Towards a precise theoretical determination of the B_s lifetime

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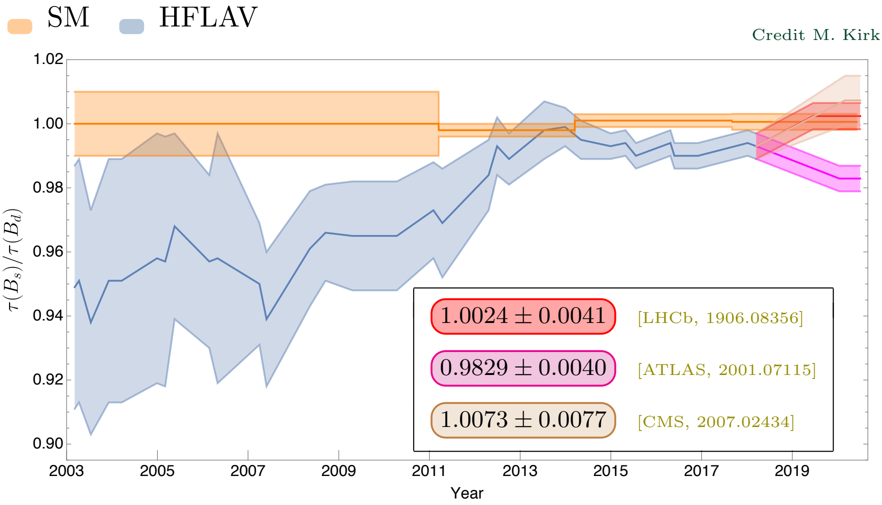
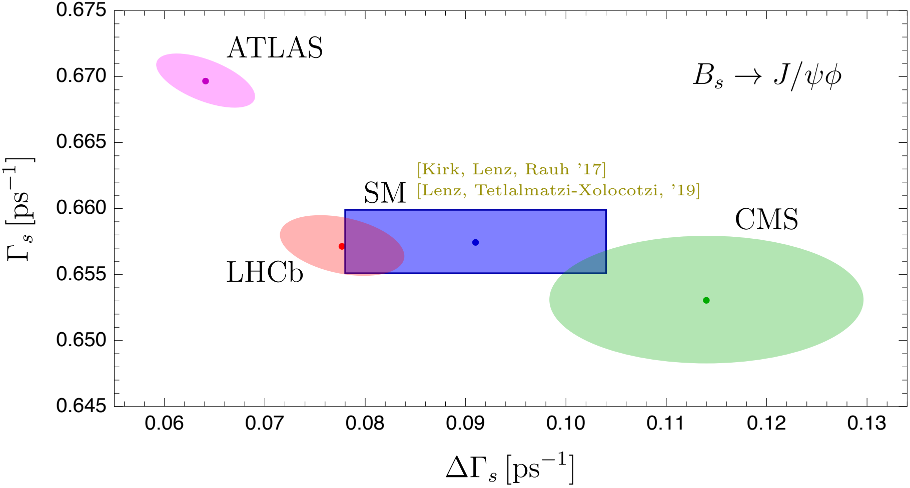
Motivation

$\tau(B_s)/\tau(B_d)$ - *Experimental status*



Closer look . . .



0.675
0.670
0.665
0.660
0.655
0.650
0.645
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
Γ_s [ps^{-1}]
$\Delta\Gamma_s$ [ps^{-1}]
ATLAS
$B_s \to J/\psi\phi$
SM
[Kirk, Lenz, Rauh '17]
[Lenz, Tetlalmatzi-Xolocotzi, '19]
CMS
LHCb

$\tau(B_s)/\tau(B_d)$ - *Theoretical status*

◇ Use Heavy Quark Expansion (HQE) [Shifman, Voloshin '85]

$$\frac{\tau(B_s)}{\tau(B_d)} = \frac{\Gamma_b + \delta\Gamma_{B_d}}{\Gamma_b + \delta\Gamma_{B_s}} = 1 + \underbrace{\tau(B_s)\left(\delta\Gamma_{B_d} - \delta\Gamma_{B_s}\right)}_{0.0007 \pm 0.0025}$$

[Kirk, Lenz, Rauh '17]

∗ Γ_b - leading contribution, free b-quark decay ∗ $\delta\Gamma_{B_q}$ - subleading terms

◇ Multiple cancellations arise

◇ Unique possibility

∗ to compete with increasing experimental precision

∗ to validate HQE

∗ to test for BSM scenarios and search for invisible decays

$\tau(B_s)/\tau(B_d)$ - *New Physics*

- BSM contributions appear in the lifetime ratio as:

$$\underbrace{\frac{\tau(B_s)}{\tau(B_d)}}_{\text{exp.}} \approx 1 + \underbrace{\tau(B_s)\left(\delta\Gamma^{\text{SM}}_{B_d} - \delta\Gamma^{\text{SM}}_{B_s}\right)}_{\text{theory}}$$

$$+ \underbrace{\left[\text{BR}(B_d \to X)^{\text{BSM}} - \text{BR}(B_s \to X)^{\text{BSM}}\right]}_{\text{indirectly constrained}}$$

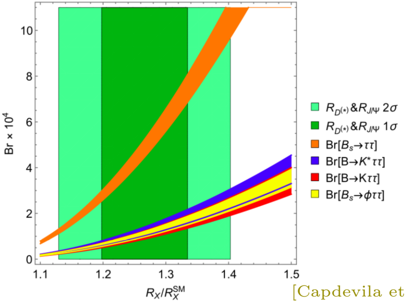
  - NP could affect differently $b \to s$ and $b \to d$ transitions
  - Possibility to constrain BSM contributions at permille level
  - Hints for NP in $b \to s\mu^+\mu^-$ and $b \to c\tau^-\bar{\nu}_\tau$ processes might point towards large effects in $b \to s\tau^+\tau^-$ [Capdevila et al. '18; Bordone et al. '19]

The $B_s \to \tau^+\tau^-$ decay

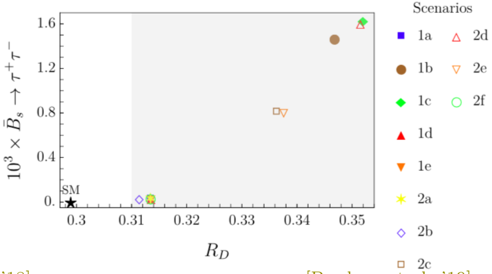
◇ Suppressed in the SM and experimentally very challenging:

$$\mathrm{Br}(B_s \to \tau^+\tau^-) \begin{cases} =_{\text{th.}} \ (7.73 \pm 0.49) \times 10^{-7} & \text{[Bobeth et al. '14]} \\ <_{\text{exp.}} \ 6.8 \times 10^{-3} & \text{[LHCb, 1703.02508]} \end{cases}$$

◇ Correlations between $R_{D^{(*)}}$, $R_{J/\psi}$ and $B_s \to \tau^+\tau^-, \ldots$



[Capdevila et al. '18]



[Bordone et al. '19]

◇ These big effects might be visible in $\tau(B_s)/\tau(B_d)$

The Heavy Quark Expansion

The theoretical framework

◇ From the optical theorem:

$$\Gamma_{B_q} = \frac{1}{2m_{B_q}} \mathrm{Im} \langle B_q | \, i \int d^4x \, \mathcal{T}\{\mathcal{L}_{\rm eff}(x), \mathcal{L}_{\rm eff}(0)\} \, | B_q \rangle$$

◇ OPE in inverse power of m_b: $p^\mu = m_b v^\mu + k^\mu$

$$\Gamma_{B_q} = \underbrace{\Gamma_3 \langle \mathcal{O}_3 \rangle}_{\Gamma_b} + \underbrace{\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]}_{\delta\Gamma_{B_q}}$$

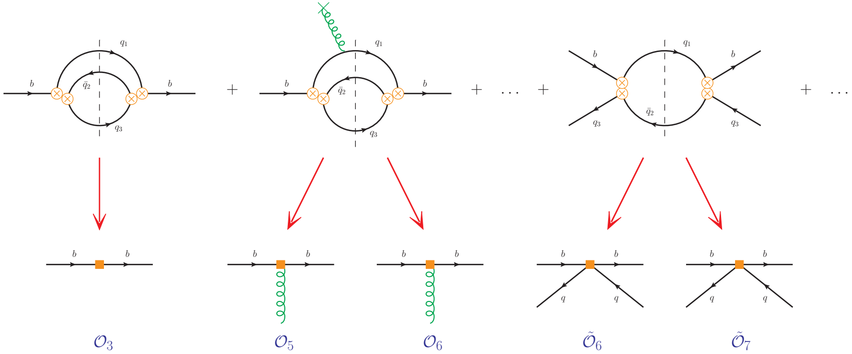
∗ $\Gamma_i, \tilde{\Gamma}_i$ - short distance coefficients

∗ $\mathcal{O}_d, \tilde{\mathcal{O}}_d$ - local quark operator of dimension d

∗ $\frac{\delta\Gamma_{B_q}^{(d)}}{\Gamma_b} \sim \left(\frac{k}{m_b}\right)^{d-3} \sim \left(\frac{1\,\mathrm{GeV}}{4.5\,\mathrm{GeV}}\right)^{d-3}$ - small parameter

The theoretical framework

$$\Gamma_{B_q} = \Gamma_3 \langle \mathcal{O}_3 \rangle + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + ... + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + ... \right]$$



The theoretical framework

◇ What has been included so far ...

	"Two – loop" contributions		"One – loop" contributions	
	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$
$\mathcal{O}(1)$	✓	✓	–	–
$\mathcal{O}\left(\frac{1}{m_b^2}\right)$	✓	✗	–	–
$\mathcal{O}\left(\frac{1}{m_b^3}\right)$	✗	✗	✓	✓
$\mathcal{O}\left(\frac{1}{m_b^4}\right)$	✗	✗	✓	✗

Some peculiarities

- Suppression of $1/m_b^2$ contributions

- "One-loop" $1/m_b^3$ corrections expected to be dominant, but

$q = d, s$

$$\delta\tilde{\Gamma}^{(6)}_{B_q} \sim \left\{ \underbrace{\left(\frac{C_1^2}{3} + 2\,C_1 C_2 + 3\,C_2^2\right)}_{\approx 10^{-2}} \left((\underbrace{B_2^q}_{\approx 1} - \underbrace{B_1^q}_{\approx 1}) + \mathcal{O}\underbrace{\left(\frac{m_c^2}{m_b^2}\right)}_{\approx 0.05}\right) + \underbrace{2C_1^2}_{\approx 2}\ \underbrace{f(\epsilon_2, \epsilon_1)}_{\text{color suppr.}} \right\}$$

- Strong suppression despite loop enhancement

- "Two-loop" $1/m_b^3$ corrections found sizeable in the SL case

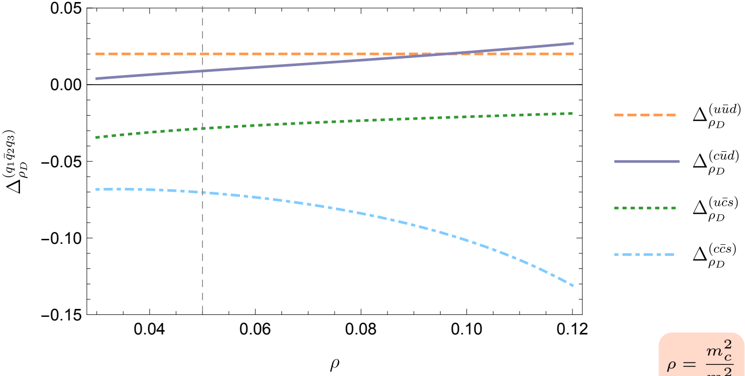
[Gremm, Kapustin, '96]

  * What about the NL case?

Contribution of the Darwin term for NL decays

Result

- Computation done by two independent groups [Lenz, Piscopo, Rusov, '20] [Mannel, Moreno, Pivovarov, '20] [Moreno, '20]
- Large relative size of $2 - 7\%$



$$\rho = \frac{m_c^2}{m_b^2}$$

Conclusion

- Large coefficient of the Darwin operator, but

$$\frac{\tau(B_s)}{\tau(B_d)} = 1 + \Big\{ \underbrace{\Gamma_5 \Big(\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B_s} \Big)}_{\checkmark} \frac{1}{m_b^2} + \underbrace{\Gamma_6}_{\checkmark} \underbrace{\Big(\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B_s} \Big)}_{\text{✗}} \frac{1}{m_b^3}$$

$$+ \Big[\underbrace{\Big(\tilde{\Gamma}_6^{B_d} - \tilde{\Gamma}_6^{B_s} \Big) \langle \tilde{\mathcal{O}}_6 \rangle_{B_d}}_{\checkmark} - \tilde{\Gamma}_6^{B_s} \underbrace{\Big(\langle \tilde{\mathcal{O}}_6 \rangle_{B_s} - \langle \tilde{\mathcal{O}}_6 \rangle_{B_d} \Big)}_{\text{✗}} \Big] \frac{1}{m_b^3} + \ldots \Big\} \tau(B_s)$$

- $SU(3)_f$ violation effects crucial

Further steps:

- Determination of $\Big(\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B_s} \Big)$ [Lenz, Piscopo, Rusov]
- Computation of $\langle \tilde{\mathcal{O}}_6 \rangle_{B_s}$ $\underbrace{\text{[King, Lenz, Rauh}}_{\text{HQET SumRules}}$, $\underbrace{\text{Witzel]}}_{\text{Lattice}}$

Final remarks on $B_s \to J/\psi\, \phi$

◇ ϕ_s

- Quite precisely measured (-21 ± 31) mrad [HFLAV '19]
- In the SM (-37 ± 1) mrad if penguin pollution neglected (± 17 mrad)
- Originally very promising BSM observable, but experimental precision approaching penguin size
- Not clear how to improve theory from first-principles

◇ Γ_s, $\Delta\Gamma_s$

- Quite precisely measured but experimental discrepancy
- Theory can be systematically improved - hard but doable
- Huge effort going into perturbative QCD and non-perturbative methods (HQET Sum Rules, lattice)

Thanks for the attention

Backup slides

Dimension-six operator basis

Two-quark operators

$$\mathcal{O}_{\rho_D} = \bar{b}_v (iD_\mu)(iv\cdot D)(iD^\mu) b_v$$

$$\mathcal{O}_{\rho_{LS}} = \bar{b}_v (iD_\mu)(iv\cdot D)(iD_\nu)(-i\sigma^{\mu\nu})\, b_v$$

Four-quark operators

$$\tilde{\mathcal{O}}^{(q)}_{6,1} = (\bar{b}^i_v \gamma_\mu (1-\gamma_5)\, q^i)(\bar{q}^j \gamma^\mu (1-\gamma_5)\, b^j_v) \quad \tilde{\mathcal{O}}^{(q)}_{6,2} = (\bar{b}^i_v \not{v} (1-\gamma_5)\, q^i)(\bar{q}^j \not{v} (1-\gamma_5)\, b^j_v)$$

$$\tilde{\mathcal{O}}^{(q)}_{6,3} = (\bar{b}^i_v \gamma_\mu (1-\gamma_5)\, q^j)(\bar{q}^j \gamma^\mu (1-\gamma_5)\, b^i_v) \quad \tilde{\mathcal{O}}^{(q)}_{6,4} = (\bar{b}^i_v \not{v} (1-\gamma_5)\, q^j)(\bar{q}^j \not{v} (1-\gamma_5)\, b^i_v)$$

Parametrisation of four-quark operators matrix elements

$$\langle B_{q'} |\, \tilde{\mathcal{O}}^{(q)}_{6,i}\, | B_{q'} \rangle = A_i\, m_B^2\, f_B^2 \left(\mathcal{B}^{(q)}_i(B)\, \delta_{qq'} + \tau^{(q)}_i(B) \right)$$

with $A_1 = A_3 = 1,\ A_2 = A_4 = (m_B/(m_b + m_q))^2, \qquad q = u, d, s$

Quark Hadron Duality

Experiment at hadron level, calculation at quark-gluon level

$$\text{QHD violation} \equiv \begin{cases} 1/m_Q \text{ corrections in } \Gamma \\ \text{oscillatory terms in } \Gamma \end{cases}$$

- In the '90s appears discrepancy:

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = \begin{cases} \sim 0.96 & \text{[Shifman, Voloshin '86]} \\ 0.798 \pm 0.034 & \text{[HFAG '03]} \end{cases}$$

- 2019 status:

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = \begin{cases} 0.935 \pm 0.054 & \text{[Lenz '14]} \\ 0.969 \pm 0.006 & \text{[HFLAV '19]} \end{cases}$$

  - Shift of $4.9\,\sigma$

Quark Hadron Duality

Experiment at hadron level, calculation at quark-gluon level

- Compare HQE with experiments:
  - No sign of any significant deviation
  - $\Delta\Gamma_s$ highly sensitive (fewer states, smaller phase space)
    - Good agreement
- Simplified models of QCD:
  - SV limit: no duality violation for SL and NL decays

    [Boyd, Grinstein, Manohar '95; Grinstein, Savrov '03]
  - 'tHooft model: no $1/m_Q$ corrections, tiny oscillatory terms

    [Grinstein, Lebed '97, '98, '01]

    [Bigi, Shifman, Uraltsev, Vainshtein '98, '99, '00]