Precision calculation of charm baryon decay constants in lattice QCD

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INTRODUCTION

- The origin of the matter-antimatter asymmetry in the Universe remains a forefront topic in particle physics, **hinging on** two key ingredients: CP violation and baryon number nonconservation **beyond the Standard Model**. Charm baryon decay constants serve as **crucial** nonperturbative inputs **for calculating** the former.
- We present the first calculation of charm baryon decay constants using 2+1 flavor gauge ensembles with lattice spacings ranging from 0.05 to 0.1 fm and pion masses between 136 and 310 MeV.
- The non-perturbative renormalization is performed using the symmetric momentum-subtraction scheme. After performing systematic chiral and continuum extrapolations, we obtain the decay constants with a precision 11–20%.

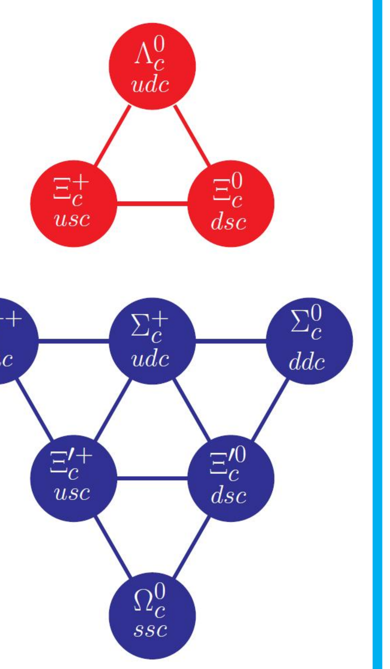

Figure 1: The charm baryon

THEORETICAL FUNDATION

- The decay constants for the $J^{PC} = (\frac{1}{2})^+$charmed baryon. The renormalized matrix element for the charm baryon $\mathcal{B}_c$ is given by:

$$Z_{\mathcal{B}_c}\left\langle 0\left|O_{\mathcal{B}_c}^{(0)}\right|\mathcal{B}_c\right\rangle = m_{\mathcal{B}_c} f_{\mathcal{B}_c} u_{\mathcal{B}_c} \qquad (1)$$

where m_{B_c}, f_{B_c}, and $Z_{B_c}$are the bare mass, decay constant, and renormalization constant of the charmed baryon, respectively, and u_{B_c} is its spinor.

- In lattice QCD, operators are typically constructed based on their symmetries. While the Λ_c and Σ_c baryons have been constructed using diquark SU(2) symmetry, we extend this method to the 3×3= $\bar{3} \oplus 6$ representation of SU(3) to build common charmed baryon operators. The anti-triplet representation of these operators is given by :

pseudoscalar current

$$O_{\Lambda_c^+} = \epsilon_{ijk}(u_i^T C\gamma_5 d_j)c_k$$
$$O_{\Xi_c^+} = \epsilon_{ijk}(u_i^T C\gamma_5 s_j)c_k$$
$$O_{\Xi_c^0} = \epsilon_{ijk}(d_i^T C\gamma_5 s_j)c_k$$

vector current

$$O_{\Xi_c'^+} = \epsilon_{ijk}(u_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k$$
$$O_{\Xi_c'^0} = \epsilon_{ijk}(d_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k$$
$$O_{\Sigma_c^+} = \epsilon_{ijk}(u_i^T C\gamma_\mu d_j)\gamma^\mu\gamma_5 c_k$$
$$O_{\Sigma_c^0} = \frac{1}{\sqrt{2}}\epsilon_{ijk}(d_i^T C\gamma_\mu d_j)\gamma^\mu\gamma_5 c_k$$
$$O_{\Sigma_c^{++}} = \frac{1}{\sqrt{2}}\epsilon_{ijk}(u_i^T C\gamma_\mu u_j)\gamma^\mu\gamma_5 c_k$$
$$O_{\Omega_c^0} = \frac{1}{\sqrt{2}}\epsilon_{ijk}(s_i^T C\gamma_\mu s_j)\gamma^\mu\gamma_5 c_k$$

LATTICE SETUP

- To compute the bare decay matrix elements, we define the two-point correlation function at the quark level as follows:

$$C_{2pt}^+ = Tr\{C_{2pt}P_+\} \qquad (2)$$

where,$P_+ = (1+\gamma_4)/2$ represents the positive parity projection operator, which projects out the $(\frac{1}{2})^+$ charmed baryon data.

- The two-point correlation function is parameterized with the form:

$$C_{2pt}^+(\tau) = 2m_{\mathcal{B}_c}^2 f_{\mathcal{B}}^{(0)\,2} e^{-m\mathcal{B}_c t}(1 + Ce^{-\Delta m\cdot\tau}) \qquad (3)$$

- In the four lattice calculations, we use CLQCD ensembles with lattice spacings ranging from 0.05199 to 0.10524 fm, which cover pion masses between 136 and 310 MeV

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 1: Information on Configurations Used in the Simulation

HYBRID RENORMALIZATION

- The renormalization constant is, in principle, independent of the external momentum. The SMOM renormalization condition is defined as

$$Z_{O_i} Z_{q1}^{-1/2} Z_{q2}^{-1/2} Z_{q3}^{-1/2} \Gamma_{O_i}|_{\text{SMOM}} = 1 \qquad (4)$$
$$Z_V Z_q^{-1} \Gamma_V|_{\text{SMOM}} = 1 \qquad (5)$$

- Since the perturbative conversion factor is derived in the massless quark limit, the non-perturbative determination of the renormalization constant must also be performed with massless quarks. In this lattice calculation, we treat the up (u), down (d), strange (s), and charm (c) quarks as light quarks, which simplifies the charm baryon operators into the following form

$$O_1 = \epsilon_{ijk}(l_1^T C\gamma_5 l_2)\, l_3 \qquad (6)$$
$$O_2 = \epsilon_{ijk}(l_1^T C\gamma_\mu l_2)\, \gamma_\mu\gamma_5 l_3 \qquad (7)$$
$$O_3 = \epsilon_{ijk}(l_1^T C\gamma_\mu l_1)\, \gamma_\mu\gamma_5 l_3 \qquad (8)$$

- The vertex functions of O_V and $O_1 \sim O_3$ are shown in Fig. 2

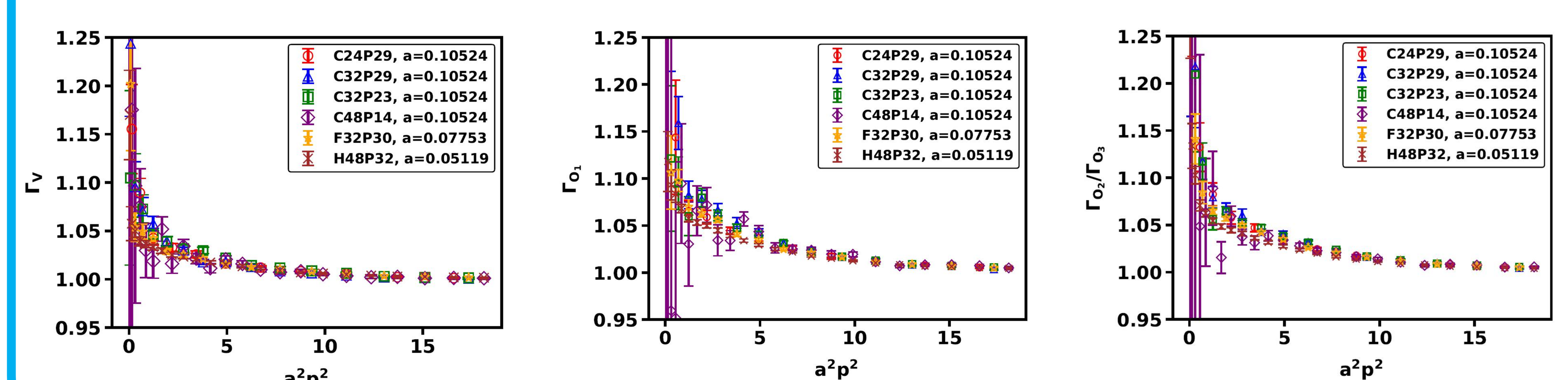

Fig. 2

Result

- The result of extrapolating the mass of the charm baryon :

$$m_{\mathcal{B}}(m_\pi, a) = m_{\mathcal{B},phy} + c_1(m_\pi^2 - m_{\pi,phy}^2) + c_2 a^2 \qquad (9)$$

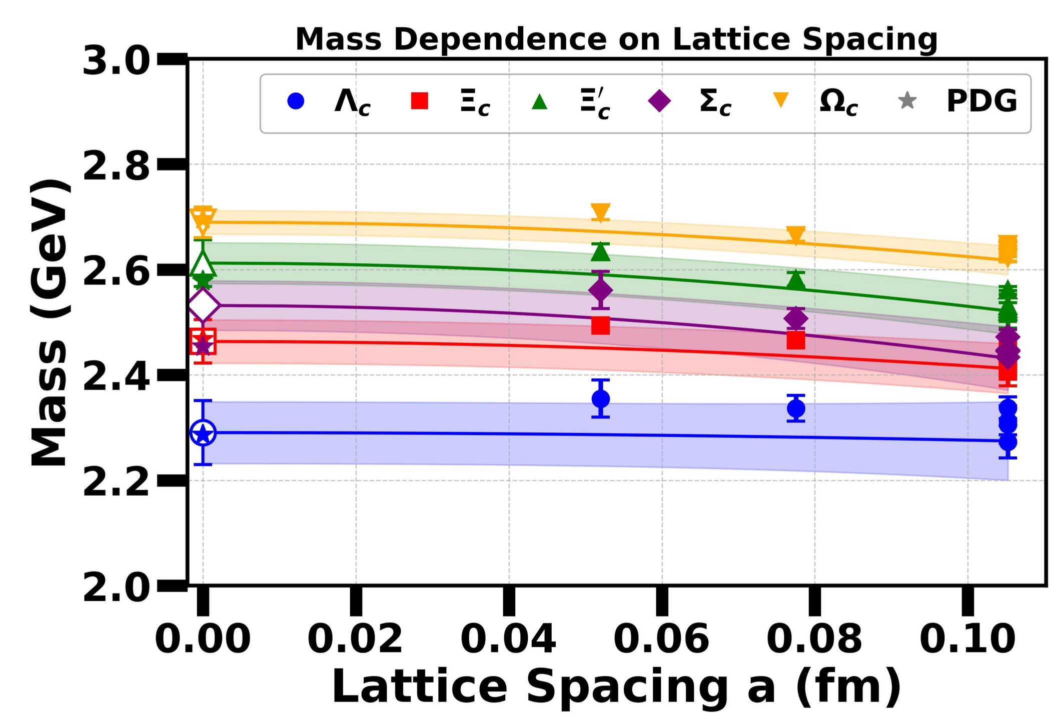

Fig 3: Charmed baryon mass

- The results of extrapolating the decay constants of charm baryons are presented in Fig. 4

$$f_{\mathcal{B}}(m_\pi, a) = f_{\mathcal{B},phy} + c_1(m_\pi^2 - m_{\pi,phy}^2) + c_2 a^2 \qquad (10)$$

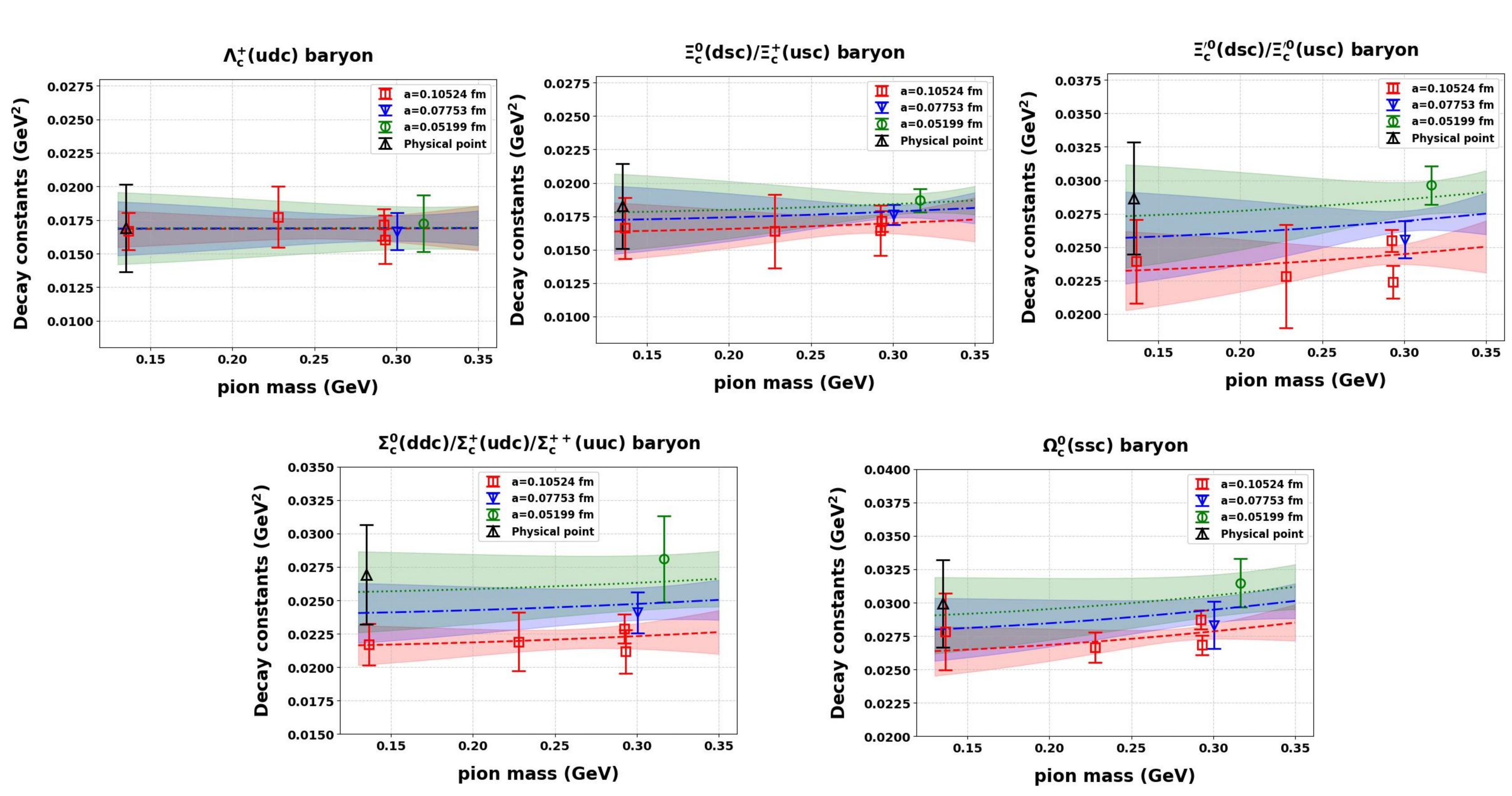

Fig 4: Charmed baryon decay constant

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)

Table 2: Final result of charmed baryon decay constant