Karlsruhe Institute of Technology

C1b: $B - \overline{B}$ mixing, CP violation, and Lifetimes

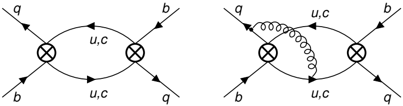
Matthias Steinhauser | CRC meeting, Karlsruhe, March 18-19, 2019

TTP KARLSRUHE

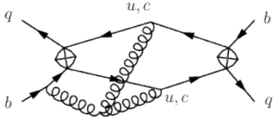
C1b: $B - \overline{B}$ mixing, CP violation, and Lifetimes

PI:	Ulrich Nierste
	Matthias Steinhauser
Postdoc:	Vladyslav Shtabovenko
PhD:	Marvin Gerlach
Guests:	Artyom Hovhannisyan, ...

Framework and aims



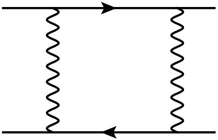
- SM
- (inclusive) B and D decays:
  lifetime differences between heavy hadrons ($Q = b, c$, $q = u, d, s$)
  semileptonic CP asymmetries of B_d and B_s decays
- origin: $B_d - \overline{B}_d$ and $B_s - \overline{B}_s$ mixing
- HQE: expansion in α_s and $\Lambda_{\mathrm{QCD}}/m_b$
  "Wilson coefficients" $\times$ "matrix element"
- NNLO [3 loops, $\mathcal{O}(\alpha_s^2)$] for leading power of HQE
- NLO $\Lambda_{\mathrm{QCD}}/m_b$ [2 loops, $\mathcal{O}(\alpha_s \Lambda_{\mathrm{QCD}}/m_b)$]



Lifetime differences

- Strucutre of theory predictions:

$$\Delta\Gamma \propto \frac{1}{m_b^3}\sum_j \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_3^{(j)} + \frac{1}{m_b^4}\sum_j \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_4^{(j)} + \ldots$$



- $\Delta B = 2$: $B_q \leftrightarrow \overline{B}_q$, $(\bar{b}, q) \leftrightarrow (b, \bar{q})$
time evolution of $(B_q, \overline{B}_q)$ system ($q = d, s$):

$$i\frac{\partial}{\partial t}\begin{pmatrix} B \\ \overline{B} \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} B \\ \overline{B} \end{pmatrix}$$

mass matrix: M decay matrix: Γ

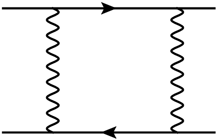
M_{12}: dispersive part of $(M - i\Gamma/2)_{12}$

$\Gamma_{12}/2$: absorptive part of $(M - i\Gamma/2)_{12}$

Lifetime differences

- Strucutre of theory predictions:

$$\Delta\Gamma \propto \frac{1}{m_b^3}\sum_j \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_3^{(j)} + \frac{1}{m_b^4}\sum_j \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_4^{(j)} + \ldots$$



- $\Delta B = 2$: $B_q \leftrightarrow \overline{B}_q$, $(\bar{b}, q) \leftrightarrow (b, \bar{q})$
  time evolution of $(B_q, \overline{B}_q)$ system ($q = d, s$):
  M_{12}: dispersive part of $(M - i\Gamma/2)_{12}$
  $\Gamma_{12}/2$: absorptive part of $(M - i\Gamma/2)_{12}$
- diagonalize $M - i\Gamma/2$ ➪ eigenvalues: $M_L - i\Gamma_L/2$, $M_H - i\Gamma_H/2$

  ➪ mass and width of B_L and B_H (“light” and “heavy”)
  ➪ mass difference $\Delta M = M_H - M_L = 2|M_{12}|$ and
  ➪ width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$; $\frac{\Delta\Gamma}{\Delta M} = -\mathrm{Re}\frac{\Gamma_{12}}{M_{12}} \simeq \frac{|\Gamma_{12}|}{|M_{12}|}$

CP asymmetry

- CP asymmetry in flavour-specific decays
  ("semi-leptonic CP asymmetry"):

➪ $$a_{\rm fs} = \frac{\Gamma(\overline{B}\to f) - \Gamma(B\to f)}{\Gamma(\overline{B}\to f) + \Gamma(B\to f)} = \mathrm{Im}\frac{\Gamma_{12}}{M_{12}}$$ ➪ "small"

- quantifies CP violation in $B - \overline{B}$ mixing
  measured in semileptonic decays
- SM: relative phase between M_{12} and $(-\Gamma_{12})$ is tiny

---

mass difference $\Delta M = M_H - M_L = 2|M_{12}|$ and

width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$; $\quad \frac{\Delta\Gamma}{\Delta M} = -\mathrm{Re}\frac{\Gamma_{12}}{M_{12}} \simeq \frac{|\Gamma_{12}|}{|M_{12}|}$

Physical quantities in C1b

- $\Delta B = 2$: $B_q - \overline{B}_q$ mixing
  - $\Gamma_{12}^s \Rightarrow \Delta\Gamma_s$
  - $\Gamma_{12}^d \Rightarrow \Delta\Gamma_d$
- $\Delta B = 0$: lifetime splittings in $[\mathrm{SU}(3)_F]$
  - $(B^+, B_d, B_s) \sim (\bar{b}u, \bar{b}d, \bar{b}s)$
  - $(\Xi_b^-, \Xi_b^0, \Lambda_b) \sim (dsb, usb, udb)$
- charmed mesons and baryons
- a_{fs}^d (and a_{fs}^s)

Theoretical background

Karlsruhe Institute of Technology

$$H^{|\Delta B|=1} = \frac{G_F}{\sqrt{2}} \sum_{j=1}^{2} C_j \left[V_{cb} V_{cq}^* Q_j{}^{cc} + V_{cb} V_{uq}^* Q_j{}^{cu} \right.$$

$$\left. + V_{ub} V_{cq}^* Q_j{}^{uc} + V_{ub} V_{uq}^* Q_j{}^{uu} \right]$$

$$- \frac{G_F}{\sqrt{2}} V_{tb} V_{tq}^* \,[\text{“penguin operators”}]$$

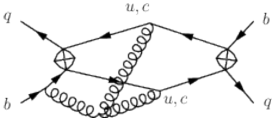
$$u', u'' \in \{u, c\}$$

$$Q_1{}^{u'u''} = \bar{u}'_L \gamma_\mu T^a b_L \, \bar{q}_L \gamma^\mu T^a u''_L \qquad Q_2{}^{u'u''} = \bar{u}'_L \gamma_\mu b_L \, \bar{q}_L \gamma^\mu u''_L$$

- RG-improved Hamiltonian to NNLO: [Gorbahn,Haisch'05]

Calculation of $\Delta\Gamma_s$

$$\Gamma_{12}^q = \frac{1}{2M_{B_s}} \text{Abs} \langle B_q | \, i \int d^4x \; T \, H^{|\Delta B|=1}(x) H^{|\Delta B|=1}(0) | \overline{B}_q \rangle$$



$$\Gamma_{12}^q = -\left[\left(\lambda_c^q\right)^2 \Gamma_{12}^{cc} + 2\,\lambda_c^q \lambda_u^q \Gamma_{12}^{uc} + \left(\lambda_u^q\right)^2 \Gamma_{12}^{uu} \right]$$

- $\Delta\Gamma_s$: $|\lambda_u^s| = |V_{us}^\star V_{ub}| \ll |V_{cs}^\star V_{cb}| = |\lambda_c^s|$ ➪ Γ_{12}^{cc} most important
- $\Delta\Gamma_d$ and $a_{\rm fs}^d$: also Γ_{12}^{uc} und Γ_{12}^{uu} needed

$$\Gamma_{12}^{ab} = \frac{G_F^2 m_b^2}{24\pi M_{B_s}} \left[\widetilde{G}^{ab} \langle B_s | Q | \overline{B}_s \rangle + \widetilde{G}_S^{ab} \langle B_s | \widetilde{Q}_S | \overline{B}_s \rangle \right] + \widetilde{\Gamma}_{12,1/m_b}^{ab}$$

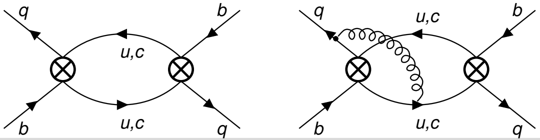
Calculation of $\Delta\Gamma_s$ (2)

$$\Gamma_{12}^{ab} = \frac{G_F^2 m_b^2}{24\pi M_{B_s}} \left[\widetilde{G}^{ab} \langle B_s|Q|\overline{B}_s\rangle + \widetilde{G}_S^{ab} \langle B_s|\widetilde{Q}_S|\overline{B}_s\rangle \right] + \widetilde{\Gamma}^{ab}_{12,1/m_b}$$

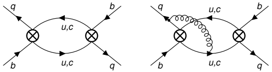
- leading power ("Γ_3")

$$\begin{aligned} Q &= \bar{s}_i\gamma_\mu(1-\gamma_5)b_i\ \bar{s}_j\gamma^\mu(1-\gamma_5)b_j, \\ \widetilde{Q}_S &= \bar{s}_i(1+\gamma_5)b_j\quad \bar{s}_j(1+\gamma_5)b_i \end{aligned}$$

- subleading power ("Γ_4", $\widetilde{\Gamma}^{ab}_{12,1/m_b}$): 5 operators

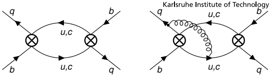


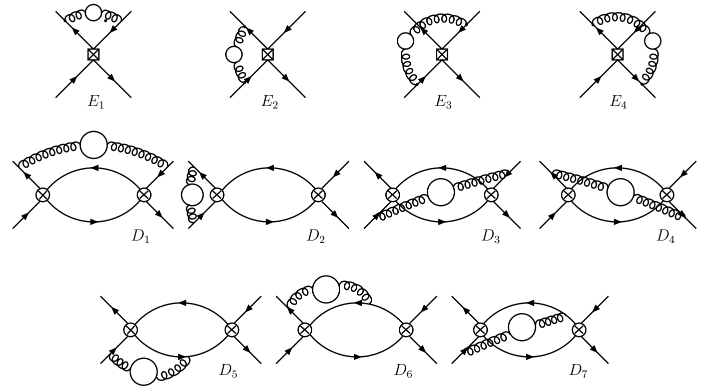
Numerical results for $\Delta\Gamma_s$



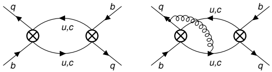
- $\langle B_s|Q|\overline{B}_s\rangle$ and $\langle B_s|\widetilde{Q}_S|\overline{B}_s\rangle$: lattice [Fermilab lattice and MILC, Bazavov et al.'16]
- Γ_{12}^{cc}, NLO (2 loops) [Beneke,Buchalla,Greub,Lenz,Nierste'99; Lenz,Nierste'07]
- Γ_{12}^{cc}, fermionic NNLO [Asatrian,Hovhannisyan,Nierste,Yeghiazaryan'17]
- $\widetilde{\Gamma}^{ab}_{12,1/m_b}$ [Beneke,Buchalla,Dunietz'96]

Numerical results for $\Delta\Gamma_s$





Numerical results for $\Delta\Gamma_s$



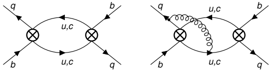
- $\langle B_s|Q|\overline{B}_s\rangle$ and $\langle B_s|\widetilde{Q}_S|\overline{B}_s\rangle$: lattice [Fermilab lattice and MILC, Bazavov et al.'16]
- Γ_{12}^{cc}, NLO (2 loops) [Beneke,Buchalla,Greub,Lenz,Nierste'99; Lenz,Nierste'07]
- Γ_{12}^{cc}, fermionic NNLO [Asatrian,Hovhannisyan,Nierste,Yeghiazaryan'17]
- $\widetilde{\Gamma}_{12,1/m_b}^{ab}$ [Beneke,Buchalla,Dunietz'96]

$$\Delta\Gamma_s = \left(0.0913 \pm 0.020_{\rm scale} \pm 0.006_{\rm lattice} \pm 0.017_{1/m_b}\right)\ \text{ps}^{-1} \qquad \text{(pole)}$$

$$\Delta\Gamma_s = \left(0.104 \pm 0.008_{\rm scale} \pm 0.007_{\rm lattice} \pm 0.015_{1/m_b}\right)\ \text{ps}^{-1} \qquad (\overline{\rm MS})$$

$$\Delta\Gamma_s^{\rm exp} = (0.089 \pm 0.006)\,\text{ps}^{-1}$$

Numerical results for $\Delta\Gamma_s$ and $a_{\rm fs}^d$



$$\Delta\Gamma_s = \left(0.0913 \pm 0.020_{\rm scale} \pm 0.006_{\rm lattice} \pm 0.017_{1/m_b}\right)\ {\rm ps}^{-1} \qquad ({\rm pole})$$

$$\Delta\Gamma_s = \left(0.104 \pm 0.008_{\rm scale} \pm 0.007_{\rm lattice} \pm 0.015_{1/m_b}\right)\ {\rm ps}^{-1} \qquad (\overline{\rm MS})$$

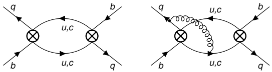
$$\Delta\Gamma_s^{\rm exp} = (0.089 \pm 0.006)\,{\rm ps}^{-1}$$

- Γ_{12}^{uc}, Γ_{12}^{uu}, NLO (2 loops) [Beneke,Buchalla,Lenz,Nierste'03; Ciuchini,Franco,Lubicz,Mescia,Tarantino'03]
  $1/m_b$ corrections [Dighe,Hurth,Kim,Yoshikawa'02]

theory: $a_{\rm fs}^d = -(4.0 \pm 0.6) \cdot 10^{-4}$

exp: $a_{\rm fs}^d = -(21 \pm 17) \cdot 10^{-4}$ ➪ Belle II and LHCb: sign. impr.

Numerical results for $\Delta\Gamma_s$ and a_{fs}^d



$$\Delta\Gamma_s = \left(0.0913 \pm 0.020_{\mathrm{scale}} \pm 0.006_{\mathrm{lattice}} \pm 0.017_{1/m_b}\right)\ \mathrm{ps}^{-1} \qquad \text{(pole)}$$

$$\Delta\Gamma_s = \left(0.104 \pm 0.008_{\mathrm{scale}} \pm 0.007_{\mathrm{lattice}} \pm 0.015_{1/m_b}\right)\ \mathrm{ps}^{-1} \qquad (\overline{\mathrm{MS}})$$

$$\Delta\Gamma_s^{\mathrm{exp}} = (0.089 \pm 0.006)\,\mathrm{ps}^{-1}$$

theory: $a_{\mathrm{fs}}^d = -(4.0 \pm 0.6) \cdot 10^{-4}$

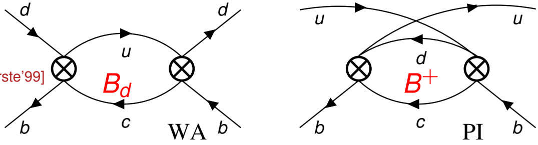
exp: $a_{\mathrm{fs}}^d = -(21 \pm 17) \cdot 10^{-4}$ ➪ Belle II and LHCb: sign. impr.

- $\Delta\Gamma_d$: LHCb via $\tau(B \to J/\psi K_S)$
- a_{fs}^s too small to be ever probed experimentally

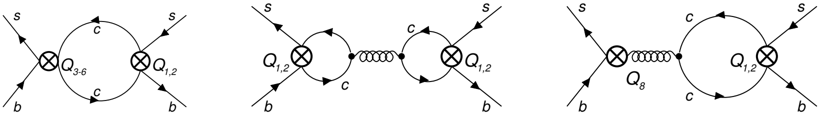
Other lifetime differences

$(B^+, B_d, B_s) \sim (\bar{b}u, \bar{b}d, \bar{b}s)$ $(\Xi_b^-, \Xi_b^0, \Lambda_b) \sim (dsb, usb, udb)$

- $\tau(B^+)/\tau(B_d)$: Weak Annihilation (WA), Pauli Interference (PI)



  - NLO QCD
    [Beneke,Buchalla,Greub,Lenz,Nierste'99]
  - $1/m_b$ LO
    [Lenz,Nierste'11]
  - no reliable lattice calculations ➪ use [Becirevic'01]
  - theory: $\tau(B^+)/\tau(B_d) - 1 = 0.045 \pm 0.025$ (20% from pert. th.)
    experiment: $\tau(B^+)/\tau(B_d) - 1 = 0.076 \pm 0.004$
- $\tau(B_s)/\tau(B_d)$
  - cancellation from $Q_{1,2}^{cc}$ and $Q_{1,2}^{cu}$ ➪ $\tau(B_s)/\tau(B_d) \approx 1$
  - ➪ penguin effects [contribute to $\tau(B_s)$ but not $\tau(B_d)$] important
    [Keum,Nierste'98]

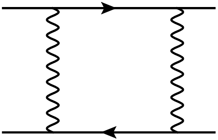


Other lifetime differences

$(B^+, B_d, B_s) \sim (\bar{b}u, \bar{b}d, \bar{b}s)$ $(\Xi_b^-, \Xi_b^0, \Lambda_b) \sim (dsb, usb, udb)$

- $\tau(B^+)/\tau(B_d)$: Weak Annihilation (WA), Pauli Interference (PI)
- $\tau(B_s)/\tau(B_d)$
  - cancellation from $Q_{1,2}^{cc}$ and $Q_{1,2}^{cu}$ ➪ $\tau(B_s)/\tau(B_d) \approx 1$
  - ➪ penguin effects [contribute to $\tau(B_s)$ but not $\tau(B_d)$] important [Keum,Nierste'98]
- $(\Xi_b^-, \Xi_b^0, \Lambda_b)$
  - experiment:
    $\tau(\Xi_b^0)/\tau(\Xi_b^-) - 1 = -0.071 \pm 0.028$
    $\tau(\Xi_b^0) \simeq \tau(\Lambda_b)$
  - perturbative input as for (B^+, B_d, B_s)
- charmed hadrons: (D^+, D^0, D_s^+)
  - experiment: precisely measured lifetimes
  - theory: NLO and $1/m_c$: adapt from B system [Lenz,Rauh'13]
  - poorly known hadronic matrix elements
  - α_s/m_c corrections important

Sensitivity to new physics



- needed: small (non-perturbative) uncertainties
- $\Delta\Gamma_s$: robust
  ΔM_s: sensitive to New Physics

$$\frac{\Delta\Gamma_s}{\Delta M_s} = (46 + 11r \pm 4.3_{\rm pert}) \cdot 10^{-4} + \delta_{1/m_b} + \ldots$$

$r = 1.09 \pm 0.16$ [Bazavov'16] ratio of hadronic matrix elements

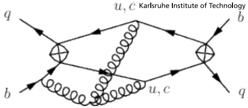
➪ distinguish New Physics in ΔM_s
from “unknown unknowns” of lattice calculations

- $a_{\rm fs}^d$ and $\Delta\Gamma_d$ “small” ➪ sensitive to NP
- (B^+, B_d, B_s), $(\Xi_b^-, \Xi_b^0, \Lambda_b)$ test HQE formalism
  and lattice and sum rules calculations on MEs

  $\tau(B_s)/\tau(B_d) \approx 1$, $\tau(\Xi_b^0)/\tau(\Lambda_b) \approx 1$

  ➪ sensitive to NP in penguin operators (C_4)

Plan



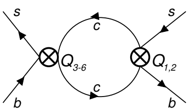
1.) Γ_{12}^{s} and Γ_{12}^{d} to NNLO for $m_c = 0$
   ➪ reduce perturbative uncertainty of leading-power contribution to $\Delta\Gamma_s$: $\sim$10% $\rightarrow$ $\sim$3%

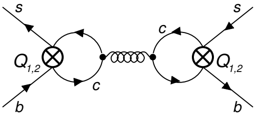
2.) Γ_{12}^{s} and Γ_{12}^{d} to $\mathcal{O}(\alpha_s/m_b)$
   ➪ reduce uncertainty in $\Delta\Gamma_q/M_q$ below 10%

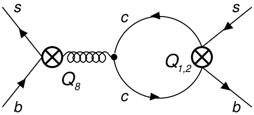
3.) $\tau(B^+)/\tau(B_d)$ and $\tau(\Xi_b^0)/\tau(\Xi_b^-)$ at $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s/m_b)$
   ➪ test formalism; HQE and lattice

4.) Charm lifetimes
   ➪ test HQE at order $1/m_Q$

5.) $\tau(B_s)/\tau(B_d)$ and $\tau(\Lambda_b)/\tau(\Xi_b^0)$
   ➪ pengiuns important



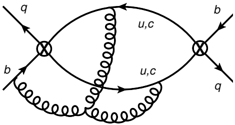




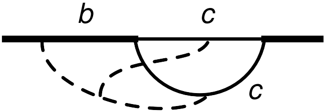
6.) Γ_{12}^{s} and Γ_{12}^{d} to NNLO, $\mathcal{O}(m_c^2/m_b^2)$
   ➪ NNLO accuracy for $a_{\rm fs}^{d}$

... + phenomenological studies ...

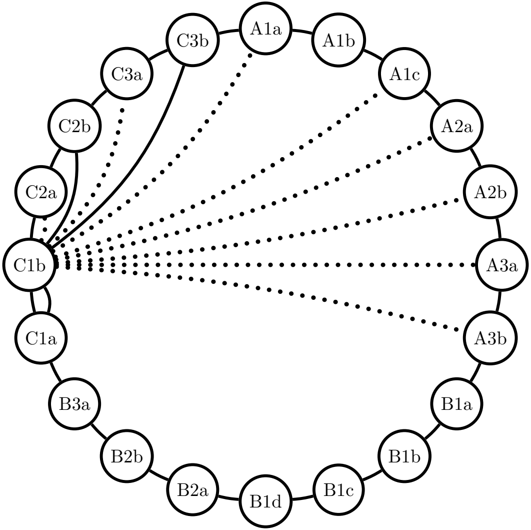
Technical issues



- 3-loop integrals, $q_{\text{light quark}} \to 0$
  ➪ 2-point function
  ➪ 2 masses: m_b and m_c
  consider $m_c^2 \ll m_b^2$
- redcution to MIs: `FIRE6` [Smirnov'19], `LiteRed` [Lee'13'14]
- "phase-space MIs"



Connection to other projects



Techniques:

A, C1a, C2b

Hadronic matrix elements:

C2a

New-physics searches:

C3b

Summary

- $\Delta\Gamma_s$, $\Delta\Gamma_d$, $a_{\rm fs}^d$; $\Delta B = 2, \Delta B = 0$
- theory uncertainties $>$ experimental errors
- NLO perturbative uncertainty $\gtrsim$ hadronic uncertainty
- NNLO and NLO $\Lambda_{\rm QCD}/m_b$
- same technique (HQE) but different sensitivity to new physics
  ➪ simultaneously test formalism and probe new physics