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Precision calculation of charm baryon decay constants in lattice QCD

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1. Motivation

In the study of heavy-flavor baryons, two-body non-leptonic decay processes can be used to search for CP violation [1].

$$\Lambda_b^0 \to \Lambda_c^+ + h\ , (h = \pi,\ K) \tag{1}$$

Semi-leptonic decay processes [2] can be used to extract the CKM matrix element V_{cb}

$$\Lambda_b^0 \to \Lambda_c^+ l \bar{\nu} \tag{2}$$

Form factors are important physical quantities in semi-leptonic and non-leptonic decays:

$$\langle \Lambda_c | i\mathcal{A} | \Lambda_b \rangle \sim C \otimes T \otimes \underbrace{\langle \Lambda_c | O_{\Lambda_c} | 0 \rangle}_{f_{\Lambda_c}\phi_{\Lambda_c}} \otimes \langle 0 | O_{\Lambda_b} | \Lambda_b \rangle \tag{3}$$

Form factors are proportional to the decay constants of charmed baryons:

$$Z_{\mathcal{B}_c} \langle 0 \mid O_{\mathcal{B}_c} \mid \mathcal{B}_c \rangle = m_{\mathcal{B}_c} f_{\mathcal{B}_c} u_{\mathcal{B}_c} \tag{4}$$

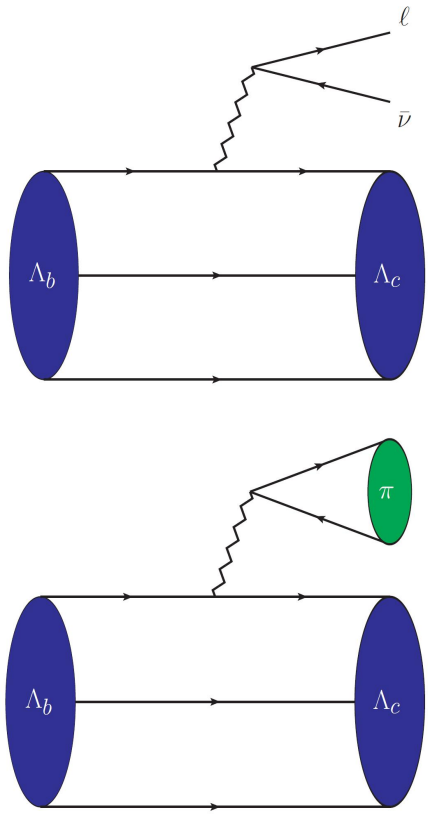

Fig. 1. Form Factors of Two-body and Semi-leptonic Processes

【1】 R. Aaij et al. [LHCb], Phys. Rev. Lett. 133, [arXiv:2409.02759 [hep-ex]].
【2】 R. Aaij et al. [LHCb], Phys. Rev. Lett. 128, no.19, 191803 (2022) [arXiv:2201.03497 [hep-ex]].

2. Calculation of Bare Decay Constants via Lattice QCD

Two-state fitting with Model Average is used to extract the effective mass m and the bare decay constant f:

$$C_{2pt}^{+}(\tau) = 2m_{\mathcal{B}_c}^{2} f_{\mathcal{B}_c}^{(0)\,2} e^{-m\mathcal{B}_c t}(1 + Ce^{-\Delta m\cdot\tau}) \qquad (5)$$

Table 1. CLQCD Configuration Information

Conf	$L^3 \times T$	a(fm)	Pion(MeV)	m_l	m_s	m_c	N_Conf	N_Src
C24P29	$24^3 \times 72$	0.105	292	-0.2770	-0.2357	0.4168	864	20
C32P29	$32^3 \times 64$	0.105	293	-0.2770	-0.2358	0.4158	984	20
C32P23	$32^3 \times 64$	0.105	228	-0.2790	-0.2338	0.4198	451	20
C48P14	$32^3 \times 96$	0.105	136	-0.2825	-0.2335	0.4205	187	30
F32P30	$32^3 \times 96$	0.077	300	-0.2295	-0.2039	0.1968	777	20
H48P32	$48^3 \times 144$	0.052	317	-0.1850	-0.1703	0.0533	550	12

Table 2. Summary of Bare Decay Constants of Charmed Baryons

	Decay constant (bare) (10^{-2}GeV^2)					
Baryon	**C24P29**	**C32P23**	**C32P29**	**C48P14**	**F32P30**	**H48P32**
$\Lambda_c^+(udc)$	1.82(12)	1.77(23)	1.72(19)	1.75(14)	1.88(15)	2.04(25)
$\Xi_c^+(usc)$	1.69(19)	1.59(27)	1.776(77)	1.69(23)	1.951(80)	2.19(10)
$\Xi_c^0(dsc)$	1.69(19)	1.59(27)	1.776(77)	1.69(23)	1.951(80)	2.19(10)
$\Xi_c'^+(usc)$	2.644(70)	2.32(39)	2.30(12)	2.44(32)	2.83(15)	3.46(17)
$\Xi_c'^0(dsc)$	2.644(70)	2.32(39)	2.30(12)	2.44(32)	2.83(15)	3.46(17)
$\Sigma_c^+(udc)$	2.45(11)	2.30(23)	2.25(17)	2.28(16)	2.72(17)	3.32(38)
$\Sigma_c^0(ddc)$	2.45(11)	2.30(23)	2.25(17)	2.28(16)	2.72(17)	3.32(38)
$\Sigma_c^{++}(uuc)$	2.45(11)	2.30(23)	2.25(17)	2.28(16)	2.72(17)	3.32(38)
$\Omega_c^0(ssc)$	2.883(45)	2.62(11)	2.670(60)	2.74(28)	3.08(19)	3.64(21)

3.Calculation of Non-Perturbative Renormalization Constants

The bare charmed baryon operator is defined as:

$$O^{(0)} = \varepsilon_{ijk}(q_i^{(0)T} C\Gamma_i q_j^{(0)})\Gamma_2 P_+ c_k^{(0)} \quad (6)$$

The renormalization constant of the charmed baryon operator is:

$$O^{(0)} = Z_O O \quad (7)$$

Non-perturbative Renormalization Condition:

$$Z_O Z_{q1}^{-1/2} Z_{q2}^{-1/2} Z_{q3}^{-1/2} \Gamma_O|_{\mathrm{SMOM}} = 1 \quad (8)$$

$$Z_V Z_q^{-1} \Gamma_V|_{\mathrm{SMOM}} = 1 \quad (9)$$

derive $$\frac{Z_{Oi}}{Z_V^{3/2}}(m_q, a^2p^2) = \frac{\Gamma_V^{3/2}}{\Gamma_O}(m_q, a^2p^2) \quad (10)$$

Finally $$Z_{Oi}(\mu) = C_{\mathrm{SMOM}}^{\overline{\mathrm{MS}}}(\mu)\frac{Z_{Oi}}{Z_V^{3/2}}(Z_l Z_s Z_c)^{3/2}(m_q = 0, a) \quad (11)$$

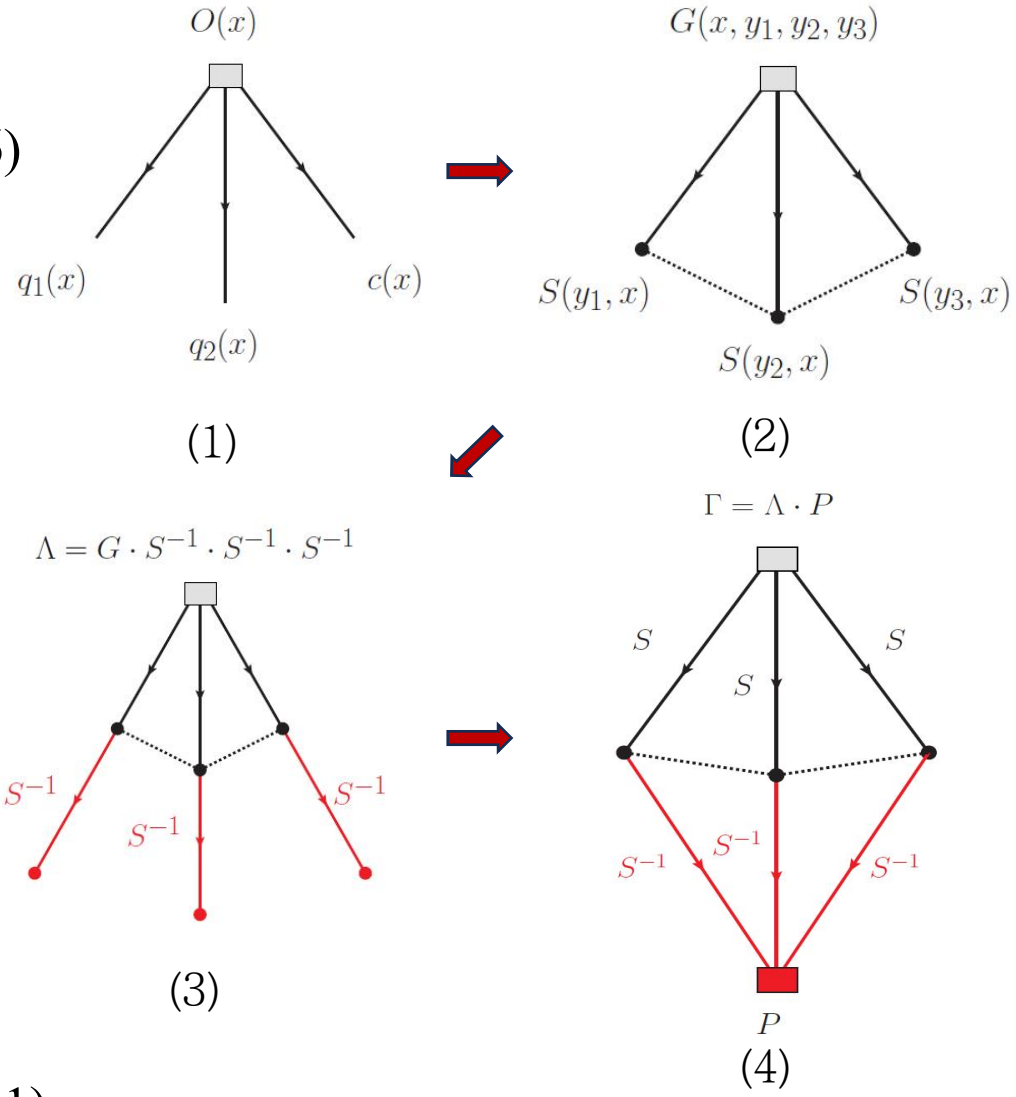

Fig. 2. Baryon Renormalization Flow

4. Calculation Results

Extrapolation of Charmed Baryon Decay Constants : $$f_{\mathcal{B}}(m_\pi, a) = f_{\mathcal{B},phy} + c_1\left(m_\pi^2 - m_{\pi,phy}^2\right) + c_2 a^2 \quad (12)$$

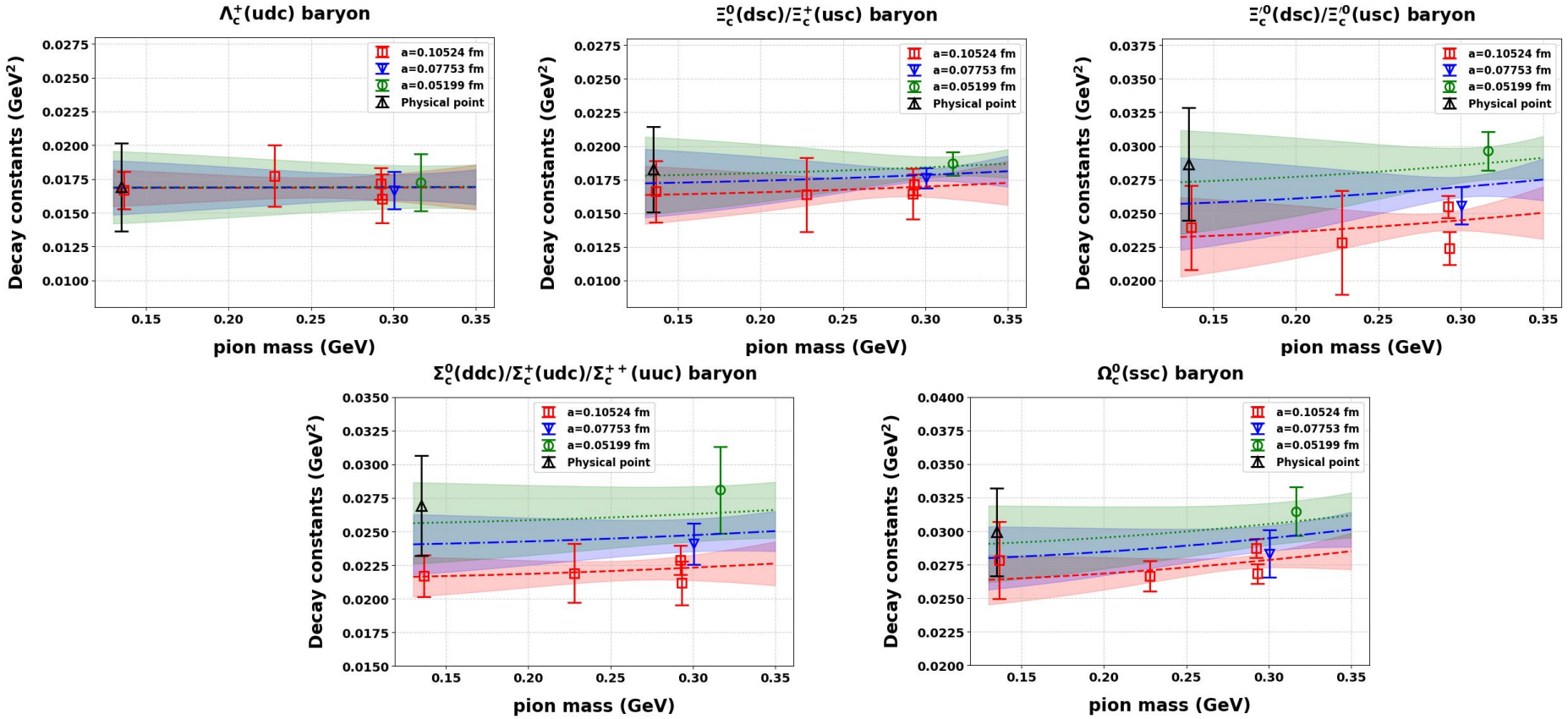

Table 5. Decay Constants of Charmed Baryons at the Scale μ=2 GeV

Baryon	Λ_c^+	Ξ_c^+/Ξ_c^0	$\Xi_c'^+/\Xi_c'^0$	$\Sigma_c^{++}/\Sigma_c^+/\Sigma_c^0$	Ω_c^0
Decay constant	0.0168(33)	0.0180(31)	0.0286(42)	0.0269(37)	0.0299(33)

The precision of the charmed baryon decay constants calculated via lattice is 11~20%.

5. Summary

1.Use of CLQCD configurations with multiple lattice spacings and volumes.Extraction of bare decay constants via two-state fits with model averaging.

2.Non-perturbative renormalization of charmed baryon operators.

3.Final results for decay constants with a precision of 11–20%.

Thanks