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Standard Model prediction of the B_c lifetime

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Outline

1. Motivation
2. Procedure
3. Setup
4. Uncertainties
5. Results
6. Novel way
7. Summary

based on: 2105.02988, 2108.10285 in collaboration with Benjamín Grinstein

Outline

LFU violation in charged currents

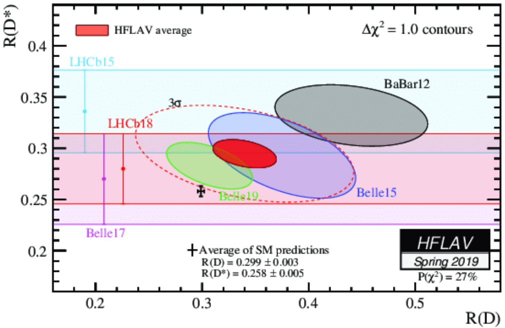
Measurement

R_D and R_{D^*}

BaBar: 1205.5442, 1303.0571, LHCb: 1506.08614, 1708.08856
Belle: 1507.03233, 1607.07923, 1612.00529

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$



HFLAV: 1909.12524

NP from τ_{B_c}

$B_c \to \tau\nu_\tau$

Not exceed τ_{B_c}

$Br(B_c \to \tau\nu_\tau)$

Pseudoscalar scenarios constrained

Alonso/Grinstein/Camalich: 1611.06676

Polarization observables

$F_L(D^*)$, τ-polarization

Blanke/Crivellin/de Boer/Kitahara/Moscati: 1811.09603
Blanke/Crivellin//Kitahara/Moscati/Nierste: 1811.09603

Status

Experimental value

$\tau_{B_c} = 0.510(9)\text{ps}$

LHCb: 1401.6932, 1411.6899
CMS:1710.08949

Theoretical predictions

Operator Product Expansion (OPE)

Beneke/Buchalla(BB): hep-ph/9601249
Bigi: hep-ph/9510325
Chang/Chen/Feng/Li: hep-ph/0007162

QCD sum rules

Kiselev/Kovalsky/Likhoded: hep-ph/0002127

Potential Models

Gershtein/Kiselev/Likhoded/Tkabladze: hep-ph/9504319

OPE result from BB

$\tau_{B_c} = 0.52\,\text{ps}, \quad 0.4\,\text{ps} < \tau_{B_c} < 0.7\,\text{ps}$

Beneke/Buchalla(BB): hep-ph/9601249

Overview of BB

Beneke/Buchalla(BB): hep-ph/9601249

OS scheme

m_b^{OS}, m_c^{OS}

Error estimate

Vary $1.4\,\text{GeV} < m_c < 1.6\,\text{GeV}$

fix m_b by B_d lifetime

Penguin contributions

Neglected

Outline

EFT approach

Effective Hamiltonian

At μ_W, RGE running

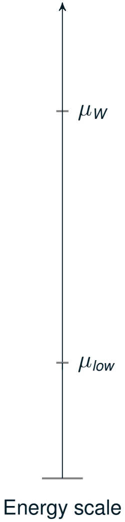
OPE

At μ_{low}

Non-Relativistic QCD (NRQCD)

Integrate out (anti-)quark fields

EFT approach



$$\mathcal{L}_{SM}$$

↓ Matching

$$\mathcal{H}_{\text{eff}} = -\sum_i C_i O_i$$

↓ RGE

OPE ⟶ NRQCD

Optical Theorem

Forward scattering

$\Gamma_{B_c} = \frac{1}{2M_{B_c}} \langle B_c | \mathcal{T} | B_c \rangle$

Transition Operator

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

OPE

$\mathcal{T} =$ series of local operators

OPE

Transition operator

$$\mathcal{T}_Q = C_Q^{(3)}\bar{Q}Q + C_Q^{(5)}\frac{1}{m_Q^2}g_s\bar{Q}\sigma_{\mu\nu}Q\,G^{\mu\nu} + \sum_i C_{Q,i}^{(6)}\frac{1}{m_Q^3}O_i^{(6)} + \mathcal{O}(\frac{1}{m_Q^4})$$

Wilson coefficients

Spectator decays, WA, PI

Contributions

$$\mathcal{T} = \mathcal{T}_{\bar{b}} + \mathcal{T}_c + \mathcal{T}_{\mathrm{WA}} + \mathcal{T}_{\mathrm{PI}}$$

Contributions

$\bar{b}$-decays

$\bar{b} \to \bar{c}u(\bar{s}+\bar{d}), \bar{c}c(\bar{s}+\bar{d}), \bar{c}\ell\nu$

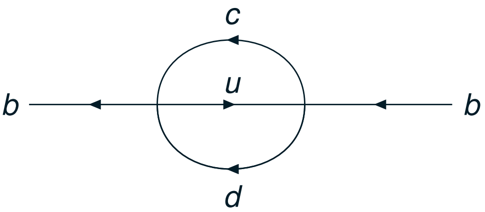
c-decays

$c \to (s+d)u(\bar{s}+\bar{d}), (s+d)\ell\nu$

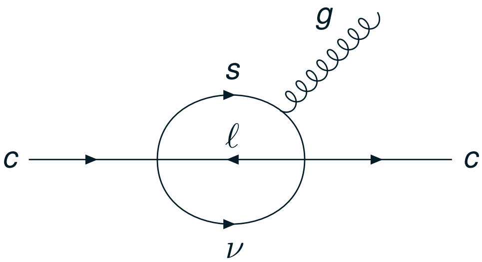
Weak Annihilation (WA), Pauli Interference (PI)

1-loop graphs

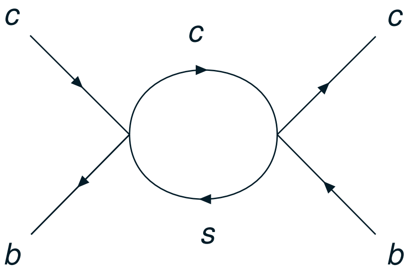
$\bar{b}$-decay



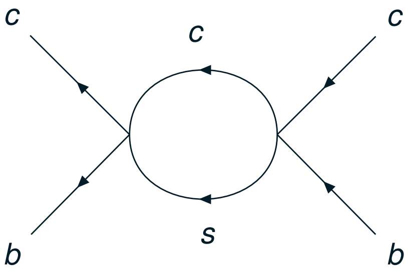
c-decay



WA



PI



Outline

Improvements over BB

Mass schemes

$\overline{\text{MS}}$, meson, Upsilon

Spin symmetry

Relates matrix elements

Typos in literature

Bagan/Ball/Fiol/Gosdzinsky: hep-ph/9502338

Corrected by KLR

Krinner/Lenz/Rauh: 1305.5390

Penguin contributions

Included

Better input values

α_s, f_{B_c}, CKM parameters

Mass schemes

$\overline{\text{MS}}$ scheme

m_b^{OS} and m_c^{OS} in terms of $\overline{m}_b(\mu_b)$ and $\overline{m}_c(\mu_c)$

Meson scheme

m_b^{OS} in terms of m_Υ
m_c^{OS} in terms of m_b^{OS} and $\overline{m}_B - \overline{m}_D$

Upsilon scheme

Like meson scheme
For c decays: m_c^{OS} in terms of Upsilon expansion of $m_{J/\psi}$

Outline

Uncertainties

Non-Perturbative (n.p.)

velocity expansion

scale uncertainty

μ dependence

Parametric

V_{cb} etc

Strange quark mass

$m_s \neq 0$

Outline

Results

Massles strange quark

$$\Gamma_{B_c}^{\overline{\text{MS}}} = \left(1.58 \pm 0.40\right|^{\mu} \pm 0.08\left|^{\text{n.p.}} \pm 0.02\right|^{\overline{m}} \pm 0.01\left|^{V_{cb}}\right) \text{ ps}^{-1}$$
$$\Gamma_{B_c}^{\text{meson}} = \left(1.77 \pm 0.25\right|^{\mu} \pm 0.20\left|^{\text{n.p.}} \pm 0.01\right|^{V_{cb}}\left.\right) \text{ ps}^{-1}$$
$$\Gamma_{B_c}^{\text{Upsilon}} = \left(2.51 \pm 0.19\right|^{\mu} \pm 0.21\left|^{\text{n.p.}} \pm 0.01\right|^{V_{cb}}\left.\right) \text{ ps}^{-1}$$

Massive strange quark

$$\Gamma_{B_c}^{\overline{\text{MS}}} = \left(1.51 \pm 0.38\right|^{\mu} \pm 0.08\left|^{\text{n.p.}} \pm 0.02\right|^{\overline{m}} \pm 0.01\left|^{m_s} \pm 0.01\right|^{V_{cb}}\left.\right) \text{ ps}^{-1}$$
$$\Gamma_{B_c}^{\text{meson}} = \left(1.70 \pm 0.24\right|^{\mu} \pm 0.20\left|^{\text{n.p.}} \pm 0.01\right|^{m_s} \pm 0.01\left|^{V_{cb}}\right) \text{ ps}^{-1}$$
$$\Gamma_{B_c}^{\text{Upsilon}} = \left(2.40 \pm 0.19\right|^{\mu} \pm 0.21\left|^{\text{n.p.}} \pm 0.01\right|^{m_s} \pm 0.01\left|^{V_{cb}}\right) \text{ ps}^{-1}$$

$(\Gamma_{B_c}^{exp} = 1.961 \pm 35 \text{ ps}^{-1})$

Possible Improvements

Higher order in α_s

To reduce μ-dependence

Higher order in v

To reduce n.p. uncertainty

Matrix elements

Lattice calculation

Outline

Novel way to determine Γ_{B_c}

JA/Grinstein: 2108.10285

General width for meson H_Q

$$\Gamma(H_Q) = \Gamma_Q^{(0)} + \Gamma^{n.p.}(H_Q) + \Gamma^{\mathrm{WA+PI}}(H_Q) + \mathcal{O}(\tfrac{1}{m_Q^4})$$

Taking difference between B, D, B_c

$$\Gamma(B) + \Gamma(D) - \Gamma(B_c) = \Gamma^{n.p.}(B) + \Gamma^{n.p.}(D) - \Gamma^{n.p.}(B_c)$$
$$+ \Gamma^{\mathrm{WA+PI}}(B) + \Gamma^{\mathrm{WA+PI}}(D) - \Gamma^{\mathrm{WA+PI}}(B_c)$$

Advantage

quark decay uncertainties drop out

Results

$\left(\boldsymbol{B^0}, \boldsymbol{D^0}\right)$ **and** $\left(\boldsymbol{B^+}, \boldsymbol{D^0}\right)$

$\Gamma_{B_c} = 3.03 \pm 0.51\ \text{ps}^{-1}$

$\left(\boldsymbol{B^0}, \boldsymbol{D^+}\right)$ **and** $\left(\boldsymbol{B^+}, \boldsymbol{D^+}\right)$

$\Gamma_{B_c} = 3.33 \pm 1.29\ \text{ps}^{-1}$

Discrepancy with experiment

$\Gamma_{B_c}^{exp} = 1.961 \pm 35\ \text{ps}^{-1}$

Possible explanations

Underestimated uncertainties

NNLO, $1/m^4$, parametric etc.

Eye graph

Not included in lattice calculation

Quark hadron duality

violated

Outline

Summary

OPE

Agreement with experiment: large scheme dependence

Improvements

NNLO, $1/m^4$, lattice results

Novel way

Discrepancy: underestimation, eye-graph, duality violation?

Upsilon scheme

Hoang/Ligeti/Monahar: hep-ph/9809423

$\bar{b}$ decays, WA, PI

$$\frac{1}{2}m_\Upsilon = m_b^{OS}\left[1 - \frac{(\alpha_s C_F)^2}{8}\left\{1 + \frac{\alpha_s}{\pi}\left[\left(\ln\left(\frac{\mu}{\alpha_s C_F m_b^{OS}}\right) + \frac{11}{6}\right)\beta_0 - 4\right] + \cdots\right\}\right]$$

$$m_b^{OS} - m_c^{OS} = \overline{m}_B - \overline{m}_D + \frac{1}{2}\lambda_1\left(\frac{1}{m_b^{OS}} - \frac{1}{m_c^{OS}}\right) \qquad \overline{m}_B, \overline{m}_D = \text{(iso)spin-averaged masses}$$

c decays

$$\frac{1}{2}m_{J/\psi} = m_c^{OS}\left[1 - \frac{(\alpha_s C_F)^2}{8}\left\{1 + \frac{\alpha_s}{\pi}\left[\left(\ln\left(\frac{\mu}{\alpha_s C_F m_c^{OS}}\right) + \frac{11}{6}\right)\beta_0 - 4\right] + \cdots\right\}\right]$$

strange mass

$m_s = 0$ or $\overline{\text{MS}}$