Charmed baryon decays

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On behalf of the BESIII Collaboration

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BESIII

Outline

- Introduction of the lightest charm baryon Λ_c^+

- Charm baryon physics at BESIII
  - ➢Λ_c^+ semi-leptonic decays
  - ➢Λ_c^+ hadronic decays

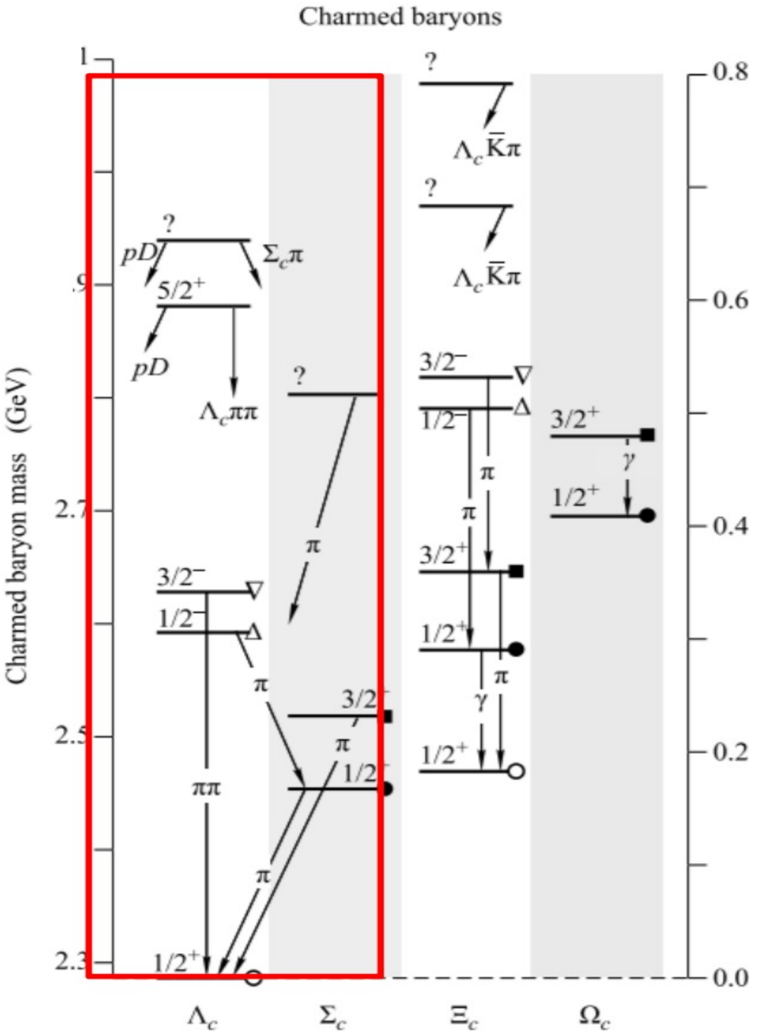
- Summary

Charmed baryon spectroscopy

- Before 2014, the charmed 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).
- Large uncertainties in experiment=>Retarder development in theory.

- Afterwards, more extensive measurements on charmed baryons are performed at BESIII, BELLE and LHCb.
  - The absolute BF measurements at BESIII and BELLE.
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE.
  - The observation of the doubly charmed baryon Ξ_{cc}^{++} at LHCb.

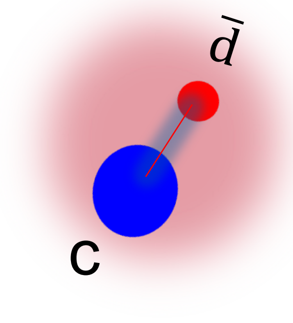
- These experimental progresses have evoked the activities in the theoretical efforts



Λ_c^+: The lightest charmed baryon spectroscopy

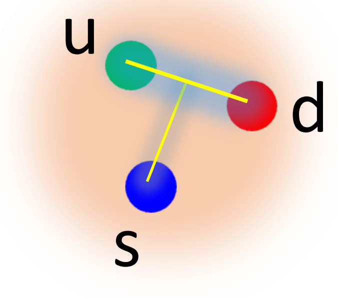
- Most of the charmed baryons will eventually decay to $\mathbf{\Lambda_c^+}$.
- The $\mathbf{\Lambda_c^+}$ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.
- Also important input to $\boldsymbol{\Lambda_b}$ (including Ξ_{cc}^{++}) physics as $\boldsymbol{\Lambda_b}$ decay preferentially to $\boldsymbol{\Lambda_c}$.

  ==>Important input to B physics and V_{ub} calculations.
- $\mathbf{\Lambda_c^+}$ may provide more powerful test on internal dynamics than D/Ds does!
- 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).



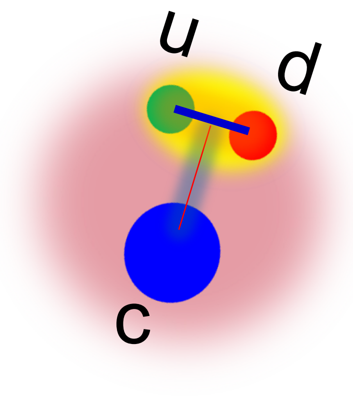
→ Charmed meson (D$^+$[c$\bar{d}$])

$m_d << m_c$ →
quark + heavy quark
(q) (Q)



→ Strange baryons (Λ[uds])

m_u, $m_d \approx m_s$ →
(qqq) uniform

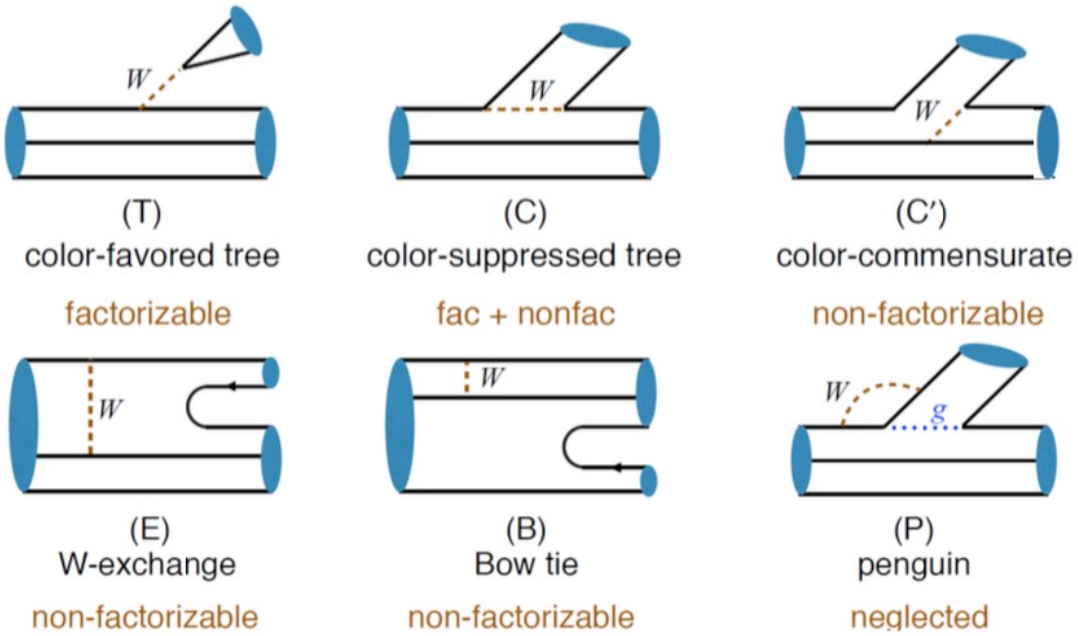


→ Charmed baryon (Λ_c[udc])

m_u, $m_d << m_c$ →
diquark + quark
(qq) (Q)

Λ_c^+ weak decays

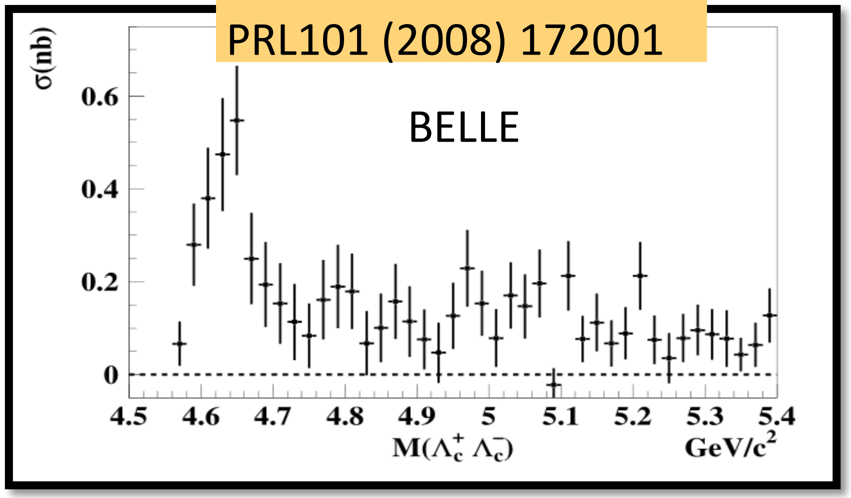
- Contrary to charmed meson, W-exchange contribution is important. (No color suppression and helicity suppression)

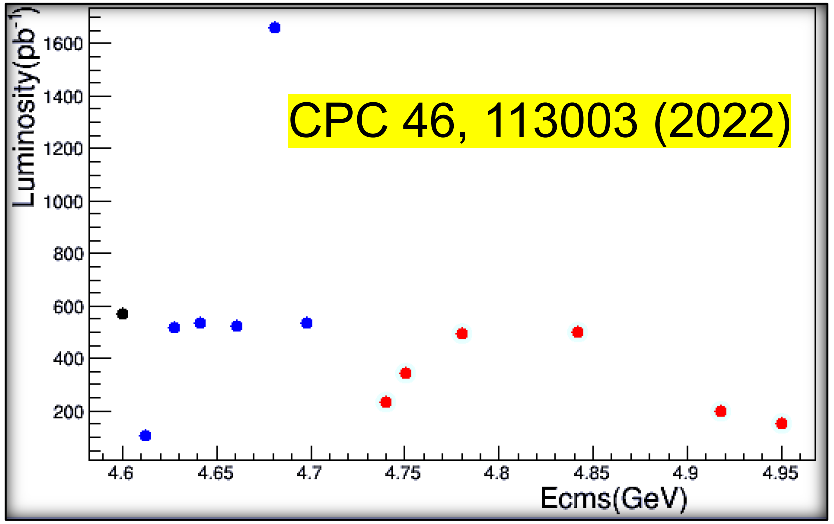


- Phenomenology aims to explain data and predict important observables.
- Calculate what they can (HQET, factorization) + parametrize what they cannot + some non-factorization processes extracted from data => explain and predict.

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.
- In 2014, BESIII took data above Λ_c^+ pair threshold and run machine at 4.6 GeV with excellent performance! $\sim 106\times 10^3$ $\Lambda_c^+\Lambda_c^-$ pairs make sensitivity to 10^{-3}.
- First time to systematically study Λ_c^+ at threshold.
- From December 2019 to June 2021, the BESIII experiment collected approximately 5.85 fb^{-1} of data at center-of-mass energies between 4.61 and 4.95 GeV.
- Will allow to improve the precision of Λ_c^+ decay rates to a level comparable to the charmed mesons.
- Provide an opportunity to study many unexplored physics observables related to Λ_c^+ decays.
- Boost our understanding of the non-perturbative effects in the charmed baryon sector.

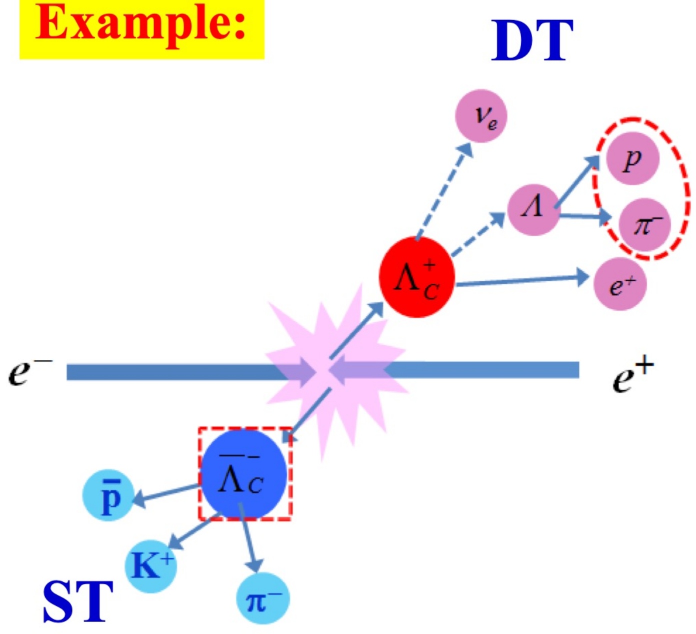

PRL101 (2008) 172001


CPC 46, 113003 (2022)

Production near threshold and tag technique

- $\Lambda_c^+\Lambda_c^-$ produced in pairs with no additional accompany hadrons (4.6~4.7 GeV).
- Clean backgrounds and well constrained kinematics.

Example:



- Single Tag (ST)

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

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

- Double Tags (DT)

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

$$M_{miss} = \sqrt{E_{miss}^2 - |\vec{p}_{miss}|^2}$$

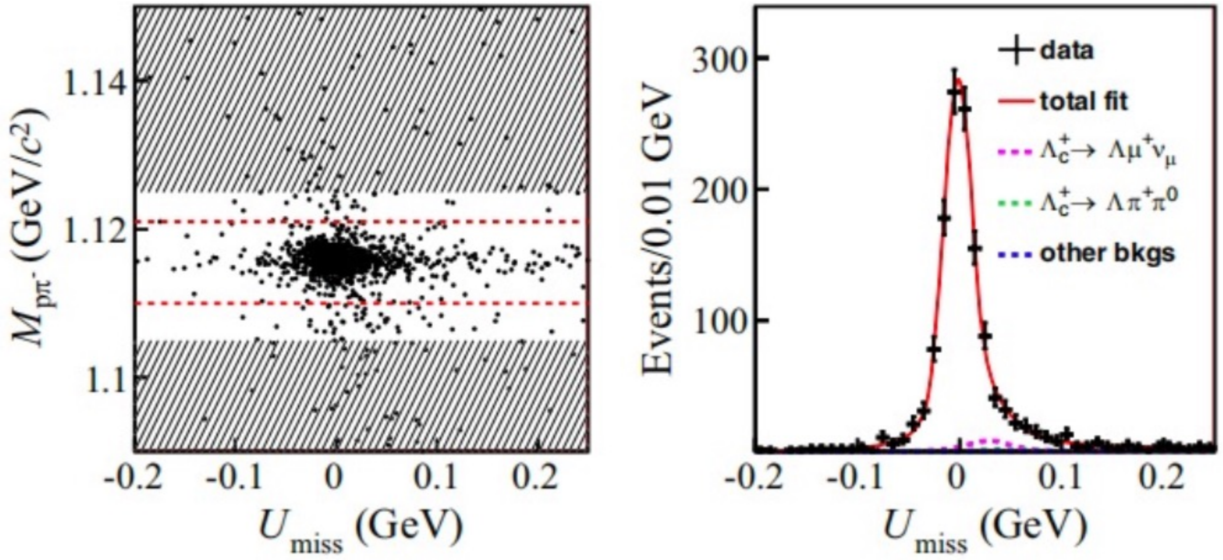
- Branching Fraction ($\mathcal{B}$)

$$\mathcal{B}_{SL} = \frac{N_{SL}}{N^{tag} \times \epsilon}$$

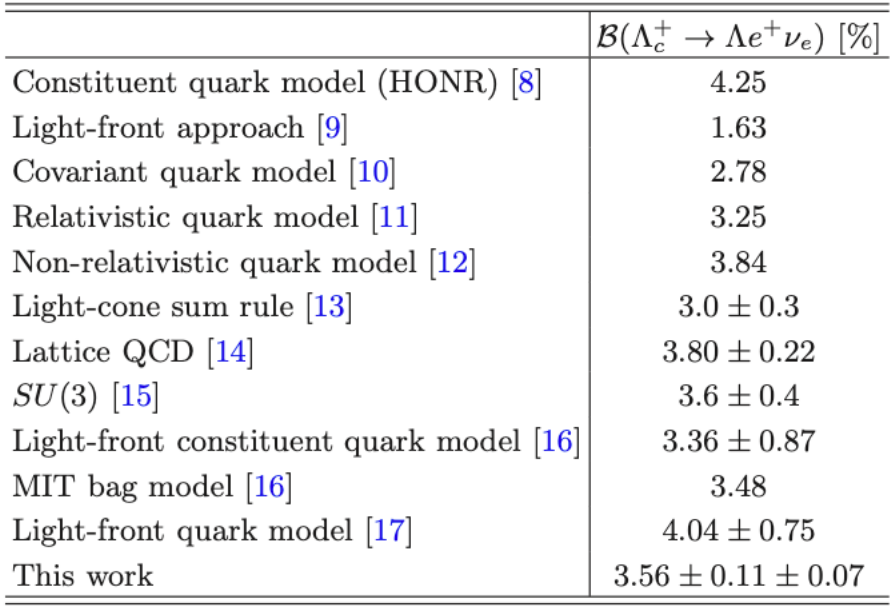
Study of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decays

- The measurement is done with 4.4 fb^{-1} data from $\sqrt{s} = 4.6 - 4.7$ GeV.
- The precision of the BF is improved by threefold [Phys. Rev. Lett. 115, 221805 (2015)], providing necessary inputs for testing various theoretical models.
- The first determination of form factors in $\boldsymbol{\Lambda_c^+ \to \Lambda e^+ \nu_e}$ decays.

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



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



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

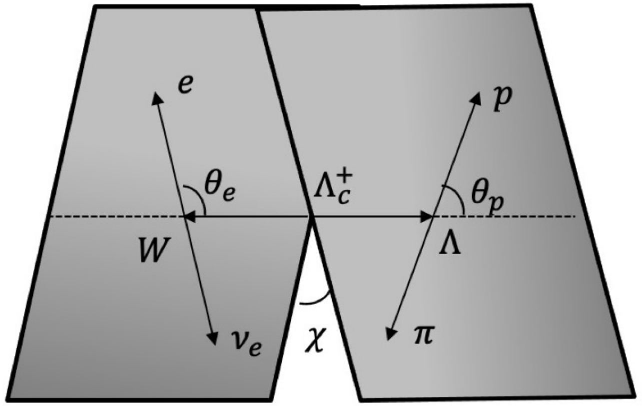
Comparisons between measurement and theoretical predictions.

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

- Helicity amplitude and form factors

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

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



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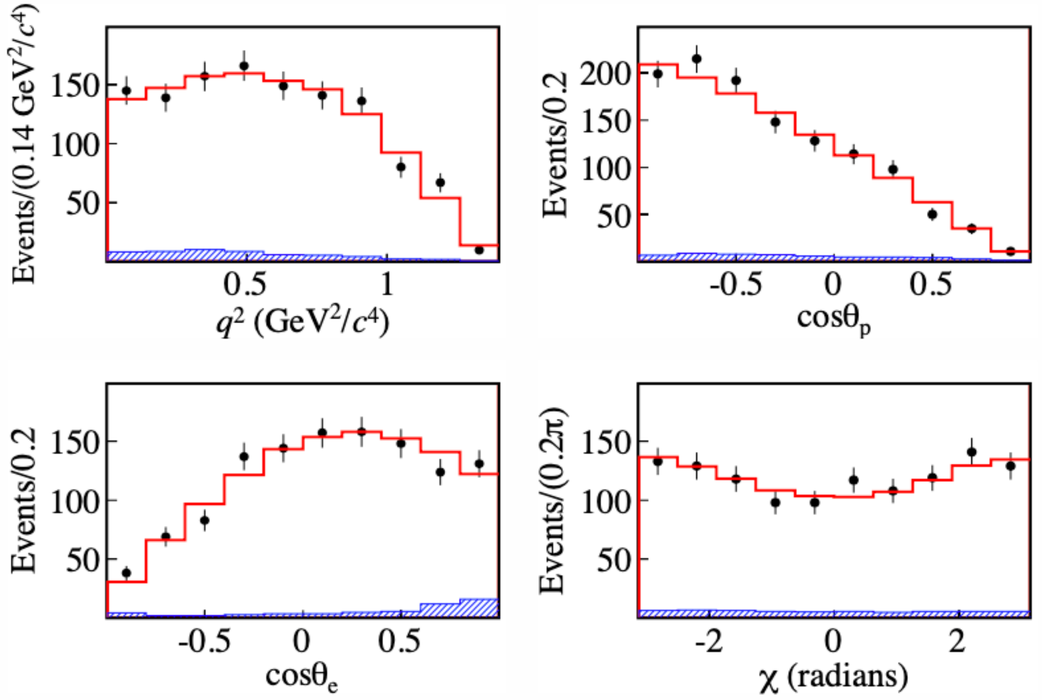
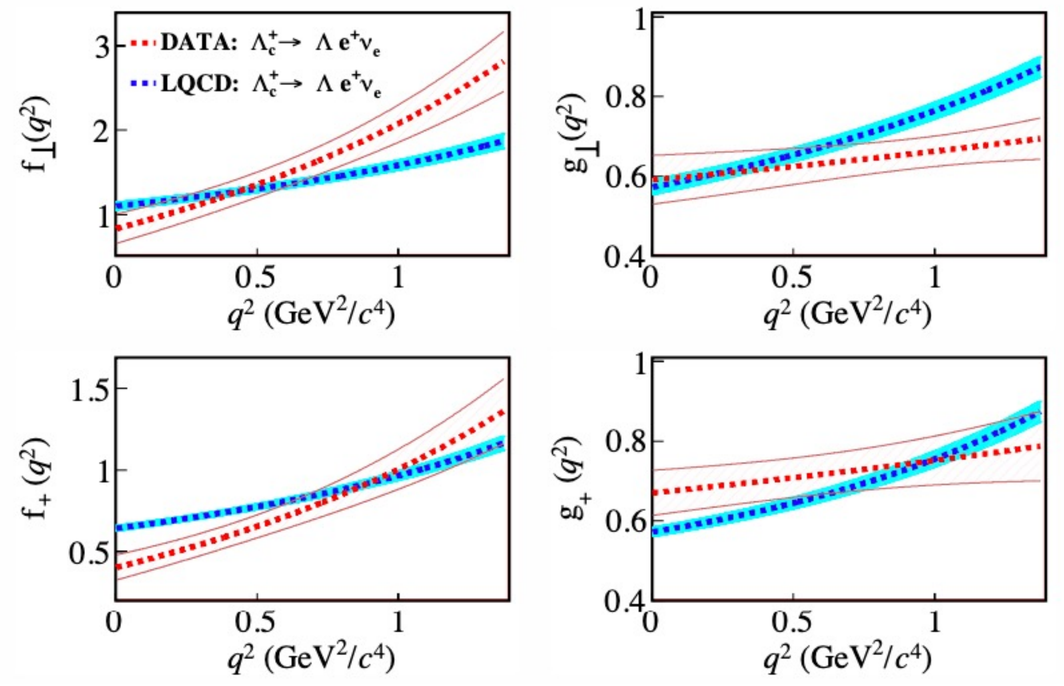


Comparisons between data and LQCD prediction

1.This analysis provides the first direct comparisons on the differential decay rates and form factors with LQCD calculations.

2.Discrepancies can be seen at high q^2 and low q^2 regions. The measurement result tends to have steeper slope than those from LQCD calculations.

2. The results provide important inputs in understanding the SL decays of charmed baryons and help to calibrate the theoretical calculation.



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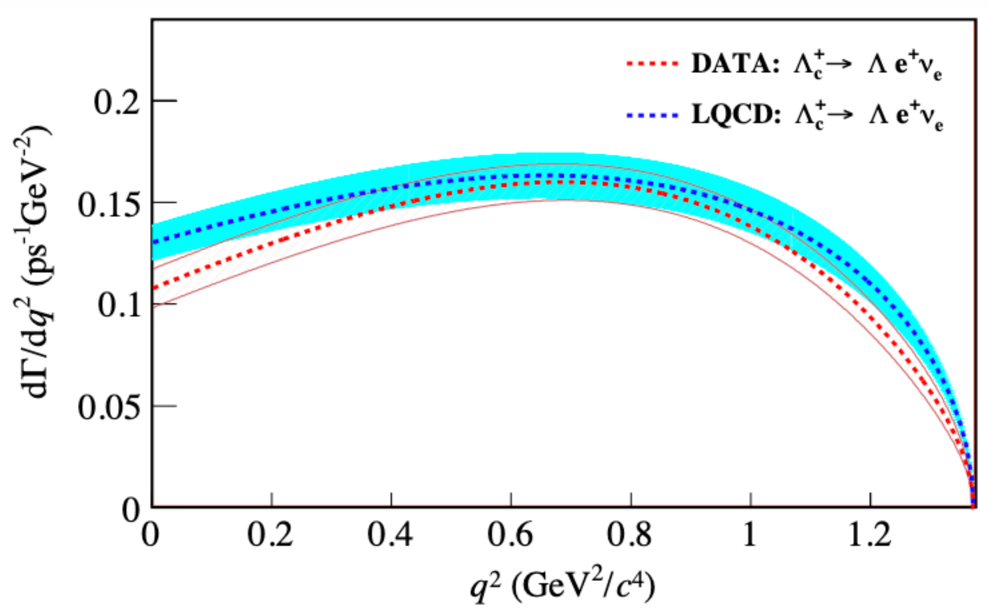
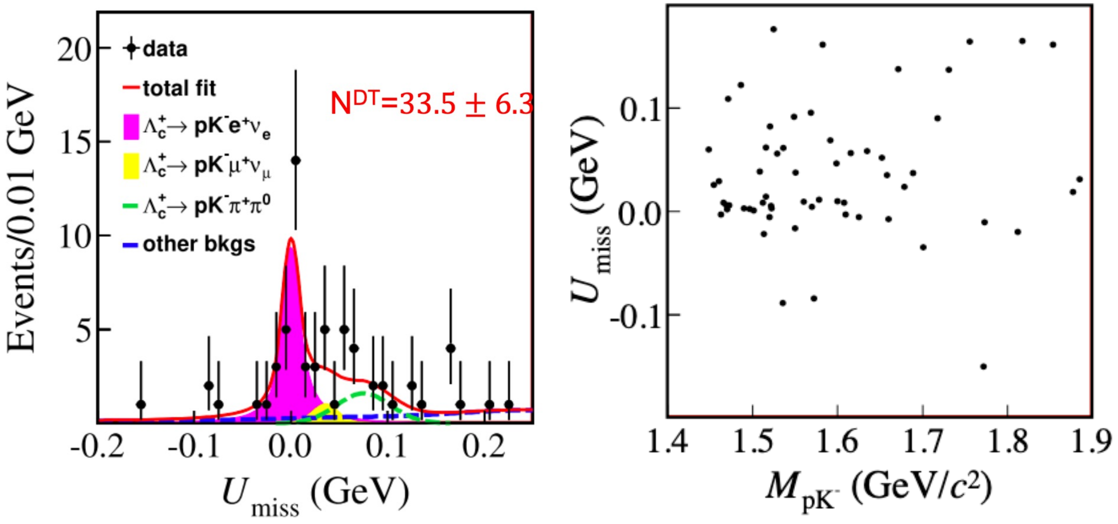
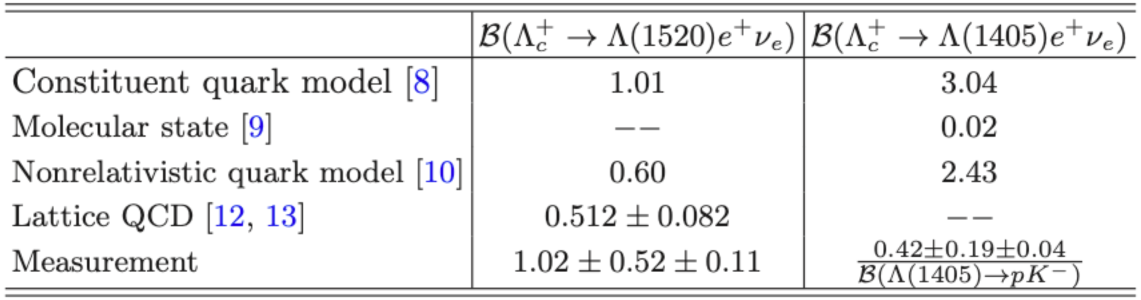


Observation of $\Lambda_c^+ \to pK^-e^+\nu_e$

Phys. Rev. D 106, 112010 (2023)

- The data we used is about 4.4 fb^{-1} data from $\sqrt{s}$ = 4.6 − 4.7 GeV.
- The new observed SL decay mode
- $\mathcal{B}(\boldsymbol{\Lambda_c^+} \to \mathbf{pK^-e^+}\boldsymbol{\nu_e}) = (\mathbf{0.88 \pm 0.15 \pm 0.07})\times \mathbf{10^{-3}}$
- Significance : 8.2σ
- This work provides a clear confirmation that the SL $\boldsymbol{\Lambda_c^+}$ decays are not saturated by the $\boldsymbol{\Lambda\ell^+\nu_\ell}$ final state.
- Study of pK^- mass spectrum can be used to understand the nature of excited Λ^* states.

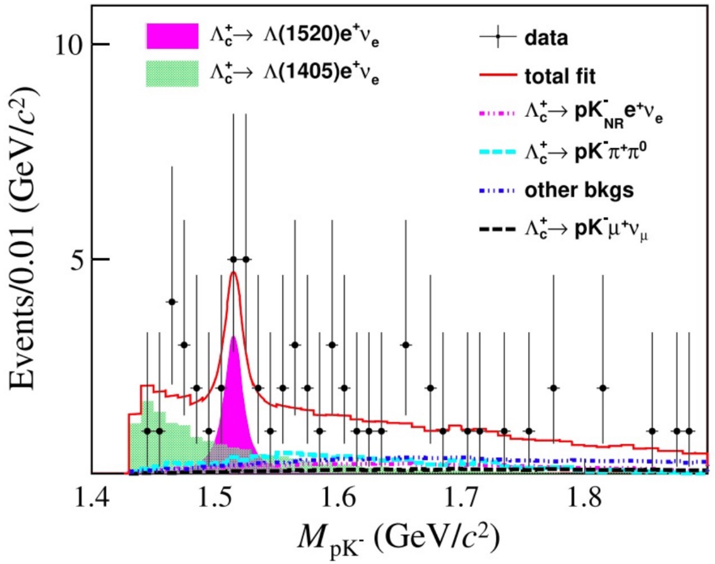


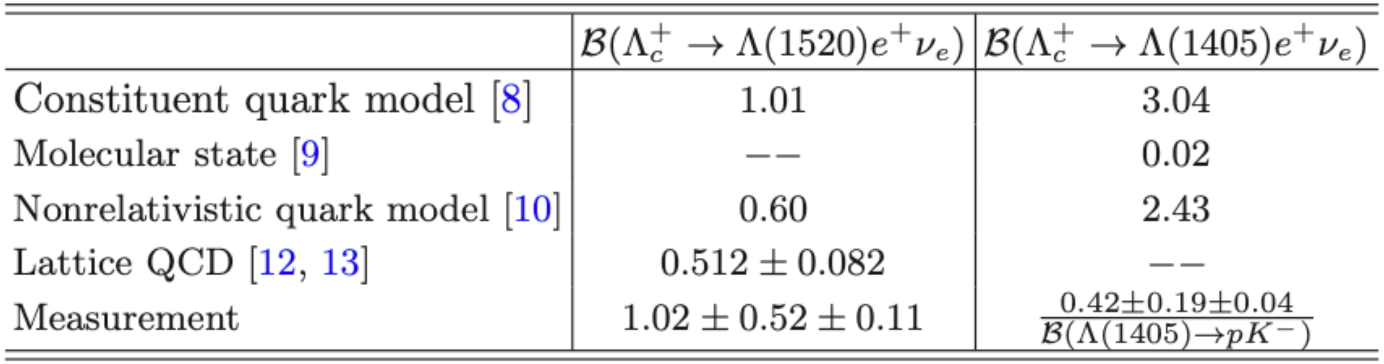


	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	−−	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12, 13]	0.512 ± 0.082	−−
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to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

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

Phys. Rev. D 106, 112010 (2023)





	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
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Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to pK^-)}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)[\to pK^-]e^+\nu_e) = (0.23 \pm 0.12 \pm 0.02)\times10^{-3}$ significance : 3.3σ

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19 \pm 0.04)\times10^{-3}$ significance : 3.2σ

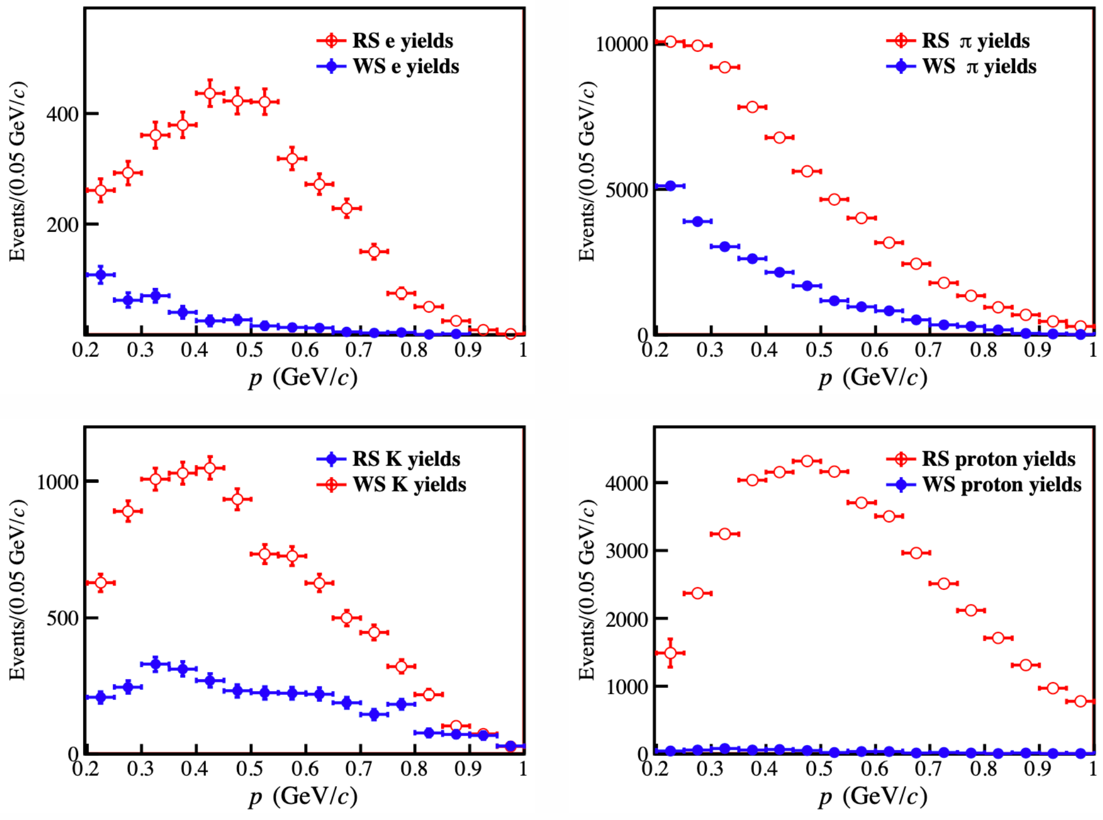
- The measured $\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)[\to pK^-]e^+\nu_e)$ is consistent with these theoretical calculations within two standard deviations.

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

Phys. Rev. D 107, 052005 (2023)

- Further $\boldsymbol{\Lambda_c^+}$ 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.

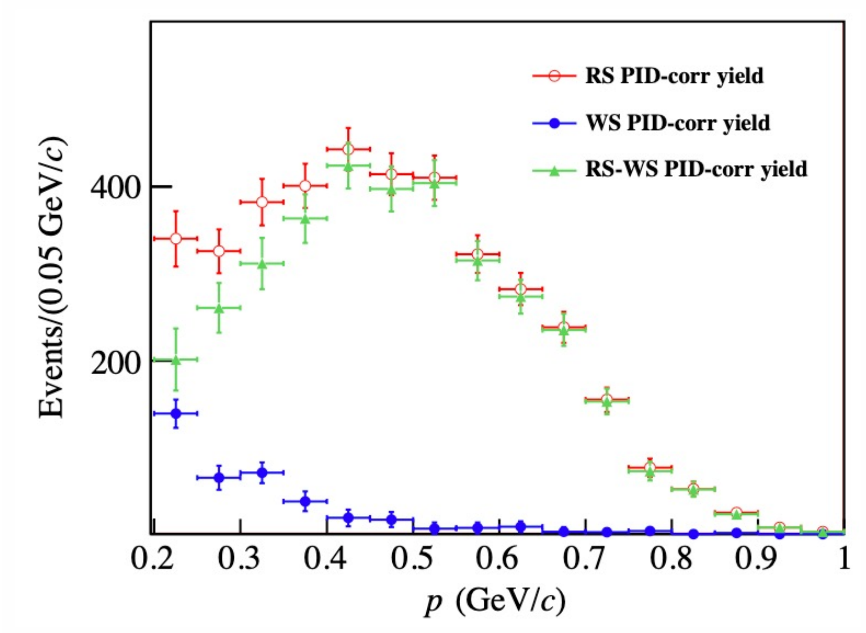
$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to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

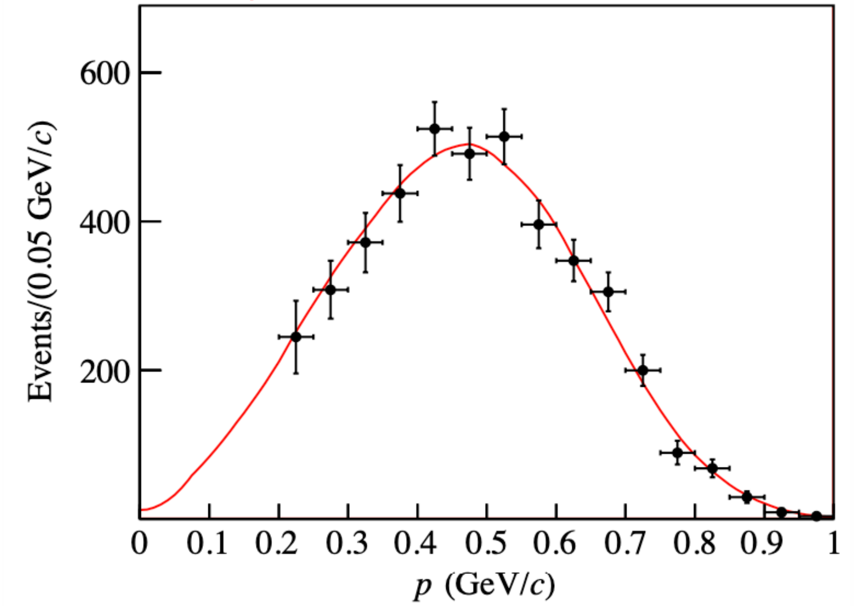


RS (WS) :the charge of the track is required to be opposite (equal) to the ST $\boldsymbol{\Lambda_c^-}$ candidate.

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

Phys. Rev. D 107, 052005 (2023)





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	

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

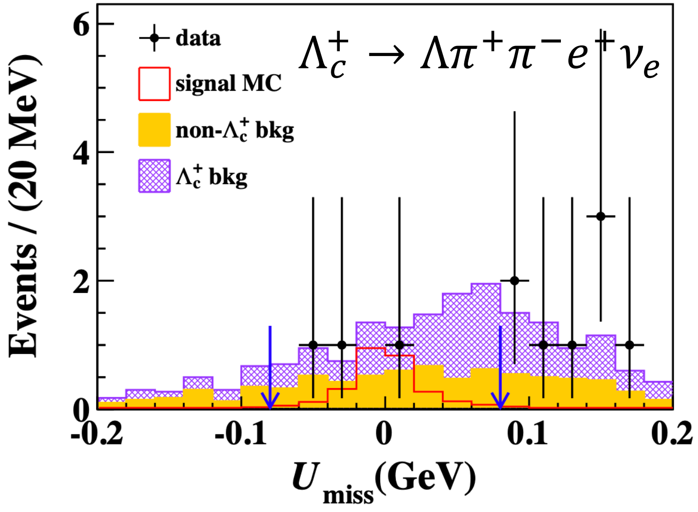
The precision is improved by threefold [Phys. Rev. Lett. 121, 251801 (2018)].

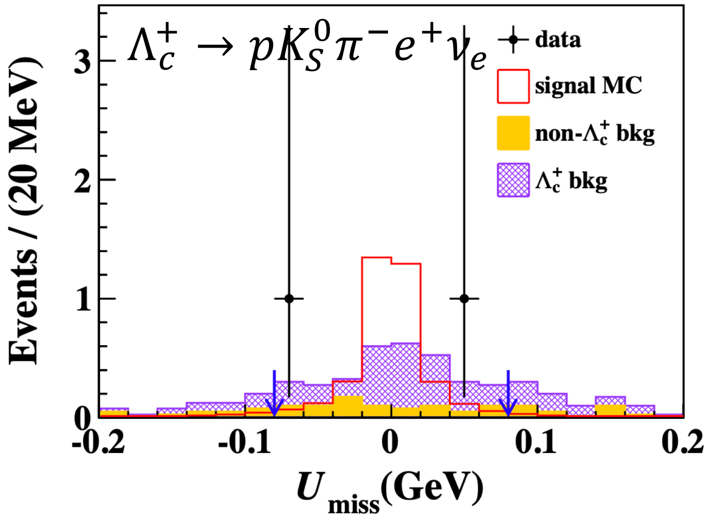
- $$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)} = 1.28 \pm 0.05,$$

$\mathcal{B}(\boldsymbol{\Lambda_c^+ \to X e^+ \nu_e}) = \boldsymbol{(4.06 \pm 0.10 \pm 0.09)\%}$
$\mathcal{B}(\boldsymbol{\Lambda_c^+ \to \Lambda e^+ \nu_e}) = \boldsymbol{(3.56 \pm 0.11 \pm 0.07)\%}$
$\mathcal{B}(\boldsymbol{\Lambda_c^+ \to p K^- e^+ \nu_e}) = \boldsymbol{(0.88 \pm 0.15 \pm 0.07) \times 10^{-3}}$

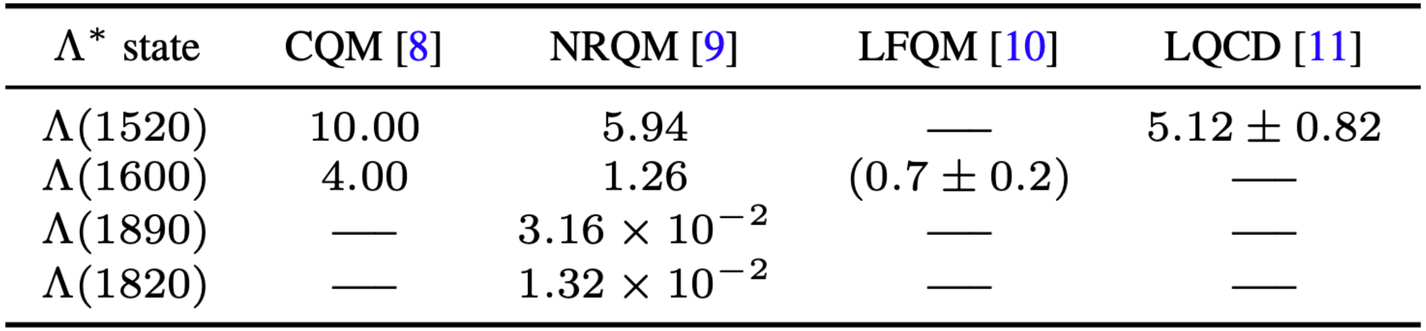
Unknow decay: 0.5%

Search for $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ and $\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$





$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e) < 3.9\times10^{-4}$ $\mathcal{B}\left(\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e\right) < 3.3\times10^{-4}$



Λ^* state	CQM [8]	NRQM [9]	LFQM [10]	LQCD [11]
$\Lambda(1520)$	10.00	5.94	—	5.12 ± 0.82
$\Lambda(1600)$	4.00	1.26	(0.7 ± 0.2)	—
$\Lambda(1890)$	—	3.16×10^{-2}	—	—
$\Lambda(1820)$	—	1.32×10^{-2}	—	—

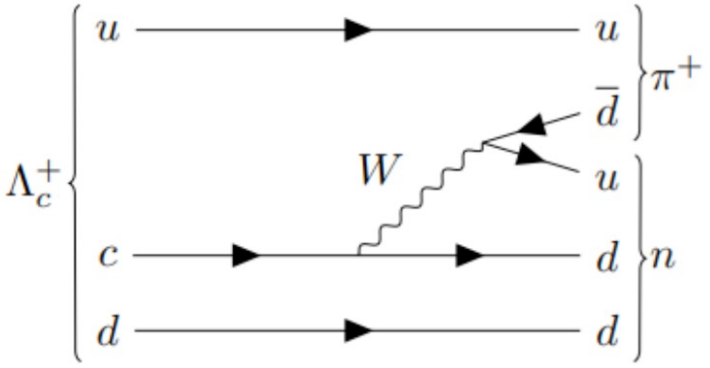
The predicted Branching fractions of $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ in units of 10^{-4}.

PLB 843,137993(2023)

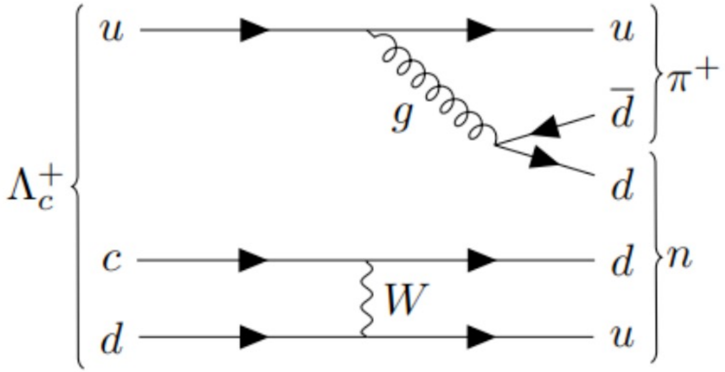
- Many theoretical calculations concerning $\Lambda_c^+ \to \Lambda^*$ form factors and Branching fractions.
- No significant signals are observed, and the upper limits on the decay branching fractions are obtained.
- Assuming all the $\Lambda\pi\pi$ combinations come from Λ^* :
  - ➢ $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3\times10^{-3}$
  - ➢ $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0\times10^{-3}$
  - ➢ Due to the limitation of statistics, the results are consistent with all theoretical calculations.
  - ➢ $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$ is consistent with the one measured via $\mathbf{\Lambda_c^+ \to \Lambda(1520)[\to pK^-]e^+\nu_e}$ [Phys. Rev. D 106, 112010 (2023)].

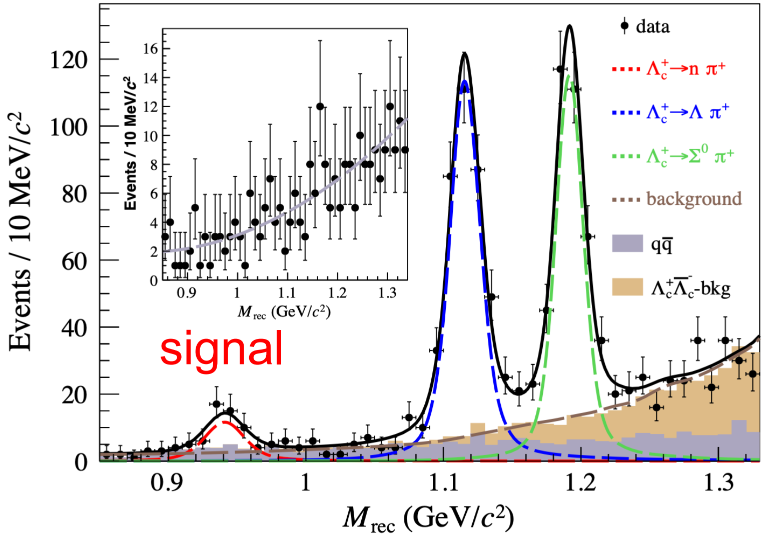
Measurement of $\Lambda_c^+ \to n\pi^+$

Internal W emission



W exchange





signal

Experimental input

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

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

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

- Studies of nonfactorizable components are critical to understanding the underlining dynamics of charmed baryon decays.

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

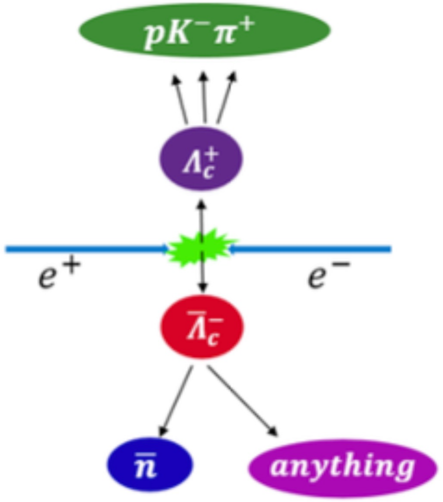
- The branching fraction and R value disagrees with the most predictions of phenomenological models, implying that the non-factorization contributions are overestimated.
- The results from this analysis provide an essential input for the phenomenological studies on the underlying dynamics of charmed baryon decays.

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

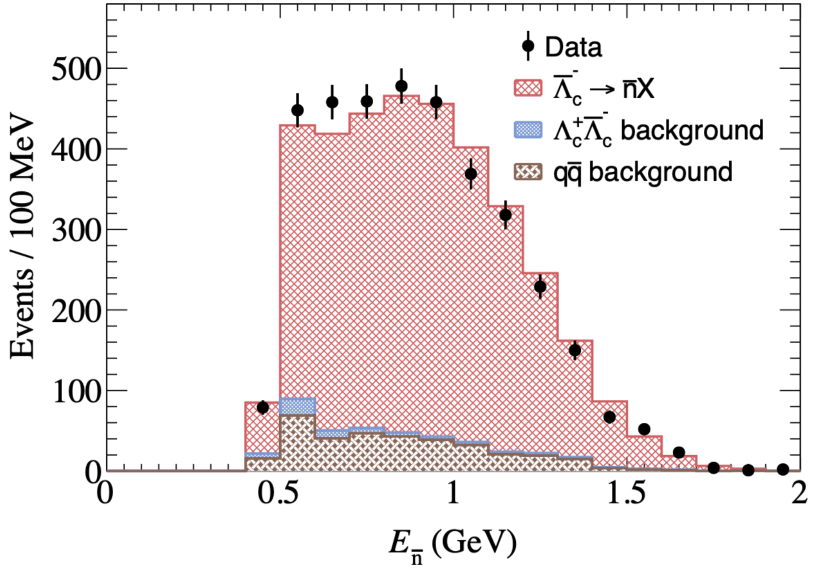
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4)\times10^{-4}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08 \pm 0.05)\times10^{-2}$
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08 \pm 0.07)\times10^{-2}$
- $R = \frac{\mathcal{B}(\Lambda_c^+\to n\pi^+)}{\mathcal{B}(\Lambda_c^+\to p\pi^0)} > 7.2\ at\ 90\%\ \mathrm{C.L.}$
- 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)

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times10^{-4}$	R	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165

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



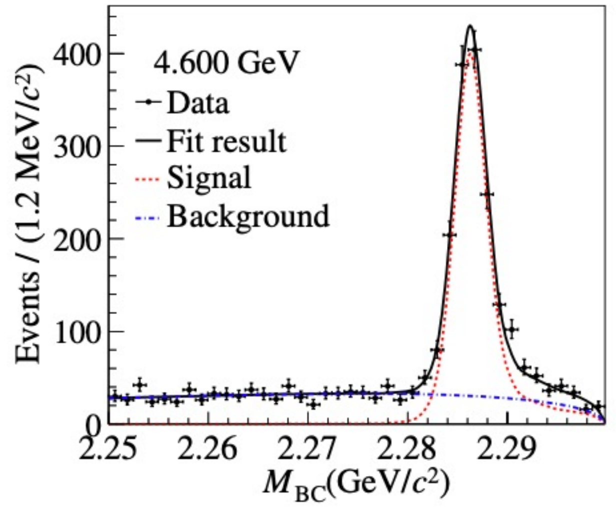
arXiv 2210.09561



- Data-driven technique to model $\bar{n}$ behavior in the detector.
- The deposited energy in EMC ($E_{\bar{n}}$) is used to identify $\bar{n}$.
- $\mathcal{B}(\overline{\Lambda}_c^- \to \bar{n}X) = (33.5 \pm 0.7 \pm 1.2)\%$
- The branching fraction of the inclusive decay is greater than the sum of the known exclusive decays, that is about 25%, which means that about one-fourth of the Λ_c^+ decays with a neutron in the final state remain to be explored in experiments.
- The result indicates the existence of an asymmetry in $\mathcal{B}(\Lambda_c^+ \to nX)$ and $\mathcal{B}(\Lambda_c^+ \to pX)$.

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

- BF of decay $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^0$ has been measured by BESIII with high precision [Phys. Rev. Lett. 116, 052001 (2016)], but no previous study on intermediate structure.
- Perform Partial Wave Analysis to obtain the information of intermediate resonances $\rho^+, \Sigma(1385)^+, \Sigma(1385)^0$ and the decay asymmetry.



Signal purity > 80%

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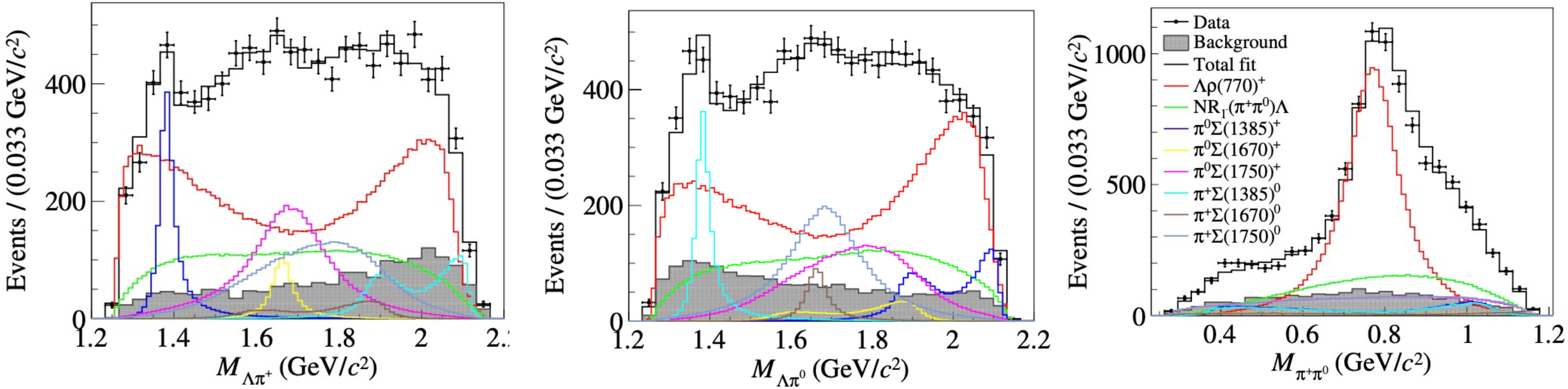
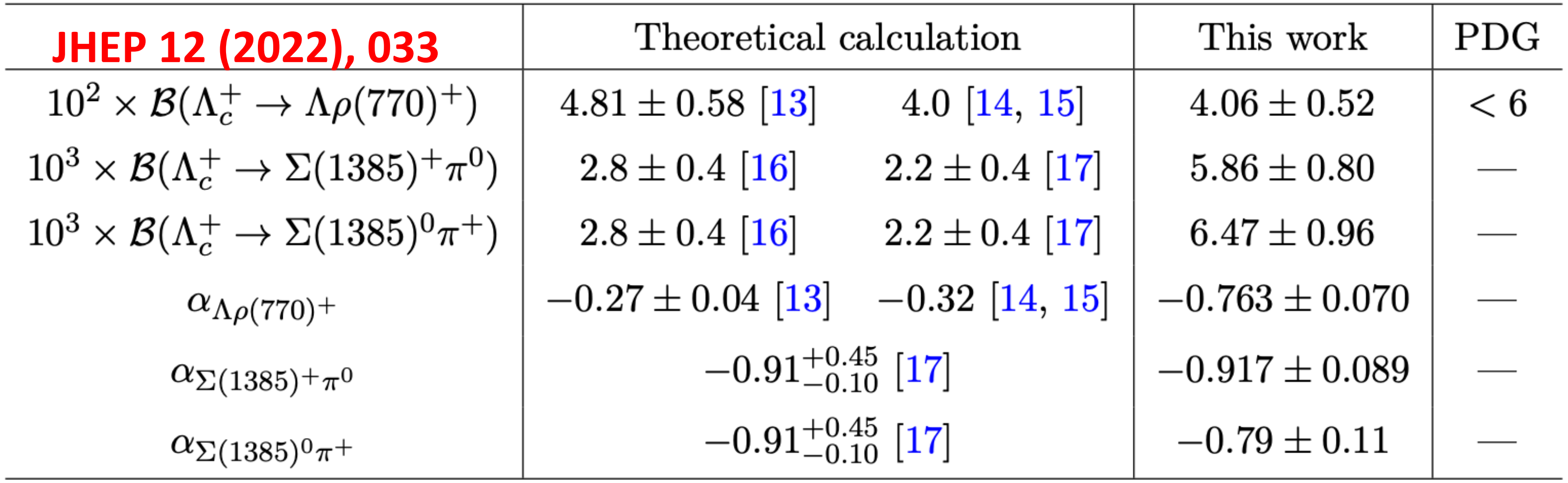


Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

1. The first PWA of the charmed baryon hadronic decay at BESIII.
2. The decay asymmetry parameters for the resonant components are determined for the first time.
3. Consistent with some theoretical predictions. None of them is able to explain both the BFs and the decay asymmetries.



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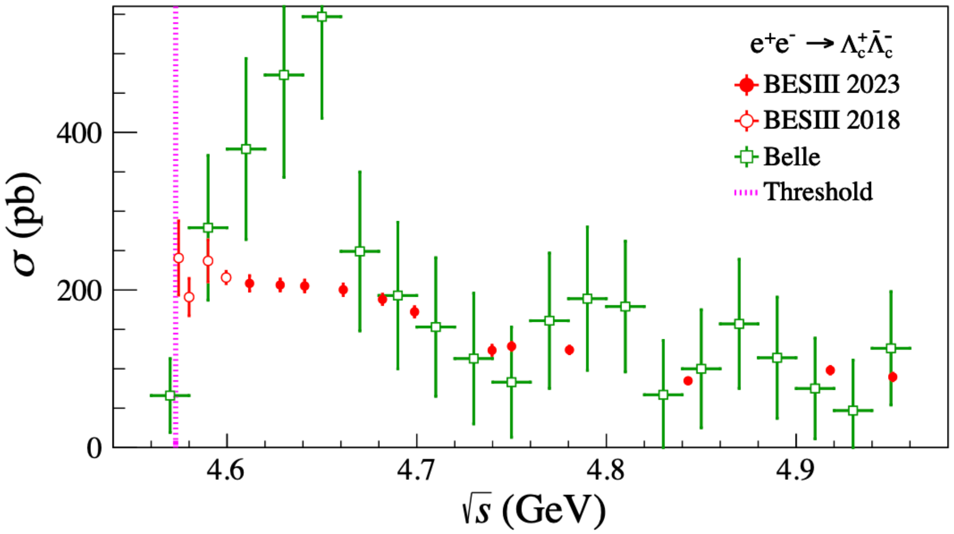
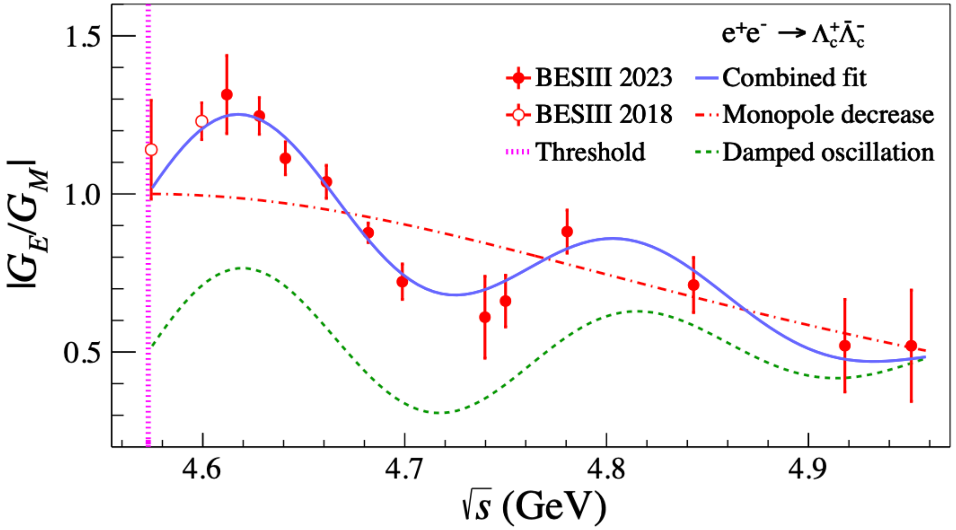
	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$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

[13] C. Q. Geng, C. W. Liu and T. H. Tsai, Phys. Rev. D 101 (2020) 053002.
[14] H. Y. Cheng and B. Tseng, Phys. Rev. D 46(1992) 1042.
[15] H. Y. Cheng and B. Tseng, Phys. Rev. D 55 (1997) 1697.
[16] Y. K. Hsiao, Q. Yi, S. T. Cai and H. J. Zhao, Eur. Phys. J. C 80 (2020) 1067.
[17] C. Q. Geng, C. W. Liu, T. H. Tsai and Y. Yu, Phys. Rev. D 99 (2019) 114022.

Energy-Dependent Electromagnetic Form Factors of Λ_c^+



arXiv:2307.07316



- The Born cross sections and effective form factors ($|G_{\mathrm{eff}}|$) are determined.

$$|G_{\mathrm{eff}}| = \sqrt{\frac{\sigma}{\frac{\sigma_0}{3}\left(1+\frac{\kappa}{2}\right)}},$$

- No indication of the resonant structure Y (4630), as reported by Belle [Phys. Rev. Lett. 101, 172001 (2008)].
- No oscillatory behavior is discerned in the $|G_{\mathrm{eff}}|$ energy-dependence of Λ_c^+, in contrast to what is seen for the proton and neutron cases.
- Form factor ratio $|G_E/G_M|$ is observed, which can be well described by an oscillatory function.

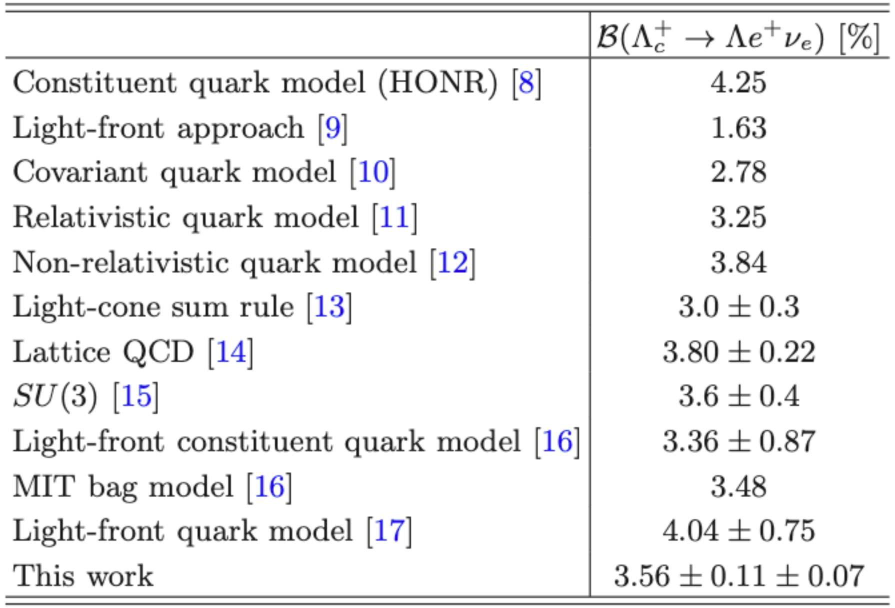
$$|G_E/G_M|(s) = \frac{1}{1+\omega^2/r_0}\left[1+r_1 e^{-r_2\omega}\sin(r_3\omega)\right],$$

Summary

- Recent results on Λ_c^+ SL and hadronic decays at BESIII are reported.
- These measurements provide important inputs for understanding the decay property of charmed baryons.
- BESIII collected approximately 5.85 fb^{-1} threshold data. More results of Λ_c^+ will be reported in the future.
- An upgrade of BEPCII (BEPCII-U) has been approved in July 2021:
  The optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum center-of-mass energy to 5.6 GeV.

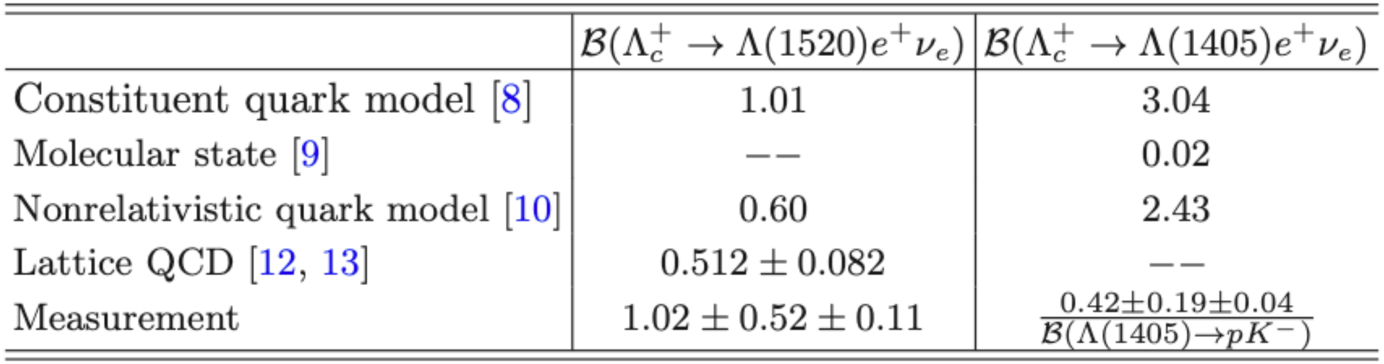
Thanks for your attention!

Reference



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

[8] Phys. Rev. C 72, 035201 (2005).
[9] Chin. Phys. C 42, 093101 (2018).
[10] Phys. Rev. D 93, 034008 (2016).
[11] Eur. Phys. J. C 76 628 (2016).
[12] Phys. Rev. D 95, 053005 (2017); Phys. Rev. D 95, 099901(E) (2017).
[13] Phys. Rev. D 80, 074011 (2009).
[14] Phys. Rev. Lett. 118, 082001 (2017).
[15] Phys. Lett. B 792, 214 (2019).
[16] Phys. Rev. D 101, 094017 (2020).
[17] Phys. Rev. D 104, 013005 (2021).



	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e)$
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	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to pK^-)}$

[8] Phys. Rev. C 72, 035201 (2005).
[9] Rev. D 93, 014021 (2016).
[10] Phys. Rev. D 95, 053005 (2017);
Phys. Rev. D 95, 099901(E) (2017).
[12] Phys. Rev. D 105, L051505 (2022).
[13] Phys. Rev. D 105, 054511 (2022).

Formula of α_ρ and interference

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\Theta_\Lambda} \propto 1 + \alpha_{\Lambda\rho(770)^+} \cdot \alpha_\Lambda \cdot \cos\Theta_\Lambda$$

$$\begin{aligned}\alpha_{\Lambda\rho(770)^+} &= \frac{|H^\rho_{\frac{1}{2},1}|^2 - |H^\rho_{-\frac{1}{2},-1}|^2 + |H^\rho_{\frac{1}{2},0}|^2 - |H^\rho_{-\frac{1}{2},0}|^2}{|H^\rho_{\frac{1}{2},1}|^2 + |H^\rho_{-\frac{1}{2},-1}|^2 + |H^\rho_{\frac{1}{2},0}|^2 + |H^\rho_{-\frac{1}{2},0}|^2} \\ &= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^\rho_{0,\frac{1}{2}} \cdot \bar{g}^\rho_{1,\frac{1}{2}} - g^\rho_{1,\frac{3}{2}} \cdot \bar{g}^\rho_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^\rho_{0,\frac{1}{2}} \cdot \bar{g}^\rho_{1,\frac{3}{2}} + g^\rho_{1,\frac{1}{2}} \cdot \bar{g}^\rho_{2,\frac{3}{2}}\right)}{|g^\rho_{0,\frac{1}{2}}|^2 + |g^\rho_{1,\frac{1}{2}}|^2 + |g^\rho_{1,\frac{3}{2}}|^2 + |g^\rho_{2,\frac{3}{2}}|^2}\end{aligned}$$

I.F.	$\Lambda + NR_{1^-}$	$\Sigma(1385)^0\pi^+$	$\Sigma(1385)^+\pi^0$	$\Sigma(1670)^0\pi^+$	$\Sigma(1670)^+\pi^0$	$\Sigma(1750)^0\pi^+$	$\Sigma(1750)^+\pi^0$
$\Sigma(1385)^0\pi^+$	-0.50 ± 0.38						
$\Sigma(1385)^+\pi^0$	-0.76 ± 0.36	-0.05 ± 0.04					
$\Sigma(1670)^0\pi^+$	-0.36 ± 0.17	-0.00 ± 0.00	-0.66 ± 0.09				
$\Sigma(1670)^+\pi^0$	-0.34 ± 0.15	-0.58 ± 0.12	0.00 ± 0.00	0.04 ± 0.02			
$\Sigma(1750)^0\pi^+$	-8.1 ± 3.1	-0.03 ± 0.00	0.43 ± 0.07	-0.01 ± 0.00	0.08 ± 0.05		
$\Sigma(1750)^+\pi^0$	-7.2 ± 3.1	0.35 ± 0.08	-0.02 ± 0.00	0.23 ± 0.05	-0.00 ± 0.00	-6.23 ± 0.92	
$\Lambda\rho(770)^+$	-2.7 ± 4.4	-5.94 ± 0.56	-6.01 ± 0.46	0.72 ± 0.29	1.29 ± 0.26	-2.1 ± 1.3	-3.1 ± 1.3