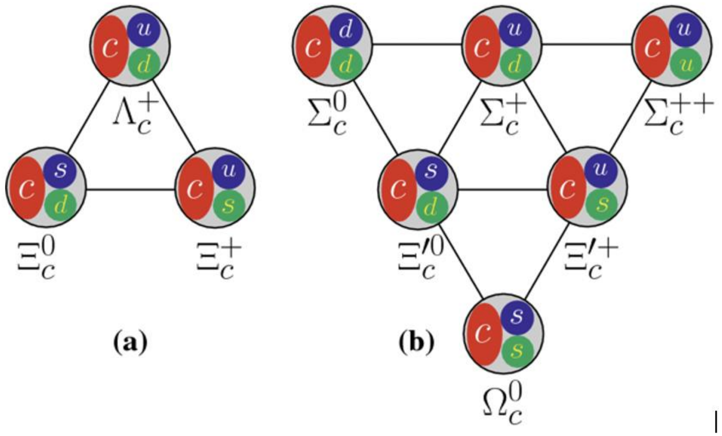

粲重子实验研究的最近进展和展望

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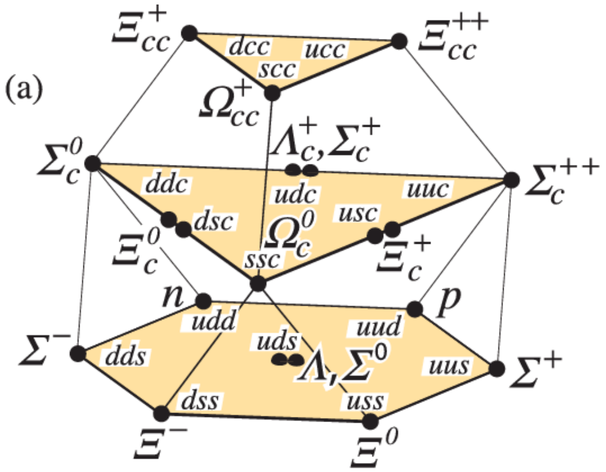
Outline

- Introduction to the charmed baryons
- Selected recent results on charmed baryons from BESIII/LHCb/Belle/Belle II
- Prospect and Summary

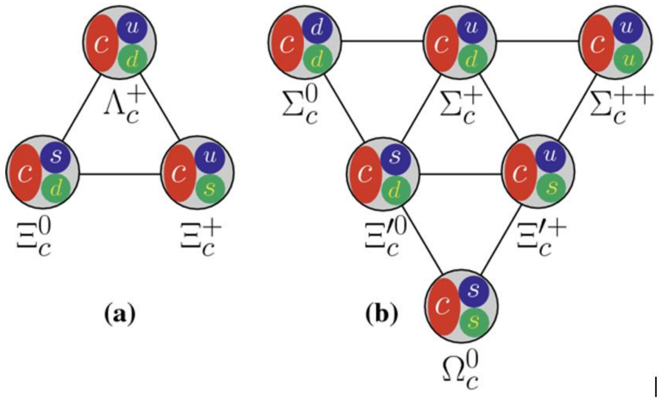
The charmed baryon family

- 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

（Doubly charmed baryon topics covered by Jibo’s talk.）

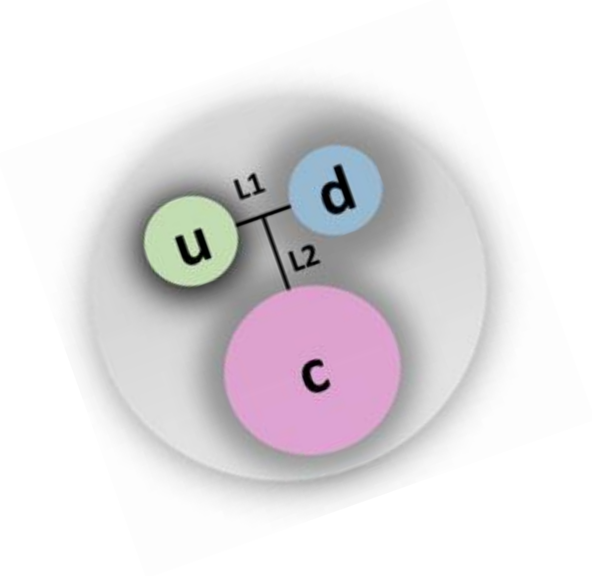


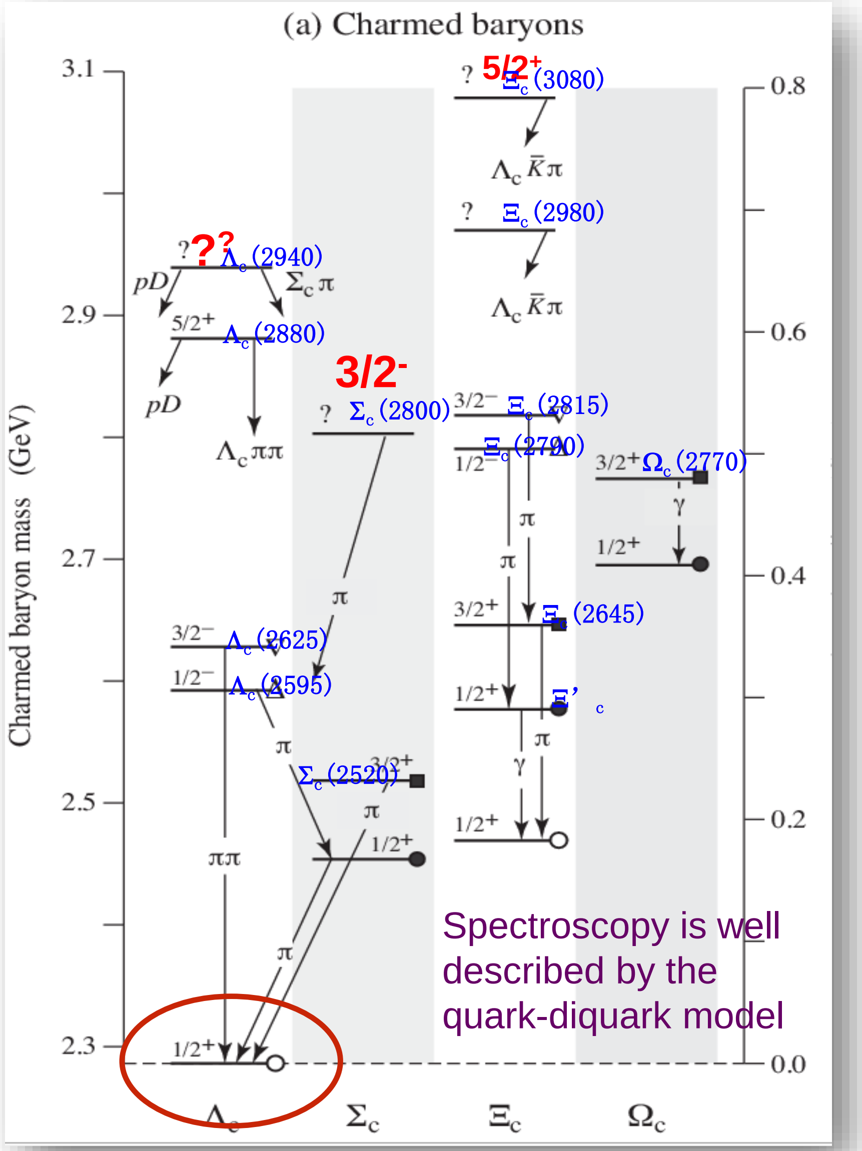
- ➢ Λ_c^+: decay only weakly, many recent experimental progress since 2014
- ➢ Σ_c : $\mathrm{B}(\Sigma_c \to \Lambda_c^+\pi)$~100%; $\mathrm{B}(\Sigma_c \to \Lambda_c^+\gamma)$?
- ➢ Ξ_c : decay only weakly; absolute BF measured with poor precision
- ➢ Ω_c : decay only weakly; no absolute BF measured



Λ_c^+ : cornerstone of charmed baryon spectroscopy

- **The lightest charmed baryon**
- **Most of the charmed baryons will eventually decay to Λ_c**
- **The Λ_c 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**

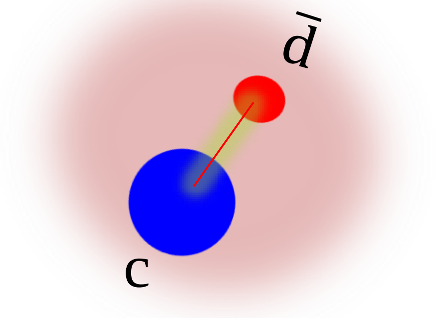


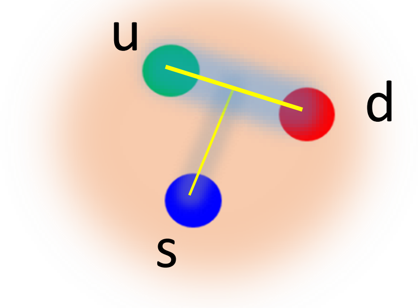


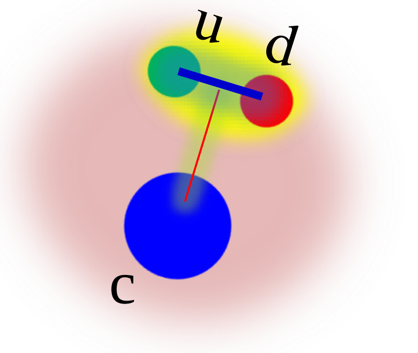
Quark model picture

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$\bar{\text{d}}$])
$m_d << m_c$ → **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)

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

Charm Facilities

Charm factory

- Threshold production: No boost
- Small X-section : Lowest Statistics
- Quantum coherence
- Inclusive charm, neutrals and neutrinos
- Absolute BFs

$$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$$
$$e^+e^- \rightarrow D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$$
$$e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$$

BESIII, STCF in the future

B factory

- Low background
- Low statistics
- Low boost
- Good for neutrals and neutrinos
- Some Absolute BFs

$$e^+e^- \rightarrow c\bar{c}$$
+ some other Stuff

Belle / Belle II

Hadron collider

- High background
- High statistics
- High boost
- Challenging for neutrals and neutrinos
- Complex and biasing triggers

$$p\bar{p} \rightarrow c\bar{c}$$
+ lots of other Stuff

LHCb

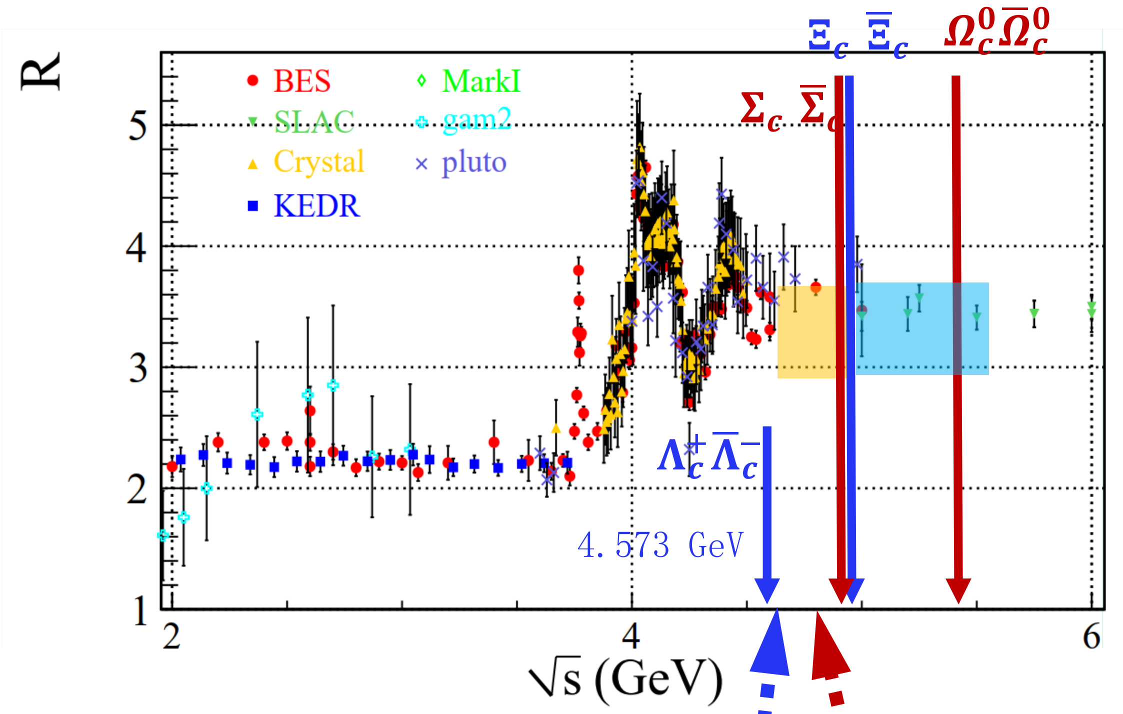
Recent studies on the Λ_c^+ at BESIII

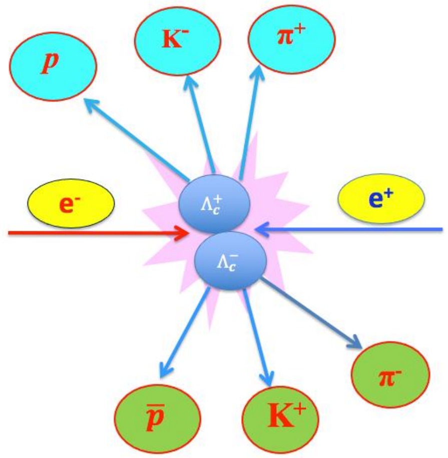
- Production cross-section at e^+e^- collision
  - ☐ $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ line shape and FF : PRL 131.191901(2023)
  - ☐ $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^{*-}$: PRD 109, L071104 (2024)
- Rare decays
  - ☐ $\Lambda_c^+ \to \gamma\Sigma^+$: PRD107, 052002 (2023).
- Λ_c^+ leptonic decays
  - ☐ $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$: PRD 108.L031105 (2023).
  - ☐ $\Lambda_c^+ \to Xe^+\nu_e$: PRD 107.052005 (2023).
  - ☐ $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_S^0\pi^-e^+\nu_e$: PLB 843.137993 (2023).
- Λ_c^+ hadronic decays(two body)
  - ☐ $\Lambda_c^+ \to p\eta, p\omega$: JHEP 11.137 (2023).
  - ☐ $\Lambda_c^+ \to p\pi^0$: PRD 109, L091101 (2024).
  - ☐ $\Lambda_c^+ \to \Xi^0K^+$: PRL 132, 031801 (2024).
- Λ_c^+ hadronic decays(multi-body)
  - ☐ $\Lambda_c^+ \to n\pi^+\pi^0$、$n\pi^+\pi^-\pi^+$、$nK^-\pi^+\pi^+$: CPC 47.023001 (2023).
  - ☐ $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$: PRD 109, 072010 (2024).
  - ☐ $\Lambda_c^+ \to \Sigma^+K^+K^-, \Sigma^+\phi, \Sigma^+K^+\pi^-(\pi^0)$:JHEP 09 125(2023)
  - ☐ $\bar{\Lambda}_c^- \to \bar{n}X$: PRD 108.L031101 (2023).
  - ☐ $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$: PRD 109, 032003 (2024).
  - ☐ $\Lambda_c^+ \to \Sigma^-K^+\pi^+$: PRD 109, L071103 (2024).
  - ☐ $\Lambda_c^+ \to \Xi^0K^+\pi^0$: PRD 109, 052001 (2024).
  - ☐ $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$:PRD 109, 053005 (2024)
  - ☐ $\Lambda_c^* \to \Lambda_c^+\pi^+\pi^-$: arXiv2401.09225.

More details can be found in Prof. Geng Cong's talk.

Charmed baryon thresholds

$\Sigma_c\ \bar{\Sigma}_c$





BESIII energy upgrades:

4.6 GeV (Phase I, 2014)

→ 4.95 GeV(Phase II, 2021)

→ 5.6 GeV (Phase III, planned in 2024)

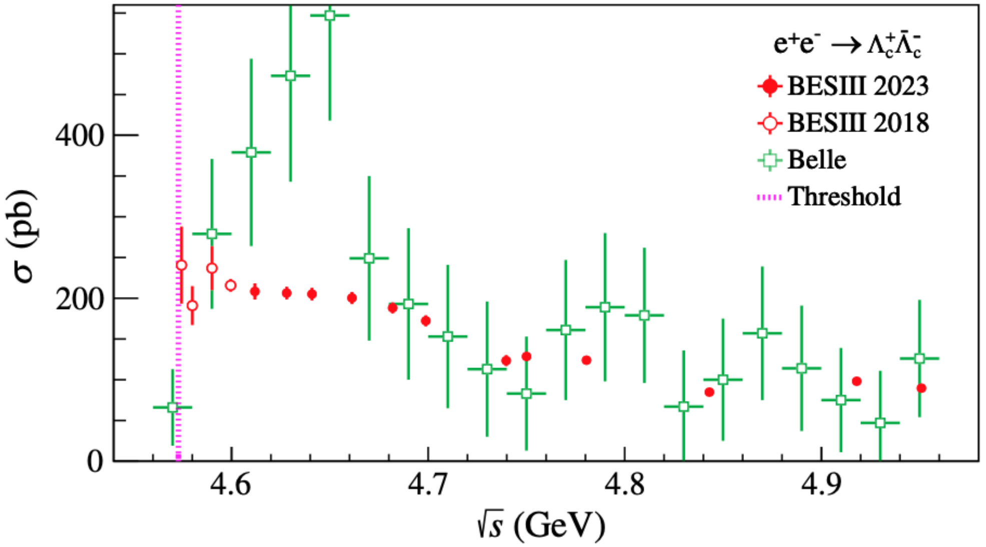
Production measurement near threshold

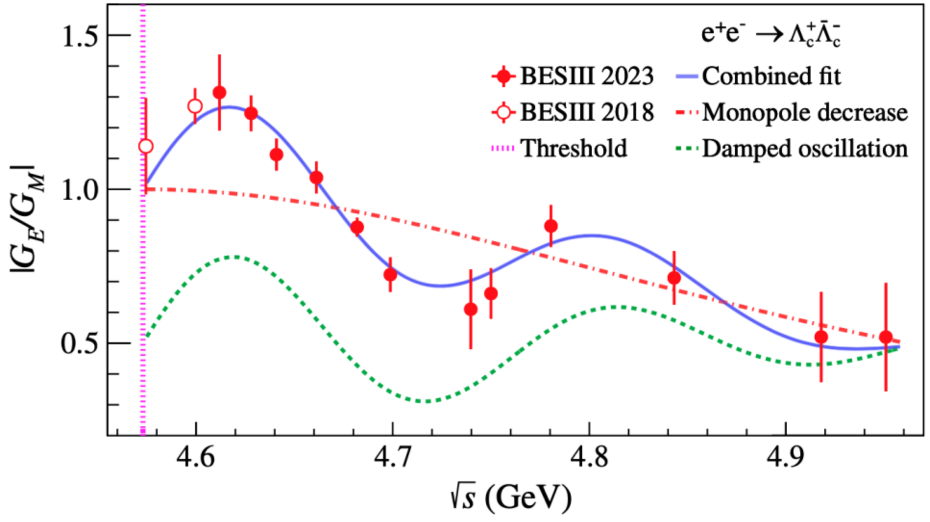
PRL 131.191901(2023)

- $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ cross section are measured at twelve energy points from 4.612-4.951GeV .

$$\sigma_{\pm} = \frac{N_{\mathrm{ST}}^{\pm}}{\varepsilon_{\mathrm{ST}}^{\pm} f_{\mathrm{ISR}} f_{\mathrm{VP}} \mathcal{L}_{\mathrm{int}} N_{\mathrm{DT}}} \sum_{n=1}^{9} \left(\frac{N_{\mathrm{ST}}^{\mp,n} \varepsilon_{\mathrm{DT}}^{n}}{\varepsilon_{\mathrm{ST}}^{\mp,n}} \right),$$

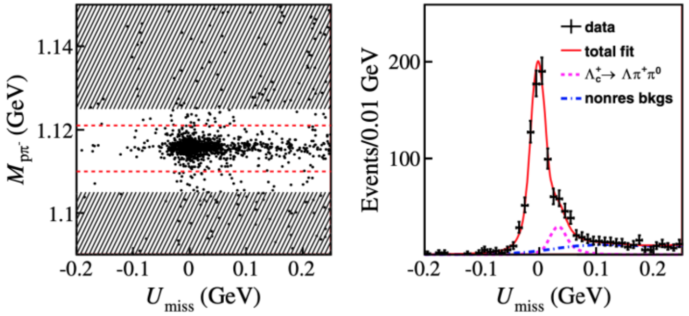
- Indicate no enhancement around Y(4630) resonance. =>Conflict with Belle.
- $|G_E/G_M|$ ratio are derived by fitting to angular distribution.
- The oscillations on $|G_E/G_M|$ ratio is significantly observed with higher frequency than that of the proton. $\Rightarrow$ may imply a non-trivial structure of the lightest charmed baryon.

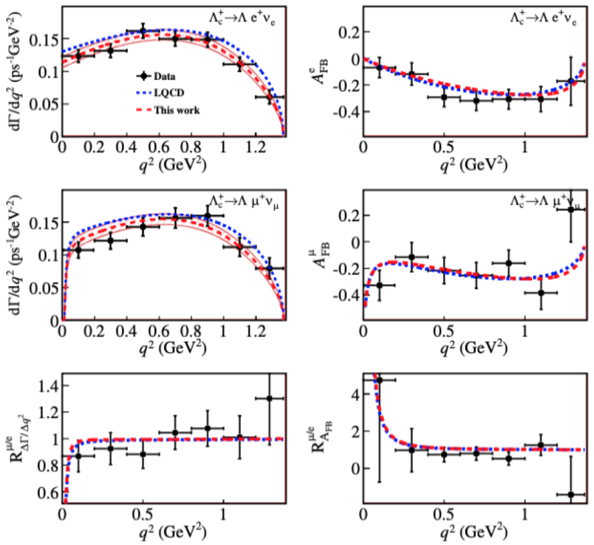




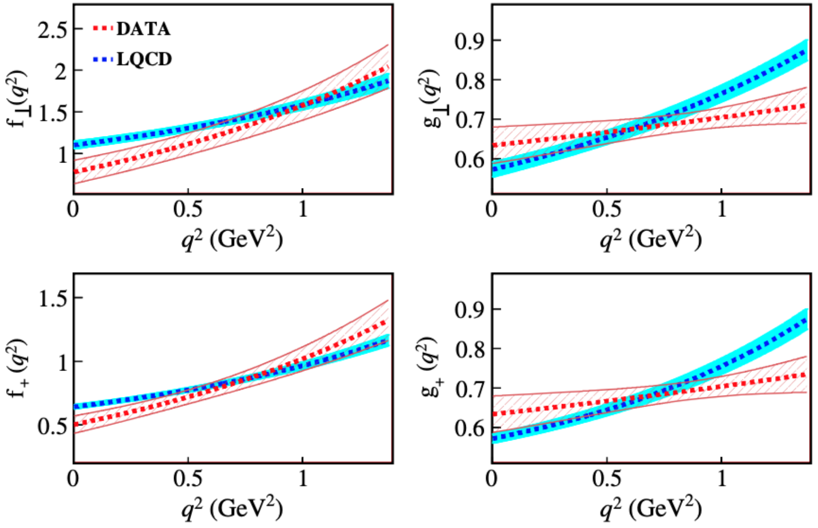
Form factors of $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

PRD 108.L031105 (2023)





$$\frac{d^4\Gamma}{dq^2 d\cos\theta'_\ell d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4}\cdot\frac{Pq^2(1-m_\ell^2/q^2)^2}{24M^2_{\Lambda_c}}\Big\{\frac{3}{8}(1-\cos\theta'_\ell)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{8}(1+\cos\theta'_\ell)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta'_\ell[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta'_\ell\sin\theta_p$$
$$\times[(1-\cos\theta'_\ell)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta'_\ell)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]+\mathcal{H}_{m_\ell^2}\Big\},$$



- BF is updated to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.48 \pm 0.14_{stat} \pm 0.10_{syst})\%$=>3times more precise.
- LFU are reported $(0.98 \pm 0.05_{stat} \pm 0.03_{syst})$ => compatible with Standard Model(0,97).
- Form-factors parameters for$\Lambda_c^+ \to \Lambda l^+\nu_l$ are determined to test and calibrate for LQCD.

$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_S^0\pi^-e^+\nu_e$

PLB 843.137993 (2023)

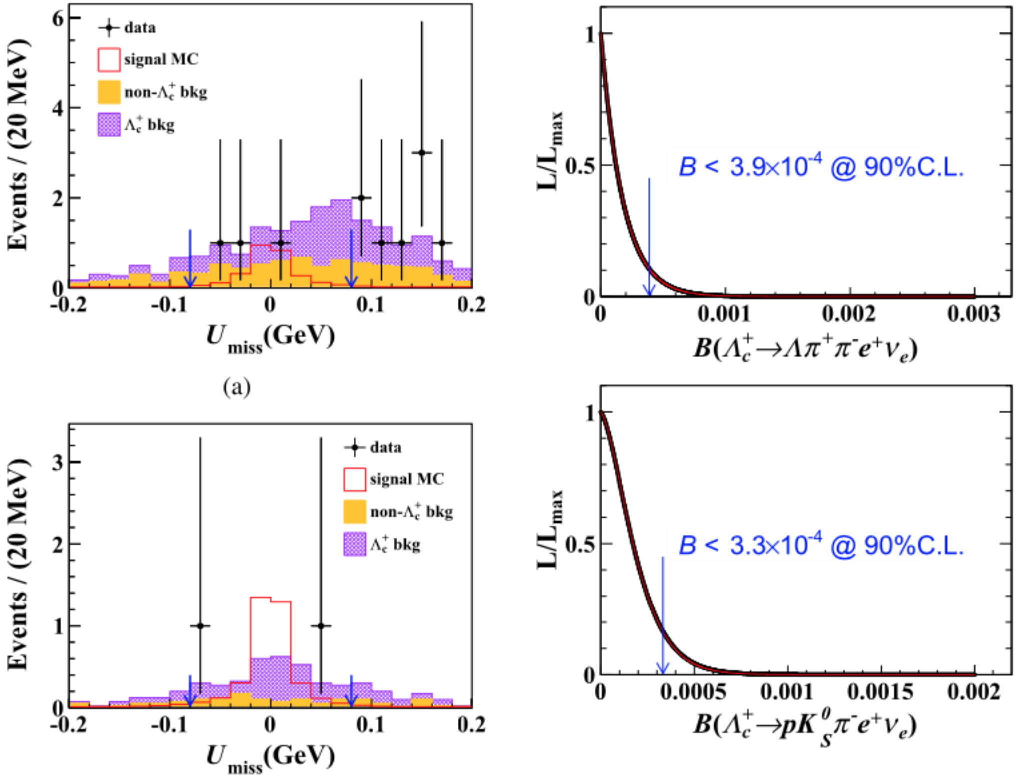


Table 1
The BFs for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ predicted by different theoretical models, in units of 10^{-4}.

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}	––	––

- **4.5fb^{-1} e$^+$e$^-$ annihilation data are used to search $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_s^0\pi^-e^+\nu_e$**

- **No significant signal is observed and**
- **$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e) < 3.9\times10^{-4}$ and $\mathcal{B}(\Lambda_c^+ \to pK_s^0\pi^-e^+\nu_e) < 3.3\times10^{-4}$ at 90% CL.**
- **$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3\times10^{-3}$ and $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0\times10^{-3}$ at 90% CL assuming all $\Lambda\pi^+\pi^-$ combinations come from Λ^*.**

- **Limited sensitivity to identify different theoretical calculations.**

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

PRL 128.142001 (2022)

PRD 109, L091101 (2024)

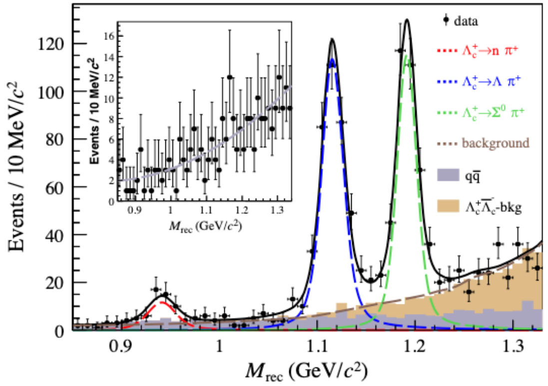
N($n\pi^+$)=50±9

- First singly Cabibbo-suppressed Λ_c^+ decay involved neutron was observed(7.3σ).
- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{stat} \pm 0.4_{syst}) \times 10^{-4}$.

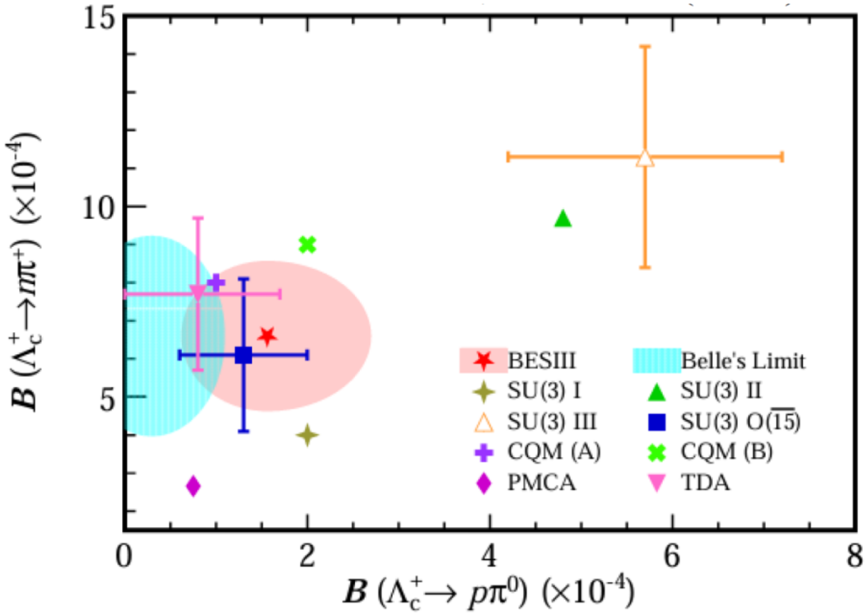
  =>Consistent with SU(3) flavor asymmetry prediction[PLB790,225(2019),]

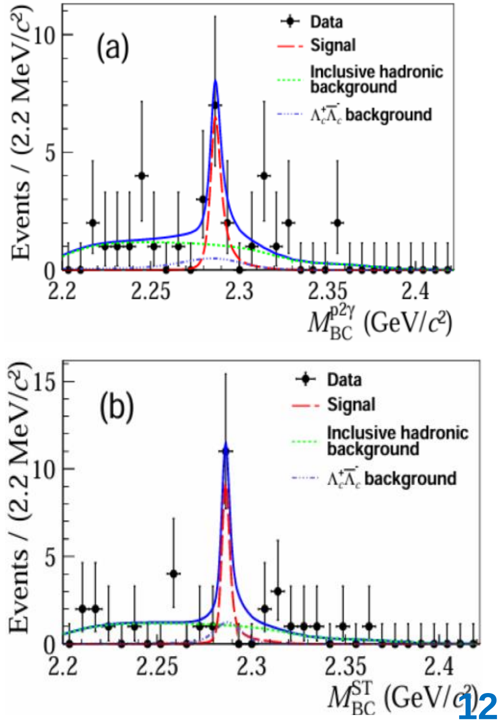
  =>twice larger than the dynamical calculation based on pole model and CA[PRD97,074028(2018)]
- $R = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} > 7.2$@90%C.L. ($\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ @90%C.L.from Belle)

  =>Disagrees with SU(3) asymmetry and dynamical calculation (2-4.7) while in consistent with SU(3) plus topological-diagram approach(9.6).
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.2_{syst}) \times 10^{-4}$; $R = 3.2^{+2.2}_{-1.2}$



More details can be found in Prof. Geng Cong's talk.





Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

PRL 132, 031801 (2024)

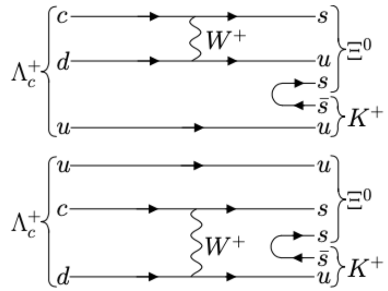
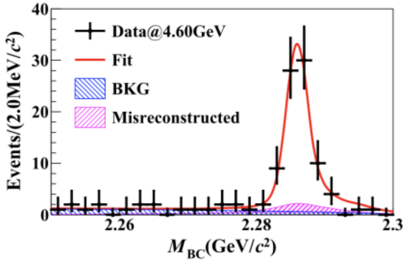


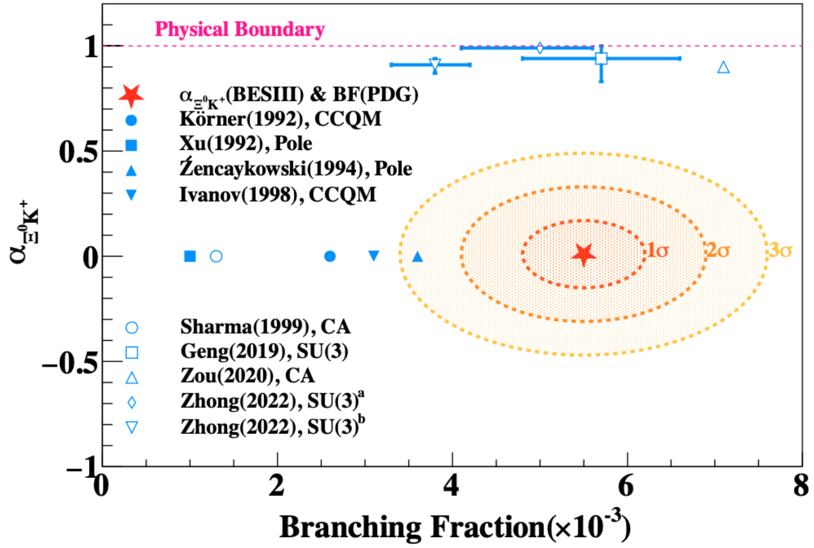
FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

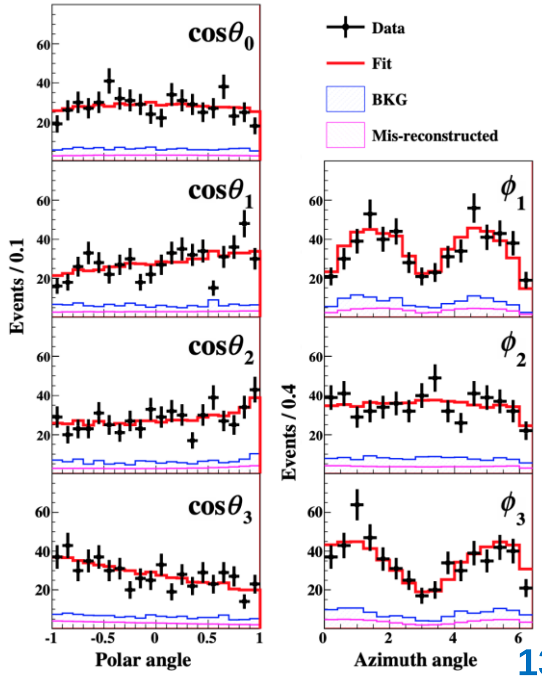
- Previous theoretical calculation on the BF lower than exp. measurement, which all predicted zero decay asymmetry
- BESIII confirmed the exp. result of BF in 2018 [PLB 783, 200 (2018)]
- In theory, BF is enhanced by enhancing the decay asymmetry close to 1

~378 signals



- three-level cascade decay $\Lambda_c^+ \to \Xi^0 K^+$, $\Xi^0 \to \Lambda\pi^0$, $\Lambda \to p\pi^-$
- First determination of decay asymmetry $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$, consistent with zero
- No theoretical model explains the current results
- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$



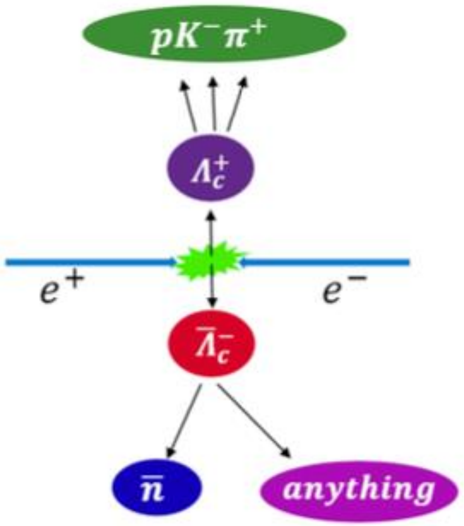


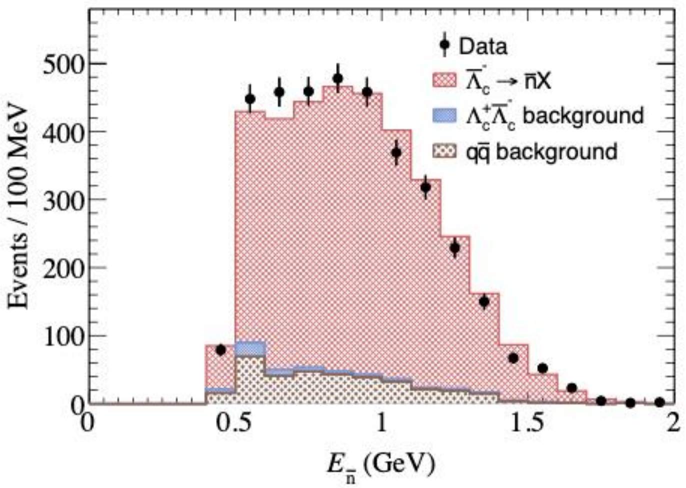
Λ_c^+ decay asymmetries

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0 K^+}$
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
PDG(for now) [24]	0.20 ± 0.50 (only BESIII)	-0.84 ± 0.09	-0.73 ± 0.18 (only BESIII)	-0.55 ± 0.11	-

BF measurement of $\bar{\Lambda}_c^- \to \bar{n}X$

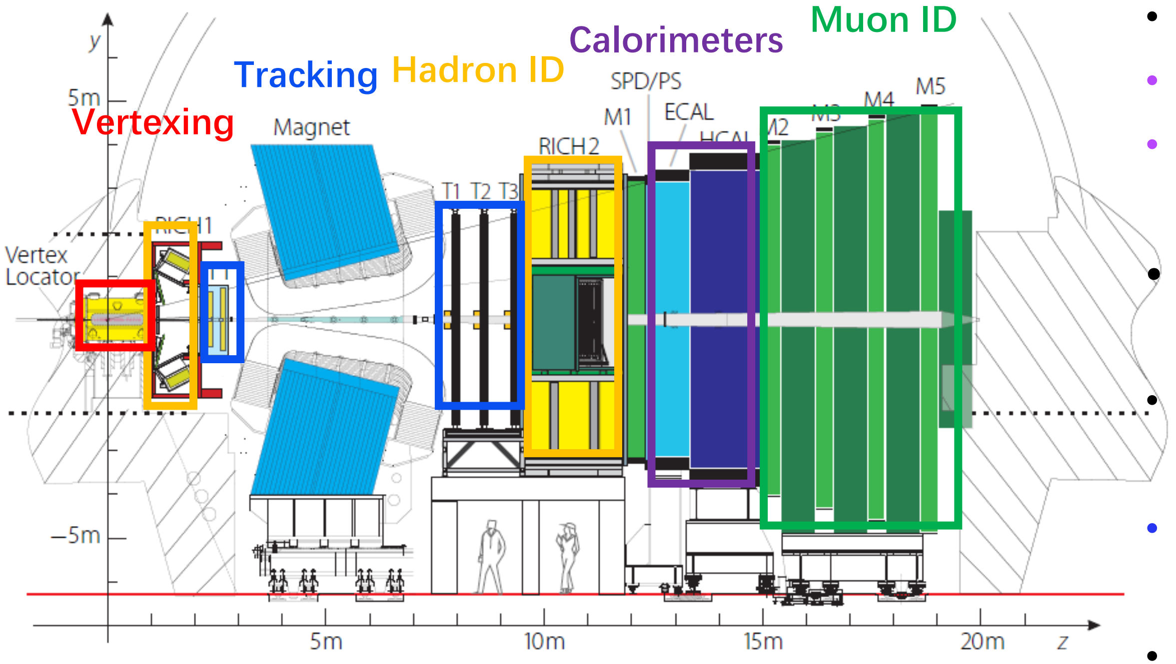
PRD 108.L031101 (2023).

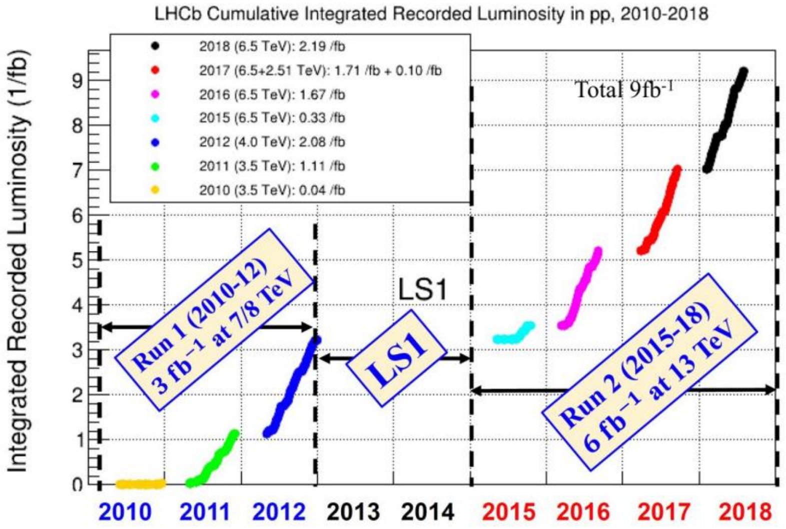




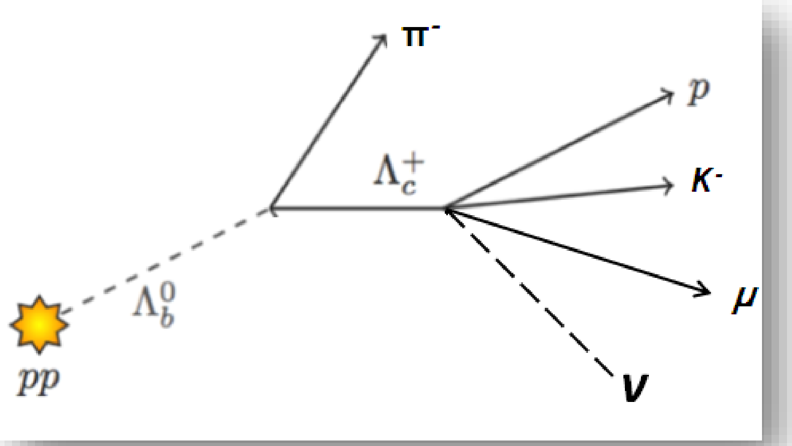
- The deposited energy in EMC is used to identify $\bar{n}$.
- Data-driven technique to model $\bar{n}$ behavior in the detector.
- Absolute BFs are measured to be
  $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n}X) = (33.5 \pm 0.7_{stat} \pm 1.2_{syst})\%$, precision up to 4%.
- All known exclusive process with neutron in final state is about 25%=>more space to be explored.
- Asymmetry between $\mathcal{B}(\Lambda_c^+ \to nX)$ and $\mathcal{B}(\Lambda_c^+ \to pX)$ is observed.

LHCb





- Huge Λc production at LHCb: ~100μb
- Prompt charm: using exclusive reconstruction
- Secondary charm from *b*-hadron decays with inclusive *b* triggers
- $\Lambda_c^+ \to pK^-\pi^+$ CF yields: 0.8M in 0.65/fb (~20% of Run I data)
- CS samples O(10^5) in Run I: BF measurement and CPV
- DCS $\Lambda_c^+ \to pK^+\pi^-$ can be measured with best precision
- Potential to set up the SL modes $pK^-\mu^+$n and $p\pi^-\mu^+$n



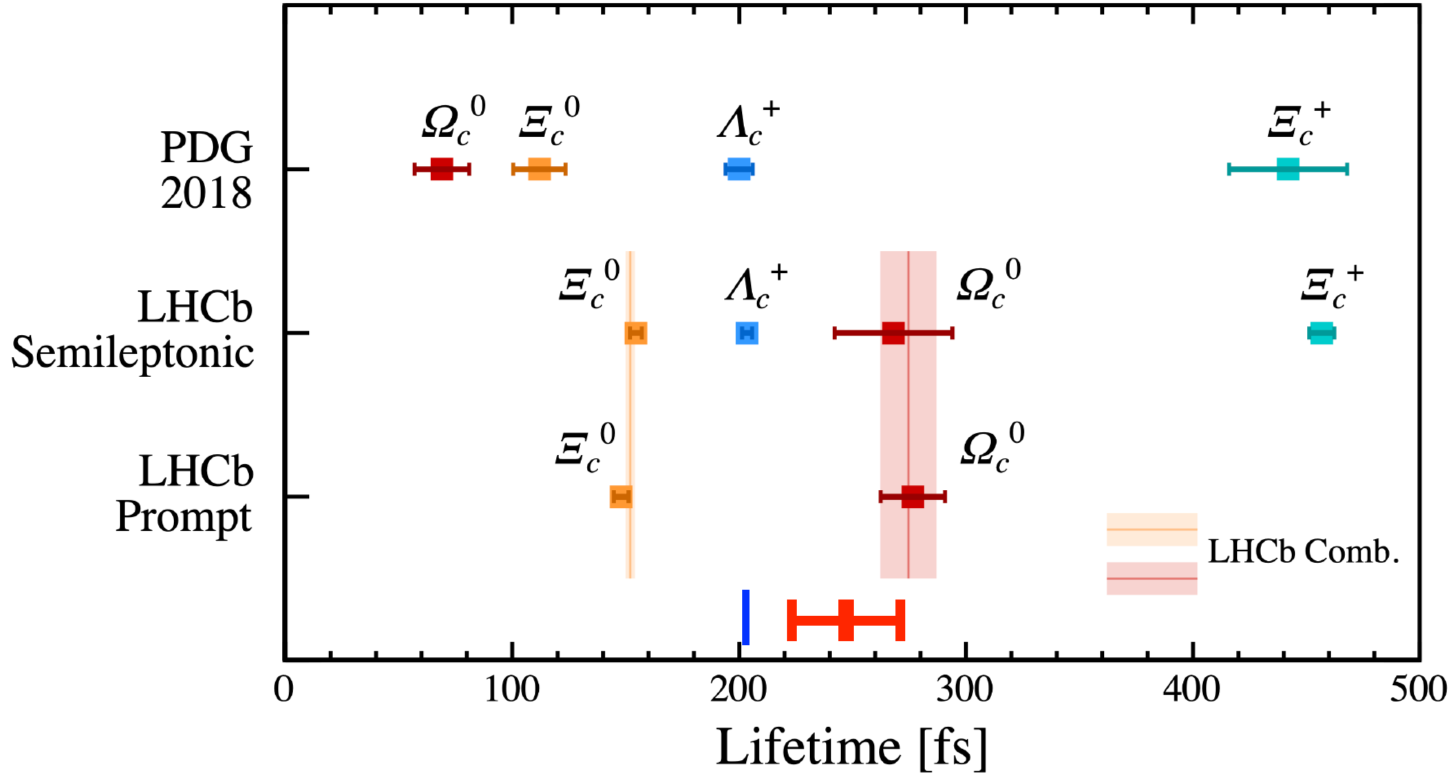
Charmed baryon results at LHCb

- singly charmed baryon
  - ✓ Ξ_c^+ mass [Phys. Rev. Lett. 113, 032001 (2014)]
  - ✓ BF for $\Lambda_c^+ \to pK^+\pi^-, pK^+K^-, p\pi^+\pi^-$ [JHEP 03, 043 (2018)]
  - ✓ CPV search in $\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$[JHEP 03, 182 (2018)]
  - ✓ Rare decay of $\Lambda_c^+ \to p\mu^+\mu^-$ [Phys. Rev. D 97, 091101 (2018)]
  - ✓ Lifetime of Ω_c^0 [Phys. Rev. Lett. 121, 092003 (2018)]
  - ✓ Lifetimes of Λ_c^+, Ξ_c^+ and Ξ_c^0 [Phys. Rev. D 100, 032001 (2019)]
  - ✓ CPV search in $\Xi_c^+ \to pK^-\pi^+$ [Eur. Phys. J. C 80, 986 (2020)]
  - ✓ Suppressed decay $\Xi_c^0 \to \Lambda_c^+\pi^-$ [Phys. Rev. D 102, 071101 (2020)]
  - ✓ Lifetime of Ω_c^0 and Ξ_c^0 [Sci. Bull. 67, 479 (2022)]
  - ✓ $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis [Phys. Rev. D 108, 012023 (2023)]
  - ✓ Λ_c^+ polarimetry [JHEP 07, 228 (2023)]
  - ✓ $\Omega_c^0 \to \Omega^-K^+, \Xi^-\pi^+$ and Ω_c^0 mass [Phys. Rev. Lett.132.081802 (2024)]
- doubly charmed baryon: Ξ_{cc}^{++} discovery and other researches since 2017
- charmed baryon spectroscopy
  - ✓ Λ_c^{**+} in $\Xi_c^+K^-$ via $\Lambda_b^0 \to D^0p\pi^-$ [JHEP 05, 030 (2017)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ via prompt production [Phys. Rev. Lett. 118,182001 (2017)]
  - ✓ Ξ_c^{**0} in $\Lambda_c^+K^-$ final states [Phys. Rev. Lett. 124, 222001 (2020)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ from $\Omega_b^- \to \Xi_c^+K^-\pi^-$ [Phys. Rev. D 104, L091102 (2021)]
  - ✓ Ω_c^{**0} in $\Xi_c^+K^-$ via prompt production [Phys. Rev. Lett. 131, 131902 (2023)]
- charmed baryon production in *pp* and *p*Pb collisions
  - Λ_c^+ in *pp* [NPB 871 (2013), JHEP06, 147 (2017)]
  - Λ_c^+ in pPb [JHEP 02, 102 (2019), JHEP06(2023)132]
  - Ξ_c^+ in pPb [Phys. Rev. C 109, 044901 (2024)]

Charm Baryon Lifetimes

HQE (up to order $1/m^3$): $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c) < \tau(\Xi_c^+)$

Obervation



Adapted from Nisar Nellikunnummel @ ICHEP 2022

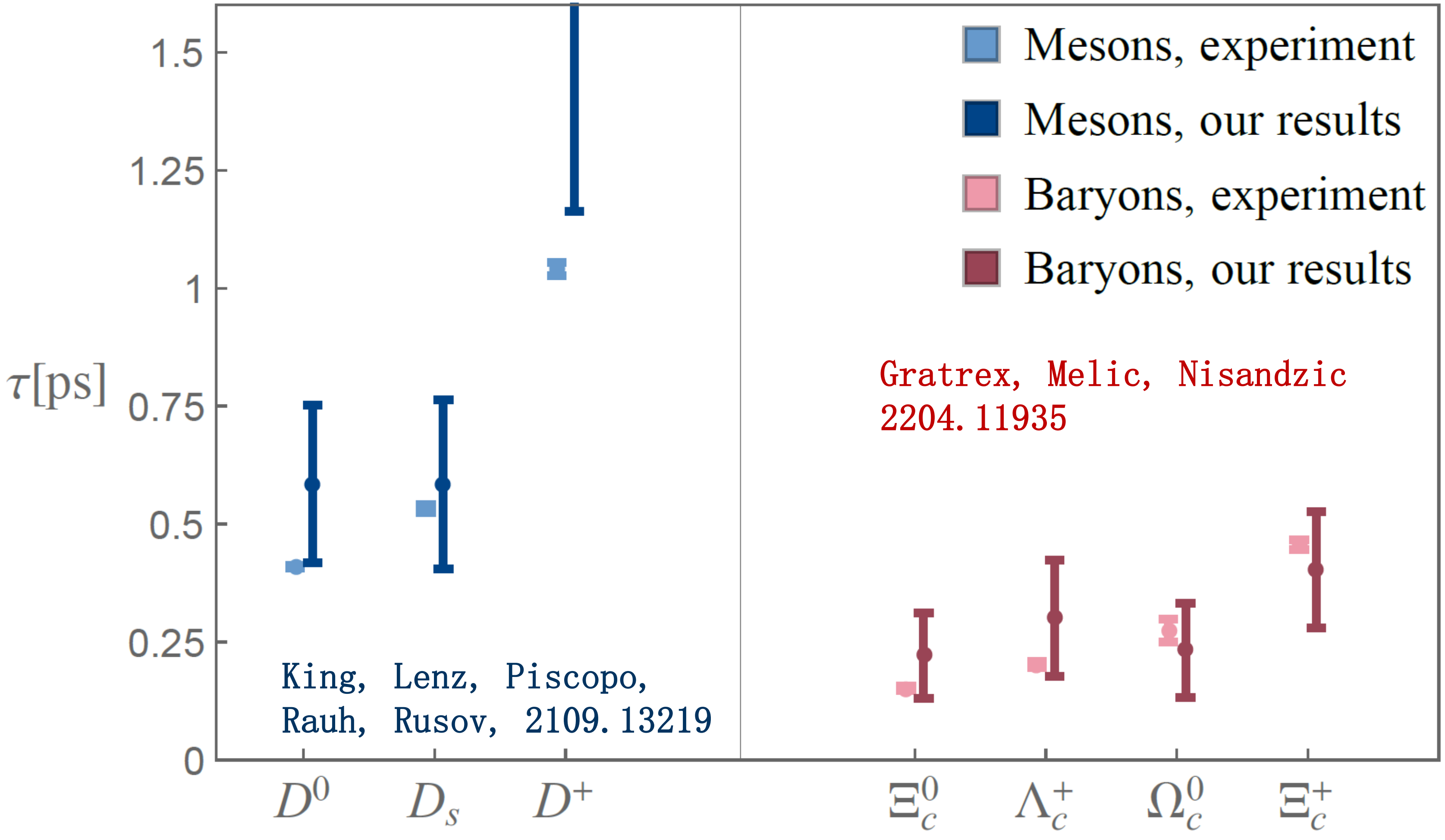
PRD 100 (2019) 3, 032001

Sci.Bull. 67 (2022) 5, 479-487

BELLE-II Ω_c^0: PRD 107 (2023) 3, L031103

BELLE-II Λ_c: PRL 130 (2023) 7, 071802

Charm lifetimes from HQE



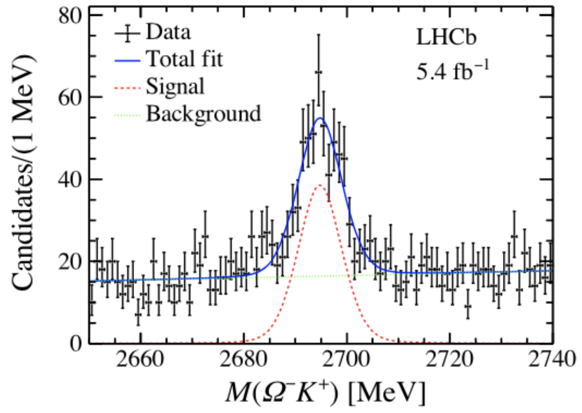
Another HQE-based calculation leading to compatible results:
Hai-Yang Cheng, Science Bulletin 67 (2022) 445–447

Mannel, Moreno, ivovarov 2304.08964 : inclusion of newly calculated NLO corrections to μ_G^2 would probably significantly reduce uncertainty

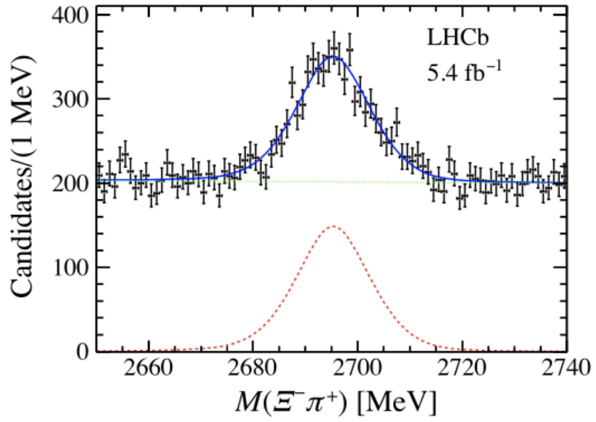
Satisfactory agreement with the experiment!

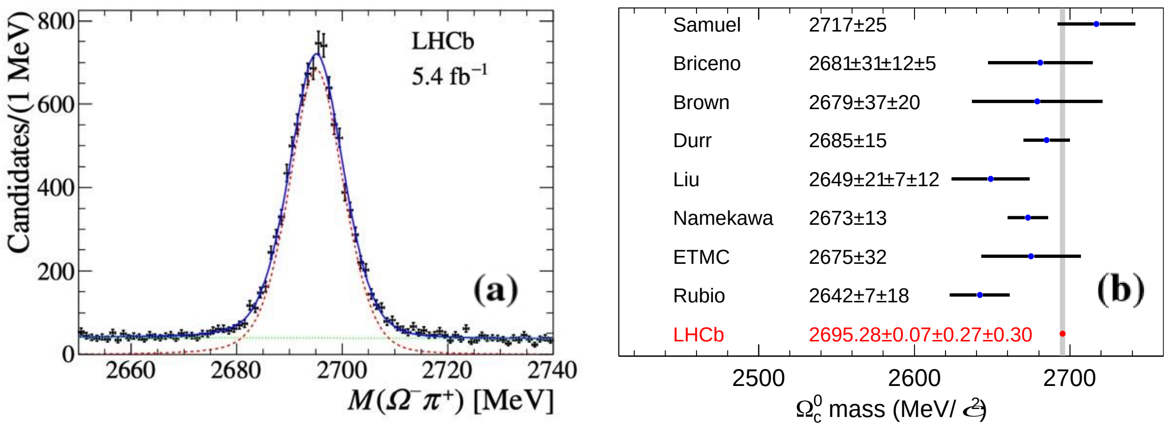
Observation of $\Omega_c^0 \to \Omega^- K^+$, $\Xi^-\pi^+$ and Ω_c^0 mass

PRL132.081802 (2024)



BF ratios	This work	CA model	LFQM	Naive estimation
$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}$	0.0608 ± 0.0064	-	-	0.0467
$\frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}$	0.1581 ± 0.0099	0.1038	0.0345	-





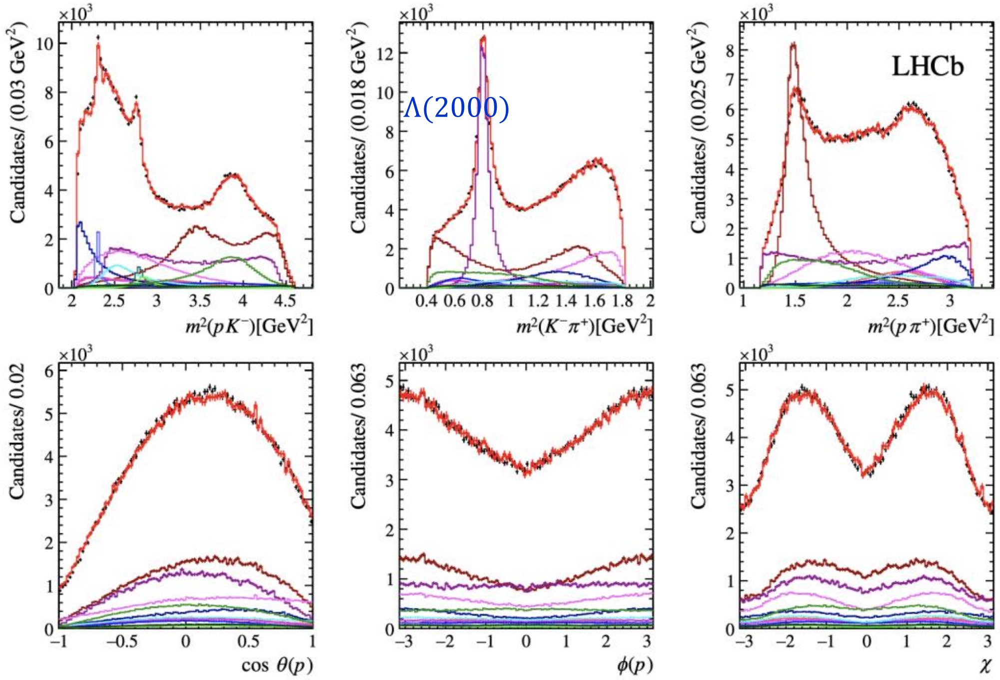
unit: MeV	$m_{\Lambda_c^+}$	$m_{\Xi_c^+}$	$m_{\Xi_c^0}$	$m_{\Omega_c^0}$
之前国际平均值	2286.46 ± 0.14	$2467.93^{+0.28}_{-0.40}$	2470.44 ± 0.28	2695.2 ± 1.7
LHCb 2014		$2467.97 \pm 0.14 \pm 0.17$		
LHCb 2023				$2695.28 \pm 0.07 \pm 0.40$
当前国际平均值	2286.46 ± 0.14	2467.95 ± 0.19	2470.44 ± 0.28	2695.28 ± 0.40

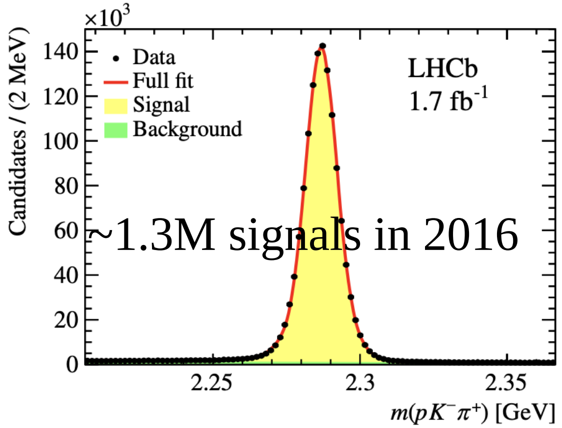
$\Lambda_c^+ \rightarrow pK^-\pi^+$ amplitude analysis

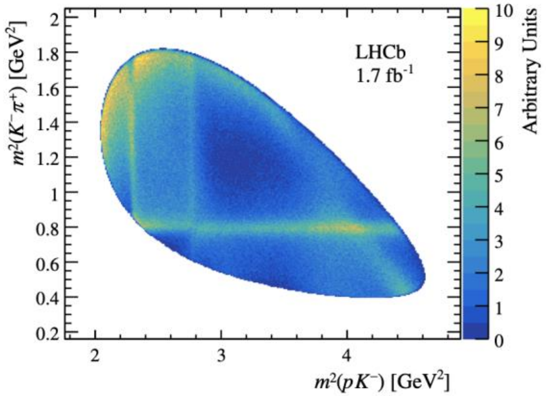
Phys. Rev. D 108, 012023 (2023)

Λ_c^+ signals are selected via $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu$ from dataset taken in 2016, where only a subset of 0.4 M signals are employed

5-dim fit







Resonance	Fit fraction (%)
$\Lambda(1405)$	7.7
$\Lambda(1520)$	1.86
$\Lambda(1600)$	5.2
$\Lambda(1670)$	1.18
$\Lambda(1690)$	1.19
$\Lambda(2000)$	9.58
$\Delta(1232)^{++}$	28.60
$\Delta(1600)^{++}$	4.5
$\Delta(1700)^{++}$	3.90
$K_0^*(700)$	3.02
$K^*(892)$	22.14
$K_0^*(1430)$	14.7

Resonance	α
Model $\sqrt{3}S$	0.662
$K^*(892)$ $\sqrt{3}S$	0.873
$\Lambda(1405)$	−0.58
$\Lambda(1520)$	−0.925
$\Lambda(1600)$	−0.20
$\Lambda(1670)$	−0.817
$\Lambda(1690)$	−0.958
$\Lambda(2000)$	−0.57
$\Delta(1232)^{++}$	−0.548
$\Delta(1600)^{++}$	−0.50
$\Delta(1700)^{++}$	−0.216
$K_0^*(700)$	−0.06
$K_0^*(1430)$	−0.34

Λ_c^+ polarization and $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

Phys. Rev. D 108, 012023 (2023)

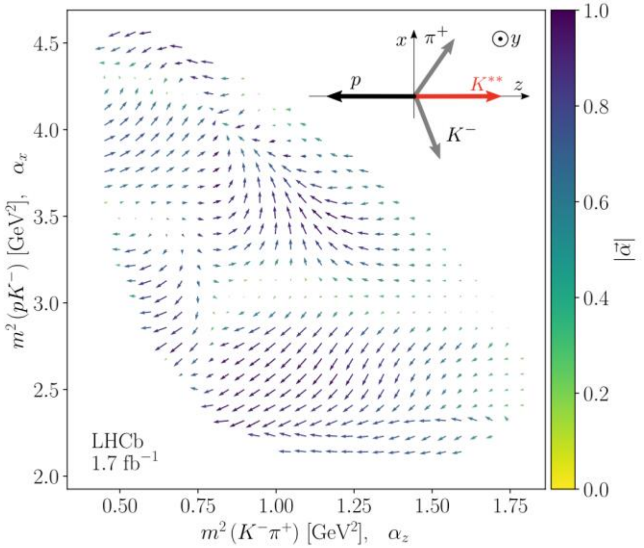
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x ($\tilde{B}$)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y ($\tilde{B}$)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z ($\tilde{B}$)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

A large Λ_c^+ polarization is found in b semi-leptonic decays $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$

- The obtained representation can facilitate polarization measurements of the Λ_c^+ baryon and eases inclusion of the $\Lambda_c^+ \to pK^-\pi^+$ decay mode in hadronic amplitude analyses.
- At BESIII, the transverse polarization of Λ_c^+ can be obtained via $\Lambda_c^+ \to pK^-\pi^+$ polarimetry

JHEP 07, 228 (2023)

The amplitude model is used to produce the distribution of the kinematic-dependent polarimeter vector in the space of Mandelstam variables to express the polarized decay rate in a model-independent way.



Recent Belle/Belle II results

1. $\Xi_c^0 \to \Xi^0 h^0$ $(h^0 = \pi^0, \eta, \eta')$ [Preliminary results]
2. **$\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ [PRD 109, 052003 (2024)]**
3. $\Lambda_c^+ \to \Sigma^+ h^0$ $(h^0 = \pi^0, \eta, \eta')$ [PRD 107, 032003 (2023)]
4. $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$ [PRD 107, 032004 (2023)]
5. $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$ [PRD 107, 032008 (2023)]
6. **$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ [PRL 130, 151903 (2023)]**
7. $\Omega_c^0 \to \Xi^-\pi^+/\Xi^-K^+/\Omega^-K^+$ [JHEP 01 (2023) 055]

Search for the semileptonic decays of $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$

Motivation

- Few baryonic neutrino-less semileptonic decays were observed experimentally [1-4].
- Only upper limits were set for $\Lambda_c^+ \to p\ell^+\ell^-$ decay for the charmed baryons [5, 6].
- With the SU(3) flavor symmetry, $\mathcal{B}(\Xi_c^0 \to \Xi^0 e^+ e^-) \leq 2.35 \times 10^{-6}$ and $\mathcal{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-) \leq 2.25 \times 10^{-6}$ [PRD 103, 013007 (2021)].
- It will help the understanding of the recent anomalies in $b \to s\ell^+\ell^-$ processes, i.e. $B \to K^{(*)}\ell^+\ell^-$.

decays	Experimental results on $\mathcal{B}_f$	Ref.
$\Xi^0 \to \Lambda e^+ e^-$	$(7.6 \pm 0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$	[1] PLB 650, 1 (2007)
$\Sigma^+ \to p\mu^+\mu^-$	$(8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$	[2] PRL 94, 021801 (2005)
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$	$(1.73 \pm 0.42 \pm 0.55) \times 10^{-6}$	[3] PRL 107, 201802 (2011)
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$	$(0.96 \pm 0.16 \pm 0.13 \pm 0.21) \times 10^{-6}$	[4] JHEP 06, 115 (2015)
$\Lambda_c^+ \to p e^+ e^-$	$< 5.5 \times 10^{-6}$ @ 90% C. L.	[5] PRD 84, 072006 (2011)
$\Lambda_c^+ \to p\mu^+\mu^-$	$< 44 \times 10^{-6}$ @ 90% C. L.	[5] PRD 84, 072006 (2011)
$\Lambda_c^+ \to p\mu^+\mu^-$	$< 7.7 \times 10^{-8}$@ 90% C. L.	[6] PRD 97, 091101(2018)

Search for the semileptonic decays of $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$

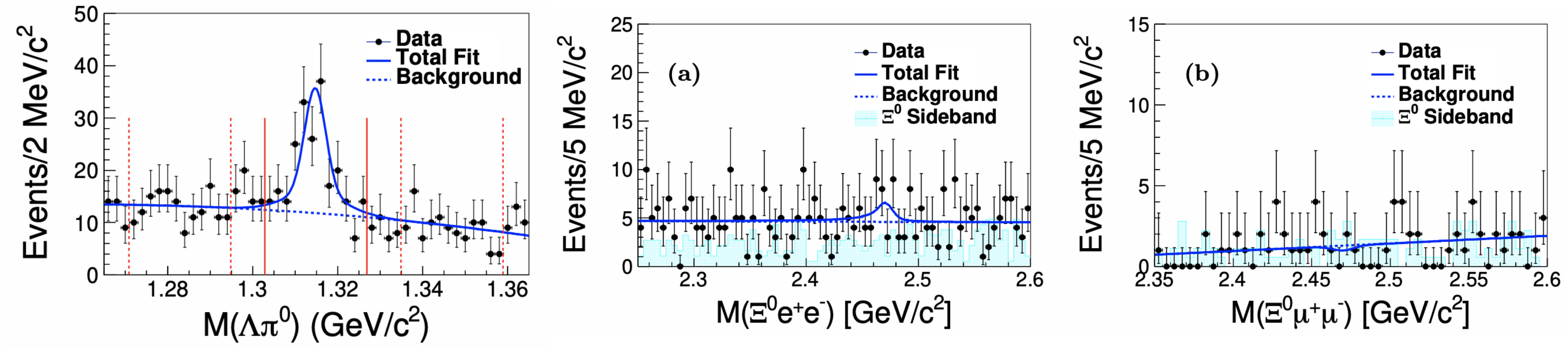
Results:

[PRD 109, 052003 (2024)]

Full Belle dataset

Ξ^0 reconstruction

$\Xi^0 \ell^+ \ell^-$ invariant-mass spectra



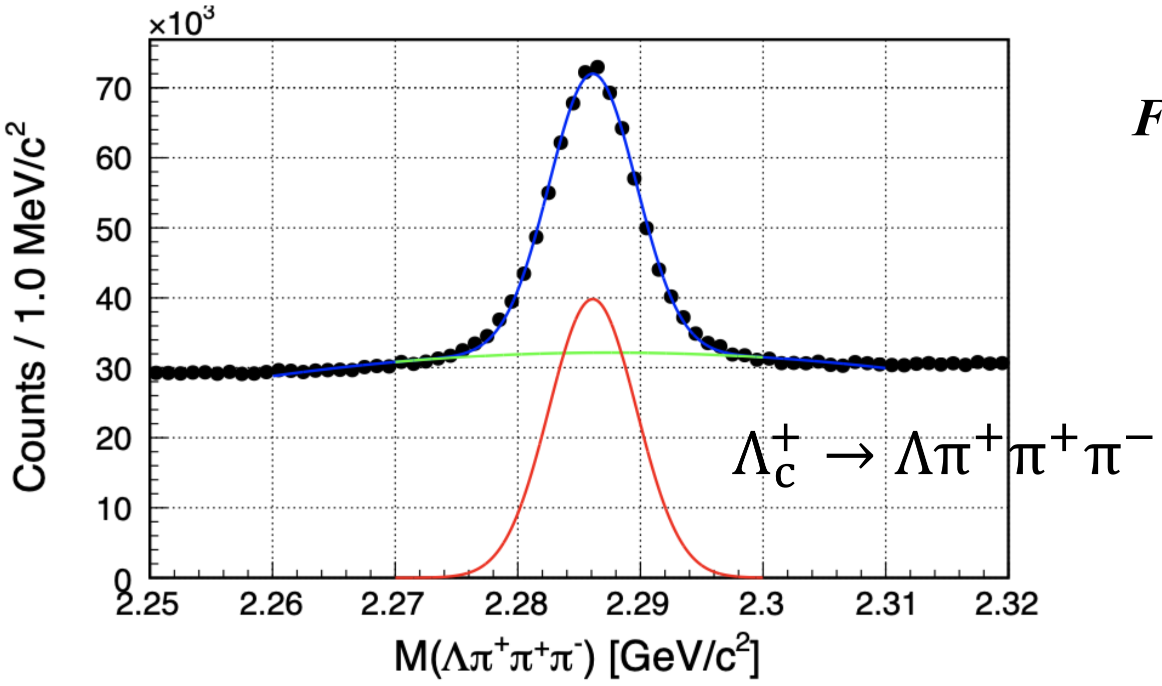
- No significant signals are observed in the $\Xi^0 \ell^+ \ell^-$ invariant-mass spectra.
- 90% credibility upper limits on branching fractions are set:
  - $\mathcal{B}(\Xi_c^0 \to \Xi^0 \ell^+ \ell^-)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) < 6.7\ (4.3) \times 10^{-3}$ and
  - $\mathcal{B}(\Xi_c^0 \to \Xi^0 \ell^+ \ell^-) < 9.9\ (6.5) \times 10^{-5}$ for electron (muon) mode.

Peak at $\bar{K}N$ threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

[PRL 130, 151903 (2023)]

■Motivation

- The Λ(1405) (I = 0) state, which has been interpreted as an orbitally excited quark-diquark [PRC 49, 2831 (1994)], or as a $\bar{K}N$ bound state [PRL 114, 132002 (2015)].
- The $\bar{K}N$ (I = 1) interaction is a virtual state could exist [PLB 500, 263 (2001)] and could be observed as a threshold cusp.

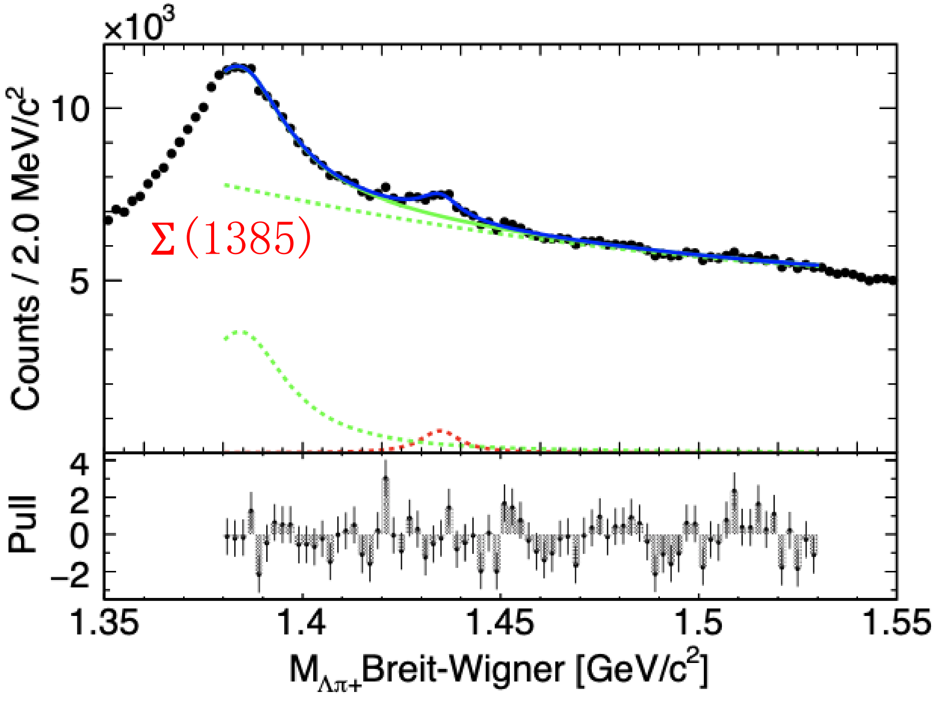


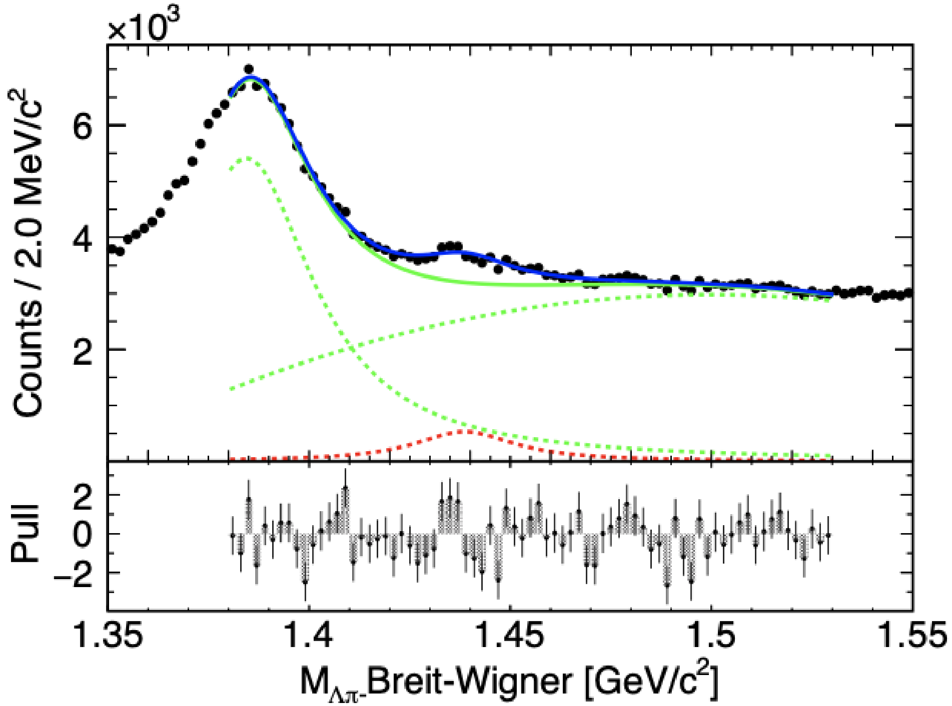
Full Belle dataset

Peak at $\bar{K}N$ threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

[PRL 130, 151903 (2023)]

Full Belle dataset





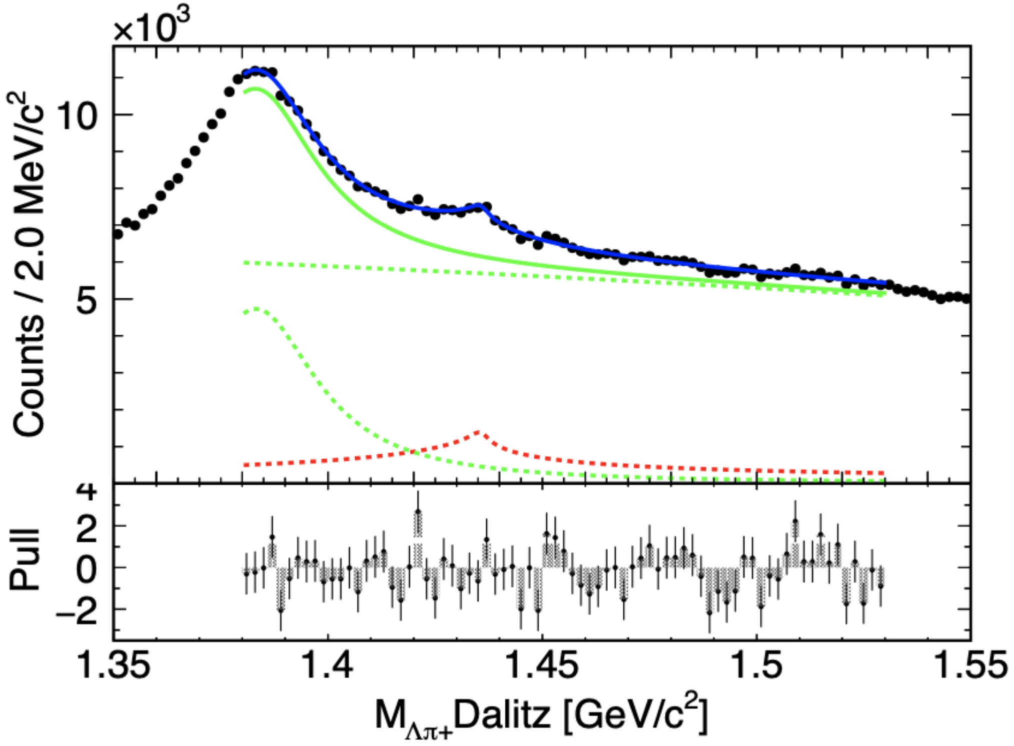
Standard Breit-Wigner

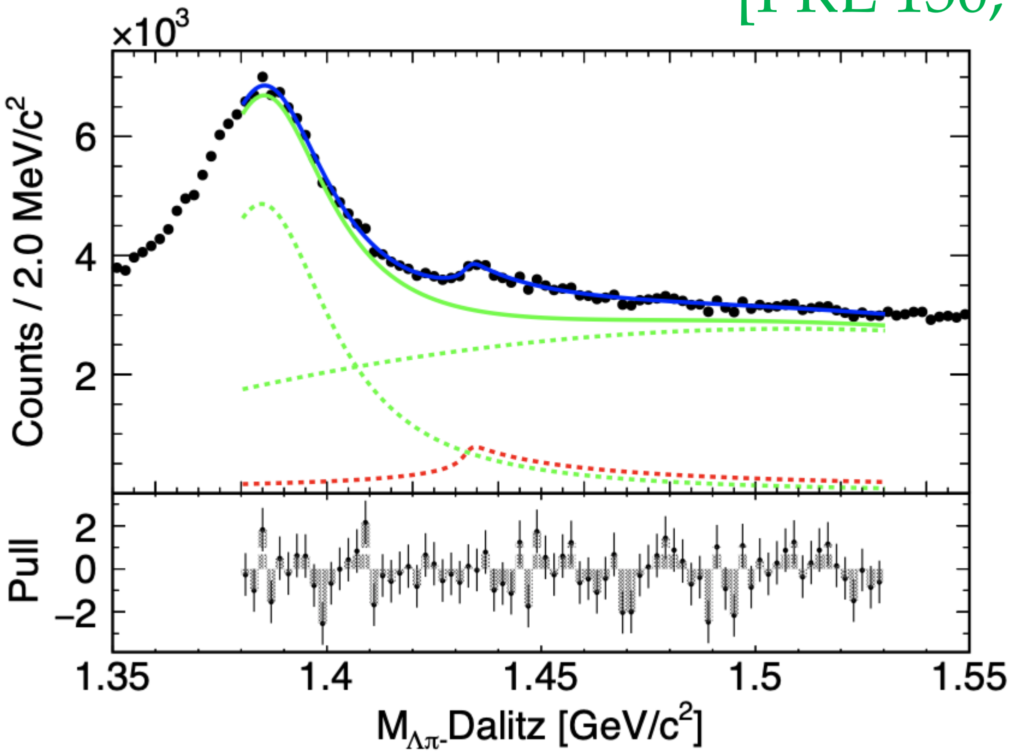
$$f_{\mathrm{BW}} = \frac{\Gamma/2}{(E - E_{\mathrm{BW}})^2 + \Gamma^2/4}$$

Mode	Mass (MeV/c²)	Width (MeV)	χ^2/NDF
$\Lambda\pi^+$	1434.3±0.6±0.9	11.5±2.8±5.3	74/68
$\Lambda\pi^-$	1438.5±0.9±2.5	33.0±7.5±23.6	92/68

Peak at $\bar{K}N$ threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

[PRL 130, 151903 (2023)]





Full Belle dataset

Dalitz model gives slightly better χ^2/NDF, but the difference is not significant.

Dalitz model (cusp) [Czech. J. Phys. B 32, 1021 (1982)]
For scattering length A=a+ib and decay momentum k/κ.

$$f_D = \frac{4\pi b}{(1+kb)^2+(ka)^2}, E > m_{\bar{K}N}$$
$$= \frac{4\pi b}{(1+\kappa a)^2+(\kappa b)^2}, E < m_{\bar{K}N}$$

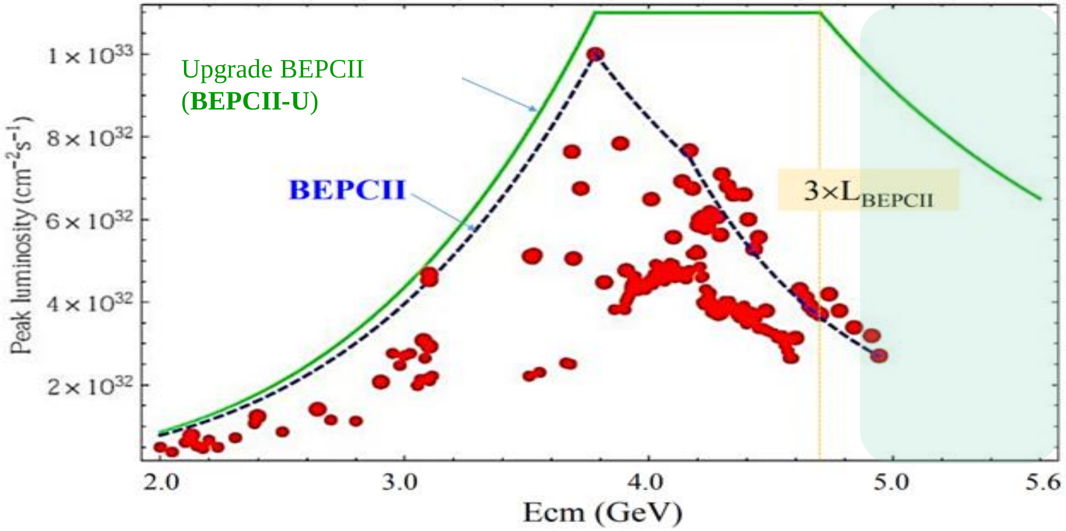
Mode	***a*** [fm]	***b*** [fm]	χ^2/NDF
$\Lambda\pi^+$	0.48±0.32±0.38	1.22±0.83±2.54	69/68
$\Lambda\pi^-$	1.24±0.57±1.56	0.18±0.13±0.20	78/68

Obtained center values for *a* are larger than most theories (e.g., *a*(K^-n)=0.3~0.6 fm for [Nucl. Phys. A 881, 98 (2012)]), but with large uncertainties.

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**

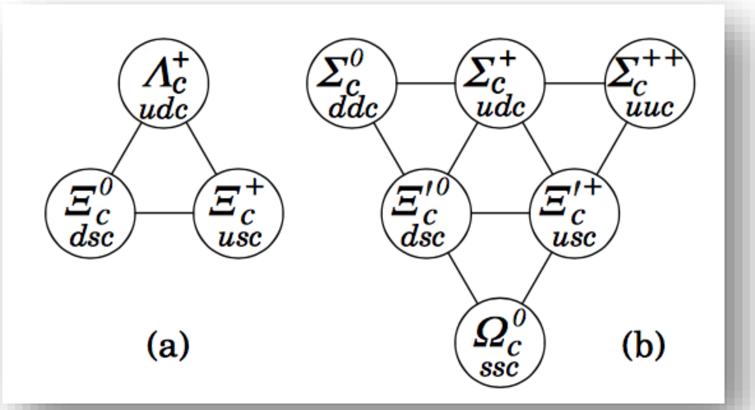


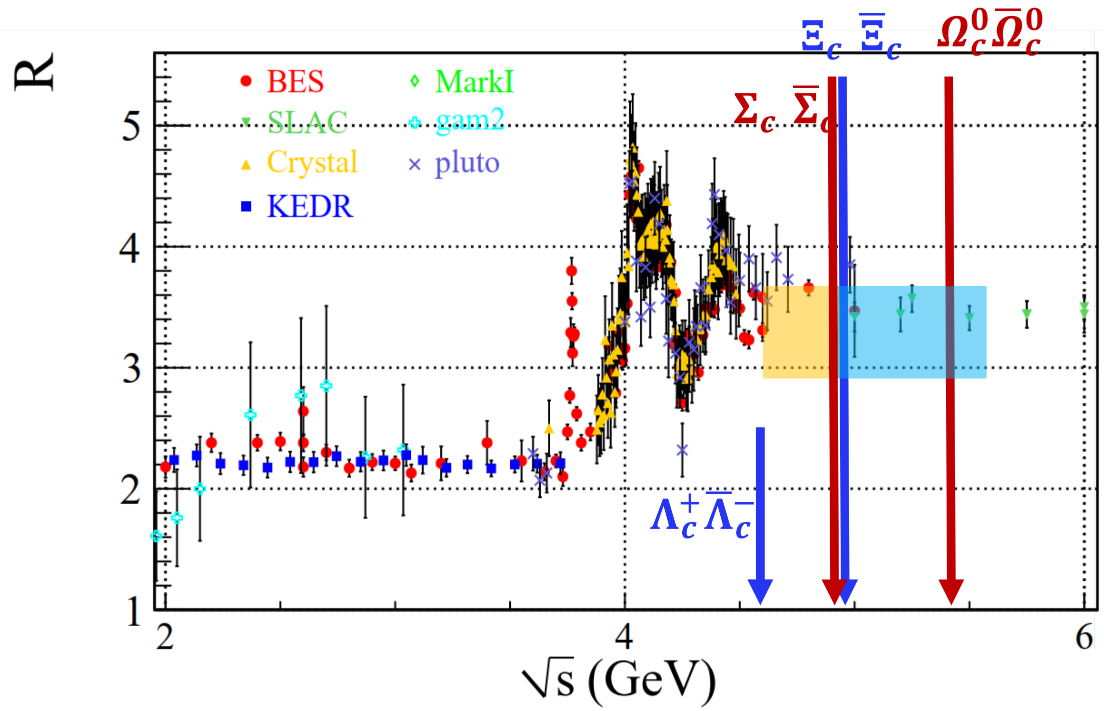
Capable of finishing the proposed luminosity of Λ_c^+ data in shorter time

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





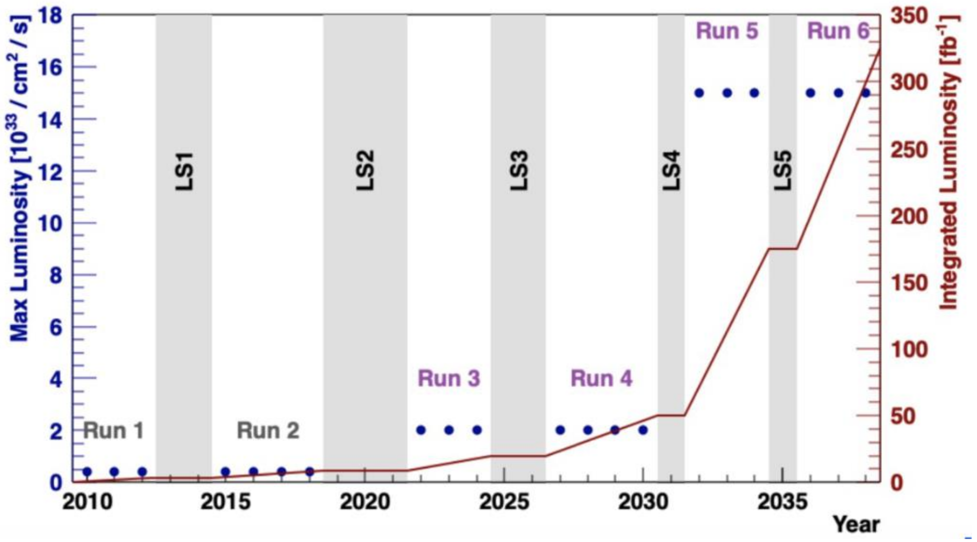
- **Energy thresholds**
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ **4.74 GeV**
  - ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ **4.88 GeV**
  - ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ **4.91 GeV**
  - ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ **4.94 GeV**
  - ✓ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$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

Future opportunity at LHCb

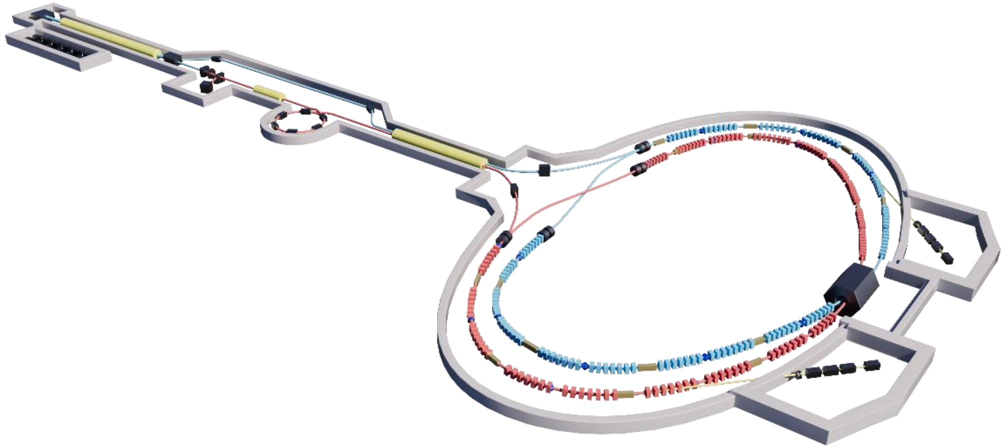
- RUN1&2: 9 fb^{-1}
- RUN3&4: 50 fb^{-1}

➔ x10 more statistics



- **Further improvement on mass and lifetime measurement**
- **SCS and DCS hadronic decays**
  - e.g. $\Xi_c^0 \to pK^-$、$\Xi_c^+ \to pK_S$、$\Omega_c^0 \to \Lambda K_S$、$pK^-$
- **Semi-leptonic decays via b-baryon four-body decays**
  - e.g. $\Lambda_c^+ \to pK^-\mu^+\nu, p\pi^-\mu^+\nu$; $\Xi_c^0 \to \Xi^-\mu^+\nu$; $\Xi_c^+ \to \Lambda\mu^+\nu$; $\Omega_c^0 \to \Omega^-\mu^+\nu$
- **Decay asymmetries and CPV search via prompt production or b-baryon decays**
  - e.g. $\Lambda_c^+ \to pK_S,\ \Lambda\pi^+,\ \Lambda K^+$; $\Xi_c^0 \to \Lambda K_S,\ \Xi^-\pi^+,\ \Xi^-K^+$; $\Omega_c^0 \to \Omega^-\pi^+, \Omega^-K^+,\ \Xi^-\pi^+$
- **Amplitude analysis of multi-body hadronic decays**

Super Tau-Charm Facility (STCF)



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032-2042	2043-2046
Form collaboration																
Conception design CDR																
R&D (TDR)																
Construction																
Operation																
Upgrade																

Anhui provice and USTC have officially endorsed 364M RMB R&D project of STCF, and great progress is achieved; the site is preliminarily decided in Hefei, and geological exploration and engineering design is ongoing.

Will apply for the construction (~4.5B RMB) during the 15th five-year plan (2026-2030) from central government.

Summary

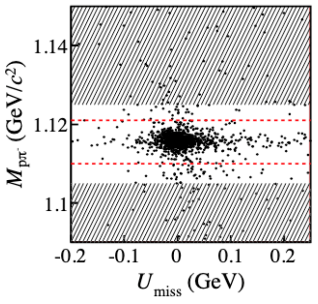
- In the past year, many important results of charm baryon decays were reported by BESIII, Belle, and LHCb.
- Non-perturbative QCD is the main challenge. The theoretical calculations are hard for the Hadronic charm baryon decays.
  - Tools are improving.
  - Collaborations between theorists and experimentalists are crucial for accelerating research.
- The future of charm is promising. Lots of high quality data coming our way: LHCb, Belle II, BESIII(+upgrade)
- A dedicated charm facility, STCF, has been proposed in China. The R&D project with 364M RMB budget has been officially supported by Anhui province and USTC.

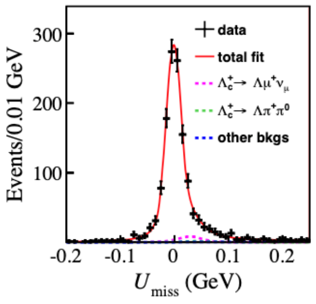
Backup

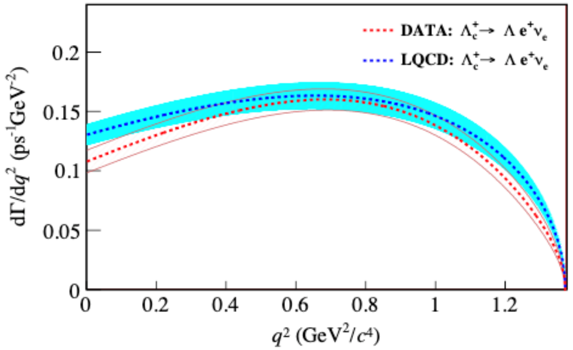
Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

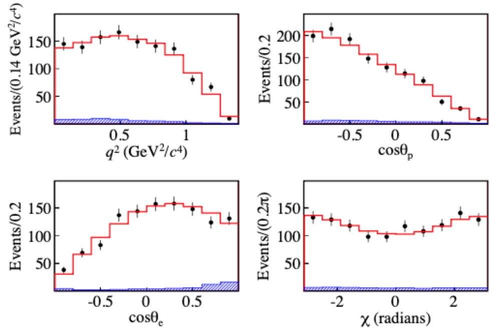
N=1253±39

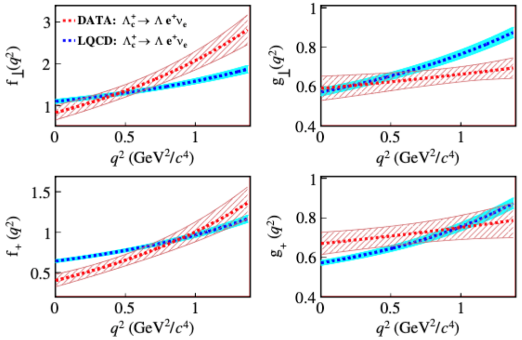
PRL 129,231803(2022)











- BF is updated to be $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.56 \pm 0.11_{stat} \pm 0.07_{syst})\%$=>precision improved.
- Helicity amplitude deduced form factors can be extracted with 4D fitting to data.
- The differential decay rate is roughly consistent with LQCD calculation while discrepancies can be noticed on FFs show different kinematic behaviors.
- |Vcs| element from charmed baryons is measured to be $0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{LQCD} \pm 0.007_{\tau_{\Lambda c}}$ which is consistent with the value obtained in charmed mesons decay.

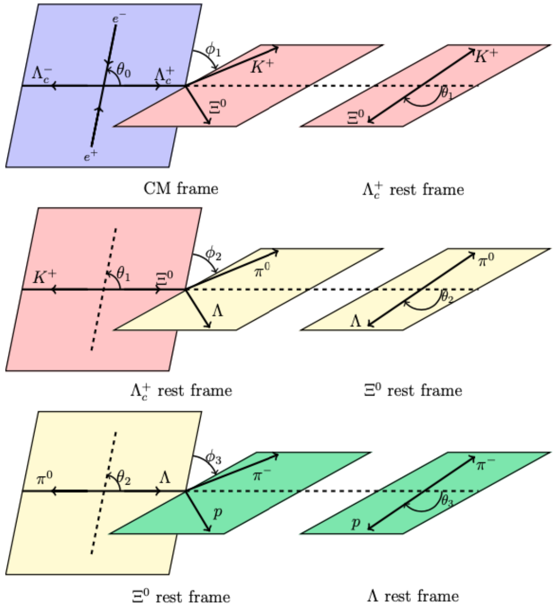
Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

$$\alpha_{BP} = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2}, \quad \gamma_{BP} = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	D_{λ_5}

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

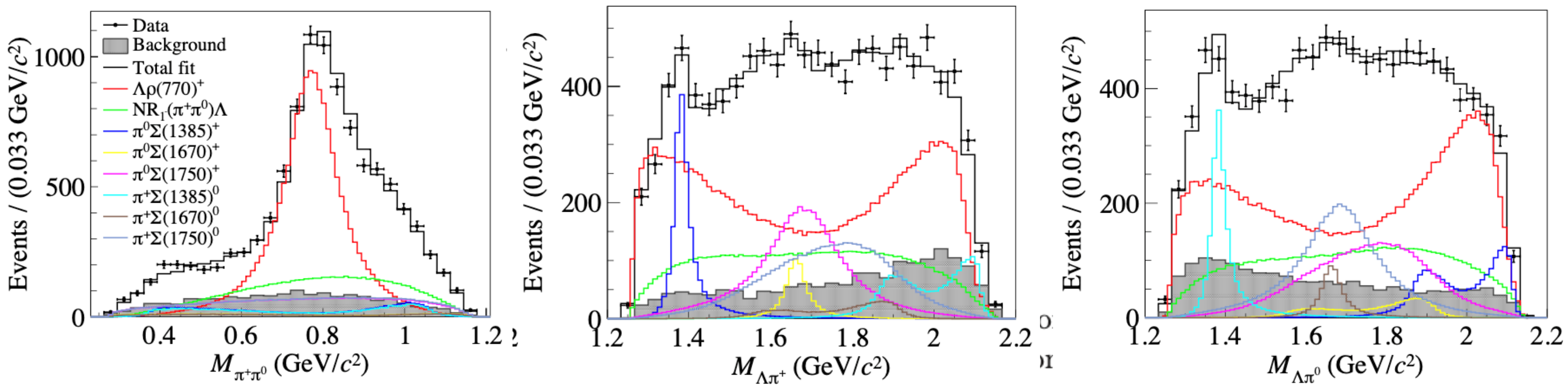
arXiv2309.02774(PRL accepted)



- The joint angular distribution for $\Lambda_c^+ \to \Xi^0 K^+$ is derived based on helicity amplitude.

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

JHEP 12.033 (2022).



Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-0.77 ± 0.23	2.90 ± 0.63	$5.1\,\sigma$
$\Sigma(1670)^0\pi^+$	0.41 ± 0.07	2.77 ± 0.20	2.65 ± 0.58	$5.2\,\sigma$
$\Sigma(1750)^+\pi^0$	1.75 ± 0.21	-1.73 ± 0.11	16.6 ± 2.2	$10.1\,\sigma$
$\Sigma(1750)^0\pi^+$	1.83 ± 0.21	1.34 ± 0.11	17.5 ± 2.3	$10.2\,\sigma$
$\Lambda + NR_{1^-}$	4.05 ± 0.47	2.16 ± 0.13	29.7 ± 4.5	$10.5\,\sigma$

	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 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

- About 10K events survived which purity is larger than 80%.
- Interference mostly exist between $\Lambda\rho(770)$ and $\Sigma(1385)^{0/+}\pi^{+/0}$.
- NO theoretical models is able to explain both BFs and decay asymmetries simultaneously.
- Decay asymmetry parameters can be obtained by the fit results of the PWA.
- provide crucial input to extend the understanding of dynamics of charmed baryon hadronic decays.

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

JHEP 12.033 (2022).

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{1,\frac{3}{2}}^{\Sigma(1385)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{1,\frac{3}{2}}^{\Sigma(1385)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{2,\frac{3}{2}}^{\Sigma(1385)^+}$	1.29 ± 0.25	2.82 ± 0.18	$g_{2,\frac{3}{2}}^{\Sigma(1385)^0}$	1.70 ± 0.38	2.70 ± 0.22
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{1,\frac{3}{2}}^{\Sigma(1670)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{1,\frac{3}{2}}^{\Sigma(1670)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{2,\frac{3}{2}}^{\Sigma(1670)^+}$	1.39 ± 0.42	0.85 ± 0.26	$g_{2,\frac{3}{2}}^{\Sigma(1670)^0}$	0.74 ± 0.18	0.29 ± 0.24
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{0,\frac{1}{2}}^{\Sigma(1750)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{0,\frac{1}{2}}^{\Sigma(1750)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{1,\frac{1}{2}}^{\Sigma(1750)^+}$	0.45 ± 0.10	-2.28 ± 0.22	$g_{1,\frac{1}{2}}^{\Sigma(1750)^0}$	0.38 ± 0.10	-2.03 ± 0.20
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(\rho(770)^+)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(NR_{1^-})$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{0,\frac{1}{2}}^{\rho}$	1.0 (fixed)	0.0 (fixed)	$g_{0,\frac{1}{2}}^{NR}$	1.0 (fixed)	0.0 (fixed)
$g_{1,\frac{1}{2}}^{\rho}$	0.48 ± 0.12	-1.69 ± 0.12	$g_{1,\frac{1}{2}}^{NR}$	0.94 ± 0.12	-0.49 ± 0.16
$g_{1,\frac{3}{2}}^{\rho}$	0.90 ± 0.10	0.48 ± 0.13	$g_{1,\frac{3}{2}}^{NR}$	0.21 ± 0.09	-2.84 ± 0.53
$g_{2,\frac{3}{2}}^{\rho}$	0.55 ± 0.08	-0.04 ± 0.18	$g_{2,\frac{3}{2}}^{NR}$	0.33 ± 0.14	-1.92 ± 0.30
$\frac{1}{2}^+(\Lambda) \to \frac{1}{2}^+(p) + 0^-(\pi^-)$					
Amplitude	Magnitude	Phase ϕ (rad)			
$g_{0,\frac{1}{2}}^{\Lambda}$	1.0 (fixed)	0.0 (fixed)			
$g_{1,\frac{1}{2}}^{\Lambda}$	0.435376 (fixed)	0.0 (fixed)			

$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^\rho_{\frac{1}{2},1}|^2 - |H^\rho_{-\frac{1}{2},-1}|^2 + |H^\rho_{\frac{1}{2},0}|^2 - |H^\rho_{-\frac{1}{2},0}|^2}{|H^\rho_{\frac{1}{2},1}|^2 + |H^\rho_{-\frac{1}{2},-1}|^2 + |H^\rho_{\frac{1}{2},0}|^2 + |H^\rho_{-\frac{1}{2},0}|^2}$$

$$= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^\rho_{0,\frac{1}{2}} \cdot \bar{g}^\rho_{1,\frac{1}{2}} - g^\rho_{1,\frac{3}{2}} \cdot \bar{g}^\rho_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^\rho_{0,\frac{1}{2}} \cdot \bar{g}^\rho_{1,\frac{3}{2}} + g^\rho_{1,\frac{1}{2}} \cdot \bar{g}^\rho_{2,\frac{3}{2}}\right)}{|g^\rho_{0,\frac{1}{2}}|^2 + |g^\rho_{1,\frac{1}{2}}|^2 + |g^\rho_{1,\frac{3}{2}}|^2 + |g^\rho_{2,\frac{3}{2}}|^2}. \quad (4.28)$$

$$\alpha_{\Sigma(1385)\pi} = \frac{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 - |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2}{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 + |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2} = \frac{2\Re\left(g^{\Sigma(1385)}_{1,\frac{3}{2}} \cdot \bar{g}^{\Sigma(1385)}_{2,\frac{3}{2}}\right)}{|g^{\Sigma(1385)}_{1,\frac{3}{2}}|^2 + |g^{\Sigma(1385)}_{2,\frac{3}{2}}|^2}.$$

- **Decay asymmetry parameters can be obtained by the fit results of the partial wave amplitudes.**

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

JHEP 12.033 (2022).

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (57.2 \pm 4.2 \pm 4.9)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) \cdot \mathcal{B}(\Sigma(1385)^+ \to \Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.18 \pm 0.60 \pm 0.64)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) \cdot \mathcal{B}(\Sigma(1385)^0 \to \Lambda\pi^0)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.92 \pm 0.72 \pm 0.80)\%.$$

$$\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+) = (4.06 \pm 0.30 \pm 0.35 \pm 0.23)\%,$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) = (5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) = (6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3},$$

$$\alpha_{\Lambda\rho(770)^+} = -0.763 \pm 0.053 \pm 0.039,$$

$$\alpha_{\Sigma(1385)^+\pi^0} = -0.917 \pm 0.069 \pm 0.046,$$

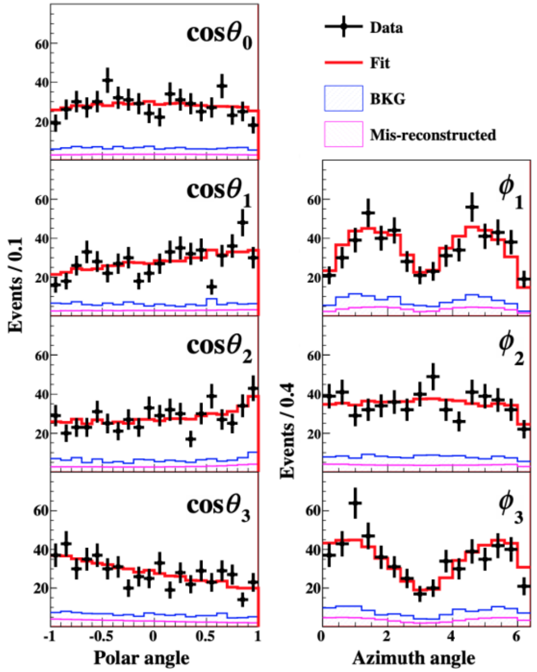
$$\alpha_{\Sigma(1385)^0\pi^+} = -0.789 \pm 0.098 \pm 0.056.$$

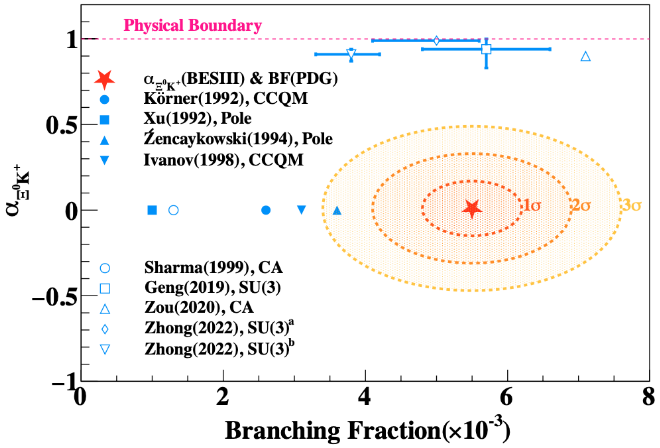
Table 9. The comparison among this work, various theoretical calculations and PDG results. Here, the uncertainties of this work are the combined uncertainties. "—" means unavailable.

	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 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

- **NO theoretical models is able to explain both BFs and decay asymmetries simultaneously.**
- **Decay asymmetry parameters can be obtained by the fit results of the PWA.**
- **Fruitful results are extracted which provide crucial input to extend the understanding of dynamics of charmed baryon hadronic decays.**

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$





- From the fit, we obtain $\alpha_{\Xi^0\mathrm{K}^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0\mathrm{K}^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0\mathrm{K}^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$

- $\alpha_{\Xi^0\mathrm{K}^+}$ is in good agreement with zero=>strong identification for theoretical predictions.

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

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

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

- Combine decay width and decay asymmetry, the decay dynamics parameters are derived.

- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero.=>not considered in previous literature.

- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0\mathrm{K}^+}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi^0\mathrm{K}^+)$ simultaneously.

Study of $\Xi_c^0 \to \Xi^0 h^0$ $(h^0 = \pi^0, \eta, \eta')$

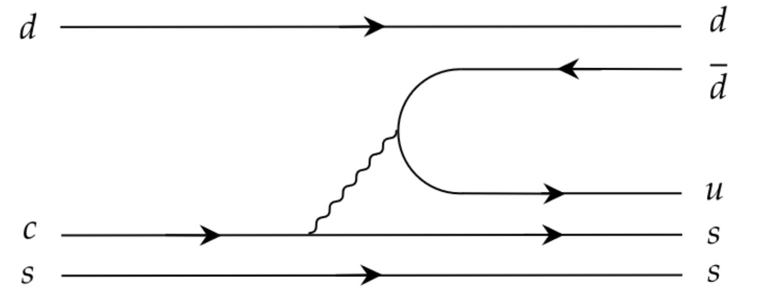
Motivation:

- Nonfactorizable amplitudes arising from internal W-emission and W-exchange lead to the difficulties for theoretical predictions in hadronic weak decay of charmed baryons.

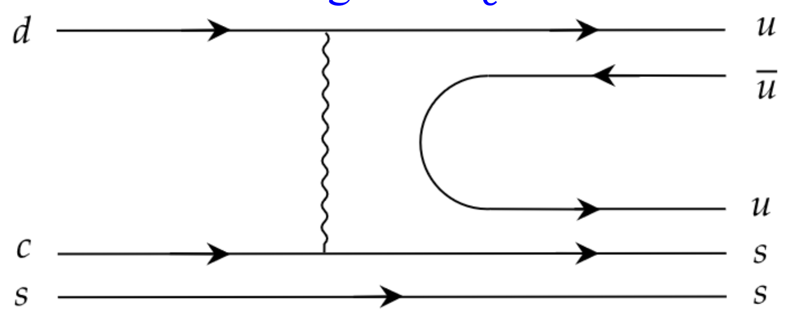
Theoretical predictions for branching fractions ($\times 10^{-3}$) and asymmetry parameters:

Reference	Model	$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$	$\alpha(\Xi_c^0 \to \Xi^0\pi^0)$
Körner, Krämer [5]	quark	0.5	3.2	11.6	0.92
Xu, Kamal [7]	pole	7.7	-	-	0.92
Cheng, Tseng [8]	pole	3.8	-	-	-0.78
Cheng, Tseng [8]	CA	17.1	-	-	0.54
Żenczykowski [9]	pole	6.9	1.0	9.0	0.21
Ivanov *et al.* [6]	quark	0.5	3.7	4.1	0.94
Sharma, Verma [11]	CA	-	-	-	-0.8
Geng *et al.* [12]	$SU(3)_F$	4.3 ± 0.9	$1.7^{+1.0}_{-1.7}$	$8.6^{+11.0}_{-6.3}$	-
Geng *et al.* [13]	$SU(3)_F$	7.6 ± 1.0	10.3 ± 2.0	9.1 ± 4.1	$-1.00^{+0.07}_{-0.00}$
Zhao *et al.* [14]	$SU(3)_F$	4.7 ± 0.9	8.3 ± 2.3	7.2 ± 1.9	-
Zou *et al.* [10]	pole	18.2	26.7	-	-0.77
Huang *et al.* [15]	$SU(3)_F$	2.56 ± 0.93	-	-	-0.23 ± 0.60
Hsiao *et al.* [16]	$SU(3)_F$	6.0 ± 1.2	$4.2^{+1.6}_{-1.3}$	-	-
Hsiao *et al.* [16]	$SU(3)_F$-breaking	3.6 ± 1.2	7.3 ± 3.2	-	-
Zhong *et al.* [17]	$SU(3)_F$	$1.13^{+0.59}_{-0.49}$	1.56 ± 1.92	$0.683^{+3.272}_{-3.268}$	$0.50^{+0.37}_{-0.35}$
Zhong *et al.* [17]	$SU(3)_F$-breaking	$7.74^{+2.52}_{-2.32}$	$2.43^{+2.79}_{-2.90}$	$1.63^{+5.09}_{-5.14}$	$-0.29^{+0.20}_{-0.17}$
Xing *et al.* [18]	$SU(3)_F$	1.30 ± 0.51	-	-	-0.28 ± 0.18

Internal W-emission for $\Xi_c^0 \to \Xi^0 h^0$



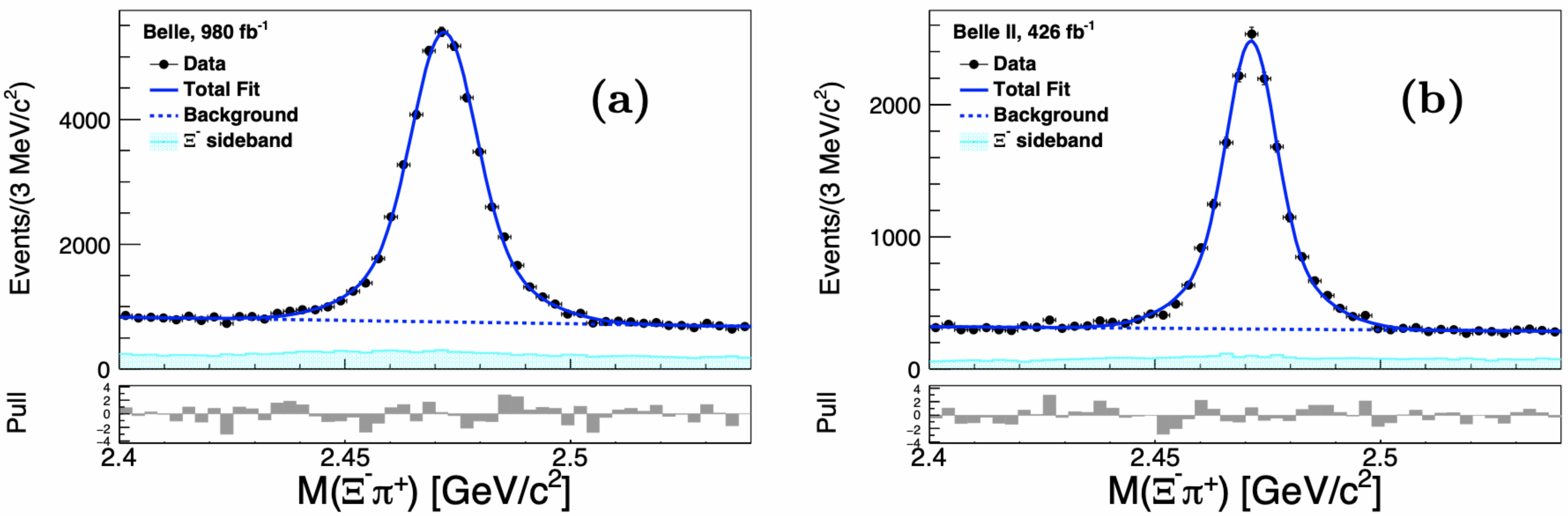
W-exchange for $\Xi_c^0 \to \Xi^0 h^0$



[5] Z. Phys. C 55 (1992) 659 [6] PRD 57 (1998) 6532 [7] PRD 46 (1992) 053004 [8] PRD 48 (1993) 4188 [9] PRD 50 (1994) 5787
[10] PRD 101 (2020) 014011 [11] EPJC 7 (1999) 217 [12] PRD 97 (2018) 073006 [13] PLB 794 (2019) 19 [14] JHEP 02 (2020) 165
[15] JHEP 03 (2022) 143 [16] JHEP 09 (2022) 35 [17] JHEP 02 (2023) 235 [18] PRD 108 (2023) 053004

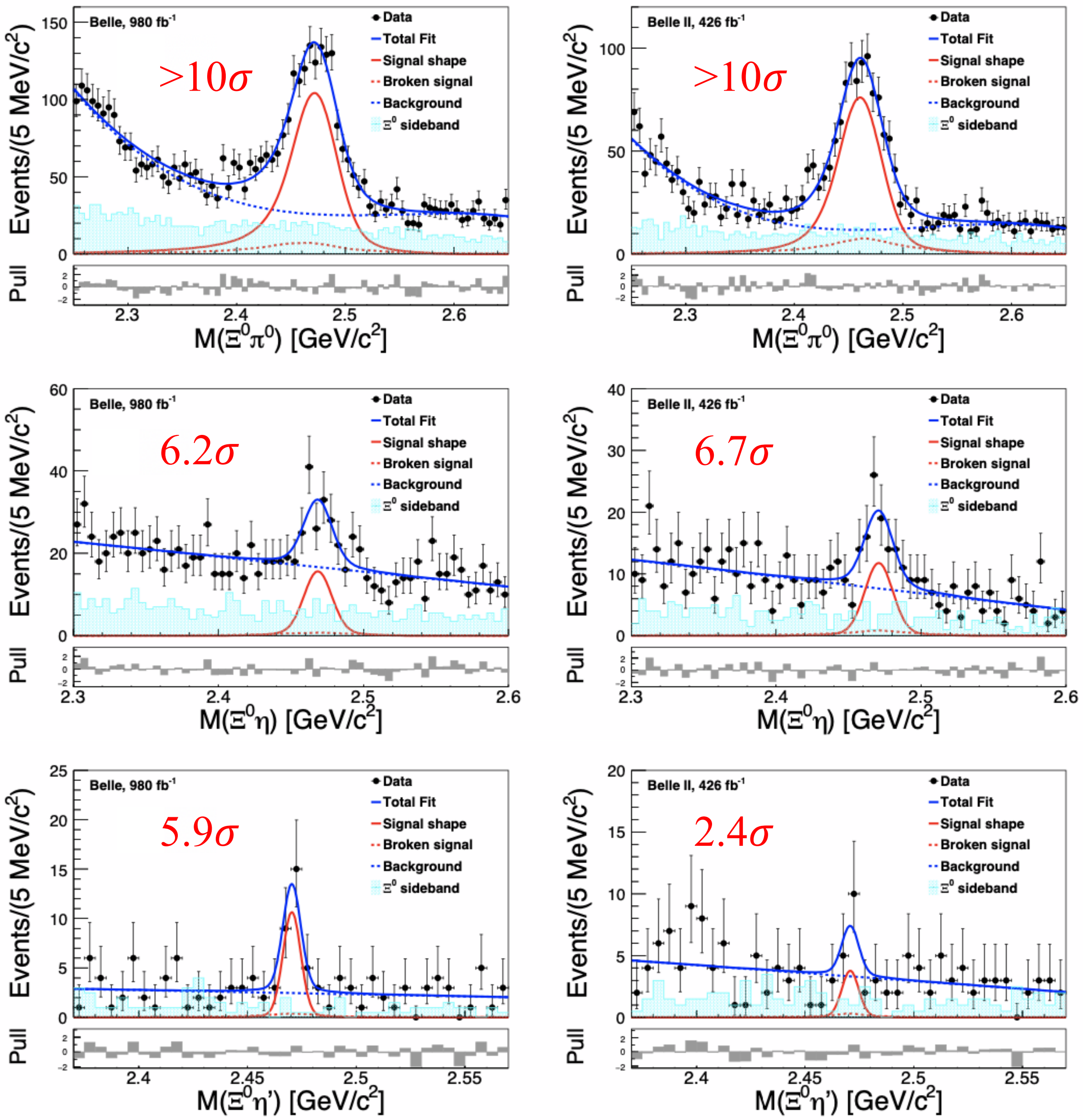
Reference mode of $\Xi_c^0 \to \Xi^- \pi^+$

First BELLE + Belle II combined charm measurement.



Datasets	Signal yield
Belle	36340 ± 348
Belle II	13719 ± 184

Branching fractions for $\Xi_c^0 \to \Xi^0 h^0$ ($h^0 = \pi^0, \eta, \eta'$)



Preliminary results, will be submitted to JHEP

Signal yield:

Channel	Belle	Belle II
$\Xi_c^0 \to \Xi^0\pi^0$	1315 ± 66	869 ± 46
$\Xi_c^0 \to \Xi^0\eta$	81 ± 15	60 ± 11
$\Xi_c^0 \to \Xi^0\eta'$	23 ± 6	8 ± 4

First measurement of the following BRs:

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3(\text{stat.}) \pm 0.5(\text{syst.}) \pm 1.5(\text{norm.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.}) \pm 0.4(\text{norm.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3(\text{stat.}) \pm 0.1(\text{syst.}) \pm 0.3(\text{norm.})) \times 10^{-3}$$

They are compatible with theoretical prediction based on $SU(3)_F$-breaking [JHEP 02, 235 (2023)].

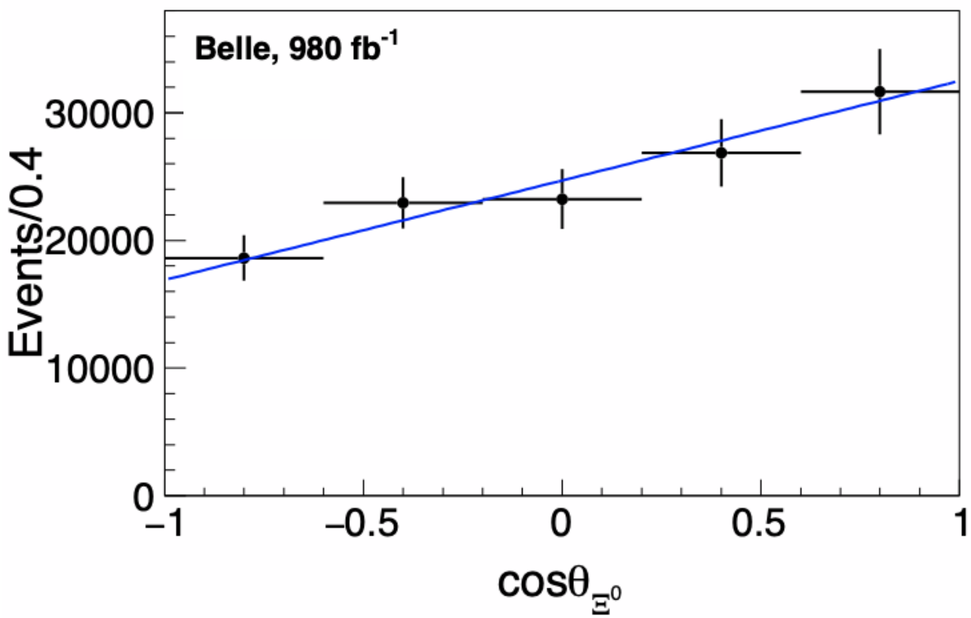
Asymmetry parameter for $\Xi_c^0 \to \Xi^0\pi^0$

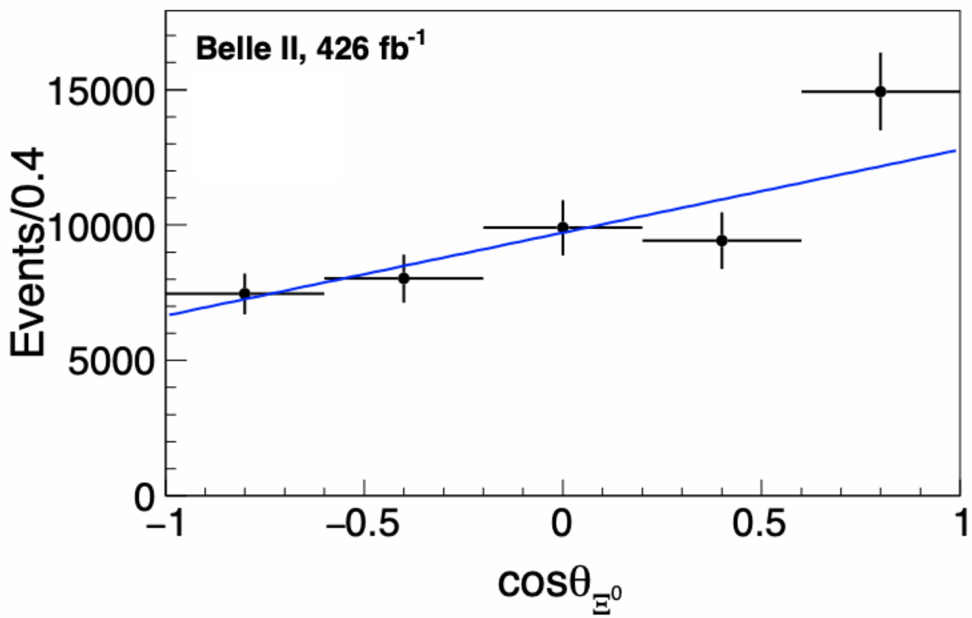
The asymmetry parameter, related to P-violation, is measured through the differential decay rate:

Preliminary results

$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)\cos\theta_{\Xi^0}$$

The $\cos\theta_{\Xi^0}$ is the angle between the Λ momentum vector and the opposite of the Ξ_c^0 momentum vector in the Ξ^0 rest frame.



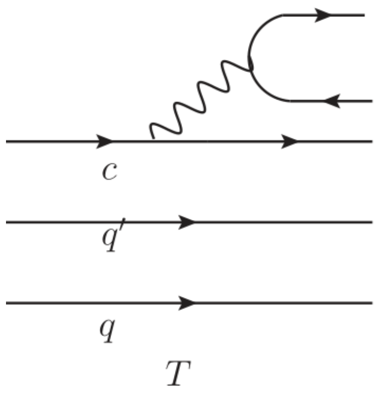


The $\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90\pm0.15\pm0.23$, which is consistent with predictions based on the pole model [PRD 48 (1993) 4188, PRD 101 (2020) 014011], CA [EPJC 7 (1999) 217], and $SU(3)_F$ flavor symmetry [PLB 794 (2019) 19] approaches.

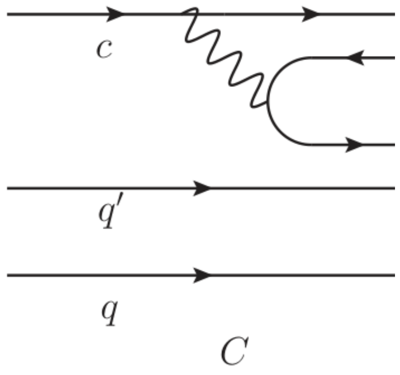
Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$, and $\Sigma^+\eta'$

Motivation

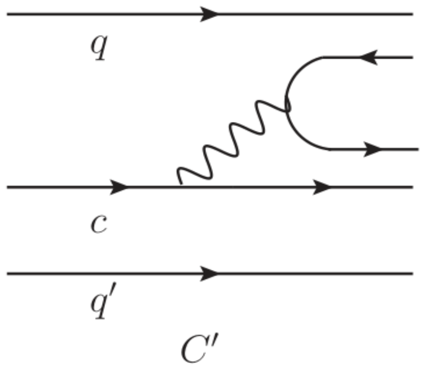
- For the charmed baryon weak decays: $\mathbf{B_c} \to \mathbf{B} + \mathbf{M}$, there are six topological diagrams. Among them, T and C are factorizable, while C′ and E_{1-3} are nonfactorizable.
- All the nonfactorizable diagrams contribute to $\Lambda_c^+ \to \Sigma^+\eta(\eta')$.



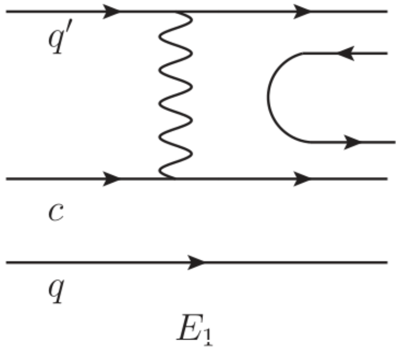
external W-emission T

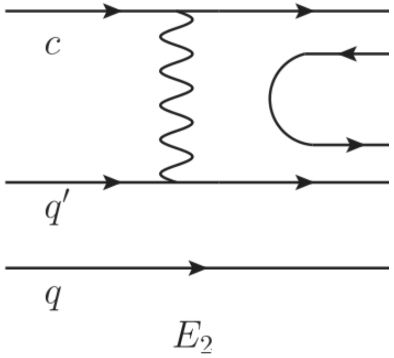


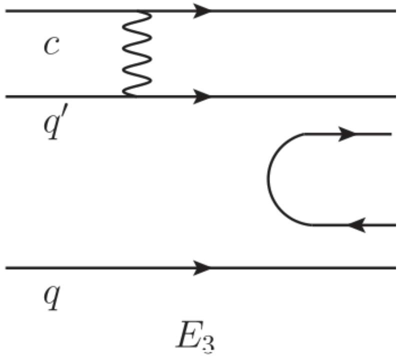
internal W-emission C



inner W-emission C′







W-exchange diagrams E_1, E_2, E_3

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$, and $\Sigma^+\eta'$

Motivation

- Theoretical predictions on the branching fractions and asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\eta(\eta')$ vary across.
- Branching fractions of $\Lambda_c^+ \to \Sigma^+\eta(\eta')$ are measured with large uncertainty ($\delta B/B>40\%$). Decay asymmetry parameters for these two modes have never been measured.

Decay	Körner [1]	Ivanov [2]	Żenczykowski [7]	Sharma [8]	Zou [10]	Geng [11]	Experiment [18]
$\Lambda_c^+\to\Sigma^+\eta$	0.16	0.11	0.90	0.57	0.74	0.32±0.13	0.44±0.20
$\Lambda_c^+\to\Sigma^+\eta'$	1.28	0.12	0.11	0.10	–	1.44±0.56	1.5±0.6
$\Lambda_c^+\to\Sigma^+\pi^0$	0.70	0.43	0.39	−0.31	−0.76	−0.35±0.27	−0.55±0.11
$\Lambda_c^+\to\Sigma^+\eta$	0.33	0.55	0.00	−0.91	−0.95	−0.40±0.47	–
$\Lambda_c^+\to\Sigma^+\eta'$	−0.45	−0.05	−0.91	0.78	0.68	$1.00^{+0.00}_{-0.17}$	–

$\times 10^{-2}$

Branching fractions

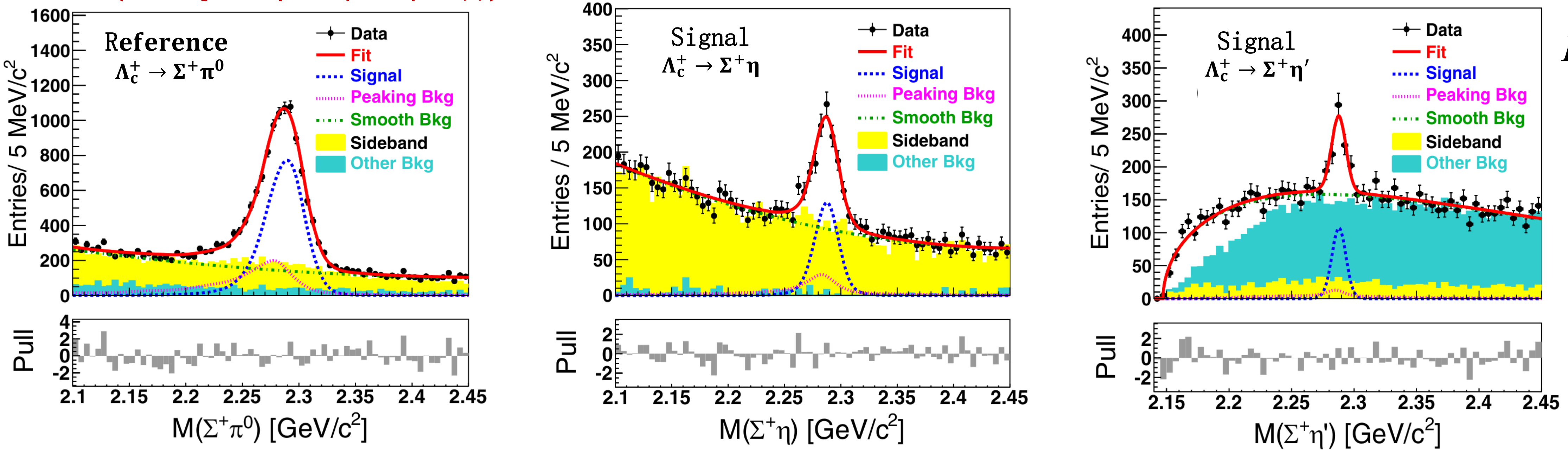
Asymmetry parameters

[1] Z. Phys. C 55, 659 (1992) [2] PRD 57, 5632 (1998) [7] PRD 50, 5787 (1994) [8] EPJC 7, 217 (1999) [10] PRD 49, 3417 (1994) [11] PLB 794, 19 (2019) [18] PTEP 2022, 083C01 (2022)

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$, and $\Sigma^+\eta'$

- **Measurements of branching fractions of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$** [PRD 107, 032003 (2023)]

  ($\Sigma^+ \to p\pi^0$; $\eta' \to \eta\pi\pi$; $\eta \to \gamma\gamma$)



Full Belle dataset

$$\frac{B(\Lambda_c^+\to\Sigma^+\eta)}{B(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.25 \pm 0.03 \pm 0.01; \qquad B(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3}$$

$$\frac{B(\Lambda_c^+\to\Sigma^+\eta')}{B(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.33 \pm 0.06 \pm 0.02; \qquad B(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3}$$

statistical systematical from $B(\Lambda_c^+ \to \Sigma^+\pi^0)$

PDG: $B(\Lambda_c^+ \to \Sigma^+\eta) = (4.4 \pm 2.0) \times 10^{-3}$

PDG: $B(\Lambda_c^+ \to \Sigma^+\eta') = (15 \pm 6) \times 10^{-3}$

Consistent with PDG. Most precise result to date.

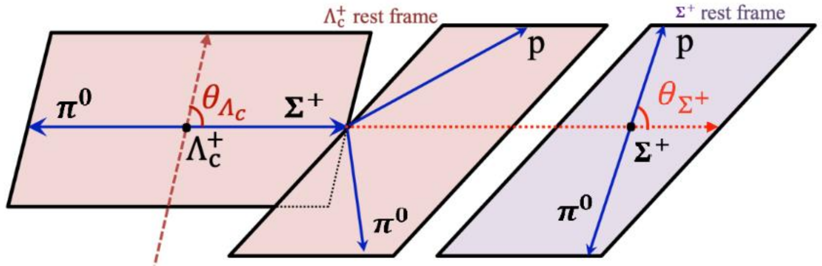
Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+\eta$, and $\Sigma^+\eta'$

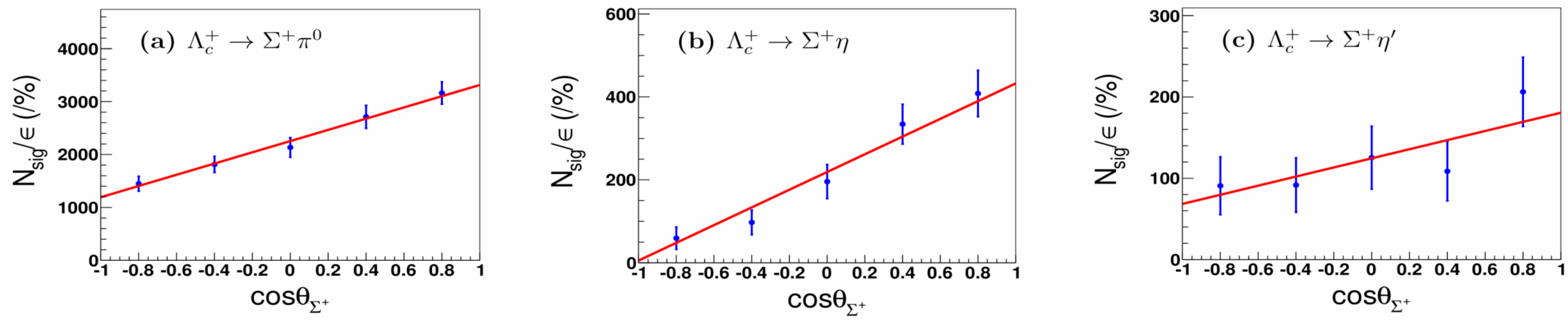
■ Measurements of asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$, $\Sigma^+\eta$, and $\Sigma^+\eta'$ [PRD 107, 032003 (2023)]

The differential decay rate depends on the asymmetry parameter $\boldsymbol{\alpha_{\Sigma^+X}}$ as:

$$\frac{dN}{d\cos\theta_{\Sigma^+}} \propto 1 + \alpha_{\Sigma^+X}\alpha_{p\pi^0}\cos\theta_{\Sigma^+}$$

$\alpha_{p\pi^0} = -0.982 \pm 0.014$ from world average value.





- $\alpha_{\Sigma^+\pi^0} = -0.48 \pm 0.02 \pm 0.02$
  - agrees with the world average value: -0.55 ± 0.11.
  - with much improved precision
  - The consistency with $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$ [Sci.Bull. 68 (2023) 583] indicates no isospin symmetry broken.
- $\alpha_{\Sigma^+\eta} = -0.99 \pm 0.03 \pm 0.05$ and $\alpha_{\Sigma^+\eta'} = -0.46 \pm 0.06 \pm 0.03$
  - measured for the first time

Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

■Motivation

- No result of branching fraction for $\Lambda_c^+ \to pK_S^0K_S^0$ (singly Cabibbo-suppressed) is reported. According to theoretically results based on $SU(3)_F$ symmetry [EPJC 79 (2019) 946], $\mathcal{B}(\Lambda_c^+ \to pK_S^0K_S^0) = (1.9 \pm 0.4) \times 10^{-3}$.

- Measured branching fraction $B(\Lambda_c^+ \to pK_S^0\eta) = (4.15 \pm 0.90) \times 10^{-3}$ has large uncertainty ($\delta B/B \sim 20\%$) [PDG].

- Check Dalitz-plot for the intermediate resonances existence, e.g. $N^*(1535) \to p\eta$.

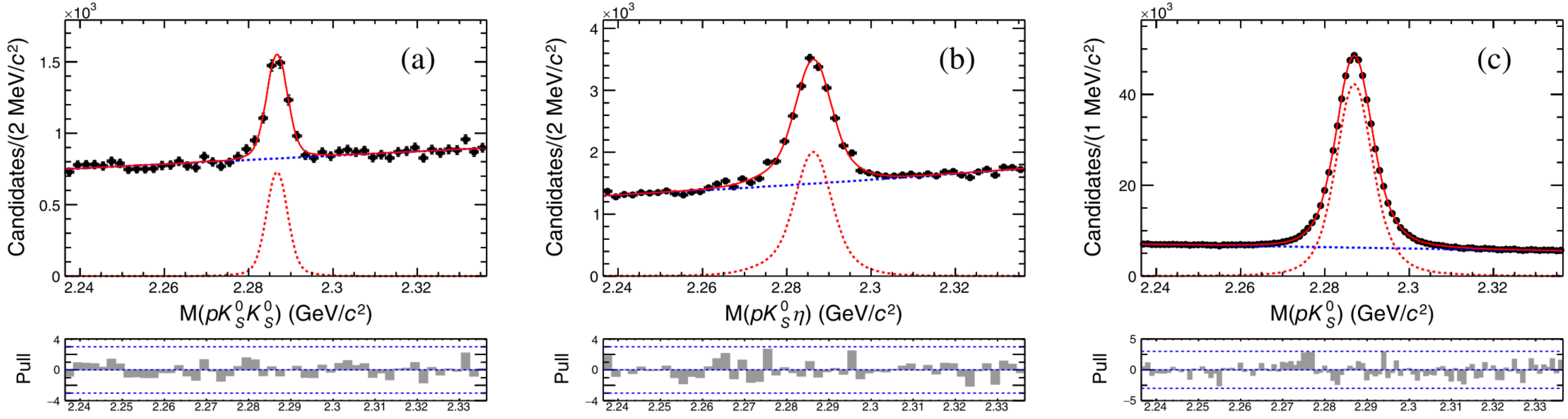
Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

■ Signal Yield Extraction

[PRD 107, 032004 (2023)]

Full Belle dataset

Signal: $\Lambda_c^+ \to pK_S^0K_S^0$ Signal: $\Lambda_c^+ \to pK_S^0\eta$ Reference: $\Lambda_c^+ \to pK_S^0$

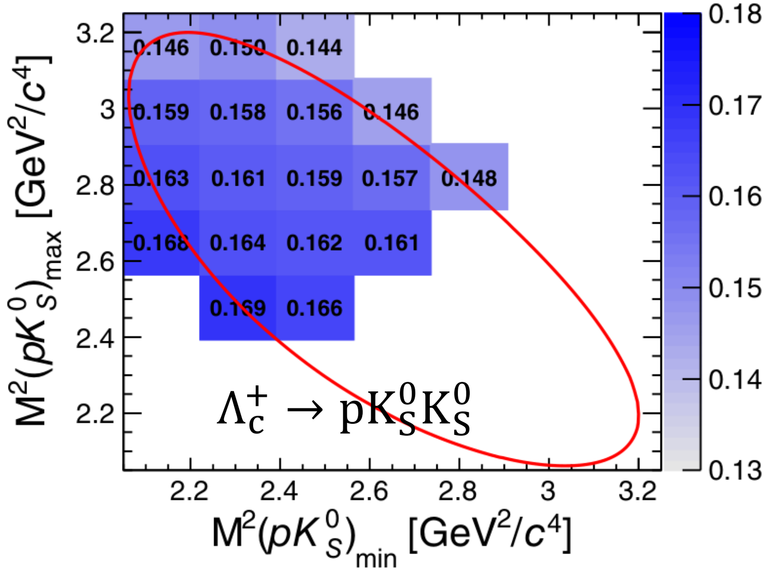


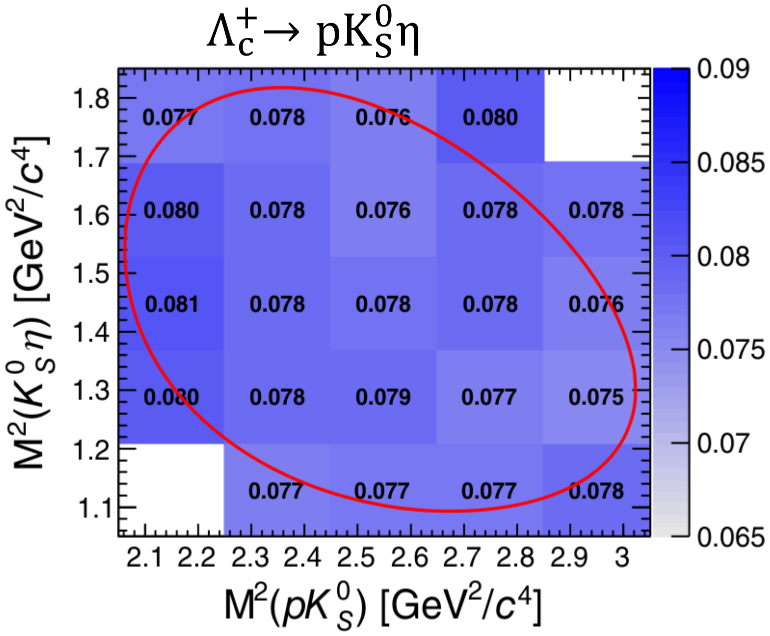
Yields	$\Lambda_c^+ \to pK_S^0K_S^0$	$\Lambda_c^+ \to pK_S^0\eta$	$\Lambda_c^+ \to pK_S^0$
$N_{\mathrm{sig}}^{\mathrm{FR}}$	2442 ± 103	12877 ± 317	515296 ± 1129

Branching fractions of $\Lambda_c^+ \to pK_S^0K_S^0, pK_S^0\eta$

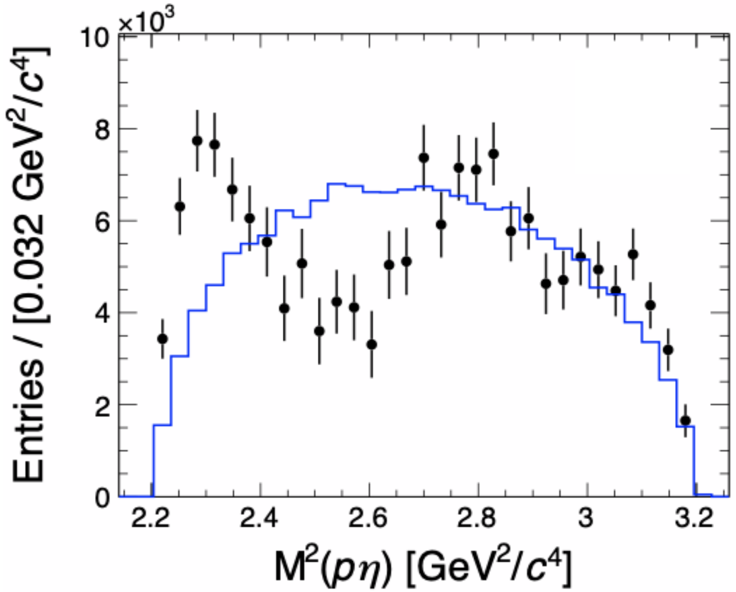
[PRD 107, 032004 (2023)]

■ Efficiency Plane





N*(1535) is observed in M(pη).



■ Branching fraction

- $\frac{B(\Lambda_c^+ \to pK_S^0K_S^0)}{B(\Lambda_c^+ \to pK_S^0)} = (1.48 \pm 0.08 \pm 0.04) \times 10^{-2}$ ➡ $B(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.07 \pm 0.12) \times 10^{-4}$
  - ➢ First observation
- $\frac{B(\Lambda_c^+ \to pK_S^0\eta)}{B(\Lambda_c^+ \to pK_S^0)} = (2.73 \pm 0.06 \pm 0.13) \times 10^{-1}$ ➡ $B(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$
  - ➢ Consistent with world average value $(4.15 \pm 0.90) \times 10^{-3}$ and threefold improvement in precision.

Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

■ Motivation

- $\Lambda_c(2625)^+$($J^P = 3/2^-$) is the excited state of Λ_c^+. It dominantly decays to $\Lambda_c^+\pi^+\pi^-$ via P-wave decay. The D-wave decay $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$ is also allowed, but its contribution is known to be small.

- The mass of the $\Lambda_c(2625)^+$, relative to the Λ_c^+ mass, is already relatively well known [PRD 84,012003 (2011)], but the large Belle data sample allows for a more precise measurement.

- No intrinsic width of the $\Lambda_c(2625)^+$ has yet been measured, and the current upper limit $\Gamma < 0.97\ \mathrm{MeV}/c^2$ at 90% confidence level is based on the CDF measurement in 2011 [PRD 84,012003 (2011)].

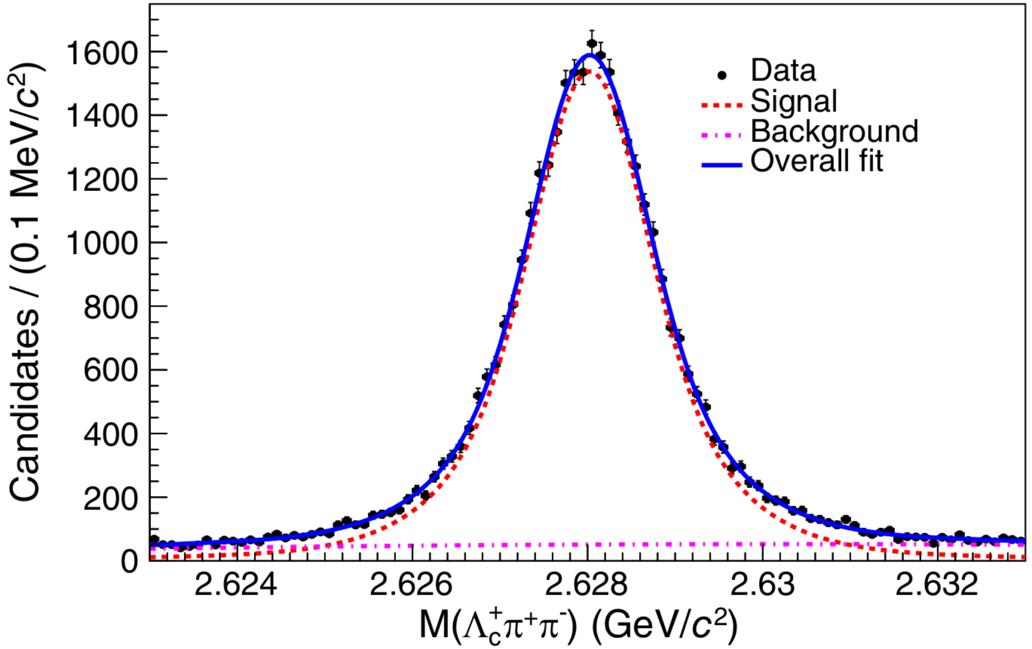
Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

■ Measurements of mass and width

[PRD 107, 032008 (2023)]

Reconstruction mode: $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-, \Lambda_c^+ \to pK^-\pi^+$

Full Belle dataset



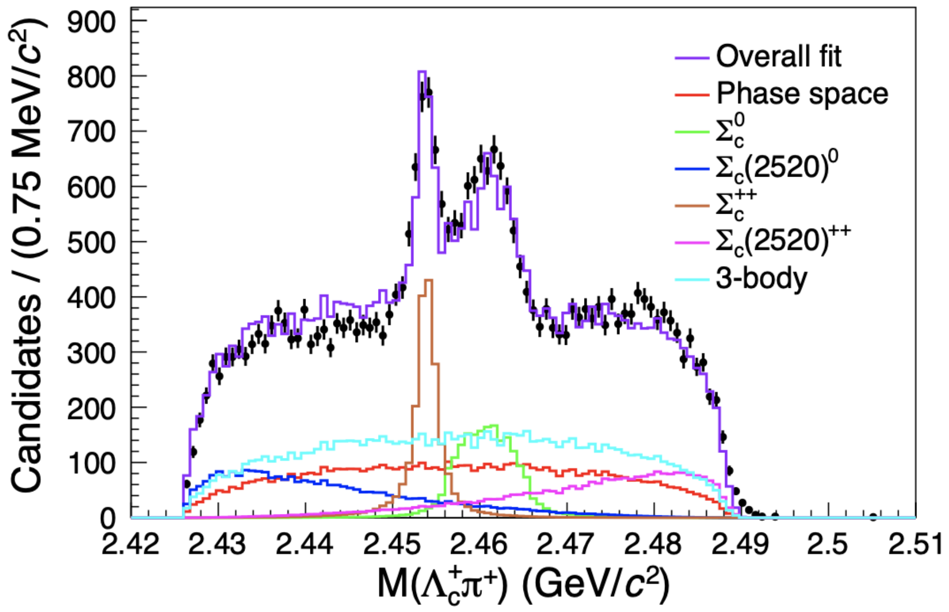
- $M[\Lambda_c(2625)^+] - M(\Lambda_c^+) = 341.518 \pm 0.006 \pm 0.049$ MeV/c^2
  - consistent with the world average value 341.65 ± 0.13 MeV/ c^2
  - has approximately half the uncertainty
- $\Gamma[\Lambda_c(2625)^+] < 0.52$ MeV
  - a factor of 2 more stringent than the previous limit $\Gamma < 0.97$ MeV
  - An improved limit on the width of the $\Lambda_c(2625)^+$ will help to constrain various theoretical predictions.

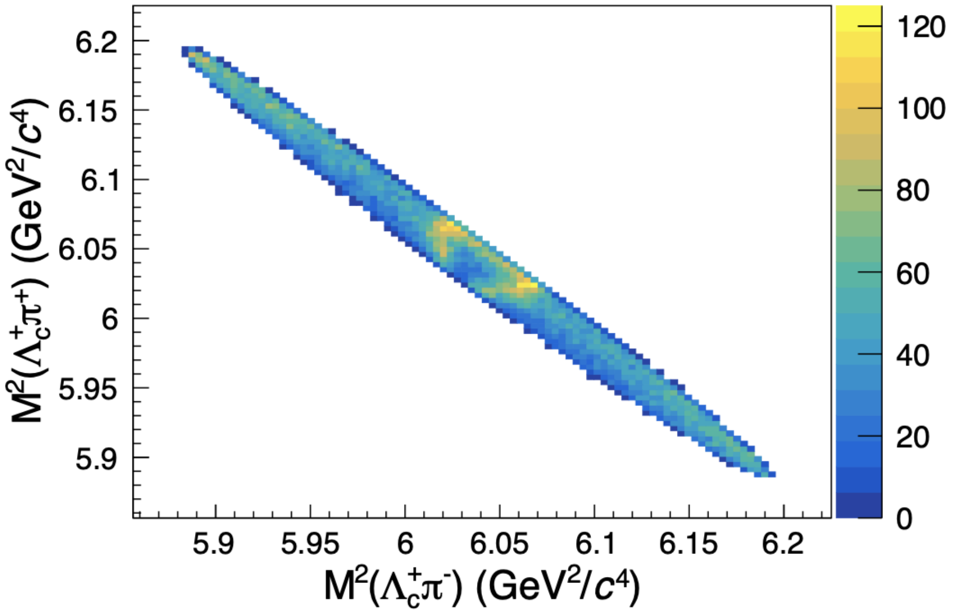
Mass and width of $\Lambda_c(2625)^+$ and BR of $\Lambda_c(2625)^+ \to \Sigma_c^{0,++}\pi$

■ Measurements of branching fractions

[PRD 107, 032008 (2023)]

Full Dalitz plot fitted with AmpTools is performed [PRD 98, 114007 (2018)].





$$\frac{B(\Lambda_c(2625)^+ \to \Sigma_c^0\pi)}{B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.19 \pm 0.23 \pm 0.40)\%$$

$$\frac{B(\Lambda_c(2625)^+ \to \Sigma_c^{++}\pi)}{B(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.13 \pm 0.26 \pm 0.32)\%$$

- The measured branching fraction ratios agree with PDG values and are the most precise to date.
- Our measurements align with the prediction that assuming $\Lambda_c(2625)^+$ is a λ mode excitation [PRD 98, 114007 (2018)].

Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-K^+$ and Ω^-K^+ decays

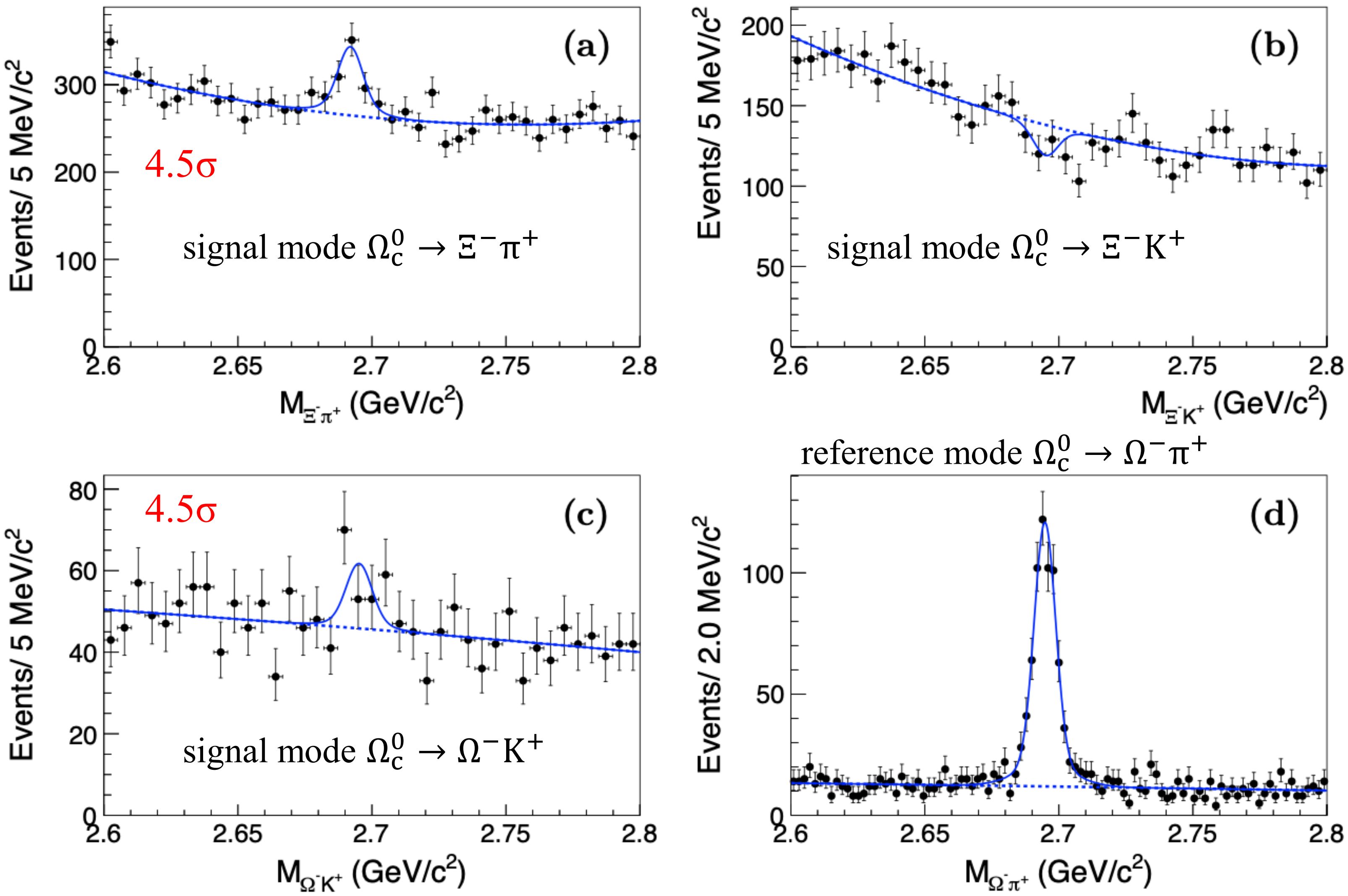
- The theoretical study of hadronic weak decays of the Ω_c^0 has a long history. But due to the low production rate of Ω_c^0 and low detection efficiency for long-lived final states, our knowledge of the Ω_c^0 state is very limited.
- The singly Cabibbo-suppressed decay $\Omega_c^0 \to \Xi^-\pi^+$ and doubly Cabibbo-suppressed decay $\Omega_c^0 \to \Xi^-K^+$ decays have been studied systematically in various theoretical models.

Predicted ratios of branching fractions for using light-front quark model (LFQM), pole model, and current algebra (CA).

Branching fraction ratios	LFQM CPC 42, 093101 (2018)	Pole model and CA PRD 101, 094033 (2020)
$\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$	1.96×10^{-3}	1.04×10^{-1}
$\mathcal{B}(\Omega_c^0 \to \Xi^-K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$	1.74×10^{-4}	1.06×10^{-2}

[JHEP 01 (2023) 055]

Full Belle dataset



The first evidence of $\Omega_c^0 \to \Xi^-\pi^+$ with a signal significance of 4.5σ including systematic uncertainties.

No significant signals are found in $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Omega^-\pi^+$.

$\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) = 0.253 \pm 0.053(\text{stat.}) \pm 0.030(\text{syst.})$
$\mathcal{B}(\Omega_c^0 \to \Xi^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.070$
$\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.29$

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 $\Lambda_c^+ \to$ p$K^-\pi^+$**

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			
$pK^-\pi^+\pi^+\pi^-$		$(1.5 \pm 1.0) \times 10^{-3}$			66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %			45.4%
Hadronic modes with a p: $S=0$ final states					
$p\pi^+\pi^-$		$(4.7 \pm 2.5) \times 10^{-3}$			45.4%
$pf_0(980)$	[q]	$(3.8 \pm 2.5) \times 10^{-3}$			53.2%
$p\pi^+\pi^+\pi^-\pi^-$		$(2.5 \pm 1.6) \times 10^{-3}$			64.0%
pK^+K^-		$(1.1 \pm 0.4) \times 10^{-3}$			36.4%
$p\phi$	[q]	$(1.12 \pm 0.23) \times 10^{-3}$			
pK^+K^- non-ϕ		$(4.8 \pm 1.9) \times 10^{-4}$			
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%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		$(7.5 \pm 1.4) \times 10^{-3}$			18.7%

Large uncertainties in experiment ➔ slow development in theory