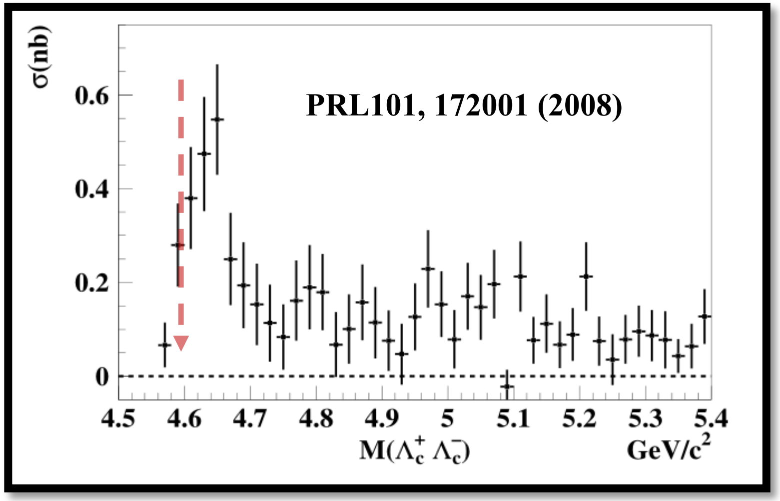
$$\mathcal{B}_i = \frac{N_{ij}^{\mathrm{DT}}}{N_j^{\mathrm{ST}}} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

Near threshold production at BESIII

In 2014, BESIII took (only!) 35 days to run at 4.6GeV and collected ~500/pb data.

Energy(GeV)	lum.(1/pb)
4.575	47.67
4.580	8.54
4.590	8.16
4.600	566.93

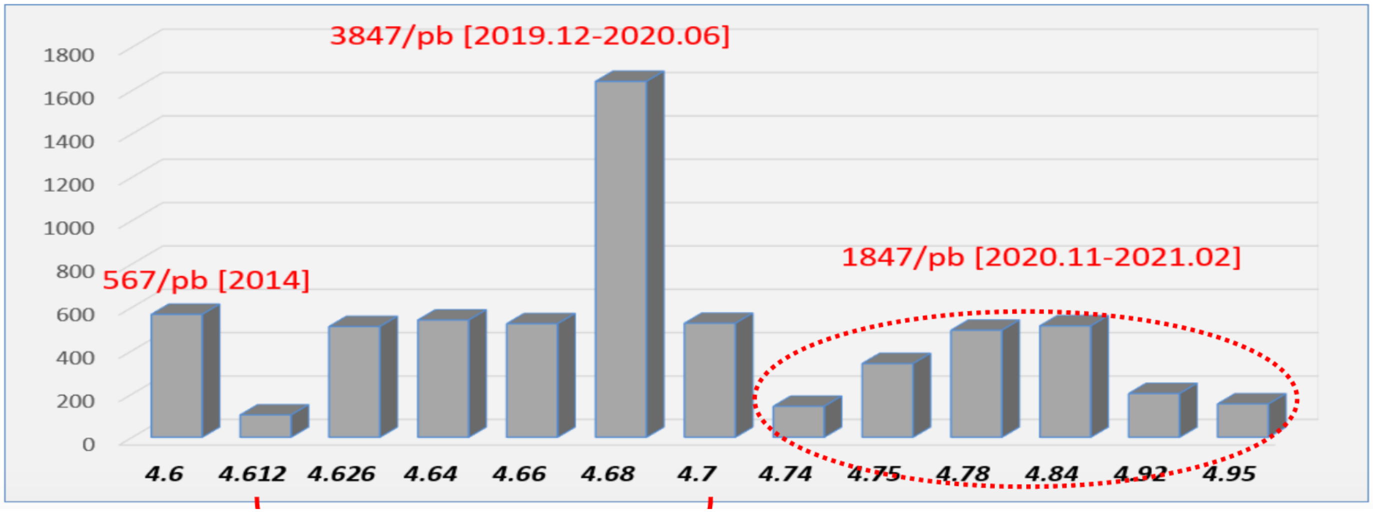
Corresponds to 0.1M Λ_c pairs



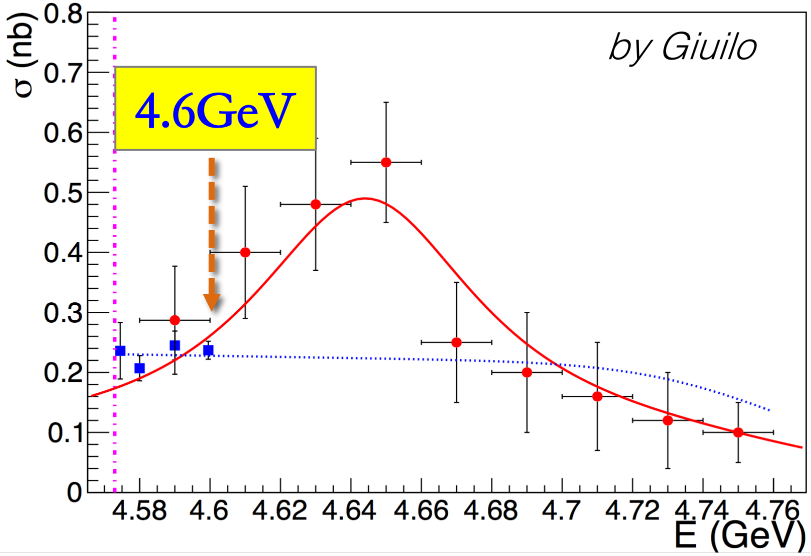
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

More Λ_c^+ data at BESIII



in total, 6.4 fb^{-1} data above Λ_c^+ threshold (~8x times more Λ_c^+ statistics)



Physics publications based on Phase I data

Published 17 papers

- A series of precise absolute BF measurements: hadronic, semi-leptonic and inclusive decays
- Observation of decays into neutron $\Lambda_c^+ \to nK_s\pi^+, \Sigma^-\pi^+\pi^+\pi^0$
- Threshold cross section and form factors of Λ_c^+ pairs
- Observation of Cabbibo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$
- First evidence of Cabbibo-suppressed decay $\Lambda_c^+ \to p\eta$
- First measurements of many decay asymmetries
- Determination of Λ_c^+ spin

Very productive for the data set taken in 35 days!

2014：0.567 fb^{-1} at 4.6 GeV

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	**PRL 116, 052001 (2016)**
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	**PRL 117, 232002 (2016)**
$\Lambda_c^+ \to nK_s\pi^+$	**PRL 118, 12001 (2017)**
$\Lambda_c^+ \to p\eta, p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB 783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD 99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC 43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD 100, 072004 (2019)
$\Lambda_c^+ \to pK_s\eta$	PLB 817, 136327 (2021)
Λ_c^+ spin determination	PRD 103, L091101(2021)

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$	**PRL 115, 221805(2015)**
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)

Inclusive decay

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

Production

$\Lambda_c^+\bar{\Lambda}_c^-$ cross section	**PRL 120,132001(2018)**

Physics publications based on Phase II data

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ and $\Lambda \mu^+ \nu_\mu$ — ***PRL129, 231803 (2022);*** *PRD108, L031105 (2023)*
- ✓ $\Lambda_c^+ \to p K^- e^+ \nu_e$ — *PRD106, 112010 (2022)*
- ✓ Search for $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $p K_s \pi^- e^+ \nu_e$ — *PLB843, 137993 (2023)*
- ✓ $\Lambda_c^+ \to n e^+ \nu_e$ — ***arXiv:2410.13515***

Neutron-involved decay

- ✓ $\Lambda_c^+ \to n \pi^+$ — ***PRL 128, 142001 (2022)***
- ✓ $\Lambda_c^+ \to n \pi^+ \pi^0$, $n \pi^+ \pi^+ \pi^-$, $n K^- \pi^+ \pi^+$ — *CPC 47, 023001 (2023) (Cover Story)*
- ✓ $\Lambda_c^+ \to n K_s K^+$ — *PRD 109, 072010 (2024)*
- ✓ $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ — *PRD 109, L071103 (2024)*
- ✓ $\Lambda_c^+ \to n K_s \pi^+ \pi^0$ — *PRD 109, 053005 (2024)*

Hadronic CS decays

- ✓ $\Lambda_c^+ \to p \pi^0$, $p \eta$, $p \omega$ — *JHEP11, 137 (2023); PRD09, L091101 (2024); arXiv:2410.13368*
- ✓ $\Lambda_c^+ \to p \eta'$ — *PRD106, 072002 (2022)*
- ✓ $\Lambda_c^+ \to \Lambda K^+$, $\Lambda K^+ \pi^0$, $\Lambda K_s \pi^+$ — *PRD106, L111101 (2022); PRD109, 032003 (2024); arXiv:2410.16912*
- ✓ $\Lambda_c^+ \to \Sigma^+ K_s$, $\Sigma^0 K^+$ — *PRD106, 052003 (2022)*
- ✓ $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$ — *JHEP09, 125 (2023);*

Hadronic CF decays

- ✓ PWA of $\Lambda_c^+ \to \Lambda \pi^+ \pi^0$ and $\Lambda \pi^+ \eta$ — *JHEP 12, 033(2022);* ***arXiv:2407.12270***
- ✓ W-exchange-only process $\Xi^0 K^+$ — ***PRL132, 031801 (2024)***
- ✓ $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ — *PRD109, 052001 (2024)*
- ✓ $\Lambda_c^+ \to p K_L$, $p K_L \pi^0$, $p K_L \pi^+ \pi^-$ — *JHEP09, 007 (2024)*

30 papers are published

Inclusive decay

- ✓ Improved BF of $\Lambda_c^+ \to e^+ X$ — *PRD107, 052005 (2023)*
- ✓ First BF of $\bar{\Lambda}_c^- \to \bar{n} X$ — *PRD108, L031101 (2023)*

Rare decay

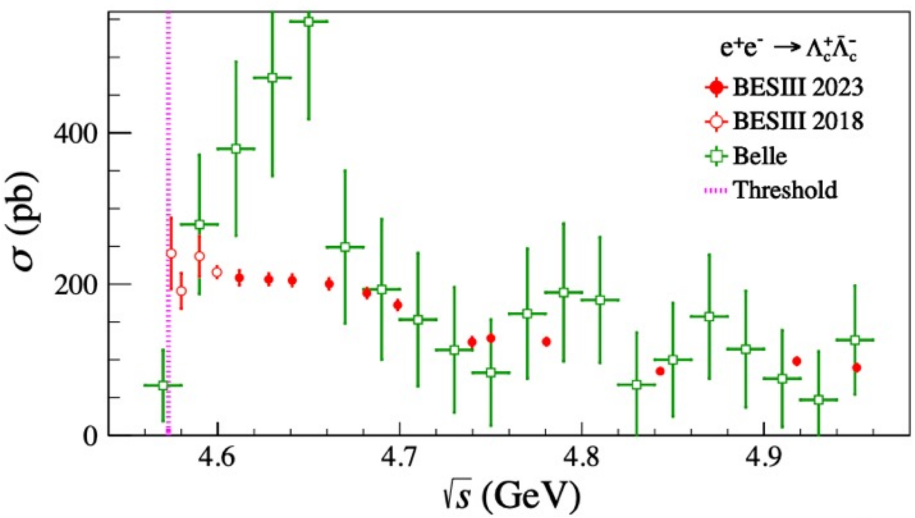
- ✓ $\Lambda_c^+ \to \gamma \Sigma^+$ — *PRD107, 052002 (2023)*

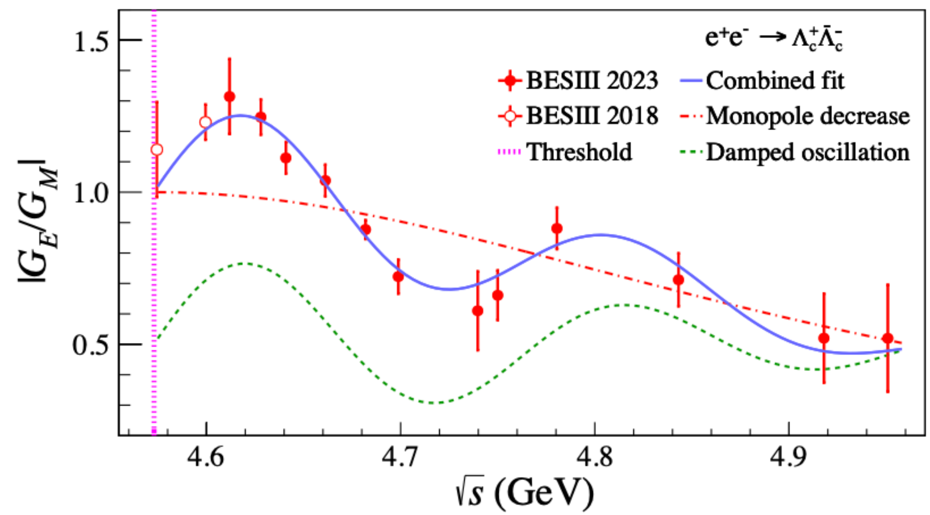
Production and excited Λ_c^+

- ✓ $\Lambda_c^+ \bar{\Lambda}_c^-$ *lineshape and form factor* — ***PRL107, 052002 (2023)***
- ✓ $\Lambda_c(2595)^+$ *and* $\Lambda_c(2625)^+$ *production and decay* — *PRD 109, L071104 (2024); PRD 109, 112007 (2024)*

Cross sections of $e^+e^- \to \Lambda_c^+\Lambda_c^-$

PRL131, 191901 (2023)

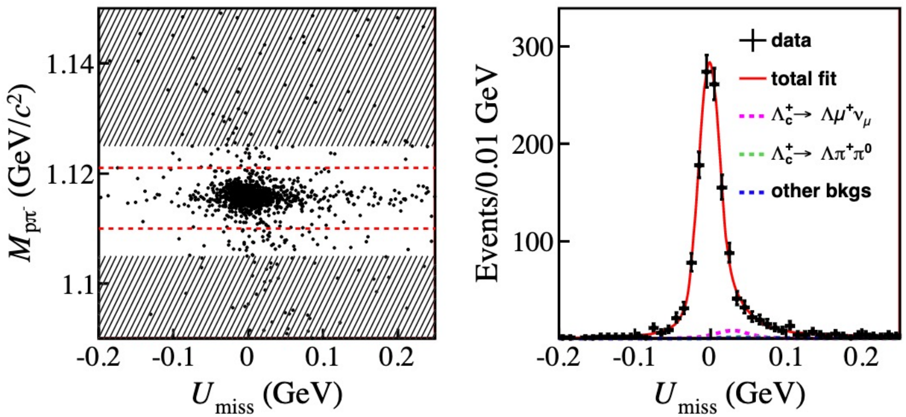




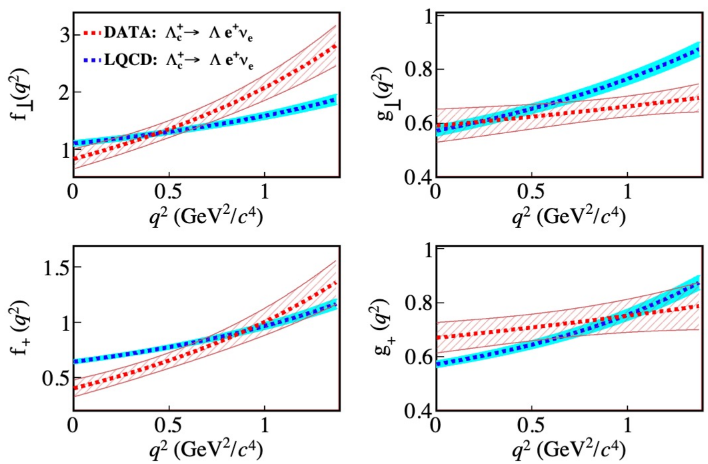
- Negate the $Y(4630)$ in decaying into $\Lambda_c^+\Lambda_c^-$ reported by BELLE
- Energy-dependence of $|G_E/G_M|$ reveals an oscillation feature, which may imply a non-trivial structure of the lightest charmed baryon.

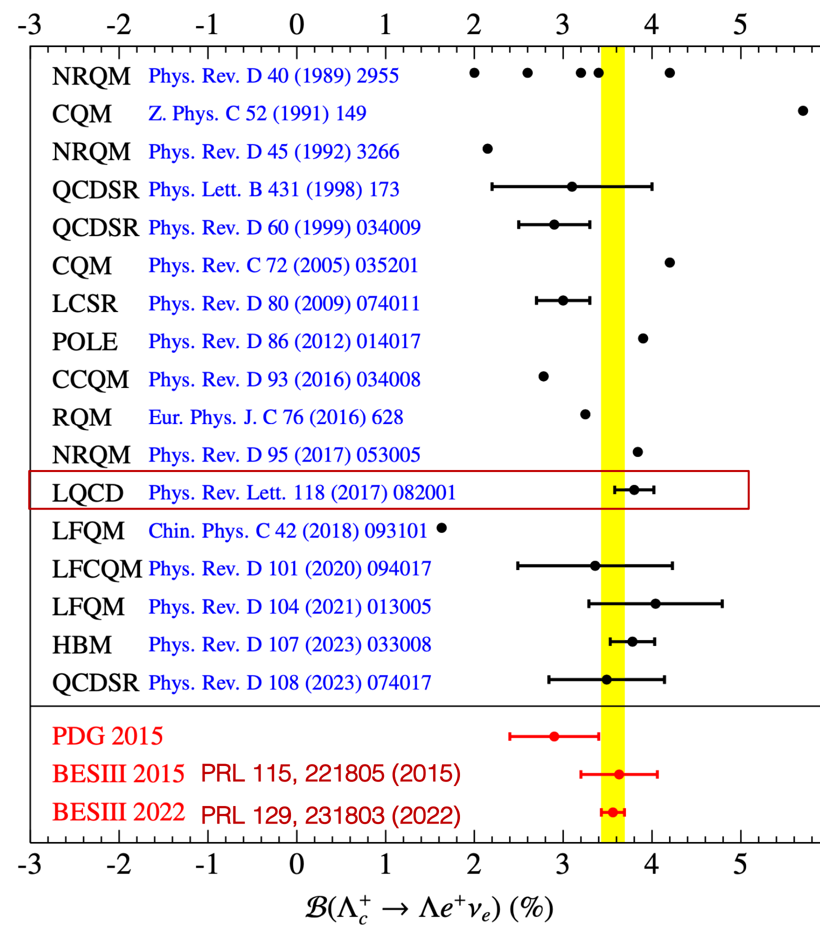
Determination of absolute form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

PRL129, 231803 (2022)



$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$

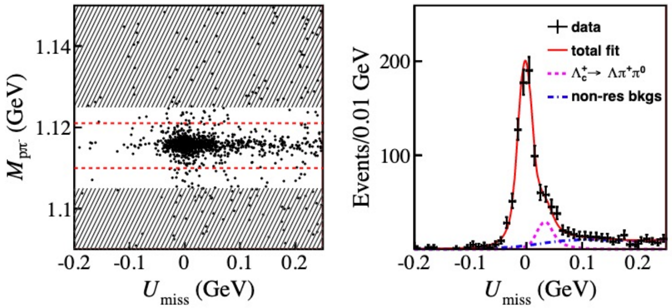


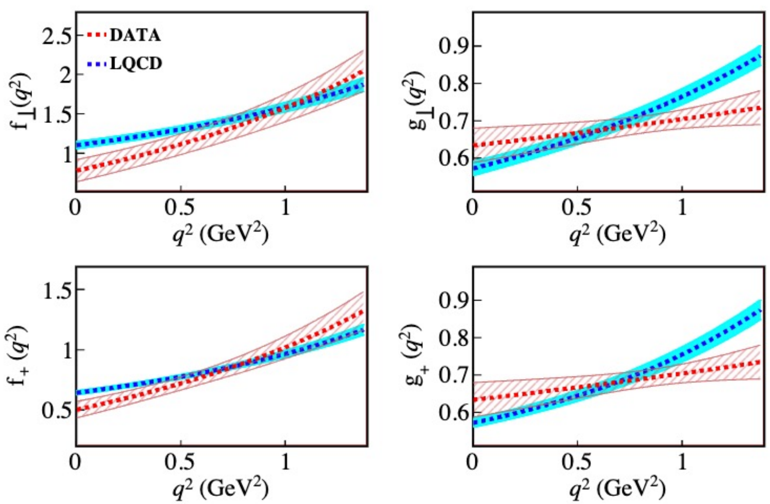


First direct comparisons on the differential decay rates and form factors with LQCD calculations

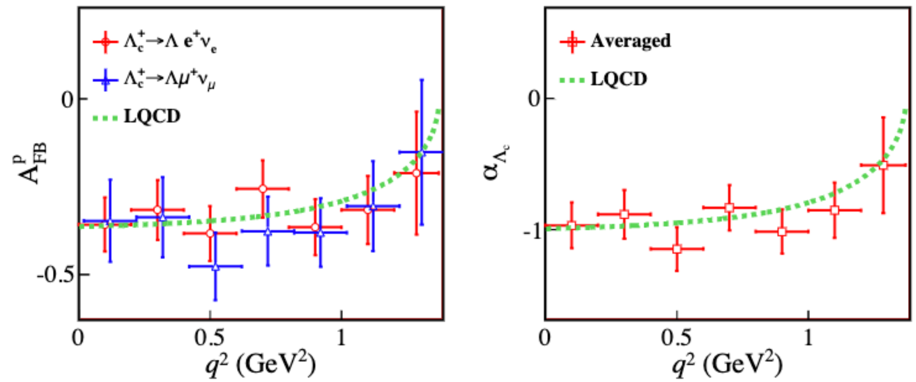
BESIII Combined form factor fits to $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ and $\Lambda e^+\nu_e$

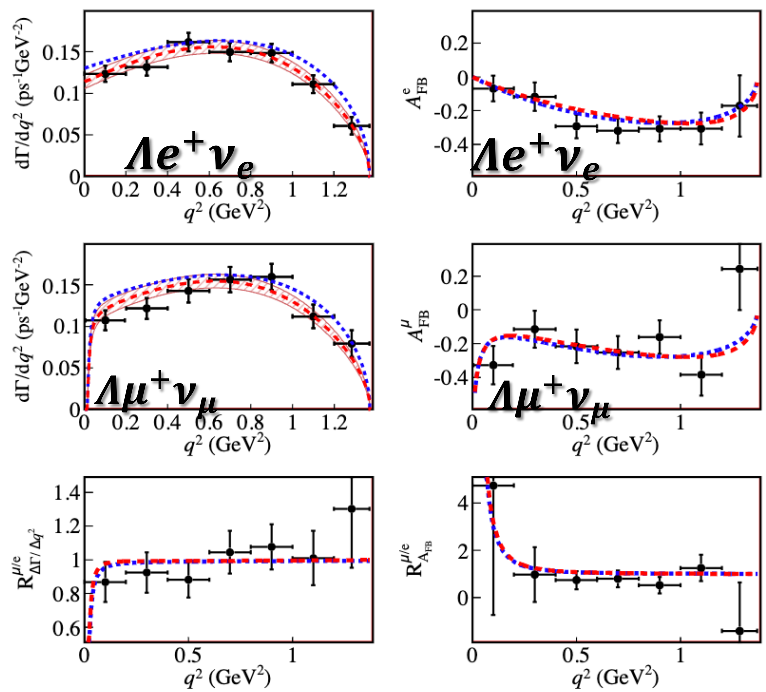
PRD 108, L031105 (2023)





$<\alpha_{\Lambda_c}> = -0.94 \pm 0.07 \pm 0.03$



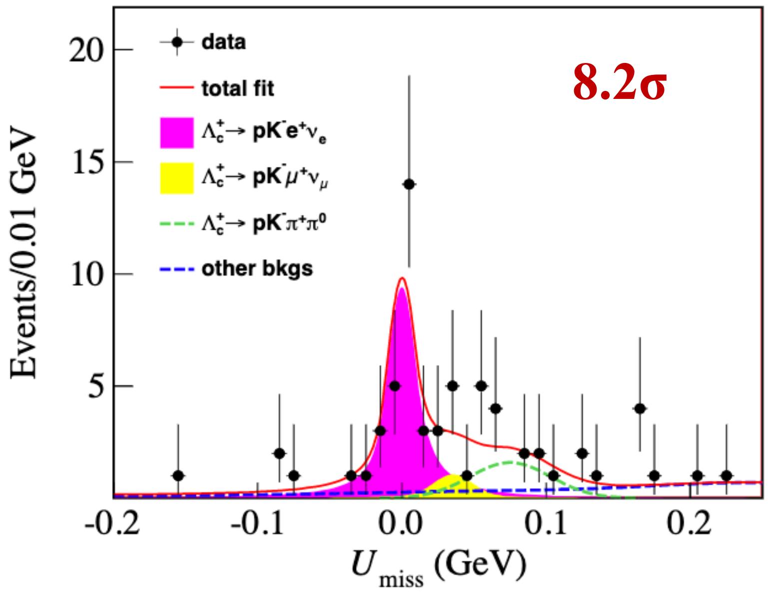


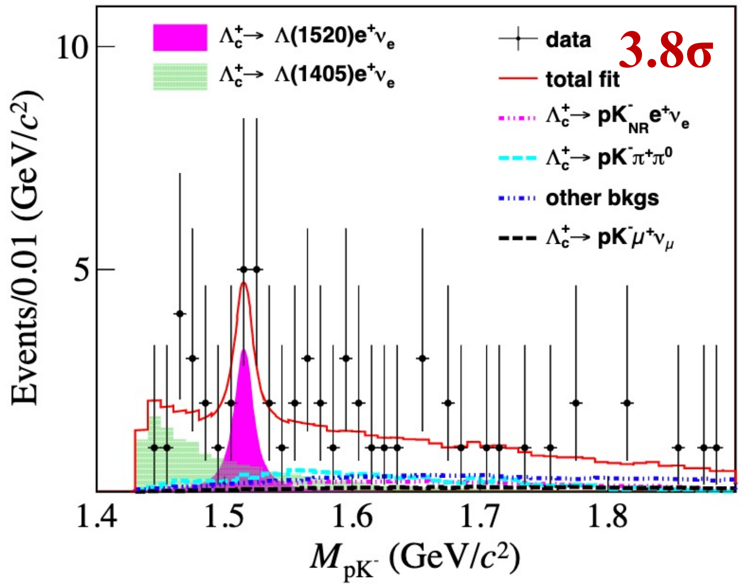
$B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.48 \pm 0.14 \pm 0.10)\%$

$B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)/B(\Lambda_c^+ \to \Lambda e^+\nu_e) = 0.98 \pm 0.05 \pm 0.03$

Observation of $\Lambda_c^+ \to pK^-e^+\nu$

PRD106, 112010 (2022)



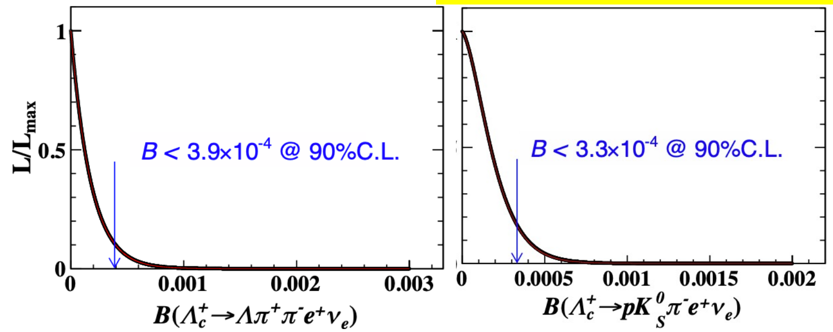


$B(\Lambda_c^+ \to pK^-e^+\nu_e) = (8.8 \pm 1.1 \pm 0.7)\times10^{-4}$

$B(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) = (10.2 \pm 5.2 \pm 1.1)\times10^{-4}$

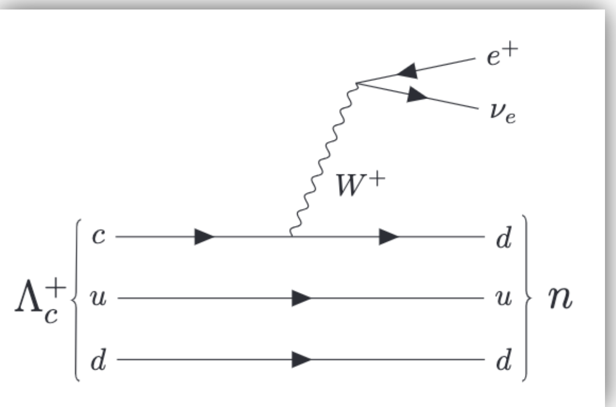
- Second leptonic decay of Λ_c^+ is observed!
- Good channel to study Λ excited states, such as Λ(1405) and Λ(1520)

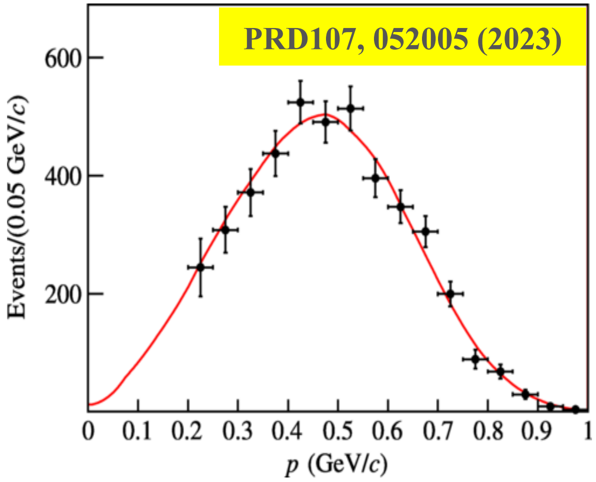
PLB 843, 137993 (2023)



Cabibbo-suppressed SL decays

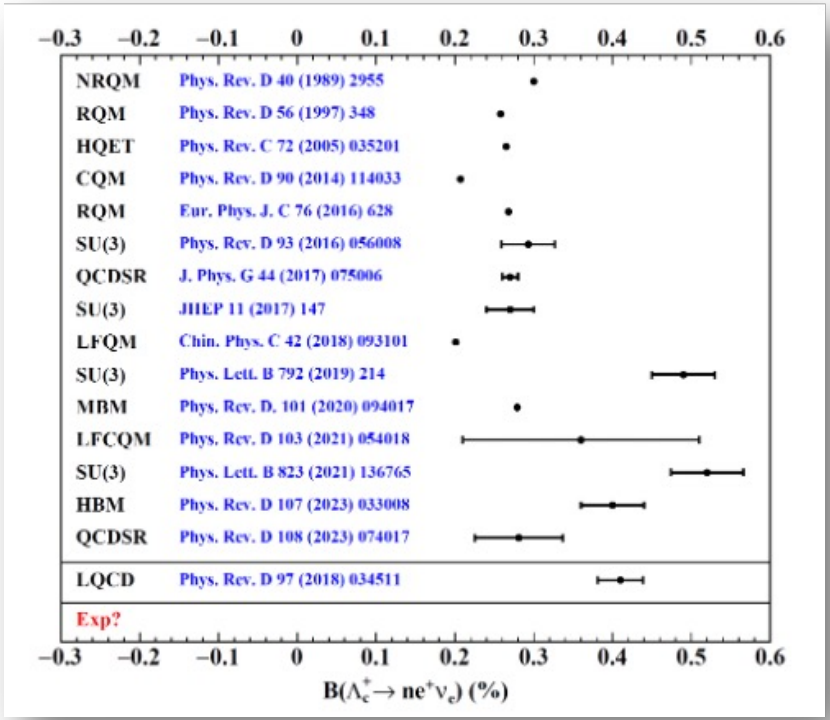
- There is still room of 0.5% for un-seen SL decay of the Λ_c^+
- The Cabibbo-Suppressed SL decays have not been studied in experiment
- $\Lambda_c^+ \to n e^+ \nu_e$ is the most promising channel for the experimental observation



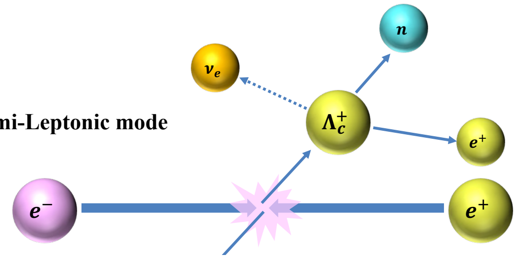


$$\mathscr{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10_{\rm stat} \pm 0.09_{\rm syst})\%.$$

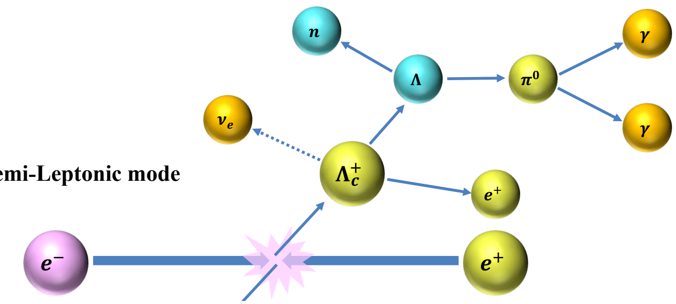
$$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$$
$$B(\Lambda_c^+ \to p K^- e^+ \nu_e) = (8.8 \pm 1.1 \pm 0.7)\times 10^{-4}$$
$$B(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e) = (10.2 \pm 5.2 \pm 1.1)\times 10^{-4}$$



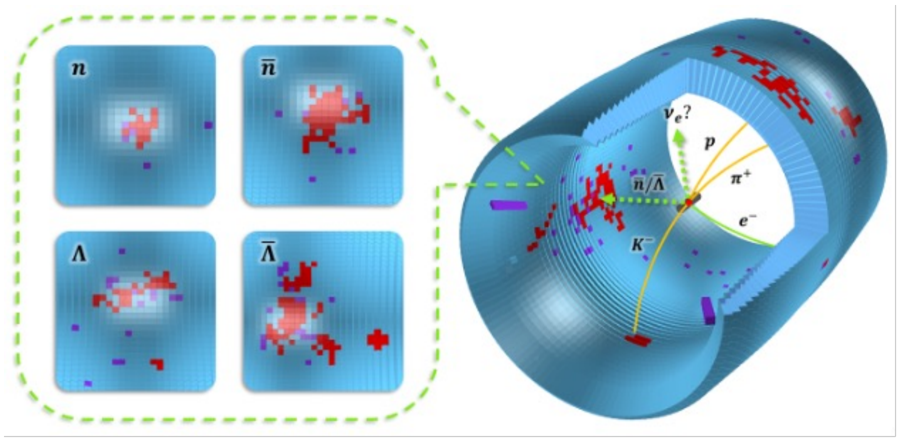
Hunting for $\Lambda_c^+ \to n e^+ \nu$

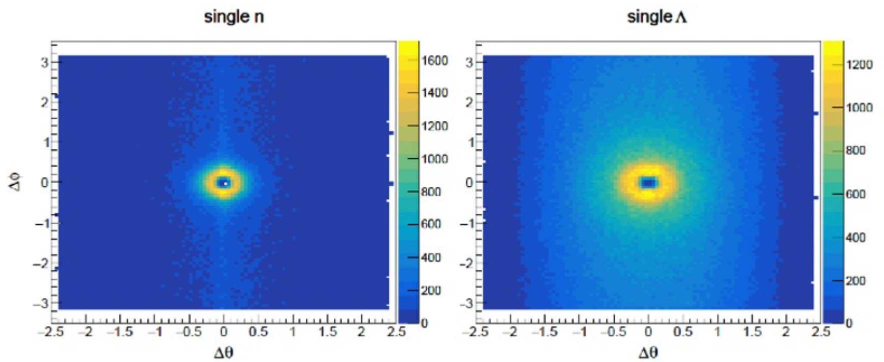


- **Important process of semi-leptonic Λ_c^+ decay to probe strong dynamics in charmed baryon**
- **Challenges:**
  - ✓ neutrino is missing in detection
  - ✓ dominant backgrounds from $\Lambda_c^+ \to \Lambda(\to n\pi^0)e^+\nu$, with ~10x yields than that of the pursuing signals
  - ✓ elusive neutron detection due to neutral charge and contaminations from the photon showers (& noises) in electro-magnetic calorimeter (EMC)



Need advanced Machine Learning tool to identify neutron showers in EMC

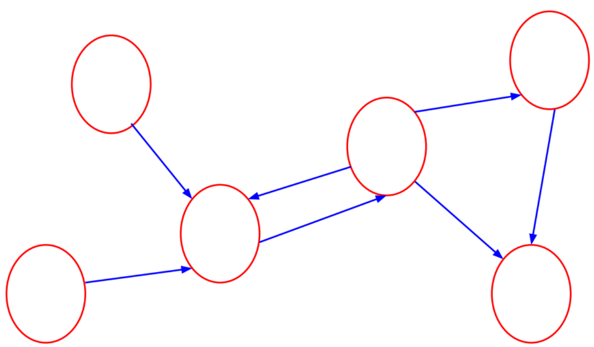


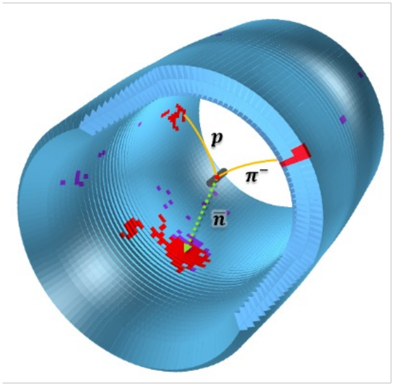


Why Graph Neural Networks (GNN)

arXiv:2410.13515

- Many neural network architectures are specialized for sequential and image-like data such as RNNs, transformers and CNNs.
- GNN can model more arbitrary relations among data objects by treating them as edges between nodes in a graph.





- Sharing of parameters across node and edge updates in the graph
- Permutation invariance

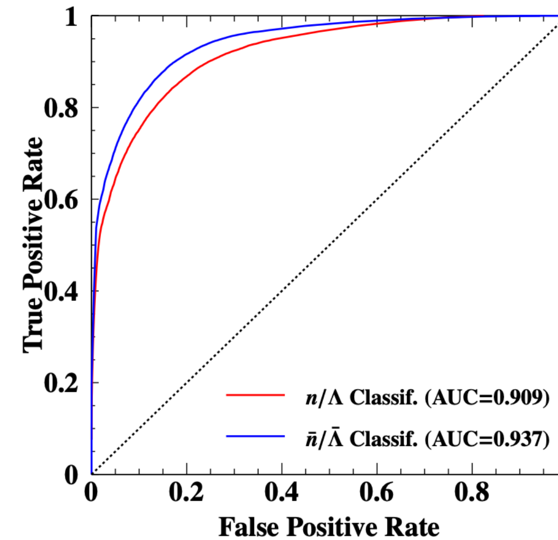
- Nearly unlimited labeled samples
- Structured data
- Clear training objectives

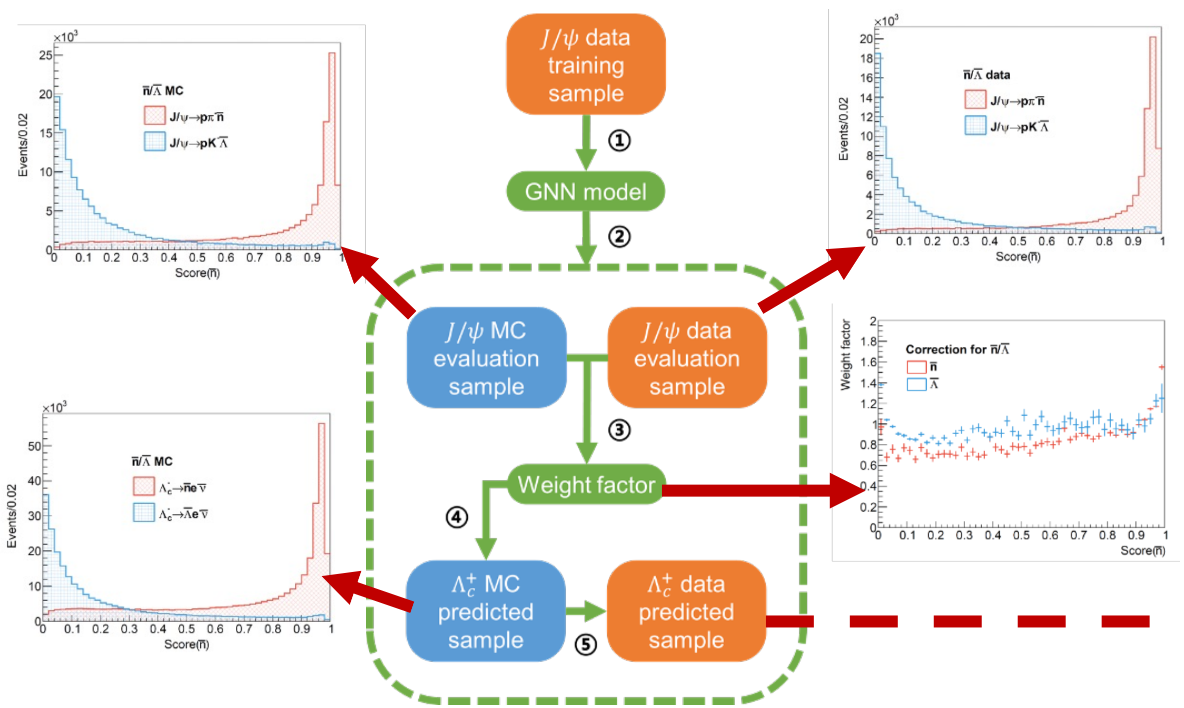
This fits well to the final state particles in physics collisions, where we deal with various objects like tracks/showers and their kinematic relations.

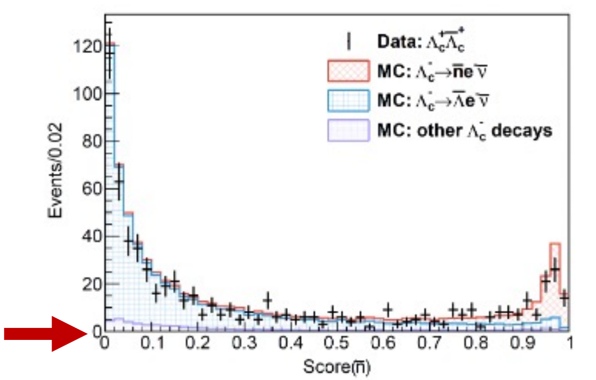
Analysis strategy

arXiv:2410.13515

- Threshold Λ_c^+ production: clean environment and Λ_c^+ tagging
- Train GNN with **ParticleNet** using control data from $J/\psi \to \bar{p}n\pi^+$, $\bar{p}\Lambda K^+$ and c.c. modes based on 10B J/ψ decays



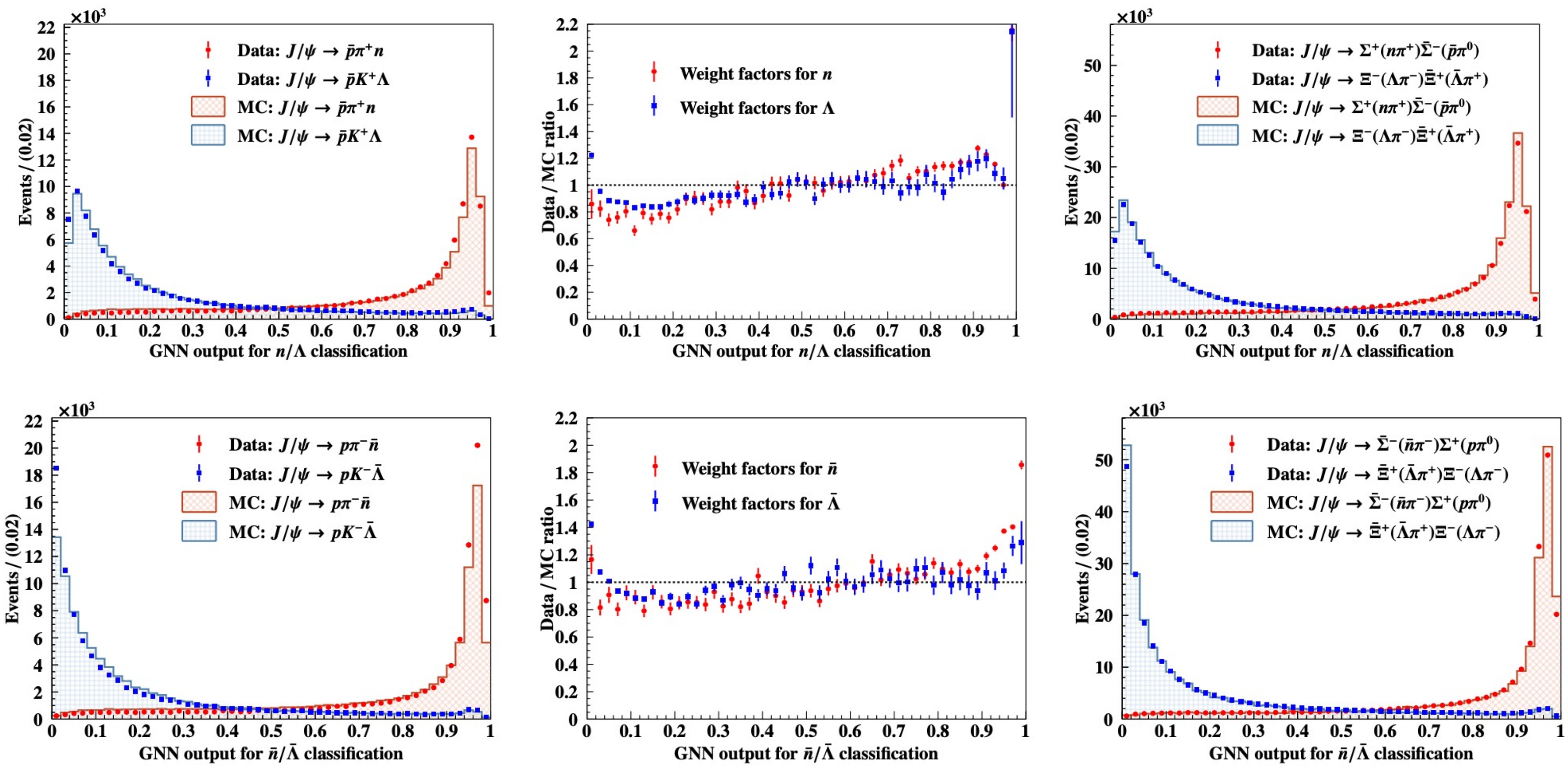




Method validation

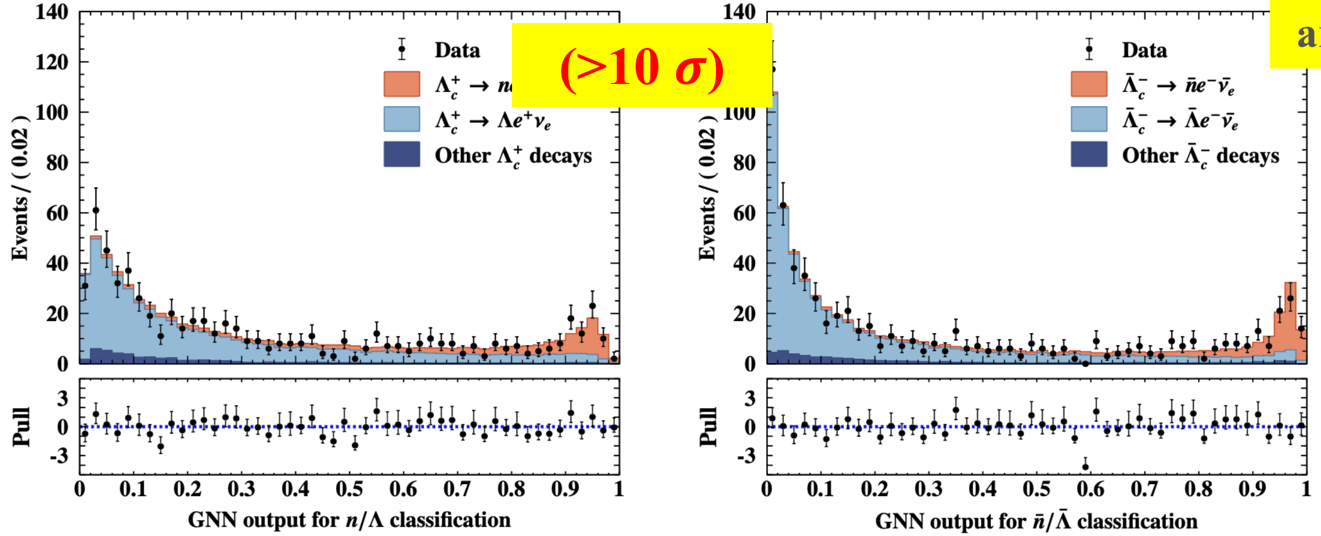
- Control channels of $J/\psi \to \Sigma^+(n\pi^+)\bar{\Sigma}^-(\bar{p}\pi^0)$ and $J/\psi \to \Xi^+(\Lambda\pi^+)\bar{\Xi}^-(\bar{\Lambda}\pi^-)$ based on 10B J/ψ decays

arXiv:2410.13515



Observation of $\Lambda_c^+ \to n e^+ \nu$

arXiv:2410.13515



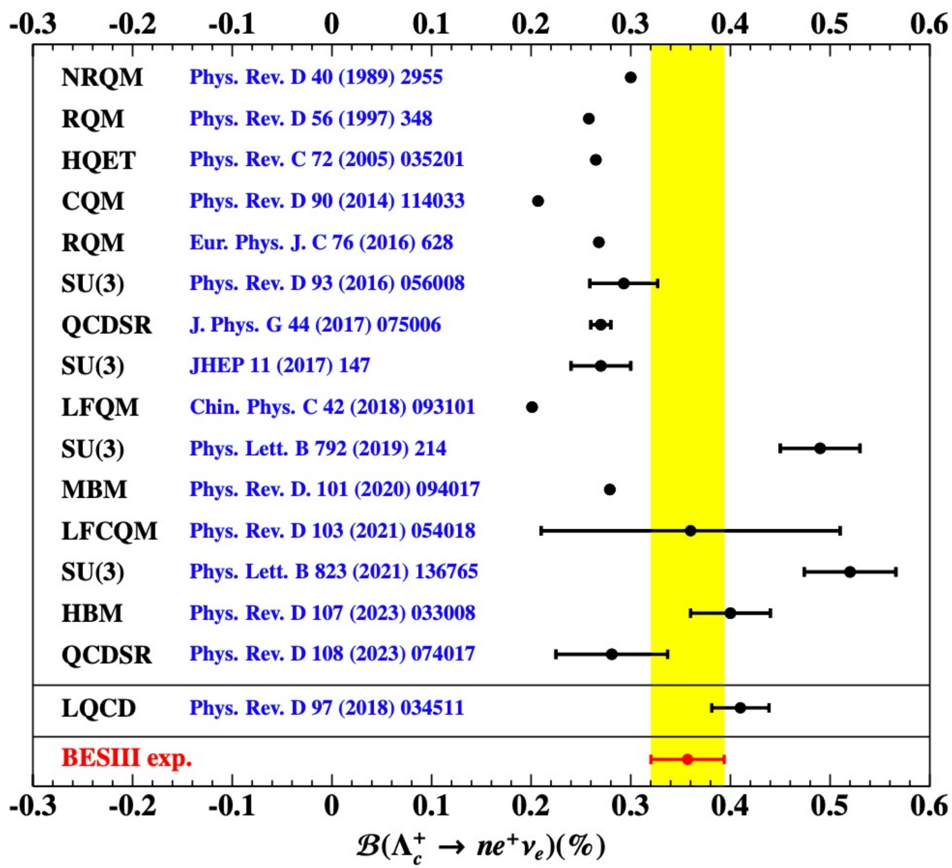
good control of systematics on GNN training

- **Model settings**: network weight initialization, batch processing sequence and dropout layer are randomly varied
- **Domain shift**: validation of independent control sample via $J/\psi \to \Sigma^+(n\pi^+)\overline{\Sigma}^-(\overline{p}\pi^0)$ and $J/\psi \to \Xi^-(\Lambda\pi^-)\overline{\Xi}^+(\overline{\Lambda}\pi^+)$

$$\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.357 \pm 0.034_{\mathrm{stat.}} \pm 0.014_{\mathrm{syst.}})\%$$

Results of BF for $\Lambda_c^+ \to n e^+ \nu$

arXiv:2410.13515
accepted by Nat. Comm.



Combing with the LQCD calculation of the Form Factors, we obtain $\Gamma(\Lambda_c^+ \to n e^+ \nu) = |V_{cd}|^2 (0.405 \pm 0.016 \pm 0.020)\ \mathrm{ps}^{-1}$,

$|V_{\rm cd}| = 0.208 \pm 0.011_{\rm exp} \pm 0.005_{\rm LQCD} \pm 0.001_{\tau_{\Lambda_c}}$

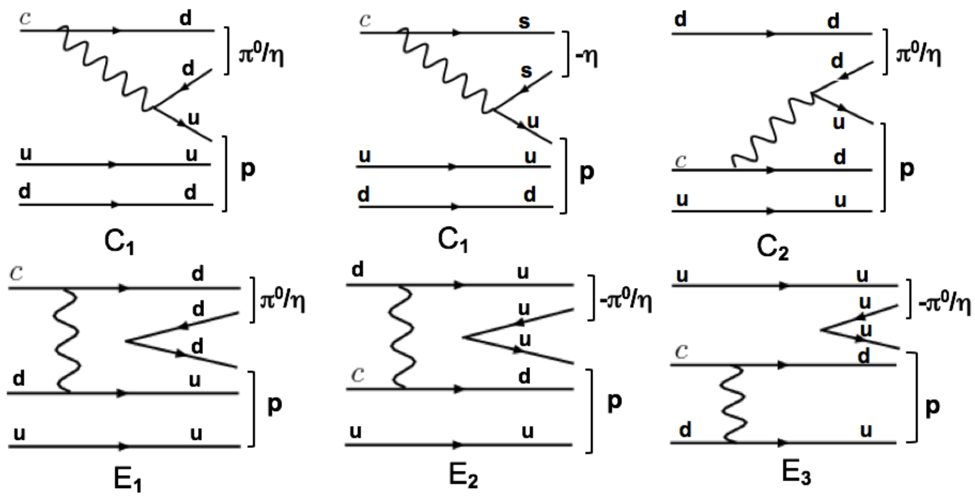
first determination of $|V_{\rm cd}|$ in charmed baryon decays

Λ_c^+ hadronic decay

Study of SCS channels: $\Lambda_c^+ \to \Lambda K^+, p\pi^0, p\eta, n\pi^+, \Sigma^0 K^+, \Sigma^+ K^0$ etc.

from HY Cheng

Singly Cabibbo-suppressed modes: $\Lambda_c^+ \to p\pi^0, p\eta$



$\pi^0 = (d\bar{d} - u\bar{u})/\sqrt{2}$, $\eta = (d\bar{d} + u\bar{u} - s\bar{s})/\sqrt{3}$ for $\eta - \eta'$ mixing angle $= 19.5^0$

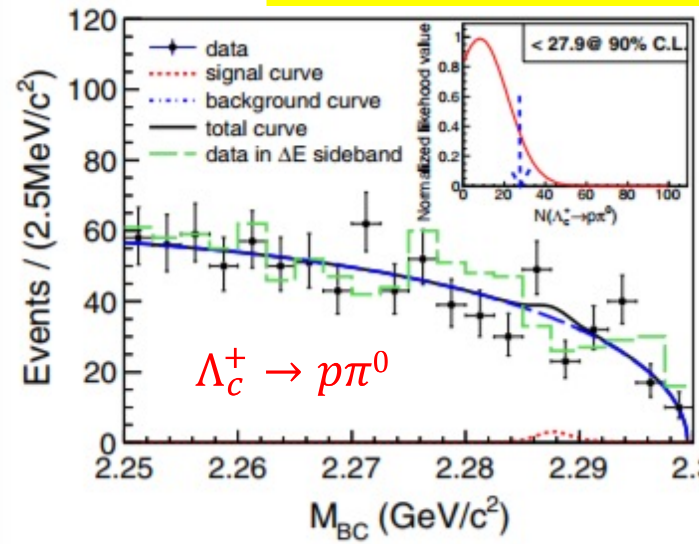
$A(\Lambda_c^+ \to p\pi^0) = (C_1 + C_2 + E_1 - E_2 - E_3)/\sqrt{2}$

$A(\Lambda_c^+ \to p\eta) = (2C_1 + C_2 + E_1 + E_2 + E_3)/\sqrt{3}$

It is most likely that

$\Gamma(\Lambda_c^+ \to p\eta) >> \Gamma(\Lambda_c^+ \to p\pi^0)$ 30

PRD95(2017)111102(R)



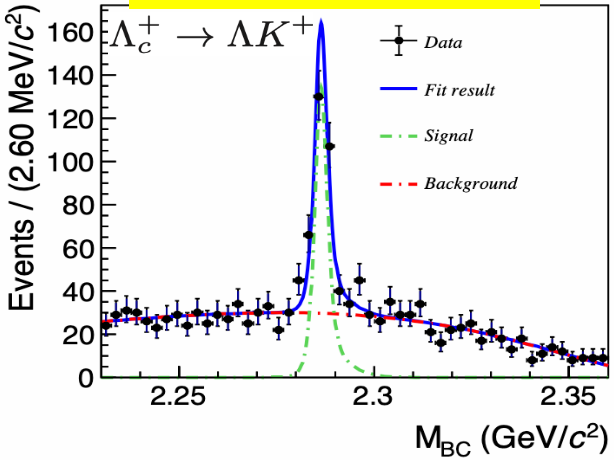
BESIII: BF<2.7×10^{-4}

$$M(\Lambda_c^+ \to n\pi^+) = \sqrt{2} M(\Lambda_c^+ \to p\pi^0),$$

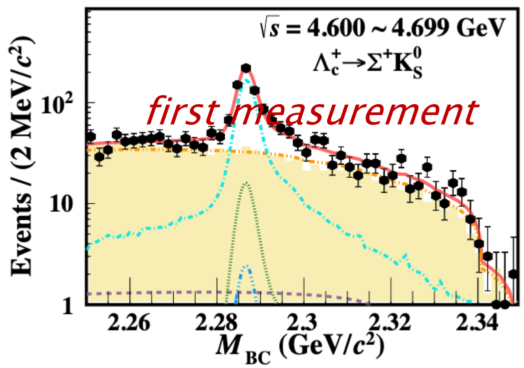
- More precise comparison of the two BFs are desired to explore the interference of different non-factorizable diagrams and BESIII result support the theoretic prediction. It is predicted that BF[$\Lambda_c^+ \to n\pi^+$]~3.5×BF[$\Lambda_c^+ \to p\pi^0$] [arXiv: 1801.08625]

Some results on SCS hadronic decays

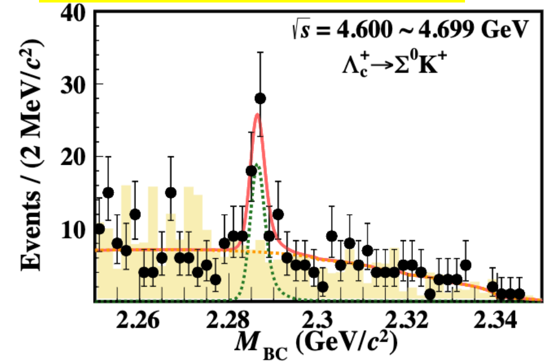
PRD106, 111101 (2022)



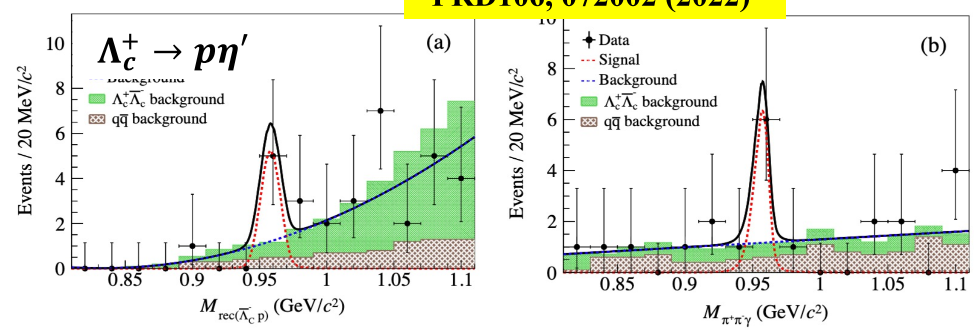
$\Lambda_c^+ \to \Sigma^+ K_S$ and $\Sigma^0 K^+$



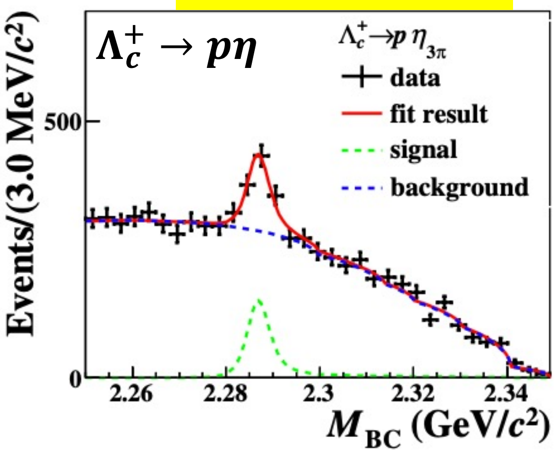
PRD106, 052003 (2022)



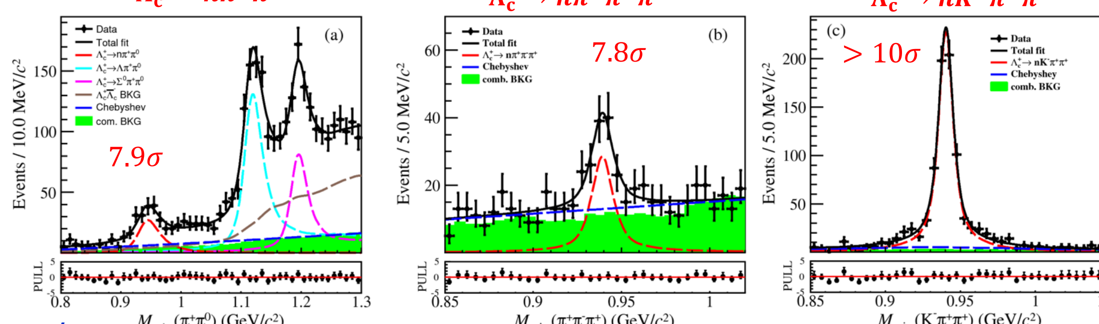
PRD106, 072002 (2022)



JHEP11, 137 (2023)



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



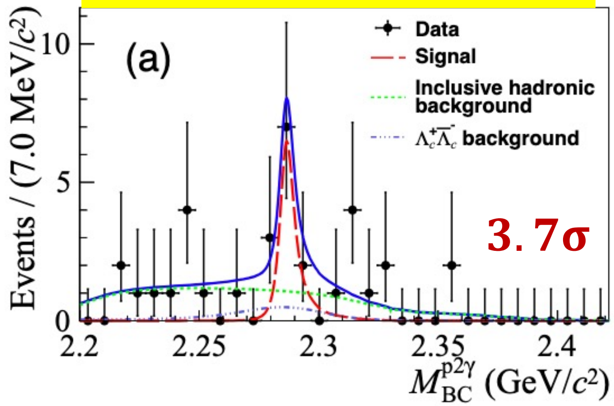
CPC47, 023001 (2023)

Many CS modes are being explored.

Singly Cabibbo-suppressed decays of $\Lambda_c^+ \to p\pi^0$ and $n\pi^+$

First evidence of $\Lambda_c^+ \to p\pi^0$

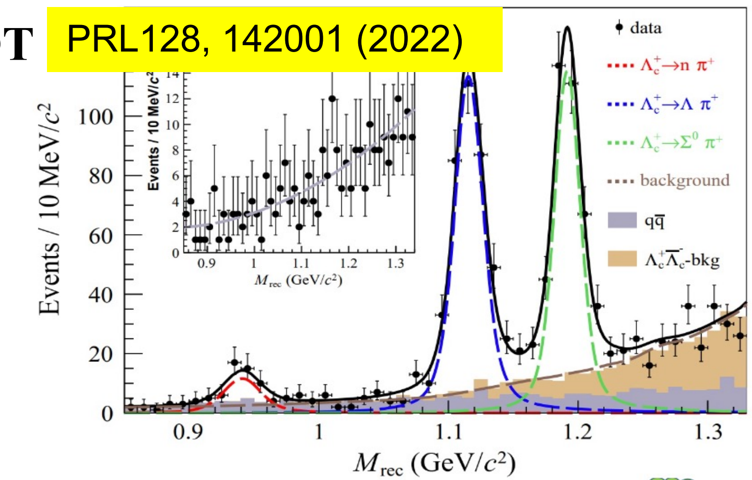
DT PRD109, L091101 (2024)



$\mathrm{BF} = (1.56^{+0.72}_{-0.58} \pm 0.20)\times 10^{-4}$

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

DT PRL128, 142001 (2022)



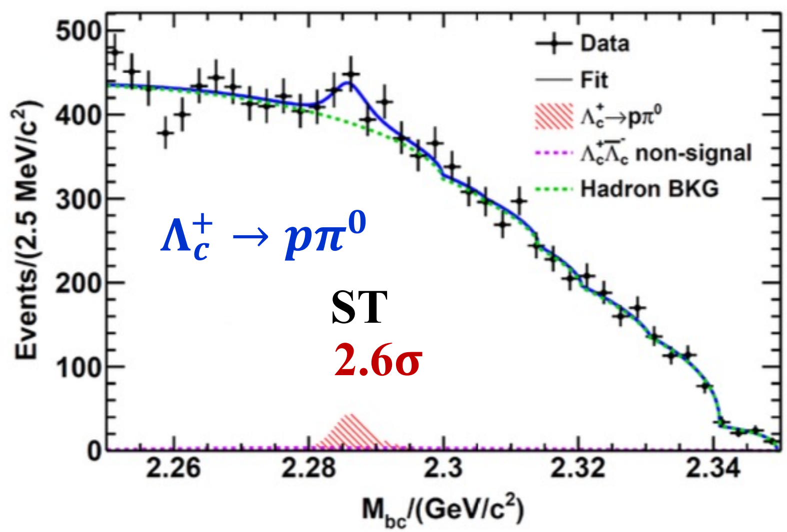
$\mathrm{BF} = (6.6 \pm 1.2 \pm 0.4)\times 10^{-4}$

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

- conflicts with BELLE (BF $<8.0\times 10^{-5}$)
- need better precision to discriminate different theoretical calculations

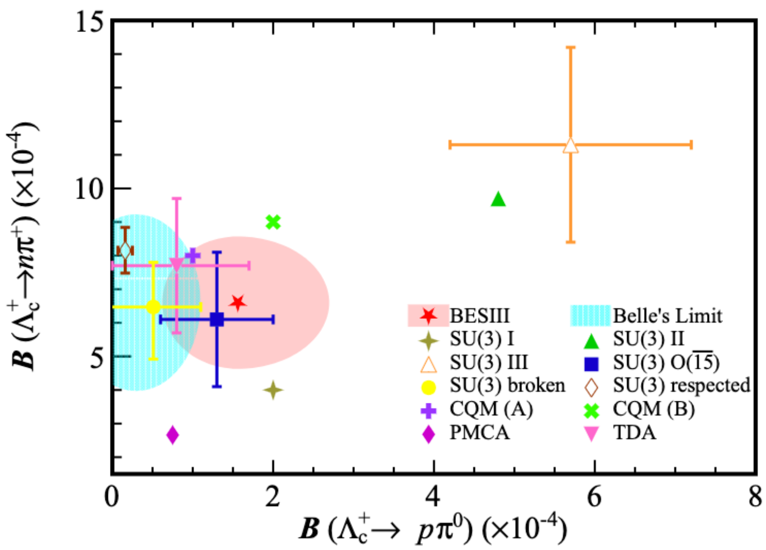
Experimental challenge

- neither ST nor DT can achieve sufficient signal sensitivity!



Branching fraction comparisons

Model	$\mathcal{B}(\Lambda_c^+ \to p\pi^0)\times 10^4$	$\mathcal{B}(\Lambda_c^+ \to p\eta)\times 10^4$	$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times 10^4$
Constituent quark model [7]	(1, 2)	3	(8, 9)
Heavy quark effective theory [8]	1.1 - 3.6	-	1.0 - 2.1
Dynamic calculation [9, 10]	(0.75, 1.3)	12.8	2.66
Topological diagram [11]	$0.8^{+0.9}_{-0.8}$	11.4 ± 3.5	7.7 ± 2.0
Topological diagram [12]	$(0.3^{+1.0}_{-0.3},\ 0.4^{+1.7}_{-0.4})$	$(14.2 \pm 2.3,\ 14.7 \pm 2.8)$	$(7.6 \pm 1.7,\ 8.3 \pm 2.6)$
SU(3) flavor symmetry [13]	2	-	4
SU(3) flavor symmetry [14]	4.8	-	9.7
SU(3) flavor symmetry [15]	5.7 ± 1.5	-	11.3 ± 2.9
SU(3) flavor symmetry [16]	1.3 ± 0.7	13.0 ± 1.0	6.1 ± 2.0
SU(3) flavor symmetry [17]	$1.1^{+1.3}_{-1.1}$	11.2 ± 2.8	7.6 ± 1.1
SU(3) flavor symmetry [18]	2.1 ± 1.0	14.1 ± 1.1	6.5 ± 2.3
BESIII experiment	< 2.7 [19] $1.57^{+0.74}_{-0.60}$ [23]	12.4 ± 3.0 [19] 15.8 ± 1.2 [20]	6.6 ± 1.3 [22]
Belle experiment	< 0.8 [21]	14.2 ± 1.2 [21]	-



ML-boosted observation of $\Lambda_c^+ \to p\pi^0$

arXiv: 2410.13368

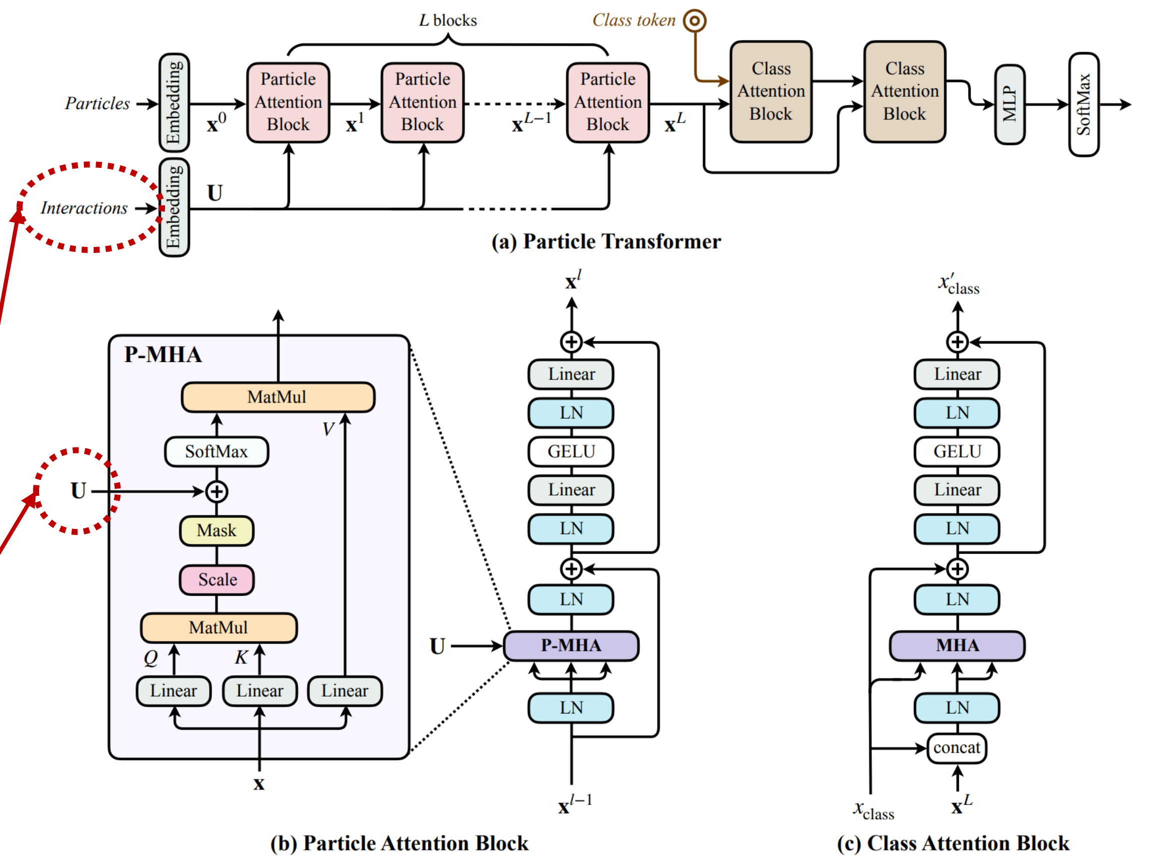
Model architecture – Transformer

- Foundation of Large Language Models like GPT
- Core concept: self-attention mechanism
- Particle Transformer: arXiv:2202.03772

✓ A transformer model tailored for particle physics

✓ Inject physics-inspired pairwise features as "bias" to the self-attention block

$$\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$
$$k_T = \min(p_{T,a}, p_{T,b})\Delta,$$
$$z = \min(p_{T,a}, p_{T,b})/(p_{T,a} + p_{T,b}),$$
$$m^2 = (E_a + E_b)^2 - \left\|\mathbf{p}_a + \mathbf{p}_b\right\|^2.$$



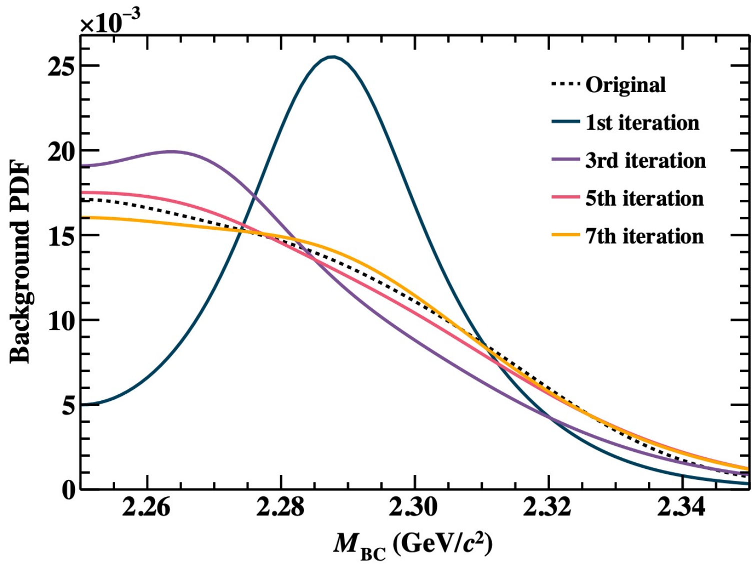
ML-boosted observation of $\Lambda_c^+ \to p\pi^0$

arXiv: 2410.13368

- Use Deep Neural Network (DNN) to identify $\Lambda_c^+(\to p\pi^0)\bar{\Lambda}_c^-(\to anything)$ **after ST selections**
  - ✓ Form point clouds with all recorded tracks & showers
  - ✓ Train Transformer model with MC samples covering all $\bar{\Lambda}_c^-$ final states
  - ✓ Randomly shuffle signal & background MC samples with equal statistics
- Take $\Lambda_c^+ \to p\eta, \eta \to \gamma\gamma$ as reference channel

- Data augmentation
  - ✓ train $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\eta$ in one uniform model
  - ✓ maximum systematic cancellation
- Mass decorrelation to ease the model decoration on the signal discriminator
  - ✓ an iterative method is implemented on beam-constrained mass in background events in loss function

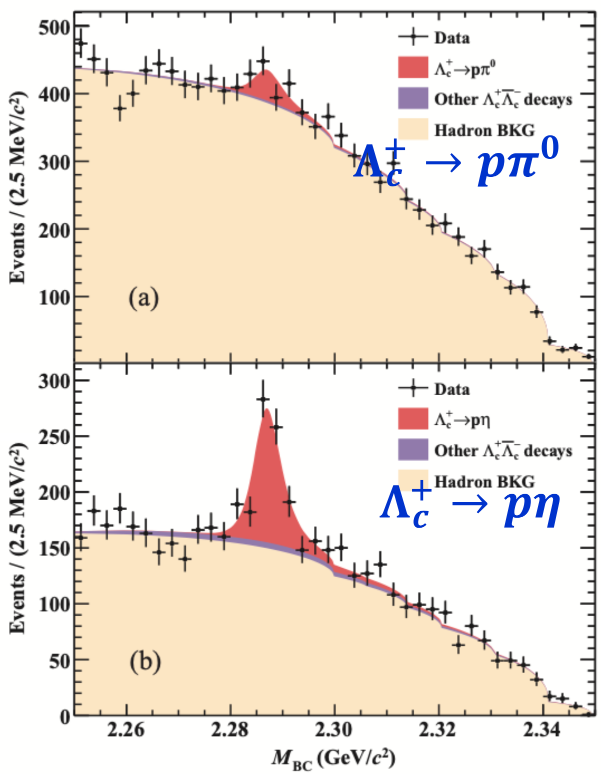
$$\omega_0(M_{BC}) = 1, \omega_i(M_{BC}) = \omega_{i-1}(M_{BC}) \cdot \frac{p_{i-1}^{BKG}(M_{BC})}{p_{orig}^{BKG}(M_{BC})}$$



ML-boosted observation of $\Lambda_c^+ \to p\pi^0$

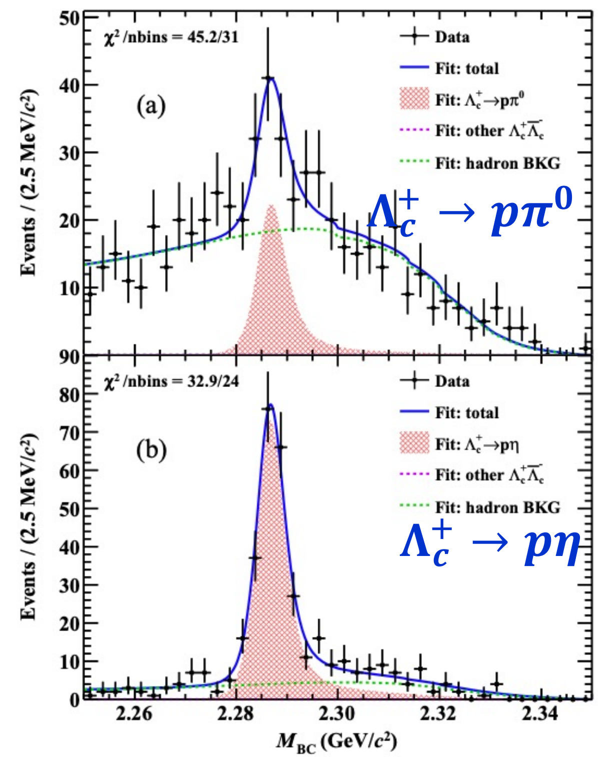
arXiv: 2410.13368

2.6σ



DNN training

5.4σ



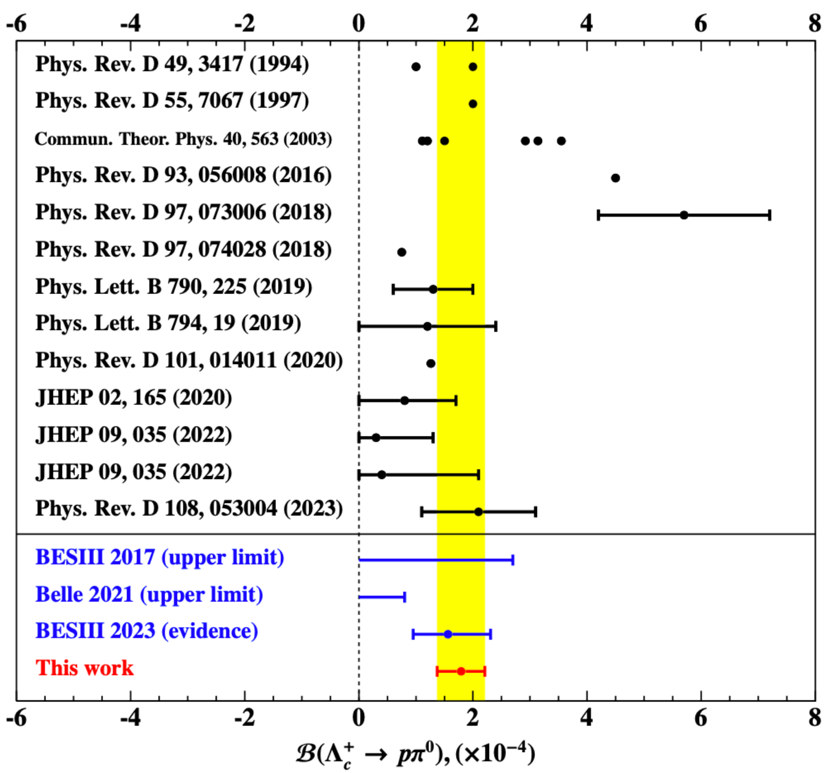
- **20 times of background suppression with 50% of signal efficiency**
- **validation samples of $\Lambda_c^+ \to pK_S\pi^0$ and $pK_S\eta$**

BESIII

SCS decays of $\Lambda_c^+ \to p\pi^0$

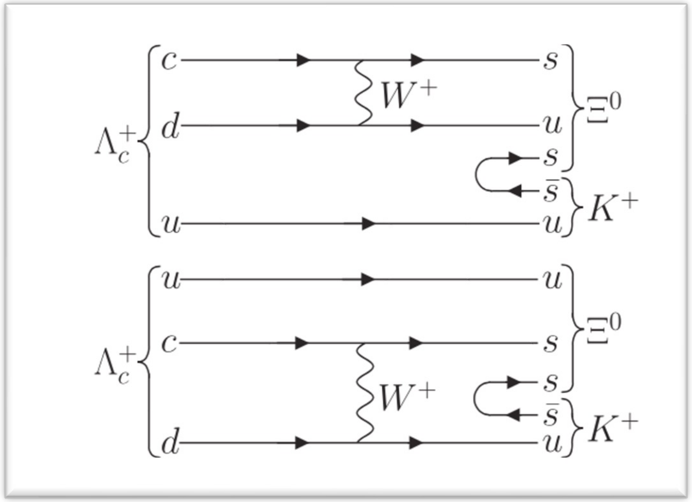
arXiv: 2410.13368

- The ratio is directly measured to be $\frac{B(\Lambda_c^+ \to p\pi^0)}{B(\Lambda_c^+ \to p\eta)} = 0.120 \pm 0.026 \pm 0.007$
- The branching fraction is obtained to be
  $B(\Lambda_c^+ \to p\pi^0) = (1.79 \pm 0.39 \pm 0.11 \pm 0.08) \times 10^{-4}$,
  by adopting the average value of $B(\Lambda_c^+ \to p\eta)$ from BESIII and BELLE.
- Agree with previous BESIII measurements and exceeds the upper limit set by BELLE



Study on W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

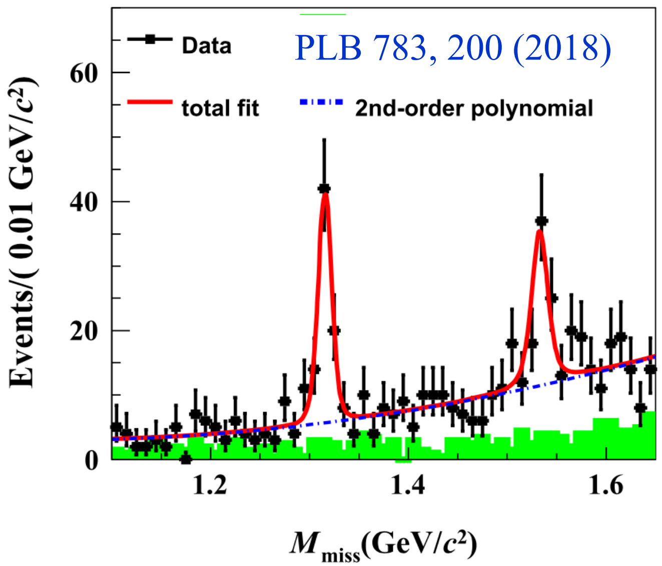
- Previous theoretical calculation on the BF lower than exp. measurement, which all predicted zero decay asymmetry
- BESIII confirmed the exp. result of BF in 2018 [PLB 783, 200 (2018)]
- In theory, BF is enhanced by enhancing the decay asymmetry α close to 1



$$\alpha_{\Xi^0 K^+} = 2\mathrm{Re}(s^* p)/(|s|^2 + |p|^2)$$

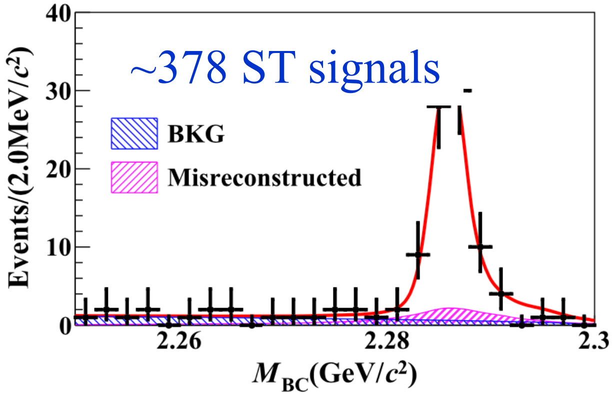
Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$
Körner (1992), CCQM [7]	2.6	0
Xu (1992), Pole [8]	1.0	0
Źencaykowski (1994), Pole [9]	3.6	0
Ivanov (1998), CCQM [10]	3.1	0
Sharma (1999), CA [11]	1.3	0
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$
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	...

DT signals



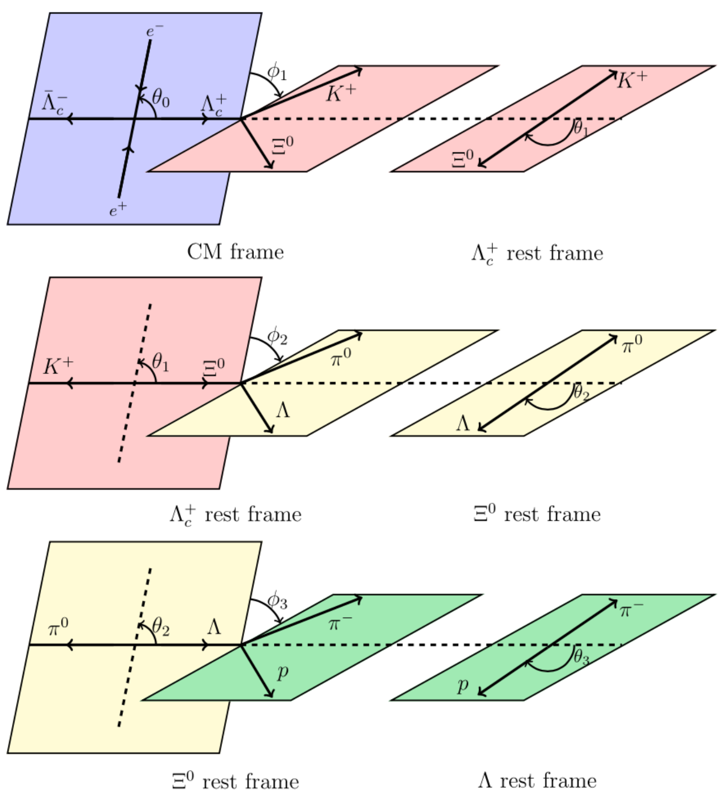
Angular fits in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

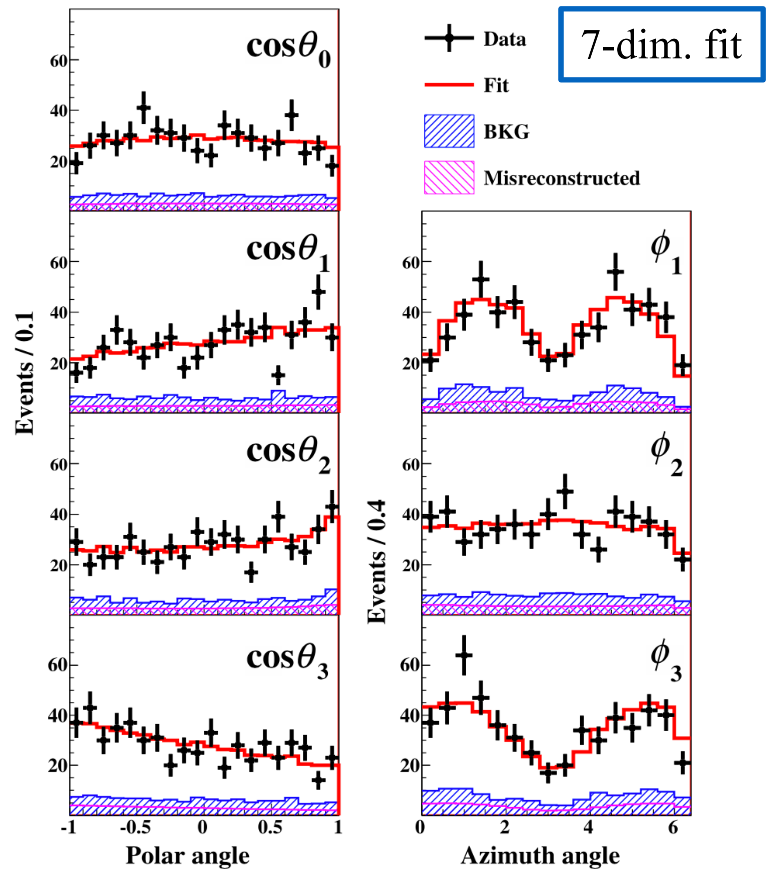
PRL132, 031801(2024)



three-level cascade decay

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

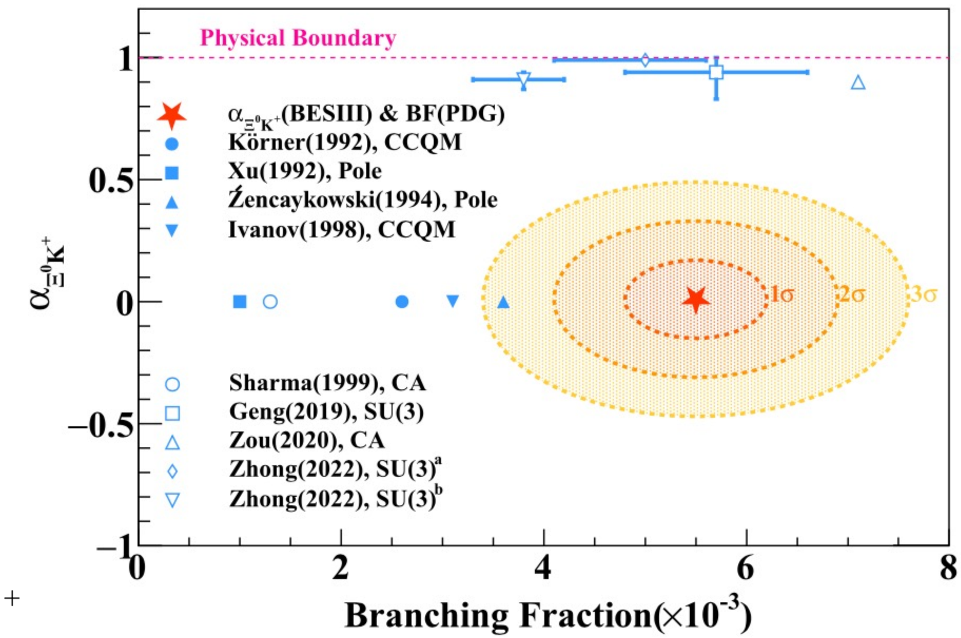




Decay asymmetry result and branching fraction

PRL132, 031801(2024)

$$
\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0\ d\cos\theta_1\ d\cos\theta_2\ d\cos\theta_3\ d\phi_1\ d\phi_2\ d\phi_3} \\
&\propto 1+\alpha_0\cos^2\theta_0 \\
&+(1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0K^+}\alpha_{\Lambda\pi^0}\cos\theta_2 \\
&+(1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0K^+}\alpha_{p\pi^-}\cos\theta_2\cos\theta_3 \\
&+(1+\alpha_0\cos^2\theta_0)\ \alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\cos\theta_3 \\
&-(1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0K^+}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0K^+}\sin\theta_1\sin\phi_1 \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Lambda\pi^0}\sin\theta_1\sin\phi_1\cos\theta_2 \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0K^+}\alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_3 \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_2\cos\theta_3 \\
&-\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_1\sin\phi_1\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+ \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\ \alpha_{\Lambda\pi^0}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\ \alpha_{\Lambda\pi^0}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2)\cos\theta_3 \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\ \alpha_{p\pi^-}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2)\cos\theta_3 \\
&-\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\ \sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\cos\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3),
\end{aligned}
$$



First determination of decay asymmetry $\alpha_{\Xi^0K^+}=0.01\pm0.16\pm0.03$, which is consistent with zero

Determination on the phase differences

- Based on the angular fit, the phase angle $\Delta_{\Xi^0 K^+} = (3.84 \pm 0.90 \pm 0.17)$ rad

$$\beta_{\Xi^0 K^+} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\sin\Delta_{\Xi^0 K^+},$$
$$\gamma_{\Xi^0 K^+} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\cos\Delta_{\Xi^0 K^+}.$$

$$\beta_{\Xi^0 K^+} = -0.64 \pm 0.69 \pm 0.13$$
$$\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58 \pm 0.11$$

- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$

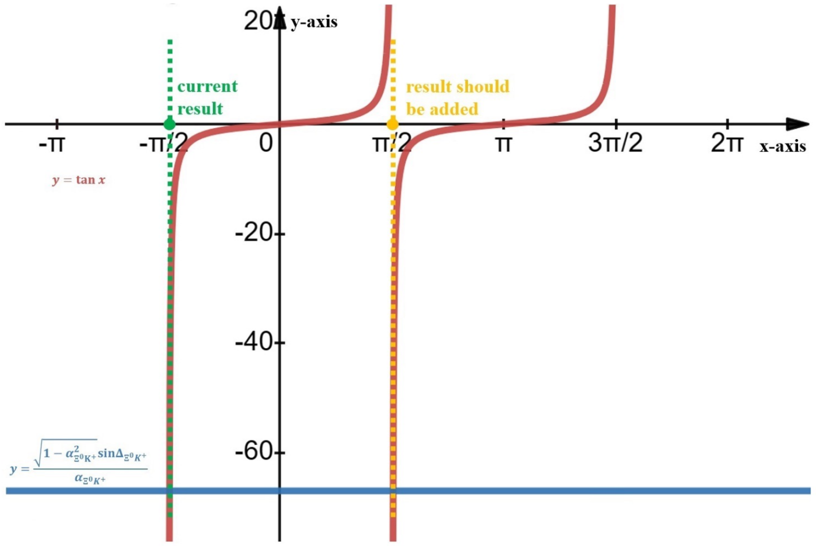
$$\Gamma_{\Xi^0 K^+} = \frac{\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi}\left[\frac{(m_{\Lambda_c^+}+m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|A|^2 + \frac{(m_{\Lambda_c^+}-m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|B|^2\right],$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p-\delta_s)}{|A|^2+\kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p-\delta_s)}{|A|^2-\kappa^2|B|^2}$$

$$\delta_p - \delta_s = \arctan\left(\sqrt{1-\alpha_{\Xi^0 K^+}^2}\sin\Delta_{\Xi^0 K^+}/\alpha_{\Xi^0 K^+}\right)$$

1st sol.: $(-1.55 \pm 0.25 \pm 0.05)$ rad
2nd sol.: $(1.59 \pm 0.25 \pm 0.05)$ rad



Λ_c^+ decay asymmetries

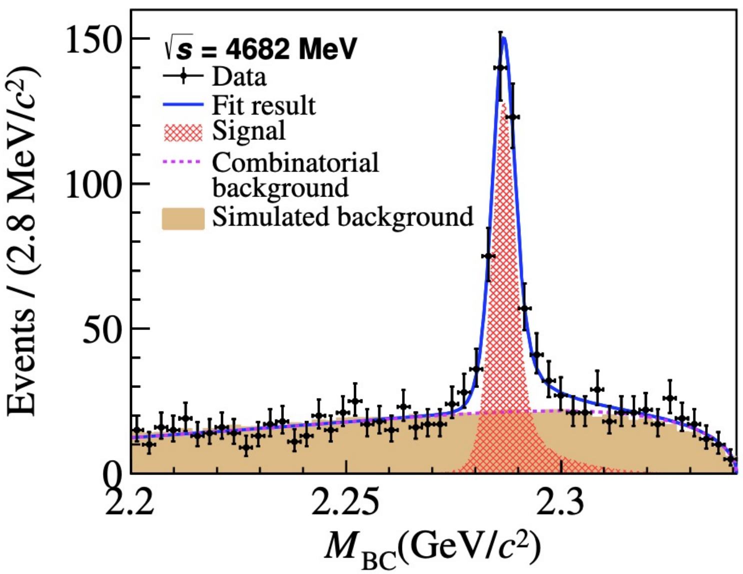
Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_s^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0K^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]	-0.10	-0.70	0.70	0.71	0
Xu(1992), Pole [4]	0.51	-0.67	0.92	0.92	0
Cheng, Tseng(1992), Pole [5]	-0.49	-0.96	0.83	0.83	-
Cheng, Tseng(1993), Pole [6]	-0.49	-0.95	0.78	0.78	-
Źencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Źencaykowski(1994), Pole [8]	-0.66	-0.99	0.39	0.39	0
CLEO(1995) [9]	-	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	-	$-0.45 \pm 0.31 \pm 0.06$	-
Alakabha Datta(1995), CA [10]	-0.91	-0.94	-0.47	-0.47	-
Ivanov(1998), CCQM [11]	-0.97	-0.95	0.43	0.43	0
Sharma(1999), CA [12]	-0.99	-0.99	-0.31	-0.31	0
FOCUS(2006) [13]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
BESIII(2018) [14]	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.73 \pm 0.17 \pm 0.07$	$-0.57 \pm 0.10 \pm 0.07$	-
Geng(2019), SU(3) [15]	$-0.89^{+0.26}_{-0.11}$	-0.87 ± 0.10	-0.35 ± 0.27	-0.35 ± 0.27	$0.94^{+0.06}_{-0.11}$
Zou(2020), CA [16]	-0.75	-0.93	-0.76	-0.76	0.90
BELLE(2022) [17, 18]	-	$-0.755 \pm 0.005 \pm 0.003$	$-0.463 \pm 0.016 \pm 0.008$	$-0.48 \pm 0.02 \pm 0.02$	-
Zhong(2022), SU(3)^a [19]	-0.57 ± 0.21	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	$0.91^{+0.03}_{-0.04}$
Zhong(2022), SU(3)^b [19]	-0.29 ± 0.24	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	0.99 ± 0.01
Liu(2023), Pole [20]	-0.81 ± 0.05	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.95 ± 0.02
Liu(2023), LP [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	-0.02
BESIII(2023) [21]	-	-	-	-	0.01 ± 0.16
Geng(2023), SU(3) [22]	-0.40 ± 0.49	-0.75 ± 0.01	-0.47 ± 0.02	-0.47 ± 0.02	-0.15 ± 0.14
Zhong(2024), TDA [23]	0.01 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.16 ± 0.13
Zhong(2024), IRA [23]	0.03 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.19 ± 0.12
LHCb(2024) [32]	$-0.754 \pm 0.008 \pm 0.006$	$-0.785 \pm 0.006 \pm 0.003$	-	-	-
Zhong(2024), TDA [31]	-0.74 ± 0.03	-0.76 ± 0.01	-0.47 ± 0.01	-0.47 ± 0.01	-0.04 ± 0.12
Zhong(2024), IRA [31]	-0.74 ± 0.03	-0.76 ± 0.01	-0.47 ± 0.01	-0.47 ± 0.01	-0.06 ± 0.12
PDG Fit(2024) [33]	0.20 ± 0.50 (only BESIII)	-0.755 ± 0.006	-0.466 ± 0.018	-0.484 ± 0.027	···

Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\eta$

arXiv:2407.12270

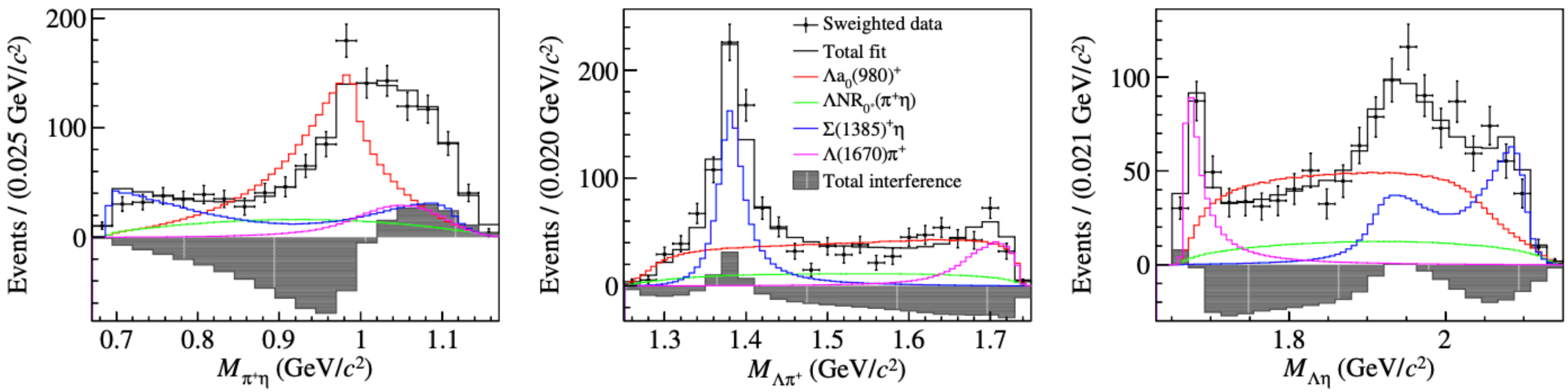
- A good channel to investigate different types of hadron states, especially tetraquark or pentaquark candidates
- $\Lambda_c^+ \to \Lambda\pi^+\eta$ decay provides a good platform to study the internal structure of $a_0(980)^+$ whose exact nature remains elusive.
- The $\Lambda\pi^+$ mode, representing a pure I = 1 combination, excludes influences from Λ^* resonances as compared to the $\Sigma\pi$ and pK modes.
- Study of low-lying excited $\frac{1}{2}^-$ state, eg $\Sigma(1380)^+$, can be performed, along with the nearby state $\Sigma(1385)^+$

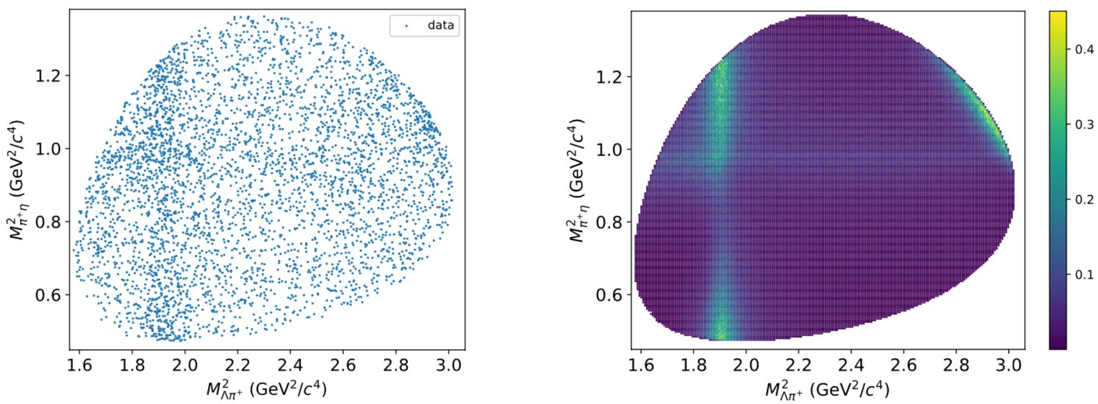
- Based on TF-PWA package: https://gitlab.com/jiangyi15/tf-pwa
- BDTG trained sample with about 1312 signals with purity of about 80%



Baseline model of $\Lambda_c^+ \to \Lambda\pi^+\eta$

arXiv:2407.12270





- **$\Lambda_c^+ \to \Lambda a_0(980)^+$ firstly observed**
- **Decay asymmetries obtained based on PWA amplitudes**

Process	FF (%)	$\mathcal{S}$	α
$\Lambda a_0(980)^+$	$54.0 \pm 8.4 \pm 2.6$	13.1σ	$0.91^{+0.09}_{-0.18} \pm 0.08$
$\Sigma(1385)^+\eta$	$30.4 \pm 2.6 \pm 0.7$	22.5σ	$-0.61 \pm 0.15 \pm 0.04$
$\Lambda(1670)\pi^+$	$14.1 \pm 2.8 \pm 1.2$	11.7σ	$0.21 \pm 0.27 \pm 0.33$
ΛNR_{0^+}	15.4 ± 5.3	6.7σ	...

$$\alpha_{\Lambda a_0(980)^+} = \frac{\left|H^{\Lambda_c^+\to\Lambda a_0(980)^+}_{\frac{1}{2},0}\right|^2 - \left|H^{\Lambda_c^+\to\Lambda a_0(980)^+}_{-\frac{1}{2},0}\right|^2}{\left|H^{\Lambda_c^+\to\Lambda a_0(980)^+}_{\frac{1}{2},0}\right|^2 + \left|H^{\Lambda_c^+\to\Lambda a_0(980)^+}_{-\frac{1}{2},0}\right|^2}$$

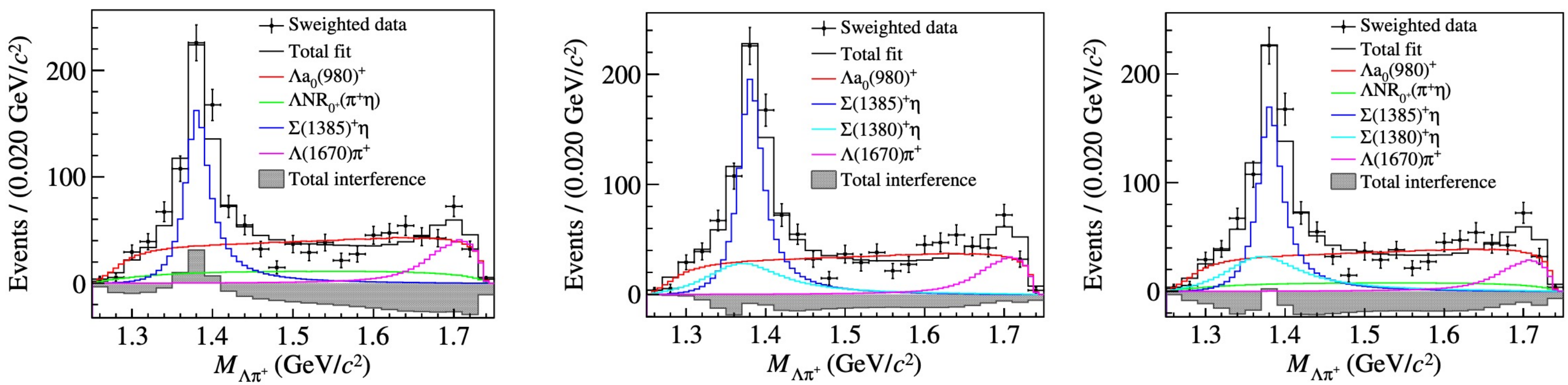
$$\alpha_{\Sigma(1385)^+\eta} = \frac{\left|H^{\Lambda_c^+\to\Sigma(1385)^+\eta}_{\frac{1}{2},0}\right|^2 - \left|H^{\Lambda_c^+\to\Sigma(1385)^+\eta}_{-\frac{1}{2},0}\right|^2}{\left|H^{\Lambda_c^+\to\Sigma(1385)^+\eta}_{\frac{1}{2},0}\right|^2 + \left|H^{\Lambda_c^+\to\Sigma(1385)^+\eta}_{-\frac{1}{2},0}\right|^2}$$

$$\alpha_{\Lambda(1670)\pi^+} = \frac{\left|H^{\Lambda_c^+\to\Lambda(1670)\pi^+}_{\frac{1}{2},0}\right|^2 - \left|H^{\Lambda_c^+\to\Lambda(1670)\pi^+}_{-\frac{1}{2},0}\right|^2}{\left|H^{\Lambda_c^+\to\Lambda(1670)\pi^+}_{\frac{1}{2},0}\right|^2 + \left|H^{\Lambda_c^+\to\Lambda(1670)\pi^+}_{-\frac{1}{2},0}\right|^2}$$

Test of $\Sigma(1380)^+$ in $\Lambda_c^+ \to \Lambda\pi^+\eta$

arXiv:2407.12270

Baseline model | Model A | Model B



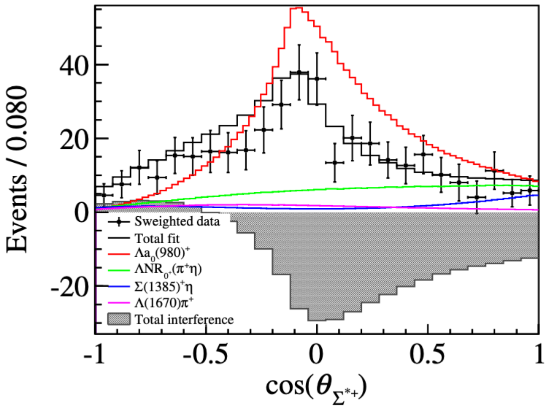
Process	Model A	Model B
$\Lambda a_0(980)^+$	$52.9 \pm 4.5\,(13.4\sigma)$	$50.6 \pm 8.0\,(11.1\sigma)$
$\Sigma(1385)^+\eta$	$36.6 \pm 2.6\,(15.8\sigma)$	$31.3 \pm 3.0\,(14.6\sigma)$
$\Lambda(1670)\pi^+$	$10.7 \pm 1.4\,(15.0\sigma)$	$9.0 \pm 1.6\,(11.9\sigma)$
$\Sigma(1380)^+\eta$	$15.5 \pm 4.4\,(6.1\sigma)$	$17.7 \pm 5.7\,(3.3\sigma)$
ΛNR_{0+}	...	$11.3 \pm 4.4\,(4.2\sigma)$

- An evidence of $\Sigma(1380)^+$ is found with significance larger than 3σ

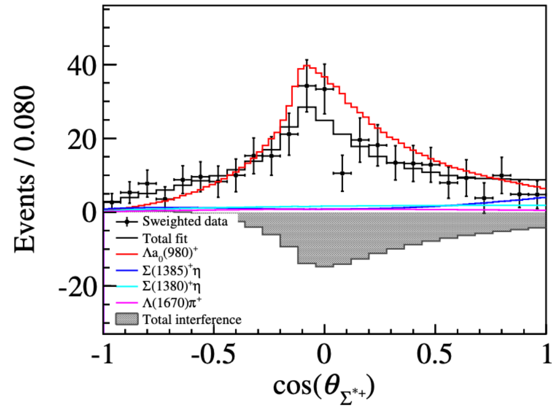
Comparison of Σ^{*+} helicity angles

arXiv:2407.12270

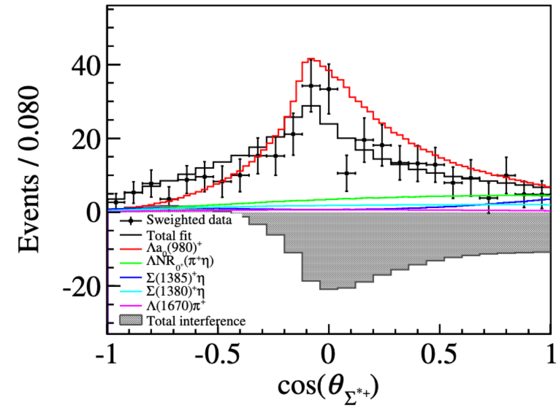
Baseline model



Model A



Model B

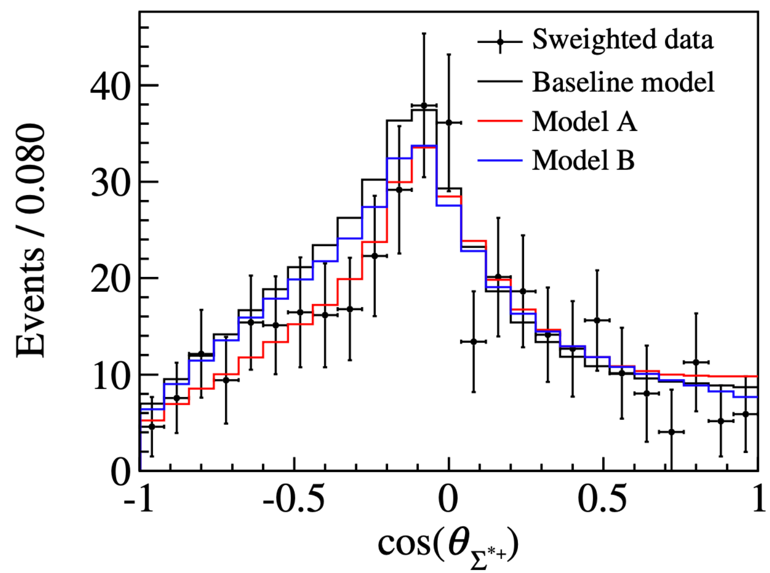


Kinematic region:

$M_{\Lambda\pi^+} > 1.44\ \mathrm{GeV/c^2}$

$M_{\Lambda\eta} > 1.72\ \mathrm{GeV/c^2}$

Better description of Σ^{*+} helicity angle distribution with inclusion of $\Sigma(1380)$



Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\eta$

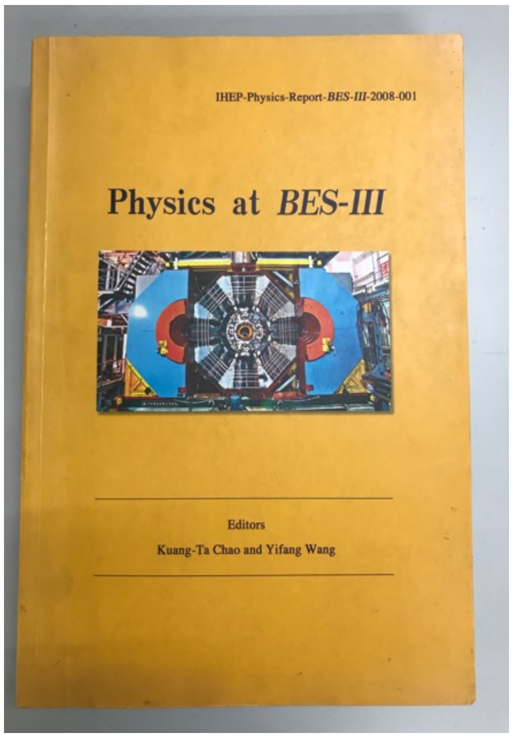
arXiv:2407.12270
accepted by PRL

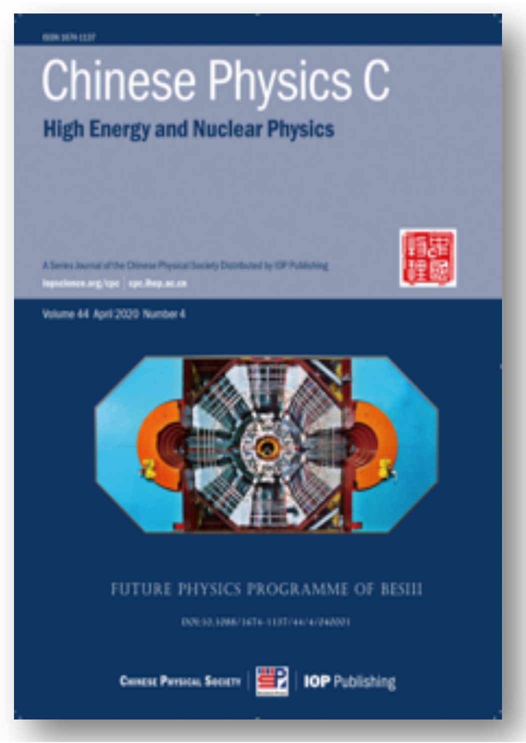
	This work	BESIII previous	Belle
$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\eta)(\%)$	1.94 ± 0.13	1.84 ± 0.26	1.84 ± 0.13
$\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+) \cdot \mathcal{B}(a_0(980)^+ \to \pi^+\eta)(\%)$	1.05 ± 0.18	—	—
$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\eta)(\times 10^{-3})$	6.78 ± 0.76	9.1 ± 2.0	12.1 ± 1.5
$\mathcal{B}(\Lambda_c^+ \to \Lambda(1670)^0\pi^+) \cdot \mathcal{B}(\Lambda(1670)^0 \to \Lambda\eta)(\times 10^{-3})$	2.74 ± 0.62	—	3.48 ± 0.53
$\alpha_{\Lambda a_0(980)^+}$	$0.91^{+0.09}_{-0.18} \pm 0.08$	—	—
$\alpha_{\Sigma(1385)^+\eta}$	-0.61 ± 0.15	—	—
$\alpha_{\Lambda(1670)^0\pi^+}$	0.21 ± 0.43	—	—

Decay Mode	Ref. [19]	Ref. [20]	Ref. [21]	Ref. [14]
$\Lambda_c^+ \to \Sigma(1385)^+\eta\,(\times 10^{-3})$	10.4	$2.1 \pm 1.1/1.4 \pm 1.0$	$6.2 \pm 0.5\,(3.1 \pm 0.6)$	$5.3 \pm 0.8\,(7.3 \pm 1.5)$
Decay Mode	Ref. [26]		Ref. [27]	
$\Lambda_c^+ \to \Lambda a_0(980)^+$	1.9×10^{-4}		$(1.7^{+2.8}_{-1.0} \pm 0.3) \times 10^{-3}$	

- If taking $\mathcal{B}(a_0(980)^+ \to \pi^+\eta) = (85.3 \pm 1.4)\%$, $\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+) = (1.23 \pm 0.21)\%$, which differs significantly larger than theoretical prediction by 1-2 orders of magnitude.
- Large decay asymmetry in $\Lambda_c^+ \to \Lambda a_0(980)^+$

BESIII Physics White Paper





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

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

Planned future data set

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

18 fb^{-1}
Λ_c^+ data

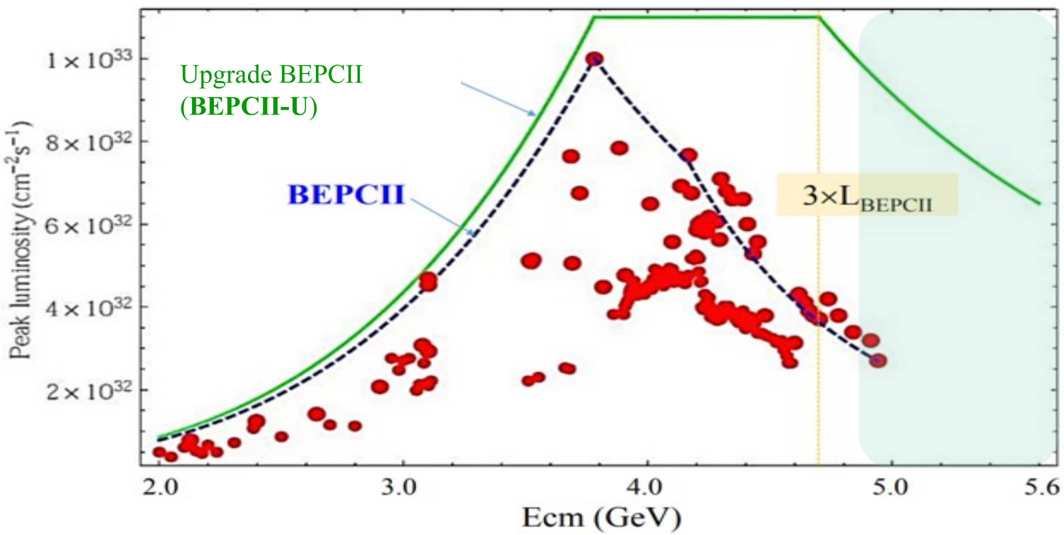
in 2020-2021, 5.8 fb^{-1} is taken

[Chin. Phys. C 46, 113003 (2022)]

Proposal of the upgrade BEPCII

An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021 and planned to be completed by the end of 2024

- ✓ **Improve luminosity by 3 times higher than current BEPCII at 4.7 GeV**
- ✓ **Extend the maximum energy to 5.6 GeV**

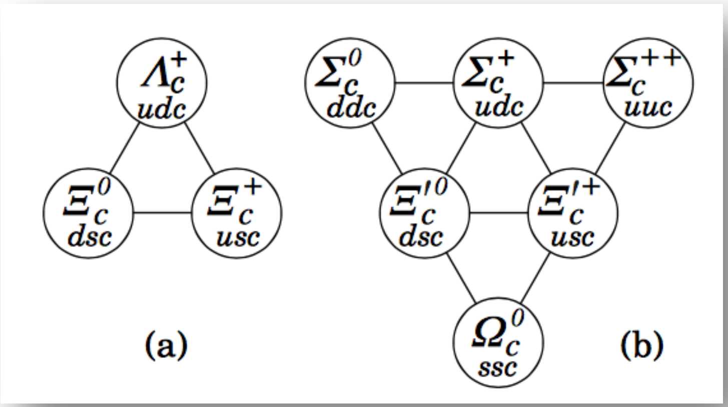


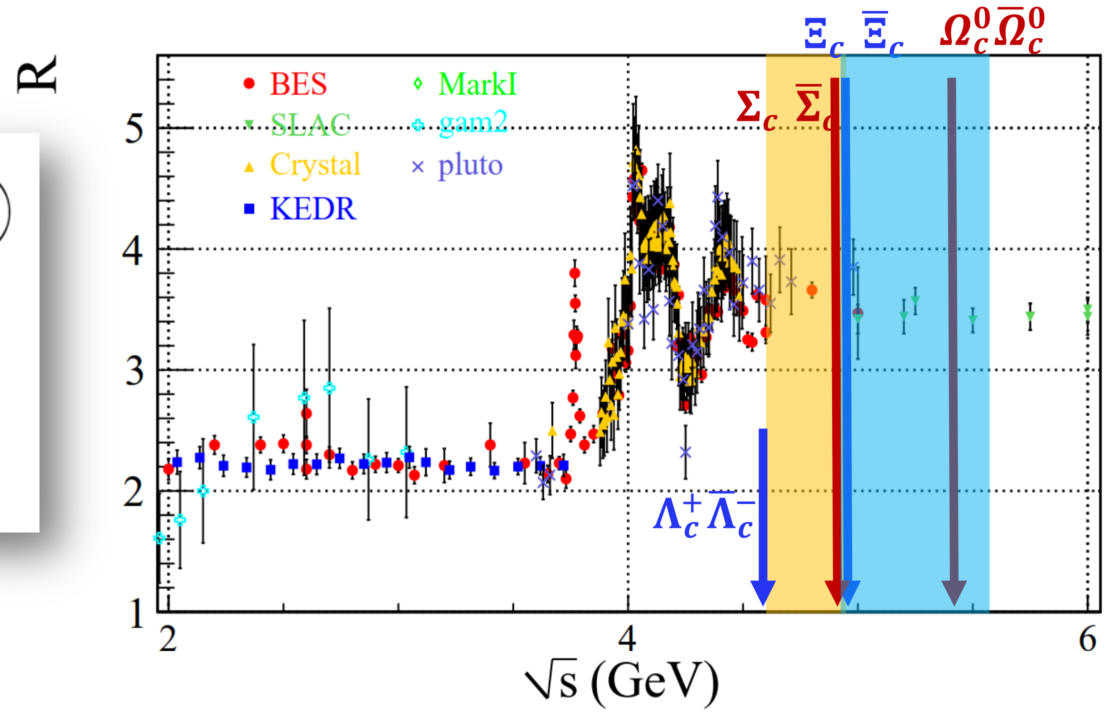
Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

1490 ➔ 600 days

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Heavier charmed baryons





- Energy thresholds
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\,\pi$ 4.88 GeV
  - ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
  - ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.94 GeV
  - ✓ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$ 5.40 GeV

- Cover all the ground-state charmed baryons: studies on their production & decays, CPV search, to help developing more reliable QCD-derived models in charm sector
- Studies on the production and decays of excited charmed baryons

Yet-to-be-Explored $\Xi_c^{+,0}$/ Ω_c^0 Decays

- We (will) have precise Λ_c^+ data after BESIII efforts
- However, $\Xi_c^{+,0}$/ Ω_c^0 has insufficient data
- A new territory for BESIII!

	Mode		Fraction (Γ_i/Γ)
	Cabibbo-favored ($S=-2$) decays		
Γ_1	$p2K_S^0$		$(2.5\pm1.3)\times10^{-3}$
Γ_2	$\Lambda\overline{K}^0\pi^+$		
Γ_3	$\Sigma(1385)^+\overline{K}^0$	[1]	$(2.9\pm2.0)\%$
Γ_4	$\Lambda K^-2\pi^+$		$(9\pm4)\times10^{-3}$
Γ_5	$\Lambda\overline{K}^*(892)^0\pi^+$	[1]	$<5\times10^{-3}$
Γ_6	$\Sigma(1385)^+K^-\pi^+$	[1]	$<6\times10^{-3}$
Γ_7	$\Sigma^+K^-\pi^+$		$(2.7\pm1.2)\%$
Γ_8	$\Sigma^+\overline{K}^*(892)^0$	[1]	$(2.3\pm1.1)\%$
Γ_9	$\Sigma^0K^-2\pi^+$		$(8\pm5)\times10^{-3}$
Γ_{10}	$\Xi^0\pi^+$		$(1.6\pm0.8)\%$
Γ_{11}	$\Xi^-2\pi^+$		$(2.9\pm1.3)\%$
Γ_{12}	$\Xi(1530)^0\pi^+$	[1]	$<2.9\times10^{-3}$
Γ_{13}	$\Xi(1620)^0\pi^+$		seen
Γ_{14}	$\Xi(1690)^0\pi^+$		seen
Γ_{15}	$\Xi^0\pi^+\pi^0$		$(6.7\pm3.5)\%$
Γ_{16}	$\Xi^0\pi^-2\pi^+$		$(5.0\pm2.6)\%$
Γ_{17}	$\Xi^0e^+\nu_e$		$(7\pm4)\%$
Γ_{18}	$\Omega^-K^+\pi^+$		$(2.0\pm1.5)\times10^{-3}$

Ξ_c^+ PDG2023

	Mode	Fraction (Γ_i/Γ)
	Cabibbo-favored ($S=-3$) decays — relative to $\Omega^-\pi^+$	
Γ_6	$\Xi^0\overline{K}^0$	1.64 ± 0.29
Γ_7	$\Xi^0K^-\pi^+$	1.20 ± 0.18
Γ_8	$\Xi^0\overline{K}^{*0}$, $\overline{K}^{*0}\to K^-\pi^+$	0.68 ± 0.16
Γ_9	$\Omega(2012)^-\pi^+$, $\Omega(2012)^-\to\Xi^0K^-$	0.12 ± 0.05
Γ_{10}	$\Xi^-\overline{K}^0\pi^+$	2.12 ± 0.28
Γ_{11}	$\Omega(2012)^-\pi^+$, $\Omega(2012)^-\to\Xi^-\overline{K}^0$	0.12 ± 0.06
Γ_{12}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{13}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0}\to\Xi^-\pi^+$	0.21 ± 0.06
Γ_{14}	$\Xi^-\overline{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{15}	$pK^-K^-\pi^+$	seen
Γ_{16}	$\Sigma^+K^-K^-\pi^+$	<0.32
Γ_{17}	$\Lambda\overline{K}^0\overline{K}^0$	1.72 ± 0.35

Ω_c^0 PDG2023

Summary

- In recent years, experimental activities on charmed baryons are reviving, esp. at BESIII, LHCb and Belle (II)
- Threshold data at BESIII opens a new door to direct measurements of the decays → comprehensive and systematic studies of charmed baryon decays
  - ✓ BESIII has published several world-leading results based on ~80 M Λ_c^+ samples
  - ✓ More efforts on hadronic decays with $n/\Sigma/\Xi$ particles & semi-leptonic decays
  - ✓ Plan to take data up to 5.6 GeV to cover all the ground-state charmed baryons
- The advanced machine-learning technique and PWA analysis becomes very competitive and powerful to achieve precise measurement
- The coming BEPCII-U will be essential for future BESIII program in charmed baryon decays