Lifetimes of heavy hadrons

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In collaboration with
F. Gabbiani and A. Onishchenko
Introduction: why do we care?

1. Nice test of our understanding of non-perturbative effects in QCD
2. One of the few unambiguous theoretical predictions that are easy to test experimentally
3. Theoretical uncertainty can be estimated: precision studies

\[ \Gamma(H_b) = \frac{G_F^2 m_Q^5}{192\pi^3} \left[ A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \ldots \right] \]

How good are the theoretical predictions?
Not surprisingly, heavy hadron lifetimes were thoroughly measured...

### Comparisons

<table>
<thead>
<tr>
<th>b hadron species</th>
<th>average lifetime, $\tau(H_b)$, ps</th>
<th>$\tau(H_b)/\tau(B^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>$1.534 \pm 0.013$</td>
<td>1</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$1.653 \pm 0.014$</td>
<td>$1.081 \pm 0.015$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$1.469 \pm 0.059$</td>
<td>$0.958 \pm 0.039$</td>
</tr>
<tr>
<td>$B_c$</td>
<td>$0.46 \pm 0.18 - 0.16$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$1.232 \pm 0.072$</td>
<td>$0.803 \pm 0.047$</td>
</tr>
<tr>
<td>$\Xi_b^-,\Xi_b^0$ mixture</td>
<td>$1.39 \pm 0.34 - 0.28$</td>
<td></td>
</tr>
<tr>
<td>b-baryon mixture</td>
<td>$1.208 \pm 0.051$</td>
<td>$0.786 \pm 0.034$</td>
</tr>
<tr>
<td>b-hadron mixture</td>
<td>$1.564 \pm 0.014$</td>
<td></td>
</tr>
</tbody>
</table>

PDG 2004/HFAG 2004
Theoretical framework

(a) Consider inclusive decay of a heavy hadron

\[ \Gamma_{\text{hadron}}(H_b) = \left| \sum_{\text{final states}} A(H_b \rightarrow h_i) \right|^2 d\Phi_i \]

(b) Use optical theorem to relate width to forward matrix element

M. Shifman, M. Voloshin,

\[ \Gamma_{\text{quark}}(H_b) = \frac{1}{2M_b} \langle H_b | T | H_b \rangle = \frac{1}{2M_b} \langle H_b | \text{Im} i \int d^4x T \{ H_{\text{eff}}^{\Delta B=1}(x) H_{\text{eff}}^{\Delta B=1}(0) \} | H_b \rangle \]

\[ H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum [ c_1 Q_1^{u'd'} + c_2 Q_2^{u'd'} ] + \text{H.c.}, \]

\[ Q_1^{u'd'} = \bar{d}_L \gamma_\mu u_L^I c_L \gamma_\mu b_L, \quad Q_2^{u'd'} = \bar{c}_L \gamma_\mu u_L^I \bar{d}_L \gamma_\mu b_L. \]
Theoretical framework

What is the relation of $\Gamma_{\text{quark}}$ to $\Gamma_{\text{hadron}}$?

$\Gamma_{\text{hadron}}(H_b) = \sum_{\text{final states}} A(H_b \rightarrow h_i) \left| d\Phi_i \right|^2$

$\Gamma_{\text{quark}}(H_b) = \Gamma_{\text{hadron}}(H_b)$

Quark-hadron duality (local)

$\Gamma_{\text{quark}}(H_b) = \frac{1}{2M_b} \langle H_b | T | H_b \rangle$

Notes aside:

1. Compute $T$ in Euclidean space and analytically continue to Minkowski space [exact calculation in ES = exact result in MS]
2. Expand $T$ in $\alpha_S$ and “$1/Q \sim 1/m_Q$”: series truncation
3. Any deviation beyond “natural uncertainty” is treated as violation of quark-hadron duality [resonances, instantons,…]

This definition is due to M. Shifman
Summary of theoretical findings before 2004

1. Assume quark-hadron duality

2. Theoretical predictions through $1/m_b^3$: "natural" uncertainty due to higher order corrections

$$O\left(\frac{\Lambda^4}{m_b^4}\right) \sim 0.2\%$$

Violations of quark-hadron duality???
Problems with experimental results???

Theoretical “questions“: what IS “natural“ uncertainty?
what does the quoted “theory error“ mean?
Theoretical expectations

- Assume quark-hadron duality: relate width to forward matrix element

\[ \Gamma(H_b) = \frac{1}{2M_b} \langle H_b | T | H_b \rangle = \frac{1}{2M_b} \langle H_b | \text{Im} \int d^4x \, T \{H_{\text{eff}}^{\Delta B=1}(x) H_{\text{eff}}^{\Delta B=1}(0)\} | H_b \rangle \]

- This correlator can be expanded using OPE


\[ \Gamma(H_b) = \sum_k \frac{C_k(\mu)}{m_b^k} \langle H_b | O_k^{\Delta B=0}(\mu) | H_b \rangle \]

What are the results?
Leading order

- Leading order (in $1/m_b$ expansion)

$\tau(B^+) = \tau(B^0) = \tau(\Lambda_b) = 1/\Gamma(H_b)$,

$\Gamma(H_b) = \eta c_3 \frac{G_F m_b^5}{192\pi^3}$

$\eta = \langle H_b | \bar{b}b | H_b \rangle \equiv \langle \bar{b}b \rangle_{H_b} \xrightarrow{m_b \to \infty} 1$

- Subleading $1/m_b$ corrections? No!

$\langle H_b | \bar{b}iD b | H_b \rangle \xrightarrow{Eq. of Motion} \langle H_b | m_b \bar{b}b | H_b \rangle$

Dimension 4 operators are eliminated through equations of motion.

Must include explicit spectator interaction to see the differences in lifetimes of different hadrons...
Subleading orders - $1/m_b^2$ corrections

Subleading $1/m_b^2$ corrections

\[
\begin{align*}
\Gamma(H_b) &= \frac{G_F^2 m_b^5}{192 \pi^3} \left[ c_3 \left\langle \bar{b}b \right\rangle_{H_b} + c_5 \frac{\left\langle g_s \bar{b} \sigma_{\mu \nu} G^{\mu \nu} b \right\rangle_{H_b}}{m_b^2} \right], \\
\end{align*}
\]

These matrix elements can be systematically expanded in $1/m_b$

\[
\begin{align*}
\left\langle \bar{b}b \right\rangle_{H_b} &= 1 - \frac{1}{2 m_b^2} \left[ \mu_\pi^2 (H_b) - \mu_G^2 (H_b) \right] + O(1/m_b^2), \\
\left\langle g_s \bar{b} \sigma_{\mu \nu} G^{\mu \nu} b \right\rangle_{H_b} &= 2 \mu_G^2 (H_b) + O(1/m_b) \\
\end{align*}
\]

HQET matrix elements

\[
\begin{align*}
\mu_\pi^2 (H_b) &= \frac{1}{2 m_b^2} \left\langle H_b (v) \left| \bar{b}_v (i D) b_v \right| H_b (v) \right\rangle, \\
\mu_G^2 (H_b) &= \frac{1}{2 m_b^2} \left\langle H_b (v) \left| \bar{b}_v \frac{g_s}{2} \sigma_{\mu \nu} G^{\mu \nu} b_v \right| H_b (v) \right\rangle
\end{align*}
\]
Subleading orders - 1/$m_b^2$ corrections

- Subleading 1/$m_b^2$ corrections

\[ \tau(B^+) = \tau(B^0) \]

\[ \frac{\tau(\Lambda_b)}{\tau(B^0)} = 1 + \frac{1}{2m_b^2} \left[ \mu^2_{\pi}(\Lambda_b) - \mu^2_{\pi}(B^0) \right] \]

\[ + \frac{C_G}{m_b^2} \left[ \mu^2_{\pi}(\Lambda_b) - \mu^2_{\pi}(B^0) \right] \]

\[ \mu^2_{\pi}(B) = (0.4 \pm 0.2) \text{ GeV}^2, \]

\[ \mu^2_{\pi}(B) - \mu^2_{\pi}(\Lambda_b) = (0.01 \pm 0.03) \text{ GeV}^2, \]

\[ \mu^2_G(B) = \frac{3}{4} \left( m_{B_s}^2 - m_B^2 \right) \simeq 0.36 \text{ GeV}^2, \]

\[ \mu^2_G(\Lambda_b) = 0. \]

About 1-2% effect...

Is there anything else???

"Natural" uncertainty:

\[ O\left( \frac{\Lambda^3}{m_b^3} \right) \sim 0.9 \% \]
Summary of theoretical findings before 2004

1. Assume quark-hadron duality

2. Theoretical predictions through $1/m_b^3$: “natural” uncertainty due to higher order corrections

$$O\left(\frac{\Lambda}{m_b}\right) \sim 0.2\%$$

Violations of quark-hadron duality???

Problems with experimental results???

Theoretical “questions”: what IS “natural” uncertainty?
what does the quoted “theory error” mean?
Subleading orders - main effect?

- Subset of subleading $1/m_b^3$ corrections

$$\Gamma(H_b) = \frac{1}{2M_b} \langle H_b | \text{Im } i \int d^4x \, T \{ H_{\text{eff}}^{\Delta B=1}(x) H_{\text{eff}}^{\Delta B=1}(0) \} | H_b \rangle$$

Two intermediate quarks: $16\pi^2$ enhanced

$$T_{\text{spec}}^u = T_{\text{spec}}^u + T_{\text{spec}}^{d'} + T_{\text{spec}}^{s'},$$

$$T_{\text{spec}}^u = \frac{G_F^2 m_b^2 (1-z)^2}{2\pi} \left[ (c_1^2 + c_2^2) O_1^u + 2c_1c_2 \tilde{O}_1^u \right],$$

$$T_{\text{spec}}^{d'} = -\frac{G_F^2 m_b^2 (1-z)^2}{4\pi} c_1^2 \left[ (1+z) O_1^{d'} + \frac{2}{3} (1+2z) O_2^{d'} \right]$$

$$+ \left( N_c c_2^2 + 2c_1c_2 \right) \left[ (1+z) \tilde{O}_1^{d'} + \frac{2}{3} (1+2z) \tilde{O}_2^{d'} \right]$$

where

$$O_1^q = \bar{b}_i \gamma^\mu (1-\gamma_5) b_i \bar{q}_j \gamma_\mu (1-\gamma_5) q_j,$$

$$O_2^q = \bar{b}_i \gamma^\mu \gamma_5 b_i \bar{q}_j \gamma_\mu (1-\gamma_5) q_j,$$

Need to estimate matrix elements of these operators!
Matrix elements can be estimated in factorization, change basis:

\[ O^q = \bar{b}_L \gamma^\mu q_L \gamma^\mu b_L, \quad O^q_S = \bar{b}_R q_L \gamma_R b_L, \]
\[ T^q = \bar{b}_L \gamma^\mu t^a q_L \gamma^\mu t^a b_L, \quad T^q_S = \bar{b}_R t^a q_L \gamma_R t^a b_L \]

For the mesons...

\[ \frac{1}{2m_{B_q}} \langle B_q | Q^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} \epsilon_1, \quad \frac{1}{2m_{B_q}} \langle B_q | T^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} \epsilon_2 \]

... and for the baryons

\[ \langle \Lambda_b | O^q_1 | \Lambda_b \rangle = -\bar{B} \langle \Lambda_b | O^q_1 | \Lambda_b \rangle = \frac{\bar{B}}{6} f_{B_q}^2 m_{B_q} m_{\Lambda_b} r, \]

As a result:

\[ \frac{\tau(\Lambda_b)}{\tau(B^0)} \cdot 0.98 - \left( d_1 + d_2 \bar{B} \right) r - \left( d_3 \epsilon_1 + d_4 \epsilon_2 \right) - \left( d_5 B_1 + d_6 B_2 \right) \]

*About 5-8% effect?*
Summary of theoretical findings before 2004

1. Assume quark-hadron duality

2. Theoretical predictions through $1/m_b^3$: "natural" uncertainty due to higher order corrections

$$O\left(\Lambda^4/m_b^4\right) \sim 0.2\%$$

Violations of quark-hadron duality???

Problems with experimental results???

Theoretical "questions": what IS "natural" uncertainty?
what does the quoted "theory error" mean?
Effects of radiative corrections

- Numerical studies reveal “accidental” cancellations & instabilities:

\[
\frac{\tau(B^+)}{\tau(B_d^0)} - 1 = \tau(B^+) \left[ \Gamma(B_d^0) - \Gamma(B^+) \right] = 0.0325 \left( \frac{|V_{cb}|}{0.04} \right)^2 \left( \frac{m_b}{4.8 \text{ GeV}} \right)^2 \left( \frac{f_B}{200 \text{ MeV}} \right)^2 \times 
\left[ (1.0 \pm 0.02) B_1 + (0.1 \pm 0.1) B_2 - (18.4 \pm 0.9) \epsilon_1 + (4.0 \pm 0.2) \epsilon_2 \right].
\]

- Radiative corrections can be quite large:

Radiative corrections enhance coefficients in front of $B_{1,2} \sim O(1)!$
Spectator effects

- Look again at $1/m^3$ corrections
  - weak annihilation/scattering occurs for the bound quarks!

\[
\frac{\tau (\Lambda_b)}{\tau (B^0)} \square 0.98 - m_b^2 \left( d_1^* + d_2^* B \right) r - m_{B^0}^2 \left[ (d_3^* \varepsilon_1 + d_4^* \varepsilon_2) - (d_5^* B_1 + d_6^* B_2) \right]
\]

\[
\Rightarrow 0.98 - m_{\Lambda_b}^2 \left( d_1^* + d_2^* B \right) r - m_{B^0}^2 \left[ (d_3^* \varepsilon_1 + d_4^* \varepsilon_2) - (d_5^* B_1 + d_6^* B_2) \right]
\]

- Can this set of corrections change anything? Look at it once more...

\[
\Gamma (\Lambda_b)_{1/m^3} \square \frac{G_F^2}{2\pi} \left| \Psi (0) \right|_{bu}^2 \left| V_{ud} \right|^2 \left| V_{cb} \right|^2 m_b^2 (1 - z^2) \left[ c_-^2 \left( 1 - z \right) c_+ \left( c_- - \frac{c_+}{2} \right) \right]
\]

Hint: go to higher order in $1/m_b$!

- Weak annihilation
- Pauli Interference

Alexey Petrov (WSU)
UW (Seattle), May 26, 2005
Subleading spectator effects

- Compute subleading corrections to spectator effects

\[ \Gamma_{\text{spec},1/m}(H_b) = \frac{1}{2M_b} \langle H_b | T_{\text{spec},1/m} | H_b \rangle \]

- Expand \( T_{\text{spec},1/m} \) in the light-quark momentum and match onto operators with derivatives...

\[
\begin{align*}
T_{\text{spec},1/m}^u &= -2 \left( c_1^2 + c_2^2 \right) \frac{1+z}{1-z} R_0^u - c_1 c_2 \frac{1+z}{1-z} \overline{R}_1^u, \\
T_{\text{spec},1/m}^{d'} &= c_1^2 \left[ \frac{8z^2}{1-z} R_0^{d'} + \frac{2}{3} \frac{1+z+10z^2}{1-z} R_1^{d'} + \frac{2}{3} (1+2z) \left( \overline{R}_2^{d'} - \overline{R}_3^{d'} \right) \right] \\
&\quad + \left( N_c c_1^2 + 2c_1 c_2 \right) \left[ \frac{8z^2}{1-z} \overline{R}_0^{d'} + \frac{2}{3} \frac{1+z+10z^2}{1-z} \overline{R}_1^{d'} + \frac{2}{3} (1+2z) \left( \overline{R}_2^{d'} - \overline{R}_3^{d'} \right) \right], \\
T_{\text{spec},1/m}^{s'} &= c_1^2 \left[ \frac{16z^2}{1-4z} R_0^{s'} + \frac{2}{3} \frac{1-2z+16z^2}{1-4z} R_1^{s'} + \frac{2}{3} (1+2z) \left( \overline{R}_2^{s'} - \overline{R}_3^{s'} \right) \right] \\
&\quad + \left( N_c c_1^2 + 2c_1 c_2 \right) \left[ \frac{16z^2}{1-4z} \overline{R}_0^{s'} + \frac{2}{3} \frac{1-2z+16z^2}{1-4z} \overline{R}_1^{s'} + \frac{2}{3} (1+2z) \left( \overline{R}_2^{s'} - \overline{R}_3^{s'} \right) \right].
\end{align*}
\]
Subleading spectator effects, cont.

- with the following set of operators...

\[ R_0^q = \frac{1}{m_b^2} b_i \gamma^\mu \gamma_5 D^\alpha b_i \bar{q}_j \gamma_\mu (1-\gamma_5) D_\alpha q_j, \]

\[ R_1^q = \frac{1}{m_b^2} b_i \gamma^\mu (1-\gamma_5) D^\alpha b_i \bar{q}_j \gamma_\mu (1-\gamma_5) D_\alpha q_j, \]

\[ R_2^q = \frac{1}{m_b^2} b_i \gamma^\mu (1-\gamma_5) D^\alpha b_i \bar{q}_j \gamma_\alpha (1-\gamma_5) D_\mu q_j, \]

\[ R_3^q = \frac{m_q}{m_b} b_i (1-\gamma_5) b_i \bar{q}_j (1-\gamma_5) q_j. \]

- with explicit power counting after taking matrix elements

\[ \langle B_q | R_q^q | B_q \rangle = \langle B_q | R_q^q | B_q \rangle / N = \frac{\beta_1}{2 N_c} f_{B_q}^2 m_{B_q}^2 \left[ \frac{m_{B_q}^2}{m_b^2} - 1 \right], \]

\[ \langle \Lambda_b | R_q^q | \Lambda_b \rangle = - \langle \Lambda_b | R_q^q | \Lambda_b \rangle = - \frac{\tilde{\beta}_1}{24} f_{B_q}^2 m_{B_q} m_{\Lambda_b} \left[ \frac{m_{\Lambda_b}^2}{m_b^2} - 1 \right], \]

\[ \langle B_q | R_{2,3}^q | B_q \rangle = - \frac{\beta_{2,3}}{4 N_c} f_{B_q}^2 (m_{B_q}^2 - m_b^2), \]

\[ \langle \Lambda_b | R_{2,3}^q | \Lambda_b \rangle = - \langle \Lambda_b | R_{2,3}^q | \Lambda_b \rangle = - \frac{\tilde{\beta}_2}{48 m_b^2} f_{B_q}^2 m_{B_q} (m_{\Lambda_b}^2 - m_b^2), \]

\[ \langle B_q | R_{2,3}^q | B_q \rangle = - \frac{\beta_{2,3}}{4} f_{B_q}^2 (m_{B_q}^2 - m_b^2), \]

\[ \langle \Lambda_b | R_{2,3}^q | \Lambda_b \rangle = - \langle \Lambda_b | R_{2,3}^q | \Lambda_b \rangle = - \frac{\tilde{\beta}_3}{\tilde{\beta}_2} \langle \Lambda_b | R_{2,3}^q | \Lambda_b \rangle. \]
As a result, the lifetime ratios become...

Dashed: LL, dash-dotted: pQCD NLL, solid: pQCD NLL + subleading spectator corrections

The effect is negligible in meson ratio and is about -(2-4)% in baryon-meson ratio
- no cancellation b/w WS and PI (enter with the same sign)
- reduces baryon/meson ratio, as required

How “good” is this expansion? Let’s estimate next term...
Estimate of higher order effects

Let's estimate convergence of expansion

Expand one order further and add background gluon operator contributions entering at this order...

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Estimate of higher order effects

... as a result, we get a collection of operators...

\[
\begin{aligned}
\delta t_{\text{new}} &= \left( \frac{m^2}{m_0^2} \right) \left[ \frac{1}{2} \frac{1 + z}{1 - z} \mathcal{O} + \frac{8z^2}{(1 - z)^2} \mathcal{W}_1 \right] + 2c_1 c_2 \left[ m^2 \frac{1 + z}{1 - z} \mathcal{O} + \frac{8z^2}{(1 - z)^2} \mathcal{W}_1 \right], \\
\delta t_{\text{old}} &= c_1 \left[ \frac{m^2}{m_0^2} \frac{1}{1 - z} \mathcal{O}_1 + \frac{m^2}{m_0^2} \frac{4z^2}{1 - z} \mathcal{O}_2 + \frac{m^2}{m_0^2} \frac{2(1 + 2z)}{3} \mathcal{O}_3 \\ &+ \frac{4z^2(7z - 5)}{(1 - z)^2} \mathcal{W}_1 + \frac{8z^2(16z - 3)}{(1 - z)^2} \mathcal{W}_2 \right] + \frac{8z^2}{1 - z} \left( \mathcal{W}_3 - \mathcal{W}_4 \right) \\
&+ \left( N c_1^2 + c_1 c_2 \right) \left[ \frac{m^2}{m_0^2} \frac{1}{1 - z} \mathcal{O}_1 + \frac{m^2}{m_0^2} \frac{4z^2}{1 - z} \mathcal{O}_2 + \frac{m^2}{m_0^2} \frac{2(1 + 2z)}{3} \mathcal{O}_3 \\ &+ \frac{4z^2(7z - 5)}{(1 - z)^2} \mathcal{W}_1 + \frac{8z^2(16z - 3)}{(1 - z)^2} \mathcal{W}_2 \right] + \frac{8z^2}{1 - z} \left( \mathcal{W}_3 - \mathcal{W}_4 \right) \\
\delta t_{\text{corr}} &= c_1 \left[ \frac{m^2}{m_0^2} \frac{2z}{1 - 4z} \mathcal{O}_1 + \frac{m^2}{m_0^2} \frac{8z^2}{1 - 4z} \mathcal{O}_2 + \frac{m^2}{m_0^2} \frac{2(1 + 2z)}{3} \mathcal{O}_3 \\ &+ \frac{8z^2(16z - 5)}{(1 - 4z)^2} \mathcal{W}_1 + \frac{16z^2(10z - 3)}{(1 - 4z)^2} \mathcal{W}_2 + \frac{16z^2}{1 - 4z} \left( \mathcal{W}_3 - \mathcal{W}_4 \right) \\
&+ \left( N c_1^2 + 2c_1 c_2 \right) \left[ \frac{m^2}{m_0^2} \frac{2z}{1 - 4z} \mathcal{O}_1 + \frac{m^2}{m_0^2} \frac{8z^2}{1 - 4z} \mathcal{O}_2 + \frac{m^2}{m_0^2} \frac{2(1 + 2z)}{3} \mathcal{O}_3 \\ &+ \frac{8z^2(16z - 5)}{(1 - 4z)^2} \mathcal{W}_1 + \frac{16z^2(10z - 3)}{(1 - 4z)^2} \mathcal{W}_2 + \frac{16z^2}{1 - 4z} \left( \mathcal{W}_3 - \mathcal{W}_4 \right) \right].
\end{aligned}
\]

\[ T_{\text{corr}} = 0, \]

\[ T_{\text{corr}} = -\frac{G_F^2 |\bar{q} q|^2}{4\pi} \left\{ c_1^2 \left[ (1 - z^2) P_1^d - (1 - z^2) P_2^d + 2z(1 - z) P_3^d + 4z P_4^d \right] \\ + 2c_1 c_2 \left[ (1 - z) P_5^d + (1 - z) P_6^d + 2z P_7^d + 2z P_8^d \right] \right\}, \]

\[ T_{\text{corr}} = -\frac{G_F^2 |\bar{q} q|^2}{4\pi \sqrt{1 - 4z}} \left\{ c_1^2 \left[ (1 - 2z) P_1^d - (1 - 4z) P_2^d + 2z P_3^d + 4z P_4^d \right] \\ + 4c_1 c_2 \left[ P_5^d + P_6^d + P_7^d + P_8^d \right] \right\}. \]

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... so estimating their matrix elements we obtain the answer!

✓ **Problem**: too many matrix elements for meaningful answer
✓ **Solution**: generate random values for parameters/matrix elements (±30% of “factorized” value)
The expansion appears well convergent for b-quark

Conservatively:

\[
\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.87 \pm 0.05 \\
\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02 \\
\frac{\tau(B_s)}{\tau(B^0)} = 1.00 \pm 0.01
\]

Comparisons

Before HFAG 2004

Results

Comparisons

Before HFAG 2004

Exp. from PDG 2004

Current

Nice agreement between theory and experiment... \( B_s \)?
Conclusions

- We calculated $1/m$ and $1/m^2$ corrections to spectator effects driving lifetime differences among heavy mesons and baryons.
- The effect is about -(2-4)%, ameliorating the problem of short $\Lambda_b$ lifetime.
- The expansion is well convergent for beauty hadrons.
- It appears that quark-hadron duality violations need not to be invoked in order to explain $\Lambda_b$ "lifetime puzzle".
- Need lattice or QCDSR calculations of R's.