Measurement of inclusive and exclusive B-hadron lifetimes at LEP

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Since the introduction of high resolution vertex detectors with 3D hit reconstruction in the four LEP experiments it has been possible to deliver very precise lifetime measurements of b-hadrons. This short review illustrates each of the three main methods developed by the LEP experiments and ends with the status of the current combined averages.

1. Introduction

The lifetimes of b hadrons depend both on the strength of the b quark coupling to the lighter c and u quarks, and on the dynamics of b hadron decay. The Spectator Model provides the simplest description of B-hadron decay. Here, the lifetime depends only on the process $b \rightarrow cW$ with the other light-quark constituent(s) playing no role in the decay dynamics. This in turn leads to the prediction that all b-hadron species have the same lifetime. However non-spectator effects such as Pauli interference, W exchange and weak annihilation can induce lifetime differences among the different B-hadron species. Based on the heavy quark expansion formalism, the difference between the lifetimes of the b baryons and mesons is predicted to depend on $1/m_b^2$ and higher order terms, whereas meson-meson differences depend only on $1/m_b^3$ and higher order terms. The predicted lifetime hierarchy is $\tau(\Lambda_b) < \tau(B^0) \sim \tau(B_s) < \tau(B^+)$, and there is a growing consensus between models that a difference in lifetime of order $5-10\%$ should exist between the B^+ and B^0 meson. There is however an on-going debate questioning some of the assumptions made by such models [1], and precise measurements of all B-species are clearly needed to clarify the situation. Furthermore measurements of specific B-hadron lifetimes are vital inputs to time dependent analyses such as B-oscillations or CP-asymmetry in the B-system. Lifetime measurements also provide tests of the non-spectator effects of the decay dynamics and of QCD-correction-models.

2. Methods

Measuring the lifetime of an unstable particle relies on two measurements: the measurement of the decay-length l and the measurement of the momentum p of the decaying particle. The decay time t of the particle is given by:

$$t = \frac{ml}{pc} \qquad (1)$$

where m is the particle rest-mass. This measurement requires good energy and vertex resolution to be able to be unbiased from the D-cascade decay vertex. Three main analysis approaches have been applied in the past. (a) In exclusive analyses, weakly decaying B-hadron is fully reconstructed by selecting different specific decay channels which have a high branching fraction and recording and identifying the decay particles. Those analyses work in general with very pure samples but with limited statistics. (b) Semi-inclusive methods are restricted to specific topologies. For example, only semi-leptonic decays are considered where the lepton is vertexed with oppositely charged pions from the $D^{*+} \rightarrow D^0\pi^+$ decay and where the D^0 is reconstructed inclusively. (c) The fully inclusive approach where the b-vertex is topologically reconstructed regardless of the decay channel, using impact parameter probabilities or sophisticated neural networks.

These analyses typically have the best statistical precision and are systematically limited.

3. Analyses

3.1. Exclusive Measurements

The ALEPH collaboration has published an exclusive measurement of the $\bar{B}^0$ and B^- meson lifetimes in July 2000 [2]. They measured the lifetimes using a sample of about 4 million hadronic Z decays collected from 1991 to 1995 by reconstructing semileptonic decays where the lepton is associated with a D^{*+} or D^0 meson. D^{*+} and D^0 were then distinguished by the existence or nonexistence of a slow pion around the nominal mass difference of 145.4 MeV/c^2. The modes used for the identification of the D^0's were in detail $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^0_s\pi^+\pi^0-$. Finally the B decay vertex position is estimated by vertexing the reconstructed D^0 track with the lepton. The D^0 candidate mass spectra for the four subsamples in the $D^{*+}l^-$ event selection are shown in Fig. 1. Corresponding plots from the $D^0 l^-$ event selection look similar. The fitted curves consist of a Gaussian function for the signal plus a linear background. Events within 2σ of the fitted D^0 mass were selected for the b-vertex reconstruction resulting in 1880 $D^{*+}l^-$ and 2856 $D^0 l^-$ candidates with $\bar{B}^0(B^-)$ purities of 85%(80%).

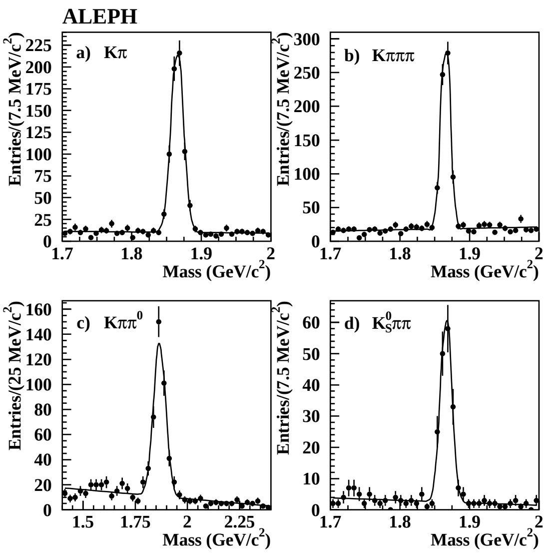

Figure 1. *The invariant mass of D^0 candidates for the four subsamples in the $D^{*+}l^-$ event selection: a) $D^0 \to K^-\pi^+$, b) $D^0 \to K^-\pi^+\pi^-\pi^+$, c) $D^0 \to K^-\pi^+\pi^0$, d) $D^0 \to K^0_s\pi^+\pi^0-$. The superimposed curves are the results of the fit described in the text.*

For the measurement an un-binned maximum likelihood fit was performed using the following likelihood function:

$$\mathcal{L} = \prod_{i=1}^{N_{D^*l}} [f^*_-(\tau_{B^-}/\tau_{\bar{B}^0})F(t_i,\sigma_i,\tau_{B^-}) \quad (2)$$
$$+f^*_0(\tau_{B^-}/\tau_{\bar{B}^0})F(t_i,\sigma_i,\tau_{\bar{B}^0}) + f^*_{bkg}F^*_{bkg}(t_i)]$$
$$\times \prod_{i=1}^{N_{D^0 l}} [f^0_-(\tau_{B^-}/\tau_{\bar{B}^0})F(t_i,\sigma_i,\tau_{B^-})$$
$$+f^0_0(\tau_{B^-}/\tau_{\bar{B}^0})F(t_i,\sigma_i,\tau_{\bar{B}^0}) + f^0_{bkg}F^0_{bkg}(t_i)]$$

The coefficients f^*_- and f^*_0 are the fractions of the $D^{*+}l^-$ sample arising from B^- and $\bar{B}^0$ decays, respectively. Similarly, f^0_- and f^0_0 are the fractions of B^- and $\bar{B}^0$ decays in the D^0l^- sample. The coefficients f^*_{bkg} and f^0_{bkg} are the background fractions of the samples, while the functions $F^*_{bkg}(t)$ and $F^0_{bkg}(t)$ are their normalized proper time distributions. The function $F(t,\sigma,\tau)$ is a exponential distribution convoluted by decay length resolution and energy correction function taking into account missing energy, mainly from the missing neutrino in the semileptonic decay. The fit to the proper time distributions of the $D^{*+}l^-$ and D^0l^- events has been performed to determine the two free parameters $\tau_{\bar{B}^0}$ and τ_{B^-}. The values obtained are

$$\tau_{B^-} = 1.648 \pm 0.049(stat.) \pm 0.035(syst.)\ ps, \quad (3)$$
$$\tau_{\bar{B}^0} = 1.518 \pm 0.053(stat.) \pm 0.034(syst.)\ ps.$$

The ratio of the lifetimes is

$$\tau_{B^-}/\tau_{\bar{B}^0} = 1.085 \pm 0.059(stat.) \pm 0.018(syst.). (4)$$

taking into account the correlation which is -0.35. The result can be seen together with other exclusive results in Fig. 3. The proper time distributions for the two samples are shown in Fig.

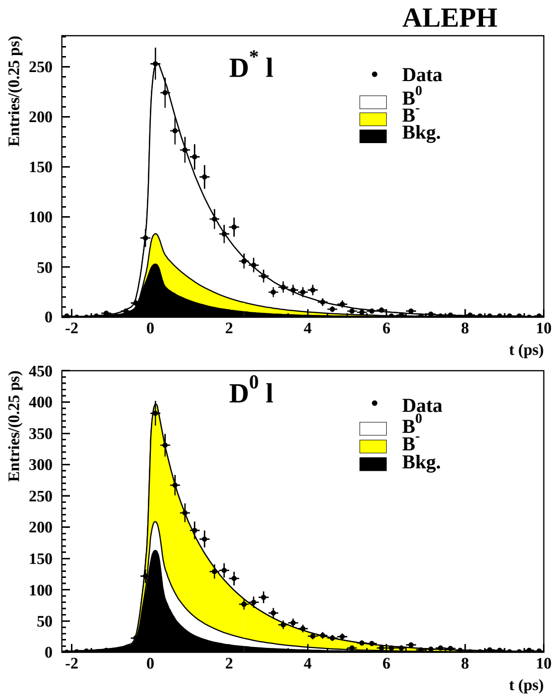

Figure 2. *Proper time distributions with the result of the fit overlaid for the two samples. The plots show the background contributions to the samples, together with the $\bar{B}^0$ and B^- components.*

2 with the results of the fit overlaid. The largest sources of systematic error were the B momentum reconstruction due to the missing energy, the background treatment due to unknown branching fractions (e.g. $BR(B \to D^{**}l\nu)$) and the parameterization of decay length resolution.

3.2. Semi-inclusive Measurements

The lifetime of the B^0 meson has been measured by the OPAL collaboration using $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ decays collected from 1991 to 1995 [3]. The reconstruction of $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ events was performed by combining high p and p_t lepton (electron or muon) candidates with oppositely charged pions from the $D^{*+} \to D^0\pi^+$ decay with small transverse momentum ($p_t < 0.3$ GeV). The selection of pions relies again on the small mass difference between the D^{*+} and the D^0. For a final selection the mass difference is formed in an inclusive way by selecting a group of tracks and calorimeter clusters compatible with a D^0 decay.

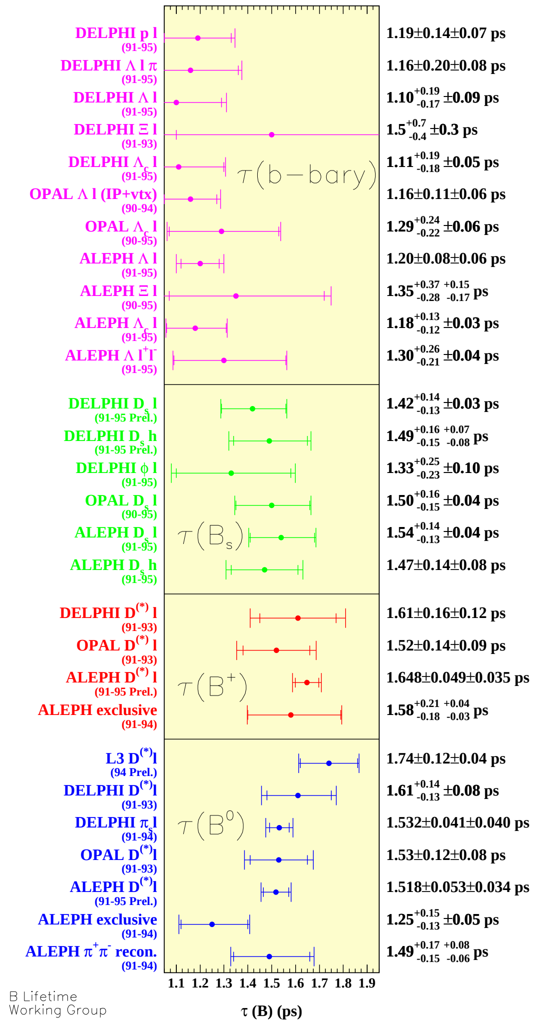

Figure 3. *The plot shows the most recent exclusive and semi-exclusive results of lifetime analyses from LEP.*

$$\Delta M = \sqrt{E_{D^*}^2 - |p_{\vec{D}^*}|^2} - m_{D^0} \tag{5}$$

were calculated for same and opposite-sign events, where the D^0 momentum vector and energy were reconstructed for opposite and same sign lepton-pion combinations and are shown in figure 4(a) and (b). For the B vertexing events with $\Delta M < 0.17$ GeV were selected where 36% of the selected opposite sign events were signal according to Monte Carlo. The resolution was parameterized as a function $R_{D^{*+}}(t, t')$ giving the expected distribution of reconstructed

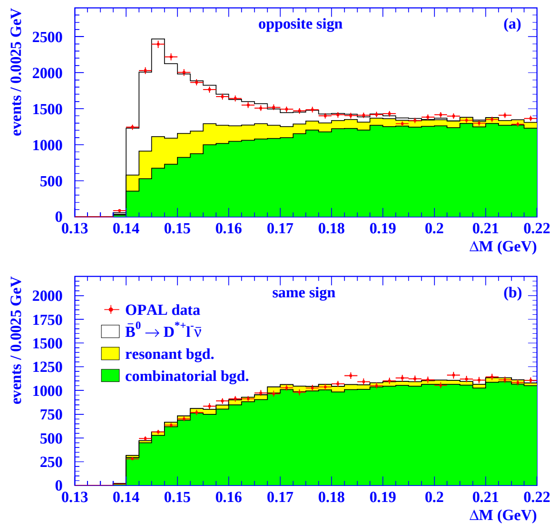

Figure 4. *Reconstructed ΔM distributions for selected (a) opposite-sign and (b) same-sign lepton-pion combinations. The data are shown by the points with error bars, and the Monte Carlo simulation contributions from signal $\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}$ decays, other resonant D^{*+} decays and combinatorial background are shown by the white, light grey and grey histograms respectively.*

t for each true value t' the resolution function was implemented as the sum of three Gaussian distributions, whose widths vary linearly with $t\prime$. Similar resolution functions $R_{D^{*+}\pi^-}(t,t\prime)$, $R_{D^{*+}\pi^0}(t,t\prime)$ and $R_{D^{*+}K^0}(t,t\prime)$ were generated for the three main D^{**} background contributions $\bar{B}^0 \rightarrow D^{*+}\pi^-l^-\bar{\nu}$, $\bar{B}^0 \rightarrow D^{*+}\pi^0l^-\bar{\nu}$ and $\bar{B}^0 \rightarrow D^{*+}K^0l^-\bar{\nu}$. τ_{B^0} was extracted by maximizing the following log-likelihood function

$$\ln \mathcal{L} = \sum_{i=1}^{M^a} \ln \mathcal{L}_i^a + \sum_{i=1}^{M^b} \ln \mathcal{L}_i^b - N^a - N^b \qquad (6)$$

were $\ln \mathcal{L}_i^a$ and $\ln \mathcal{L}_i^b$ are the individual event log-likelihoods taken over all the M^a observed opposite-sign and M^b same-sign events in the data sample, and N^a and N^b are the corresponding expected numbers of events. From the fit a result of

$$\tau_{B^0} = 1.541 \pm 0.028(stat.) \pm 0.023(syst.)\ ps \qquad (7)$$

was obtained. The distributions of reconstructed proper time t for opposite and same sign data events with $\delta M < 0.17$ GeV, together with the fit results are shown in Figure 5. The most dominant

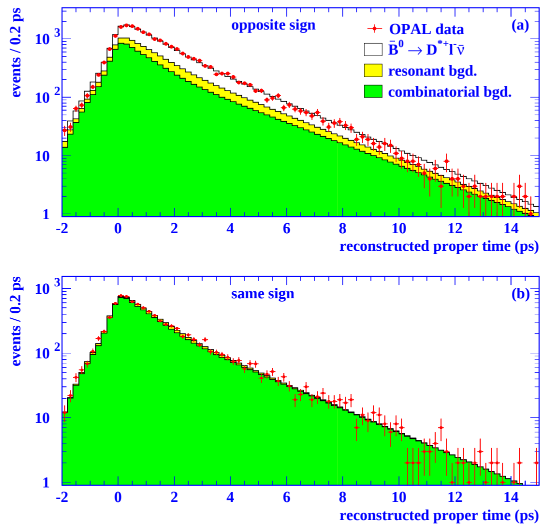

Figure 5. *Distributions of reconstructed proper time t for (a) opposite sign and (b) same sign events with $\delta M < 0.17$ GeV. The data are shown by the points with error bars and the expectation from the fit result by the histograms. The contributions from signal $\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}$, resonant and combinatorial backgrounds are indicated.*

sources of systematic errors were the B^+ lifetime which was a parameter of the fit, the branching fraction $BR(b \rightarrow D^{*+}D_s^{(*)-})$, the tracking resolution, details of the fitting method and other opposite sign background involving a genuine lepton and slow pion from D^{*+} decay.

3.3. Inclusive Measurements

DELPHI has a new preliminary analysis based on data taken in 1994 and 1995 using elaborate neural network techniques for both reconstruction and enhancement of B^+ and B^0 vertices. A neural network (TrackNet) was designed to supply for each track in a given hemisphere, a probability of whether that track originated from a weakly decaying B-hadron or not. The main inputs to the network were impact parameter-based probabilities that the track belonged to the primary or secondary vertex and track rapidity. In addition, a neural network (BD-Net) was designed to discriminate between tracks whose origin was the weakly decaying B-hadron or the subsequent cascade D-meson decay, using also particle identification tags, impact parameter information and details of decay kinematics. For the separation and the enhancement of B^+ and B^0 mesons an additional neural network utilizing 4 output nodes was developed (BHBN net). Each output node delivered a probability for an event hemisphere to contain a B-hadron of a particular type (B^+, B^0, B_s or b-baryon). Input variables included TrackNet-weighted vertex charge and error, the number of charged pions per hemisphere, charged and neutral reconstructed energy in the hemisphere, probabilities that identified kaon/pion candidates stem from fragmentation or b-decay and quality variables like the invariant mass of the reconstructed vertex or a hemisphere quality factor. The distribution of the two output nodes which were relevant for this analysis (B^+ and B^0 node) are shown in Figure 6. For the event selection cuts on the two output nodes were applied to achieve a purity of $\sim 70\%$. For each event one out of four different decay length algorithms were chosen. These algorithms differed by details of the track-selection for the vertex fit based on the TrackNet and the BD-Net. Choice of the algorithm was dictated by optimizing the resolution and minimizing any bias while still retaining the best possible efficiency. This resulted in the selection of two data sets containing 38988(11573) $B^+(B^0)$ candidates respectively. Monte Carlo events were run through the same selection procedure and in addition, were reweighted to compensate for known discrepancies between data and MC (e.g. hemisphere quality). The lifetimes were extracted from a binned χ^2 fit based on the following χ^2 function:

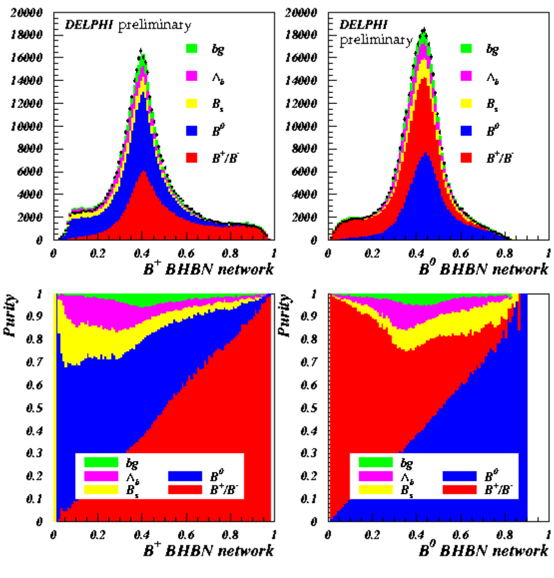

Figure 6. *The upper plots show the output of the B^+ and B^0 output nodes of the BHBN-net in the 1994 data. overlaid is the b-hadron composition as seen in the Monte Carlo and the lower plots trace the change in purity per bin. The background, labeled 'bg' consists of light and charm quark events.*

$$\chi^2 = \sum_{B^\pm, B^0} \left[\sum_{i=1}^{N_bins} \frac{(W_i^{MC} - N_i^{DATA})^2}{(\sigma_i^{MC})^2 + (\sigma_i^{DATA})^2} \right] \tag{8}$$

Here σ_i^{MC} and σ_i^{DATA} are the error for the MC and the data entries in bin i respectively. N_i^{DATA} is the data entry in bin i and W_i^{MC} is the total MC weight in bin i. The sum goes over both samples. The χ^2 function is minimized with respect to the two fit parameters, τ_{B^+} and τ_{B^0}. The time distribution of the two samples together with the fit can be seen in Figure 7. The result of the fit was:

$$\begin{aligned} \tau_{B^+} &= 1.631 \pm 0.012(stat.) \pm 0.021(syst.)\ ps, \\ \tau_{B^0} &= 1.546 \pm 0.018(stat.) \pm 0.035(syst.)\ ps. \\ \tau_{B^+}/\tau_{B^0} &= 1.054 \pm 0.017(stat.) \pm 0.027(syst.). \end{aligned} \tag{9}$$

The most significant systematic errors were the time resolution, the detector acceptance, B to D branching fractions, the position of the working point and details of the fit and quality miss-match between data and Monte Carlo. The result of the OPAL and the DELPHI analysis can be seen together with the results from other inclusive and semi-inclusive LEP measurements in Fig. 8.

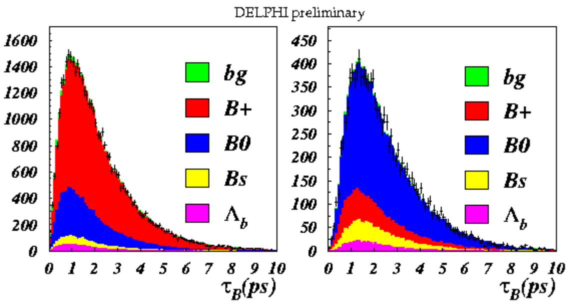

Figure 7. *The result of the fit in the B^+ (left) and B^0 (right) samples compared data with the B-hadron composition overlaid as given by the Monte Carlo. Here, 'bg' refers to the background from light and charm quark events. The fits for 1994(1995) had a $\chi^2/d.o.f.$ of 186/178(152/161) corresponding to a χ^2 probability of* 33%(68%) *and a correlation parameter between τ_{B^+} and τ_{B^0} of -0.49(0.50) respectively.*

4. Conclusion and Outlook

To summarize the results, the current world averages including measurements from LEP, BABAR, SLD and the Tevatron are presented together with the theoretical predictions in Figure 9. As one can see the predicted B-hadron lifetime hierarchy is broadly confirmed for all B-hadron species. Only for the b-baryons the measurement and the prediction differ still by more than two standard deviations. For the near future the experiments BELLE and BABAR at the two b-factories KEK-B and PEP-II will soon deliver the most precise measurements for B^+ and B^0. From the Tevatron RunII, improved exclusive measurements of b-baryon and B_s meson lifetimes are expected.

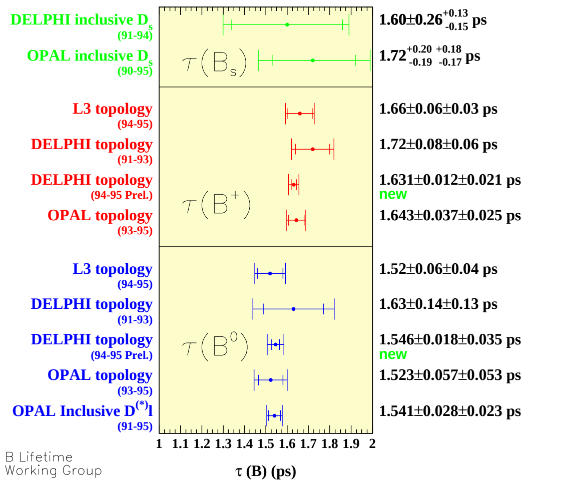

Figure 8. *The plot shows the most recent inclusive and semi-inclusive results from LEP.*

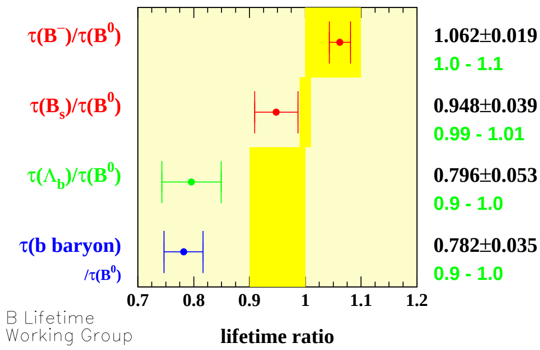

Figure 9. *The current world average lifetime ratios of all b-Hadron species except B_c with respect to τ_{B^0} are shown together with the total error bars. The dark grey bands show the theoretical predictions and their uncertainties.*

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