Beijing Spectrometer(BESIII) Experiment

Charmed baryon decays at BESIII

Wenhui Tian, Cong Geng

Sun Yat-sen University

Beijing Spectrometer (BESIII) Experiment

On behalf of the BESIII Collaboration

Jun, 12, 2025

Outline

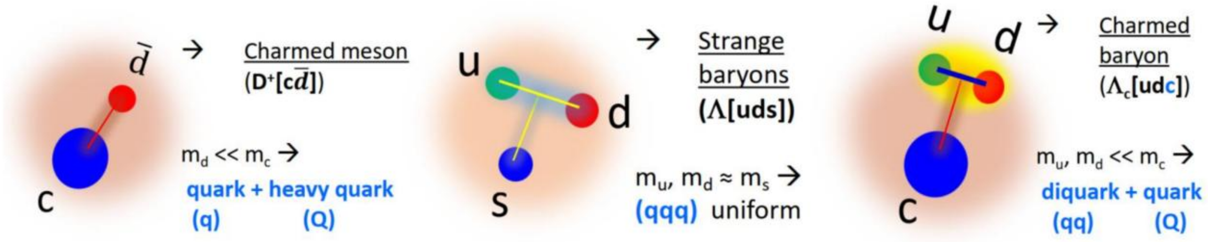
- Introduction
- BESIII experiment
- Λ_c^+ new results
  - Semi-leptonic decays
  - Hadronic decays
  - Excited charmed baryons
- Summary

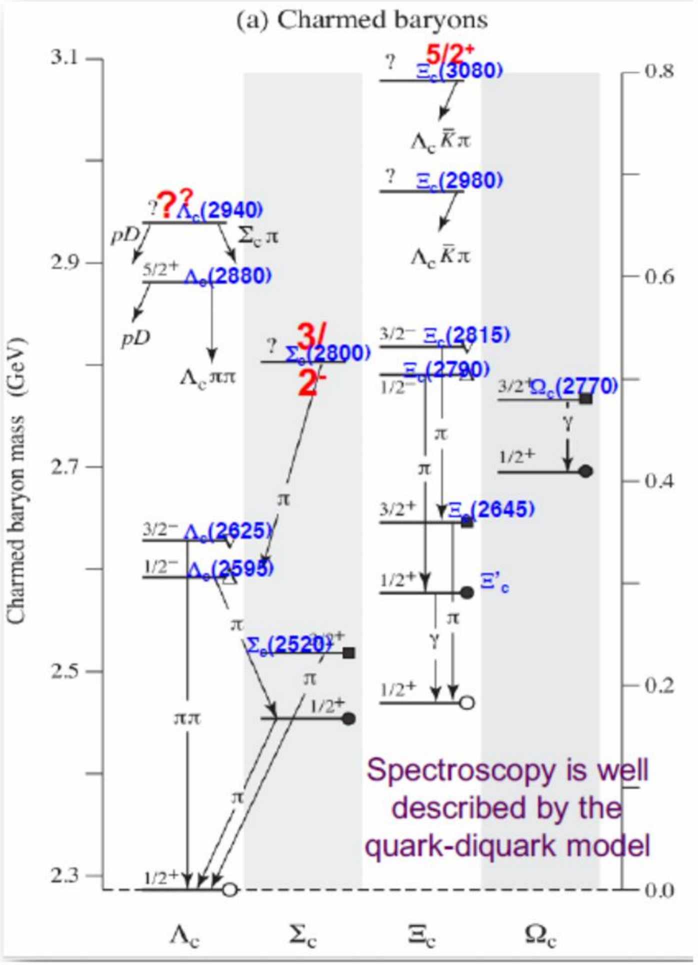
Introduction

- Most of the charmed baryons will eventually decay to Λ_c^+, which is the lowest lying state of charmed baryon;
- Important tagging for charmed baryons and Bottom baryons;
- The characteristics of Λ_c^+ are still not very clear;

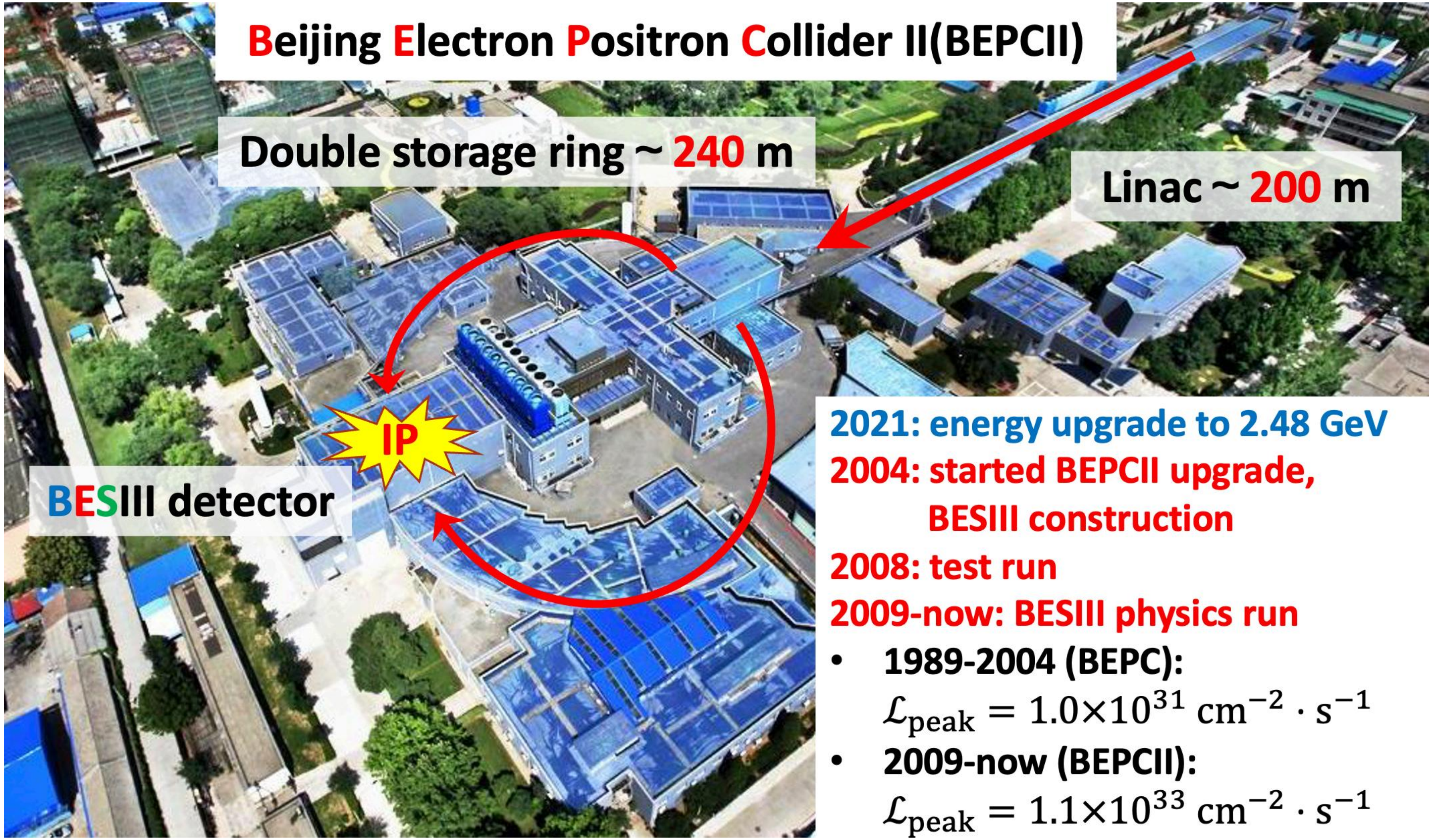
- Singly charmed baryons $\boldsymbol{\Lambda_c^+}$, Σ_c, Ξ_c, Ω_c have been established;
- Doubly charmed baryon Ξ_{cc}^{++} observed;
- Triply charmed baryon unobserved;

- Provides crucial information of strong and weak interactions in charm region, complementary to $D_{(s)}$





Beijing Electron Position Collider (BEPCII)



2021: energy upgrade to 2.48 GeV

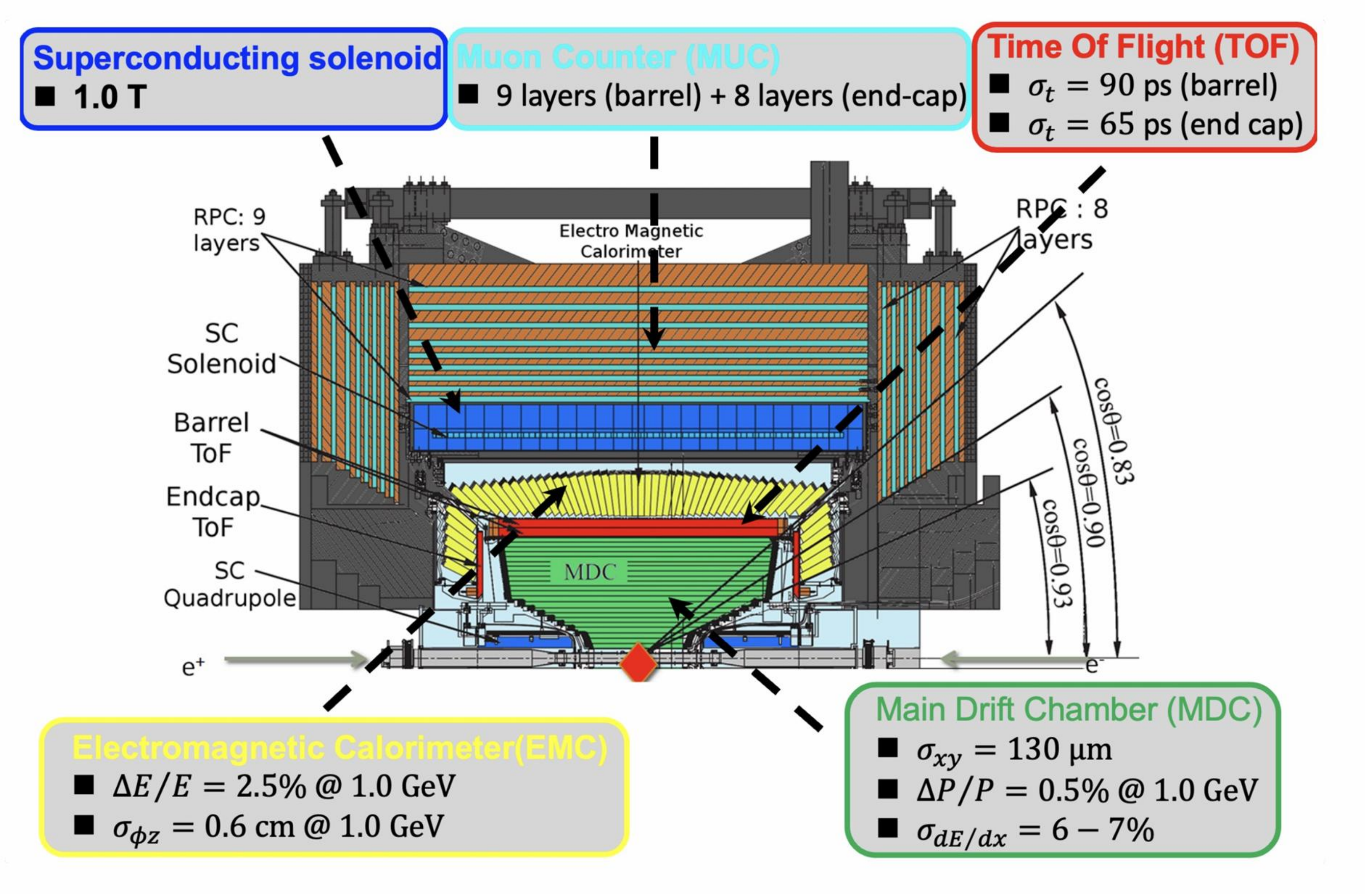
2004: started BEPCII upgrade, BESIII construction

2008: test run

2009-now: BESIII physics run

- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

BESIII detector



Data Samples

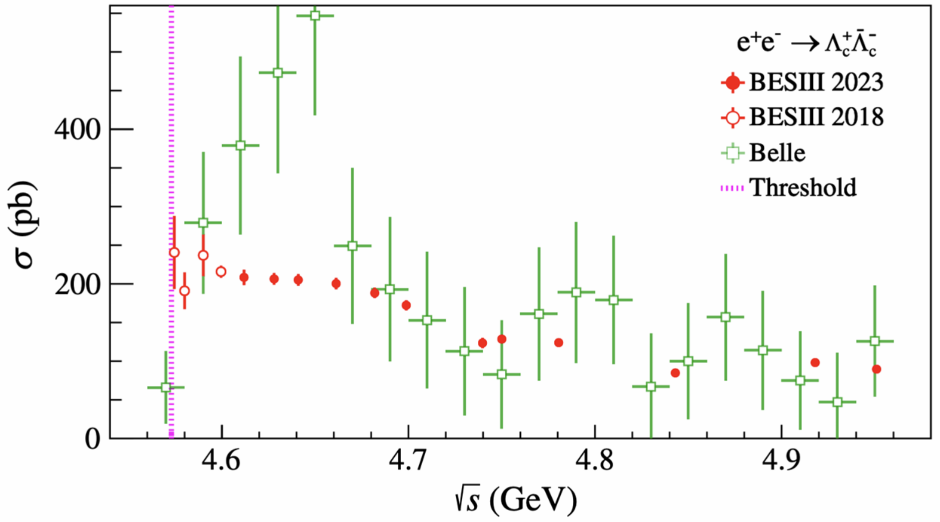
- Overall: about 50 fb^{-1}@ $\sqrt{s}=1.85\sim4.95$ GeV after 15 years of data taking
- Data for charmed baryon studies：
  - 0.567 fb^{-1} @ $\sqrt{s}=4.60$ GeV in 2014
  - 3.9 fb^{-1} $\sqrt{s}=4.61\sim4.70$ GeV scan data in 2020-2021
  - 1.9 fb^{-1} $\sqrt{s}=4.74\sim4.95$ GeV scan data in 2021-2022
  - **Totally ~6.4 fb^{-1} data from 13 energy points, ~1million events**

The largest dataset of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs in the world.

CPC **46**, 113003 (2022)

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

PRL **131**, 191901 (2023)



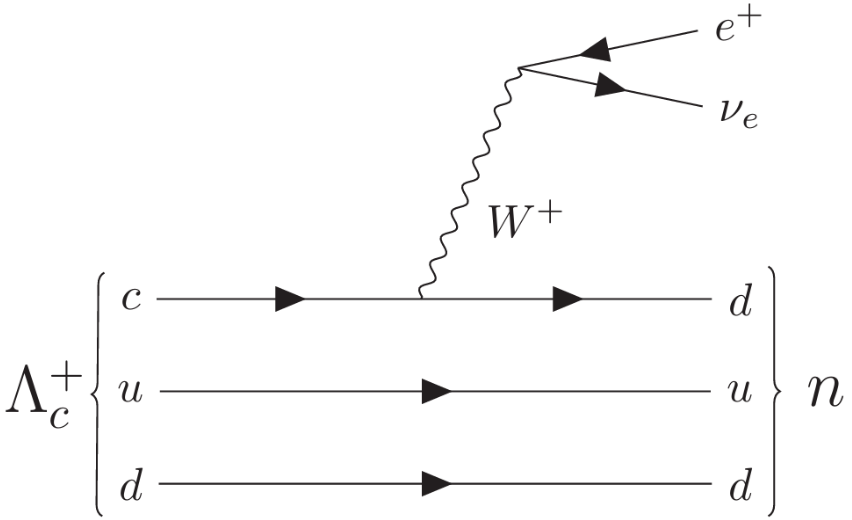
The Λ_c^+ Semi-leptonic decays

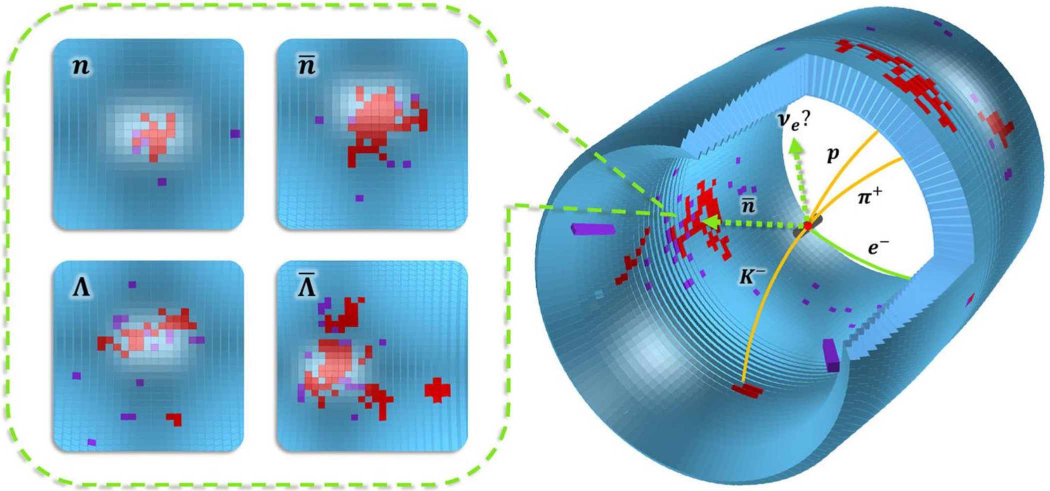
$$\Lambda_c^+ \to n e^+ \nu_e; \Lambda_c^+ \to X e^+ \nu_e; \overline{\Lambda}_c^- \to \overline{n} + X$$

$\Lambda_c^+ \to n e^+ \nu_e$

Nat. Comm. 16, 681 (2025)

- Λ_c^+ CS(Cabibbo-suppressed)) transition $c \to d\ l^+\nu$ beta decay never been observed;
- Significant challenges: two missing particles, neutron and neutrino;
- Dominant background: $\Lambda_c^+ \to \Lambda e^+ \nu_e$ $(\Lambda \to n\pi^0)$;

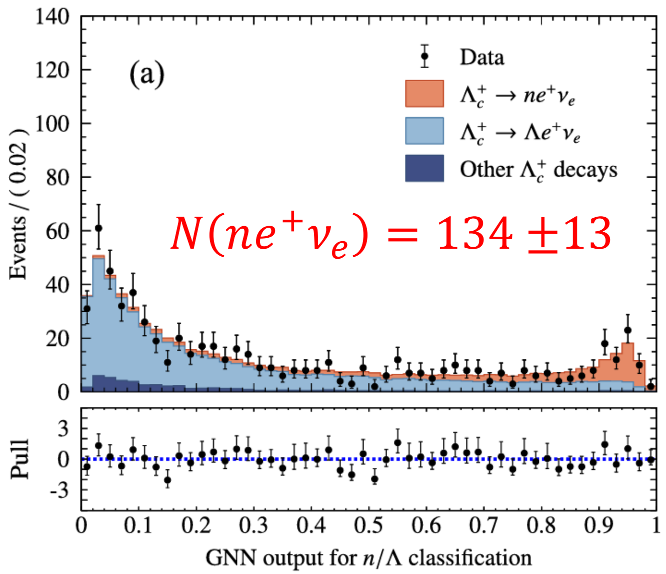


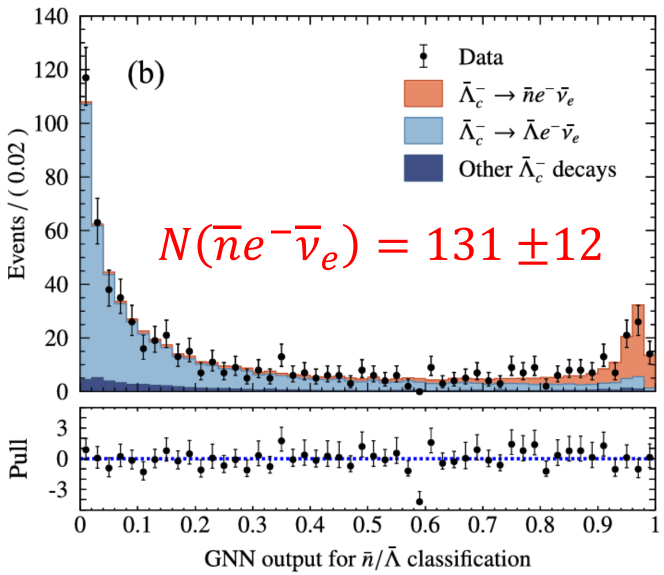


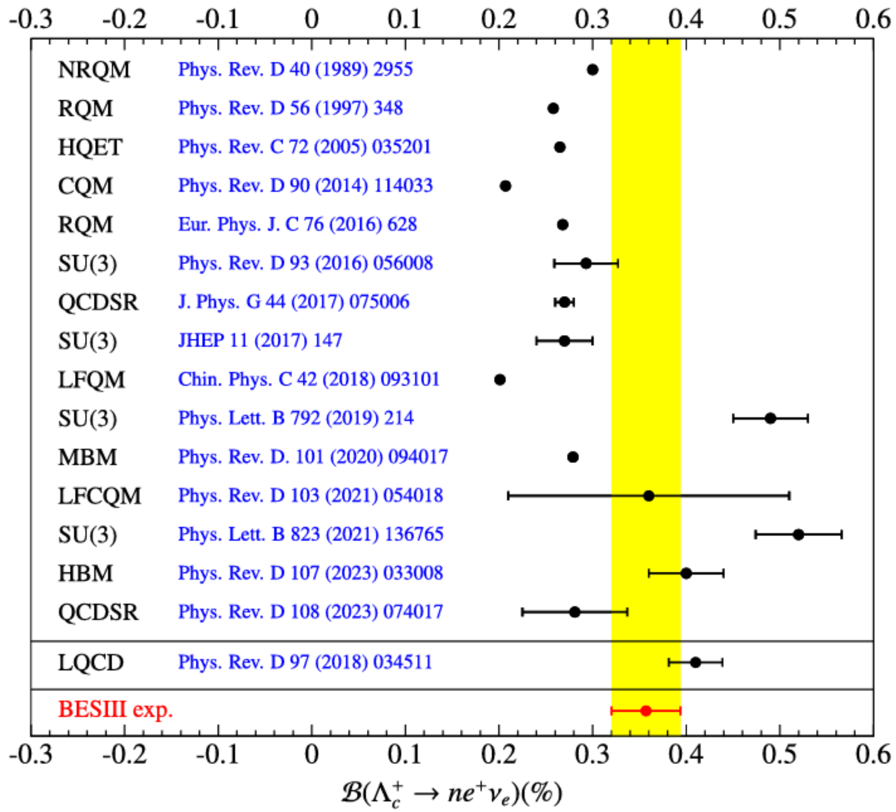
- A novel deep learning method of graph neural network(GNN) ⇒ distinguish the energy deposition patterns of neutrons from those of Λ in the Electromagnetic Calorimeter(EMC) of BESIII detector;

$\Lambda_c^+ \to ne^+\nu_e$

Nat. Comm. 16, 681 (2025)







Statistical significance of $\Lambda_c^+ \to ne^+\nu_e$ $> 10\sigma$!

- First observation of Cabibbo-suppressed in semi-leptonic decays!

$$\mathbf{BR}(\Lambda_c^+ \to ne^+\nu_e) = (0.357 \pm 0.034_{\text{stat.}} \pm 0.014_{\text{syst.}})\%$$

- First determination of $|V_{cd}|$ from charmed baryon decays !

$$|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD}} \pm 0.001_{\tau_{\Lambda_c^+}}$$

$\Lambda_c^+ \to Xe^+\nu_e$

Phys. Rev. D 107, 052005 (2023)

- **BR($\Lambda_c^+ \to Xe^+\nu_e$) = $(4.06 \pm 0.10_{\text{stat.}} \pm 0.09_{\text{syst.}})\%$**
- Ratio of the inclusive semi-leptonic decay width for the Λ_c^+ and D:

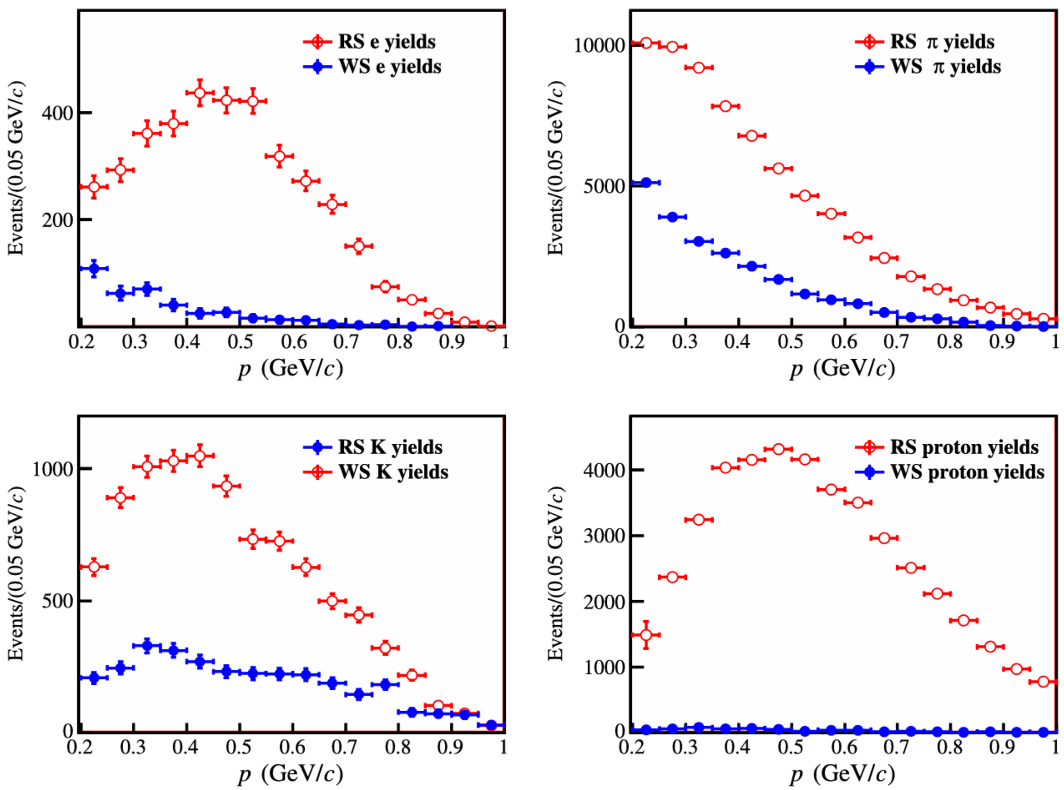
$$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\Gamma(D \to Xe^+\nu_e)} = \boxed{1.28 \pm 0.05}$$

Greatly improved accuracy !!!

- Use unfolding method to calibrate particle misidentification:

$$\begin{bmatrix} N_e^{\text{obs}} \\ N_\pi^{\text{obs}} \\ N_K^{\text{obs}} \\ N_p^{\text{obs}} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to p} & P_{K\to p} & P_{p\to p} \end{bmatrix} \begin{bmatrix} N_e^{\text{true}} \\ N_\pi^{\text{true}} \\ N_K^{\text{true}} \\ N_p^{\text{true}} \end{bmatrix}$$

RS: Right-sign WS: Wrong-sign



Constraint on unobserved Λ_c^+ semi-leptonic decays :

- Combine inclusive & exclusive measurements, assume all uncertainties are uncorrelated:

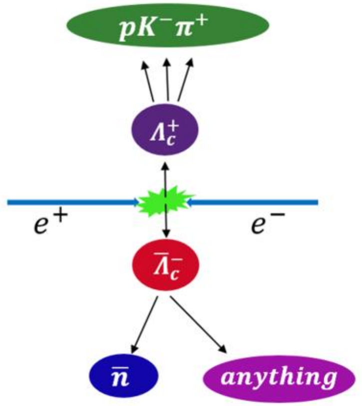
$$\text{BR}(\Lambda_c^+ \to Xe^+\nu_e)_{X\neq\Lambda,n,pk} = (0.55 \pm 1.53_{\text{stat.}} \pm 1.15_{\text{syst.}}) \times 10^{-3}$$

The majority of experimental gap has been filled.

$\overline{\Lambda}_c^- \rightarrow \overline{n} + X$

Phys. Rev. D 108, L031101 (2023)

- Measurement of inclusive neutron decays
  - pointing out the search direction of unknown channels
  - provide direct information about whether there exists a significant difference between $\Lambda_c^+ \rightarrow pX$ and $\Lambda_c^+ \rightarrow nX$

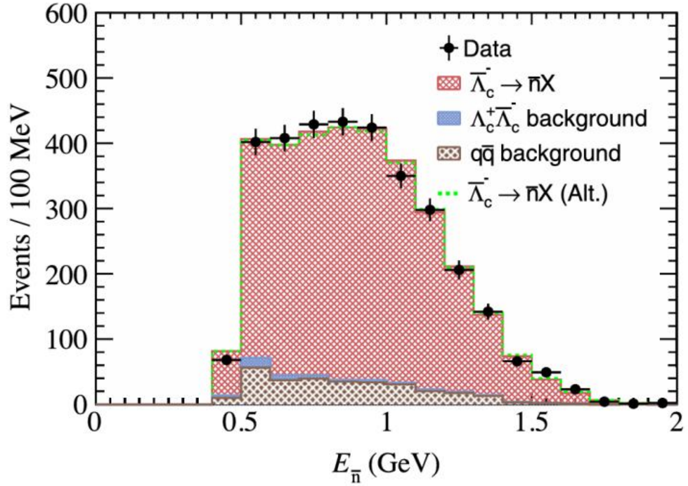


- Methods:
  - Use energy deposition on EMC as observable
  - Only study anti-neutron which can annihilate with material
  - Use data-driven method to model $\overline{n}$ behavior in the detector

- Results:

$$\mathrm{BR}\left(\overline{\Lambda}_c^- \rightarrow \overline{n} + X\right) = \left(32.4 \pm 0.7_{\mathrm{stat.}} \pm 1.5_{\mathrm{syst.}}\right)\%$$ **precision up to 5%**

- **About 25% of Λ_c^+ decays with a neutron are still unobserved**
- Indicate an asymmetry between $\Lambda_c^+ \rightarrow pX$ and $\Lambda_c^+ \rightarrow nX$



$\overline{n}$ deposited energy distribution is consistent between data and MC after using data-driven method

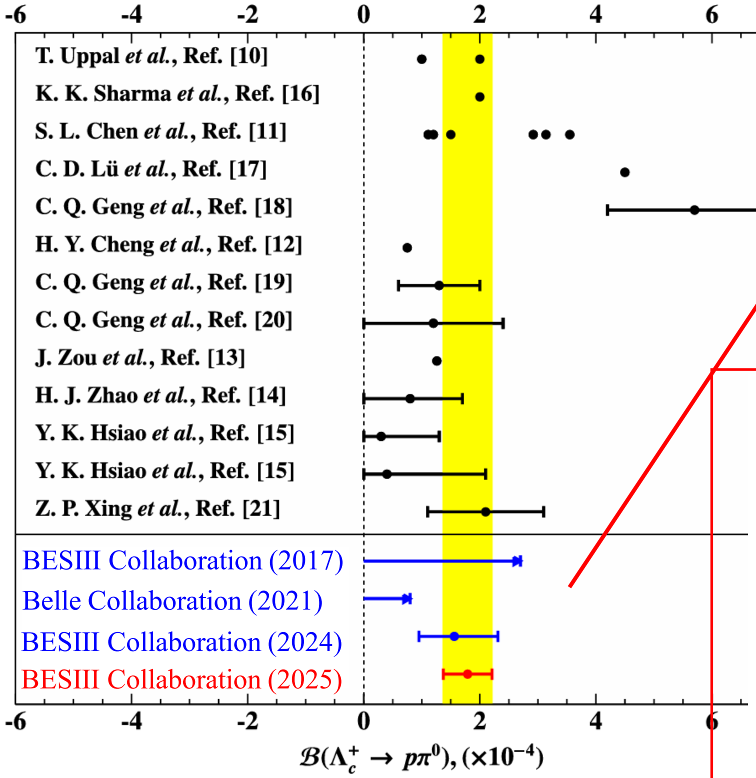
The Λ_c^+ hadronic decays

$\Lambda_c^+ \to p\pi^0$; $\Lambda_c^+ \to \Xi^0 K^+$; $\Lambda_c^+ \to \Lambda\pi^+\pi^0$; $\Lambda_c^+ \to \Lambda\pi^+\eta$;

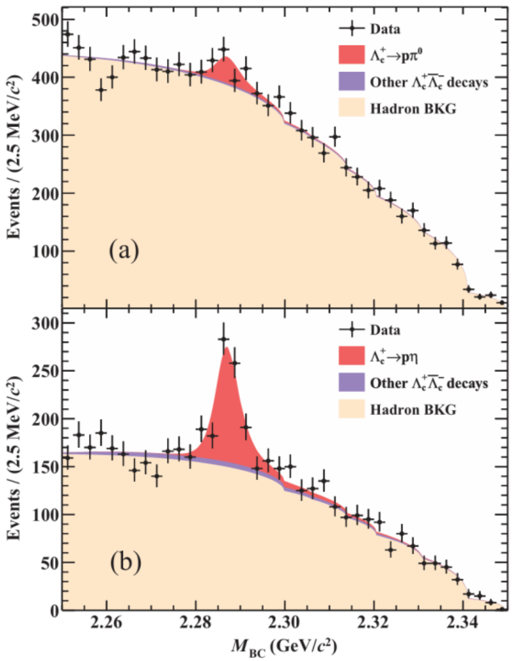
$\Lambda_c^+ \to pK_L^0$; $\Lambda_c^+ \to pK_L^0\pi^+\pi^-$ and $\Lambda_c^+ \to pK_L^0\pi^0$

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

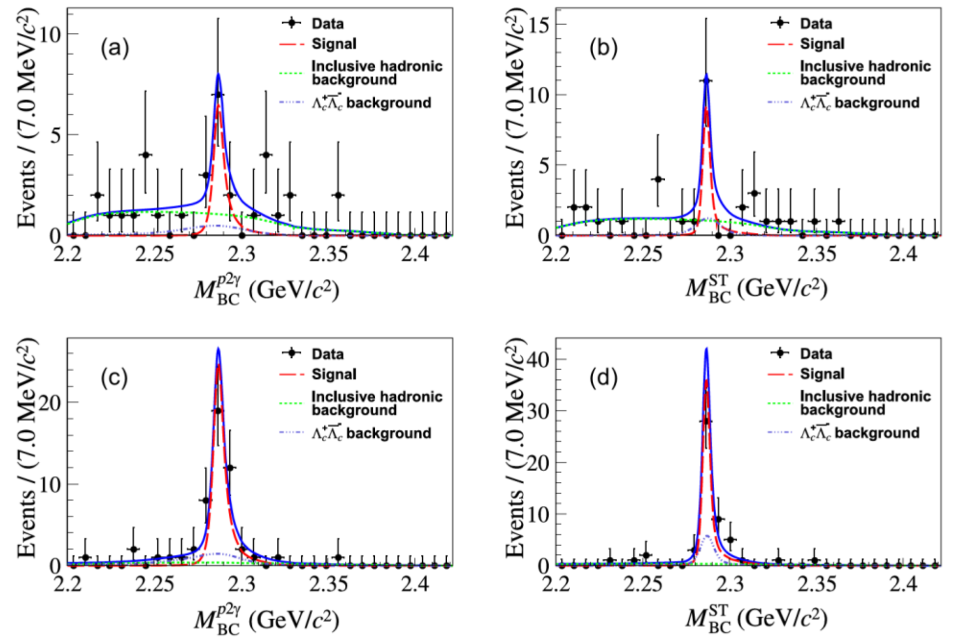
Phys. Rev. D 109, L091101 (2024)
Phys. Rev. D 111, L051101 (2025)



- Previous experimental constraints show inconsistency:
  - BESIII 2017 with ST: $B\left(\Lambda_c^+ \to p\pi^0\right) < 2.7 \times 10^{-4}$@90% C.L.
  - Belle 2021: $B\left(\Lambda_c^+ \to p\pi^0\right) < 0.8 \times 10^{-4}$ @90% C.L.
  - BESIII 2024 with DT: $B\left(\Lambda_c^+ \to p\pi^0\right) = (1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$ with 3.7σ
  - BESIII 2025 with ST: $B\left(\Lambda_c^+ \to p\pi^0\right) = (1.79 \pm 0.39 \pm 0.11 \pm 0.08) \times 10^{-4}$



BESIII 2025 with ST: high efficiency, high background

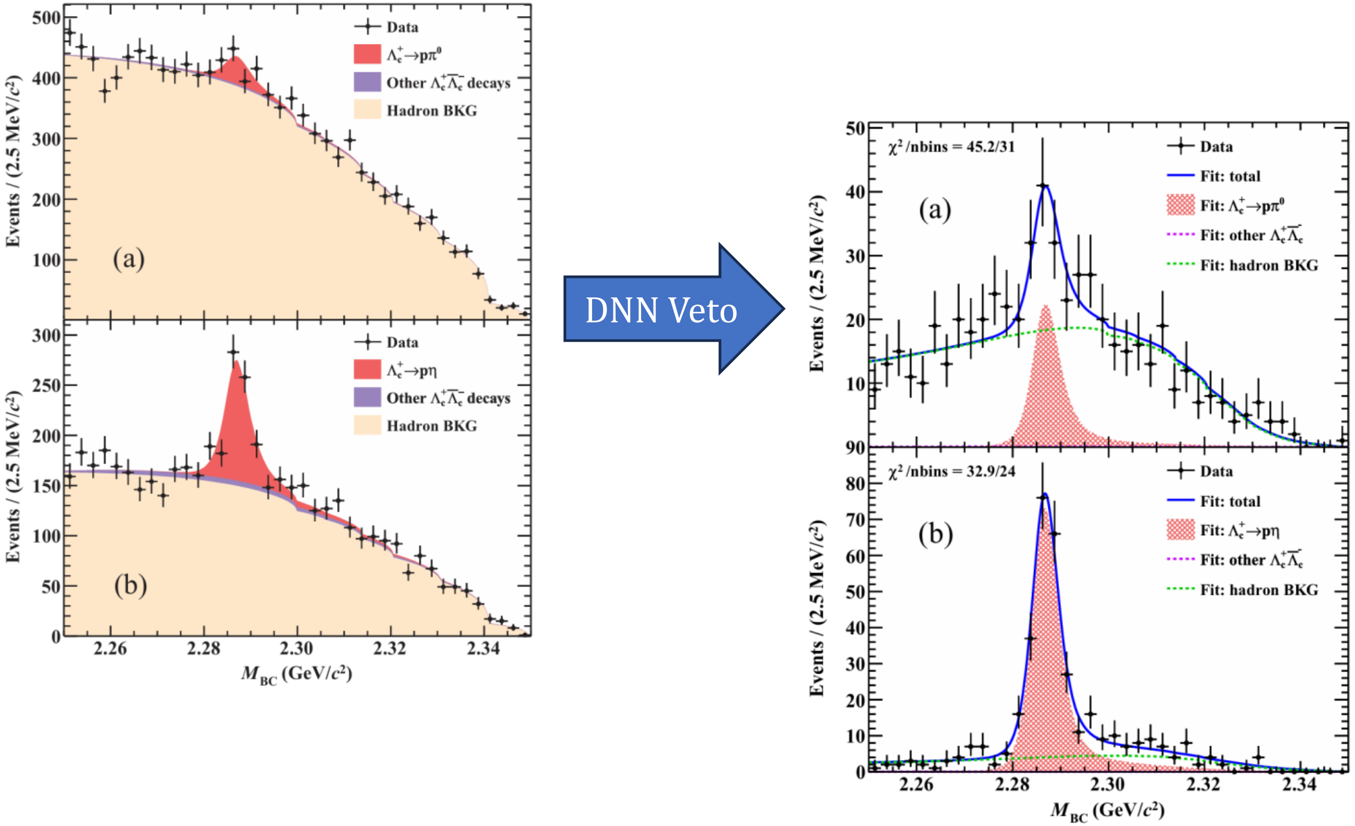


BESIII 2024 with DT: low efficiency, low background

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

Phys. Rev. D 111, L051101 (2025)

- A novel deep learning method is developed to suppress non- Λ_c^+ hadronic backgrounds efficiently .
  - Use Transformer-based deep neural network (DNN) to classify signal and background decay topologies.
  - $\Lambda_c^+ \to p\eta$ as reference channel.



- Results:
- $B\left(\Lambda_c^+ \to p\pi^0\right) =$
  $(1.79\pm0.39\pm0.11\pm0.08) \times 10^{-4}$
  consistent with previous BESIII evidence, yet exceeds the upper limit set by Belle
- $\frac{B\left(\Lambda_c^+\to p\pi^0\right)}{B\left(\Lambda_c^+\to p\eta\right)} = 0.120 \pm 0.026 \pm 0.007$ with 5.4σ

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

Phys. Rev. Lett. 132, 031801(2024)

- Pure W-exchange process
  - Only receives non-factorizable contribution
  - Large contribution in charmed baryon decays
  - Long-standing puzzle on how large the S-wave amplitude
- Based on multidimensional angular fit using helicity basis

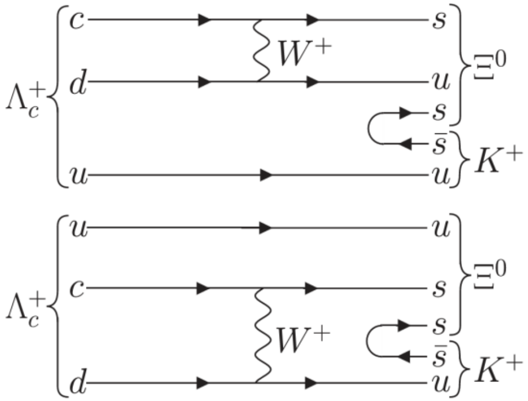


Fig. (1)

Lee-Yang parameters
[PRD 108, 1645 (1957)]

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

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

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

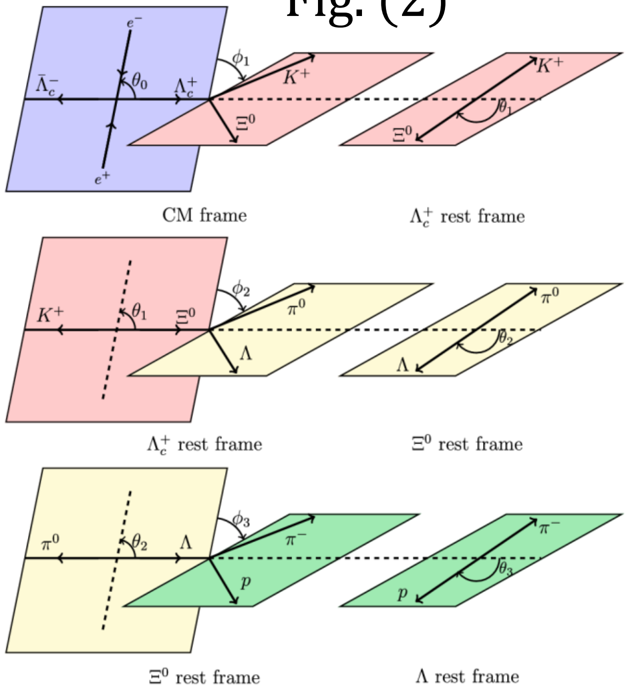
$$\gamma = \sqrt{1-\alpha^2}cos\Delta$$

Fig. (2)

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

$\Xi^0 \to \Lambda\pi^0$:

$\Lambda \to p\pi^-$:



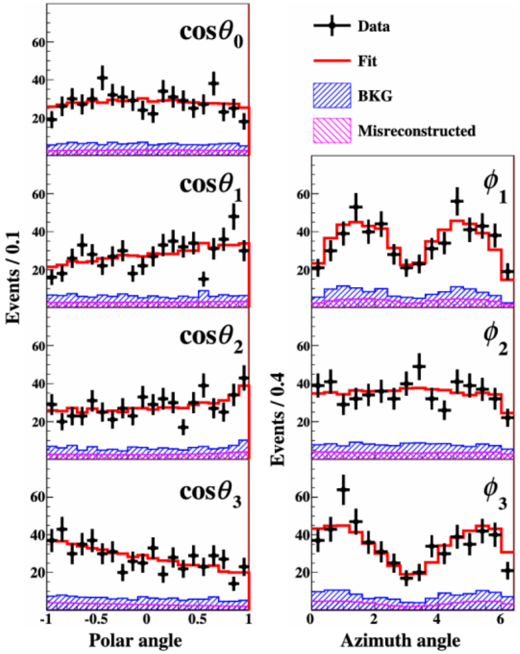
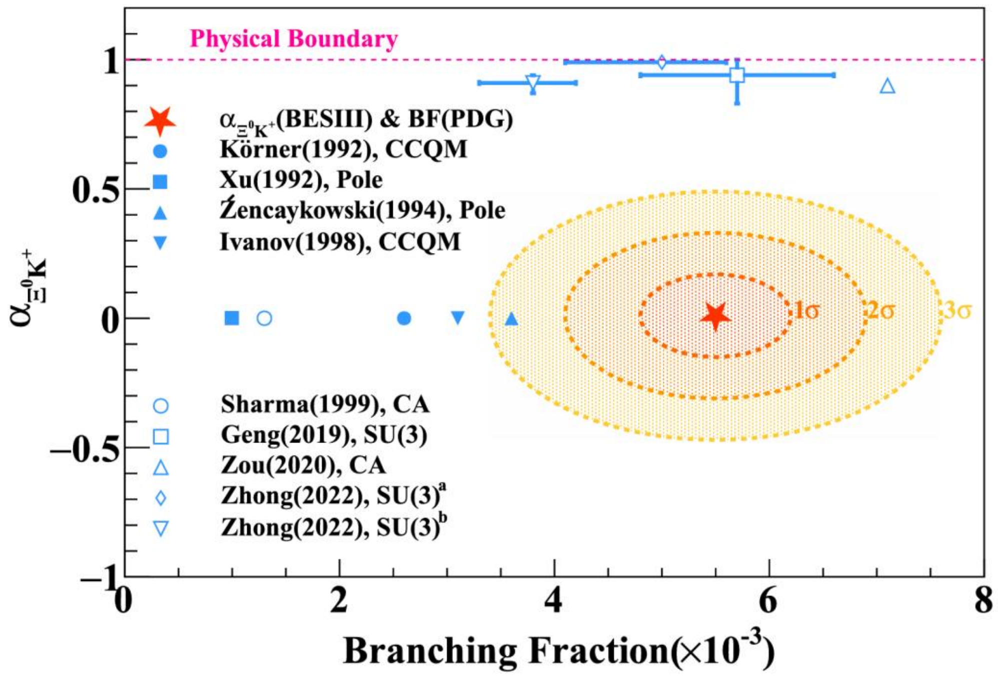


Fig. (3)

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

- Decay asymmetry results:
  - $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$
  - $\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90 \pm 0.17$ rad
  - $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69 \pm 0.13$
  - $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58 \pm 0.11$



- Phase difference between ***S*** and ***P***-waves
  - Solution1: $\delta_p - \delta_S = -1.55 \pm 0.25 \pm 0.05$ rad
  - Solution2: $\delta_p - \delta_S = 1.59 \pm 0.25 \pm 0.05$ rad

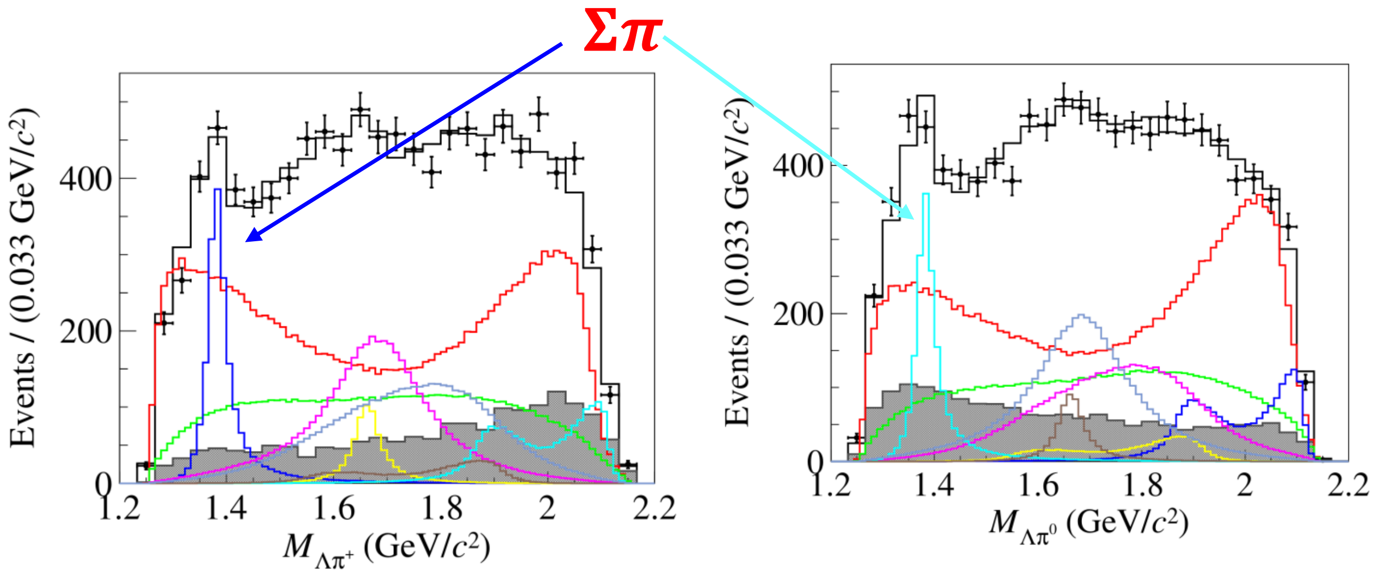
- Discussions
  - $\alpha_{\Xi^0 K^+}$ in good agreement with zero, providing strong identification for theoretical predictions
  - $\cos(\delta_p - \delta_S)$ close to zero, which is not considered in previous study
  - Fill the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$, and $B(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously

Phys. Rev. Lett. 132, 031801 (2024).

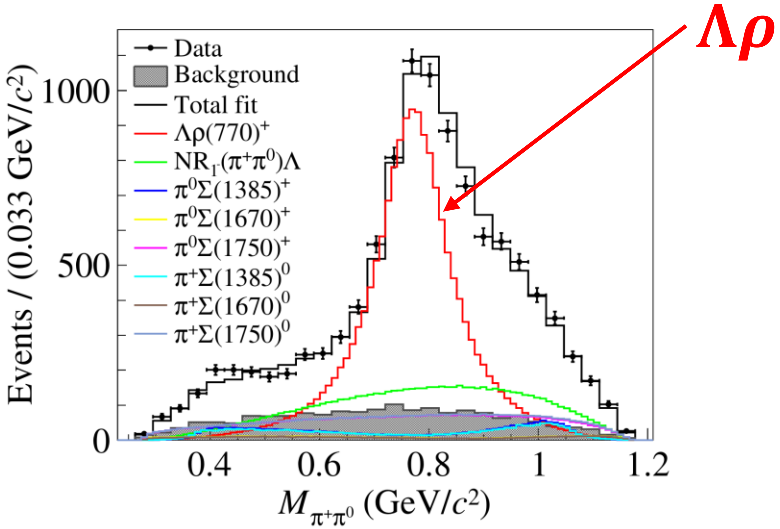
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12, 033 (2022)

- First Partial Wave Analysis(PWA) for charm baryon at BESIII:
  Use TF-PWA, based on helicity amplitude.
- BFs & decay asymmetries of $\Lambda_c^+ \to \Lambda\rho(770)^+$ and $\Lambda_c^+ \to \Sigma(1385)^{(+/0)}\pi^{(0/+)}$
- No theoretical prediction can well describe the BF and decay asymmetry simultaneously.



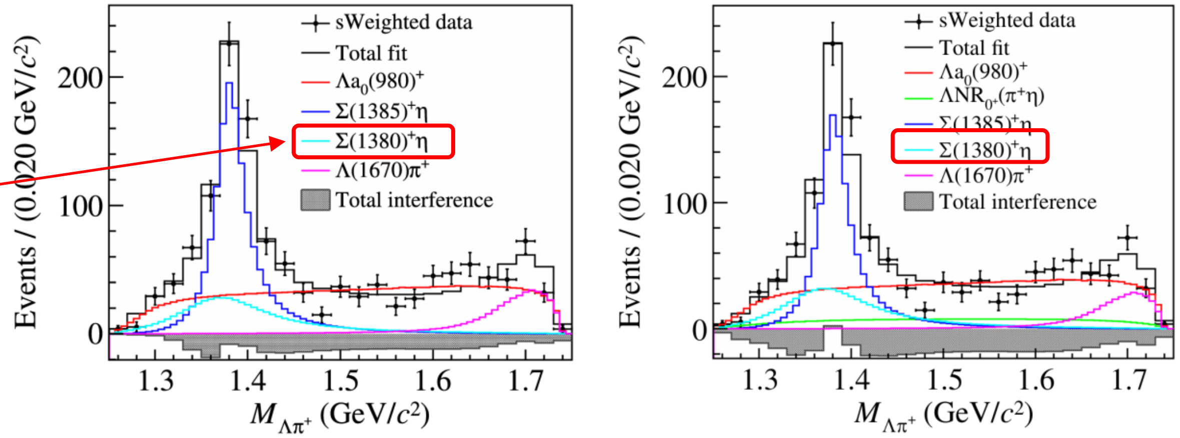
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	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	—



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

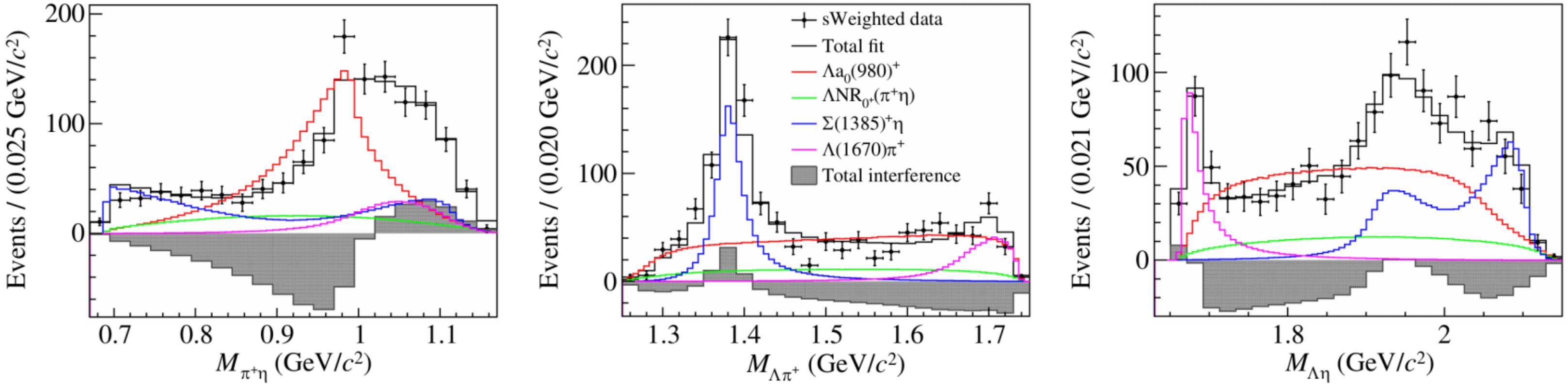
Phys. Rev. Lett. 134, 021901 (2025)

- **First observation of $\Lambda_c^+ \to \Lambda a_0(980)^+, a_0(980)^+ \to \pi^+\eta$**
  - $B(\Lambda_c^+ \to \Lambda a_0(980)^+) \times B(a_0(980)^+\pi^+\eta)$
    $= (1.05 \pm 0.16_{stat.} \pm 0.05_{syst.} \pm 0.07_{ext.})\%$ with 13.1σ
- **Evidence of potential pentaquark state $\Sigma(1380)^+ \to \Lambda\pi^+$**
  - Statistical significance 6.1σ (3.3σ) without (with) $\pi^+\eta$ non resonant contribution



Process	FF (%)	$\mathcal{S}$	α
$\Lambda a_0(980)^+$	$54.0 \pm 8.4 \pm 2.6$	13.1σ	$-0.91^{+0.18}_{-0.09} \pm 0.08$
$\Sigma(1385)^+\eta$	$30.4 \pm 2.6 \pm 0.7$	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	...

- $\alpha(\Lambda_c^+ \to \Sigma(1385)^+\eta)$ consistent with $-0.97^{+0.43}_{-0.03}$ in SU(3) [1]
- $\alpha(\Lambda_c^+ \to \Lambda a_0(980)^+)$ contradicts with the small value(~0) in Triangle re-scattering [2]



[1] SU(3) effective Hamiltonian: Phys. Rev. D.99 (2019) 114022
[2] Triangle re-scattering: J. Phys. G. 36.075005 (2009)

$\Lambda_c^+ \to pK_L^0$; $\Lambda_c^+ \to pK_L^0\pi^+\pi^-$ and $\Lambda_c^+ \to pK_L^0\pi^0$

JHEP 09 (2024) 007

- K_S-K_L asymmetry offer possibility to DCS(doubly Cabibbo-suppressed) decays:
  - Non-zero asymmetry value indicates existence of DCS decays;
  - Arises from interference of CF(Cabibbo-favored) and DCS, provide new way to indirect search for DCS;
  - The ratio of amplitudes for CF and DCS is expected to be proportional to $|V_{ud}^* V_{cs}/V_{us}^* V_{cd}|$

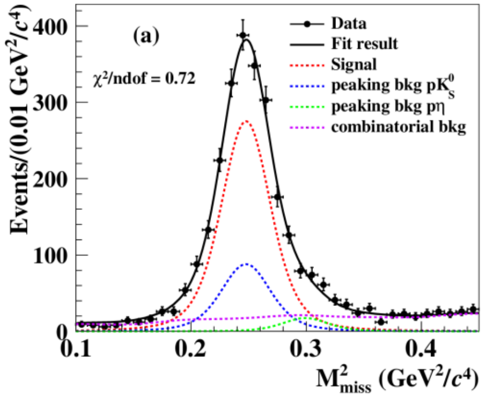
$$R(\Lambda_c^+, K_{S,L}^0 X) = \frac{B(\Lambda_c^+ \to K_S^0 X) - B(\Lambda_c^+ \to K_L^0 X)}{B(\Lambda_c^+ \to K_S^0 X) + B(\Lambda_c^+ \to K_L^0 X)}$$

(X is p, $p\pi^+\pi^-$ or $p\pi^0$)

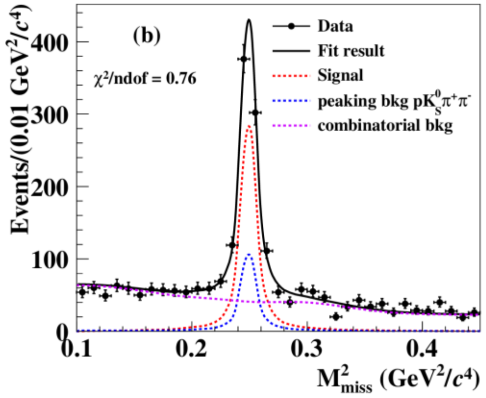
Mode	$\mathcal{B}(\Lambda_c^+ \to K_L^0 X)$ (%)	$\mathcal{B}(\Lambda_c^+ \to K_S^0 X)$ (%) [22]	$R(\Lambda_c^+, K_{L,S}^0 X)$
$\Lambda_c^+ \to pK_{L,S}^0$	$1.67 \pm 0.06 \pm 0.04$	1.59 ± 0.07	-0.025 ± 0.031
$\Lambda_c^+ \to pK_{L,S}^0\pi^+\pi^-$	$1.69 \pm 0.10 \pm 0.05$	1.60 ± 0.11	-0.027 ± 0.048
$\Lambda_c^+ \to pK_{L,S}^0\pi^0$	$2.02 \pm 0.13 \pm 0.05$	1.96 ± 0.12	-0.015 ± 0.046

- No obvious asymmetry is observed in any of the three decays
- $R(\Lambda_c^+, K_{S,L}^0 X)$ in $\Lambda_c^+ \to pK_{S,L}^0$ is compatible with SU(3) prediction of (-0.010,0.087)

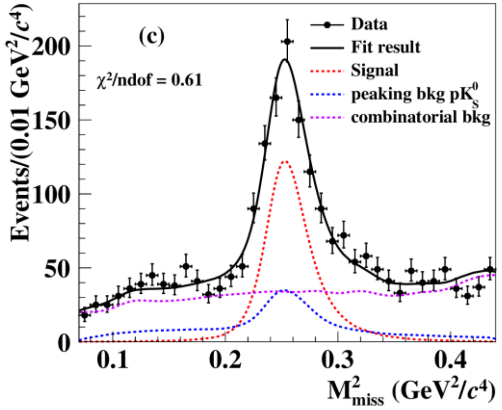
$\Lambda_c^+ \to pK_L^0$



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



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



Summary

- The world's largest threshold data make BESIII dominant Λ_c^+ measurements.
- Fruitful results have been published during recently 2022~2025
  - Semi-leptonic decays
  - Hadronic decays
  - Excited charmed baryons
- Utilizing advanced **deep learning methods**, we conducted precise measurements of $\boldsymbol{\Lambda_c^+ \to n e^+ \nu_e}$ and $\boldsymbol{\Lambda_c^+ \to p\pi^0}$ for the first time and obtained critical experimental results, which provide opportunity to many analyses of BESIII.
- Prospect:
  - 9 $\boldsymbol{fb^{-1}}$ more $\boldsymbol{\Lambda_c^+}$ data @ 4.68 GeV has been planned in 2025-2026
  - above 5 GeV data will start in 2028

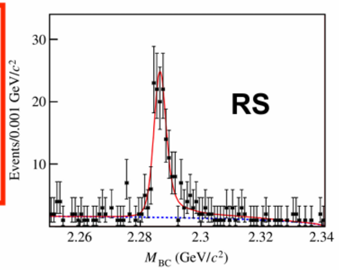
Thanks for your attention!

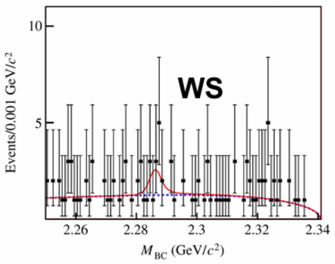
BACK UP

$\Lambda_c^+ \to Xe^+\nu_e$

WS technique is used to subtract charge symmetric backgrounds in each momentum bin, e.g., $\pi^0 \to \gamma e^+ e^-$

Momentum range: 500-550 MeV/c
Data collected at 4682 MeV

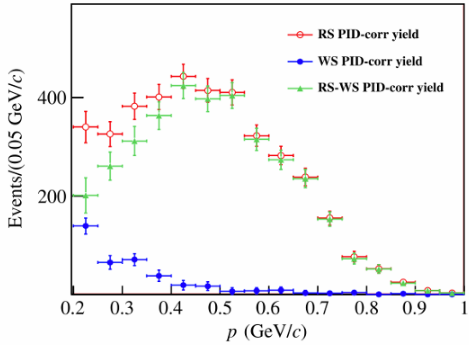




$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to \pi} & P_{\pi\to \pi} & P_{K\to \pi} & P_{p\to \pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to p} & P_{K\to p} & P_{p\to p} \end{bmatrix} \begin{bmatrix} N_e^{\rm true} \\ N_\pi^{\rm true} \\ N_K^{\rm true} \\ N_p^{\rm true} \end{bmatrix}$$

PID migration matrix

Contamination of other particle types (p, π^+, K^+)



Reconstruct RS and WR sample In different momentum bin → PID unfolding → WS subtraction → Tracking efficiency unfolding → PHSP Extrapolation → BF determination

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

$$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)} = 1.28 \pm 0.05$$

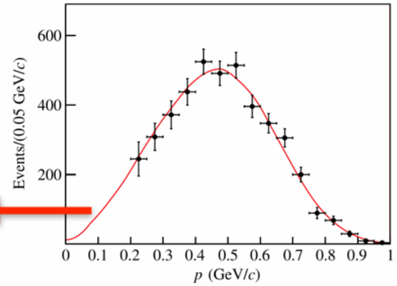
Compared with HQE(1.2), EQM(1.67)

$$N_{\rm e}^{\rm true}(i) = \sum_j A_{\rm TRK}(e|i,j) N_{\rm e}^{\rm prod}(j)$$

- Geometrical acceptance
- Track reconstruction efficiency
- Resolution smearing

Decay	$\mathcal{B}$ [%]	Model
$\Lambda_c^+ \to \Lambda e^+\nu_e$	$3.56 \pm 0.11 \pm 0.07$	References [6]
$\Lambda_c^+ \to pK^-(n\bar{K}^0)e^+\nu_e$	$0.088 \pm 0.017 \pm 0.007$	PHSP [7]
$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$	0.24	HQET [27,28]
$\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$	0.06	HQET [27,28]
$\Lambda_c^+ \to ne^+\nu_e$	0.20	Quark model [29]

Based on our knowledge of MC model



ST and DT

- ➢ Single-Tag method (ST)
  - ✓ High efficiency vs High background
- ➢ Double-Tag method (DT)
  - ✓ Low background vs low efficiency
  - ✓ Absolute BFs
  - ✓ Missing particles
- ➢ Deep learning method
  - ✓ Powerful vs validation
  - ✓ Event level topology
  - ✓ Two missing particles
  - ✓ …