Fermi National Accelerator Laboratory

FERMILAB-Conf-97/385-E
CDF

Lifetime Results from Heavy Quark Systems

Vaia Papadimitriou
For the CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 1997

Published Proceedings of the *17th International Conference on Physics in Collisions (PIC97)*, Bristol, England, June 25-27, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Disclaimer

Distribution

CDF/PUB/BOTTOM/PUBLIC/4391

LIFETIME RESULTS FROM HEAVY QUARK SYSTEMS

VAIA PAPADIMITRIOU
Texas Tech University, Department of Physics, Box 41051,
Lubbock, TX, U.S.A

We present the latest measurements of weakly decaying b-hadrons from experiments at e^+e^- and $p\bar{p}$ colliders. These measurements include the average lifetime of b-hadrons, lifetimes of the B^-, B^0 and B_s^0 mesons, the average lifetime of b-baryons and lifetimes of the Λ_b and Ξ_b baryons.

1 Introduction

In the spectator model all charm (c) and beauty (b) lifetimes are due to the $c \to sW^+$ and $b \to cW^-$ decays respectively, which implies that all the c hadron lifetimes are the same and all the b hadron lifetimes are the same. The spectator model failed in the prediction of the equality of the lifetimes of hadrons containing c quarks. The most recent measurements of the lifetimes of c hadrons are listed in Ref. 1 and we see that $\tau(D^\pm) \approx 2.5\tau(D^0) \approx 2.3\tau(D_s^\pm) \approx 5.1\tau(\Lambda_c^\pm) \approx 3.0\tau(\Xi_c^\pm) \approx 10.8\tau(\Xi_c^0) \approx 16.5\tau(\Omega_c^0)$. These lifetime differences are attributed to non-spectator effects such as quark interference, weak annihilation and W exchange diagrams. Applying the same ideas to b hadron results we expect the lifetime hierarchy: $\tau(\Lambda_b^0) < \tau(B^0) \approx \tau(B_s^0) < \tau(B^\pm)$.

Using the heavy quark expansion formalism, the differences between the lifetimes of the b baryons and b mesons are predicted to depend on $1/m_b^2$ and higher terms while meson-meson differences are predicted to depend on $1/m_b^3$ and higher terms [2,3]. Differences between lifetimes are expected to be small, therefore precise measurements are required.

The experimental results reported in this review come from e^+e^- collisions at the Z^0 resonance (LEP at CERN and SLC at SLAC) and from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV (the Tevatron at Fermilab). At the e^+e^- colliders of LEP and SLC the environment is clean and the b hadrons have a large boost (average value of 6). The average momentum of the b hadron is 30 GeV/c and the mean distance travelled by a b hadron is 3 mm. On the Z^0 resonance, $b\bar{b}$ production is 22% of the hadronic cross section. At LEP one currently has 1.7×10^6 b hadrons per experiment and at SLD $\sim$ 90,000 b hadrons. At the Tevatron, the inclusive b hadron cross section is approximately 78 μb [4], which is very large, but the background is high. CDF accumulated $\sim 10^9$ b hadron decays during Run I (1992-1996). The CDF triggers used for the results presented in this review are a dimuon trigger and an inclusive lepton trigger (e, μ). The average transverse momentum of the b hadrons from the dimuon trigger is 10 GeV/c, and from the inclusive lepton trigger is 20 GeV/c.

2 Lifetimes of Weakly-decaying b Hadrons

2.1 Methods of Lifetime Determination

Two general methods have been used so far to measure the lifetimes of b hadrons: the decay length method and the impact parameter method. The first method for measuring lifetimes is based on the decay length, which is the distance from the b hadron production point to the b hadron decay point. The decay length L is related to the lifetime $c\tau$ by the Lorentz boost $\beta\gamma$: $L = \beta\gamma c\tau$. For fully reconstructed b hadron decays the boost value is: $\beta\gamma = p_b/m_b$, where p_b is the b hadron momentum and m_b is the b hadron mass. We get the lifetime by fitting the data with an exponential convoluted with a resolution function taking the background into account. In the second method for measuring lifetimes we use the distance of closest approach to the collision point of the extrapolated trajectories of the charged particles coming from the b-hadron decay. We fit the data with a convolution of a function describing the underlying physics processes-determined from Monte Carlo models-and a resolution function. The average impact parameter is proportional to the lifetime of the b hadron and it is fairly insensitive to the hadron boost.

2.2 Average Lifetime of b Hadrons

The measurement of the average lifetime of b hadrons is useful in the measurement of $|V_{cb}|$, but it is most useful for checking the consistency of individual b lifetime results. Measurements of the average b lifetime have been made using both the impact parameter method and the decay length method. The techniques used for this measurement are inclusive and usually the measurement has low statistical errors. The results are summarized in fig. 1.

Three measurements based on lepton impact parameter are reported by the ALEPH[5], L3[6] and OPAL[7] experiments. DELPHI[8] uses the hadron impact parameter method.

Six measurements based on reconstructed decay vertices are reported by the ALEPH [9], CDF [10], DELPHI [11], L3 [6], OPAL [12] and SLD [13] experiments. The LEP experiments and SLD reconstruct the decay length of vertices found

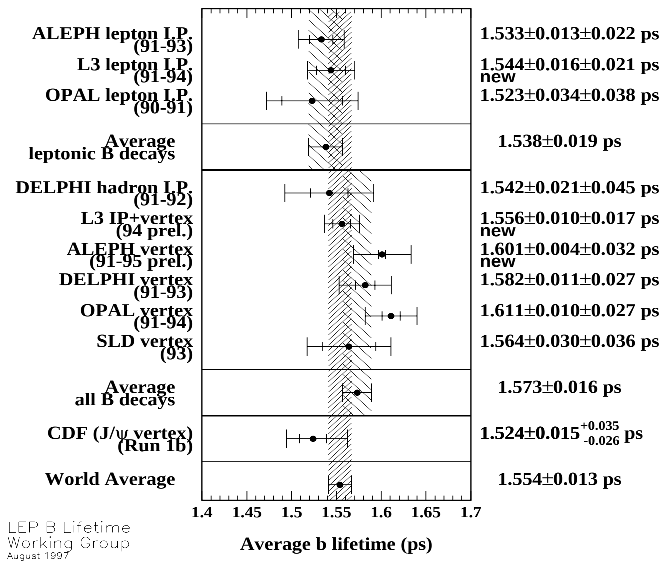

Figure 1: Average lifetime of b-hadrons.

in hadronic Z^0 decays. CDF uses the vertex reconstructed from $J/\psi \to \mu^+\mu^-$ decays which originate from $B \to J/\psi X$ decays.

The dominant systematic errors in these measurements are due to the modeling of b quark fragmentation and b hadron decay. These average lifetime results have to be compared very carefully because the different methods may select different mixtures of b hadrons and therefore might not be measuring the same average.

2.3 Individual Lifetimes of b hadrons

Three types of signatures have been used to measure species specific b lifetimes. Fully reconstructed b hadron decays, partially reconstructed b hadron decays with a fully reconstructed c hadron and partially reconstructed, more inclusive, b hadron decays. The full reconstruction of the decay products of the b hadrons has the advantage that the vertex of the decay and the boost are well known, there is very little dependence on Monte Carlo simulations and one can easily obtain the relevant backgrounds from sidebands of mass distributions.

The disadvantage is that the statistics are poor. This method works well at the CDF experiment that has a very large sample of reconstructed b decays. The partial reconstruction of the final state with a fully reconstructed c hadron is a commonly used method that has good vertex determination. The missing particles degrade the boost determination. This method has more statistics than the method of full reconstruction and works well at the CDF and LEP experiments. Finally, the inclusive vertex reconstruction method has large statistics but worse vertex resolution. It can be heavily Monte Carlo dependent but it works well at the SLD experiment which has very good vertexing capabilities and at the LEP experiments.

2.3.1 B^0 and $B^\pm$ Lifetimes

The lifetimes of the B^0 and $B^\pm$ mesons are summarized in figures 2 and 3 respectively and the lifetime ratio in fig. 4.

Two experiments have reported lifetimes of B^0 and $B^\pm$ based on exclusive decays. CDF [10] uses a $J/\psi \to \mu^+\mu^-$ trigger to reconstruct $B^\pm$ mesons in the decay modes $J/\psi K^\pm$, $J/\psi K^*(892)^+$, $\psi(2S)K^\pm$ and $\psi(2S)K^*(892)^+$ and B^0 mesons in the decay modes $J/\psi K^0_s$, $J/\psi K^*(892)^0$, $\psi(2S)K^0_s$ and $\psi(2S)K^*(892)^0$. From a data sample of 110 pb^{-1}, they have a signal of 824 ± 36 $B^\pm$ and 436 ± 27 B^0. The ALEPH experiment [14] takes advantage of good particle identification and very good particle momentum resolution to reconstruct 94 $B^\pm$ and 121 B^0 candidates from a large number of final states.

Five measurements of the lifetimes of the B^0 and $B^\pm$ mesons based on partially reconstructed exclusive final states have been reported by the ALEPH[14], CDF[15], DELPHI[16], L3[6], and OPAL[17] experiments. To perform these measurements, the experiments use the semileptonic decay $B \to D^{(*)}l\nu(\mathrm{X})$ where the $D^{(*)}$ is completely reconstructed. The existence of higher D meson resonances (D^{**}) means that particular charge correlations of a D meson and a lepton do not just originate from one flavour of B meson. A knowledge of the fraction of B mesons that decay to $D^{**}l\nu(\mathrm{X})$, f^{**}, is therefore required and the experiments use $f^{**} = 36\pm12\%$, as measured by the CLEO experiment.

DELPHI and SLD report measurements of $\tau(B^0)$ and $\tau(B^\pm)$ based on inclusive vertexing with charge determination. In the DELPHI [18] analysis b-hadrons are tagged as jets with a well separated secondary vertex and the charge of the b-hadron candidate is taken to be the sum of the charges of the particles in the secondary vertex. This procedure finds 1817 b-hadron candidates in a sample of 1.4×10^6 hadronic Z^0 decays, which according to Monte Carlo have a b purity of 99.1%. Requiring a well separated vertex means that the time distribution of the accepted events is not exponential over all time.

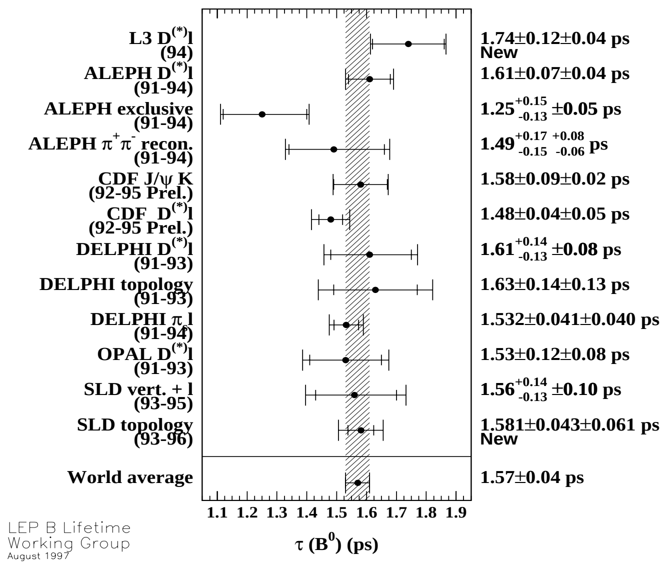

Figure 2: B^0 lifetime.

However, by making an estimate of the minimum possible decay length measurable in each event and subtracting this from the measured decay length, the new reconstructed time distribution is exponential. The mean lifetime of the mixture of neutral b-hadrons in this data sample is $1.58 \pm 0.11 \pm 0.09$ psec. The corresponding mean lifetime of B^0 mesons shown in fig. 2 is derived from the neutral b-hadron lifetime after assuming that the selected neutral b-hadrons are composed of B^0, B^0_s and Λ_b and using the lifetimes of B^0_s and Λ_b as measured in independent analyses. The systematic uncertainties here come largely from possible fit biases and, for the B^0 lifetime, from the B^0_s contribution in the neutral b-hadron mixture as well. SLD[19] uses 150,000 hadronic Z^0 decays detected with their original vertex detector and 50,000 hadronic decays detected with their upgraded detector. Their analysis method is similar to the topological method of DELPHI. They also reconstruct well displaced vertices, but they take the expected shape of the data from a Monte Carlo simulation. Exploiting their unique vertexing capabilities, they use a novel algorithm to reconstruct vertices in three dimensions. The analysis isolates 20,783 b-hadron candidates with b purity of $\sim 98\%$. This sample is significantly larger than the one recon-

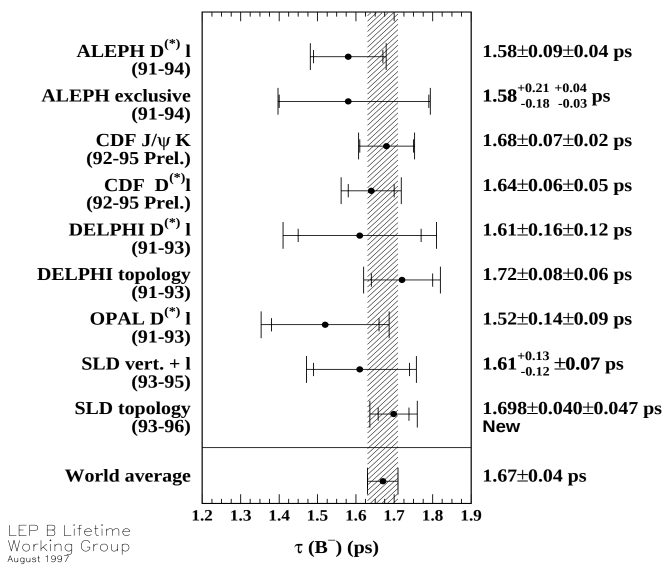

Figure 3: B^- lifetime.

structed by DELPHI despite the fact that SLD started with less statistics. The main sources of systematic errors here are b-fragmentation, tracking efficiency and the uncertainty in the fraction of b-baryons. The systematics due to the fitting procedure are smaller than in the DELPHI topological analysis.

By far the most accurate single measurement of the B^0 lifetime is the DELPHI [20] measurement using $\pi^+ l^-$ correlations. They use the decay mode $\bar{B}^0 \to D^{*+} X l^- \bar{\nu}$, $D^{*+} \to D^0 \pi^+$. In events with high p_t leptons they reconstruct inclusively the D candidate by clustering tracks in a jet up to 2.2 GeV. Then they search for a pion which alters the cluster mass and they look for an excess of events on the right sign over the wrong sign $\pi - l$ combinations. They find 3523±150 D^* candidates attributed to $\bar{B}^0$ decays. The result of the lifetime measurement is shown in fig. 2. The dominant systematic errors here are due to the fraction and the lifetime of the combinatorial background, resolution effects and the fitting procedure.

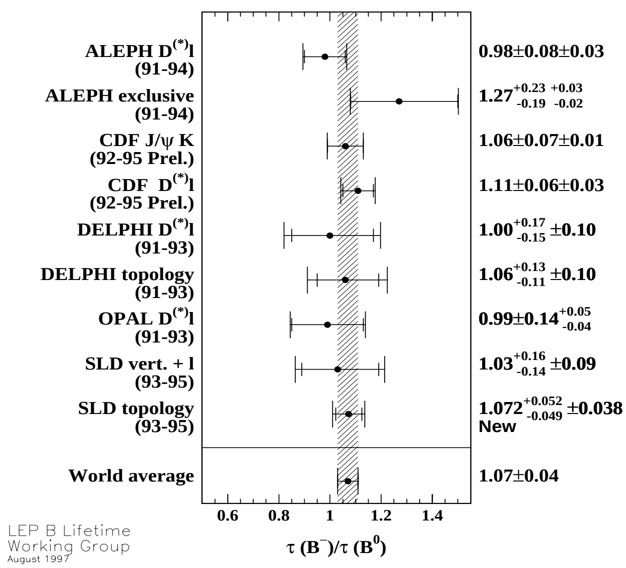

Figure 4: B^- and B^0 lifetime ratio.

2.3.2 B_s^0 Lifetime

The measurements of the B_s^0 lifetime are summarized in fig. 5. The most common signature used to measure the B_s^0 lifetime is opposite-charge $l^+ D_s^-$ combinations from the decay $B_s^0 \to D_s^- l^+ \nu X$. ALEPH [21], CDF [15], DELPHI [22] and OPAL [23] all use this mode, but while the LEP experiments reconstruct many D_s decay modes CDF uses only the $\phi\pi$ mode. The most common decay modes used to reconstruct the D_s^- meson are $\phi\pi^-$ and $K^{*0}K^-$. The ALEPH experiment uses the additional hadronic modes $\phi\pi^+\pi^-\pi^-$, $K_s^0 K^-$ and $K^0 K^{*-}$, as well as the semileptonic mode $\phi l^- \bar{\nu}$. The DELPHI experiment uses the decay mode $f^0\pi^-$ as well. Although ALEPH reconstructs 181 signal events in seven decay channels and DELPHI 173 signal events in seven decay channels, CDF reconstructs 254±21 signal events in the $\phi\pi^-$ channel alone.

Four other signatures have been used to measure the B_s lifetime. ALEPH [24] and DELPHI [25] present B_s measurements by reconstructing the decay length from the vertex of the D_s^- with a positively charged hadron from the B_s^0 decay. DELPHI [25] uses also $l\phi$ correlations from $B_s^0 \to D_s^- l^+ \nu X$, $D_s^- \to \phi X$ decays.

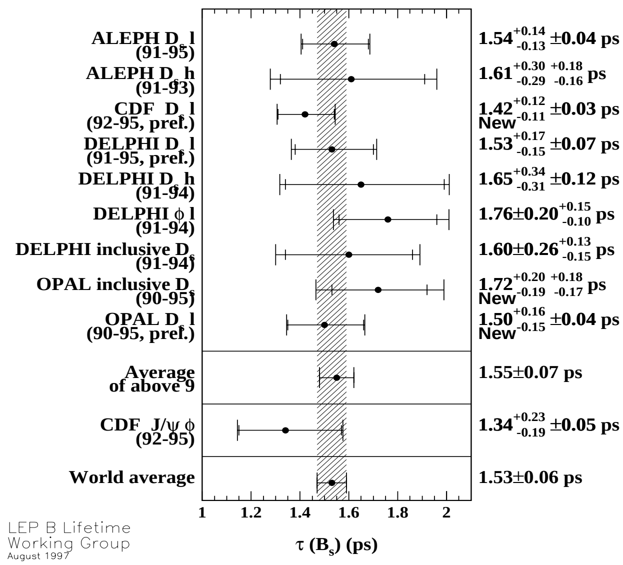

Figure 5: B_s^0 lifetime.

DELPHI [25] and OPAL [26] use as well inclusive D_s^- reconstruction. Finally CDF [27] reports on a low statistics measurement based on an exclusive sample of 58±12 $B_s \to J/\psi\phi$ decays. This mode is interesting because it has a different CP eigenstate composition from the semileptonic final state. There may be a lifetime difference of up to 30% [28] between the odd and even CP eigenstates of B_s, but no significant lifetime difference is observable with the current data.

2.3.3 b-baryon Lifetimes

A summary of the average lifetime of b-baryons is presented in fig. 6. Summaries of the lifetimes of the Λ_b^0 and Ξ_b baryons specifically, are presented in fig. 7.

A mixture of b-baryon states is produced at LEP: Λ_b^0, Σ_b, Ξ_b and Ω_b. From these b-baryons, only the ground state baryons Λ_b^0, Ξ_b^0, Ξ_b^- and Ω_b^- should decay weakly. Three LEP experiments (ALEPH, DELPHI and OPAL) report on measurements of the average b-baryon lifetime. One technique to measure this lifetime is by observing properly correlated b-baryon decay products $(\Lambda l^-, \bar{\Lambda} l^+)$

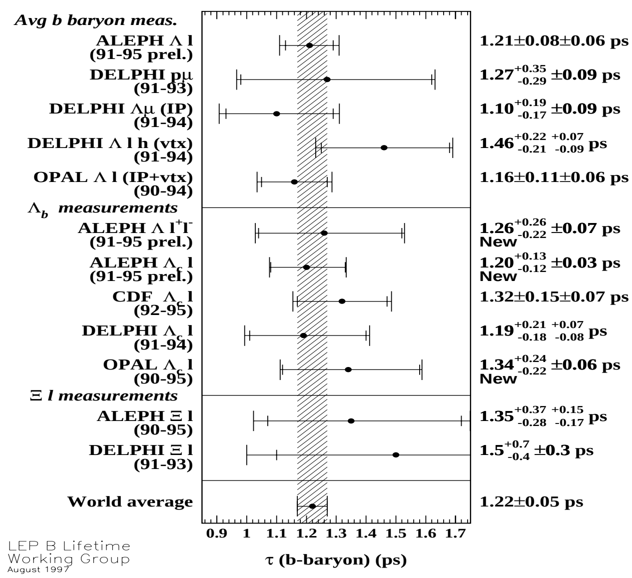

Figure 6: Average b-baryon lifetime.

from the decays $\Lambda_b^0/\Xi_b^0/\Xi_b^-/\Omega_b^- \rightarrow \Lambda l^- \bar{\nu} X$, $\Lambda \rightarrow p\pi^-$. This technique has the highest statistical precision. The lifetime is measured by employing either the decay length method or the impact parameter method. The decay length method is employed by OPAL [29] using the $\Lambda - l$ vertex and by DELPHI using either the $\Lambda - l - \pi$ vertex [30] or the $proton - \mu$ vertex [31]. The impact parameter method is employed by ALEPH [32], DELPHI [30] and OPAL [29]. One of the major contributions to the systematic error in the lepton impact parameter method arises from the lack of knowledge of the Λ_b^0 polarization. The decay length method is less sensitive to this systematic uncertainty.

A second technique relies on full reconstruction of Λ_c^+'s paired with high momentum leptons, corresponding to the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ l^- \bar{\nu} X$. The Λ_c^+ candidates are reconstructed in the decay modes: $\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow p\bar{K}^0$, $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^-\pi^+$ and $\Lambda_c^+ \rightarrow \Lambda\pi^+$. Four measurements of the lifetime based on this method are reported by ALEPH [32], CDF [33], DELPHI [30] and OPAL [23]. These measurements are presented in both figures 6 and 7.

A third technique to measure average b-baryon lifetime employs a similar method as the second technique, but uses partially reconstructed Λ_c^+ candi-

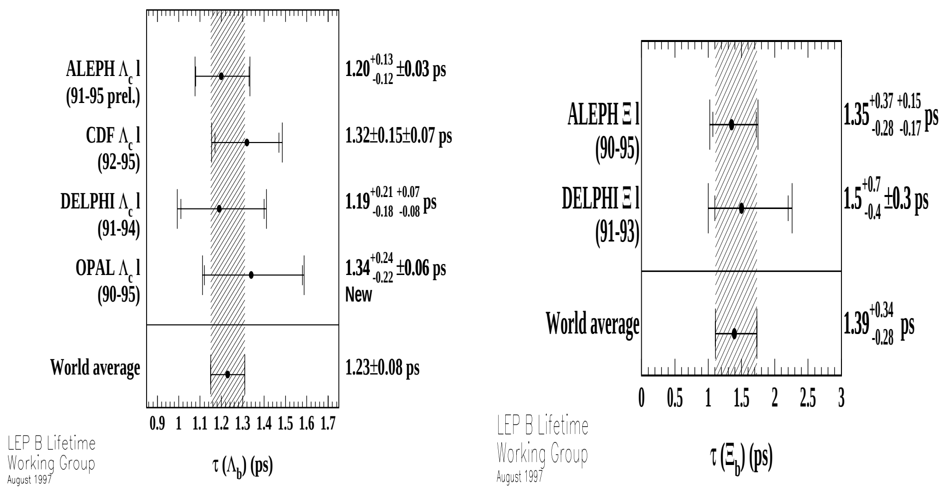

Figure 7: Λ_b^0 and Ξ_b lifetimes.

dates, namely $\Lambda_b^0 \to \Lambda_c^+ l^- \bar{\nu} X$ with $\Lambda_c^+ \to \Lambda l^+ X$. ALEPH [32] measures the average b-baryon lifetime with this technique using 46 $\Lambda l^- l^+$ events. According to Monte Carlo simulations, 86% of these events come from Λ_b^0 decays and 5.9% from Ξ_b decays.

ALEPH, DELPHI and OPAL all report excesses of same-sign $l^\pm \Xi^\pm$ pairs over opposite-sign pairs. ALEPH and DELPHI use this excess to determine the Ξ_b lifetime. DELPHI [34] has 10 candidate events and ALEPH [35] has 44 events. The 44 ALEPH events split into 30 $\Xi - \mu$ and 14 $\Xi - e$ pairs, and the lepton impact parameter method is used to extract the lifetime. A summary of the measurememnts of the Ξ_b lifetime is presented in fig. 7.

3 Conclusion-Prospects

As we have discussed in the previous sections, a large number of b-hadron lifetime measurements is available. The average lifetimes of the B^0 and $B^\pm$ mesons are known with an uncertainty of $\sim 2.5\%$; the average lifetimes of the B_s meson and b-baryon are known with an uncertainty of $\sim 5\%$. Finally the average lifetimes of the Λ_b and Ξ_b baryons are known with uncertainties $\sim$ 7% and $\sim$ 20% respectively. A summary of the measured ratios of various b-

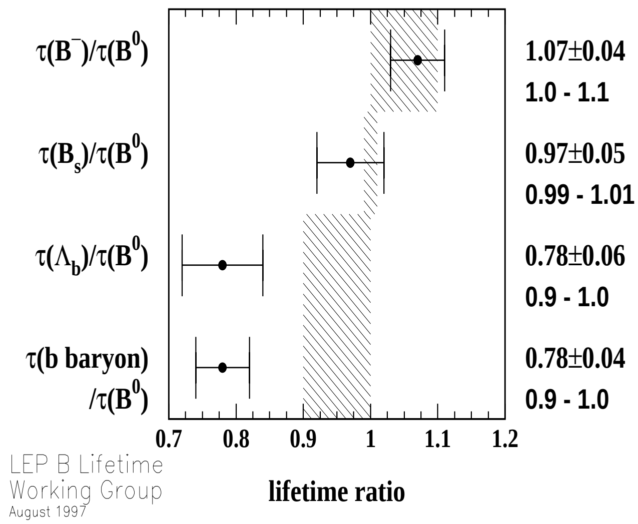

Figure 8: Comparison of lifetime ratios between theoretical predictions and experiment.

hadron lifetimes over the B^0 lifetime are presented in fig. 8 together with the theoretical expectations. The agreement with the theory is good for the ratio $\tau(B^{\pm})/\tau(B^0)$. The ratio is greater than 1 by about one standard deviation. One can use this measurement to start imposing constraints on the coefficients in the heavy quark expansion mentioned in section 1. For the ratio $\tau(B_s/\tau(B^0)$ the agreement is again good but the measurements are not precise enough to test the theoretical uncertainty of 1% in the prediction. The $\tau(\Lambda_b^0)/\tau(B^0)$ and $\tau(b-baryon)/\tau(B^0)$ experimental ratios are interestingly below the theoretical bounds but we will need more data in order to convince ourselves that the low experimantal value is not a statistical fluctuation.

Although most of the CDF, LEP and SLD available data have been already analyzed, CDF and SLD expect to collect more data in the near future. SLD expects to collect 200,000 more hadronic Z^0 decays with their upgraded vertex detector that has excellent three dimensional capabilities. CDF expects to collect in Run II, starting in late 1999, 20 times more statistics than their currently available sample. CDF will be also equipped with upgraded vertex detectors of excellent capabilities during Run II. The D0 experiment at Fermilab will also start measuring b-hadron lifetimes in Run II and the asymmetric b-factories will measure the B^0 and $B^{\pm}$ lifetimes as well. Wider use of new methods and our ability to use more challenging decay channels for these measurements should give further improvement and will allow us to increase the precision of the measurements.

Acknowledgments

I would like to thank the following people who have been very helpful in providing information about the material presented in this summary: Juan Alcaraz (L3), Dale Koetke (OPAL), Joachim Mnich (L3) Hans-Gunther Moser (ALEPH), Claire Shepherd-Themistocleous (OPAL), Franco Simonetto (DELPHI), Hans Wenzel (CDF) and Stephane Willocq (SLD).

References

1. Particle Data Group, *Phys. Rev.* D **54**, 445 (1996).
2. I.I. Bigi, *Nuovo Cimento* **109**, 713 (1996).
3. M. Neubert, C.T. Sachrajda, *Nucl. Phys.* B **483**, 339 (1997).
4. P. Nason, S. Dawson, R.K. Ellis, *Nucl. Phys.* B **303**, 607 (1988), *Nucl. Phys.* B **327**, 49 (1989); F. Abe *et al.*, *Phys. Rev. Lett.* **75**, 1451 (1995).
5. D. Buskulic *et al.*, *Phys. Lett.* B **369**, 151 (1996).
6. The L3 Collaboration, see http://hpl3sn02.cern.ch/analysis/bphysics /preliminary_for_conferences.html, Aug. 1997.
7. P.D. Acton *et al.*, *Z. Phys.* C **60**, 217, (1993).
8. P. Abreu *et al.*, *Z. Phys.* C **63**, 3, (1994).
9. The ALEPH Collaboration, see http://alephwww.cern.ch/ALPUB/ oldconf/HEP97/conf.html, Aug. 1997.
10. F. Abe *et al.*, *FERMILAB-PUB*-97/352-E, submitted to *Phys. Rev. D.*
11. P. Abreu *et al.*, *Phys. Lett.* B **377**, 195 (1996).
12. P.D. Acton *et al.*, *Z. Phys.* C **73**, 397, (1997).
13. K. Abe *et al.*, *Phys. Rev. Lett.* **75**, 3624 (1995).
14. D. Buskulic *et al.*, *Z. Phys.* C **71**, 31, (1996).
15. CDF Collaboration, http://www-cdf.fnal.gov/physics/new/ bottom/ bottom.html.
16. P. Abreu *et al.*, *Z. Phys.* C **68**, 13, (1995).
17. R. Akers *et al.*, *Z. Phys.* C **67**, 379, (1995).
18. W. Adam *et al.*, *Z. Phys.* C **68**, 363, (1995).
19. The SLD Collaboration, SLAC-PUB-7635, Aug. 1997.
20. P. Abreu *et al.*, *Z. Phys.* C **74**, 19, (1997).

21. D. Buskulic *et al.*, *Phys. Lett.* B **377**, 205 (1996).
22. The DELPHI Collaboration, ICHEP-96 PA01-042, Paper Contributed to the XXVIII Int. Conf. on High Energy Physics, Warsaw, Poland, July 1996.
23. The OPAL Collaboration, *EPS-HEP*97-PN305, submitted to EPS Conference, Jerusalem, 19-26 August 1997.
24. D. Buskulic *et al.*, *Z. Phys.* C **69**, 585, (1996).
25. P. Abreu *et al.*, *Z. Phys.* C **71**, 11, (1996).
26. The OPAL Collaboration, *CERN-PPE*/97-095, July 1997.
27. F. Abe *et al.*, *Phys. Rev. Lett.* **77**, 1945 (1996).
28. I. Dunietz, *Phys. Rev.* D **52**, 3048 (1995).
29. R. Akers *et al.*, *Z. Phys.* C **69**, 195, (1996).
30. P. Abreu *et al.*, *Z. Phys.* C **71**, 199, (1996).
31. P. Abreu *et al.*, *Z. Phys.* C **68**, 375, (1995).
32. The ALEPH Collaboration, *EPS-HEP*97-604, submitted to EPS Conference, Jerusalem 19-26 August 1997.
33. F. Abe *et al.*, *Phys. Rev. Lett.* **77**, 1439 (1996).
34. P. Abreu *et al.*, *Z. Phys.* C **68**, 541, (1995).
35. D. Buskulic *et al.*, *Phys. Lett.* B **384**, 449 (1996).