B^+, B_d^0 AND b-BARYON LIFETIMES

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Abstract

We review recent B^+, B_d^0 and b-baryon lifetime measurements performed by the LEP, SLD and CDF collaborations. Lifetime ratios of $\tau(B^+)/\tau(B_d^0) = 1.070 \pm 0.027$ and $\tau(b\ \text{baryon})/\tau(B_d^0) = 0.77 \pm 0.04$ are obtained using all existing measurements. The ratio between charged and neutral B meson lifetimes is in good agreement with theory but the ratio between b-baryon and B meson lifetimes remains somewhat lower than expected.

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We review recent B^+, B_d^0 and b-baryon lifetime measurements performed by the LEP, SLD and CDF collaborations. Lifetime ratios of $\tau(B^+)/\tau(B_d^0) = 1.070 \pm 0.027$ and $\tau(b\ \text{baryon})/\tau(B_d^0) = 0.77 \pm 0.04$ are obtained using all existing measurements. The ratio between charged and neutral B meson lifetimes is in good agreement with theory but the ratio between b-baryon and B meson lifetimes remains somewhat lower than expected.

1 Introduction

The study of exclusive b-hadron lifetimes provides an important test of our understanding of b-hadron decay dynamics. Lifetimes are especially useful to probe the strong interaction effects arising from the fact that b quarks are not free particles but are confined inside hadrons. In the naive spectator model, the b quarks are treated as if they were free and one therefore expects $\tau(B^+) = \tau(B_d^0) = \tau(B_s^0) = \tau(\Lambda_b)$. However, this picture does not hold in the case of charm hadrons for which the lifetimes follow the pattern $\tau(D^+) \simeq 2.3\ \tau(D_s) \simeq 2.5\ \tau(D^0) \simeq 5\ \tau(\Lambda_c^+)$. These factors are predicted to scale with the inverse of the heavy quark mass squared and the b-hadron lifetimes are thus expected to differ by only 10-20%. Using the Heavy Quark Expansion, Bigi et al.[1] predict $\tau(B^+)/\tau(B_d^0) = 1 + 0.05\ (f_B/200\,\text{MeV})^2$, where f_B is the B-meson decay constant ($f_B = 200 \pm 40$ MeV), and $\tau(\Lambda_b)/\tau(B_d^0) \simeq 0.9$. However, Neubert and Sachrajda[2] argue that a more theoretically conservative approach yields $0.8 < \tau(B^+)/\tau(B_d^0) < 1.2$ and $0.85 < \tau(\Lambda_b)/\tau(B_d^0) < 1.0$.

Precise knowledge of exclusive b-hadron lifetimes is required for accurate measurements of $|V_{cb}|$ and B mixing, and is also an important input parameter for $Z^0 \to b\bar{b}$ electroweak measurements.

2 B^+ and B_d^0 Lifetimes

The LEP, SLD and CDF collaborations have taken advantage of their precision vertex detectors and of the significant boost for b hadrons produced in high energy e^+e^- and $\bar{p}p$ collisions to measure exclusive b-hadron lifetimes. Three main analysis techniques have been used to measure B^+ and B_d^0 lifetimes. The first method relies on fully reconstructed B decays (e.g. $B \to J/\psi K$). This is the ideal method for a lifetime measurement since there is little or no modelling uncertainty in the B energy and the sample composition. However, exclusive branching ratios for B decays are typically small (10^{-4} to 10^{-3}) which severely limits the statistics available at current facilities. The second and most utilized method selects semileptonic decays of the type $B \to D^{(*)}l\nu X$, where the $D^{(*)}$ meson is fully reconstructed. Sample composition can be controlled from the data using the charge correlation between the lepton and the $D^{(*)}$ meson. A complication arises from decays of the type $B \to D^{**}l\nu$ which spoil the B^+ and B_d^0 purity of the respective $\overline{D^0}l^+$ and $D^{*-}l^+$ samples, and whose rates are not well known.

The CDF collaboration has finalized a study[3] based on the full Run-I data sample and corresponding to an integrated luminosity of 110 pb^{-1}. A "B^+" sample consisting of $\overline{D^0}l^+$ pairs is selected with fully reconstructed $\overline{D^0} \to K^+\pi^-$ decays. Similarly, a "B^0" sample consisting of $D^{*-}l^+$ pairs is selected by reconstructing the decays $D^{*-} \to \overline{D^0}\pi^-$ where $\overline{D^0} \to K^+\pi^-(\pi^0)$ or $\overline{D^0} \to K^+\pi^-\pi^+\pi^-$. The B decay vertex is then formed by intersecting the lepton and $D^{(*)}$ trajectories.

A fit using decay length and momentum information for the $\overline{D^0}l^+$ and $D^{*-}l^+$ samples yields $\tau(B^+) = 1.637 \pm 0.058(\text{stat})^{+0.045}_{-0.043}(\text{syst})$ ps, $\tau(B_d^0) = 1.474 \pm 0.039(\text{stat})^{+0.052}_{-0.051}(\text{syst})$ ps, and $\tau(B^+)/\tau(B_d^0) = 1.110 \pm 0.056(\text{stat})^{+0.033}_{-0.030}(\text{syst})$. Contamination from $B \to D^{**}l\nu$ decays is estimated to be 10-15% and constitutes the dominant systematic uncertainty in the lifetime ratio.

A third method for lifetime measurements relies on inclusive topological vertexing, pioneered by the DELPHI and SLD collaborations. Here, the charged particle topology of the decays is reconstructed and the separation between charged and neutral b hadrons is achieved simply using the sum of the charges of all tracks associated with a secondary vertex. This method has the advantage of large statistics but requires good control in the detailed simulation of b hadron production and decay.

The SLD collaboration has updated its topological vertexing analysis[4] with data taken during the first part of the 1997-98 run. A set of 49,664 B decay candidates is selected with an efficiency of 50% and a purity of 98%. Separation between B^+ and B_d^0 decays is performed on the basis of the total charge Q_{tot} of tracks associated with the secondary vertex (see Fig. 1). The charged (neutral) sample consists of 30,028 (19,636) decays with $|Q_{tot}| =$
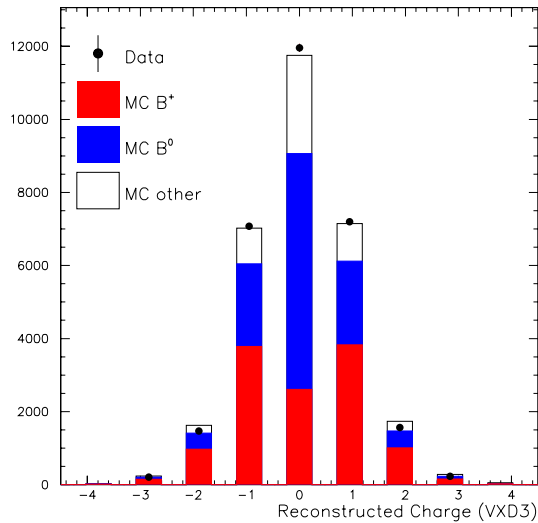
Figure 1: Distribution of the vertex charge for the SLD 1997-98 data (points) and Monte Carlo simulation (histograms) indicating the contributions from charged and neutral B mesons. The category "MC other" contains mostly neutral b hadrons: B_s^0 and b baryons.

$1, 2, 3$ ($Q_{tot} = 0$). The charge separation is enhanced somewhat by taking into account the dependence upon the reconstructed vertex mass and the b-quark charge at production (using techniques developed for the study of time-dependent B^0–$\overline{B^0}$ mixing). An effective $B^+ : B_d^0$ ($B_d^0 : B^+$) separation of $2.6 : 1$ is then obtained in the charged (neutral) sample.

The lifetimes are extracted with a simultaneous fit to the decay length distributions of the charged and neutral samples. Combining with previous data, corresponding to a total sample of 400,000 hadronic Z^0 decays, the lifetimes are $\tau(B^+) = 1.686 \pm 0.025 \text{(stat)} \pm 0.042 \text{(syst)}$ ps, $\tau(B_d^0) = 1.589 \pm 0.026 \text{(stat)} \pm 0.055 \text{(syst)}$ ps, and $\tau(B^+)/\tau(B_d^0) = 1.061^{+0.031}_{-0.029} \text{(stat)} \pm 0.027 \text{(syst)}$. These are currently the most precise determinations of the B^+ and B_d^0 lifetimes. The dominant contribution to the lifetime measurement error arises from the uncertainty in the b-fragmentation function. Specifically, the range of scaled b-hadron energy was taken to be $\langle x_E \rangle_b = 0.700 \pm 0.011$, which translates into an uncertainty of ± 0.035 ps in both B^+ and B_d^0 lifetimes. This uncertainty cancels out in the lifetime ratio since all b-hadrons are assumed to have the same fragmentation function. It should be noted that recent measurements of $\langle x_E \rangle_b$, including an analysis by SLD using the same topological technique,[5] find a somewhat larger value for $\langle x_E \rangle_b \simeq 0.72$ (see also the L3 measurement below). Such a value would shift the above lifetimes down by about 0.064 ps.

The L3 collaboration has also developed an inclusive topological vertexing technique, first applied to measure the average b-hadron lifetime.[6] The vertexing algo-
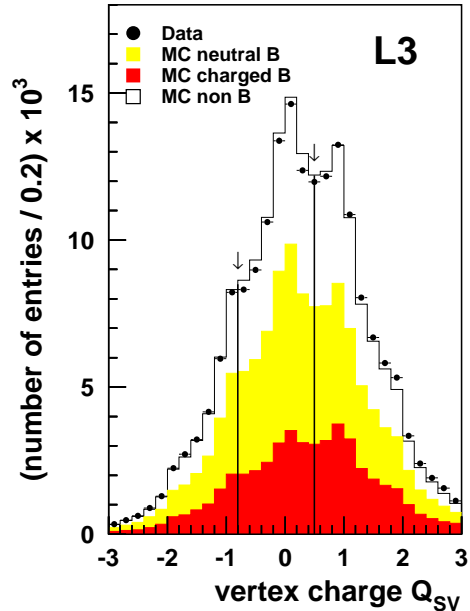

Figure 2: Distribution of the vertex charge for L3 data (points) and Monte Carlo simulation (histograms) for charged and neutral B mesons.

rithm uses the 3-D impact parameters and rapidity of tracks to reconstruct 3 vertices per event corresponding to the one primary and two secondary vertices expected in $Z^0 \to b\bar{b}$ decays. Here, the lifetime is extracted from either the secondary vertex decay length or the impact parameters of tracks attached to the secondary vertex. The latter has the advantage of having a reduced dependence on the b fragmentation uncertainty. Since the two different variables have different sensitivities to this uncertainty, they can be combined to yield very precise determinations of both the average b-hadron lifetime $\tau_b = 1.556 \pm 0.010 \text{(stat)} \pm 0.017 \text{(syst)}$ ps and the average scaled b-hadron energy $\langle x_E \rangle_b = 0.709 \pm 0.004 \text{(stat+syst)}$.

L3 extended this technique to the study of B^+ and B_d^0 lifetimes.[7] From a sample of 2×10^6 hadronic Z^0 decays, the analysis selects 890,506 secondary vertices. The separation between charged and neutral decays is then obtained by forming the vertex charge Q_{SV} defined as the product of the weighted sum of track charges and the sign of the Jet Charge, where the weight represents the probability to belong to the secondary vertex. Fig. 2 shows the vertex charge distribution and the cuts used to define the charged ($Q_{SV} > 0.5$) and neutral ($-0.8 < Q_{SV} < 0.5$) samples. For $Q_{SV} > -0.8$, the sample is 69% pure in b hadrons. The $B^+ : B_d^0$ ($B_d^0 : B^+$) separation is estimated to be $1.25 : 1$ ($1.10 : 1$) in the charged (neutral) sample. To reduce the b-fragmentation uncertainty, the lifetimes are extracted using weighted average track impact parameters and a b tag is used in the opposite hemisphere
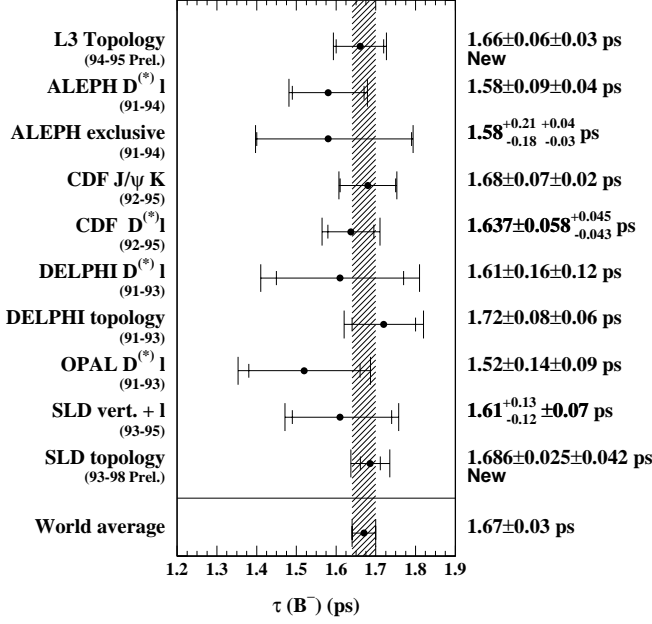
Figure 3: Measurements of the B^+ lifetime.

to suppress the background. As a result, the lifetimes are found to be $\tau(B^+) = 1.662 \pm 0.056(\text{stat}) \pm 0.025(\text{syst})$ ps, $\tau(B_d^0) = 1.524 \pm 0.055(\text{stat}) \pm 0.037(\text{syst})$ ps, and $\tau(B^+)/\tau(B_d^0) = 1.09 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$.

The measurements presented above have been combined with all previous measurements (see Figs. 3-5) to yield the following world averages:

$$\tau(B^+) = 1.67 \pm 0.03 \text{ ps}, \qquad (1)$$

$$\tau(B_d^0) = 1.57 \pm 0.03 \text{ ps}, \qquad (2)$$

$$\tau(B^+)/\tau(B_d^0) = 1.070 \pm 0.027. \qquad (3)$$

It is interesting to note that the recent progress in inclusive topological techniques has allowed a reduction of about 25% in overall uncertainty since the last summer conferences. Furthermore, the measurements are becoming precise enough to begin to measure a difference between B^+ and B_d^0 lifetimes.

3 b-baryon Lifetime

As mentioned earlier, the lifetime of b baryons is expected to be about 10% shorter than that of B_d^0 mesons. However, measurements over the past few years have indicated that the effect may be as large as 20-25% which remains somewhat difficult to accommodate. Measurements of b-baryon lifetimes are challenging since b baryons represent only about 10% of all b hadrons produced in $Z^0 \to b\bar{b}$ decays and the properties of b baryons
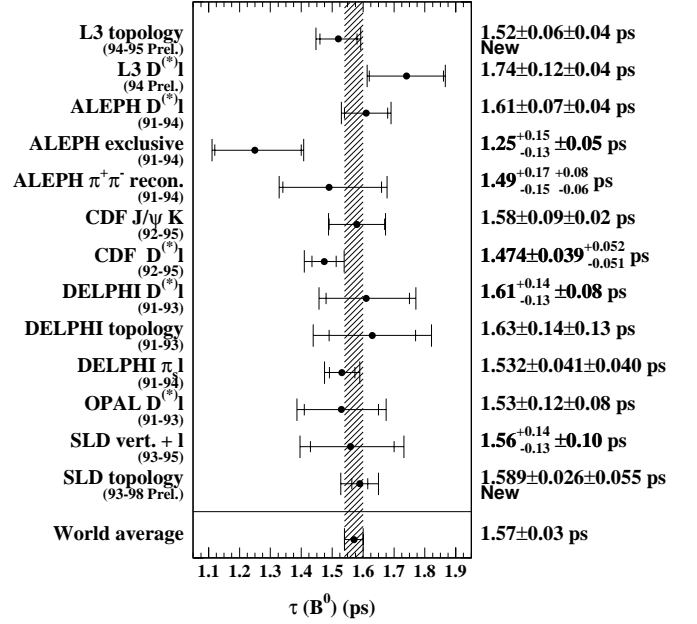

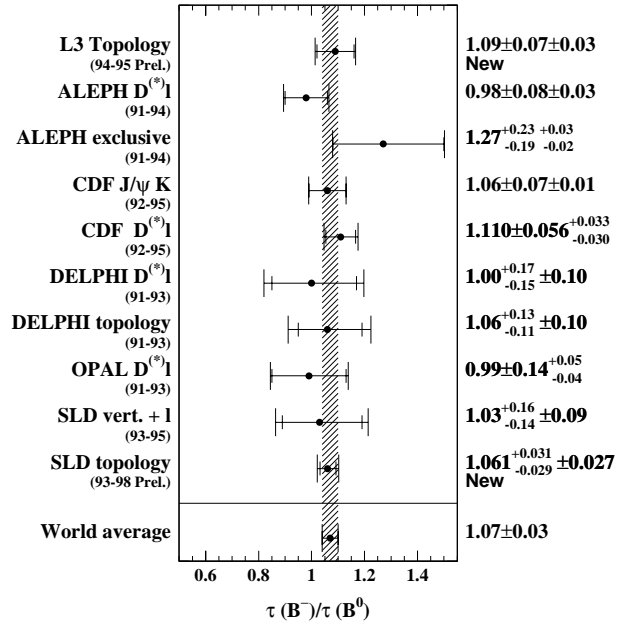Figure 4: Measurements of the B_d^0 lifetime.

Figure 5: Measurements of the ratio between B^+ and B_d^0 lifetimes.

are not well known. Therefore, most measurements have concentrated on semileptonic decays and have relied on charge correlations between Λ_c^+-lepton or Λ-lepton pairs to enhance the signal fraction and control the sample composition.

The OPAL collaboration has finalized a study [8] of partially reconstructed $\Lambda_b \to \Lambda_c^+ l^- \overline{\nu} X$ decays with $\Lambda_c^+ \to p K^- \pi^+$ or $\Lambda_c^+ \to \Lambda l^+ \nu X$ decays in a total sample of 4.4×10^6 hadronic Z^0 events. The $\Lambda_c^+ l^-$ signal is estimated to be 129 ± 25 events and the Λ_b lifetime extracted from the reconstructed decay length distribution is $\tau(\Lambda_b) = 1.29^{+0.24}_{-0.22}(\text{stat}) \pm 0.06(\text{syst})$ ps.

The DELPHI collaboration released a preliminary study of the same modes using a sample of 3.6×10^6 hadronic Z^0 events. [9] Charge-correlations allow the signal fraction to determined from the data to be $f_{signal} = (56 \pm 6)\%$. A lifetime fit to the reconstructed proper time distribution yields $\tau(\Lambda_b) = 1.17^{+0.20}_{-0.18}(\text{stat})^{+0.04}_{-0.05}(\text{syst})$ ps. DELPHI also studied more inclusive final states consisting of Λ-lepton and proton-lepton pairs. These have the advantage of increasing the statistical sensitivity of the measurement but the sample composition is more difficult to control which leads to higher systematic uncertainties. The proton-lepton analysis is unique and proceeds by applying an inclusive reconstruction of b-hadron semileptonic decays which relies on both vertexing and kinematical information. Then, vertices containing an opposite-sign proton-lepton pair are selected, where the proton is required to be the fastest hadron in the vertex and to be positively identified by the RICH particle identification system. A rejection factor of ~ 10 is achieved for both pion/proton and kaon/proton separation over most of the momentum range of interest (3 to 20 GeV/c). This analysis is only applied to the 1994-95 data sample, corresponding to 2×10^6 hadronic Z^0 decays, since the RICH was not fully operational before 1994. The b-baryon lifetime is then extracted from the reconstructed proper time distribution of the proton-lepton sample (Fig. 6): $\tau(b \text{ baryon}) = 1.19 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})$ ps with $f_{signal} = (47 \pm 5)\%$ as estimated from the data. A study of Λ-lepton pairs yields $\tau(b \text{ baryon}) = 1.16 \pm 0.20(\text{stat}) \pm 0.09(\text{syst})$ ps with $f_{signal} = (35 \pm 8)\%$ as estimated from the data.

Measurements of the b-baryon lifetime are summarized in Fig. 7. Averaging Λ_c^+-lepton with more inclusive Λ-lepton and proton-lepton measurements yields the following world average:

$$\tau(b \text{ baryon}) = 1.21 \pm 0.05 \text{ ps.} \tag{4}$$

4 Summary

B^+, B_d^0 and b-baryon lifetimes have been measured by the LEP, SLD and CDF collaborations. Recent progress
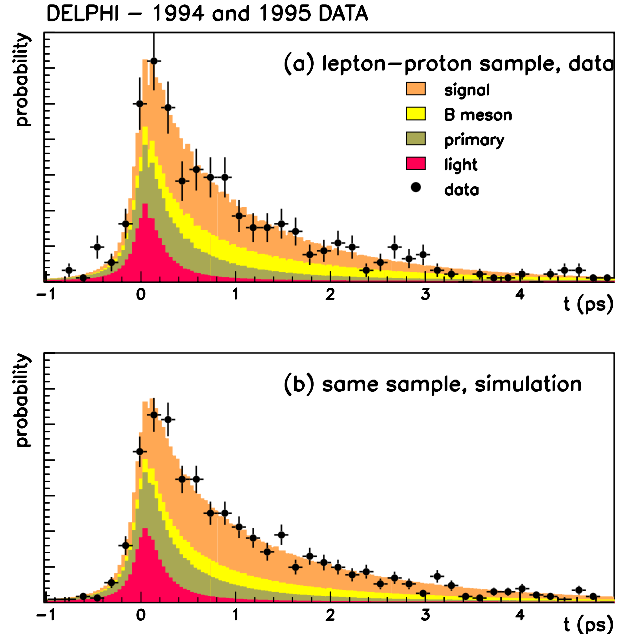

Figure 6: Reconstructed proper time distribution for the DELPHI proton-lepton analysis for 1994-95 data (points) and the various sample components (histograms).

in the precision of B^+ and B_d^0 lifetimes has stemmed from the application of inclusive topological techniques and the addition of new data collected by SLD. As seen in Fig. 8, lifetime differences are small and the observed hierarchy $\tau(\Lambda_b) < \tau(B_s^0) < \tau(B_d^0) < \tau(B^+)$ is consistent with predictions based on the Heavy Quark Expansion. [a] The measurements are becoming precise enough to begin to see a difference between B^+ and B_d^0 lifetimes, the significance being at the $2.6\,\sigma$ level. The b-baryon lifetime remains significantly low which continues to spur theoretical activity.

Further improvements are expected in the near future from SLD with the inclusion of the full 1997-98 data sample, corresponding to an increase of $\sim 40\%$ in statistics. In the longer term, the next step in precision will come from experiments at the B Factories and the Tevatron.

[a] A review of B_s^0 lifetime measurements was presented by A. Ribon at this conference.

Figure 7: Measurements of the *b*-baryon lifetime.

Figure 8: World averages for various *b*-hadron lifetime ratios. The hatched bands indicate the approximate range of predictions. [1]

References

1. I. I. Bigi *et al.*, in *B Decays*, ed. S. Stone (World Scientific, New York, 1994), p. 132.
2. M. Neubert and C.T. Sachrajda, *Nucl. Phys.* B **483**, 339 (1997).
3. CDF Collaboration, *Improved Measurement of the B^- and $\overline{B^0}$ Meson Lifetimes using Semileptonic Decays*, FERMILAB-Pub-98/167-E, Paper ICHEP98-PA08/731 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
4. SLD Collaboration, *Measurement of the B^+ and B^0 Lifetimes using Topological Vertexing at SLD*, SLAC-PUB-7868, Paper ICHEP98-PA08/180 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
5. SLD Collaboration, *A Preliminary Improved Measurement of the B Hadron Energy Distribution in Z^0 Decays*, SLAC-PUB-7826, Paper ICHEP98-PA03/261 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
6. L3 Collaboration, *Phys. Lett.* B **416**, 220 (1998), Paper ICHEP98-PA08/554 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
7. L3 Collaboration, *Upper Limit on the Lifetime Difference of Short- and Long-Lived B_s^0 Mesons*, L3 Note 2281, Paper ICHEP98-PA08/557 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
8. OPAL Collaboration, *Phys. Lett.* B **426**, 161 (1998), Paper ICHEP98-PA08/317 contributed to the XXIXth International Conference on High Energy Physics, 23-29 July 1998, Vancouver, Canada.
9. DELPHI Collaboration, *Measurement of the Lifetime of b-baryons*, DELPHI 98-72 CONF 140, Paper ICHEP98-PA08/156 contributed to the XXIXth International Conference on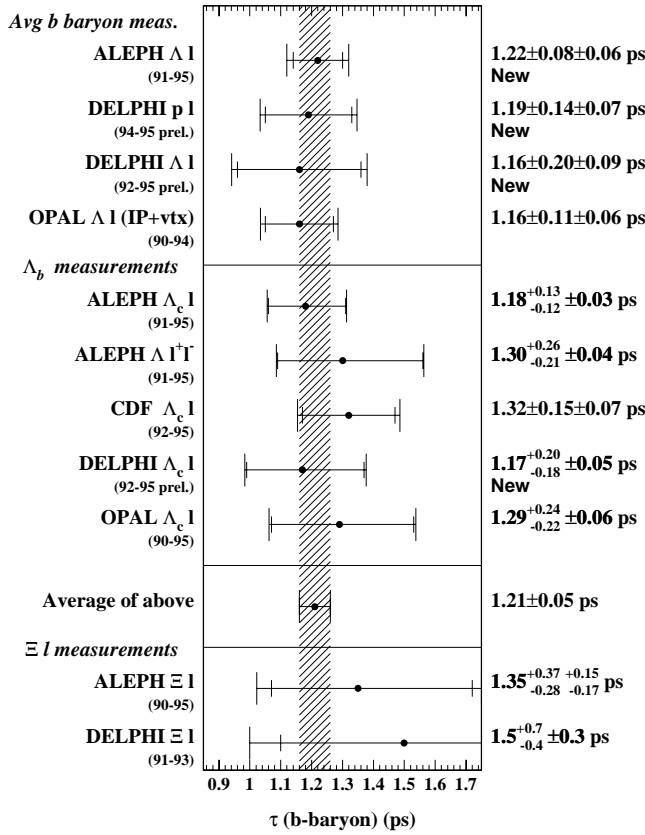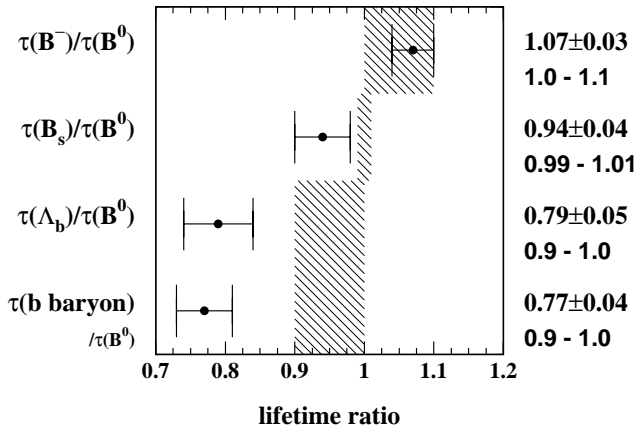 High Energy Physics, 23-29 July 1998, Vancouver, Canada.