Theoretical overview of lifetimes

Maria Laura Piscopo

Nikhef Theory Group, Amsterdam

"More than a lifetime" workshop

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Why lifetimes?

- The lifetime $\tau = \Gamma^{-1}$ is a fundamental property of particles
- For heavy hadrons H_Q, systematic framework to compute Γ
- Consider both the beauty and charm systems
  - Experimental precision very high [HFLAV, PDG]

    See overview talks from LHCb, ATLAS, CMS, Belle II and BESIII
  - Aim at improving theoretical precision to:
    - Test the SM and the framework used

      Insights into interplay of strong and weak interactions
    - Perform indirect new physics (NP) searches

The theoretical framework

Effective field theories for heavy hadrons decays

- Weak decays of heavy hadrons define multi-scale problem

$$\underbrace{m_W}_{\sim 80\ \text{GeV}} \gg \underbrace{m_Q}_{\sim [1-4.5]\ \text{GeV}} \gg \underbrace{\Lambda_{QCD}}_{\sim 0.3\ \text{GeV}}$$

- At scales $\mu \sim m_Q$
  - Use weak effective theory (WET) e.g. [Buchalla, Buras, Lautenbacher '96]
  - Observables computed in terms of expansion in $1/m_W^2$
- At scales $\mu \sim \Lambda_{QCD}$
  - Use heavy quark effective theory (HQET) e.g. [Isgur, Wise '89; Georgi '90]
  - Observables computed in terms of expansion in $1/(2m_Q)$

The total decay width of a heavy hadron

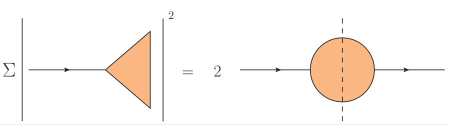
- Start from the definition

Effective Hamiltonian describing leptonic and non-leptonic Q decays

$$\Gamma(H_Q) = \frac{1}{2m_{H_Q}} \sum_n \int_{\rm PS} (2\pi)^4 \delta^{(4)}(p_n - p_{H_Q}) |\langle n|\mathcal{H}_{\rm eff}|H_Q\rangle|^2$$

- Use optical theorem to rewrite [Shifman, Voloshin '85]

$$\Gamma(H_Q) = \frac{1}{2m_{H_Q}} {\rm Im}\, \langle H_Q| \, i \int d^4x \, {\rm T}\left\{\mathcal{H}_{\rm eff}(x)\,, \mathcal{H}_{\rm eff}(0)\right\}|H_Q\rangle$$



The heavy quark expansion (HQE)

- Q carries most of the hadron momentum $p^\mu_{H_Q} = m_{H_Q} v^\mu$

- Introduce parametrisation

$$p^\mu_Q = m_Q v^\mu + k^\mu \qquad k \sim \Lambda_{QCD} \ll m_Q$$

- Define rescaled heavy-quark field

$$Q(x) = e^{-i m_Q v \cdot x}\, Q_v(x)$$

- The action of the covariant derivative

$$i D_\mu Q(x) = e^{-i m_Q v \cdot x} \big(m_Q v_\mu + i D_\mu \big) Q_v(x)$$

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

The HQE

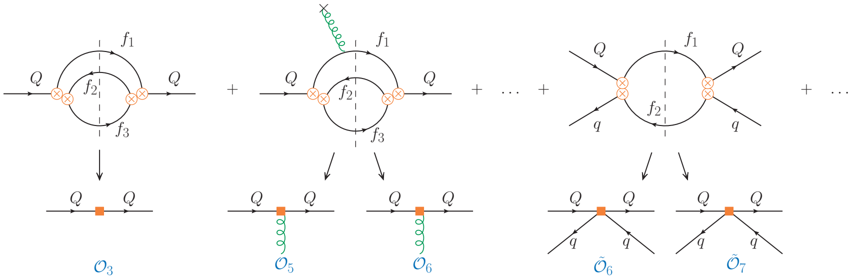
- Obtain systematic expansion

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

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

The HQE

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



$$\langle \mathcal{O}_d \rangle \propto \langle H_Q | \bar{Q} \underbrace{(iD_\mu) \ldots (iD_\nu)}_{d-3} Q | H_Q \rangle$$

$$\langle \tilde{\mathcal{O}}_d \rangle \propto \langle H_Q | \big(\bar{Q} \Gamma q \big) \big(\bar{q} \Gamma \underbrace{(iD_\mu) \ldots}_{d-6} Q \big) | H_Q \rangle$$

HQE: beauty vs. charm

- The HQE is a double expansion in $\alpha_s(m_Q)$ and Λ_{QCD}/m_Q
- In the beauty system ($m_b \sim 4.5\text{GeV}$):

$$\alpha_s(m_b) \sim 0.22 \qquad \frac{\Lambda_{QCD}}{m_b} \sim 0.10$$

  - Applicability of the HQE is well justified

- In the charm system ($m_c \sim 1\text{GeV}$):

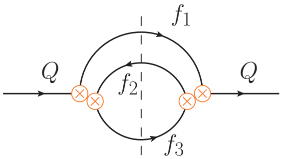
$$\alpha_s(m_c) \sim 0.33 \qquad \frac{\Lambda_{QCD}}{m_c} \sim 0.30$$

  - Can we still *reliably* apply the HQE?

Must compare HQE predictions with measurements

A closer look into HQE

Dimension-three contribution



Include all possible final state leptons and quarks f_i

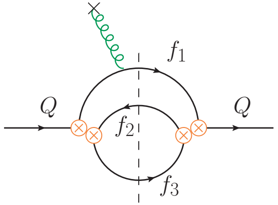
- Total decay width of free Q quark

$\langle H_Q | \bar{Q}_v Q_v | H_Q \rangle = 2 m_{H_Q} + \ldots$

$$\Gamma_3 = \underbrace{\frac{G_F^2 m_Q^5}{192\pi^2}}_{\Gamma_0} \left(c_3^{(0)} + \frac{\alpha_s}{4\pi} c_3^{(1)} + \left(\frac{\alpha_s}{4\pi}\right)^2 c_3^{(2)} + \ldots \right)$$

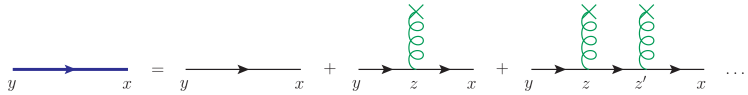
- Strong dependence on the mass-scheme choice for Q

Power corrections due to two-quark operators



- Parametrise soft-gluons exchange
- Expand quark propagators and Q field in D_μ
- Use background field method and Fock-Schwinger gauge

See e.g. [Novikov, Shifman, Vainshtein, Zakharov '83]



Dimension-five contribution

- Parametrised by the *kinetic* and *chromomagnetic* operators:

$$2m_{H_Q}\mu_\pi^2(H_Q) = -\langle H_Q|\bar{Q}_v(iD_\mu)(iD^\mu)Q_v|H_Q\rangle$$

$$2m_{H_Q}\mu_G^2(H_Q) = \langle H_Q|\bar{Q}_v(iD_\mu)(iD_\nu)(-i\sigma^{\mu\nu})Q_v|H_Q\rangle$$

- Result at order $1/m_Q^2$:

$$\Gamma_5\frac{\langle\mathcal{O}_5\rangle}{m_Q^2} = \Gamma_0\left[c_{\mu_\pi}\frac{\mu_\pi^2}{m_Q^2} + \left(c_G^{(0)} + \frac{\alpha_s}{4\pi}c_G^{(1)} + \ldots\right)\frac{\mu_G^2}{m_Q^2}\right]$$

- The coefficient of the kinetic operator: $c_{\mu_\pi} = -c_3/2$

From the reparameterization invariance of the HQE

Dimension-six contribution

- Parametrised by the *Darwin* operator:

$$2m_{H_Q}\rho_D^3(H_Q) = \langle H_Q|\bar{Q}_v(iD_\mu)(iv\cdot D)(iD^\mu)Q_v|H_Q\rangle$$

- IR divergences from expansion of light-quark propagators

$$\Gamma_6\frac{\langle\mathcal{O}_6\rangle}{m_Q^3} = \Gamma_0\left[\mathcal{C}_D^{(0)} + \frac{\alpha_s}{4\pi}\mathcal{C}_D^{(1)}\dots\right]\frac{\rho_D^3}{m_Q^3}$$

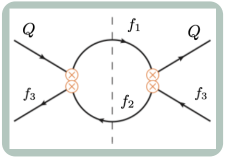
with

$$\mathcal{C}_D \underset{m_q\to 0}{\sim} \log\left(\frac{m_q^2}{m_Q^2}\right) \qquad q = \{u,d,s\}$$

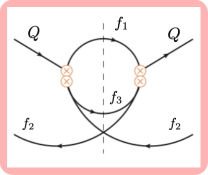
  - Sensitivity to long-distance dynamics $\Lambda_{QCD} \sim m_q \ll m_Q$
  - Signal of mixing with four-quark operators at order $1/m_Q^3$

Power corrections due to four-quark operators

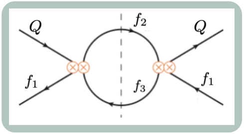
Weak Exchange



Pauli inteference



Weak Annihilation



- Arise first at order $1/m_Q^3$
- Different size of corresponding topologies:
  - Large contribution from Pauli interference
  - Small effect due to helicity suppression from WE and WA

See talk by F. Moretti

Dimension-six contribution

- Possible choice for the four-quark operator basis

$$\tilde{\mathcal{O}}_1^q = (\bar{Q}_v \gamma_\mu (1-\gamma_5) q)(\bar{q}\gamma^\mu (1-\gamma_5) Q_v)$$

$$\tilde{\mathcal{O}}_2^q = (\bar{Q}_v (1-\gamma_5) q)(\bar{q}(1+\gamma_5) Q_v)$$

$$\tilde{\mathcal{O}}_3^q = (\bar{Q}_v \gamma_\mu (1-\gamma_5) t^a q)(\bar{q}\gamma^\mu (1-\gamma_5) t^a Q_v)$$

$$\tilde{\mathcal{O}}_4^q = (\bar{Q}_v (1-\gamma_5) t^a q)(\bar{q}(1+\gamma_5) t^a Q_v)$$

- Corresponding parametrisation:

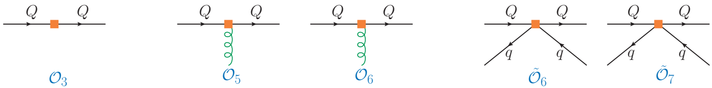
$$\langle H_Q^q | \tilde{\mathcal{O}}_i^q | H_Q^q \rangle = f_{H_Q}^2 m_{H_Q}^2 \left(1 + \frac{4}{3}\frac{\alpha_s}{\pi}\right) \tilde{B}_i^q$$

$$\langle H_Q^q | \tilde{\mathcal{O}}_i^{q'} | H_Q^q \rangle = f_{H_Q}^2 m_{H_Q^q}^2 \tilde{\delta}_i^{q' q} \qquad q \neq q'$$

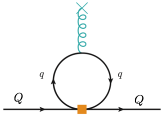
$\tilde{B}_{1,2}^q = 1 + \delta \tilde{B}_{1,2}^q \qquad \tilde{B}_{3,4}^q = 0 + \tilde{\epsilon}_{1,2}^q \qquad \tilde{\delta}_i^{q' q} \ll 1$ (eye-contractions)

Operator mixing at dimension-six

- Recall



- $\tilde{\mathcal{O}}_6$ and $\mathcal{O}_6$ mix under renormalisation

$\langle$  $\rangle$

$$\sim \left[\frac{1}{\epsilon} + \log\left(\frac{\mu^2}{m_q^2}\right) + c\right] \langle \mathcal{O}_{\rho_D} \rangle + \mathcal{O}\left(\frac{1}{m_Q}\right)$$

  - All dependence on $\log\left(m_q^2\right)$ in $\mathcal{C}_D$ cancels
  - Constant c depends on choice of op. basis See e.g. [Fael, Mannel, Vos '19]
  - Found sizeable contribution of the Darwin operator

[Lenz, MLP, Rusov '20; Mannel, Moreno, Pivovarov '20]

Where do we stand

Status of the HQE (perturbative side)

$$\Gamma_d = \Gamma_d^{(0)} + \frac{\alpha_s}{\pi}\Gamma_d^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \Gamma_d^{(2)} + \left(\frac{\alpha_s}{\pi}\right)^3 \Gamma_d^{(3)} \ldots$$

Semileptonic (SL) modes	
$\Gamma_3^{(3)}$	Fael, Schönwald, Steinhauser '20 Czakon, Czarnecki, Dowling '21
$\Gamma_5^{(1)}$	Alberti, Gambino, Nandi '13 Mannel, Pivovarov, Rosenthal '15
$\Gamma_6^{(1)}$	Mannel, Moreno, Pivovarov '19
$\Gamma_7^{(0)}$	Dassinger, Mannel, Turczyk '06
$\Gamma_8^{(0)}$	Mannel, Turczyk, Uraltsev '10
$\tilde{\Gamma}_6^{(1)}$	Lenz, Rauh '13

Non-leptonic (NL) modes	
$\Gamma_3^{(2)}$	Egner, Fael, Schönwald, Steinhauser '24
$\Gamma_3^{(1)}$	Ho-Kim, Pham '83; Altarelli, Petrarca '91 Bagan et al. '94; Krinner, Lenz, Rauh '13 Lenz, Nierste, Ostermaier '97
$\Gamma_5^{(1)}$	Mannel, Moreno, Pivovarov '23, '24, '25
$\Gamma_6^{(0)}$	Lenz, MLP, Rusov '20 Mannel, Moreno, Pivovarov '20
$\tilde{\Gamma}_6^{(1)}$	Beneke, Buchalla, Greub, Lenz, Nierste '02 Franco, Lubicz, Mescia, Tarantino '02
$\tilde{\Gamma}_7^{(0)}$	Gabbiani, Onishchenko, Petrov '03

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See talks by K. Schönwald and D. Moreno

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Status of the HQE (non-perturbative side)

- Most inputs are known only for the B^0 (and B^+) mesons

	B^0, B^+	B_s
$\langle \mathcal{O}_5 \rangle$	*Fits to SL data* ◇ *Lattice QCD* + *HQET sum rules* *	*Spectroscopy relations* **
$\langle \mathcal{O}_6 \rangle$	*Fits to SL data* ◇ *EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$	*Sum rules estimates* ** *EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$
$\langle \tilde{\mathcal{O}}_6 \rangle$	*HQET sum rules* ‡ *Lattice QCD* †	*HQET sum rules* ‡
$\langle \tilde{\mathcal{O}}_7 \rangle$	*Vacuum insertion approximation*	

◇[Finauri, Gambino '23; Bernlochner, et al. '22] *[Ball, Braun '94; Neubert '96] **[Bigi et al. '11]

+[Gambino et al. '17; Bazavov et al. '18] † [Black, Harlander, Lange, Rago, Shindler, Witzel '23, '24]

‡[Kirk, Lenz, Rauh '18; King, Lenz, Rauh '20; Black, Lang, Lenz, Wüthrich '24]

See talks by M. Black, M. Lang, F. Lange and J. Lin

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Status of the HQE (non-perturbative side)

- Beyond the B^0-meson system:
  - First steps towards extraction of $\langle \mathcal{O}_{5,6} \rangle$ for B_s from data

    [De Cian, Feliks, Rotondo, Vos '23]
  - Prospects for measuring moments in SL D decays at BESIII

    [Bernlochner, Gilman, Malde, Prim, Vos, Wilkinson '24]
  - First attempt to extract inputs for the D system from current data

    [Shao, Huang, Qin '25]

    See talks by A. Gilman, Th. Mannel, C. Schwanda and K. Vos
  - Baryonic matrix elements are less constrained:
    - Use of spectroscopy relations and simplified models of QCD
    - Recent study of $\langle \mathcal{O}_{5,6} \rangle$ for Λ_b using small-velocity sum rules

      [Melić, Nišandžić '25]

B-meson lifetimes

The observables

- Compute total widths

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

  - Strong dependence on value of b-quark mass in Γ_3

- And lifetime ratios

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

  - No two-quark op. contributions for $\tau(B^+)/\tau(B_d)$ in isospin limit
  - Crucial effect of $SU(3)_{\mathrm{F}}$ breaking for $\tau(B_s)/\tau(B_d)$

The value of the quark masses

- The numerical value of the quark masses plays a fundamental role
- Different renormalisation schemes: on-shell (OS), $\overline{\text{MS}}$ ...
- Current SL fits are based on the kinetic scheme

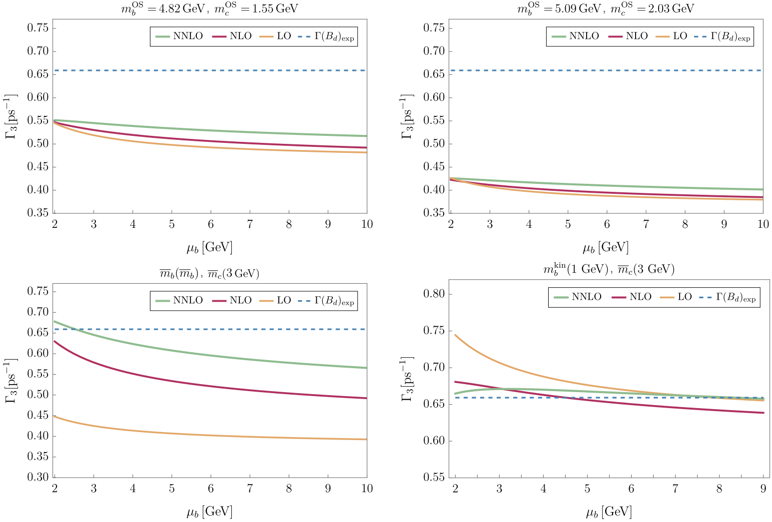
[Bigi, Shifman, Uraltsev, Vainshtein '97]

$$m_b^{\text{OS}} = m_b^{\text{kin}}(\mu^{\text{cut}}) + [\Lambda(\mu^{\text{cut}})]_{\text{pert}} + \frac{[\mu_\pi^2(\mu^{\text{cut}})]_{\text{pert}}}{2m_b^{\text{kin}}(\mu^{\text{cut}})} + \ldots$$

  - Similarly for parameters of two-quark operators matrix elements
  - Conversion relations known up to N^3LO-QCD

[Fael, Schönwald, Steinhauser '21, '20]

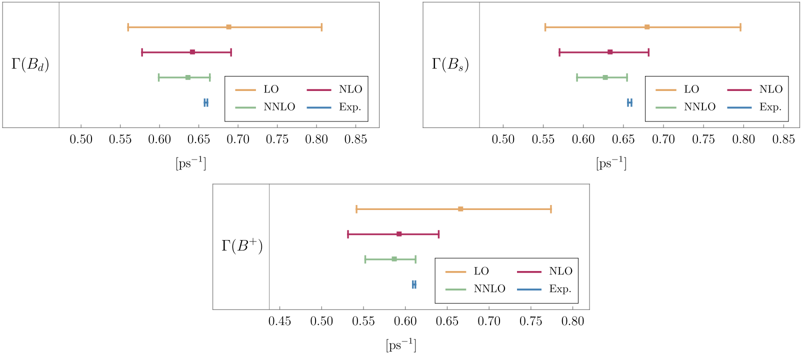
Mass-scheme dependence



[Egner, Fael, Lenz, MLP, Rusov, Schönwald, Steinhauser '24]

Results for B-meson lifetimes

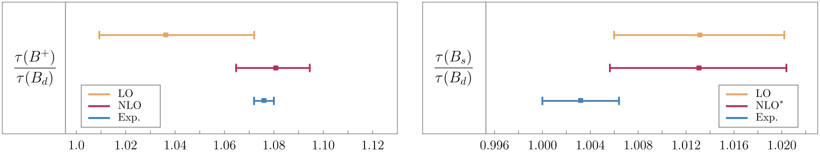
[Egner, Fael, Lenz, MLP, Rusov, Schönwald, Steinhauser '24]



- Significant improvement in renormalisation scale dependence

Results for B-meson lifetime ratios

[Egner, Fael, Lenz, MLP, Rusov, Schönwald, Steinhauser ’24]



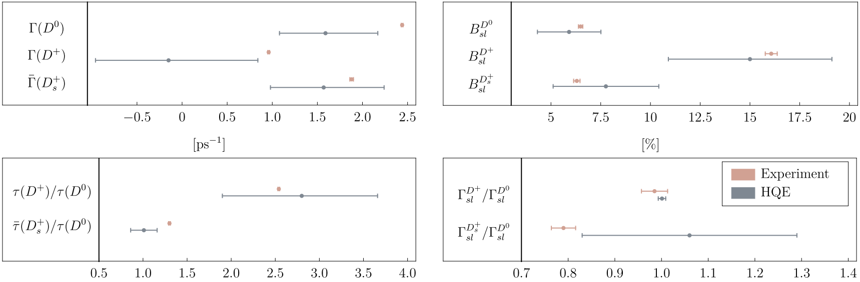
- Unaffected by the NNLO results for leading term Γ_3
- Good agreement with data for $\tau(B^+)/\tau(B_d)$
- Complete NLO corrections for $\tau(B_s)/\tau(B_d)$ still missing
  - Large uncertainties from poorly known size of $SU(3)_{\mathrm{F}}$ breaking

Particularly in the Darwin operator contribution

D-meson lifetimes

Test the HQE in the charm sector

[King, Lenz, MLP, Rauh, Rusov, Vlahos '21]



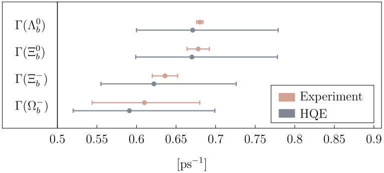
Obtained in the kinetic scheme with $\mu^{\text{cut}} = 0.5\text{GeV}$

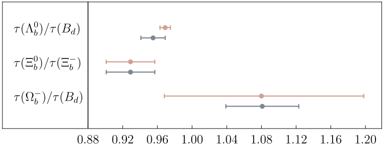
- Can accommodate data but with *very large* uncertainties due to:
  - Charm-quark mass
  - Poorly known non-perturbative inputs
- Results confirmed by independent study [Gratrex, Melić, Nišandžić '22]

What about baryons?

HQE for beauty and charm baryons

- For b-baryons:





[Gratrex, Lenz, Melić, Nišandžić, MLP, Rusov '23]

  - Very good agreement of HQE predictions with data

    Also with the new more precise measurements of $\tau(\Xi_b^{0,-})$ by LHCb

    [2507.12402; 2406.12111]

  - Main uncertainties from scale variation and dim-six four-quark op.

- Good agreement found also for charmed baryons

  - Can accommodate experimentally observed hierarchies

    [Gratrex, Melić, Nišandžić '22; Dulibić, Gratrex, Melić, Nišandžić '23]

    See also [Cheng, Liu '23]

Lifetimes beyond the SM

In the presence of NP effects

- Lifetime ratios are theoretically more clean

$$\underbrace{\frac{\tau(B^+)}{\tau(B_d)}}_{\text{exp.}} = 1 - \underbrace{\tau(B^+)\left[\delta\Gamma(B^+) - \delta\Gamma(B_d)\right]^{\text{HQE}}}_{\text{theory}} - \underbrace{\tau(B^+)\left[\delta\Gamma(B^+) - \delta\Gamma(B_d)\right]^{\text{NP}}}_{\text{indirectly constrained}}$$

- Potential to constrain BSM decays of the b quark
- Mainly limited by theory uncertainties
- Until further insights on size of $SU(3)_{\text{F}}$ break., use $\tau(B^+)/\tau(B_d)$

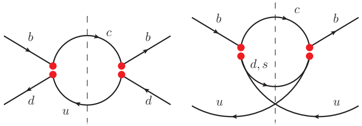
BSM effects in $\tau(B^+)/\tau(B_d)$ and mixing

◇ Tensions in NL B-decays triggered by $b \to c\bar{u}d(s)$

[Bordone, Gubernari, Huber, Jung, van Dyk '20]

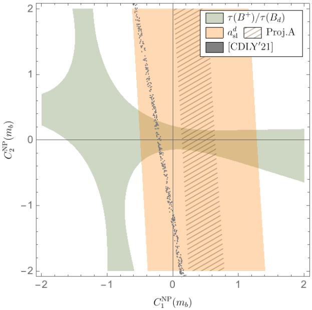
- How large is space for NP in $b \to c\bar{u}d(s)$ decays ?
- Repeat computation with 20 additional NP operators, also for a_{sl}^d

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



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

[Cai, Deng, Li, Yang '21]



[Lenz, Müller, MLP, Rusov '22]

Summary

Conclusions

- The HQE is a very successful framework
  - Enormous progress made in increasing its accuracy
  - Main limitation from knowledge of non-perturbative inputs

However, big efforts in improving current precision

- Predictions for B-meson lifetimes at NNLO-QCD:
  - Strong reduction of scale and mass-scheme dependence
  - Precision reaches now the order of a few %
    - Subleading QCD corrections and QED effects become relevant!

      May significantly affect not only the uncertainties but also the central values

    - Combined semileptonic and lifetime fit? See talk by M. Prim

Conclusions

- Testing the HQE beyond the B system:
  - b-baryon lifetimes found in very good agreement with data
  - Predictions in charm sector can accommodate observed patterns
    - Dominant sources of uncertainties from poor convergence of the perturbative expansion and lack of precise non-perturbative inputs

Crucial the inclusion of NNLO-QCD corrections to Γ_3

- Potential to indirectly constraint certain BSM b-quark decays

See also recent study [Lenz, Mohamed, Wüthrich '24]

See talk by A. Lenz

  - Main limitation due to theoretical uncertainties

Thanks for the attention!