Lifetimes of Charmed Hadrons

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Motivation from ΔA_{CP}

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

where

$$A_{CP}(f,t) = \frac{\Gamma(D^0(t)\to f)-\Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f)+\Gamma(\bar{D}^0(t)\to f)}$$

- Current value: $\Delta A_{CP} = (15.6 \pm 2.9) \times 10^{-4}$ [arXiv:1903.08726]
- This is a 5.3σ deviation from SM
- What could be missing?
  - i Statistics
  - ii Big non perturbative effects
  - iii New physics

Motivation from ΔA_{CP}

What does this have to do with lifetimes?

- We want to constrain further the three possible explanations
- Inclusive decays are easier than exclusive ones
- If a theory is working well for the easy case then it could work also for the complicated case - BUT this is not a proof

Charm Baryon Lifetimes

- The last couple of years LHCb published papers on precision measurements of $\Omega_c^0, \Lambda_c^+, \Xi_c^+$ and Ξ_c^0 [arXiv:1807.02024] [arXiv:1906.08350]

  i $\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2\mathrm{fs}$
  ii $\tau(\Lambda_c^+) = 203.5 \pm 1 \pm 1.3 \pm 1.4\mathrm{fs}$
  iii $\tau(\Xi_c^+) = 456.8 \pm 3.5 \pm 2.9 \pm 3.1\mathrm{fs}$
  iv $\tau(\Xi_c^0) = 154.5 \pm 1.7 \pm 1.6 \pm 1\mathrm{fs}$

- Theoretical predictions are far less precise
- Test framework on simpler cases (mesons) and then apply them to baryons

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Framework

Effective Hamiltonian: $\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left[C_1 Q_1 + C_2 Q_2 + Q_e + Q_\mu \right]$

$$Q_1 = \bar{s}'_j \gamma_\mu (1 - \gamma_5) c_i \bar{u}_i \gamma^\mu (1 - \gamma_5) d'_j$$

$$Q_2 = \bar{s}'_i \gamma_\mu (1 - \gamma_5) c_i \bar{u}_j \gamma^\mu (1 - \gamma_5) d'_j$$

$$Q_l = \bar{s}' \gamma_\mu (1 - \gamma_5) c \bar{l} \gamma^\mu (1 - \gamma_5) \nu$$

- Q_i involves long distance physics
- C_i involves short distance physics

Heavy Quark Expansion(HQE)

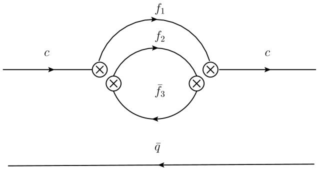
- $\Gamma(H \to X) = \frac{1}{2m_H} \sum_X \int_{\mathrm{PS}} (2\pi)^4 \delta^{(4)}\left(p_H - p_X\right) \left|\langle X \left| \mathcal{H}_{eff} \right| H \rangle\right|^2$
- Using the Optical Theorem: $\Gamma(H \to X) = \frac{1}{2m_B} \langle H | \mathcal{T} | H \rangle$ where

$$\mathcal{T} = \mathrm{Im}\, i \int d^4x T \left[\mathcal{H}_{eff}(x) \mathcal{H}_{eff}(0)\right]$$

- Finally expanding in inverse powers of m_Q we get:

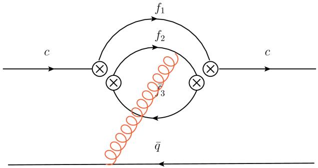
$$\Gamma = \Gamma_0 \left[c_3 \frac{\langle H | \bar{Q} Q | H \rangle}{2M_H} + \frac{c_5}{m_Q^2} \frac{\langle H | \bar{Q} g_s \sigma_{\mu\nu} G^{\mu\nu} Q | H \rangle}{2M_H} + \frac{c_6}{m_Q^3} \frac{\langle H | (\bar{Q} q) \bar{q} Q | H \rangle}{2M_H} + \ldots \right]$$

Dimension 3 contribution



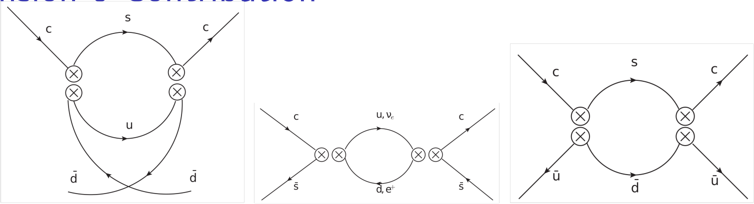
- The leading term comes from the decay of the charm quark
- Diagrams appear at 2-loop level
- We want to consider all possible decay channels
- By adding all possible fermion combinations: $c_3 \approx 6.5$

Dimension 5 Contribution



- First correction in HQE: soft interaction with spectator quark
- In the charm system $c_5 \approx -0.6$

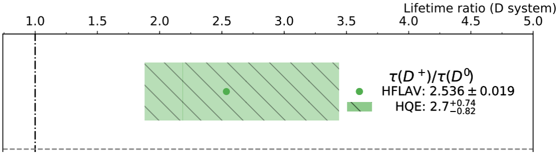
Dimension 6 Contribution



- Next correction: Interaction involving the spectator quark (3 topologies)
- Diagrams appear at 1-loop level $\Rightarrow$ enhancement by $16\pi^2$ compared to previous diagrams
- Non-perturbative effects: $B_{1,2}$ and $\epsilon_{1,2}$

Non-perturbative effects

First calculation of bag parameters for D mesons was completed in 2018:



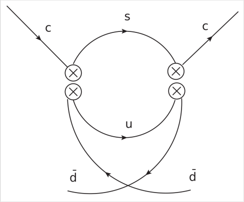
[Kirk, Lenz, Rauh, '18]

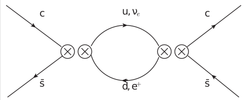
Non-perturbative effects

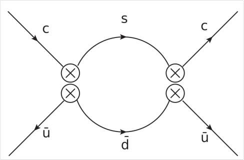
Obs.	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$\langle O^{d=6} \rangle$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$\langle O^{d=7} \rangle$	Σ	
$\tau(B^+)/\tau(B_d)$	++	++	0	+	++	0	0	**	(7+)
$\tau(B_s)/\tau(B_d)$	++	++	0	$\frac{+}{2}$	++	0	0	**	(6.5+)
$\tau(\Lambda_b)/\tau(B_d)$	++	$\frac{+}{2}$	0	$\frac{+}{2}$	+	0	0	**	(4+)
$\tau(b - baryon)/\tau(B_d)$	++	0	0	0	+	0	0	*	(3+)
$\tau(B_c)$	+	0	0	+	0	0	0	*	(2+)
$\tau(D^+)/\tau(D^0)$	++	++	0	+	++	0	0	**	(7+)
$\tau(D_s^+)/\tau(D^0)$	++	++	0	$\frac{+}{2}$	++	0	0	**	(6.5+)
$\tau(c - baryon)/\tau(D^0)$	++	0	0	0	+	0	0	*	(3+)

[Lenz '18]

Dimension 7 Contribution



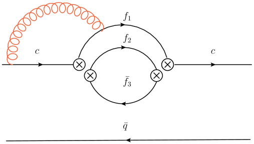


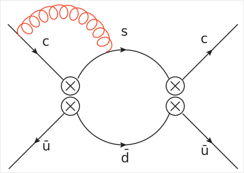


- Expanding further the above diagrams one obtains dimension 7 operators $\Rightarrow$ bag parameters ρ_{1-6}, σ_{1-6}
- Still undetermined but use vacuum insertion approximation: $\rho_i = 1 \pm 1/12, \sigma_i = 0 \pm 1/6$

[Lenz, Rauh, '13]

Next-to-leading Order





[Hokim, Pham '84]

[Bagan, Ball, Braun '94]

[Lenz, Nierste, Ostermaier '97]

[Greub, Liniger '00]

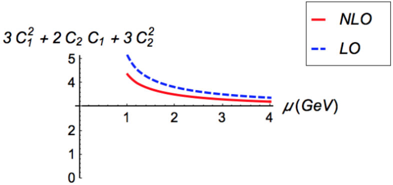
[Krinner, Lenz, Rauh '13]

[Franco et al '02]

- Do we really need to go to NLO?

Next-to-leading Order

- LO can give unphysical results (e.g. $\tau(D^+) < 0$) [arXiv:1807.00916v3]
- Two NLO components for a full calculation
  - i LO diagrams with NLO Wilson coefficients
  - ii NLO diagrams with LO Wilson coefficients
- $\alpha_s(m_c) = 0.42 \approx 2\alpha_s(m_b)$
- Indications of big corrections at dimension 3 [Review by Lenz]



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Lifetime Ratios

- $$\frac{\tau(D_1)}{\tau(D_2)} = \frac{1+\frac{\mu_\pi^2(D_2)}{2m_c^2}+\frac{c_G}{c_3}\frac{\mu_G^2(D_2)}{2m_c^2}+\frac{1}{2m_c^2}\sum_{B_x}\frac{c_{6,B_x}^{D_2}}{c_3}B_x^{D_2}+\ldots}{1-\frac{\mu_\pi^2(D_1)}{2m_c^2}+\frac{c_G}{c_3}\frac{\mu_G^2(D_1)}{2m_c^2}+\frac{1}{2m_c^2}\sum_{B_x}\frac{c_{6,B_x}^{D_1}}{c_3}B_x^{D_1}+\ldots}$$
- $$\frac{\tau(D_1)}{\tau(D_2)} \approx 1 + \frac{\mu_\pi^2(D_2)-\mu_\pi^2(D_1)}{2m_c^2} + \frac{c_G}{c_3}\frac{\mu_G^2(D_1)-\mu_G^2(D_2)}{2m_c^2} + + \sum_{B_x}\frac{c_{6,B_x}^{D_1}B_x^{D_1}-c_{6,B_x}^{D_2}B_x^{D_2}}{c_3 m_c^3} + \ldots$$
- $$\frac{\tau(D_1)}{\tau(D_2)} \approx 1 + \Gamma_0 \cdot \tau_1\left[c_3\frac{\mu_\pi^2(D_1)-\mu_\pi^2(D_2)}{2m_c^2} + c_G\frac{\mu_G^2(D_2)-\mu_G^2(D_1)}{2m_c^2} + \sum\frac{c_{6,B_x}^{D_2}B_x^{D_2}-c_{6,B_x}^{D_1}B_x^{D_1}}{m_c^3} + \ldots\right]$$

Numerical results

- $$\left(\frac{\tau(D^+)}{\tau(D^0)}\right)_{\overline{\mathrm{MS}}} = 2.2 \pm 0.4(\mathrm{hadr.}) \begin{array}{c} +0.3 \\ -0.7 \end{array} (\mathrm{scale}) \pm 0.0(\mathrm{param.})$$
  [Lenz, Rauh, '13]
- $$\left(\frac{\tau(D^+)}{\tau(D^0)}\right)_{\overline{\mathrm{Exp}}} = 2.536 \pm 0.19$$
- $$\left(\frac{\bar{\tau}(D_s^+)}{\tau(D^0)}\right)_{\overline{\mathrm{MS}}} = 1.19 \pm 0.12(\mathrm{hadr}) \pm 0.04(\mathrm{scale}) \pm 0.01(\mathrm{param.})$$
  [Lenz, Rauh, '13]
- $$\left(\frac{\tau(D_s^+)}{\tau(D^0)}\right)_{\overline{\mathrm{Exp}}} = 1.289 \pm 0.019$$

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Conclusion

- In order to test the $1/m_c$ expansion in ΔA_{CP} calculations it's good to verify its validity by applying in a simpler calculation (hadron lifetimes)
- HQE is a powerful tool for the B system but it's still open to verify how fast it converges in the charm system
- Going NLO in α_s looks to have significant effects in lifetime calculations
- Current numerical results look to be in line with experiments but pushing the expansion in α_s and $1/m_c$ will help test the validity of pert. theory and HQE near the charm scale
- Then can move to the more complicated case of baryons and test against the new experimental values

Thank you for your attention!