B-meson lifetimes within the HQE

Maria Laura Piscopo

CPPS, Theoretische Physik 1, Universität Siegen

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In collaboration with A. Lenz, J. Müller and A. Rusov

Center for Particle Physics Siegen

UNIVERSITÄT SIEGEN

Motivation

- Lifetime $\tau = \Gamma^{-1}$ is one of the fundamental properties of particles
- For heavy hadrons: systematic framework to compute $\Gamma(H_Q)$

  $m_Q \gg \Lambda_{QCD}$

- Focus on the B-system $m_b \sim 4.5\,\text{GeV} \gg 0.5\,\text{GeV} \sim \Lambda_{QCD}$
  - Experimental precision very high $\mathcal{O}(‰)$ [HFLAV '21]
  - Aim at competitive theoretical precision to
    - Test the framework used
    - Perform indirect NP searches

$$\underbrace{\frac{\tau(B_1)}{\tau(B_2)}}_{\text{exp.}} = 1 + \underbrace{\left[\Gamma^{\text{SM}}(B_2) - \Gamma^{\text{SM}}(B_1)\right]\tau^{\text{exp.}}(B_1)}_{\text{theory}} + \underbrace{\left[\Gamma^{\text{BSM}}(B_2) - \Gamma^{\text{BSM}}(B_1)\right]\tau^{\text{exp.}}(B_1)}_{\text{indirectly constrained}}$$

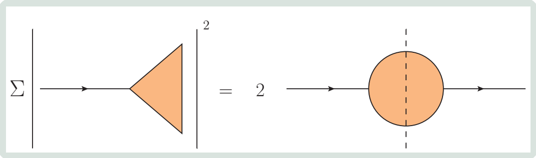
The total decay width of a B-meson

- Start from the definition

$$\Gamma(B) = \frac{1}{2m_B} \sum_n \int_{\text{PS}} (2\pi)^4 \delta^{(4)}(p_n - p_B) |\langle n|\mathcal{H}_{eff}|B\rangle|^2$$

- $\mathcal{H}_{eff}$ - weak effective Hamiltonian describing b-quark decays
- Use optical theorem to rewrite [Shifman, Voloshin '85]

$$\Gamma(B) = \frac{1}{2m_B} \text{Im} \langle B| i \int d^4x \, \text{T}\Big\{\mathcal{H}_{eff}(x) \, , \mathcal{H}_{eff}(0)\Big\}|B\rangle$$



The heavy quark expansion (HQE)

- Heavy b-quark carries most of the hadron momentum $p_B^\mu = m_B v^\mu$

- Introduce parametrisation

$$p_b^\mu = m_b v^\mu + k^\mu$$

$k \sim \Lambda_{QCD} \ll m_b$

- Rescale heavy quark field

$$b(x) = e^{-i m_b v\cdot x}\, b_v(x)$$

- Action of the covariant derivative

$$iD_\mu b(x) = e^{-i m_b v\cdot x}\left(m_b v_\mu + iD_\mu\right) b_v(x)$$

$D_\mu = \partial_\mu - i A_\mu^a(x) t^a$

The HQE

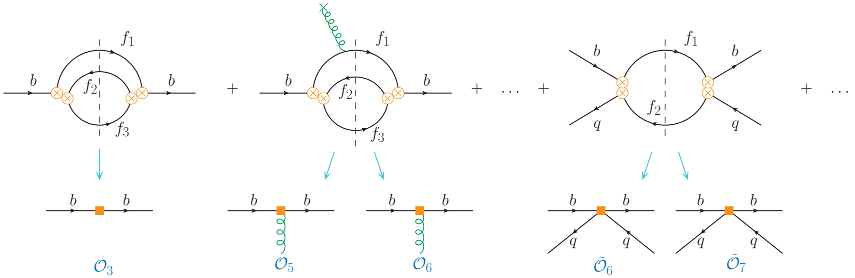
◇ Obtain systematic expansion

$$\Gamma(B) = \underbrace{\Gamma_3}_{\Gamma(b)} + \underbrace{\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]}_{\delta\Gamma(B)}$$

- $\Gamma_d, \tilde{\Gamma}_d$ - short distance coefficients
- $\mathcal{O}_d, \tilde{\mathcal{O}}_d$ - local operators bilinear in the heavy quark field
- $\Gamma(b)$ - total decay width of free b quark
- $\delta\Gamma(B)$ - effects due to interaction with soft gluons and quarks

The HQE

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$



Very advanced framework thanks to huge effort of big community

Status of HQE: perturbative side

$$\Gamma_d = \Gamma_d^{(0)} + \left(\frac{\alpha_s(m_b)}{4\pi}\right)\Gamma_d^{(1)} + \left(\frac{\alpha_s(m_b)}{4\pi}\right)^2 \Gamma_d^{(2)} + \dots$$

Semileptonic modes (SL)	
$\Gamma_3^{(3)}$	Fael, Schönwald, Steinhauser '20 Czakon, Czarnecki, Dowling '21
$\Gamma_3^{(2)}$	Czarnecki, Melnikov, v. Ritbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola '97-'13
$\Gamma_5^{(1)}$	Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal '13-'15
$\Gamma_6^{(1)}$	Mannel, Moreno, Pivovarov '19, '21, '22
$\Gamma_7^{(0)}$	Dassinger, Mannel, Turczyk '06
$\Gamma_8^{(0)}$	Mannel, Turczyk, Uraltsev '10

Non-leptonic modes (NL)	
$\Gamma_3^{(2)}$	Czarnecki, Slusarcyk, Tkachov '05 *
$\Gamma_3^{(1)}$	Ho-Kim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Gosdzinsky, Fiol, Lenz, Nierste, Ostermaier, Krinner, Rauh '84-'13
$\Gamma_5^{(0)}$	Bigi, Uraltsev, Vainshtein, Blok, Shifman '92
$\Gamma_6^{(0)}$	Lenz, MLP, Rusov, Mannel, Moreno, Pivovarov '20-'21
$\tilde{\Gamma}_6^{(1)}$	Beneke, Buchalla, Greub, Lenz, Nierste, Franco, Lubicz, Mescia, Tarantino, Rauh '02-'13
$\tilde{\Gamma}_7^{(0)}$	Gabbiani, Onishchenko, Petrov '03-'04

* Only partial result

Status of HQE: non-perturbative side

★ Fit to experimental data on semileptonic B-decays ★ HQET sum rules ★ Lattice QCD

	B_d, B^+	B_s
$\langle \mathcal{O}_5 \rangle$	Bernlochner et al. '22, ★ Bordone, Capdevila, Gambino, Schwanda et al. '13, '14, '21 ★ Ball, Braun, Neubert '93-'95 ★ Kronfeld, Simone, Gambino, Melis, Simula '00 -'17 ★	SU(3)$_\mathrm{F}$-breaking for μ_π^2 Bigi, Mannel, Uraltsev '11 Spectroscopy relation for μ_G^2
$\langle \mathcal{O}_6 \rangle$	Bernlochner et al. '22, ★ Bordone et al. '13, '14, '21 ★ EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$	EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$
$\langle \tilde{\mathcal{O}}_6 \rangle$	Kirk, Lenz, Rauh '17 ★	King, Lenz, Rauh '21 ★
$\langle \tilde{\mathcal{O}}_7 \rangle$	Vacuum insertion approximation (VIA)	

- Some tension between different fits for ρ_D^3
- Fits to experimental semileptonic B_s-decays highly desirable

Belle II, BESIII, LHCb, super tau-charm factory?

Our setup

- The observables

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$

$$\tau(B_{(s)}^{(+)})/\tau(B_d) = 1 + \left[\Gamma(B_d)^{\mathrm{HQE}} - \Gamma(B_{(s)}^{(+)})^{\mathrm{HQE}} \right] \tau(B_{(d)}^{(+)})^{\mathrm{exp}}$$

- No two-quark contributions in $\tau(B^+)/\tau(B_d)$ in isospin limit
  - Theoretically more clean
- For $\tau(B_s)/\tau(B_d)$ crucial role of $\mathrm{SU}(3)_\mathrm{F}$ breaking effects
  - Two-quark dimension-six coefficient Γ_6 found to be large
    [Lenz, MLP, Rusov '20; Mannel, Moreno, Pivovarov '20]
  - Poor control on size of non-pert. input and of $SU(3)_\mathrm{F}$ breaking

Result

◇ Scenario A

∗ Larger input for B_d

[Bordone et al. '21]

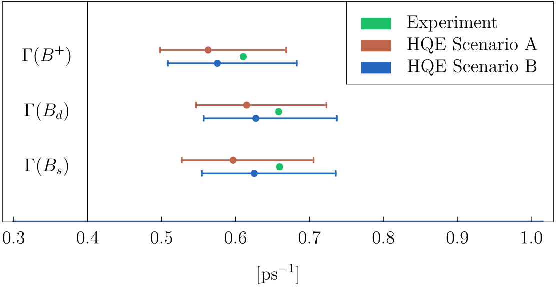
∗ Larger $SU(3)_F$ breaking

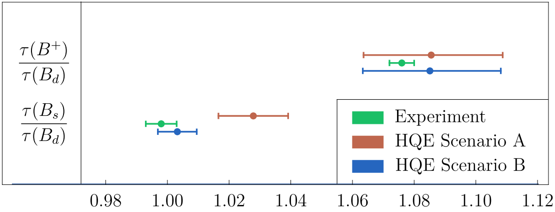
◇ Scenario B

∗ Smaller input for B_d

[Bernlochner et al. '22]

∗ Smaller $SU(3)_F$ breaking



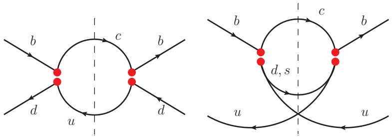


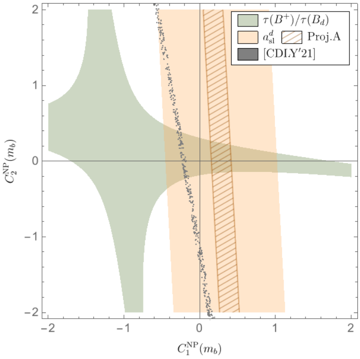
[Lenz, MLP, Rusov '22]

BSM effects in lifetimes and mixing

- Good agreement of HQE with data for $\tau(B^+)/\tau(B_d)$
- How large is space for NP in $b \to c\bar{u}d(s)$ decays ?
- Repeat computation with 20 additional NP operators, also for a_{sl}^d

$$\mathcal{H}_{eff} = \mathcal{H}_{eff}^{\rm SM} + \mathcal{H}_{eff}^{\rm NP}$$





Compare with study of decays like $\bar{B}_s \to D_s^+\pi^-$

[Cai, Deng, Li, Yang '21]

[Lenz, Müller, MLP, Rusov '22]

Conclusion

- Up-to-date analysis of B-meson lifetimes (ratios) within HQE
- Very good agreement with data, but larger uncertainties
- Need better control on size of two-quark non-pert. input
  - Accuracy of prediction for $\tau(B_s)/\tau(B_d)$ largely affected!
- Possibility to constrain coefficients of some NP operators

Thanks for the attention

Backup

Status of B-mesons lifetime ratios

	HFLAV	[Lenz, MLP, Rusov '22]
$\frac{\tau(B^+)}{\tau(B_d)}$	1.076(4)	1.085(23)
$\frac{\tau(B_s^0)}{\tau(B_d)}$	0.998(5)	$1.004(5) + 0.247 \underbrace{\rho_D^3(B_d)}_{\text{exp. fit}} \times \underbrace{\left[\frac{\rho_D^3(B_s)}{\rho_D^3(B_d)} - 1\right]}_{\text{EOM}}$

- Good agreement of HQE with data for $\tau(B^+)/\tau(B_d)$
- Prediction for $\tau(B_s)/\tau(B_d)$ significantly affected by Darwin term
  - Extract ρ_D^3 from fit to SL B-decays
    e.g. [Bernlochner et al. '22; Bordone et al. '21]
  - Estimate size of $SU(3)_F$ from EOM for gluon field
    e.g. [Bigi, Mannel, Uraltsev '11]

The Darwin operator

- The Darwin operator can be rewritten as penguin operator

$$\mathcal{O}_{\rho_D^3} = \frac{1}{4m_B}\bar{b}_v[iD_\mu,[iD^\rho,iD^\mu]]v_\rho b_v = -\frac{g_s^2}{4m_B}(\bar{b}_v\gamma^\mu t^a b_v)\sum_q(\bar{q}\gamma_\mu t^a q) + \mathcal{O}\left(\frac{1}{m_b}\right)$$

- Apply Fierz-transformation and use VIA

$$\frac{\rho_D^3(B_s^0)}{\rho_D^3(B_d^0)} = \frac{f_{B_s}^2\, m_{B_s}}{f_B^2\, m_B}$$

- Obtain $SU(3)_F$ breaking effects of $\sim 50\%$!

Overestimate size of $SU(3)_F$ breaking effects?