The Λ_b lifetime

Alexander Lenz, Siegen University, 5th November 2020 @ b-baryon Fest

Outline

1) Lambda_b
2) Classic expectations for the lifetimes of heavy hadrons
3) Basics of HQE
4) Ancient experiments
5) Quark Hadron duality
5) Old experiments
6) Status Quo in experiments
7) Status of Theory - how to improve

$$\Lambda_b = udb$$

$\boxed{\Lambda_b^0}$ $I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

In the quark model, a Λ_b^0 is an isospin-0 $u\,d\,b$ state. The lowest Λ_b^0 ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Λ_b^0 MASS

$m_{\Lambda_b^0}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5619.60± 0.17 OUR AVERAGE				

Γ_{38}	$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything	[b]	(10.9 ± 2.2) %
Γ_{39}	$\Lambda_c^+ \ell^- \overline{\nu}_\ell$		$(6.2\ ^{+1.4}_{-1.3})$ %
Γ_{40}	$\Lambda_c^+ \pi^+ \pi^- \ell^- \overline{\nu}_\ell$		(5.6 ± 3.1) %
Γ_{41}	$\Lambda_c(2595)^+ \ell^- \overline{\nu}_\ell$		$(7.9\ ^{+4.0}_{-3.5}) \times 10^{-3}$
Γ_{42}	$\Lambda_c(2625)^+ \ell^- \overline{\nu}_\ell$		$(1.3\ ^{+0.6}_{-0.5})$ %

Classical expectations

1986 Heavy Quark Expansion

$$\left.\frac{\tau(B_s)}{\tau(B_d)}\right|^{\mathrm{HQE}\ 1986} \approx 1\,, \qquad \left.\frac{\tau(B^+)}{\tau(B_d)}\right|^{\mathrm{HQE}\ 1986} \approx 1.1\,, \qquad \left.\frac{\tau(\Lambda_b)}{\tau(B_d)}\right|^{\mathrm{HQE}\ 1986} \approx 1\,,$$

Hierarchy of Lifetimes of Charmed and Beautiful Hadrons
Mikhail A. Shifman, M.B. Voloshin (Moscow, ITEP). 1986. 30 pp.
Published in **Sov.Phys.JETP 64 (1986) 698, Zh.Eksp.Teor.Fiz. 91 (1986) 1180-1193**
ITEP-86-83
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 281 records 250+

HFLAV 2020

b-hadron species	average lifetime	lifetime ratio
B^0	1.519 ± 0.004 ps	
B^+	1.638 ± 0.004 ps	$B^+/B^0 = 1.076 \pm 0.004$
B_s^0	1.515 ± 0.004 ps	$B_s^0/B^0 = 0.998 \pm 0.004$

Basics of the HQE

Heavy Quark Expansion I:

The standard expression for the decay rate is

$$\Gamma(B \to X) = \frac{1}{2m_B} \sum_X (2\pi)^4 \delta^{(4)}(p_B - p_X) |\langle X|\mathcal{H}_{eff}|B\rangle|^2$$

The optical theorem gives

$$\Gamma(B \to X) = \frac{1}{2m_B} \langle B|\mathcal{T}|B\rangle$$

with the transition operator

$$\mathcal{T} = \text{Im}\, i \int d^4x T \left[\mathcal{H}_{eff}(x), \mathcal{H}_{eff}(0)\right]$$

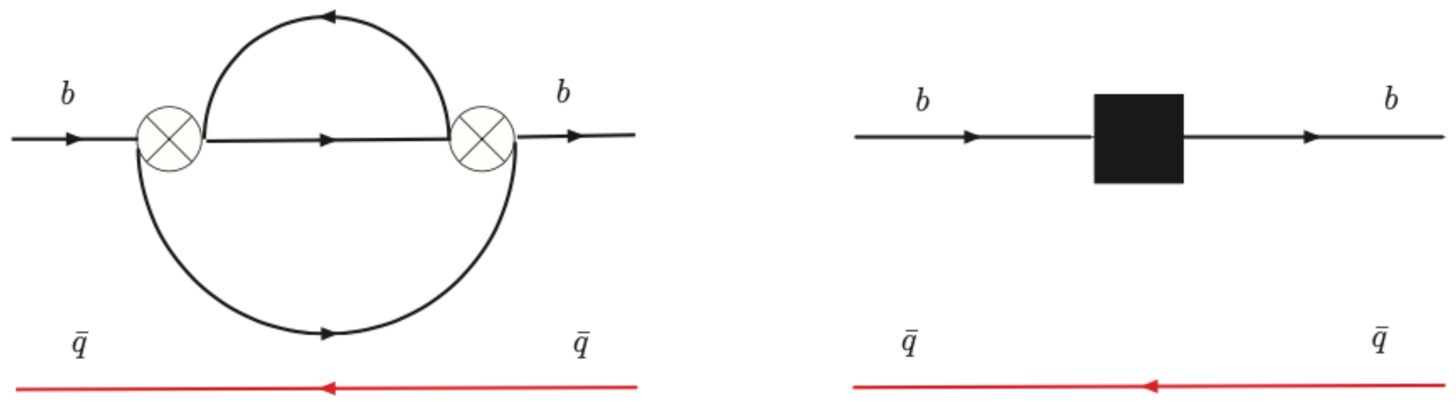
An operator-product-expansion for $\mathcal{T}$ yields

$$\mathcal{T} = c_3 \bar{b}b + \frac{c_5}{m_b^2} \bar{b} g_s \sigma_{\mu\nu} G^{\mu\nu} b + \frac{\tilde{c}_6}{m_b^3} (\bar{b}q)_\Gamma (\bar{q}b)_\Gamma + \ldots$$

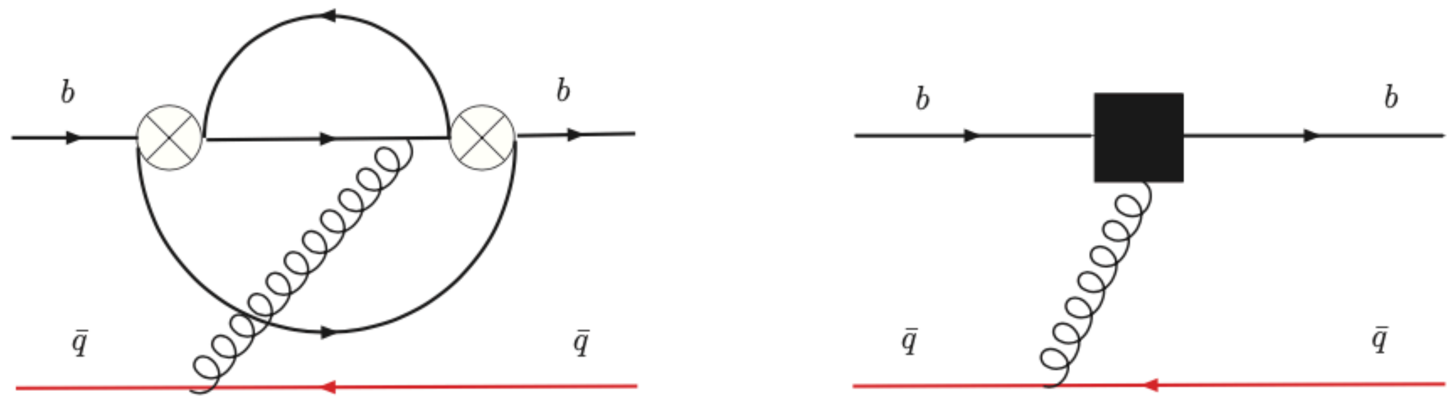
Voloshin, Uraltsev, Khoze, Shifman

Heavy Quark Expansion II:

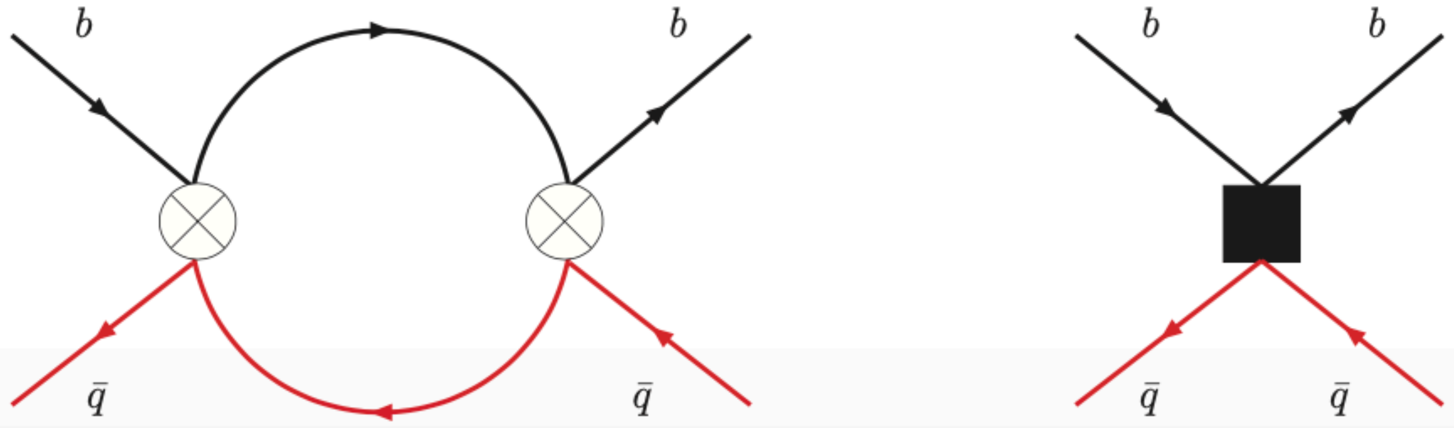
- $\bar{b}b$: Free quark decay (2-loop)



- $\bar{b} g_s \sigma_{\mu\nu} G^{\mu\nu} b$: Chromomagnetic operator (2-loop)



- $(\bar{b}q)_\Gamma (\bar{q}b)_\Gamma$:Spectator effects - weak annihilation (1-loop) $\rightarrow 16\pi^2$



Basics of the HQE

Heavy Quark Expansion III:

The decay rate reads now

$$\Gamma = \Gamma_0 \left[c_3 \langle \bar{b} b \rangle_B + \frac{c_5}{m_b^2} \langle \bar{b} \frac{g_s}{2} \sigma_{\mu\nu} G^{\mu\nu} b \rangle_B + \frac{c_6}{m_b^3} \langle (\bar{b} q)_\Gamma (\bar{q} b)_\Gamma \rangle_B + \mathcal{O}\left(\frac{1}{m_b^4}\right) \right]$$

with

- $\Gamma_0 = (G_F^2 m_b^5)/(192\pi^3)$
- Wilsoncoefficients c_i; calculable in perturbation theory:
  - Renormalization scale dependence $c_i = c_i(\mu)$
  - Renormalization scheme dependence (arises in NLO!)
- Matrix elements of local operators $\langle Q \rangle_B = \langle Q \rangle_B(\mu)$ Determination via non-perturbative methods

!!!
Unphysical μ- and renormalization scheme dependence
has to cancel
between Wilsoncoefficients and matrix elements

Heavy Quark Expansion IV:

Determination of the matrix elements

- $\mathcal{O}(1)$: Non-relativistic expansion

$$\langle \bar{b} b \rangle_B = 1 - \frac{\mu_\pi^2 - \mu_G^2}{2 m_b^2} + \mathcal{O}(m_b^{-3})$$

- $\mathcal{O}(m_b^{-2})$: Experiment (*Chromomagnetic operator*)

$$\langle \bar{b} \frac{g_s}{2} \sigma_{\mu\nu} G^{\mu\nu} b \rangle_B =: \mu_G^2 + \mathcal{O}\left(m_b^{-1}\right) \approx 0.36 \text{ GeV}^2$$

Sum rules - momentum analysis: (*Kinetic operator*)

$$\langle \bar{b} (i\vec{D})^2 b \rangle_B =: \mu_\pi^2 + \mathcal{O}\left(m_b^{-1}\right) \approx 0.450.10 \text{ GeV}^2$$

Ball, Braun; Neubert

- $\mathcal{O}(m_b^{-3})$: lattice, sum rules (*Four quark operator*)

$$\langle (\bar{b} q)_\Gamma (\bar{q} b)_\Gamma \rangle_B =: f_B^2 m_B \sum_\Gamma c_\Gamma B_\Gamma$$

f_B: decay constant, B: Bag-Parameter

UKQCD;JLQCD; Becirevic et al.; Jamin, Lange; Kronfeld

Basics of the HQE

$\tau(\Lambda_b)/\tau(B_d)$ at order $1/m_b^2$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1 + \frac{\Lambda^2}{m_b^2}\left(\Gamma_2^{(0)} + \dots\right) + \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \dots\right) + \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \dots\right) + \frac{\Lambda^5}{m_b^5}\left(\Gamma_5^{(0)} + \dots\right) + \dots$$

Leading Term

$$\begin{aligned}
\frac{\Lambda^2}{m_b^2}\Gamma_2 &= \frac{\mu_\pi^2(\Lambda_b) - \mu_\pi^2(B_d)}{2m_b^2} + c_5\frac{\mu_G^2(\Lambda_b) - \mu_G^2(B_d)}{m_b^2} \\
&= \frac{(0.1 \pm 0.1)\mathrm{GeV}^2}{2m_b^2} + 1.2\frac{0 - 0.33\mathrm{GeV}^2}{2m_b^2} \\
&\approx 0.002 - 0.017 = -0.015
\end{aligned}$$

$\tau(\Lambda_b)/\tau(B_d)$ at order $1/m_b^3$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1 - 0.015 + \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \dots\right) + \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \dots\right) + \frac{\Lambda^5}{m_b^5}\left(\Gamma_5^{(0)} + \dots\right) + \dots$$

Γ_3 is a linear combination of perturbative Wilson coefficients and non-perturbative matrix elements

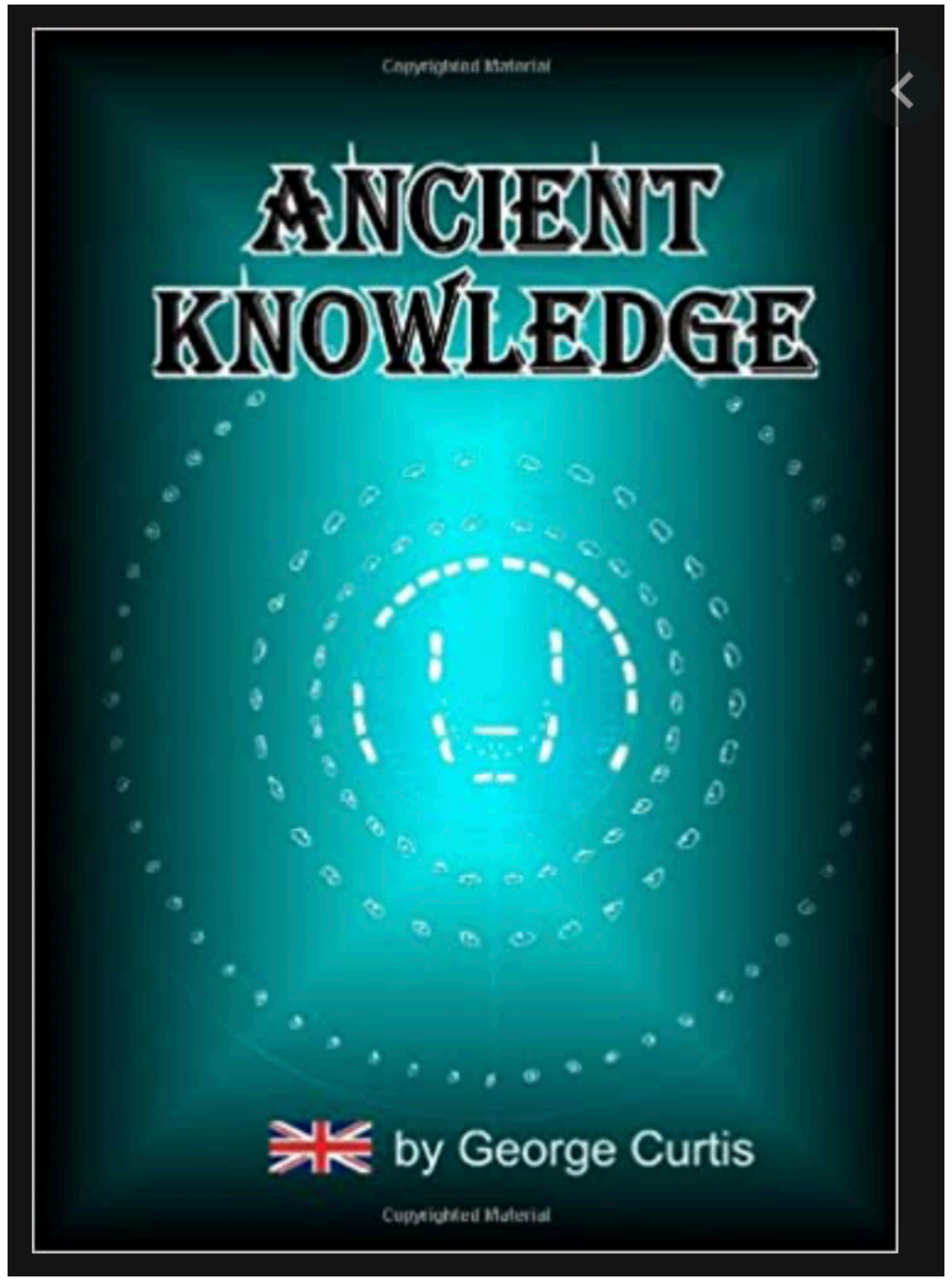
- Wilson coefficient of $\Gamma_3^{(0)}$ with full m_c dependence:
  1996 Neubert and Sachrajda Uraltsev
- Matrixelement
  HQET: only two different matrix elements (instead of four)

$$\frac{1}{2m_{\Lambda_b}}\langle\Lambda_b|\bar{b}_L\gamma_\mu q_L \cdot \bar{q}_L\gamma^\mu b_L|\Lambda_b\rangle =: -\frac{f_B^2 m_B}{48}r$$

$r \approx 0.2$ *Bag model* Guberina, Nussino, Peccei, Rückl, 1979

$r \approx 0.5$ *NR quark model* –"–

Experimental numbers for $\tau(\Lambda_b)$



2003	HFAG	average	1.212 ± 0.052	0.798 ± 0.034
1998	OPAL	$\Lambda_c l$	1.29 ± 0.25	$0.85 \pm 0.16*$
1998	ALEPH	$\Lambda_c l$	1.21 ± 0.11	$0.80 \pm 0.07*$
1995	ALEPH	$\Lambda_c l$	1.02 ± 0.24	$0.67 \pm 0.16*$
1992	ALEPH	$\Lambda_c l$	1.12 ± 0.37	$0.74 \pm 0.24*$

vs. a theoretical expectation of about 1

Quark Hadron Duality

Many theory paper appeared

Some claiming HQE fails

FAILURE OF LOCAL DUALITY IN INCLUSIVE NON-LEPTONIC HEAVY FLAVOUR DECAYS

G. Altarelli

Theoretical Physics Division, CERN, CH-1211 Geneva 23 and
Dipartimento di Fisica, Terza Università di Roma, Roma

G. Martinelli, S. Petrarca and F. Rapuano

Dip. di Fisica dell'Università *La Sapienza* and
INFN, Sez. di Roma I
P.le A. Moro 2, 00185 Roma, Italy

arXiv:hep-ph/9604202v3 5 Apr 1996

ABSTRACT

We argue that there is strong experimental evidence in the data of b- and c-decays that the pattern of power suppressed corrections predicted by the short distance expansion, the heavy quark effective theory and the assumption of local duality is not correct for the non-leptonic inclusive widths. The data indicate instead the presence of $1/m$ corrections that should be absent in the above theoretical framework. These corrections can be simply described by replacing the heavy quark mass by the mass of the decaying hadron in the m^5 factor in front of all the non-leptonic widths.

Nature (or experimentalists) might be nasty

Experiment in 1996 shows

$$\Gamma^{\rm NL} = \frac{G_F^2 m_{\rm Meson}^5}{192\pi^3} \quad \text{vs.} \quad \Gamma^{\rm NL} = \frac{G_F^2 m_{\rm b}^5}{192\pi^3}$$

Works | **Works Not**

Quark Hadron Duality

arXiv.org > hep-ph > arXiv:hep-ph/0304202v1

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High Energy Physics – Phenomenology

Explicit Quark-Hadron Duality Violations in B-Meson Decays

Benjamin Grinstein, Michael Savrov

(Submitted on 22 Apr 2003 (this version), **latest version 29 Apr 2003** *(v2))*

We consider the weak decay of heavy mesons in QCD. We compute the inclusive hadronic decay rate in leading order in the large N_c expansion, with masses chosen to insure the final state mesons recoil slowly (the SV limit). We find, by explicit computation, violations to quark-hadron duality at order 1/M in the heavy mass expansion. The violation to duality is linear in the slope of the form factor for the associated semileptonic decay. Differences in slopes of form factors may help understand the puzzle of lifetimes of b-hadrons.

Comments:	17 pages, no figures, latex/revtex4
Subjects:	**High Energy Physics – Phenomenology (hep-ph)**
Report number:	UCSD/PTH 03-05
Cite as:	**arXiv:hep-ph/0304202**
	(or **arXiv:hep-ph/0304202v1** for this version)

Bibliographic data

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Submission history

From: Benjamin Grinstein [view email]
[v1] Tue, 22 Apr 2003 05:10:07 UTC (16 KB)
[v2] Tue, 29 Apr 2003 21:34:58 UTC (0 KB)

Inventive Theorists

Matrix elements for the Λ_b baryon I

Values for r:

$r \approx 0.2$	*Bag model* Guberina, Nussino, Peccei, Rückl, 1979
$r \approx 0.5$	*NR quark model* –"–
$r = 0.9 \pm 0.1$	*spectroscopy* Rosner, 1996
$r = 1.8 \pm 0.5$	*spectroscopy* –"–
$r = 0.2 \pm 0.1$	*QCD sum rules* Colangelo, de Fazio, 1996

Neubert, Sachrajda: $\frac{\tau(\Lambda_b)}{\tau(B_d^0)}$ " > 0.9"

$r = 1.2 \pm 0.2 \pm ?$	*lattice* di Pierro, Sachrajda, Michael 1999
$r = 2.3 \pm 0.6$	*QCD sum rules* Huang, Liu, Zhu, 2000
$r = 6.2 \pm 1.6$	*QCD sum rules* –"–

$$!!! \quad \frac{\tau(\Lambda_b)}{\tau(B_d^0)} - 1 \propto r \quad !!!$$

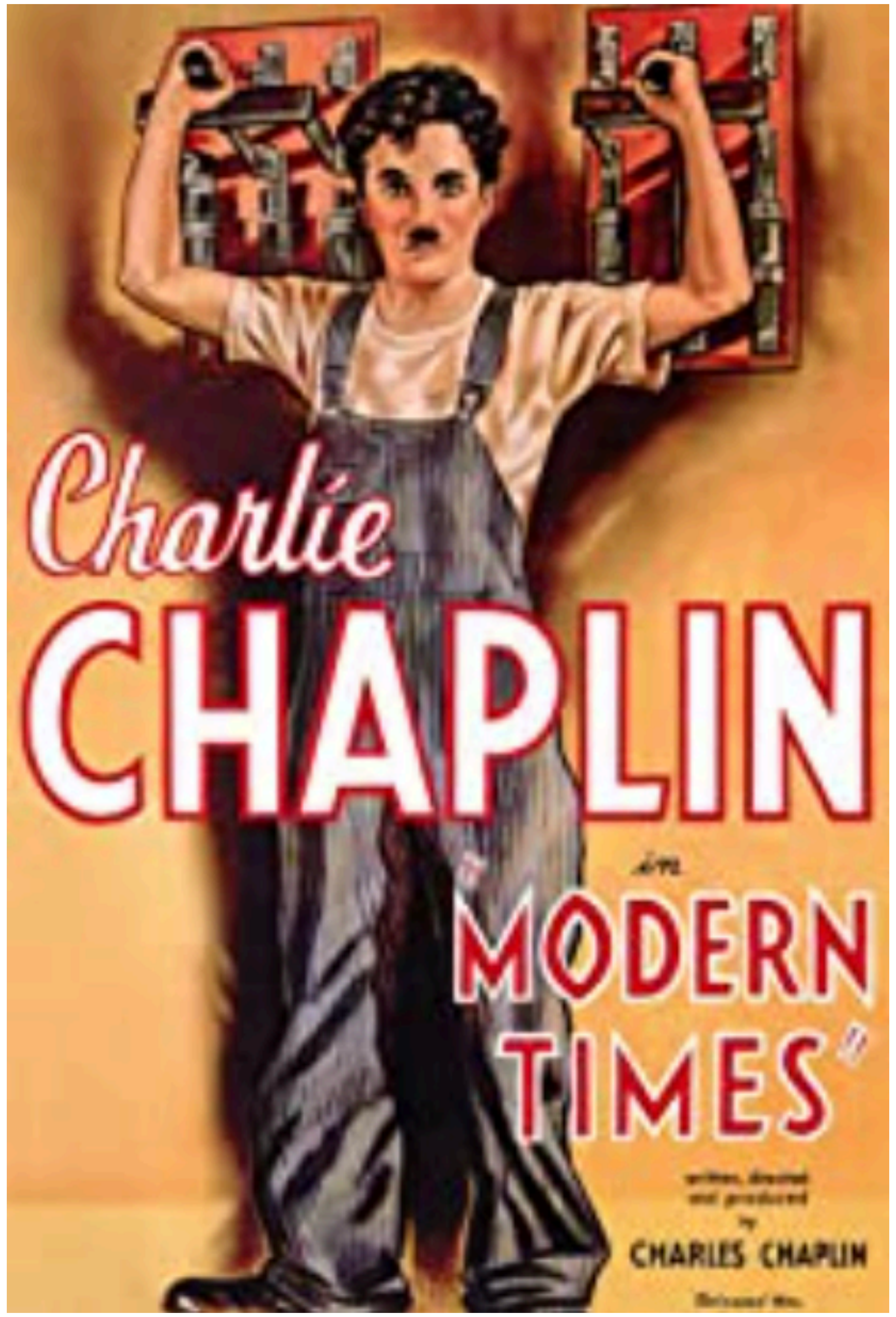
Matrix elements for the Λ_b baryon III

1999 DiPierro, Sachrajda, Michael:
currently the only lattice determination

- 12 years old
- The authors call their study *exploratory*
  - Larger lattice should be used
  - Larger sample of gluon configurations should be used
  - Matching to continuum only at leading order
  - No chiral extrapolation attempted
  - Penguin contractions are missing - see below

1999 Huang, Liu, Zhu:
QCD sum rule result, which is up to a factor of 31 larger than the one by Colangelo and DeFazio

Experimental numbers for $\tau(\Lambda_b)$



Year	Exp	Decay	$\tau(\Lambda_b)$ [ps]	$\tau(\Lambda_b)/\tau(B_d)$
2011	HFAG	average	1.425 ± 0.032	0.938 ± 0.022
2010	CDF	$J/\psi\Lambda$	1.537 ± 0.047	1.020 ± 0.031
2009	CDF	$\Lambda_c + \pi^-$	1.401 ± 0.058	0.922 ± 0.038
2007	D0	$\Lambda_c \mu\nu X$	1.290 ± 0.150	$0.849 \pm 0.099*$
2007	D0	$J/\psi\Lambda$	1.218 ± 0.137	$0.802 \pm 0.090*$
2006	CDF	$J/\psi\Lambda$	1.593 ± 0.089	1.049 ± 0.059
2004	D0	$J/\psi\Lambda$	1.22 ± 0.22	0.87 ± 0.17
2003	HFAG	average	1.212 ± 0.052	0.798 ± 0.034
1998	OPAL	$\Lambda_c l$	1.29 ± 0.25	$0.85 \pm 0.16*$
1998	ALEPH	$\Lambda_c l$	1.21 ± 0.11	$0.80 \pm 0.07*$
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1992	ALEPH	$\Lambda_c l$	1.12 ± 0.37	$0.74 \pm 0.24*$

Experimental Status Quo

HFLAV 2020

$$\tau(\Lambda_b) = (1.471 \pm 0.009)\text{ps}$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.969 \pm 0.006$$

2003	HFAG	average	1.212 ± 0.052	0.798 ± 0.034

Lesson 1:
Experimental numbers can change by 5 sigma....

```
In[1]:= (1.471 - 1.212) / 0.052
Out[1]= 4.98077
```

Theoretical Status Quo

arXiv.org > hep-ph > arXiv:hep-ph/0304202

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High Energy Physics – Phenomenology

Explicit Quark-Hadron Duality Violations in B-Meson Decays

Benjamin Grinstein, Michael Savrov

(Submitted on 22 Apr 2003 (v1), last revised 29 Apr 2003 (this version, v2))

Duality is not violated at order Delta/M once j=3/2 and j=1/2+ states are properly accounted for.

Comments:	Paper withdrawn by authors, due to crucial omission of higher resonances
Subjects:	**High Energy Physics – Phenomenology (hep-ph)**
Report number:	UCSD/PTH 03-05
Cite as:	arXiv:hep-ph/0304202
	(or arXiv:hep-ph/0304202v2 for this version)

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Submission history

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[v1] Tue, 22 Apr 2003 05:10:07 UTC (16 KB)
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Lesson 2: Theorists can be wrong....

Theoretical Status Quo

- Comparison of experiment and theory for B-meson lifetimes and Delta Gamma_s show no sign of a deviation from the HQE predictions

- Theoretical studies of duality violations, e.g. in the t'Hooft model show no sign of any sizeable duality violation

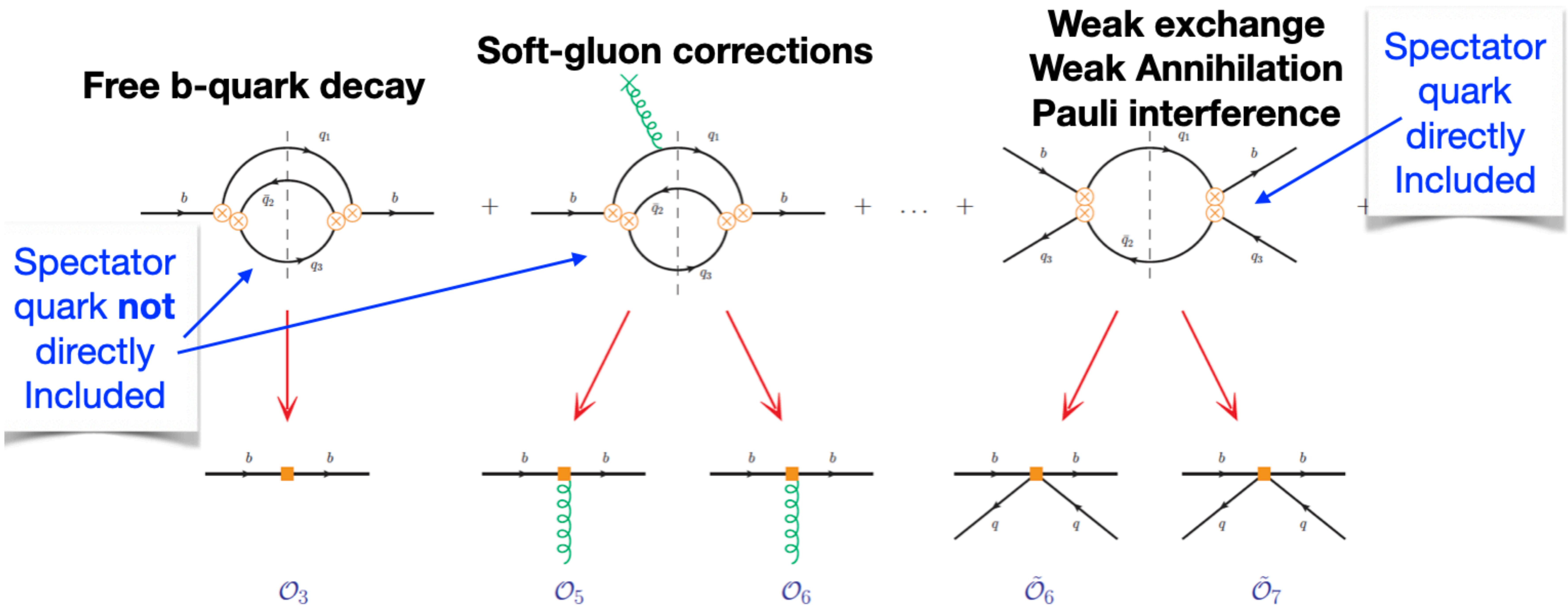
How precise can we predict the Lambda_b lifetime?

Theoretical Status Quo

Shifman, Voloshin, Khoze; Bigi, Uraltsev, Vainshtein; (1983 -'92)

The total decay rate can be expanded as

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



Spectator quark indirectly included in different values of matrix elements for different hadrons

Theoretical Status Quo

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

$$\Gamma_j = \Gamma_j^{(0)} + \frac{\alpha_s(\mu)}{4\pi}\Gamma_j^{(1)} + \frac{\alpha_s^2(\mu)}{(4\pi)^2}\Gamma_j^{(2)} + \ldots .$$

Non-leptonic:

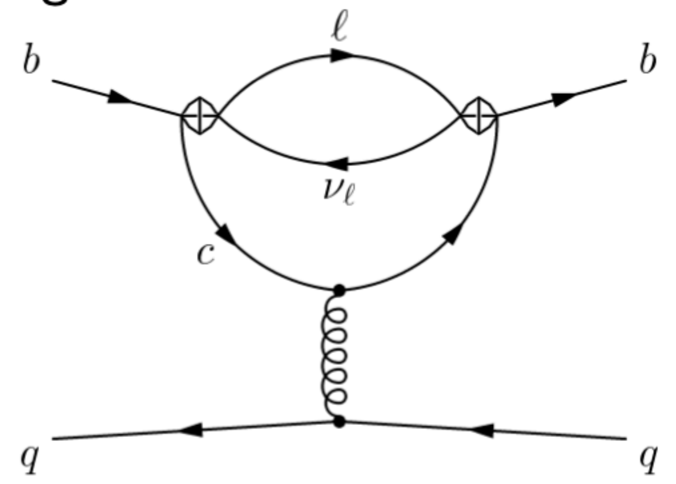
- $\Gamma_3^{(1)}$ • Ho-Kim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Gosdzinsky, Fiol, AL, Nierste, Ostermaier, Krinner, Rauh; 1984 - 2013
- $\Gamma_3^{(2)}$ • Czarnecki, Slusarcyk, Tkachov 2005 (m_c=0, not all color structures)
- $\Gamma_5^{(0)}$ • Bigi, Uraltsev, Vainshtein, Blok, Shifman 1992
- $\Gamma_6^{(0)}$ • AL, Piscopo, Rusov, Mannel, Moreno, Pivovarov 2020
- $\tilde{\Gamma}_6^{(1)}$ • Beneke, Buchalla, Greub, AL, Nieste, Franco, Lubicz, Mescia, Tarantino, Rauh 2002-13
- $\tilde{\Gamma}_7^{(0)}$ • *AL, Nierste*, Gabbiani, Onishchenko, Petrov 2003-04

New& Large!

Penguin effects I

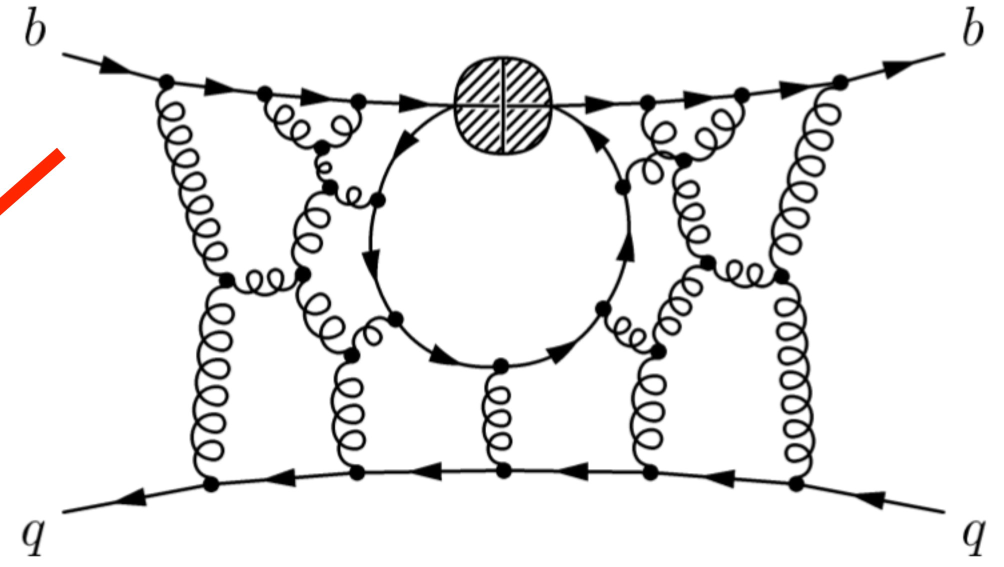
Besides the calculated diagrams, **penguin effects** contribute to the lifetime of b-hadrons.

1. Perturbative Penguins:



MISSING

2. Non-perturbative analogue: **Eye contractions**



MISSING

Still no first principle determination of matrix elements of 4 quark operators
Update of Rosner's spectroscopy method

Theoretical Status Quo

- **Neglecting the Darwin term**
- **Neglecting the NLO Penguins**
- **Using spectroscopy for the matrix elements**

$$\left.\frac{\tau(\Lambda_b)}{\tau(B_d)}\right|^{\text{HQE 2019}} = 0.935 \pm 0.054$$

1996 Rosner

$$r = \frac{4}{3}\frac{m^2_{\Sigma_b^*} - m^2_{\Sigma_b}}{m^2_{B^*} - m^2_B}$$

In 1996 b-baryon masses were hardly known

- $m^2_{\Sigma_b^*} - m^2_{\Sigma_b} \approx m^2_{\Sigma_c^*} - m^2_{\Sigma_c} = (0.384 \pm 0.035)\mathrm{GeV}^2$

$$\Rightarrow r = 0.9 \pm 0.10$$

- $m_{\Sigma_b^*} - m_{\Sigma_b} = (56 \pm 16)$ MeV

$$\Rightarrow r = 1.8 \pm 0.5$$

- Use the values from PDG 2011

$$\boxed{\Rightarrow r = 0.68 \pm 0.10}$$

Outlook

- **HQE is in good shape**
- **Large uncertainties in the HQE prediction for baryons**

$$\left.\frac{\tau(\Lambda_b)}{\tau(B_d)}\right|^{\text{HQE 2019}} = 0.935 \pm 0.054$$

- **First principle determination of the D=6 matrix elements**
- **Include the Darwin term**
- **Determine the NLO Penguins**