Charm baryon decays at BESIII

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Baryon weak decays -
from experiment to lattice QCD
Warsaw, Poland
4-5 March 2024

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
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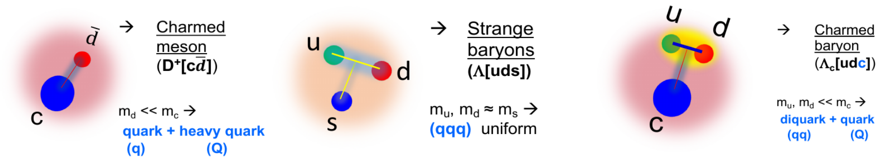
Institute of High Energy Physics
Chinese Academy of Sciences

Λ_c^+: the lightest charmed baryon spectroscopy

- Most of charmed baryons will eventually decay to Λ_c^+
- Λ_c^+: one of important tagging hadrons in c-quark counting in the productions at high energy experiment
- Also important input to Λ_b (including Ξ_{cc}^{++}) physics as Λ_b decay preferentially to Λ_c^+ $\rightarrow$ Important input to B physics and V_{ub} calculations
- Λ_c^+ may provide more powerful test on internal dynamics than D/D_s does!
- Naive quark model picture:

  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)



[PLB237(1990)527] [ConfProcC900318(1990)583] [PLB240(1990)447] [NPB343(1990)1]

[NPB339(1990)253] [PLB234(1990)511] [PLB249(1990)295]

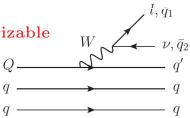
Charm baryon decays

[ChinJPhys78(2022)324][ZPhysC55(1992)659]

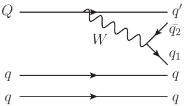
- Contrary to charmed mesons, W-exchange contribution is important

  $\to$ No color suppression and helicity suppression

factorizable

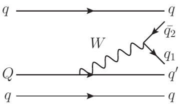


(a) External spectator (color-favored tree)



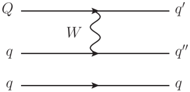
(b1) Internal spectator (color-suppressed tree)

factorizable+ non-factorizable

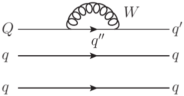


(b2) Inner spectator (color-sommensurate)

non-factorizable



(c) W-exchange



(d) Pengiun

neglegted

- Phenomenology goal: explain data and predict important observables
- Calculation (what we can: HQET, factorization) + parametrization (what we cannot) + measurement (some non-factorization processes)

Data taking at Λ_c^+ pair threshold

- Unique measurement using threshold pair-production via e^+e^- annihilation $\rightarrow$ simple and straightforward
- Double-tag method
  - Lower background and kinematic relation to constrain missing particle
  - Cancellation of most systematic uncertainties in tag side
- BESIII energy upgrades:

  4.6 GeV (Phase I, 2014)

- 2014: First time to systematically study CB at threshold

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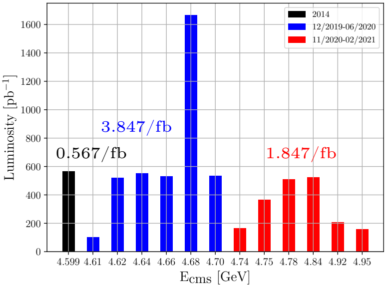
- 2019-2021: ~5.85/fb
- Improvement of precision of Λ_c^+ decay rates to level comparable to charmed mesons
- Opportunity to study many unexplored physics observables related to Λ_c^+ decays
- Boost our understanding of the non-perturbative effects in CB sector

[CPC46(2022)113003]



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[CPC46(2022)113003]

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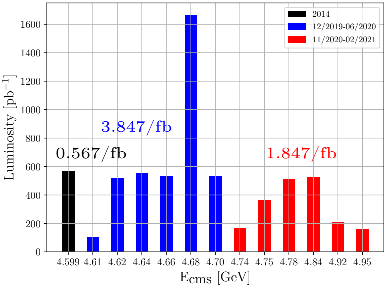
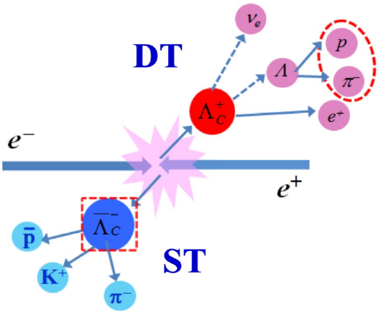


Tag technique



- Single Tag (ST):
  - $\Delta E = E_{\Lambda_c^+} - E_{beam}$
  - beam-constrained mass

  $M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_{\Lambda_c^+}|^2}$
- Double Tag (DT):
  - kinematic variable to obtain neutrino information

  $U_{miss} = E_{miss} - c|\vec{p}_{miss}|$
- Branching fraction:

  $\mathcal{B} = \frac{N_{DT}}{N_{ST}} \frac{\varepsilon_{ST}}{\varepsilon_{DT}}$

- Full reconstruction of ST CBD by hadronic decays with large $\mathcal{B}$
- Allow to access absolute $\mathcal{B}$s and decay dynamics

Λ_c^+ decay modes

	Hadronic mode	$\mathcal{B}[\%]$ [PDG2023]
1	$\Lambda\pi^+\pi^0$	7.02 ± 0.35
2	$pK^-\pi^+$	6.26 ± 0.29
3	$\Sigma^+\pi^+\pi^-$	4.48 ± 0.23
4	$pK^-\pi^+\pi^0$	4.45 ± 0.28
5	$\Lambda\pi^-2\pi^+$	3.62 ± 0.26
6	$\Sigma^0\pi^+\pi^0$	3.5 ± 0.4
7	$pK_S^0\pi^0$	1.96 ± 0.12
8	pK_S^0	1.59 ± 0.07
9	$pK_S^0\pi^+\pi^-$	1.6 ± 0.11
10	$\Lambda\pi^+$	1.29 ± 0.05
11	$\Sigma^0\pi^+$	1.27 ± 0.06
12	$\Sigma^+\pi^0$	1.25 ± 0.09
13	$\Sigma^0\pi^-2\pi^+$	1.10 ± 0.30
14	$p\pi^+\pi^-$	0.46 ± 0.03

~40%

	Semileptonic mode	$\mathcal{B}[\%]$ [PDG2023]
1	$\Lambda e^+\nu_e$	3.56 ± 0.13
2	$\Lambda\mu^+\nu_\mu$	3.5 ± 0.5
3	$\Lambda(1520)e^+\nu_e$	0.10 ± 0.05

Semileptonic decay modes

created by particlezoo.net

Semileptonic baryon decay

- Momenta and masses: $B_1(p_1, M_1) \to B_2(p_2, M_2) + l^-(p_l, m_l) + \bar{\nu}_l(p_{\bar{\nu}_l}, 0)$
- FF for the weak current-induced baryonic $1/2^+ \to 1/2^+$ transitions [EPJ C59 (2009) 27]:

$$\langle B_2(p_2)|J_\mu^{V+A}|B_1(p_1)\rangle = \bar{u}(p_2)\left[\gamma_\mu(F_1^V(q^2) + F_1^A(q^2)\gamma_5) + \frac{i\sigma_{\mu\nu}q^\nu}{M_1}(F_2^V(q^2) + F_2^A(q^2)\gamma_5) + \frac{q^\mu}{M_1}(F_3^V(q^2) + F_3^A(q^2)\gamma_5)\right]u(p_1)$$

where $q_\mu = (p_1 - p_2)_\mu$

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- For $B_1 \to B_2 e^- \bar{\nu}_e$ at $\mathcal{O}(\frac{m_e^2}{2q^2}) \to 0 \Longrightarrow F_3^{V,A}(q^2) \to 0$
- $H_{\lambda_2 \lambda_W} = (H^V_{\lambda_2 \lambda_W} + H^A_{\lambda_2 \lambda_W})$ with ($\lambda_2 = \pm 1/2; \lambda_W = t, 0, \pm 1$): $H^{V,A}_{\lambda_2 \lambda_W} \equiv H^{V,A}_{\lambda_2 \lambda_W}(F^{V,A}_{1,2}(q^2))$

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vector helicity amplitudes

$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}\left(-F_1^V - \frac{M_+}{M_1}F_2^V\right),$$
$$H^V_{\frac{1}{2}0} = \sqrt{\frac{Q_-}{q^2}}\left(M_+F_1^V + \frac{q^2}{M_1}F_2^V\right),$$
$$H^V_{\frac{1}{2}t} = \sqrt{\frac{Q_+}{q^2}}\left(M_-F_1^V + \frac{q^2}{M_1}F_3^V\right),$$

axial-vector helicity amplitudes

$$H^A_{\frac{1}{2}1} = \sqrt{2Q_+}\left(F_1^A - \frac{M_-}{M_1}F_2^A\right),$$
$$H^A_{\frac{1}{2}0} = \sqrt{\frac{Q_+}{q^2}}\left(-M_-F_1^A + \frac{q^2}{M_1}F_2^A\right),$$
$$H^A_{\frac{1}{2}t} = \sqrt{\frac{Q_-}{q^2}}\left(-M_+F_1^A + \frac{q^2}{M_1}F_3^A\right)$$

where $Q_\pm = (M_1 \pm M_2)^2 - q^2 \equiv M_\pm^2 - q^2$, $\quad H^{V,A}_{-\lambda_2,-\lambda_W} = \pm H^{V,A}_{\lambda_2,\lambda_W}$

Form factors (1)

- Neglecting possible CP-odd weak phase, $\mathrm{FF}(l^-, \bar{\nu}_l) = sign\ \mathrm{FF}(l^+, \nu_l)$
- In limit of exact SU(3) symmetry, F_2^A and $F_3^V \to 0$

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- In limit of exact SU(3) symmetry, F_2^A and $F_3^V \to 0$
- FF parametrization for **hyperons** [PLB478(2000)417][EPJC81(2021)226]:

$$F_i^{V,A}(q^2) = \frac{F_i^{V,A}(0)}{1 - \frac{q^2}{M_{V,A}^2}} \frac{1}{1 - \alpha_{\mathrm{BK}} \frac{q^2}{M_{V,A}^2}} \Longrightarrow F_i^{V,A}(q^2) = F_i^{V,A}(0) \left[1 + r_i^{V,A} q^2 + ...\right]$$

with $r^{V,A} = 2/m_{V,A}^2$ [AnnRevNuclPartSci34(1984)351] [AnnRevNuclPartSci53(2003)39]

- $\Delta S = 0$: $m_V = 0.84$ GeV [RivNuovoCim2(1972)241], $m_A = 1.08$ GeV [BNL-24848]
- $|\Delta S| = 1$: $m_V = m_{K^*(892)} = 0.89$ GeV, $m_A = m_{K^*(1270)} = 1.27$ GeV

Decay	$\mathcal{B}(\times 10^{-4})$	$g_{av}^D(0)$	$g_w^D(0)$	$M_1 - M_2$ [MeV]	Ref.
$\Lambda \to p e^- \bar{\nu}_e$	8.32(14)	0.718(15)	1.066	177	[1, 2]
$\Sigma^+ \to \Lambda e^+ \nu_e$ [a]	0.20(05)	0.01(10)	2.4(17)	74	[1]
$\Xi^- \to \Lambda e^- \bar{\nu}_e$	5.63(31)	0.25(5)	0.085	206	[2, 3]

[a] Since $F_1^{\Sigma} = 0$, g_{av} and g_w are defined as F_1^V/F_1^A and F_2^V/F_1^A, respectively

[1] PTEP2022 083C01(2022) [2] AnnRevNuclPartSci53(2003)39 [3] ZPhysC21(1983)1

Form factors (2)

- FF parametrization for **charm baryons**:
  [EPJC76(2016)628] [PRD93(2016)034008] [PRD80(2009)074011] [PRC72(2005)035201] [Chin.Phys.C42(2018)093101] [PRD40(1989)2944] [PRD40(1989)2955] and many others
- Relativistic quark model based on quasi-potential approach with QCD-motivated potential:

$$F_i(q^2) = \frac{1}{1 - q^2/(M_{\mathrm{pole}}^{F_i})^2} \sum_{n=0}^{n_{\max}} a_n^{F_i} [z(q^2)]^n$$

where $z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$ with $t_0 = (M_1 - M_2)^2$

Decay	$\sqrt{t_+}$	$m(F_{1,2}^V)$ [GeV]	$m(F_3^V)$ [GeV]	$m(F_{1,2}^A)$ [GeV]	$m(F_3^A)$ [GeV]	$M_1 - M_2$ [GeV]	Ref.
$\Lambda_c^+ \to \Lambda l^+ \nu_l$	$m_D + m_K$	2.11	2.32	2.46	1.97	1.17	[1]
$\Xi_c \to \Xi l \nu_l$	$m_{D_s} + m_K$	2.11	2.54	2.54	1.97	1.15	[2]
$\Xi_c \to \Lambda l \nu_l$	$m_D + m_\pi$	2.01	2.42	2.42	1.87	1.35	[2]

[1] [PRL118(2017)082001] [2] [EPJC79(2019)695] [3] ZPhysC21(1983)1

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Decay	$\sqrt{t_+}$	$m(F_{1,2}^V)$ [GeV]	$m(F_3^V)$ [GeV]	$m(F_{1,2}^A)$ [GeV]	$m(F_3^A)$ [GeV]	$M_1 - M_2$ [GeV]	Ref.
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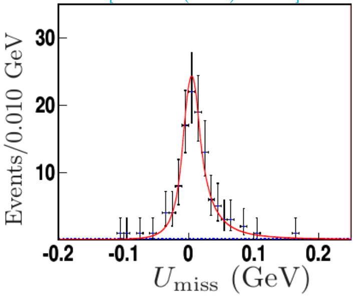
- Differential decay rate:

$$\frac{d\Gamma(B_1 \to B_2 l \nu_l)}{dq^2} \propto G_F^2 |V_{ij}|^2 q^2 p \left[(1 - \frac{3}{2}\delta)(F_1^V)^2 + (3 - \frac{9}{2}\delta)(F_1^A)^2 - 4\delta F_1^A F_2^A + \mathcal{O}(\delta^2) \right]$$

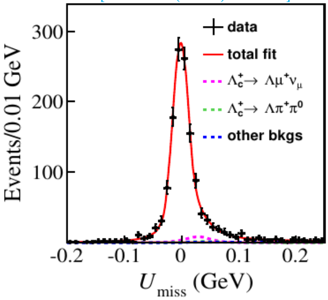
with $\delta = (M_1 - M_2)/M_1$ and $F_{1,2}^{V,A} \equiv F_{1,2}^{V,A}(q^2)$

Study of decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ (1)

[PRL115(2015)221805]



[PRL129(2022)231803]



- **Data**: 0.567/fb @ 4.6 GeV
- $N_{\rm sig} = 103.5 \pm 10.9$
- First absolute $\mathcal{B}$ measurement:

  $\mathcal{B} = (3.63 \pm 0.38 \pm 0.20)\%$ (∼12%)

- **Data**: 4.5/fb @ 4.6-4.699 GeV
- $N_{\rm sig} = 1253 \pm 39$
- Update $\mathcal{B}$ and first FFs measurement:

  $\mathcal{B} = (3.56 \pm 0.11 \pm 0.07)\%$ (∼4%)

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

- Consistent with $|V_{cs}| = 0.939/0.972 \pm 0.038/0.007$ using $D \to K l \nu_l$ within 1σ [PDG2020/PDG2023]

Study of SL Λ_c^+ decay kinematics

[PRL129(2022)231803]

- Differential decay rate:

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

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$$+ \frac{3}{4}\sin^2\theta_e [|H_{\frac{1}{2}0}|^2 (1+\alpha_\Lambda\cos\theta_p) + |H_{-\frac{1}{2}0}|^2 (1-\alpha_\Lambda\cos\theta_p)]$$
$$+ \frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta_e\sin\theta_p \left[(1-\cos\theta_e) H_{-\frac{1}{2}0} H_{\frac{1}{2}1} + (1+\cos\theta_e) H_{\frac{1}{2}0} H_{-\frac{1}{2}-1}\right] \Big\}$$

- Helicity amplitudes:

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

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$$\Big\{\frac{3}{8}(1-\cos\theta_e)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)+\frac{3}{8}(1+\cos\theta_e)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta_e[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]$$
$$+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta_e\sin\theta_p\,[(1-\cos\theta_e)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta_e)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]\Big\}$$

- Helicity amplitudes:

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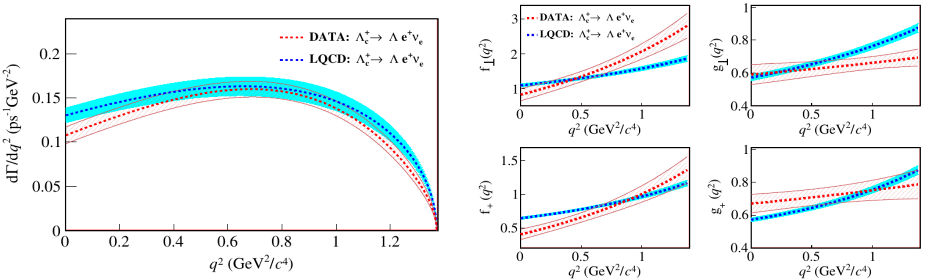
$$H^V_{\frac{1}{2}0}=\sqrt{Q_-/q^2}f_+(q^2)(M_{\Lambda_c}+M_\Lambda),$$
$$H^A_{\frac{1}{2}0}=\sqrt{Q_+/q^2}g_+(q^2)(M_{\Lambda_c}-M_\Lambda)$$

- z-expansion for form factor parametrization:

$$f(q^2)=\frac{a_0^f}{1-q^2/\left(m^f_{\rm pole}\right)^2}\left[1+\alpha_1^f\times z(q^2)\right]$$

- Used the same in LQCD calculations [PRL118(2017)082001]
- 5 fitted parameters: $\alpha_1^{g_\perp}$, $\alpha_1^{f_\perp}$, r_{f_+}, $r_{f_\perp}$, r_{g_+}

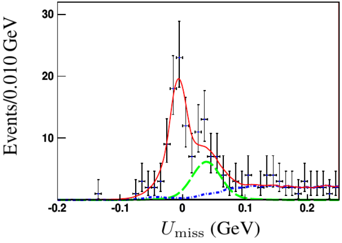
Experiment [PRL129(2022)231803] / LQCD comparison [PRL118(2017)082001]



- First direct comparison on $d\Gamma/dq^2$ rates and FFs with LQCD calculations
  - Discrepancies at high q^2 for $f_\perp$ and $g_\perp$ and at low q^2 for f_+ and g_+
  - Fair agreement in $d\Gamma$ throughout q^2 region
- Important inputs in understanding SL CB decays and help to calibrate theor. calculations

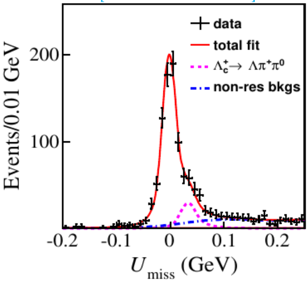
Study of decay $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ (1)

[PLB767(2017)42]



- **Data**: 0.567/fb @ 4.6 GeV
- $\text{N}_{\text{sig}} = 77.1 \pm 11.4$
- First absolute $\mathcal{B}$ measurement: $\mathcal{B} = (3.49 \pm 0.46 \pm 0.27)\%$ (∼15%)
- $R^{\mu e} = 0.96 \pm 0.16 \pm 0.04$

[arXiv:2306.02624]



- **Data**: 4.5/fb @ 4.6-4.699 GeV
- $\text{N}_{\text{sig}} = 752 \pm 31$
- Update $\mathcal{B}$ and first FFs measurement: $\mathcal{B} = (3.48 \pm 0.14 \pm 0.10)\%$ (∼5%)
- $R^{\mu e} = 0.98 \pm 0.05 \pm 0.03$ vs. **SM**: 0.97

$$|V_{cs}| = 0.937 \pm 0.014_{\mathcal{B}} \pm 0.024_{\text{LQCD}} \pm 0.007_{\tau_{\Lambda_c}}$$

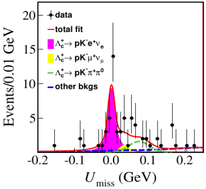
- Most precise measurement with SL CB decays
- Consistent with $|V_{cs}| = 0.972 \pm 0.007$ using $D \to K l \nu_l$ within 1.2σ [PDG2023]

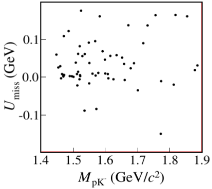
Study of decay $\Lambda_c^+ \to pK^- e^+ \nu_e$

[PRD106(2022)112010]

- **Data**: 4.5/fb @ 4.6-4.7 GeV
- $N_{sig} = 33.5 \pm 6.3$
- New observed mode clearly confirms that SL Λ_c^+ decays are not saturated by $\Lambda l^+ \nu_l$

$$\mathcal{B} = (0.88 \pm 0.17 \pm 0.07) \cdot 10^{-3} \ (8.2\sigma)$$



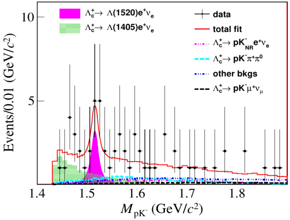


- To study the internal structure of excited Λ^*:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)[\to pK^-]e^+\nu_e) = (0.23 \pm 0.12 \pm 0.02) \cdot 10^{-3} \ (3.3\sigma)$$
$$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19 \pm 0.04) \cdot 10^{-3} \ (3.2\sigma)$$

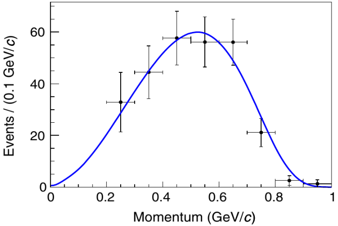
	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)[\times 10^{-3}]$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)[\times 10^{-3}]$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	$\cdots$	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12,13]	0.512 ± 0.082	$\cdots$
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42 \pm 0.19 \pm 0.04}{\mathcal{B}(\Lambda(1405) \to pK^-)}$

$\mathcal{B}(\Lambda(1405) \to pK^-)$ is unknown [PDG2020]

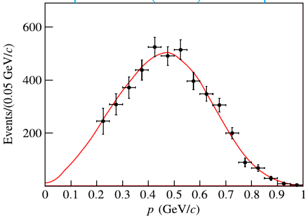


Study of decay $\Lambda_c^+ \to X e^+ \nu_e$

[PRL121(2018)251801]



[PRD107(2023)052005]



- **Data**: 0.567/fb @ 4.6 GeV
- $N_{sig} = 228.0 \pm 15.1$

- **Data**: 4.5/fb @ 4.6-4.699 GeV
- $N_{sig} = 3706 \pm 71$

Result	$\Lambda_c^+ \to X e^+ \nu_e$	$[\Gamma(\Lambda_c^+ \to X e^+ \nu_e) / \bar{\Gamma}(D \to X e^+ \nu_e)]$
BESIII 2018	3.95 ± 0.35 ($\sim$ 9%)	1.26 ± 0.12
BESIII 2023	4.06 ± 0.13 ($\sim$ 3%)	1.28 ± 0.05
MARK II [11]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark method [8,9]		1.67
Heavy-quark expansion [10]		1.2

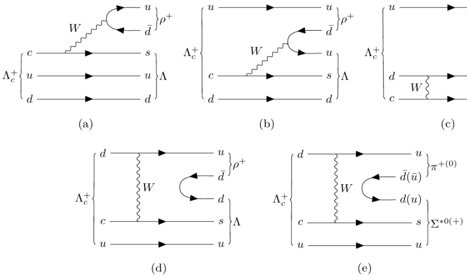
- $\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e) < 3.9 \cdot 10^{-4}$ @90%C.L.
- $\mathcal{B}(\Lambda_c^+ \to p K_S^0 \pi^- e^+ \nu_e) < 3.3 \cdot 10^{-4}$ @90%C.L. [PLB843(2023)137993]

Hadronic decay modes

created by particlezoo.net

Study of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ (1)

[JHEP12(2022)033]



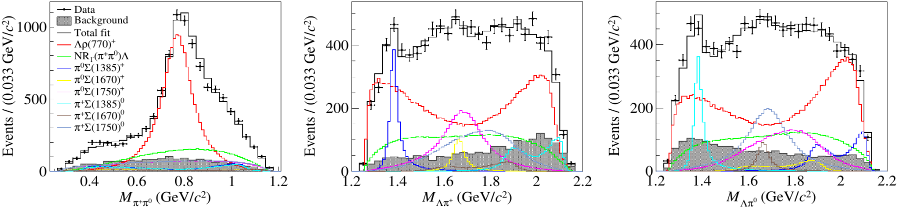
- $\Lambda_c^+ \to \Lambda\rho^+$: factorizable (a) and non-factorizable (b-d) contributions
- $\Lambda_c^+ \to \Sigma(1385)\pi$: pure non-factorizable (e) contribution

- Previous measurement of $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)$ by BESIII [PRL116(2016)052001] without intermediate structure study
- Important inputs to improve theoretical calculations of non-factorizable contributions
- First BESIII amplitude analysis of CB multi-hadronic decays
- Use TF-PWA package to construct decay amplitudes

Study of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ (2)

[JHEP12(2022)033]

- **Data**: 4.4/fb @ 4.6-4.7 GeV
- $N_{sig} \sim 10^4$ with purity $> 80\%$



Study of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ (2)

[JHEP12(2022)033]

- **Data**: 4.4/fb @ 4.6-4.7 GeV
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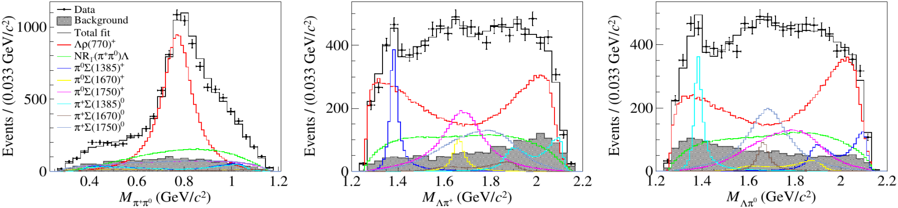


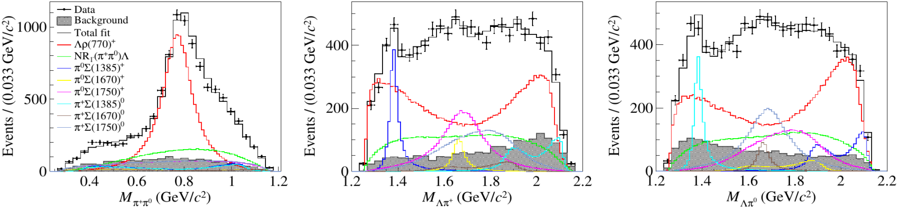
	Theoretical calculation		This work	PDG	FF (%)	Significance
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14,15]	4.06 ± 0.52	< 6	57.2 ± 4.2	$36.9\,\sigma$
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—	7.18 ± 0.60	$14.8\,\sigma$
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—	7.92 ± 0.72	$16.0\,\sigma$
$\alpha_{\Lambda\rho(770)^+}$	-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	—		

- First measurement of decay asymmetry parameters for resonant components

Study of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ (2)

[JHEP12(2022)033]

- **Data**: 4.4/fb @ 4.6-4.7 GeV
- $N_{sig} \sim 10^4$ with purity > 80%



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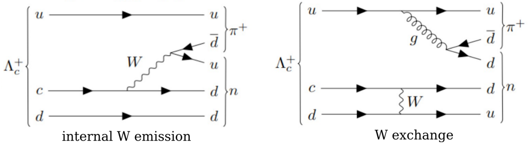
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—		

- First measurement of decay asymmetry parameters for resonant components
- None of theoretical predictions explains both $\mathcal{B}$ and decay asymmetry

Study of decay $\Lambda_c^+ \to n\pi^+$ (1)

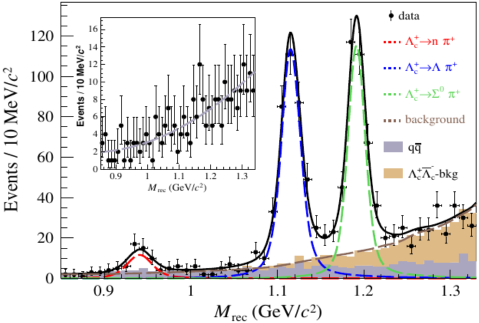
[PRL128(2022)142001]

non-factorizable contribution



- SCS decays provide information about factorizable and non-factorizable interference
- Exp. inputs are required to improve understanding of validity of different theor. models

- **Data**: 3.9/fb @ 4.612-4.7 GeV
- $N_{sig}(\Lambda_c^+ \to n\pi^+) = 50 \pm 9$
- $N_{sig}(\Lambda_c^+ \to \Lambda\pi^+) = 376 \pm 22$
- $N_{sig}(\Lambda_c^+ \to \Sigma^0\pi^+) = 343 \pm 22$



Study of decay $\Lambda_c^+ \to n\pi^+$ (2)

[PRL128(2022)142001]

Theoretical models	$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	$\mathcal{B}(\Lambda_c^+ \to n\pi^+) / \mathcal{B}(\Lambda_c^+ \to p\pi^0)$
SU(3) flavor symmetry (1997) [1]	4	2
SU(3) flavor symmetry (2016) [2]	9	2
SU(3) flavor symmetry (2018) [3]	11.3 ± 2.9	2
Constituent quark (1994) [4]	8 or 9	4.5 or 8.0
Pole model and CA (2018) [5]	2.66	3.5
SU(3) + $\mathcal{O}(\overline{15})$ (2019) [6]	6.1 ± 2.0	4.7
Topological-diagram (2020) [7]	7.7 ± 2.0	9.6

$$\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4) \cdot 10^{-4}$$

- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08 \pm 0.05) \cdot 10^{-2}$
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08 \pm 0.07) \cdot 10^{-2}$
- Use $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \cdot 10^{-5}$ @90% C.L. by Belle [PRD103(2021)072004]

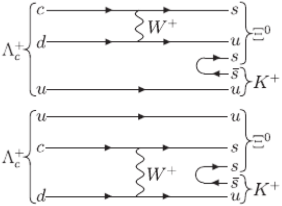
$$\frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} > 7.2 \text{ @90\% C.L.}$$

- Disagreement with most predictions of theor. models, implying that non-factorization contributions are overestimated

Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (1)

[PRL132(2024)031801]

- Significant dependence on non-factorizable contributions from W-boson-exchange diagrams → differ from charmed mesons (helicity suppressed)
- **Goal**: measurement of asymmetry parameter and decay dynamic parameters



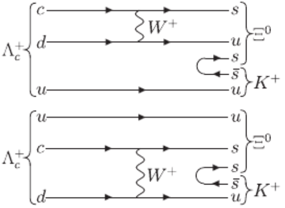
Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ ($\times 10^{-3}$)	$\alpha_{\Xi^0 K^+}$	$\lvert A \rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\lvert B \rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	...	...	...
Xu (1992), Pole [8]	1.0	0	0	7.94	...
Źencaykowski (1994), Pole [9]	3.6	0	...	...	...
Ivanov (1998), CCQM [10]	3.1	0	...	...	...
Sharma (1999), CA [11]	1.3	0	...	...	...
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	...
Zou (2020), CA [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3)^a [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	...
Zhong (2022), SU(3)^b [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	...
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (1)

[PRL132(2024)031801]

- Significant dependence on non-factorizable contributions from *W*-boson-exchange diagrams → differ from charmed mesons (helicity suppressed)

- **Goal**: measurement of asymmetry parameter and decay dynamic parameters



Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\lvert B\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (rad)
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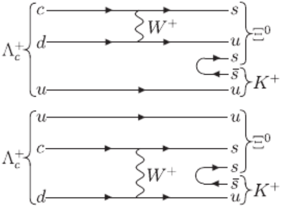
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Explained as strong cancellation in S- and P-wave amplitudes, corresponding to L=0 and L=1 orbital angular momenta of $\Xi^0 - K^+$ system

Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (1)

[PRL132(2024)031801]

- Significant dependence on non-factorizable contributions from W-boson-exchange diagrams
  $\to$ differ from charmed mesons (helicity suppressed)
- **Goal**: measurement of asymmetry parameter and decay dynamic parameters



Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ $(\times 10^{-2} G_F$ GeV$^2)$	$\lvert B\rvert$ $(\times 10^{-2} G_F$ GeV$^2)$	$\delta_p - \delta_s$ (rad)
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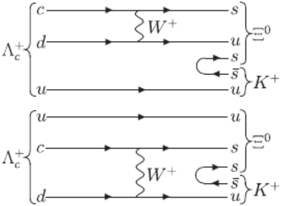
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Due to vanishing S-wave amplitude

Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (1)

[PRL132(2024)031801]

- Significant dependence on non-factorizable contributions from *W*-boson-exchange diagrams
  → differ from charmed mesons (helicity suppressed)
- **Goal**: measurement of asymmetry parameter and decay dynamic parameters



Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ ($\times 10^{-3}$)	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\lvert B\rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\delta_p - \delta_s$ (rad)
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BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Reproduction of relatively large exp. Br introduces large positive decay asymmetry

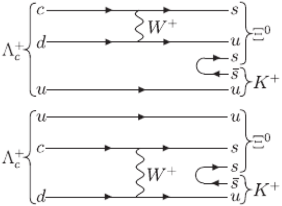
- Renewed interest in theor. community after BESIII 2018 result:
  → adoption of approach with large value of decay asymmetry
  → theor. discussions about proper construction of *S*-wave amplitude → Stefan's talk

Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (1)

[PRL132(2024)031801]

- Significant dependence on non-factorizable contributions from W-boson-exchange diagrams
  $\to$ differ from charmed mesons (helicity suppressed)

- **Goal**: measurement of asymmetry parameter and decay dynamic parameters



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Ivanov (1998), CCQM [10]	3.1	0	...	...	...
Sharma (1999), CA [11]	1.3	0	...	...	...
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	...
Zou (2020), CA [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$			
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01			
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...			
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Reproduction of relatively large exp. Br introduces large positive decay asymmetry

Exp. measurement is crucial to test the calculations and confirm vanishing S-wave contribution

- Renewed interest in theor. community after BESIII 2018 result:
  $\to$ adoptation of approach with large value of decay asymmetry
  $\to$ theor. discussions about proper construction of S-wave amplitude $\to$ Stefan's talk

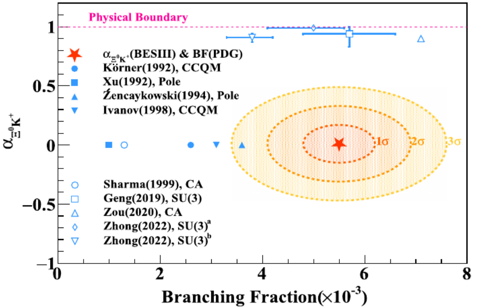
Study of decay $\Lambda_c^+ \to \Xi^0 K^+$ (2)

[PRL132(2024)031801]

$$\alpha_{\Xi^0 K^+} = \frac{2\Re(s*p)}{|s|^2+|p|^2}$$
$$\beta_{\Xi^0 K^+} = \frac{2\Im(s*p)}{|s|^2+|p|^2} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\sin\Delta_{\Xi^0 K^+}$$
$$\gamma_{\Xi^0 K^+} = \frac{|s|^2-|p|^2}{|s|^2+|p|^2} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\cos\Delta_{\Xi^0 K^+}$$

- **Data**: 4.4/fb @ 4.6-4.7 GeV
- $N_{sig} = 378 \pm 21$
- First measurement of decay parameters
- Value of $\alpha_{\Xi^0 K^+}$ is consistent with theor. predictions from 1990s

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



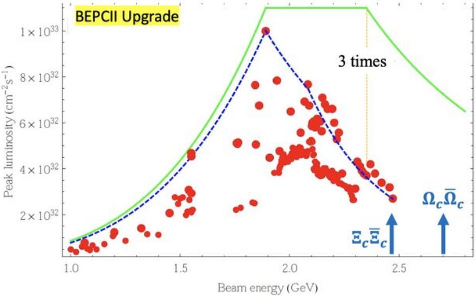
More published analyses

- Neutron-involved decays
  - $\mathcal{B}$ of CS $\Lambda_c^+ \to n\pi^+\pi^-$, $n\pi^+\pi^-\pi^+$ and CF $\Lambda_c^+ \to nK^-\pi^+\pi^+$ [CPC47(2023)023001]
- Hadronic CS decays
  - $\mathcal{B}$ of $\Lambda_c^+ \to \Sigma^0 K^+$ and $\Sigma^+ K_S^0$ [PRD106(2022)052003]
  - Absolute $\mathcal{B}$ of $\Lambda_c^+ \to p\eta'$ [PRD106(2022)072002]
  - $\mathcal{B}$ of $\Lambda_c^+ \to \Lambda K^+$ [PRD106(2022)L111101]
  - $\mathcal{B}$ of $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-(\pi^0)$ [JHEP09(2023)125]
- Hadronic CF decays
  - $\mathcal{B}$ of $\Lambda_c^+ \to \Sigma^+ K^+ K^-$ and $\Sigma^+\phi$ [JHEP09(2023)125]
- Inclusive decays
  - Absolute $\mathcal{B}$ of $\bar{\Lambda}_c^- \to \bar{n}X$ [PRD108(2023)L031101]
- Rare decays
  - Search for $\Lambda_c^+ \to \Sigma^+\gamma$ [PRD107(2023)052002]
  - Search for $\Lambda_c^+ \to p\gamma$ [PRD106(2022)072008]

Planned future data sets + upgrade

- BESIII has made good progress on exploration of lightest CB Λ_c^+
- Near threshold production is unique to directly measure Λ_c^+ decay properties
- Opportunities to study other charmed baryons (Σ_c, Ξ_c, Ω_c) in BEPCII-U phase

[PoS CHARM2020(2021)016]



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	$\Sigma_c^+\Lambda_c^-$ 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

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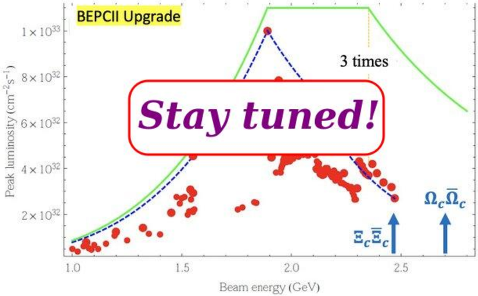

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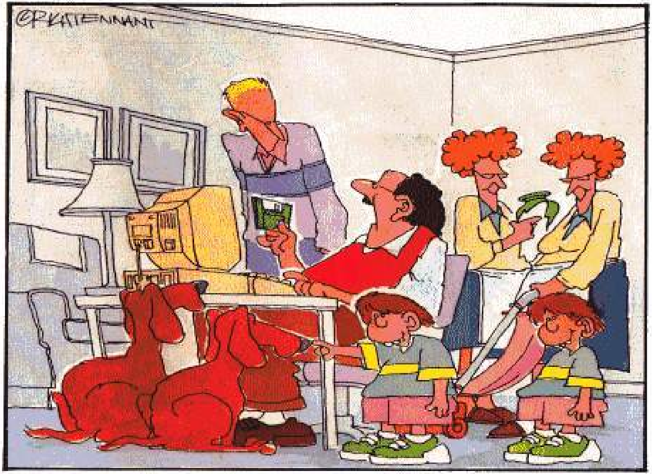
Backups



" I ALWAYS BACK UP EVERYTHING."

V_{cs} using decay $D \to K\nu_l$

- SL decays involve interaction of leptonic current with hadronic current

$$\mathcal{M} = -i\frac{G_F}{\sqrt{2}}V_{cs}L^{\mu}H_{\mu}$$

- Hadronic current when final state is pseudoscalar:

$$H_{\mu} = \langle K(p)|\bar{s}\gamma_{\mu}c|D(p')\rangle = f_{+}(q^2)\left[(p'+p)_{\mu} - \frac{m_D^2 - m_K^2}{q^2}q_{\mu}\right] + f_0(q^2)\frac{m_D^2 - m_K^2}{q^2}q_{\mu}$$

- Kinematics require: $f_{+}(0) = f_0(0)$. For e-mode only $f_{+}(q^2)$ is relevant
- Differential partial width:

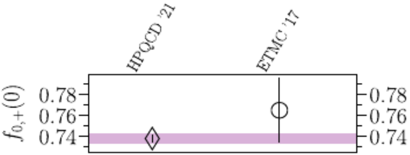
$$\frac{d\Gamma(D \to Kl\nu_l)}{dq^2} \propto G_F^2|V_{cs}|^2 p^{*3}|f_{+}(q^2)|^2$$

- Many different $f_{+}(q^2)$ parametrizations

Parameter	2021	2023
$\lvert V_{cs}\rvert f_{+}^{DK}(0)$	0.7180(33)[1]	
$f_{+}^{DK}(0)$	0.765(31)[2]	0.7385(44)[3]
$\lvert V_{cs}\rvert^{D\to Kl\nu_l}$	0.939(38)[4]	0.972(7)[5]
$\lvert V_{cs}\rvert^{\Lambda_c^+\to\Lambda e^+\nu_e}$	0.936(30)[6]	

[1] [HFLAV2021] [2] [PRD96(2017)054514]
[3] [PRD104(2021)034505] [4] [PDG2020]

[5] [PDG2023] [6] [PRL129(2022)231803]



[PRD104(2021)034505]