单粲重子寿命的理论研究：
初步结果

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Outline

- Introduction
- QCD sum rules analysis
- Heavy quark limit
- Numerical results
- Conclusions

Introduction

The Ω_c lifetime puzzle

- In 2018, LHCb measured the lifetime of Ω_c^0 via $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$ [Phys.Rev.Lett. 121 (2018) 9, 092003]:

$$\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$

PDG2018: $\tau(\Omega_c^0) = 69 \pm 12$ fs

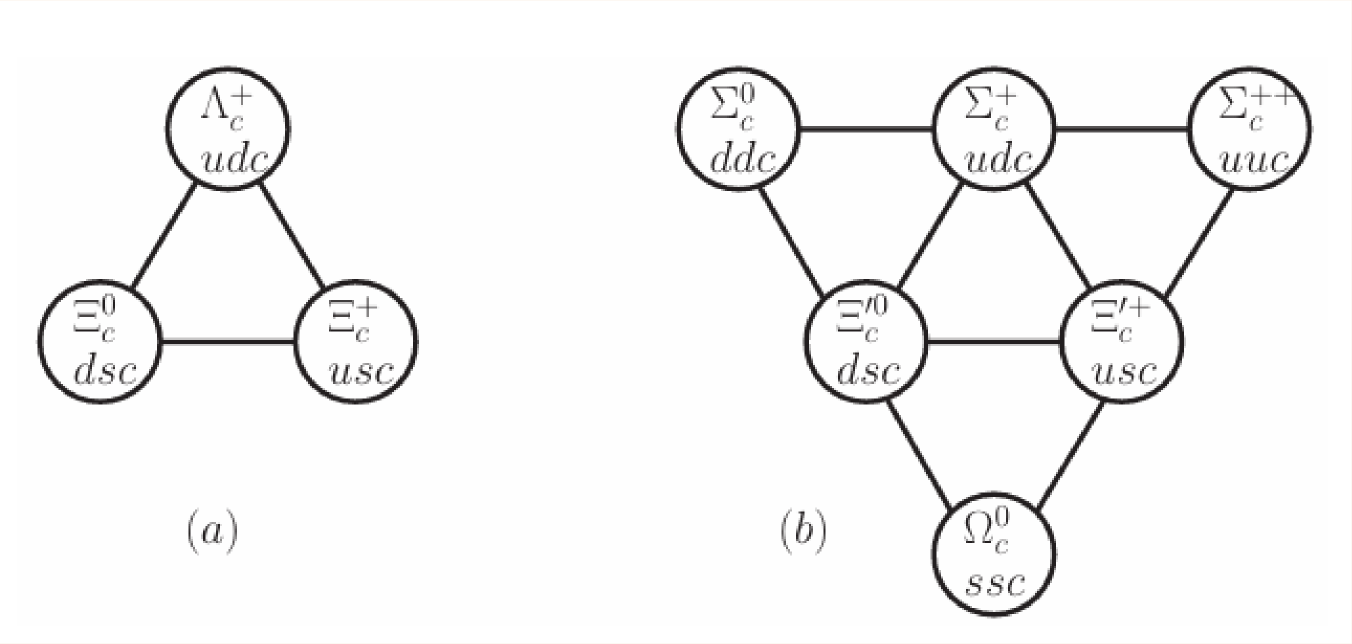
- In 2021, LHCb measured the Ω_c^0 lifetime using produced directly from proton-proton collision [Sci.Bull. 67 (2022) 5, 479-487]:

$$276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs}$$

- In 2022, Belle-II also reported a similar result using $\Omega_c^0 \to \Omega^- \pi^+$ decays [Phys.Rev.D 107 (2023) 3, L031103]:

$$243 \pm 48 \pm 11 \text{ fs}$$

lifetimes



Λ_c^+: 202.6 ± 1.0 fs
Ξ_c^+: 453 ± 5 fs
Ξ_c^0: 150.4 ± 2.8 fs
Ω_c^0: 273 ± 12 fs

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

Heavy quark expansion (HQE)

- With the help of the optical theorem

$$\Gamma = \frac{1}{2m_H}\text{Disc}\int d^4x\,\langle H|T\{\mathcal{H}_{\text{eff}}^{\dagger}(x)\mathcal{H}_{\text{eff}}(0)\}|H\rangle,$$

$\mathcal{H}_{\text{eff}}$: effective weak Hamiltonian governing $Q \to X_f$

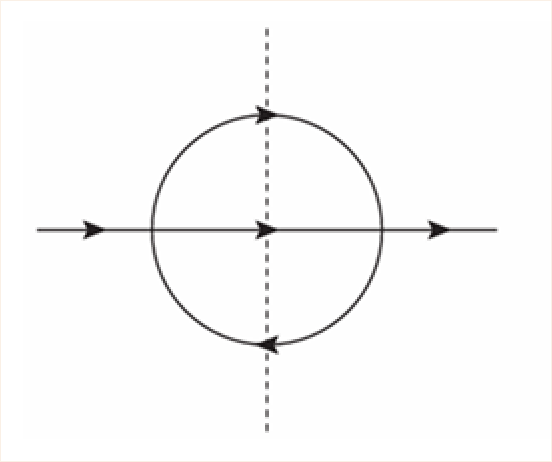
- Denote

$$\hat{\Gamma} \equiv \text{Disc}\int d^4x\,T\{\mathcal{H}_{\text{eff}}^{\dagger}(x)\mathcal{H}_{\text{eff}}(0)\},$$

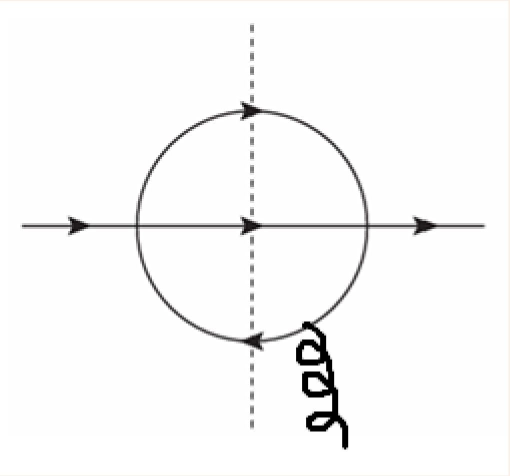
- OPE:

$$\hat{\Gamma} = c_3\,\bar{Q}Q + c_5\,\frac{1}{m_Q^2}\bar{Q}g_s\sigma_{\mu\nu}G^{\mu\nu}Q + c_6\,\frac{1}{m_Q^3}\bar{Q}\Gamma_\mu q\bar{q}\Gamma'^{\mu}Q + \cdots$$

Contributions of dim3 and dim5



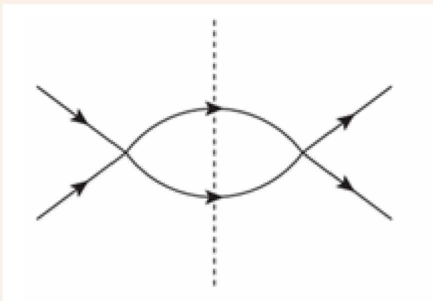
Dim3 -- $\bar{Q}Q$



Dim5 -- $\bar{Q}g_s\sigma_{\mu\nu}G^{\mu\nu}Q$

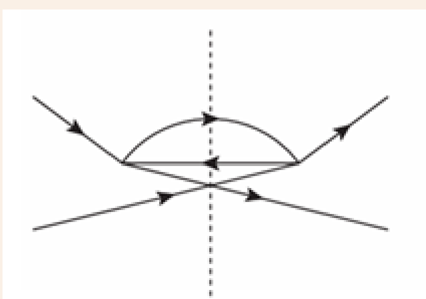
- Non-spectator
- Same for H_Q

Contributions of dim6 and dim7



WE

- Dim6 -- Order of $\left(\frac{1}{m_Q}\right)^0$ for c6
- Dim7 -- Order of $\left(\frac{1}{m_Q}\right)^1$ for c6



PI

- Spectator
- Main source of lifetime difference

Two steps

$$\hat{\Gamma} = c_3 \boxed{\bar{Q}Q} + c_5 \frac{1}{m_Q^2} \boxed{\bar{Q} g_s \sigma_{\mu\nu} G^{\mu\nu} Q} + c_6 \frac{1}{m_Q^3} \boxed{\bar{Q} \Gamma_\mu q \bar{q} \Gamma'^\mu Q} + \cdots$$

- HQE --- to obtain c_i
- $\langle \mathcal{B}_c | O_i | \mathcal{B}_c \rangle, \quad i = 3,5,6, \ldots$

Existing references

- Hai-Yang Cheng, JHEP 11 (2018) 014
- nonrelativistic quark model (NQM)

- James Gratrex, Blaženka Melić, Ivan Nišandžić, JHEP 07 (2022) 058
- relativistic (RCQM) and nonrelativistic (NRCQM) constituent quark models
- $\langle O_7 \rangle = \Lambda_{\mathrm{QCD}} * \langle O_6 \rangle$

- Hai-Yang Cheng, Chia-Wei Liu, JHEP 07 (2023) 114
- improved bag model (BM)

- This work: Full QCD sum rules

QCD sum rule analysis

QCD sum rule analysis

$$\hat{\Gamma} = c_3 \boxed{\bar{Q}Q} + c_5 \frac{1}{m_Q^2} \boxed{\bar{Q} g_s \sigma_{\mu\nu} G^{\mu\nu} Q} + c_6 \frac{1}{m_Q^3} \boxed{\bar{Q}\Gamma_\mu q \bar{q} \Gamma'^\mu Q} + \cdots$$

- forward scattering matrix elements:

$$\langle \mathcal{B}_c | O_i | \mathcal{B}_c \rangle, \quad i = 3, 5, 6, \ldots$$

- 3-point correlation function:

$$\Pi(p_1, p_2) = i^2 \int d^4x d^4y \, e^{-ip_1 \cdot x + ip_2 \cdot y} \langle 0 | T\{J(y) O(0) \bar{J}(x)\} | 0 \rangle$$

Hadron level $|\mathcal{B}_c\rangle\langle\mathcal{B}_c|$ $|\mathcal{B}_c\rangle\langle\mathcal{B}_c|$

Hadron level

$$\langle \mathcal{B}_c(q,s)|O_i|\mathcal{B}_c(q,s)\rangle = \bar{u}(q,s)(a+b\gamma_5)u(q,s)$$
$$= 2\,a\,m_{\mathcal{B}},$$

Insert the complete set of baryon states and consider the contribution of negative parity baryons:

$$\begin{aligned}\Pi^{\rm had}(p_1,p_2) = \lambda_+\lambda_+ &\frac{(\not{p}_2+M_+)(\boxed{a^{++}}+b^{++}\gamma_5)(\not{p}_1+M_+)}{(p_2^2-M_+^2)(p_1^2-M_+^2)}\\ &+\lambda_+\lambda_-\frac{(\not{p}_2+M_+)(a^{+-}+b^{+-}\gamma_5)(\not{p}_1-M_-)}{(p_2^2-M_+^2)(p_1^2-M_-^2)}\\ &+\lambda_-\lambda_+\frac{(\not{p}_2-M_-)(a^{-+}+b^{-+}\gamma_5)(\not{p}_1+M_+)}{(p_2^2-M_-^2)(p_1^2-M_+^2)}\\ &+\lambda_-\lambda_-\frac{(\not{p}_2-M_-)(a^{--}+b^{--}\gamma_5)(\not{p}_1-M_-)}{(p_2^2-M_-^2)(p_1^2-M_-^2)}\\ &+\cdots,\end{aligned}$$

QCD level

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

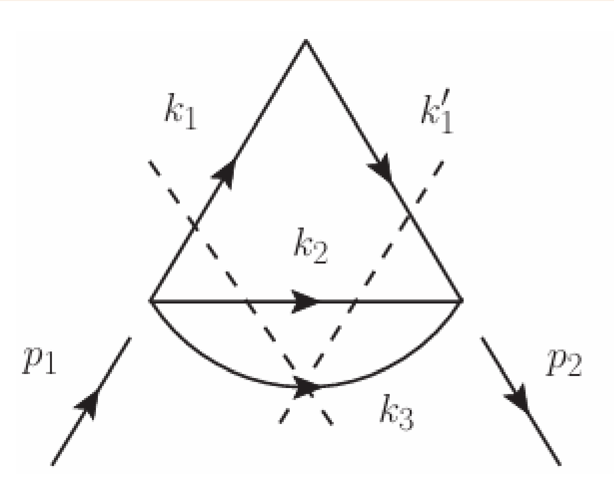
$$a^{++} = \frac{\{M_-^2, M_-, M_-, 1\}.\{\mathcal{B}A_1, \mathcal{B}A_2, \mathcal{B}A_3, \mathcal{B}A_4\}}{\lambda_+^2(M_+ + M_-)^2}\exp\left(\frac{2M_+^2}{T^2}\right),$$

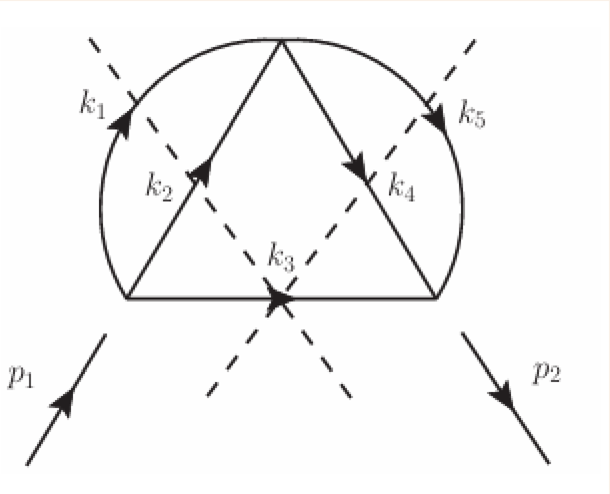
$$\mathcal{B}A_i = \int^{s_0} ds_1 \int^{s_0} ds_2\, \rho^{A_i}(s_1,s_2,q^2)\exp\left(-\frac{s_1+s_2}{T^2}\right),$$

s_0 -- continuum threshold parameter

T^2 -- Borel parameter

Calculation at the QCD level – cutting rule





for dim-3,5 $\bar{Q}Q$

for dim-6,7 $\bar{Q}\Gamma q\bar{q}\Gamma Q$

Heavy quark limit

Heavy quark limit (HQL) for 2-pt correlator

$$(M_+ + M_-)\lambda_+^2 \frac{1}{M_+^2 - p^2} = \int^{s_0} ds\, (M_-\rho^A + \rho^B)\frac{1}{s - p^2},$$

2-pt full QCD sum rule (without Borel transform)

$$M_\pm = (m_b + \Delta_\pm), \quad p^2 = (m_b + \omega)^2, \quad s = (m_b + \sigma)^2, \quad s_0 = (m_b + \omega_c)^2,$$

$$\lambda_+^2 \frac{1}{(\Delta - \omega)} = \int^{\omega_c} d\sigma\, (m_Q\rho^A + \rho^B)\frac{1}{(\sigma - \omega)}.$$

Heavy quark limit (without Borel transform)

$$\rho_{\mathrm{HQL}}(\sigma) = \frac{\sigma^5}{20\pi^4} + \frac{\langle \bar{q}q \rangle^2}{6}\delta(\sigma),$$

Heavy quark limit (HQL) for 3-pt correlator

$$\lambda_+^2 (M_+ + M_-)^2 a^{++} \frac{1}{(M_+^2 - p_1^2)(M_+^2 - p_2^2)}$$
$$= \int^{s_0} ds_1 \int^{s_0} ds_2 \, \{M_-^2, M_-, M_-, 1\}.\{\rho^{A_1}, \rho^{A_2}, \rho^{A_3}, \rho^{A_4}\} \frac{1}{(s_1 - p_1^2)(s_2 - p_2^2)}.$$

3-pt full QCD sum rule (without Borel transform)

$$M_\pm = (m_b + \Delta_\pm), \quad p_{1(2)}^2 = (m_b + \omega_{1(2)})^2, \quad s_{1(2)} = (m_b + \sigma_{1(2)})^2, \quad s_0 = (m_b + \omega_c)^2.$$

$$\lambda_+^2 a^{++} \frac{1}{(\Delta - \omega)(\Delta - \omega')}$$
$$= \int^{\omega_c} d\sigma \int^{\omega_c} d\sigma' \, \{M_-^2, M_-, M_-, 1\}.\{\rho^{A_1}, \rho^{A_2}, \rho^{A_3}, \rho^{A_4}\} \frac{1}{(\sigma - \omega)(\sigma' - \omega')}.$$

non-trival -- Heavy quark limit (without Borel transform)

$$\rho_{\rm HQL}(\sigma_1, \sigma_2) = \rho^{(\rm pert)}(\sigma_1, \sigma_2) + \rho^{(D=6)}(\sigma_1, \sigma_2) \, \langle \bar{q} q \rangle^2 + \cdots \, ,$$

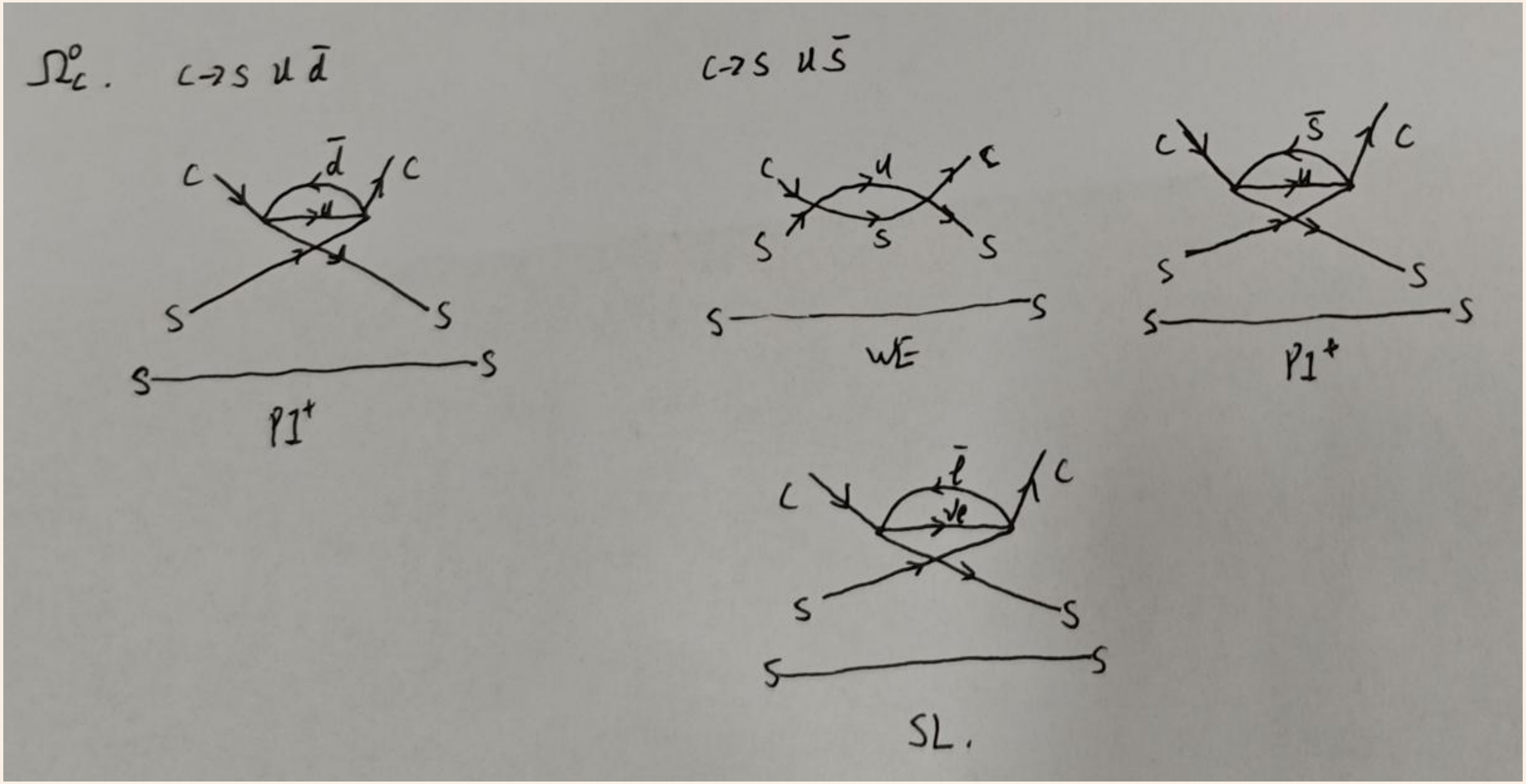
Numerical results

Inputs

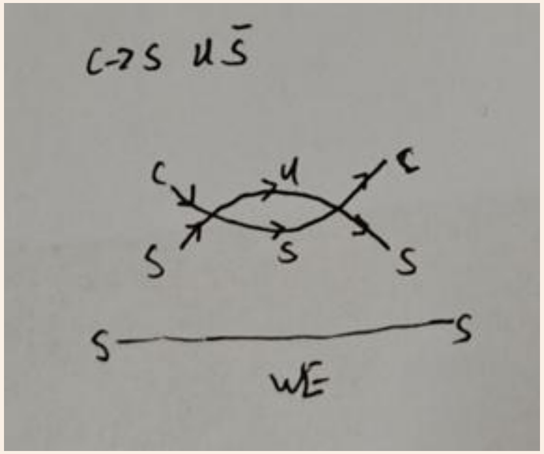
- $m_c^{1S} = 1.55$ GeV
- $\mu = 1$ GeV
- Condensate parameters: standard

P. Colangelo and A. Khodjamirian, hep-ph/0010175

Dim6 contribution for Ω_c



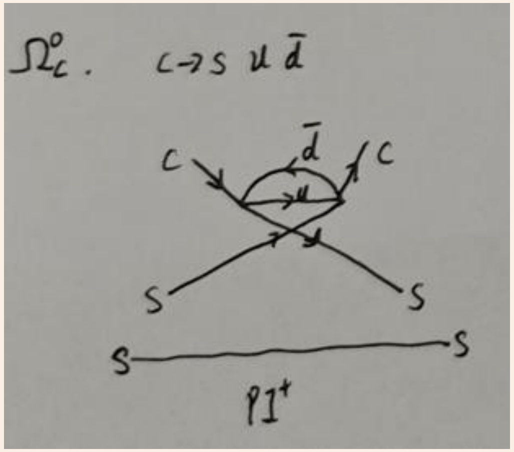
Calculation of WE



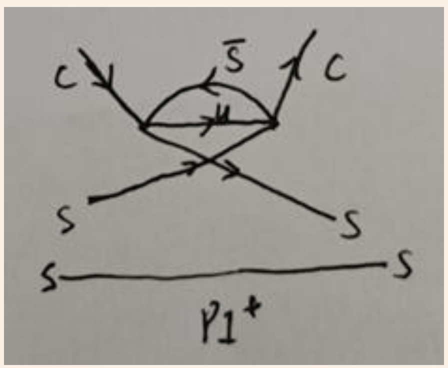
- $c_6 \sim s_+(1 - m_s^2/s_+)^2$, $s_+ = (p_c + p_s)^2$
- expanded by p_s
- Order 0: $m_c^2\left(1 - \frac{m_s^2}{m_c^2}\right)^2$
- Order 1: $2\left(1 - \frac{m_s^4}{m_c^4}\right)(p_c \cdot p_s)$
- Order 2: $\left(1 - \frac{m_s^4}{m_c^4}\right)p_s^2 + \frac{4m_s^4}{m_c^6}(p_c \cdot p_s)^2$
- …

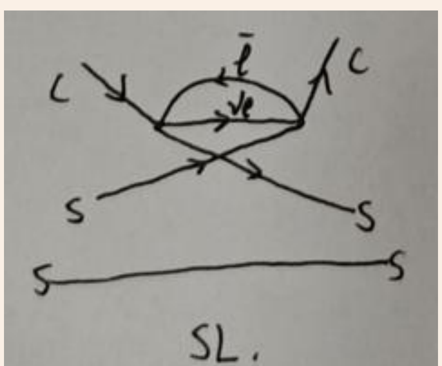
In QCDSR, $p_c^2 \sim p_c \cdot p_s = \frac{s_+ - m_c^2 - m_s^2}{2}$, $s_+ \in [(m_c + m_s)^2, s_0]$

Calculation of PI



- $c_6 \sim s_- = (p_c - p_s)^2$
  $= p_c^2 - 2p_c \cdot p_s + p_s^2$
- 0th ≈ (-1)*1st





- $c_6 \sim (2s_- + m_s^2)(1 - m_s^2/s_-)^2$
- $s_- = (p_c - p_s)^2 = (k_5 - k_2)^2$
- Expand by p_s
- similar to WE: 0th + 1st
- converge quickly

preliminary results of dim6 for Ω_c

表 6: The dim6 term of Ω_c^0, in units of GeV, up to 0th of c_6.

	WE	PI^+	$semi-e$	$semi-\mu$
$c-s,u\bar{d}$		3.32×10^{-12}		
$c-s,u\bar{s}$	5.78×10^{-13}	1.75×10^{-13}	1.08×10^{-12}	1.07×10^{-12}

表 7: The dim6 term of Ω_c^0, in units of GeV, up to 1th of c_6.

	WE	PI^+	$semi-e$	$semi-\mu$
$c-s,u\bar{d}$		3.09×10^{-13}		
$c-s,u\bar{s}$	1.34×10^{-12}	1.47×10^{-14}	1.00×10^{-13}	8.57×10^{-14}

We need the help of experimentalists here!

Lifetimes of singly charmed baryons (pre)

$\mathcal{B}_Q$	Γ_3	Γ_5	$\Gamma_6(initial)$	Γ_6
Λ_c^+	1.16×10^{-12}	-1.19×10^{-15}	1.07×10^{-12}	2.31×10^{-12}
Ξ_c^0	1.14×10^{-12}	-1.95×10^{-15}	3.31×10^{-12}	3.57×10^{-12}
Ξ_c^+	1.14×10^{-12}	-1.95×10^{-15}	1.37×10^{-12}	6.98×10^{-13}
Ω_c^0	1.14×10^{-12}	-1.01×10^{-14}	6.22×10^{-12}	1.85×10^{-12}

$\Gamma_{tot}(initial)$	Γ_{tot}	$\tau(initial)$	τ	τ_{exp}
2.23×10^{-12}	3.46×10^{-12}	2.95×10^{-13}	1.90×10^{-13}	2.026×10^{-13}
4.45×10^{-12}	4.71×10^{-12}	1.48×10^{-13}	1.40×10^{-13}	1.504×10^{-13}
2.51×10^{-12}	1.84×10^{-12}	2.62×10^{-13}	3.58×10^{-13}	4.53×10^{-13}
7.35×10^{-12}	2.98×10^{-12}	0.89×10^{-13}	2.21×10^{-13}	2.73×10^{-13}

Summary and outlook

Summary and outlook

- We have calculated all the matrix elements in HQE for singly charmed baryons using the full QCD sum rules, and obtained preliminary results.
- Cheng: 1807.00916, consider dim7
- Preliminary results -> central values and errors
- More heavy baryons …

Thank you for your attention!