Charmed baryon decays at BESIII

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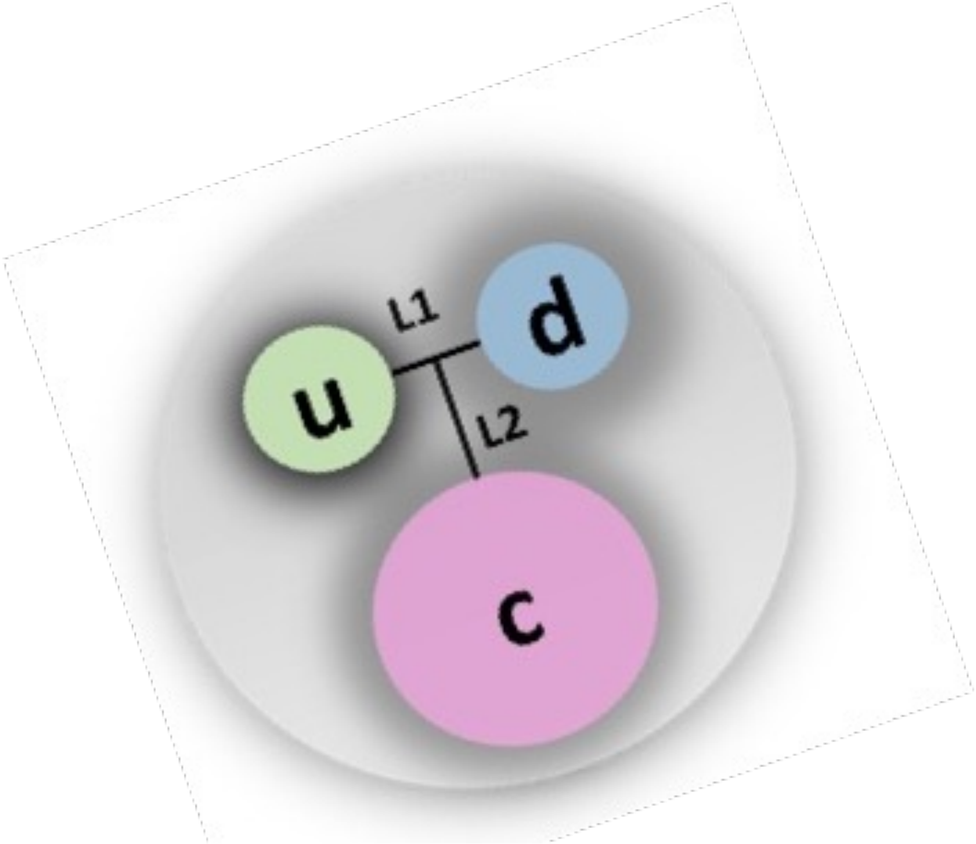
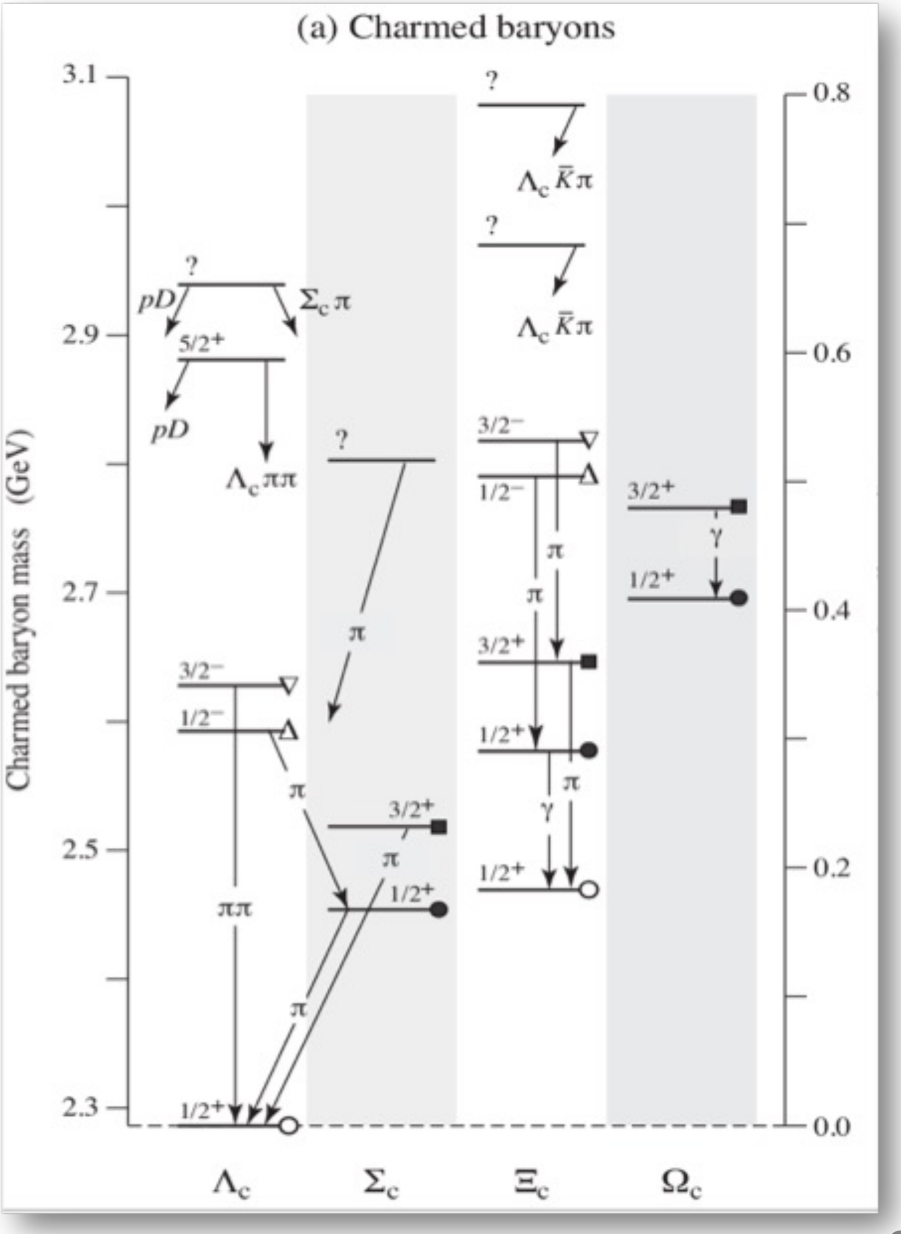
Outline

- ➢ The lightest charm baryon Λ_c^+
- ➢ Charm baryon physics at BESIII
  - Λ_c^+ semi-leptonic decays
  - Λ_c^+ hadronic decays
- ➢ Summary



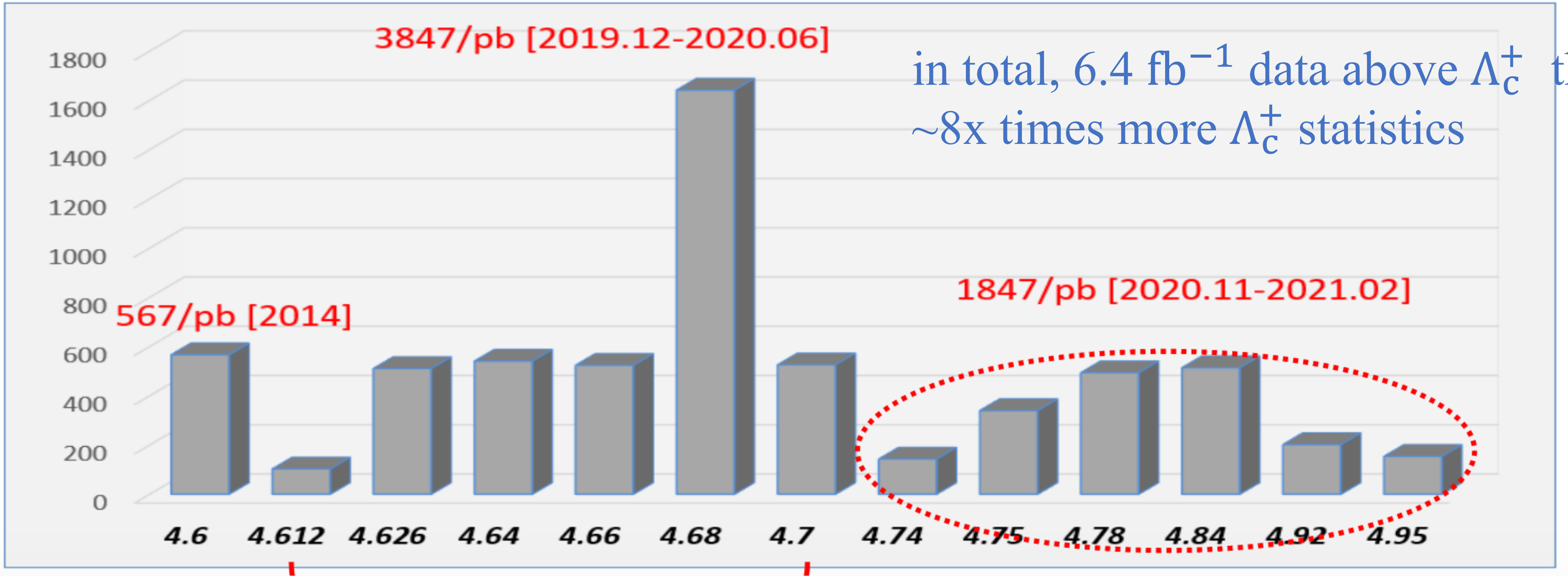
Λ_c^+: The lightest charmed baryon spectroscopy

- Naive 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 (HQET)
- Cornerstone of charmed baryons:
  - Most of the charmed baryons will eventually decay to Λ_c^+
- Important input to study the decays of b flavor hadron involving Λ_c^+ final state and V_{ub} calculations
- The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment
- Total measured BF (PDG2022) is ~70%
  - Poorly understood compared to charm mesons
- Excellent platform for understanding non-perturbative QCD and weak decay mechanism



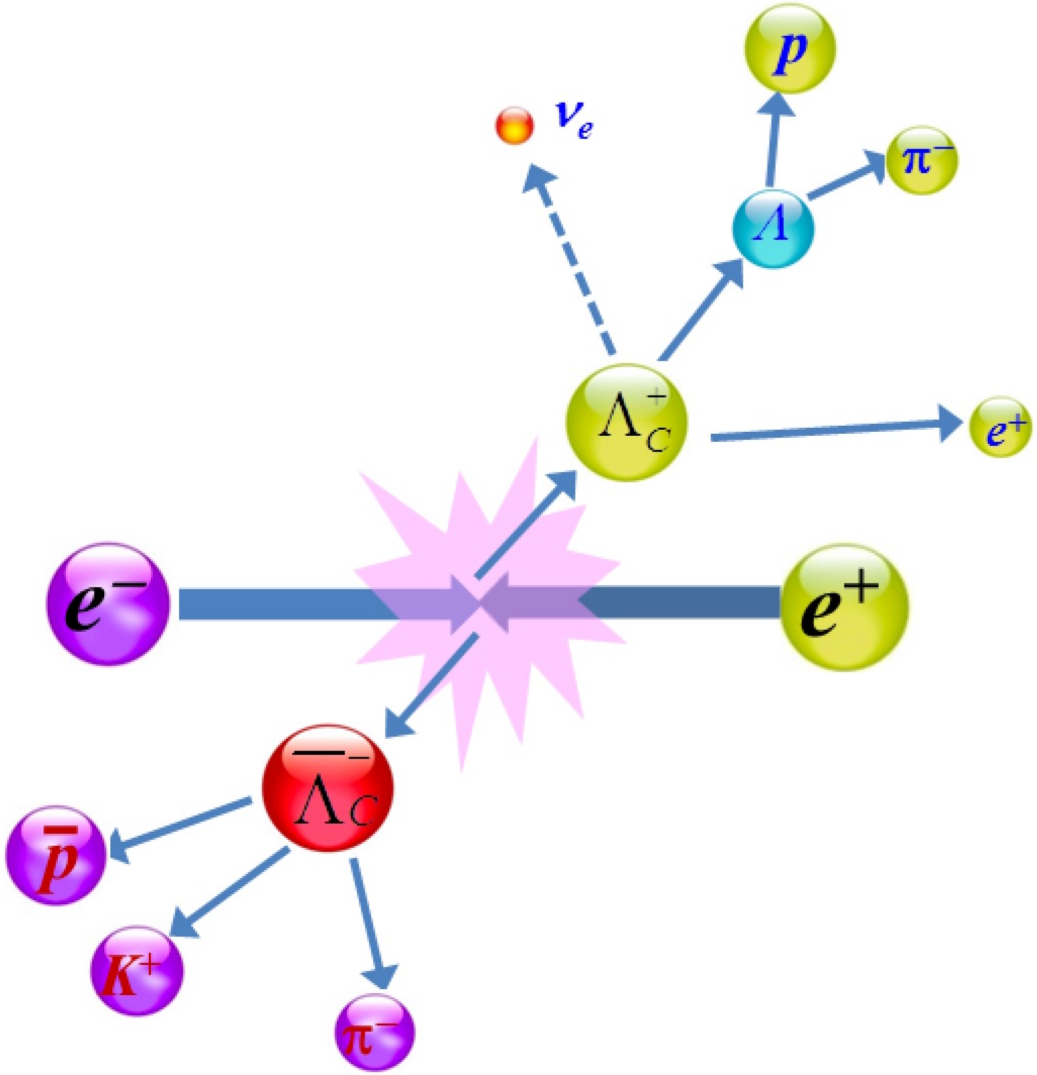
BESIII data taking at Λ_c^+ pair threshold

- Measurement using the threshold pair-productions via e^+e^- annihilations is unique: the most simple and straightforward
- Double-tag (DT) method can be used:
  - Lower backgrounds and kinematic relation to constrain missing particle
  - Most systematic uncertainties in tag side can be cancelled



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

Production near threshold and tag technique



- Single Tag (ST)

$$\Delta E = E_{\Lambda_c^+} - E_{beam}$$

$$M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_{\Lambda_c^+}|^2}$$

- Double Tags (DT)

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

- Branching Fraction ($\mathcal{B}$)

$$N^{ST} = 2N_{\text{tot}}B_{tag}\varepsilon^{ST}$$

$$N^{semi} = 2N_{\text{tot}}B_{tag}B_{SL}\varepsilon_{ij}^{DT}$$

$$\mathcal{B}_{SL} = \frac{N^{semi}}{N^{ST} \times \epsilon}$$

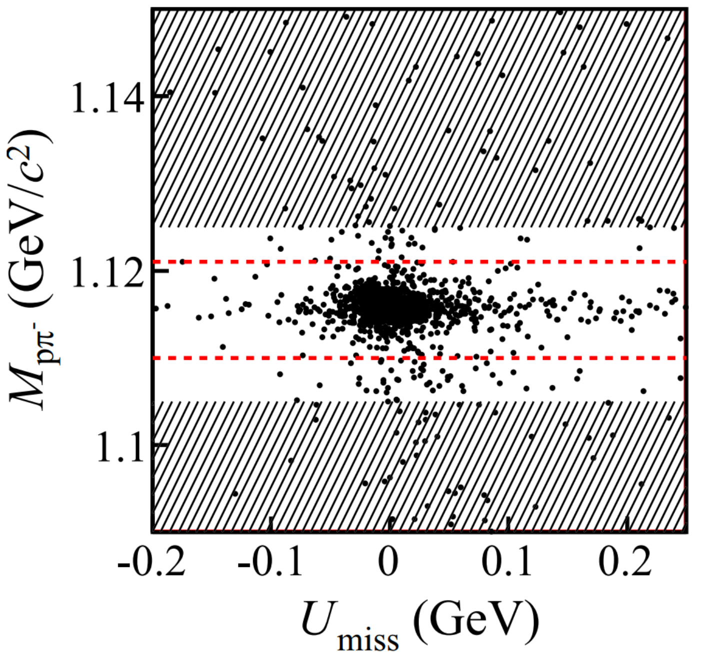
- Clean sample of ST charmed baryons can be fully reconstructed by hadronic decays with large BFs
- Based on this, one can access to absolute BFs and dynamics in the decays

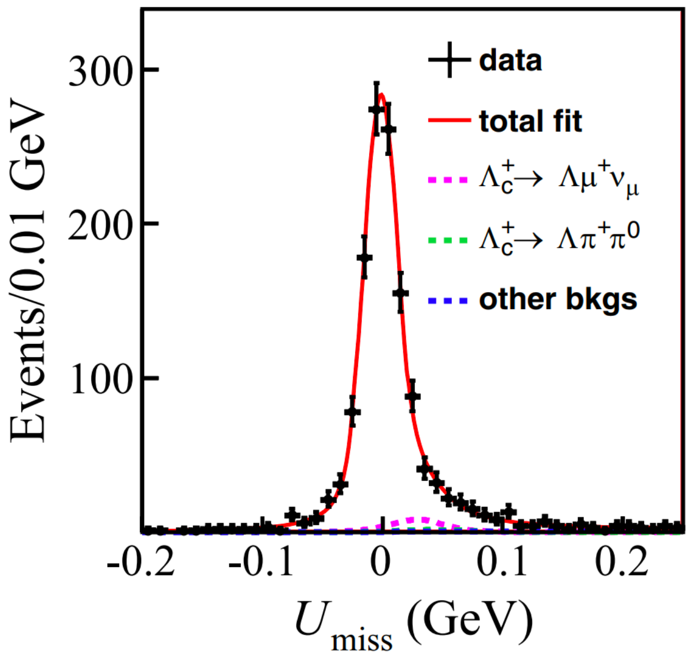
Study of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decays

Phys. Rev. Lett. 129, 231803 (2022)

$4.5\ \text{fb}^{-1}$ data @ $4.6 - 4.7$ GeV

$N^{DT} = 1253 \pm 39$





Comparisons between measurement and theoretical predictions:

	$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ [%]
Constituent quark model (HONR) [8]	4.25
Light-front approach [9]	1.63
Covariant quark model [10]	2.78
Relativistic quark model [11]	3.25
Non-relativistic quark model [12]	3.84
Light-cone sum rule [13]	3.0 ± 0.3
Lattice QCD [14]	3.80 ± 0.22
$SU(3)$ [15]	3.6 ± 0.4
Light-front constituent quark model [16]	3.36 ± 0.87
MIT bag model [16]	3.48
Light-front quark model [17]	4.04 ± 0.75
This work	$3.56 \pm 0.11 \pm 0.07$

$$\mathcal{B}[\Lambda_c^+ \to \Lambda e^+ \nu_e] = (3.56 \pm 0.11 \pm 0.07)\%$$

$$|V_{cs}| = 0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{LQCD} \pm 0.007_{\tau_{\Lambda_c}}$$

- Best precision BF to date: twofold improvement, larger than 2σ deviation with some theoretical models
- Consistent with $|V_{cs}| = 0.939 \pm 0.038$ measured in $D \to K\ell\nu_\ell$ decays within 1σ
- Measurement of $|V_{cs}|$ via $\Lambda_c \to \Lambda\ell\nu_\ell$ is an important consistency test for the SM and a probe for new physics

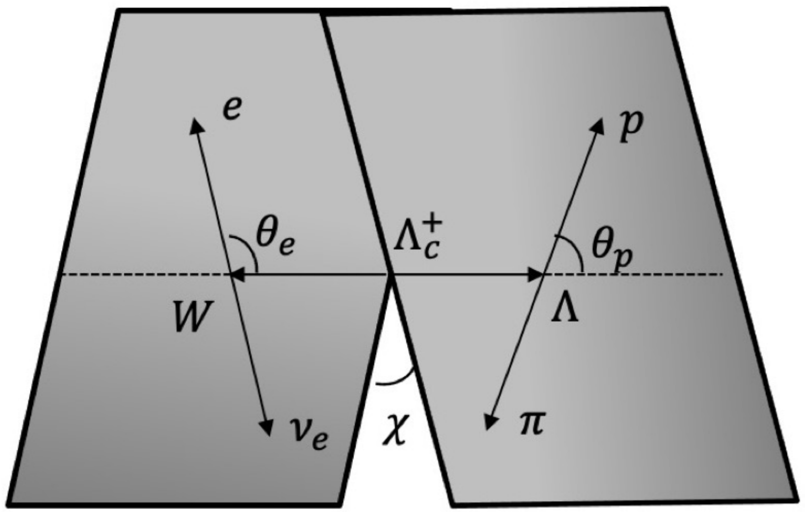
Study of the kinematics in $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decay

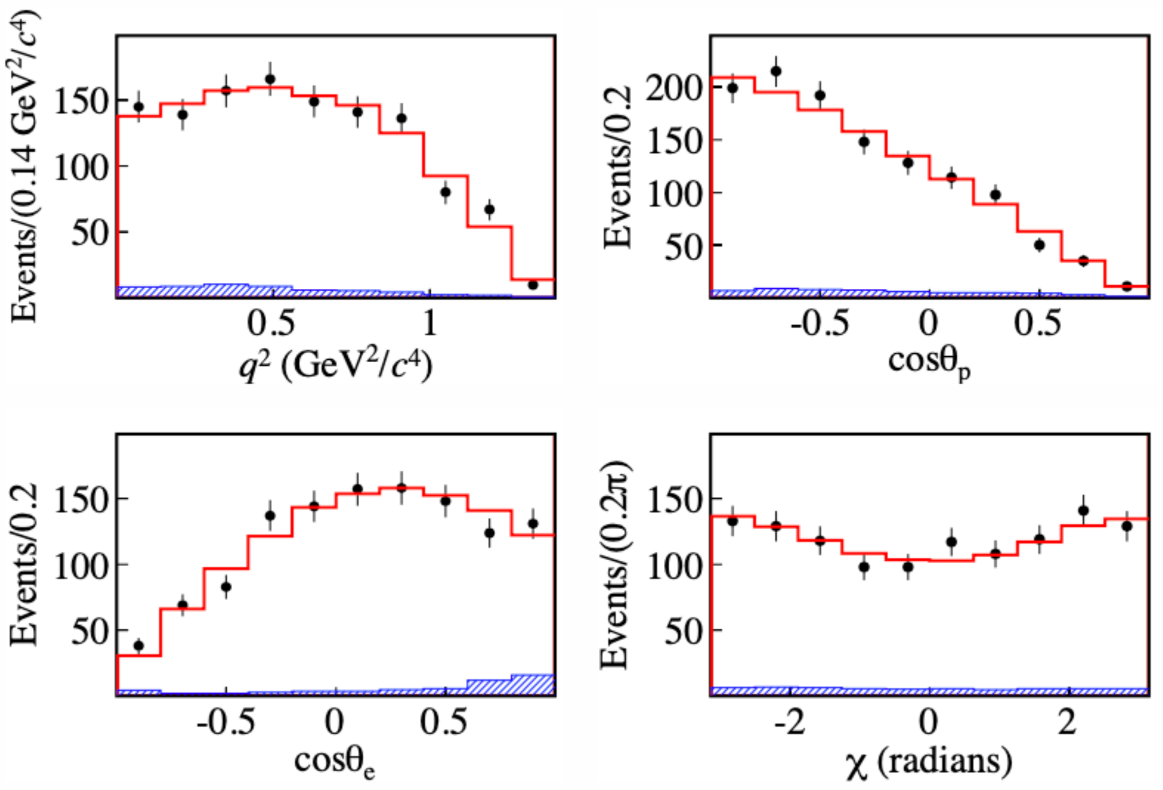
Phys. Rev. Lett. 129, 231803 (2022)

- Helicity amplitude and form factors

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_e d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4} \cdot \frac{Pq^2}{24M_{\Lambda_c}^2} \times$$
$$\Big\{\frac{3}{8}(1-\cos\theta_e)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{8}(1+\cos\theta_e)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta_e[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]$$
$$+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta_e\sin\theta_p \times$$
$$[(1-\cos\theta_e)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta_e)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]\Big\} \quad (2)$$

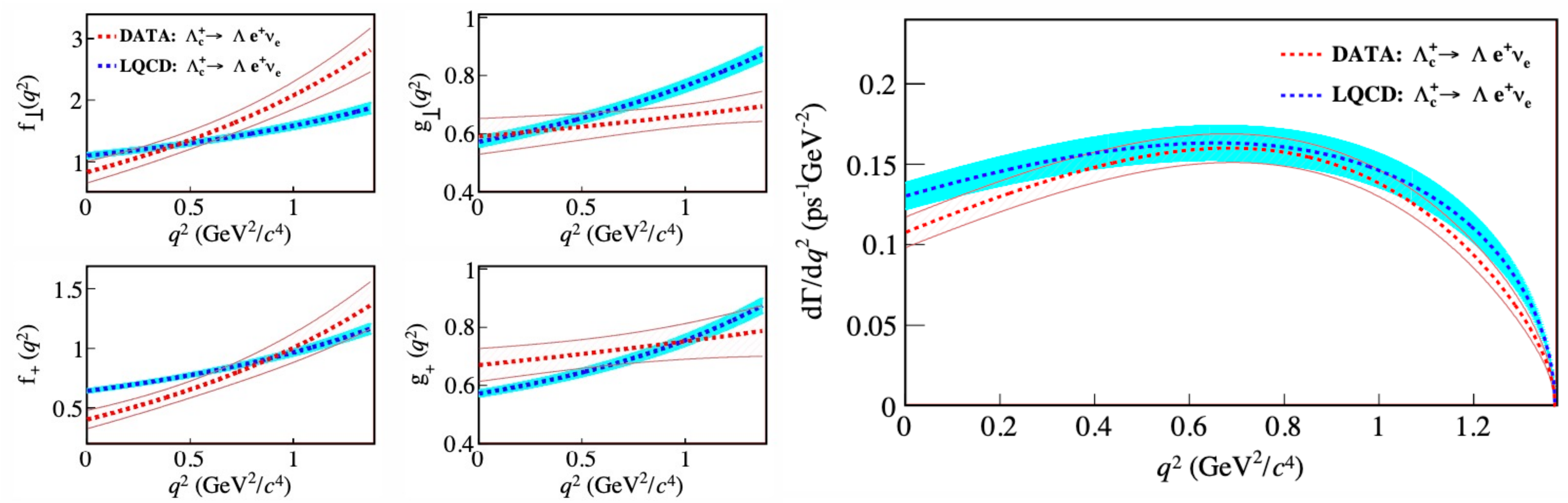
$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}\, f_\perp(q^2), \quad H^A_{\frac{1}{2}1} = \sqrt{2Q_+}\, g_\perp(q^2),$$
$$H^V_{\frac{1}{2}0} = \sqrt{Q_-/q^2}\, f_+(q^2)\,(M_{\Lambda_c}+M_\Lambda),$$
$$H^A_{\frac{1}{2}0} = \sqrt{Q_+/q^2}\, g_+(q^2)\,(M_{\Lambda_c}-M_\Lambda),$$





Comparisons between data and LQCD prediction *Phys. Rev. Lett. 129, 231803 (2022)*

- The first direct comparisons on the differential decay rates and form factors with LQCD calculations
- Different kinematic behavior compared to LQCD can be seen at high q^2 and low q^2 regions
- The results provide important inputs in understanding the SL decays of charmed baryons and help to calibrate the theoretical calculation



Steeper slope

Gentle slope

LQCD prediction: Phys. Rev. Lett. 118, 082001 (2017)

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

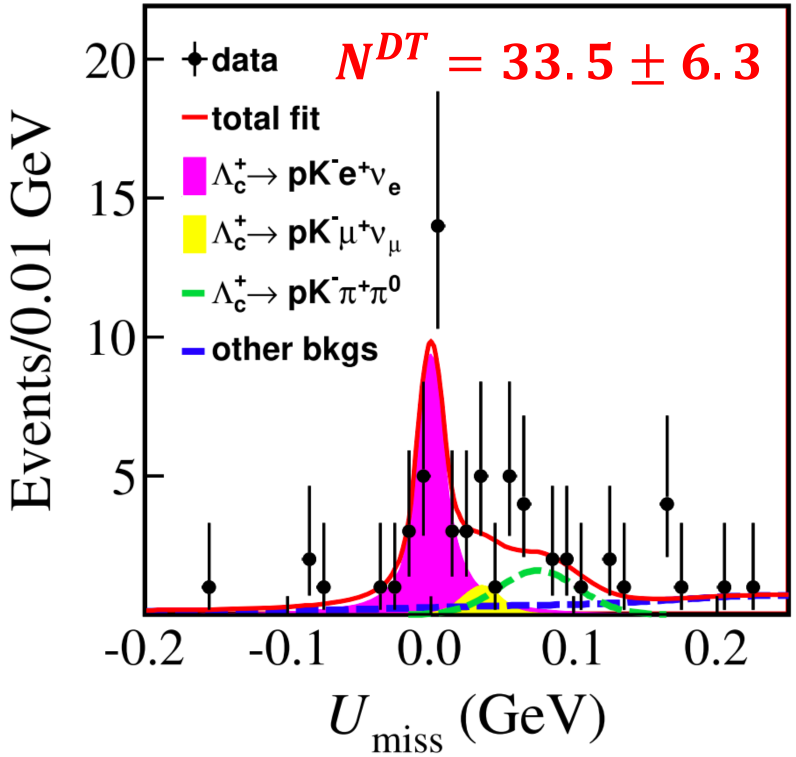
Phys. Rev. D 106, 112010 (2023)

- Second leptonic decay of Λ_c^+ is observed

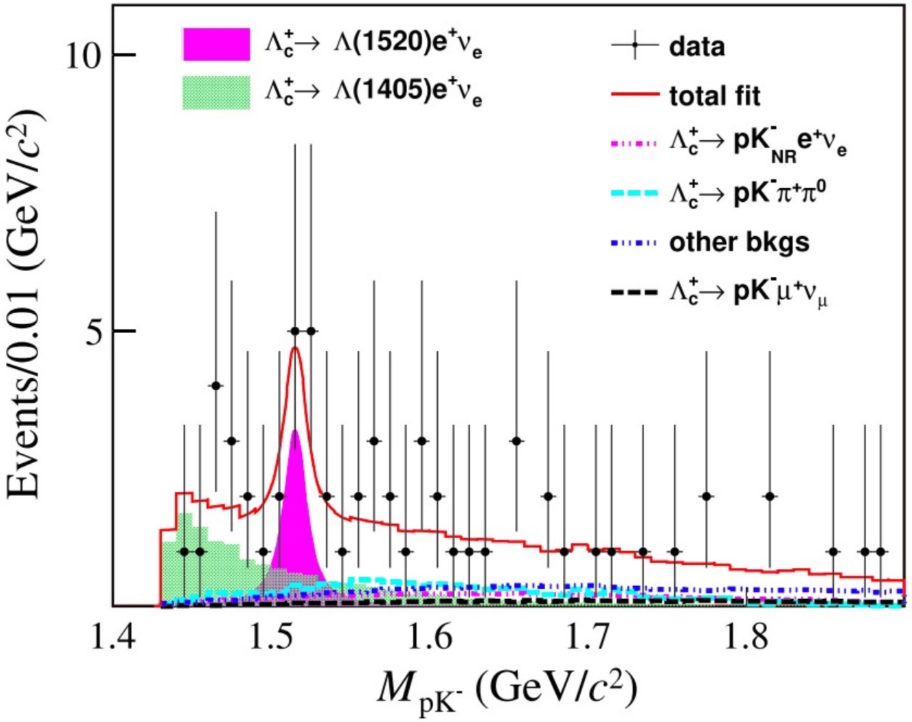
$\mathcal{B}(\Lambda_c^+ \to pK^- e^+ \nu_e) = (0.88 \pm 0.15 \pm 0.07)\times 10^{-3}$ **8.2σ**

- This work provides a clear confirmation that the SL Λ_c^+ decays are not saturated by the $\Lambda \ell^+ \nu_\ell$ final state
- Study of pK^- mass spectrum can be used to understand the nature of excited Λ^* states

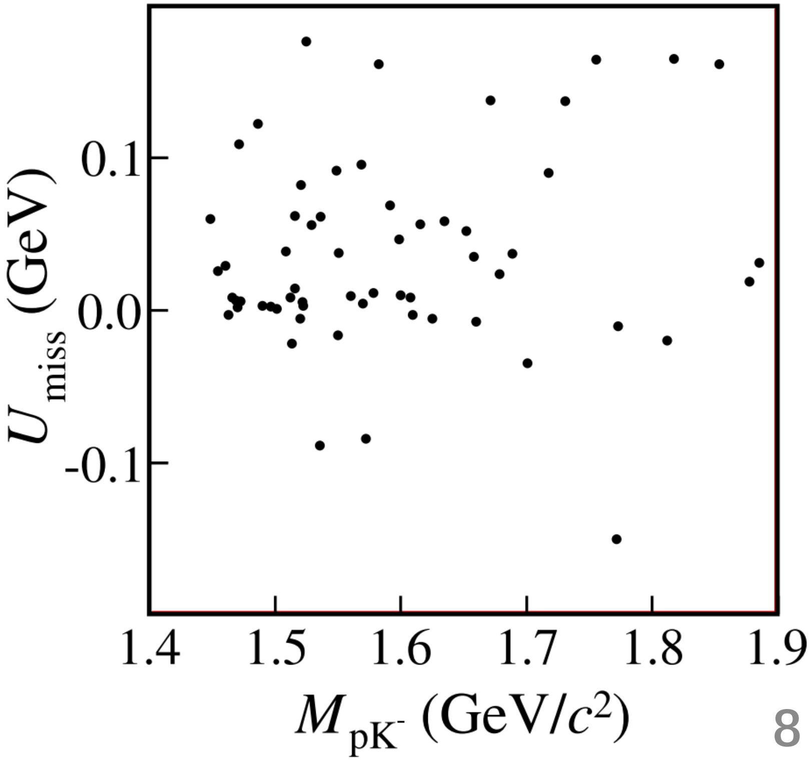
4.5 fb^{-1} data @ 4.6 – 4.7 GeV



$\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e$ **3.3σ**



$\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e$ **3.2σ**



Evidence of $\Lambda_c^+ \to \Lambda^*(\to pK^-)e^+\nu$

Phys. Rev. D 106, 112010 (2023)

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)\; e^+\nu_e) = (1.02 \pm 0.52 \pm 0.11)\times 10^{-3}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)[\to pK^-]e^+\nu_e) = (0.23 \pm 0.12 \pm 0.02)\times 10^{-3}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19 \pm 0.04)\times 10^{-3}$

hypotheses of BF differ by a factor of roughly 100 times

all consistent within 2σ

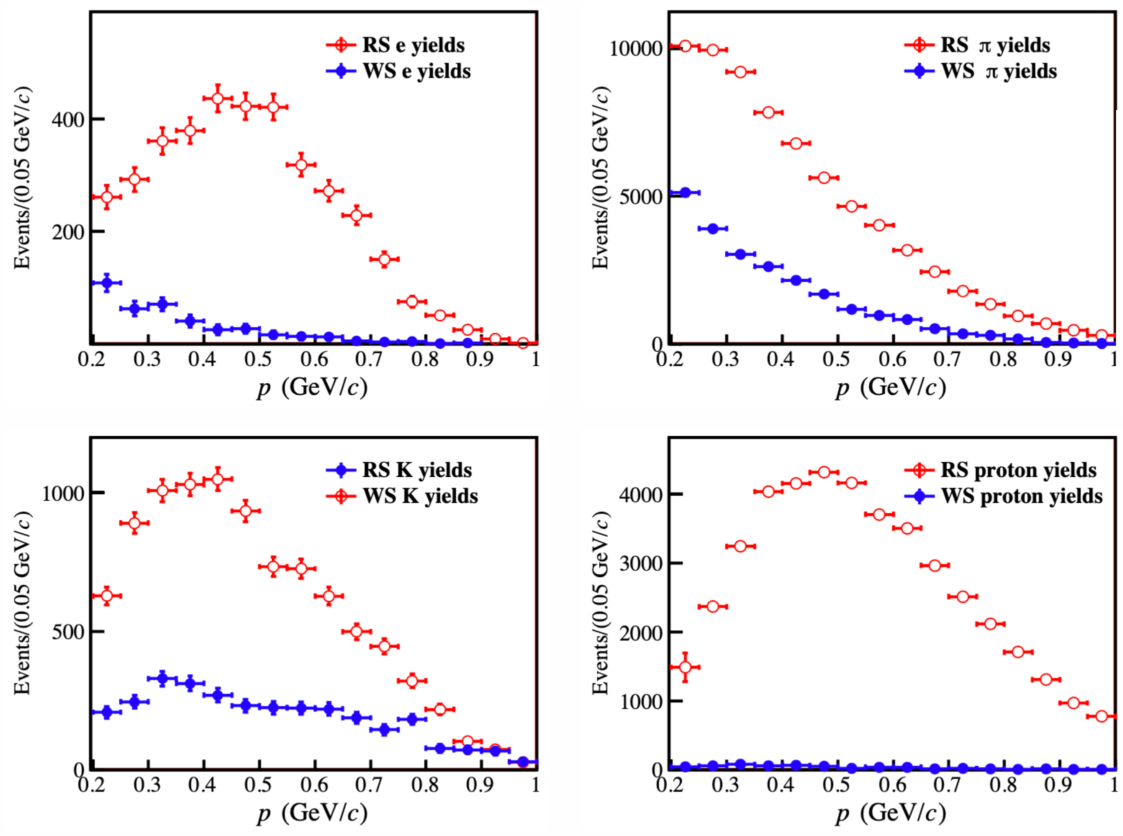
	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	$--$	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12, 13]	0.512 ± 0.082	$--$
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to pK^-)}$

- Prospect: With larger samples, amplitude analysis of pK^- mass spectrum, form factor and to understand the Λ^* internal structure of the contributing Λ states would be preformed

Inclusive SL decay $\Lambda_c^+ \to e^+ X$

Phys. Rev. D 107, 052005 (2023)

- Further Λ_c^+ SL decays may exist
- Comparing with the charge-averaged non-strange D SL decay width is helpful for testing current theoretical predictions
- Unfolding method to obtain true signal yields. The matrix can be obtained using selected control samples



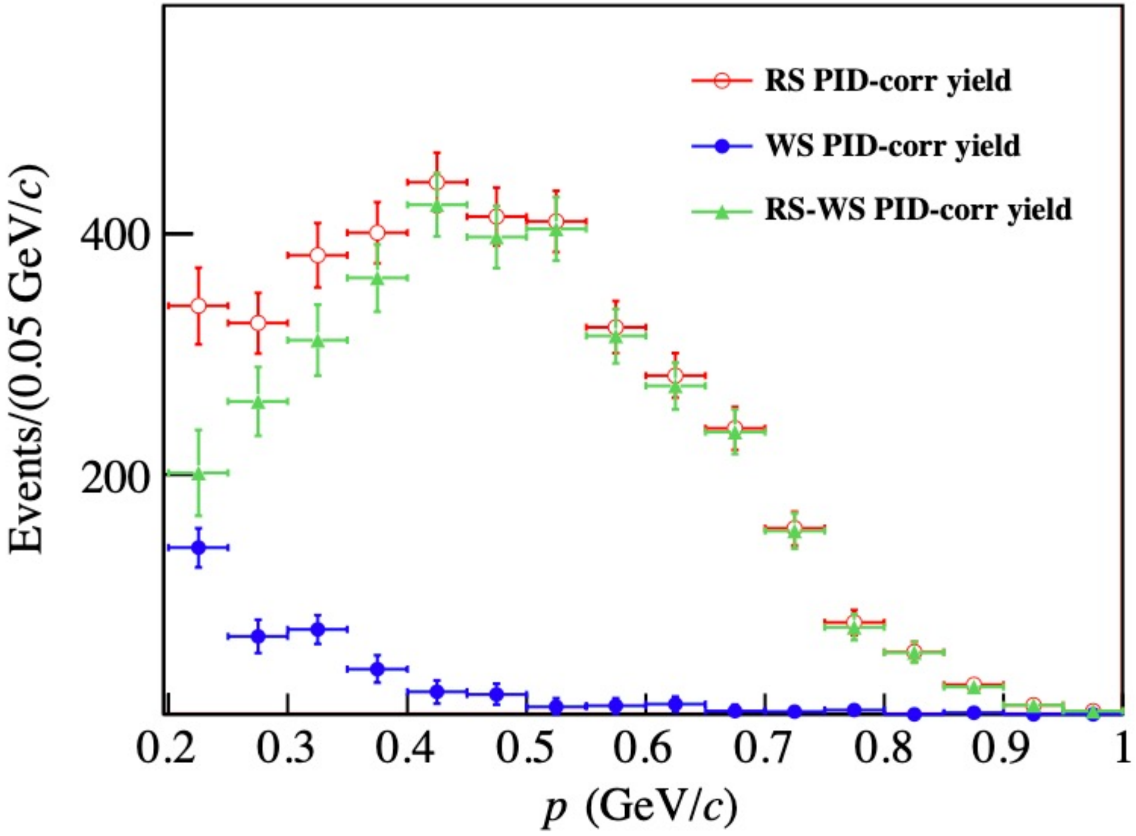
RS (WS): the charge of the track is required to be opposite (equal) to the ST $\mathbf{\Lambda_c^-}$ candidate.

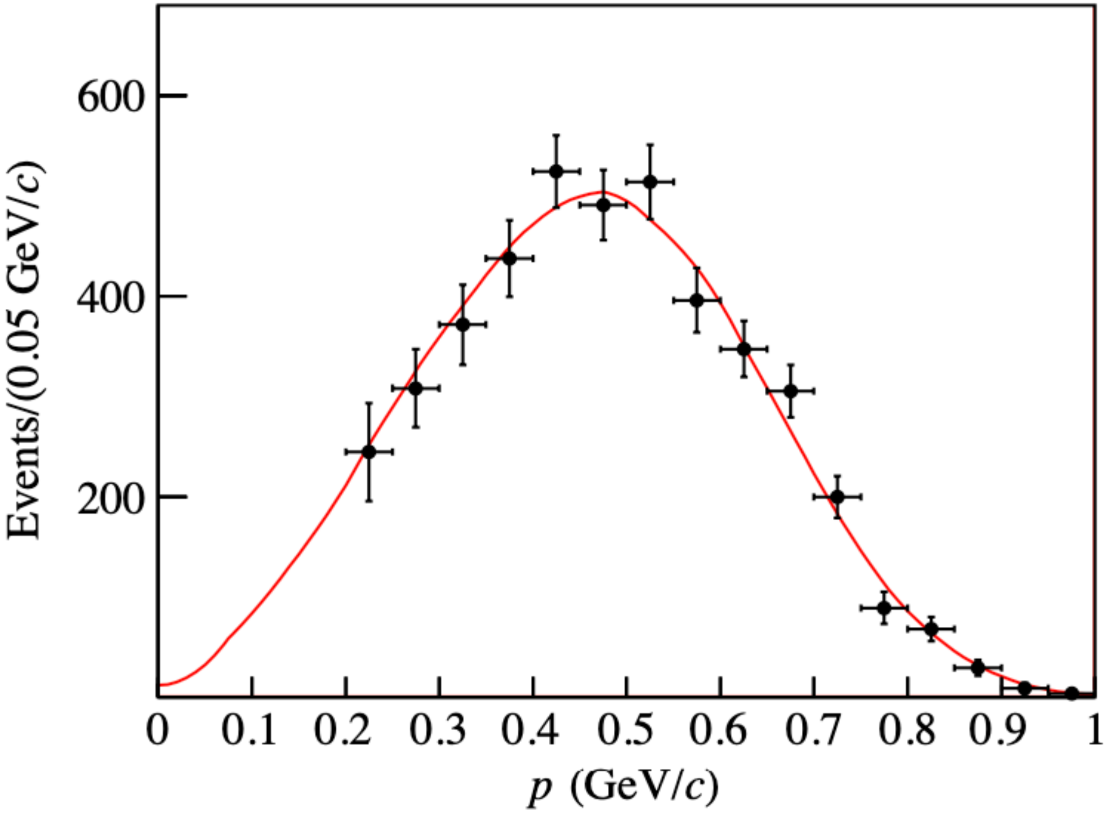
$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to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

Correction (see text)	RS yields	WS yields
Observed yields	3706 ± 71	394 ± 31
PID unfolding yields	3865 ± 80	376 ± 33
WS subtraction	3489 ± 87	
Tracking unfolding yields	4333 ± 107	
Extrapolation	4692 ± 117	

Inclusive SL decay $\Lambda_c^+ \to e^+ X$

Phys. Rev. D 107, 052005 (2023)





- The precision is improved by threefold [Phys. Rev. Lett. 121, 251801 (2018)]

$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10 \pm 0.09)\%$

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

$\mathcal{B}(\Lambda_c^+ \to p K^- e^+ \nu_e) = (0.88 \pm 0.15 \pm 0.07)\times 10^{-3}$

} Unknow decay: 0.5%

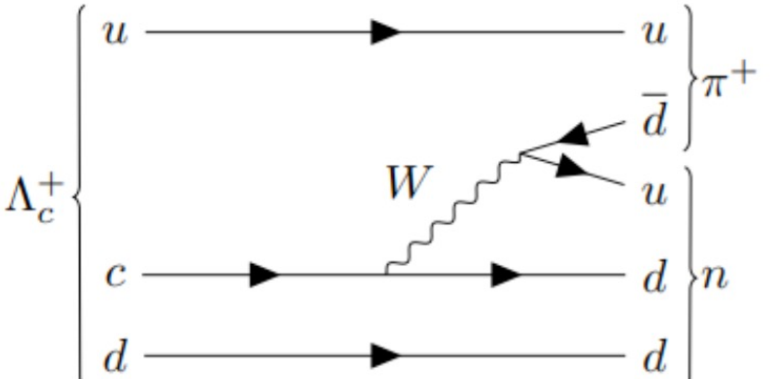
Measurement of $\Lambda_c^+ \to n\pi^+$

Phys. Rev. Lett. 128, 142001 (2022)

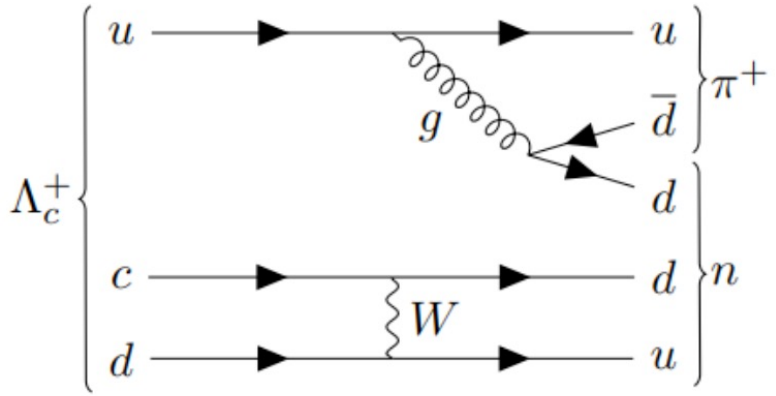
- Singly-Cabbibo-Suppressed(SCS) decay, which can't ignore non-factorizable contributions
- Studies of nonfactorizable components are critical to understand the underlining dynamics of charmed baryon decays

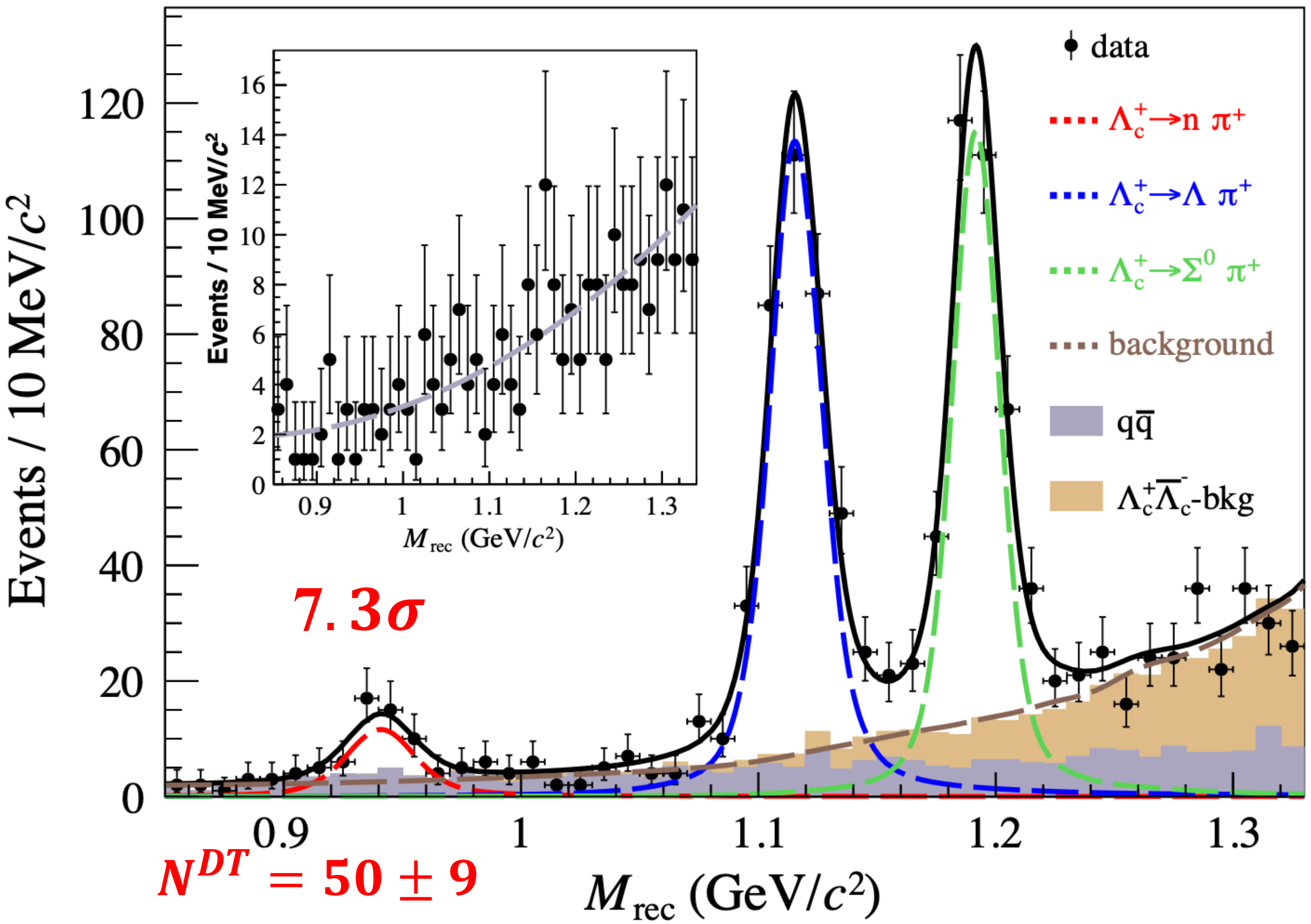
$4.5\ \mathrm{fb}^{-1}$ data @ $4.6 - 4.7$ GeV

Internal W emission



W exchange





$N^{DT} = 50 \pm 9$

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

Phys. Rev. Lett. 128, 142001 (2022)

➢ $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4)\times10^{-4}$ $R = \frac{\mathcal{B}(\Lambda_c^+\to n\pi^+)}{\mathcal{B}(\Lambda_c^+\to p\pi^0)} > 7.2\ at\ 90\%\ \mathrm{C.L.}$

Use $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0\times10^{-5}\ at\ 90\%\ \mathrm{C.L.}$ of Belle from PRD 103, 072004 (2021)

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)$	R	Reference	phenomenological models
4	2	PRD 55, 7067 (1997)	SU(3) flavor symmetry model
9	2	PRD 93, 056008 (2016)	
11.3 ± 2.9	2	PRD 97, 073006 (2018)	
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)	constituent quark model
2.66	3.5	PRD 97, 074028 (2018)	a dynamical calculation based on pole model and current-algebra
6.1 ± 2.0	4.7	PLB 790, 225 (2019)	SU(3) flavor symmetry including the contributions from $\mathcal{O}(\mathbf{15})$
7.7 ± 2.0	9.6	JHEP 02 (2020) 165	topological-diagram approach

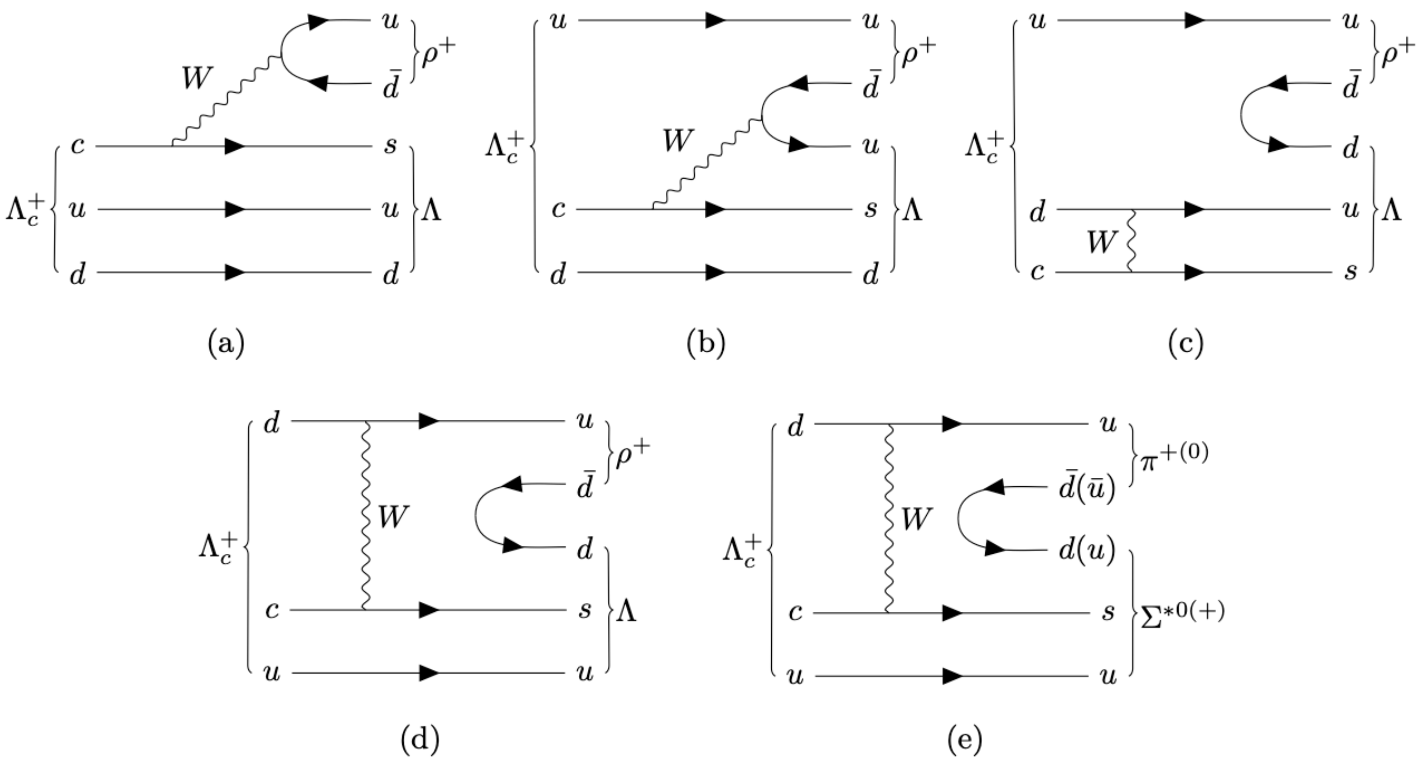
➢ The branching fraction and R value disagrees with the most predictions of phenomenological models, implying that the non-factorization contributions are overestimated

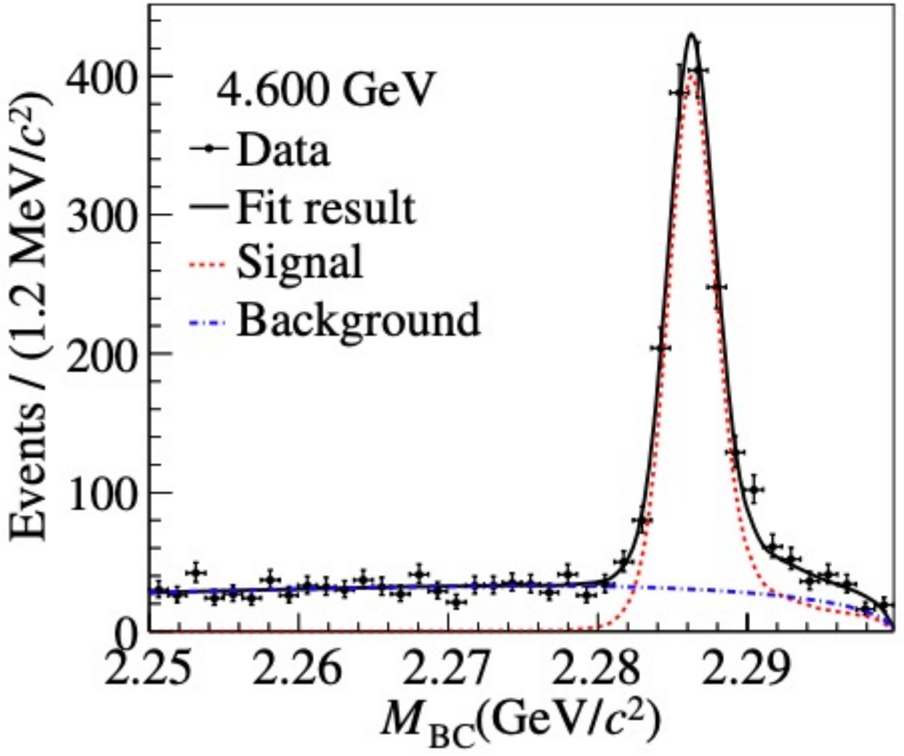
Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12 (2022), 033

- First amplitude analysis of charmed baryon multi-hadronic decays
- Crucial test on $\Lambda_c^+ \to \Lambda\rho(770), \Sigma(1385)\pi^+$ which suffer non-factorizable contributions
- The single tag method is applied to select $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ events
- BF and decay asymmetry parameters are determined

~10k signal events
Signal purity > 80%



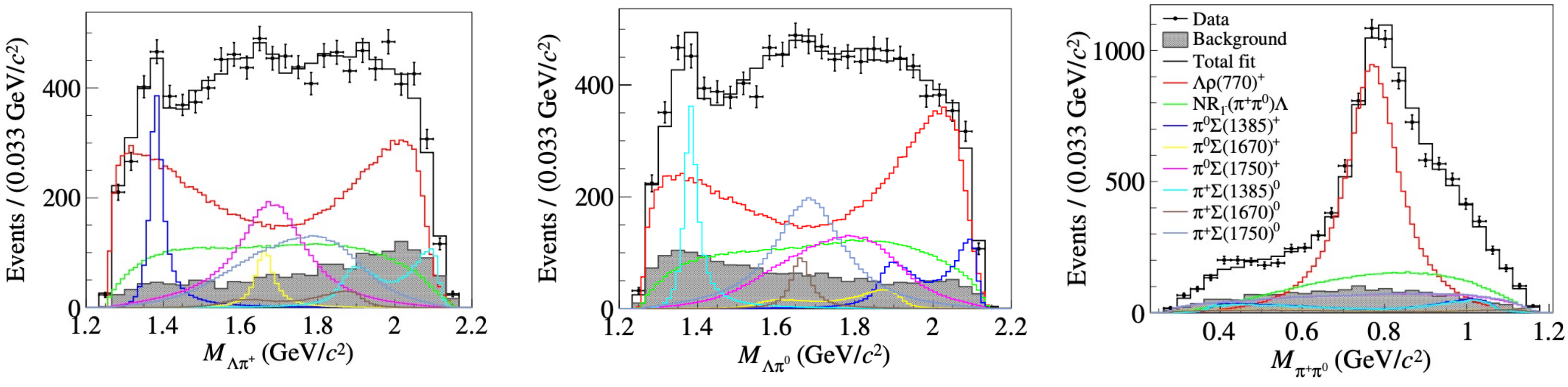


(a) Factorizable (b-e) non-factorizable

Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12 (2022), 033

➢ Helicity amplitude fit implemented by TF-PWA (https://github.com/jiangyi15/tf-pwa) TF-PWA



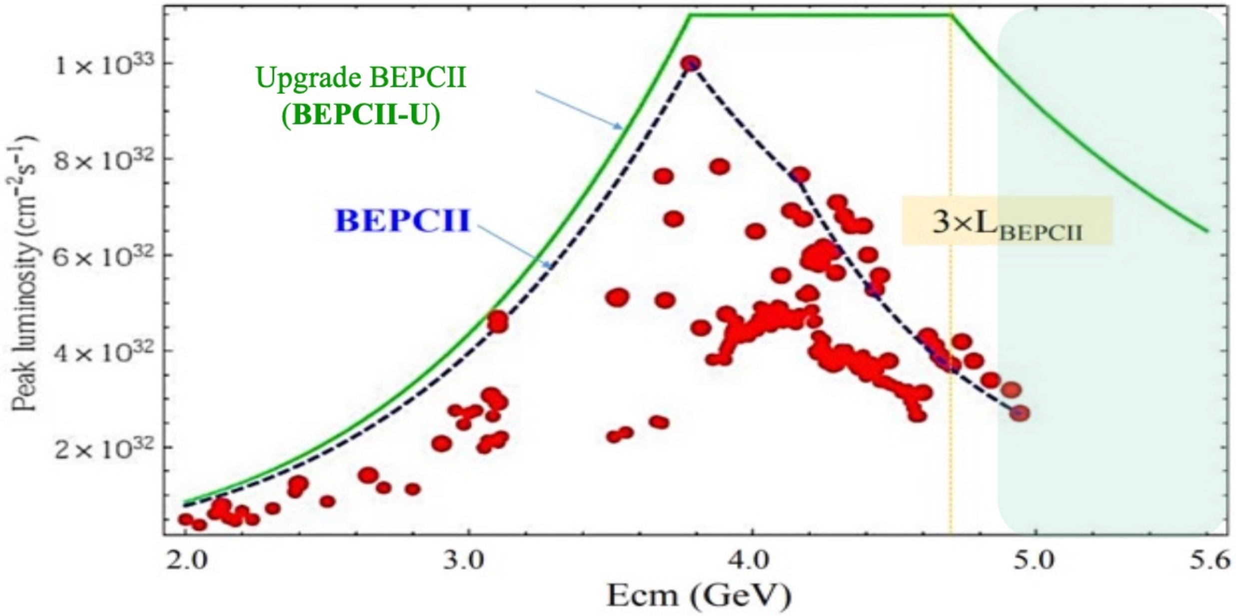
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$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

Other Λ_c^+ results

- Semi-leptonic decays
  - $\Lambda_c^+ \to \Lambda\, \mu^+ \nu_\mu$ [arXiv:2306.02624]
  - $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ *and* $p K_s \pi^- e^+ \nu_e$ [PLB843,137993(2023)]
- Hadronic decays
  - $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\omega$ [arXiv:2307.09266]
  - $\Lambda_c^+ \to \Sigma^+ h^+ h^- (\pi^0)$ [arXiv:2304.09405]
  - $\Lambda_c^+ \to \bar{n}\, X$ [PRD108, L031101(2023)]
  - $\Lambda_c^+ \to n\pi^+\pi^0, n\,\pi^+\pi^-\pi^+$ *and* $n\, K^-\pi^+\pi^-$ [CPC47,023001(2023)]
  - $\Lambda_c^+ \to \Lambda K^+$ [PRD106,L111101(2022)]
  - $\Lambda_c^+ \to \Sigma^0 K^+$ *and* $\Sigma^+ K_S^0$ [PRD 106, 052003 (2022)]
  - $\Lambda_c^+ \to p\eta'$ [PRD106,072002(2022)]
- Rare decays
  - $\Lambda_c^+ \to \Sigma^+ \gamma$ [PRD107,052002(2023)]
  - $\Lambda_c^+ \to p\gamma'$ [PRD106,072008(2022)]

Summary

- BESIII has made pretty good progresses on the exploration of the charmed baryon Λ_c^+
- Near threshold production is unique to directly measure the Λ_c^+ decay properties
- Opportunities to study other charmed baryons ($\Sigma_c, \Xi_c, \Omega_c$) in the BEPCII-U phase



Energy thresholds

$e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV

$e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ 4.88GeV

$e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV

$e^+e^- \to \Xi_c\bar{\Xi}_c$ 4.94 GeV

$e^+e^- \to \Omega_c\bar{\Omega}_c$ 5.40GeV

	cross-sections	at different $\sqrt{s}$	at different $\sqrt{s}$	
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