The Lifetime of Doubly Heavy Baryons from QCD Sum Rules

Improving HQE lifetime predictions for doubly charmed baryons

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HFCPV 2025,   2025.10. 26

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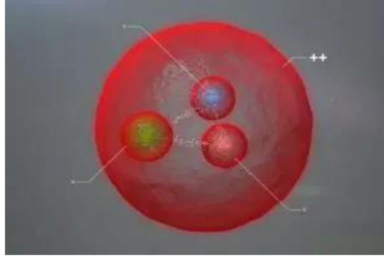
I. Research Motivation



- Doubly charmed baryons (Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}) test heavy-quark dynamics in the charm sector.
- To provide precise theoretical input for interpreting experimental results from facilities like LHCb.
- To offer reliable guidance for future searches of undiscovered doubly and triply heavy baryons.
- HQE successfully explains b-hadron lifetimes but is less accurate for c-hadrons due to poorly known four-quark operator matrix elements.

Our goal: compute them using QCD Sum Rule (QCDSR) rather than relying on phenomenological models.

II. Background: HQE Framework

$$\Gamma(H_Q) = \boxed{\Gamma_3 + \frac{\Gamma_5}{m_Q^2}} + \boxed{\frac{\Gamma_6}{m_Q^3}} + \cdots$$

Spectator Non-spectators

- Γ_3 : free-quark decay
- Γ_5 : kinetic + chromomagnetic corrections
- Γ_6 : four-quark operators (dim-6) → Weak Exchange & Pauli Interference

$$\Gamma(H_c \to f) = \frac{G_F^2 m_c^5}{192\pi^3}|V_{CKM}|^2\{c_3(f)\langle H_c|\bar{c}c|H_c\rangle + c_5(f)\frac{\langle H_c|\bar{c}i\sigma_{\mu\nu}G^{\mu\nu}c|H_c\rangle}{m_c^2} + \sum_i c_6^{(i)}(f)\frac{\langle H_c|\boxed{(\bar{c}\Gamma_i q)(\bar{q}\Gamma_i c)}|H_c\rangle}{m_c^3} + \mathcal{O}(\frac{1}{m_c^4})\}$$

HQE precision depends on accurate evaluation of dim-6 operator matrix elements.

[1] Chang et al., arXiv:0704.0016

III.Theoretical Context

- Chang et al. (2007): HQE analysis for Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+} using model inputs.
- Lenz (2014): identified missing nonperturbative input as main uncertainty.
- Cheng et al. (2018): introduced dimension-7 corrections based on Chang et al. to estimate higher-order effects.

This work: QCDSR provides a first-principles evaluation, leading to improved lifetime predictions.

[1] Chang et al,2007., arXiv:0704.0016
[2] Lenz, 2014, arXiv:1405.3601
[3] Gershon et al 2018. arXiv:1809.08102

IV. Four-Quark Operator Structures

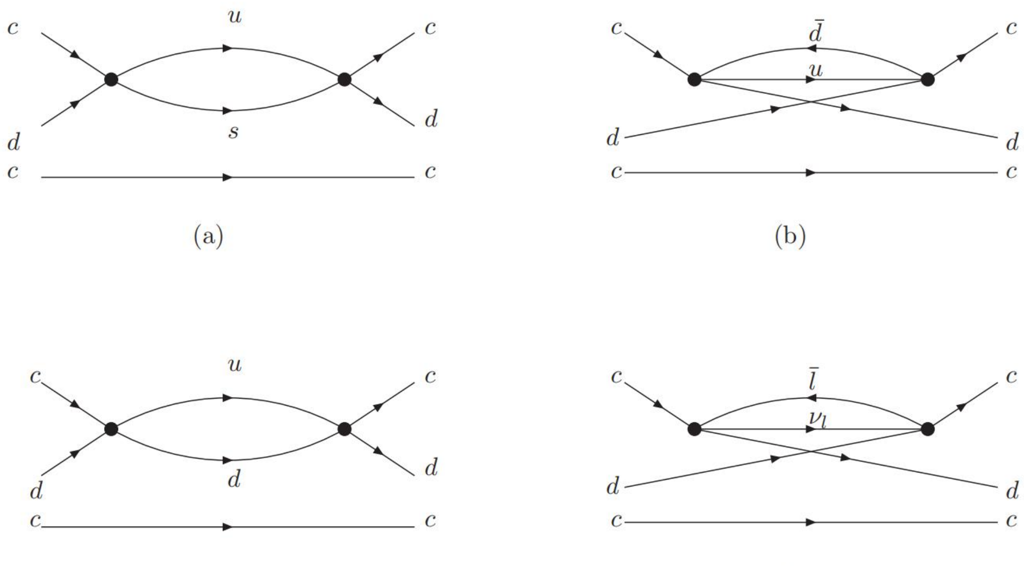
Four-quark operator :

$$
\begin{cases}
O_1^q = (\bar{c}\gamma_\mu(1-\gamma_5)q)(\bar{q}\gamma^\mu(1-\gamma_5)c) \\
O_2^q = (\bar{c}_i\gamma_\mu(1-\gamma_5)q_j)(\bar{q}_j\gamma^\mu(1-\gamma_5)c_i) \\
O_3^q = (\bar{c}(1-\gamma_5)q)(\bar{q}(1+\gamma_5)c) \\
O_4^q = (\bar{c}_i(1-\gamma_5)q_j)(\bar{q}_j(1+\gamma_5)c_i)
\end{cases}
$$

- color structures:
- These appear in Weak Exchange (WE) and Pauli Interference (PI) processes, which dominate the lifetime differences among Ξ_{cc}^{++}, Ξ_{cc}^{+} and Ω_{cc}^{+}.

V. Strategy and Improvements

Aspect	Chang (2007)	This Work
Matrix elements	Model-based	Computed via QCDSR
Input parameters	Fixed	Extracted self-consistently
Errors	Model dependence	Controlled via Borel stability
Accuracy	Moderate	Improved, closer to data



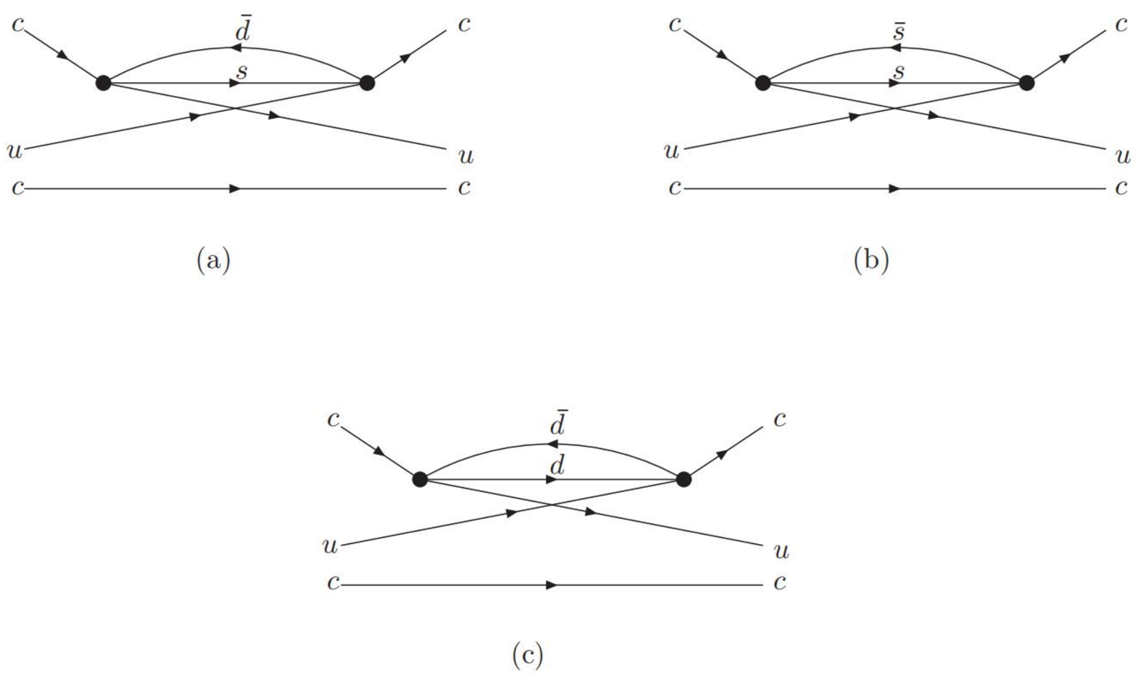
(a) (b) (c) (d)

Non-spectator effects contribution to lifetime of Ξ_{cc}^{+}

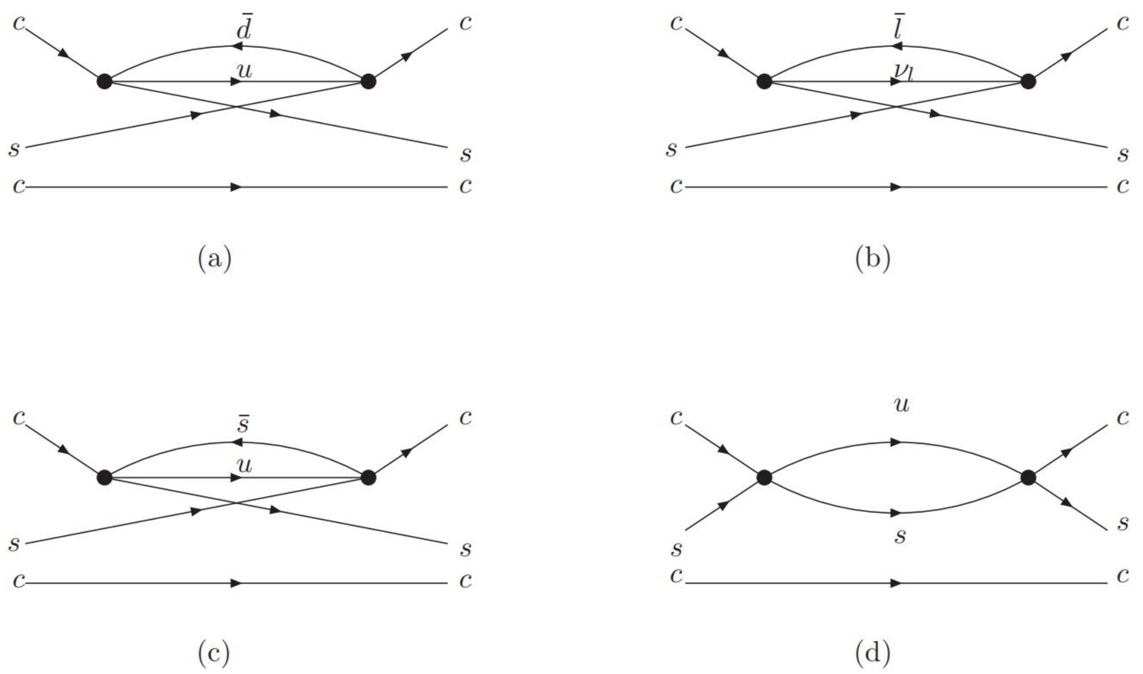
$$\hat{\Gamma}_{WE} = \frac{1}{2m_H}\frac{G_F^2}{2}|V_{cs}|^2|V_{ud}|^2\frac{1}{(2\pi)^2}4\times(16AP^2+4BP^2)$$
$$\times\left[(c_1^2+c_2^2)\boxed{\bar{c}^i\gamma_\alpha(1-\gamma_5)c^i\bar{d}^j\gamma^\alpha(1-\gamma_5)d^j}\right.$$
$$\left.+\,2c_1c_2\boxed{\bar{c}^i\gamma_\alpha(1-\gamma_5)d^i\bar{d}^j\gamma^\alpha(1-\gamma_5)c^j]}\right.$$

[1] Chang et al., 2007 ,arXiv:0704.0016

V. Strategy and Improvements

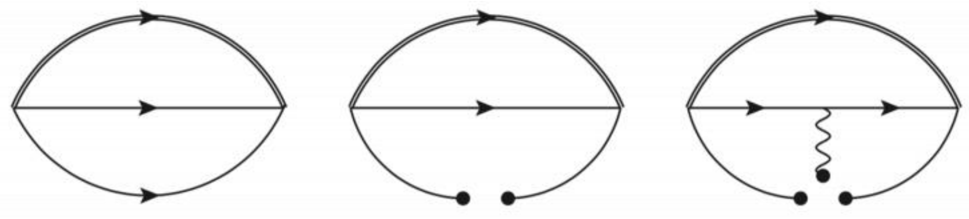


Non-spectator effects contribution to lifetime of Ξ_{cc}^{++}



Non-spectator effects contribution to lifetime of Ω_{cc}^{+}

VI. QCD Sum Rule Method



- the two-point correlation function:

$$\Pi(p) = i\int d^4x e^{i\cdot px}\langle 0|T\{J(x)\bar{J}(0)\}|0\rangle$$

$$\boxed{\Pi^{had}(p) = \lambda_+^2 \frac{\not{p}+M_+}{M_+^2-p^2} + \lambda_-^2 \frac{\not{p}-M_-}{M_-^2-p^2}\cdots} \longleftrightarrow \boxed{\Pi^{QCD}(p) = A(p^2)\not{p} + B(p^2)}$$

$$\boxed{\lambda_+^2 = \frac{\int ds[\rho^B(s)+(M_-)\rho^A(s)]\exp(-\frac{s}{T_+^2})}{(M_+ + M_-)}\exp(\frac{M_+^2}{T_+^2})}$$

$$\boxed{M_+^2 = \frac{\int ds[\rho^B(s)+(M_-)\rho^A(s)]s\exp(-\frac{s}{T_+^2})}{\int ds[\rho^B(s)+(M_-)\rho^A(s)]\exp(-\frac{s}{T_+^2})}}$$

Borel window and threshold s_0

VI. QCD Sum Rule Method

- Construct the three-point correlation function using the interpolating current for Ξ_{cc} :

$$\Pi(p_1, p_2) = i^2 \int d^4x d^4y e^{ip'\cdot x - ip\cdot y} < 0|T\{J(x)\Gamma_6 \bar{J}(y)\}|0 >$$

$$J_{\Xi_{cc}} = \varepsilon_{abc} \left(Q_a^T C\gamma^\mu Q_b\right) \gamma_\mu \gamma_5 u_c$$

- Expand via OPE: perturbative + condensate terms .
- apply a double Borel transform to suppress continuum contributions.

VI. QCD Sum Rule Method

hardon level:

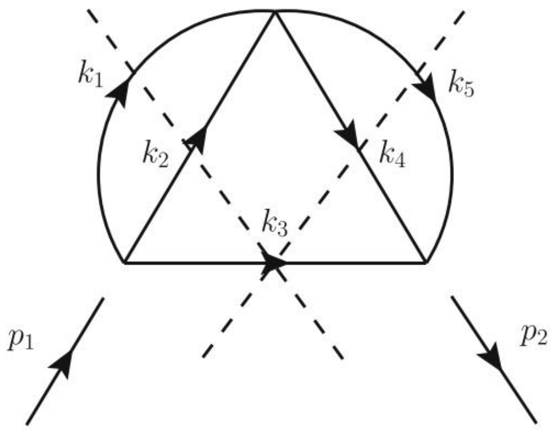
$$\Pi^{\text{had}}(p_1,p_2)=\lambda_H^2\frac{(\not{p}_2+M)(a+b\gamma_5)(\not{p}_1+M)}{(p_2^2-M^2)(p_1^2-M^2)}+\cdots$$

QCD level:

$$\Pi^{QCD}(p_1,p_2)=A_1\not{p}_2\not{p}_1+A_2\not{p}_2+A_3\not{p}_1+A_4+A_5\not{p}_2\gamma_5\not{p}_1+A_6\not{p}_2\gamma_5+A_7\gamma_5\not{p}_1+A_8\gamma_5$$

double dispersion integrals:

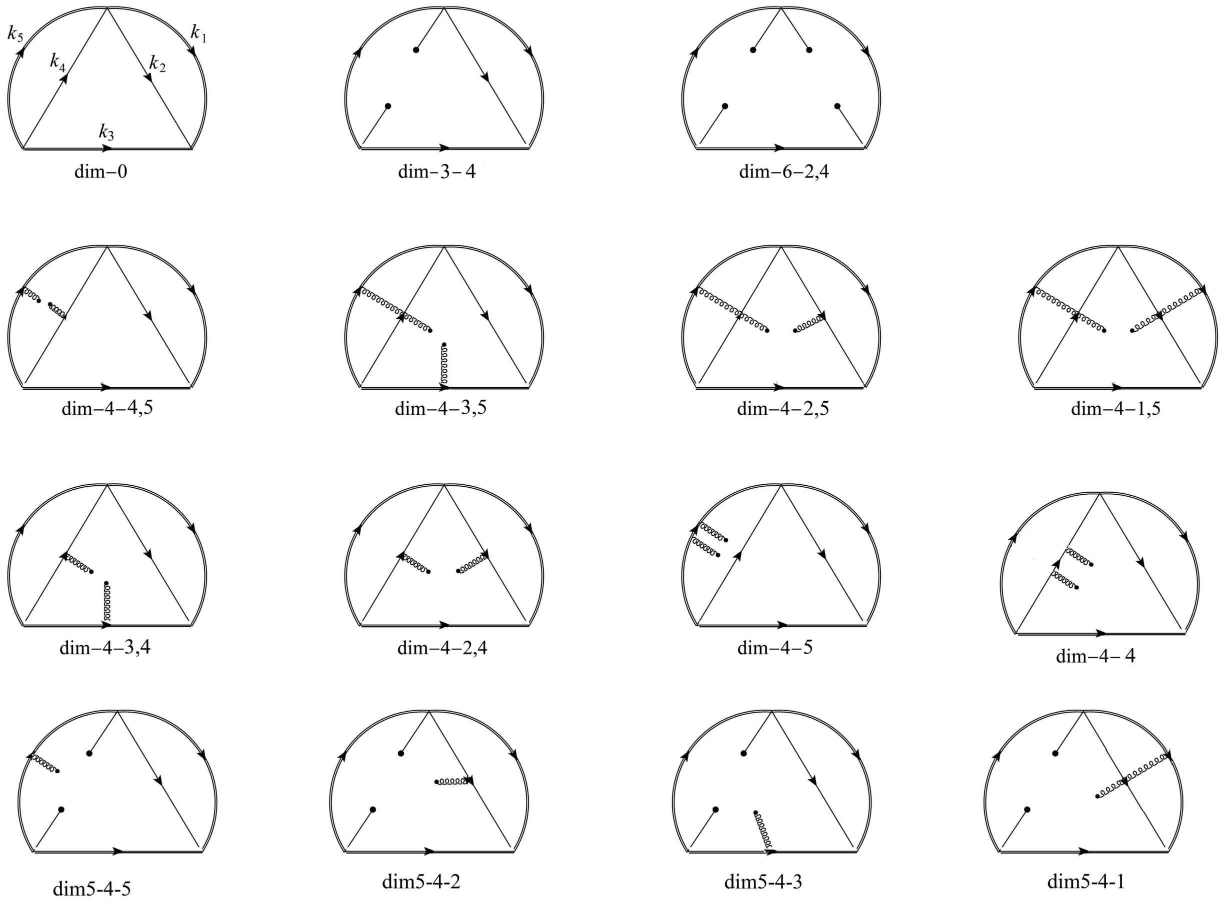
$$A_i(p_1^2,p_2^2,q^2)=\iint ds_1 ds_2\frac{\rho_{A_i}(s_1,s_2,q^2)}{(s_1-p_1^2)(s_2-p_2^2)}$$



$$\langle H_Q|\Gamma_6|H_Q\rangle=\bar{u}(q,s)(a+b\gamma_5)u(q,s)=2am_H$$

[4] Zhao et al., 2021, arXiv:2101.11874

VI. QCD Sum Rule Method



Eur. Phys. J. C (2024) 84:48
https://doi.org/10.1140/epjc/s10052-023-12299-9
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

On the four-quark operator matrix elements for the lifetime of Λ_b

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[4] Zhao et al., 2024, arXiv:2101.11874

VII. Our Result

- Input: $m_c = 1.56\mathrm{GeV}, m_{u(d)} = 0.0\mathrm{GeV}, m_s = 0.107\mathrm{GeV}$ $\mu = 1GeV$

- Predicted lifetimes (in ps):

baryon	Ξ_{cc}^{++}	Ω_{cc}^{+}	Ξ_{cc}^{+}	
τ(ps)	$\boxed{0.330}$	0.257	0.108	This work
τ(ps)	0.52	0.22	0.19	Chang
τ(ps)	0.520	0.078	0.057	Cheng (dim-6)
τ(ps)	0.298	0.206	0.044	Cheng (dim-7)
τ(ps)	$\boxed{0.256 \pm 0.027}$			Experiment

Note: We present the results of a preliminary calculation in this work.

Results are consistent with the experimental value of Ξ_{cc}^{++} from LHCb.

[1] Chang et al., 2007, arXiv:0704.0016
[5] Cheng et al., 2018, arXiv:1807.00916

VIII. Discussion: Lattice QCD and Beyond

- Lattice QCD (Mathur & Padmanath, 2018) predicts $M_{\Omega cc}$=3.712GeV , but no lifetime yet.
- Four-quark operator calculations remain difficult, and QCDSR currently provides the only available non-model estimate.
- Future synergy between Lattice QCD and QCDSR will be essential for cross-validation.

IX. Theoretical Uncertainties

- OPE truncation (dimension ≤ 6)
- Condensate parameter uncertainties
- Borel window and threshold s_0
- Scale dependence (μ varied from 0.8 to 1.2 GeV)

X. Summary

- Computed four-quark operator matrix elements via QCDSR.
- Improved HQE predictions for Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}.
- Results for Ξ_{cc}^{++} are close to LHCb data.
- QCDSR provides a reliable nonperturbative input to HQE.

XI. Outlook

- Include NLO corrections and operator mixing.
- Apply renormalization-scale evolution to match HQE scheme.
- Extend to Singly heavy baryons (Λ_b , Λ_c) .
- Using theoretical results to explain the Ω_c puzzle.
- Anticipate future LHCb/Belle measurements to validate results.
- These improvements will enhance the predictive power of HQE and deepen our understanding of charm-quark dynamics.

感谢各位的聆听!