Heavy Quark Physics from LEP

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Representing the LEP Collaborations

ABSTRACT

A review of some of the latest results on heavy flavor physics from the LEP Collaborations is presented. The emphasis is on B physics, particularly new results and those where discrepancies with theory are emerging. A brief description is given of the many techniques which have been developed to permit these analyses.

CONTENTS

1 Introduction

Heavy flavor physics has become one of the great successes of the LEP experiments due to the high efficiency with which the Z decays to a pair of b quarks can be tagged. Consequently, in this review I shall concentrate on results in the b sector even though there are now a number of interesting charm results emerging.

By the end of 1994, each of the LEP experiments ALEPH, DELPHI, L3, and OPAL had recorded between three and four million hadronic Z decays, and hence, about 700 K $Z \rightarrow b\bar{b}$ per experiment. However, not all have been recorded with the full detector, and in particular, L3 has only recently introduced a silicon microvertex detector. These detectors take time to run, and so far no results have been presented with this detector, and hence, there will be few L3 results in this talk.

Although the LEP experiments cannot hope to compete on the sheer numbers of B events which are available at the $\Upsilon(4S)$ to CLEO, the higher energy does yield a number of advantages. At LEP, the b's result from Z decay, and this gives a unique opportunity to test the electroweak standard model in the quark sector where the sensitivity to the electroweak parameters can be much greater than for the leptonic Z decays. Of course, longitudinal polarization of the beams gives even greater opportunity for stringent electroweak tests in the b sector, but this looks as though it will continue to remain a dream at LEP.

At the high energy, the B_s, Λ_b, and excited B states are produced as well as the $B^{\pm}$ and B^0, and all are produced with sufficient energy to travel long distances compared to the precision which can be achieved with the silicon vertex detectors. This enables the measurement of accurate lifetimes and direct measurements of the oscillations resulting from neutral B mixing. The high energies cause the B states to be produced in jets with additional fragmentation particles. Although this is frequently a cause of signal dilution and increased background, it does enable an understanding of heavy quark fragmentation and helps to isolate those particles which come from a common B parent.

The results presented in this review will be based on those presented at the Pisa International Heavy Flavour Symposium, the Beauty '95 Workshop at Oxford, and the submissions currently available for the Brussels and Beijing conferences. However, where preliminary results have since been finalized, the final reference is given.

2 Tools and Techniques

A substantial array of tools have been developed by the LEP experiments to undertake bottom physics. The most significant are briefly reviewed below.

2.1 Tagging via Displaced Vertices

This is the great breakthrough which has made b physics so productive. It requires a silicon microstrip vertex detector with a point resolution of ~10 μm giving an impact parameter resolution of ~40 μm. Secondary vertex resolution along the direction of flight of the B is ~300 μm, and the flight paths are 1-2 mm. The ideal detector has readout in both the $r\phi$ and z coordinates, but although all experiments now have such detectors, only ALEPH, which has had a double-sided detector since 1991, has used this for the present results. DELPHI has a three-layer vertex detector. This helps with redundancy and pattern recognition but has little effect on the vertex resolution.

The major problem associated with "lifetime" tagging comes from the charm background, particularly the proportion of charged D's as their long lifetime can give decay lengths comparable to those from the B states. Evaluation of charm contamination depends upon knowledge of both the production of the various charm states in $Z \rightarrow c\bar{c}$ decays and the topological decay rates for these states. Whilst these are known adequately for most investigations, they remain a serious problem for precision measurements such as the measurement of R_b. The other failing of the lifetime tag is the fact that it gives no information on whether it was a b or a $\bar{b}$ quark which caused the tag. For asymmetry, mixing, and branching ratio measurements, this is crucial, and therefore in these cases, the lifetime tag must be supplemented with a measure of the quark sign.

2.2 Tagging via High p_t Leptons

This was the first method to be employed before the vertex detectors were installed. Approximately 20% of b decays are semileptonic to either an electron or a muon, and due to the high mass of the B and its hard fragmentation, about half of these give rise to a high-momentum lepton (≥ 3 GeV/c) with high momentum transfer (≥ 1 GeV/c) with respect to the B direction.

As prompt leptons constitute only about 1% of the charged tracks, the detectors must have good electron and muon identification, and, particularly good ability to minimize hadron background in the lepton sample. These were major design criteria for the four experiments and have been successfully achieved. Consequently, lepton tagging remains a powerful tool, particularly when associated with an identified hadron.

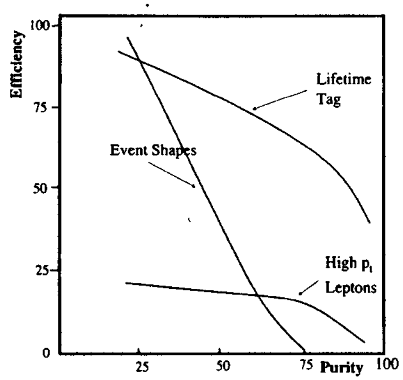

Fig. 1. Typical Efficiency vs Purity Curves for the three tagging techniques.

The major problem is the low efficiency which arises from the basic branching ratio. Additional difficulties arise from charm production as the charm semileptonic decay rate is comparable with that from beauty, although as the transverse momentum from charm is much smaller, it can be significantly reduced with the p_t cut. In principle, the lepton gives the sign of the b quark, negative lepton from b, positive from $\bar{b}$; however, this is changed if the B's mix before decaying or the observed lepton results from the semileptonic decay of the charm quark from the b decay. These dilution factors must be understood and corrected for where this is important. In many analyses, lack of complete knowledge of both the b-decay spectrum and the b-fragmentation function limits the accuracy.

2.3 Tagging with Event Shapes

This method is used more rarely and now virtually never on its own. Due to the high mass of the B hadrons, the $Z \to b\bar{b}$ events are slightly more spherical than those from the lighter quarks, and this fact can be used to achieve some discrimination. As the method uses all decay modes, a high efficiency can be achieved, but this is at the expense of low purity. Estimates of the efficiency and purity depend on the simulation of the nonperturbative fragmentation, and so it is hard to achieve an absolute measurement with known systematics. Nevertheless, the method is not without merit; perhaps the most significant being that, unlike the above two approaches, charm events are more *uds*-like than b-like. It can, hence, be of significant value in forming a charm tag when coupled with a lifetime or lepton signature.

Typical efficiency/purity plots for these three basic b-tags are shown in Fig. 1.

2.4 D^* Reconstruction

In the multiparticle B jets, combinatorial background usually makes it extremely difficult to identify the decaying hadrons in the B decay products. However, the very low Q value for the decay $D^{*+} \to D^0\pi^+$ enables a D^* sample to be extracted with low background. D^* states, of course, are also produced in charm events, but partial discrimination can be achieved on the basis of the momentum spectrum, as those from charm production are primary D^*'s and have a substantially harder spectrum than those cascading down from the B decay. However, when an identified D^{*+} is combined with a negative lepton on the same side of the event, this forms a very strong and clean signature for the decay $B \to D^*\ell\nu$ or $B \to D^*\pi\ell\nu$. Statistics are such that $D^{*\pm}\ell^{\mp}$ tags are now a very useful signature.

2.5 Hadron Identification

The Cabibbo favored decay chain $b \to c \to s$ requires that one of the final hadrons should be a kaon. Identification of this kaon significantly reduces combinatorial background when examining the decay products. All experiments use *dE/dx* from their main tracking chambers, but here DELPHI have a significant advantage due to their RICH counters which give good π/K separation up to 20 GeV.

2.6 E_{miss}—Neutrino Energy

Many of the investigations at LEP use semileptonic decays to identify particular states for analysis. Clean signals can then be achieved, but as the semileptonic decays involve a missing neutrino, a full kinematic reconstruction in the B rest frame is impossible. However, if the detector is hermetic and the calorimeters have sufficient directional and energy resolution, a good estimate can be made of the missing neutrino energy. As energy is not shared equally between the two halves of an event, this must frequently be estimated with an algorithm such as the following:

$$E_\nu = E_{beam} - E_{vis} + \frac{M_{same}^2 - M_{opp}^2}{4E_{beam}}.$$

This is used by ALEPH and gives them a resolution on the neutrino energy of about 2.5 GeV. It makes possible a number of the following analyses based on semileptonic decays.

2.7 Estimation of the B Momentum

This is a procedure sometimes referred to as inclusive B reconstruction. As true exclusive reconstruction is impossible for all but a very few B decays, alternative techniques have been evolved by which tracks in a hadronic b jet are associated with either the decaying B or the primary vertex on the basis of quantities such as vertex information, rapidity along the jet axis, etc. The exact procedure varies from collaboration to collaboration and depends upon the particular study under consideration. The technique has proved to be particularly effective when searching for excited B states because similar errors occur for both B and B^*, and hence, cancel in the difference which gives the signal.

2.8 Tag Calibration Using Two Hemispheres

This is a powerful and increasingly useful method. When events are divided by a plane perpendicular to the thrust axis, usually each hemisphere will contain one of the primary quarks. With the increase in statistics, it has become possible to use this to calibrate tags by comparing the number of tags in single hemispheres with the number of events which have tags in both hemispheres. The relations are

$$N_1 = \varepsilon_b R_b + \varepsilon_c R_c + \varepsilon_{uds}(1 - R_b - R_c)$$
$$N_2 = C\varepsilon_b^2 R_b + \varepsilon_c^2 R_c + \varepsilon_{uds}^2(1 - R_b - R_c)\ .$$

The ε's define the efficiencies of the tag for b, c, and uds hemispheres, and C represents a correlation between the hemispheres as the two b's will not always be on opposite sides. It is assumed that C, ε_c, and ε_{uds} are small.

R_b can be eliminated, and hence, the tagging procedure can be calibrated without further recourse to models or Monte Carlo except for the small parameters. Alternatively, the tagging efficiency can be eliminated to determine R_b, and this is the basis of all competitive measurements of R_b. The main problems result from the charm efficiency and the correlation term, as these cannot be eliminated and must be obtained in another way, usually from Monte Carlo.

2.9 Jet Charge

Jet charge is defined by

$$Q_{jet} = \frac{\sum_i q_i x_i^\kappa}{\sum_i x_i^\kappa},$$

with x a kinematical quantity such as p, p_{long}, or y relative to the jet axis, and κ is a weighting factor usually chosen between 0.5 and 1.

This provides an alternative method to determine whether a B jet contains a b or a $\bar{b}$. Although not as clean as the lepton method, it has the major advantage that it is not restricted to semileptonic decays, and it therefore complements the lifetime tagging technique. Moreover, unlike general jet charge algorithms which are heavily dependent on Monte Carlo for their efficiency estimation, the lifetime tag can be used to establish the important charge separation parameter for the b's directly from the data. As in so many cases, the major problem then becomes an understanding of the background from charm events.

3 Electroweak B Physics

The ability to tag $Z \to b\bar{b}$ events with high efficiency and purity has made it possible to perform tests of the Standard Model in the quark sector with a precision comparable to that in the lepton sector. The b sector, however, allows the test of electroweak vertex corrections due to the high coupling of the b to top with the strength of these corrections being proportional to m_{top}^2. As a result of the high top mass, these corrections are of the order of 1% for $R_b = \Gamma_{b\bar{b}}/\Gamma_{had}$, and hence, just within the realm of experimental measurement. The other major electroweak measurement which is performed with b quarks at LEP is the forward-backward asymmetry in Z decay. This provides the single most sensitive measurement from the LEP experiments for the measurement of $\sin^2 \vartheta_W^{eff}$.

3.1 Z Decay Width to b Quarks, R_b

Measurements of R_b must aim at an accuracy of ~1%, and therefore, cannot rely upon Monte Carlo for efficiency estimations. For these measurements, the use of double hemisphere tags to eliminate the basic efficiency of the b tag is vital.

The best methods rely upon the lifetime tag, and these can now reach individual accuracies approaching the 1% level. Difficulties result from the charm background and the correlations between the hemispheres which may result, e.g., from hard gluon production.

Both of these must be taken from Monte Carlo. Results using these procedures have been given by the three experiments with vertex detectors; all are currently systematic limited, but there is certainly the capability to reduce the errors by understanding these problems. The LEP electroweak working group is investigating the problem and is establishing principles by which each experiment quotes its results so that a realistic attempt at combining them may be made.

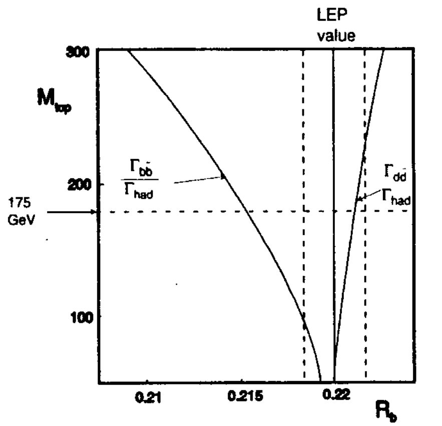

Fig. 2. The current LEP value of R_b with predictions for both R_b and R_d in the Standard Model as a function of the top mass.

The second significant technique is to use the lepton tag. This suffers from lower statistics as well as similar problems with charm background and hemisphere correlations. The analyses fit variables related to the single and dilepton p and p_t spectra. Such analyses, referred to as "global analyses," do not just give the electroweak parameters such as the b and c widths and asymmetries, but also other quantities of interest for b physics such as the $b \to \ell$ and $b \to c \to \ell$ branching ratios, the mean energy fraction taken by the b and c hadrons in the fragmentation and the integrated mixing parameter, χ. The accuracy for R_b is, however, roughly a factor of two worse than that from the lifetime methods.

Methods which are becoming increasingly popular use more than one tag. These can certainly improve the tagging rate, and hence, the statistical accuracy; however, the trade-off with systematics is not always simple to establish.

In the review by Karlsson[1] at the recent Pisa meeting, the average LEP value for R_b was given as 0.2196 ± 0.0019 with R_c fixed at the Standard Model value of 0.171. This gives a discrepancy at the 2—3 σ level with the expected value of 0.2155 for a top mass of 175 GeV as shown in Fig.2. However, one must be careful in quoting confidence limits as measurements are now systematically limited,which makes the combination of results from different techniques, and even more, from different collaborations, hazardous as such errors are highly unlikely to be Gaussian.

Precision measurements at this level are difficult but the LEP community has been making significant efforts to understand and overcome the problems both with the individual measurements and how to combine them. Nevertheless, R_b probes unexplored areas of the Standard Model, so its measurement is currently both exciting and challenging, and conceivably, it is giving the first indication of a deviation from the Standard Model.

3.2 The *b* Forward-Backward Asymmetry

The forward-backward asymmetry is given in terms of the vector and axial couplings of the electron and the produced fermion by

$$A_{FB}^{f\bar{f}} = \frac{3}{4}\frac{4v_e a_e v_f a_f}{\left(v_e^2 + a_e^2\right)\left(v_f^2 + a_f^2\right)}.$$

The most sensitive asymmetry measurement to determine $\sin^2 \vartheta_W^{eff}$ in unpolarized Z decay results from $b\bar{b}$ production. This can be seen from

$$\frac{\partial A_{FB}^{f\bar{f}}}{\partial \sin^2\theta_W} = 4\left(-2I_3^f - Q_f + 8Q_f \sin^2\theta_W\right)$$
$$\sim 3 \quad \text{for} \quad Z \to b\bar{b}$$
$$\sim 0.6 \quad \text{for} \quad Z \to \mu^+\mu^-.$$

The lepton tag still provides the basis for most measurements of this asymmetry; however, the high efficiency of the lifetime tag can now be employed when coupled to jet charge measurements to determine the direction of the b quark. The accuracy of the two methods is comparable, and as there is little correlation between the samples, they can be combined with comparative ease. It is also relatively simple to combine results from the LEP experiments to achieve an overall value as statistical uncertainties still dominate, and this gives the single most accurate technique at LEP for measurement of $\sin^2 \vartheta_W^{eff}$.

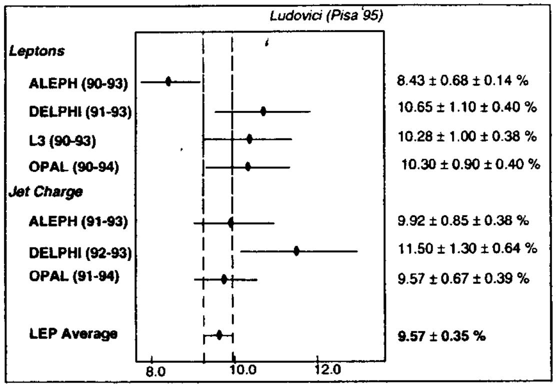

Fig. 3. Summary of the LEP $A_{fb}(b\bar{b})$ measurements from Ludovici's review at Pisa 1995.

The asymmetry values, as summarized by Ludovici[2] at Pisa, are given in Fig. 3. The average at the Z pole is 0.0957 ± 0.0035, which leads to a value of $\sin^2 \vartheta_W^{eff}$ of 0.23182 ± 0.00064.

4 *b* Quark Fragmentation Function

One of the parameters given by the global lepton analyses described above is the mean B energy in the fragmentation. However, the analyses assume that the fragmentation follows the model of Petersen et al.,[3] although there is no direct confirmation of this.

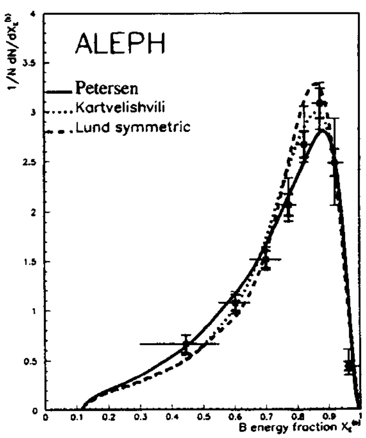

Fig. 4. The measured B energy fraction with model predictions.

Recently, ALEPH[4] have made use of the ability to reconstruct the missing neutrino energy to reconstruct the semileptonic $D^*\ell\nu$, $D^+\ell^-\nu$, and $D^0X\ell^-\nu$ decay modes to determine the $x = E_b/E_{beam}$ distribution. This is compared in Fig. 4 with predictions from the JETSET Monte Carlo for fragmentation schemes by Kartvelishvili[5] and the Lund symmetric procedure[6], usually used for the light quarks in JETSET simulations, as well as the Petersen prescription. The measurements yield a mean value for $\langle x_b \rangle$ of $0.715 \pm 0.007 \pm 0.013$. However, after adjusting the model parameters the data is still inadequate to distinguish these schemes although they verify that there is no significant discrepancy with the Petersen procedure after the ε parameter is correctly chosen.

In a similar analysis, OPAL[7] obtain a value of $\langle x_b \rangle = 0.695 \pm 0.006 \pm 0.008$.

5 Excited B States

There has been a major attempt recently to establish what percentage of B hadrons are formed in the s-wave states, B or B^*, or in one of the p-wave states, generically termed B^{**}. The predicted B^{**} states are given in Table 1. Heavy quark effective theory predicts that two will be narrow ($\Gamma \sim 10$ MeV) whilst two will be broad ($\Gamma \sim 100$ MeV).

State	J^P	Width	Decays to
B_2^*	2^+	narrow	$B\pi$, $B^*\pi \to B\pi\gamma$
B_1	1^+	narrow	$B^*\pi \to B\pi\gamma$
B_1^*	1^+	wide	$B^*\pi \to B\pi\gamma$
B_0^*	0^+	wide	$B\pi$

Table 1. B^{**} states predicted by heavy quark effective theory.

The standard inclusive analyses use various types of inclusive B reconstruction, with the inclusive "B" paired with either a low energy γ (for the B^*) or a low energy π or K for the B^{**} or B_s^{**}. All states should have low Q values, given by $Q = M("B"X) - M("B") - M(X)$, with X either a γ, π, or K. This is plotted, and as errors due to inadequate B reconstruction mainly cancel in the difference, evidence for these excited states is revealed by a peak in the Q spectrum. In the B^{**} analysis, the resolution of approximately 45 GeV is such that the loss of the soft γ in the decays $B^{**} \to B^*\pi \to B\pi\gamma$ does not significantly affect the signal.

5.1 The B*

The B^* was first observed by L3 (Ref. 8) and makes full use of their BGO calorimeter which has considerably superior energy resolution, particularly for low-energy photons, than the electromagnetic calorimeters of the other LEP experiments. In the absence of an operational vertex detector, L3 tags the B using a high p_t muon, determines the B^* direction from the direction of the jet containing the muon, and sets the magnitude of the B^*

momentum to the mean value expected from the fragmentation spectrum of 37 GeV. This allows the associated photon momentum to be transferred into the "B*" rest frame, where a peak indicates the two-body decay of the B^*. This is shown in Fig. 5, the peak is at 46.3 ± 1.9 MeV, and they estimate the vector to pseudoscalar production ratio to be

$$\frac{N_{B^*}}{N_{B^*}+N_B}=0.76\pm0.10,$$

which is very close to the simple 3:1 prediction.

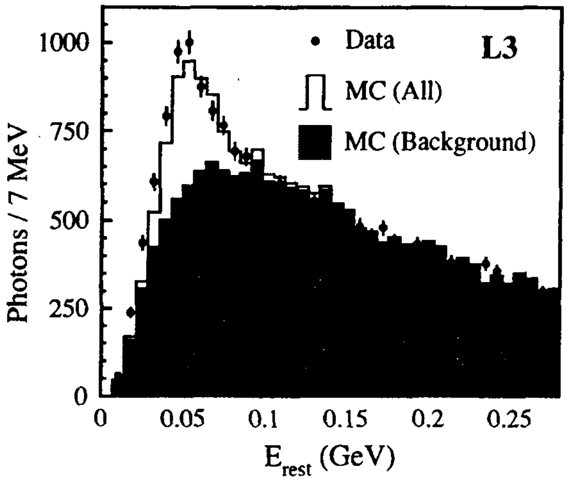

Fig. 5. B* Production in L3. The photon energy in the "B*" rest frame.

ALEPH[9] and DELPHI[10] also report similar analyses, but, as their calorimeters are inferior at these low energies, they use electron-positron conversions to detect the low energy photons. However, both use their vertex detectors to obtain a higher tagging efficiency and have more comprehensive inclusive B algorithms which permit estimates of both the B^* direction and energy. The results are quite consistent with the L3 ones.

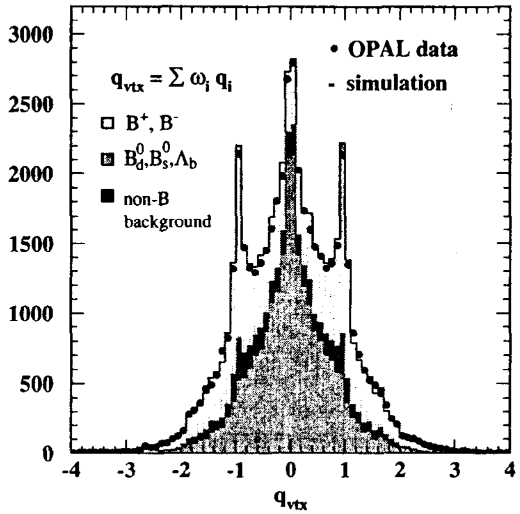

Fig. 6. The inclusive B reconstruction procedure used by OPAL using charge weighting.

5.2 The B^{**}

Inclusive evidence for the B^{**} states has come from ALEPH,[9] DELPHI,[11] and OPAL.[12] In ALEPH and DELPHI, the inclusive B reconstruction depends upon the rapidity along the jet axis coupled with vertex or impact parameter cuts. OPAL have evolved a different procedure which enables them to also have some estimate of the charge of the B state. They use the charged tracks to determine secondary vertices in jets and then weight each track in the jet with the probability, ω_i, that it came from the secondary, and then sum these weights multiplied by the charge of the relevant track. In this way, they obtain an estimate of both the charge of the secondary, $q_{vtx}=\sum\omega_i q_i$, and the momentum vector of the charged decay products. To this, they add 70% of the observed neutral energy in a cone around the P direction to give the estimate of P_B. The results of the procedure for the charge separation are shown in Fig. 6; the composition of the sample following a cut $|q_{vtx}| > 0.6$ is 54% charged B's and 33% neutral B's, whilst for $|q_{vtx}| < 0.6$ it is 24% charged B's and 67% neutrals. Agreement of the procedure between data and Monte Carlo is good, as can be seen from Fig. 6.

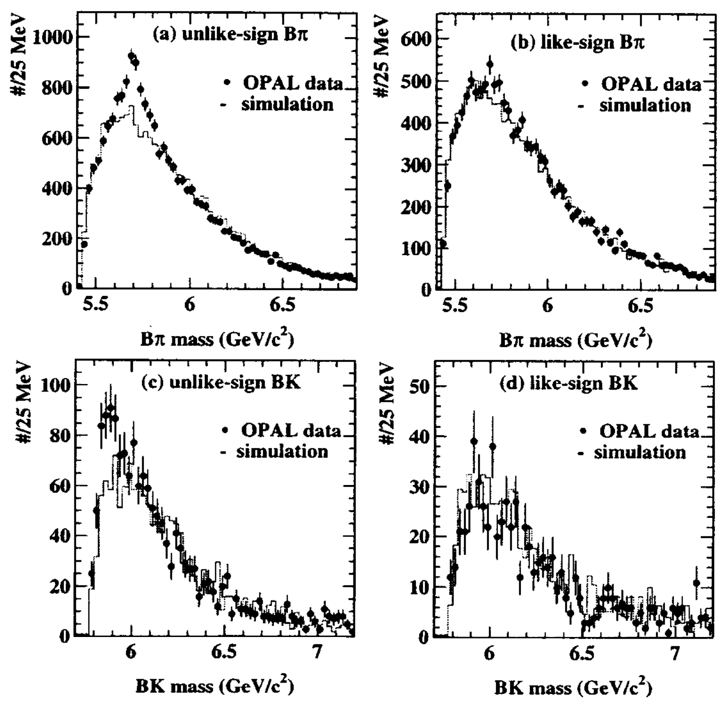

Fig. 7. OPAL results on inclusive B** production. Unlike and like sign Bπ combinations are shown in (a) and (b), unlike and like sign BK combinations in (c) an (d)

Following this procedure, OPAL pair a primary π or K with like or unlike charge to that of the B. The results are shown in Fig. 7, where good peaks are observed in the $B\pi(K)$ plots when the B and $\pi(K)$ have opposite signs. No peaks are observed when the B is paired with a π or K of like sign. They also have a peak (not shown) when a neutral B is paired with a charged π but no peak when paired with a kaon. All these observations are as expected from the production of excited B^{**}states.

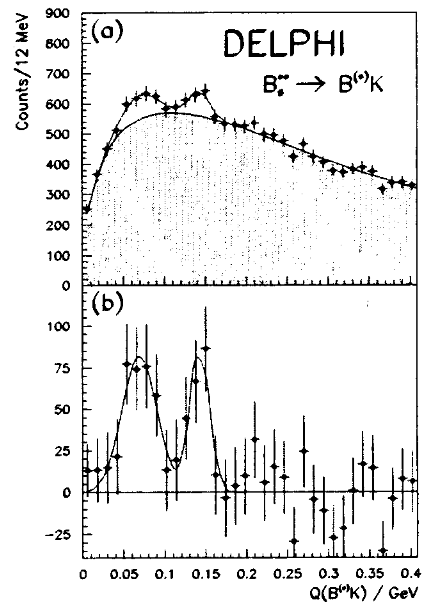

Fig. 8. DELPHI results for the Q value for BK combinations showing evidence for two narrow B_s^{**} states. Full results are given in (a), background subtracted in (b).

ALEPH and DELPHI plot the Q value for the supposed B^{**} decay but make no attempt to search for charge correlations. DELPHI uses information from both dE/dx and their RICH counters to distinguish π's from kaons, and this plot yields some evidence for the production of two B_s^{**} states attributed to the two narrow ones. The results are shown in Fig. 8. A two Gaussian fit to these peaks yields mean values of $70 \pm 4 \pm 8$ MeV and $142 \pm 4 \pm 8$ MeV with widths of 21 ± 6 and 13 ± 6 MeV. However, as the widths of the Gaussian fits to these two peaks are less than the resolution, this preliminary result must await further confirmation.

All experiments indicate that the proportion of b quarks fragmenting to B^{**} is approximately 30%.

5.3 Exclusive B^{**} Reconstruction

Whilst the inclusive technique demonstrates unambiguously the production of B^{**} states, the mass resolution of typically 45 MeV is such that it is unlikely to yield information on the relative production rates of the different states. ALEPH[13] have preliminary results on exclusive B^{**} production using a substantial sample (435) of exclusively reconstructed B mesons decaying to a variety of final states. They pair the reconstructed B mesons with the pion which has the maximum p_{long} along the corresponding jet axis and then compare right- and wrong-sign mass combinations to look for the signal. The mass resolution is approximately 5 MeV, much better than for the inclusive B analysis. The right-sign $B\pi$ mass plot is shown in Fig. 9; an enhancement is clearly visible with respect to the background determined from the wrong-sign pairs. A single Gaussian does not fit this well; two give a much better fit which is consistent with the two narrow states expected from heavy quark theory. The two Gaussian fit yields masses of 5585^{+74}_{-34} MeV and 5703 ± 14 MeV with widths of 28^{+18}_{-14} and 42^{+41}_{-18} MeV. However, this cannot yet be considered a confirmation; in particular, statistics do not allow any information to be extracted on the spin-parity of the decaying B^{**}.

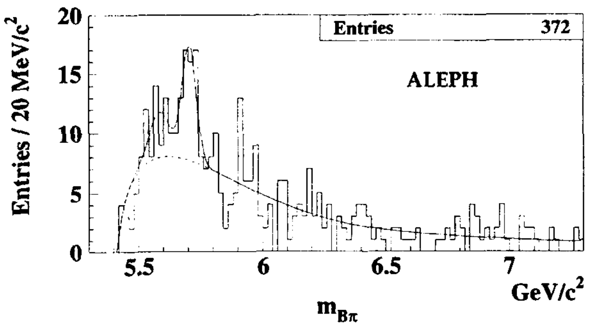

Fig. 9. Right sign $B\pi$ combinations from exclusive B decays reconstructed by ALEPH.

The overall rate of B^{**} production from this exclusive analysis is also found to be $30 \pm 6\%$ in agreement with the inclusive analyses.

5.4 Evidence for Σ_b and Σ_b^* Baryons

DELPHI[14] have taken this analysis further and produced the first preliminary evidence for Σ_b and Σ_b^* baryons at LEP. They extend the basic B^{**} analysis by looking for inclusively reconstructed B hadrons which are enriched in baryons, by identifying protons, reconstructed lambdas, and neutral hadron showers in the B jets. Examination of the Q value distribution for these states yields a 9σ enhancement which can best be fitted by two Gaussians with means of $33 \pm 3 \pm 8$ and $89 \pm 3 \pm 8$ MeV with both widths fixed at the expected resolution. It is shown in Fig. 10(a). These two peaks are ascribed to the Σ_b and Σ_b^* respectively, and from the size of the peaks, they find that $4.8 \pm 0.6 \pm 1.5\%$ of all b's produced in Z decay fragment to a Σ_b or Σ_b^*, which is approximately half of the expected b-baryon production. Repeating the analysis with an antibaryon cut shows no signal, see Fig. 10(b).

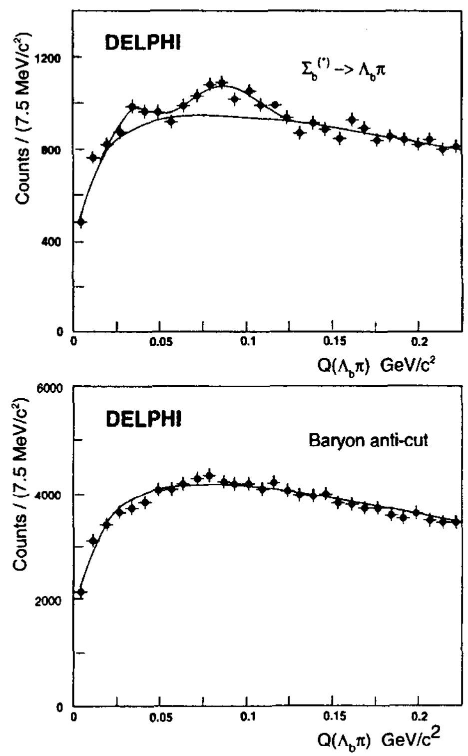

Fig. 10. DELPHI Q value distributions for (a) inclusive "Λ_b"π combinations showing evidence for the production of Σ_b and Σ_b^*, (b) with an antibaryon cut.

6 Λ_b Polarization

If, as indicated from the above DELPHI results, there is a significant amount of $\Sigma_b^{(*)}$ production, then the high polarization of the b quark resulting from the Z decay (~−94%) is likely to be lost by the time the lowest baryon, the Λ_b, is produced. Any Λ_b polarization is reflected in the energy spectra of both the charged lepton and the neutrino. ALEPH have used this to measure the Λ_b polarization using a variable, y, equal to the ratio of the mean energies of charged leptons and neutrinos. This is particularly sensitive to the polarization but demands a good estimate of the missing neutrino energy. The relation to the polarization is given by

$$y=\frac{<E_\ell>}{<E_\nu>}=\frac{7-P_{\Lambda_b}}{6+2P_{\Lambda_b}}+O\left(\frac{m^2_{\Lambda_c}}{m_b^2}\right).$$

The procedure adopted is then to compare the measured value of y with that from a Monte Carlo in which the Λ_b is produced unpolarized

$$R(y)=\frac{y_{data}}{y_{MC}}.$$

The relationship of $R(y)$ to P_{Λ_b} is shown in Fig. 11 together with the ALEPH value. Their result is

$$P_{\Lambda_b}=-0.28^{+0.23+0.13}_{-0.20-0.12},$$

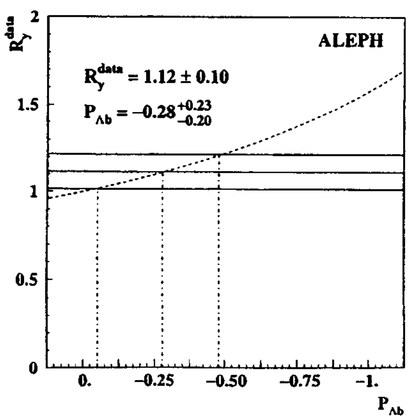

Fig. 11. The ALEPH value of $R(y)$ and its relationship to the Λ_b polarization.

which suggests that much of the b quark polarization is indeed lost in the formation of the Λ_b, consistent with substantial $\Sigma_b^{(*)}$ production.

7 Decays

7.1 Inclusive Semileptonic

The rate of semileptonic B decay is the cause of two problems. The values which have been measured at both the Z and the $\Upsilon(4S)$, typically between 10 and 12%, are lower than theoretical expectations and the value measured at the Z is systematically higher than that measured at the $\Upsilon(4S)$. In fact, the reverse would be expected due to the production of the Λ_b at LEP, which is expected to have a lower semileptonic branching ratio than the B meson in keeping with its lower lifetime.

Until recently, most LEP measurements have relied upon the overall "global" fits to the single and dilepton spectra, and values have been produced in conjunction with measurements of R_b, R_c, etc. However, this summer ALEPH[16] has produced two new analyses dedicated purely to the task of measuring the primary $b \to \ell$ branching ratio and the cascade $b \to c \to \ell$ rates.

Both of these use the "lifetime" tag in one hemisphere to select a pure sample of $Z \to b\bar{b}$ events and then examine the leptons in the opposite hemisphere. In the first approach, hemispheres opposite to the tag which contain either a single lepton or two oppositely charged leptons are selected and an overall likelihood fit made to both the numbers of single and dilepton hemispheres and to the p_t spectra. The numbers are sensitive to the absolute tagging efficiency, which is determined on the data using single- and double-tag information, whilst the fit to the spectra is affected more by modeling uncertainties than the absolute efficiency. The two aspects of the fit are therefore complementary. The fit to the final single-lepton p_t spectrum is shown in Fig. 12, and the analysis yields the preliminary result

$$Br(b \to \ell\nu X)=11.34 \pm 0.13 \pm 0.27^{+0.41}_{-0.27}\%$$

$$Br(b \to c \to \ell\nu X)=7.86 \pm 0.19^{+0.46+0.39}_{-0.36-0.47}\%$$

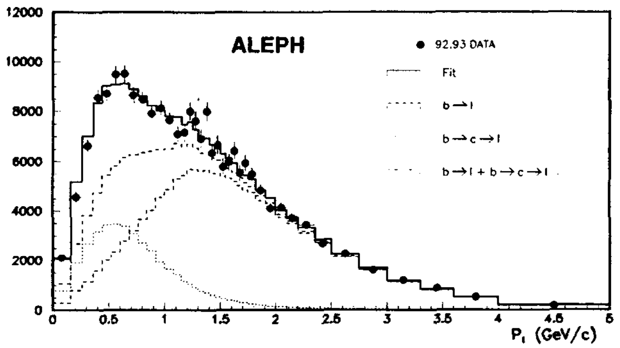

Fig. 12. The fit to the lepton p_t spectrum in B decay from the ALEPH analysis using models for the decay distribution.

with the errors respectively statistical, systematic, and modeling. It is clear that whilst this method has good statistical precision, the modeling of the lepton spectra seriously limits the accuracy.

To attempt to overcome this, the second approach builds on techniques adopted earlier at ARGUS and CLEO to minimize the model dependence. Two samples are prepared; the first uses the "lifetime" tag with a very hard cut to establish a sample of hemispheres with a very high b purity containing a single lepton. A second sample of opposite side dileptons is then prepared in which one of the leptons has a high p_t and is used as a tag lepton; this, after corrections for mixing, etc., yields the sign of the decaying b quark. To improve the statistical precision, the dilepton sample is augmented by a single-lepton sample with an opposite hemisphere jet charge identification and a soft lifetime cut. The contribution of primary and cascade b decays to both of these samples can be simply estimated with no reference to models although the necessary cuts which have to be applied to the samples for the lepton identification, etc., imply that the model dependence is not totally zero.

The overall p_t dependence is shown in Fig. 13. It is clear that the statistical precision is inferior to the first method but the preliminary value obtained

$$Br(b \to \ell \nu X) = 11.01 \pm 0.23 \pm 0.28 \pm 0.11\%$$
$$Br(b \to c \to \ell \nu X) = 8.30 \pm 0.31 \pm 0.42 \pm 0.12\%$$

shows the much reduced model dependence.

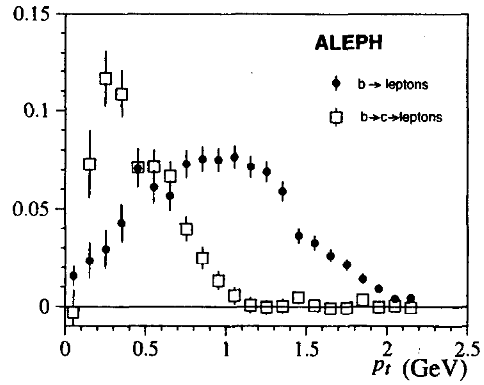

Fig. 13. The results of ALEPH for the model independent fit of the lepton p_t spectrum in B decay.

These two measurements are consistent with each other, consistent with the earlier measurements at the Z, and higher than the latest $\Upsilon(4S)$ measurements. At the Pisa conference, Schmitt,[17] in his summary, combined the LEP measurements to yield $Br(b \to \ell \nu X)$ =11.25 ± 0.24%, whereas when he takes the latest $\Upsilon(4S)$ value and predicts the expected value at LEP after correcting for Λ_b production, he obtains 10.0 ± 0.4%, a discrepancy between 2 and 3σ. Whilst not that strong statistically, the fact that this discrepancy has remained for so long suggests that there could be a systematic flaw in one of the analyses.

7.2 Measurement of $|V_{cb}|$

Effective heavy quark theory can be used to extract a value of the CKM-matrix element V_{cb} from an analysis of the decay $B^0 \to D^{*-}\ell^+\nu$. In the heavy quark limit for zero recoil of the D^*, the normal three form factors reduce to a single one, $F(\omega)$. This is a function of the q^2 to the lepton-neutrino system and normally written in terms of a variable ω defined by

$$\omega = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

such that

$$\text{as } q^2 \to q^2_{\max}, \qquad \omega \to 1,$$

and in the heavy quark limit, $F(\omega) \cong 1$.

This method has already been used by CLEO with substantially more events than are available to the LEP experiments. However, for this particular measurement, the boost given to the B state at LEP is of value because, as a result, the D^* products have a substantial momentum in the apparatus, whereas at the $\Upsilon(4S)$, the two B's are produced virtually at rest and the pion from the D^* decay in the limit of zero recoil is very soft and suffers from reconstruction difficulties. In practice, ω is determined using the decay kinematics and an extrapolation made to $\omega = 1$ using the linear form

$$F(\omega) = F(1)\left[1 + a^2(1-\omega)\right].$$

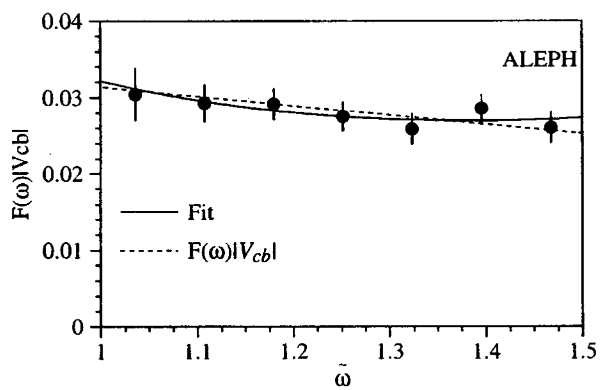

Fig. 14. Linear extrapolation of $F(\omega)|V_{cb}|$ as a function of ω.

This yields $F(1)|V_{cb}|$. However, as the resolution function varies with ω, the linear function is modified for the fit to the data. Such an analysis has been made by ALEPH[18] and their result is shown in Fig. 14, where $F(\omega)|V_{cb}|$ is plotted against ω. In this plot, the underlying linear extrapolation, which is totally adequate for the experimental precision, is shown by the dashed line. Extrapolation to $\omega = 1$ making due allowance for the resolution yields the value of $F(1)|V_{cb}|$. This extrapolation yields

$$F(1)\,|\,V_{cb}\,| = (31.4 \pm 2.3 \pm 2.5) \times 10^{-3}$$

$$a^2 = 0.39 \pm 0.21 \pm 0.12.$$

In the limit of infinitely heavy quarks, $F(1)$ is expected to equal one, but for finite mass b quarks, there are corrections which are the source of some controversy. Using Neubert's[19] value for $F(1) = 0.91 \pm 0.04$, the resulting value of $|V_{cb}|$ is

$$|\,V_{cb}\,| = (34.5 \pm 2.5 \pm 2.7 \pm 1.5_{theory}) \times 10^{-3}.$$

The analysis also yields a competitive value for the $D^* l\nu$ branching ratio

$$Br(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}) = (5.18 \pm 0.30 \pm 0.62)\%.$$

7.3 The Branching Ratios for $b \rightarrow \tau X \nu$ and $b \rightarrow \tau \nu$

ALEPH[20] and L3 (Ref. 21) have made the only measurements so far of the $Br(b \to \tau X \nu_\tau)$; ALEPH has also obtained the first upper limit for the exclusive branching ratio $Br(b \to \tau \nu_\tau)$.

The ALEPH analysis takes advantage of their lifetime b tag to first select a pure sample of B decays. They then eliminate b hemispheres in which a lepton is identified and fit the missing energy spectrum in each nonleptonic hemisphere for the τ component. As there are two neutrinos produced in $b \to \tau$ decays, there is more missing energy in the hemisphere than for all other decays, particularly after the removal of the majority of the semileptonic decays to electrons and muons.

In Fig. 15, the hemisphere missing energy plot for this analysis is shown with a clear contribution from the inclusive $b \rightarrow \tau X \nu$ decay. The value obtained by ALEPH for the branching ratio is

$$Br(b \to \tau X \overline{\nu}_\tau) = 2.75 \pm 0.30 \pm 0.37\%.$$

The exclusive decay rate, $b \to \tau \overline{\nu}$, is characterized by an even greater hemisphere missing energy, and an upper limit can be established by examining the spectrum above 30 GeV. With current statistics, no signal is observed and a 90% confidence level upper limit of

$$Br(b \to \tau \overline{\nu}_\tau) < 1.8 \times 10^{-3} \text{ at 90\% C.L.}$$

is found.

Both values are consistent with predictions based on the Standard Model, 0.023 and 5×10^{-5} respectively. They are of particular interest because the rate could be strongly enhanced by charged Higgs intermediaries in the MSSM and an enhanced

$b \to \tau$ rate had also been considered a possible explanation for the low semileptonic branching ratio. From the measured inclusive rate, a limit

$$\frac{\tan\beta}{m_{H^\pm}} < 0.52\ \mathrm{GeV}^{-1}$$

can be set at 90% C.L.

The L3 value for $Br(b \to \tau X \nu_\tau)$ of $2.4 \pm 0.7 \pm 0.8\%$ agrees with the ALEPH value.

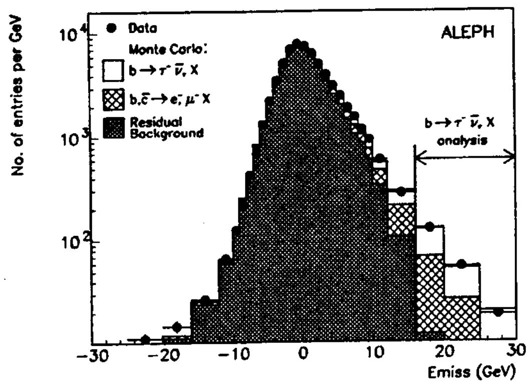

Fig. 15. The hemisphere missing energy spectrum for the ALEPH $b \to \tau X \nu$ analysis.

8 Exclusive Reconstruction and Mass of the Λ_b

Attempts at exclusive reconstruction of the Λ_b have proved to be more difficult than imagined. There are new preliminary results from ALEPH[22] and OPAL,[23] with candidates for the reconstruction $\Lambda_b \to \Lambda_c^+ \pi^-$. Unfortunately, this channel is more subject to misinterpretation from backgrounds from other B decays than the cleanest one, $\Lambda_b \to J/\psi\ \phi$. At the present time, none of the LEP experiments has any candidates for this decay, but OPAL claims one candidate for $\Lambda_b \to \Lambda_c^+ \pi^-$, whilst ALEPH has five candidates with $P_{\Lambda_b} > 20$ GeV and four for $P_{\Lambda_b} > 30$ GeV where potential backgrounds are small. This mass plot is shown in Fig. 16. ALEPH claim a significance of 2.5σ for the four events with $P_{\Lambda_b} > 30$ GeV, and for these they quote a mass of

$$M(\Lambda_b) = 5621 \pm 17 \pm 15\ \mathrm{MeV}.$$

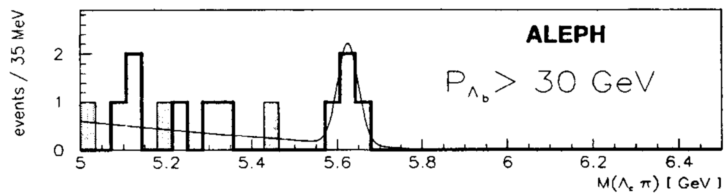

Fig. 16. The Λ_b signal in the ALEPH $\Lambda_c\pi$ mass plot.

9 Lifetimes

Most methods use the semileptonic decays which are isolated most cleanly in the data. Early methods which relied on the impact parameter of the lepton as an estimator for the lifetime have in general given way to methods involving vertexing of both the charm and the bottom vertex. Nevertheless, the impact parameter method still proves useful when vertexing proves difficult, such as with the Λ_b or for inclusive measurements when the exact nature of the final states is poorly known. In the latter case, the weak sensitivity of the impact parameter to the actual momentum of the B state is advantageous.

9.1 Inclusive

The inclusive lifetime, $<\tau_b>$, is given by

$$<\tau_b> = \sum f_i \tau_i$$

with f the fraction of decays for the particular analysis channel. Hence, it need not necessarily be the same in all analyses.

There are two new measurements, a final one from ALEPH[24] using, for the first time, the three-dimensional impact parameter and a new preliminary one from DELPHI[25] using an inclusive vertexing technique. For the former, there is only a low sensitivity to the B momentum, and this correction is taken from Monte Carlo in which the models for semileptonic B decay have been optimized. For the latter, the B momentum is estimated from the visible momentum of the tracks which are used for

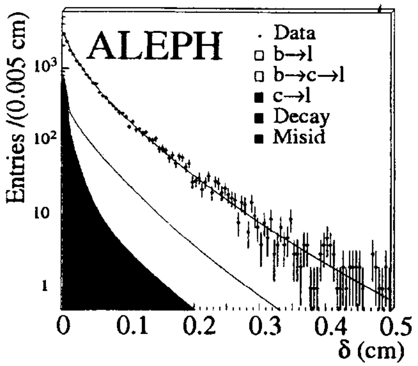

Fig. 17. The ALEPH impact parameter distribution for the mean B lifetime.

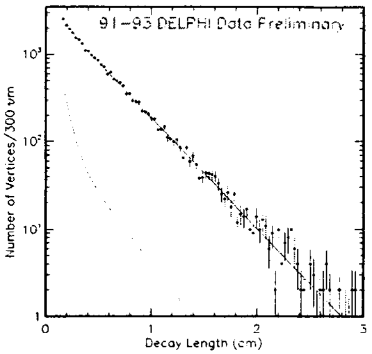

Fig. 18. The DELPHI decay length distribution for the mean B lifetime.

the vertexing and this is scaled to the estimated B momentum on the basis of the Monte Carlo. The results are:

$$<\tau_b> = 1.533 \pm 0.013 \pm 0.022 \text{ ps} \qquad \text{ALEPH,}$$

$$<\tau_b> = 1.600 \pm 0.010 \pm 0.028 \text{ ps} \qquad \text{DELPHI.}$$

Both results are limited by systematics, but they are barely consistent; any discrepancy must be due to either the different event samples or an underestimation of the effects of the unknown B momentum. The plots of the ALEPH impact parameter distribution and the DELPHI decay length distribution with the fits are shown in Figs. 17 and 18, respectively. They show the high statistical quality of the data now available.

9.2 Exclusive

Most measurements of exclusive lifetimes depend upon a partial reconstruction of a semileptonic decay mode which serves both to identify the b state from which the final state originates and to establish both the decay path length and an estimate of the momentum of the B state. The usual procedure is to select events which characterize the particular state in question, such as same side $D_s^{\pm}\ell^{\mp}$ for the B_s. The charm decay products are first identified using the relevant invariant mass. These give the charm momentum vector and are vertexed to give the charm decay point. The lepton and the charm momentum vector are then vertexed to give the B decay point. The magnitude of the B momentum is estimated using the missing energy corrected to take account of non-two jet topologies as described in Sec. 2.6 for the neutrino energy. The B direction is determined from the e^+e^- interaction point and the B decay point.

The techniques for the momentum and direction determination, and the cuts to select the sample, vary considerably from experiment to experiment depending upon the nature of the vertex detector and the hermeticity of the overall detector. The latest exclusive lifetimes are given in Fig. 19, which is taken from the summary by Rizzo[26] at the Beauty '95 conference. Many numbers are still preliminary.

9.2.1 B^+/B^0 Lifetime

Separation of a pure sample of either B^+ or B^0 mesons without full exclusive reconstruction is difficult, and although there are now first results from ALEPH[27] using exclusive reconstruction, the statistics are still too limited to enable measurement at a level which could challenge any predictions. In the absence of a full reconstruction, the traditional method is to rely upon the semileptonic decays and use the fact that the easiest charm state to identify is the D^0 after its decay into $K\pi$, $K\pi\pi$, $K\pi\pi\pi$. Furthermore, it is relatively simple to establish whether this D^0 has resulted from the decay of a charged D^* as this yields a slow charged pion and a very clean peak in the $M(D^0\pi) - M(D^0)$ mass plot. The method then relies upon the fact that in charged B decay, a neutral charm state is produced, whereas in neutral B decay, a charged charm state is produced. Hence, an identified D^{*+} with a negative lepton is assumed to have originated from a B^0 whilst a D^0, not identified as the daughter of a charged D^*, is assumed to have originated from a $B^{\pm}$.

The main difficulty in the method results from the difficulty in knowing the charged B background in the neutral B sample and vice-versa. Potential causes of this result from failure to successfully reconstruct the slow charged pion from the D^* decay, background under the D^* signal resulting from combinatorial association of an unrelated π with a D^0 from a charged B, and the poorly known production rate for higher D^*'s (D^{**}) in semileptonic B decay. The latter is the most serious, and the difficulty is compounded by the even less well-known relative production ratios of the possible D^{**} states. Some of these can decay to $D^*\pi$, others to $D\pi$, and one to both. The overall percentage of decays to D^{**} states is believed to be about 30%. This leads to a systematic error, but determining the magnitude of this is difficult as the error depends upon the ratio of the lifetimes, and hence, the uncertainty from cross population of the channels can only be estimated when the lifetimes are well-known! The present results from LEP using this method show a surprising tendency to give a B^+/B^0 lifetime ratio of one. The results are:

ALEPH[27]	$0.98 \pm 0.08 \pm 0.02$
DELPHI[28]	$1.00 \pm 0.16 \pm 0.10$
OPAL[29]	$0.99 \pm 0.14 \pm 0.05$.

With such uncertainties, the fact that the results are all so close to one is surprising, and even more so when one compares the mean B^+/B^0 lifetime using this method which is 1.60, 1.61, and 1.53 for the three experiments respectively.

In addition to the ALEPH exclusive reconstruction, another method which has been used to determine these lifetimes at LEP is a topological one from DELPHI[30] in which they attempt to determine the number of charged tracks emanating from the B decay. This requires an excellent understanding of the performance of the vertex detector as the efficiency has to be established from the simulation. The results are given in Fig. 19. The best LEP average values given by Rizzo at Beauty '95 are

$$\tau(B^+) = 1.63 \pm 0.06 \text{ ps}$$
$$\tau(B^0) = 1.56 \pm 0.06 \text{ ps}.$$

The LEP measurements are, thus, consistent with the difference between the B^+ and B^0 lifetimes, which is expected at the ~5% level. The current error quoted is about 6%, but because of the difficulties associated with fully separating the two charge states, it is probably unlikely that LEP measurements will be capable of measuring a difference with much greater precision. Full reconstruction would seem to be by far the most successful approach, but this will only be possible with an adequate sample at the hadron colliders.

9.2.2 B_s Lifetime

The semileptonic decay of the B_s to $D_s X \ell \nu$ resulting in same side $D_s^{\pm}\ell^{\mp}$ gives the best result, but statistics are limited. Such measurements have been performed by all three experiments with the average dominated by a recent ALEPH[31] result with an error ~0.16 ps.

DELPHI[32] and ALEPH[33] have also used other methods which depend primarily on the observation of just a D_s in the event. Such techniques produce a much larger sample of events but suffer from high and poorly known backgrounds which lead to substantial uncertainties. The current results are given in Fig. 19, and the average LEP value is

$$\tau(B_s) = 1.59 \pm 0.11 \text{ ps}.$$

The average is extremely close to the values for the B^+ and B^0 as expected.

9.2.3 Λ_b Lifetime

Present evidence on the B meson decays suggests that the spectator model with small QCD corrections is valid. Such models also predict that the Λ_b lifetime, effectively the lifetime of the lowest lying B baryon, should be within 10% of the meson lifetimes. Measurements of this quantity come only from the LEP experiments, and they are now giving a precision which can, and does, seriously challenge this prediction.

All measurements rely upon the correlation of a baryon with an appropriately charged same-side lepton. The decay chain used is

$$\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$$
$$\Lambda_c^+ \to \Lambda X, pX$$

and the signal is then isolated using a same-side correlation of $\Lambda\ell^-$, $p\ell^-$, or $\Lambda_c^+\ell^-$ with the Λ_c^+ decaying to $pK^-\pi^+$, $\Lambda\pi^+\pi^+\pi^-$, or pK^0. The actual methods used differ between the collaborations. All use a vertexing procedure for the $\Lambda_c^+\ell^-$ events, but whilst OPAL[34] and DELPHI[35] use a similar technique for the statistically superior $\Lambda\ell^-$ and $p\ell^-$ samples, ALEPH[36] rely upon the lepton impact parameter rather than vertex the Λ with the lepton. The results from the three experiments are remarkably consistent, all showing a value about 20% lower than the B meson lifetimes. The actual values are shown in Fig. 19, and the OPAL data are shown in Fig. 20. The LEP average is

$$\tau(\Lambda_b) = 1.20 \pm 0.07 \text{ ps}.$$

This is $25 \pm 8\%$ less than the average B^+/B^0 lifetime and suggests that additional corrections are necessary in the spectator model to satisfactorily describe the bottom baryons.

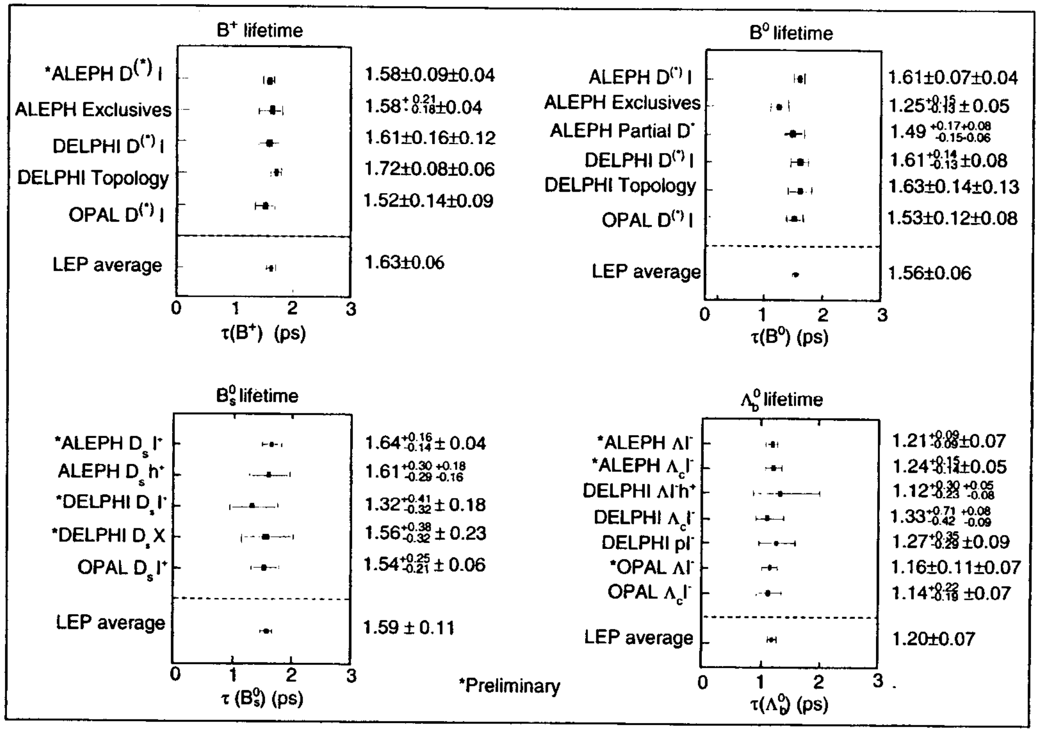

Fig. 19. Exclusive B lifetime results from Rizzo's review at Beauty'95.

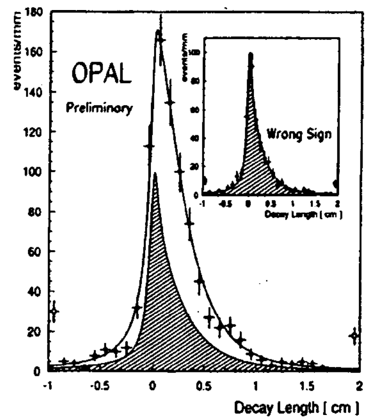

Fig. 20. The decay length distribution for the OPAL Λ_b lifetime measurement.

9.2.4 Ξ_b Lifetime

A preliminary measurement has been made of the Ξ_b lifetime by ALEPH[37] using same-side correlation of $\Xi^{\pm}\ell^{\mp}$ to identify the events and a similar impact parameter procedure to the one used for the Λ_b. The value obtained, $\tau(\Xi_b) = 1.15^{+0.35}_{-0.25} \pm 0.20$ ps, still has substantial uncertainty but again shows a low value with respect to the B meson lifetimes. The method used cannot distinguish the Ξ_b^0 from the Ξ_b^-. An earlier preliminary DELPHI[38] measurement had given $1.5^{+0.7}_{-0.4} \pm 0.3$ ps.

10 Time-Dependent Mixing

The use of the silicon vertex detectors has enabled the observation and measurement of the $B^0 - \overline{B}^0$ oscillations resulting from the second-order weak process. The results are quite beautiful.

For a produced B^0, the decaying particle is either a B^0 or $\overline{B}^0$ given by:

$$\begin{matrix} B^0 \\ \overline{B}^0 \end{matrix} = \tfrac{1}{2} e^{-\Gamma t}\left[1 \pm \cos\Delta m t\right],$$

where Δm is the mass difference between the two B^0 states and Γ is the decay constant. This is usually assumed to be the same for both B^0 states, although there are suggestions that for the B_s^0, there could be a lifetime difference approaching 10% between the two mass eigenstates. The quantity $x = \Delta m / \Gamma$ can be expressed, for the B_d^0, by

$$x_d = \tau_{B_d} \frac{G_F^2}{6\pi^2} m_{top}^2 f_{B_d}^2 B_{B_d} f_t\left(\frac{m_t^2}{m_W^2}\right)\left|V_{td}^* V_{tb}\right|^2 .$$

This contains the important matrix element V_{td}, which defines one of the sides of the conventional unitarity triangle describing CP violation in the B system, but as the structure and bag constants are poorly known, a measurement of x_d cannot yield an accurate measurement of V_{td}. However, whilst the absolute values of these constants are not well-known, many uncertainties drop out when one considers the ratio of mixing in the B_s and B_d systems. The analogous relation for x_s is

$$x_s = \tau_{B_s} \frac{G_F^2}{6\pi^2} m_{top}^2 f_{B_s}^2 B_{B_s} f_t\left(\frac{m_t^2}{m_W^2}\right)\left|V_{ts}^* V_{tb}\right|^2 ,$$

and predictions for the ratio give

$$\frac{x_s}{x_d} = (1.34 \pm 0.15)\left|\frac{V_{ts}}{V_{td}}\right|^2 .$$

Hence, as one expects that $|V_{ts}| \cong |V_{cb}|$, measurement of x_d and x_s enable a measurement of V_{td}. For the B_d, the oscillation time is comparable with the lifetime, and so x_d can be determined from the integrated mixing parameter, χ, which can be expressed in terms of x_d by

$$\chi = \frac{x^2}{2(1+x^2)} .$$

This has been measured from the like-sign dilepton rate at the $\Upsilon(4S)$ where only the B_d is produced, but where time-dependent measurements are not practicable.

For the B_s, however, the oscillation rate is predicted to be considerably higher, and so integrated measurements have no sensitivity to x_s. This is in agreement with current integrated measurements made at LEP which are all consistent with the maximum χ value of 0.5 corresponding to infinite x_s.

To measure the oscillations, it is necessary to measure the decay time for a $B^0(\overline{B}^0)$ state to decay by means of a channel which reveals whether it was a B^0 or $\overline{B}^0$ at decay, and it is also necessary to use a tag which identifies whether it was produced as a B^0 or $\overline{B}^0$. The situation is described in Fig. 21. The identified event is split into two halves usually with respect to the thrust axis, and then on the probe side, it is necessary to determine the B^0 or $\overline{B}^0$ nature and estimate the proper time for the decay from the reconstructed B momentum and decay distance. On the opposite side, the tag side, some property is used to identify the nature of the B on that side which, after corrections for dilutions from mixing, backgrounds, etc., tags the nature of the B produced on the probe side.

There are now an increasing number of signatures, particularly for the probe side. Those for which results are currently available use either a D^*, a D^* and lepton, or just a lepton on the probe side with either a lepton or a measure of the jet charge on the tag side. The D^* and D^*-lepton procedures allow better vertexing for the proper time, but as the B_s does not decay to a D^*, these measurements only give information on x_d. When a lepton is used on the probe side, the decay can come from either a B_d or a B_s, and so these methods have the potential to also give information on Δm_s.

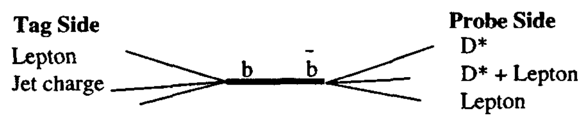

Fig. 21. Possible arrangements for the measurements of B oscillations.

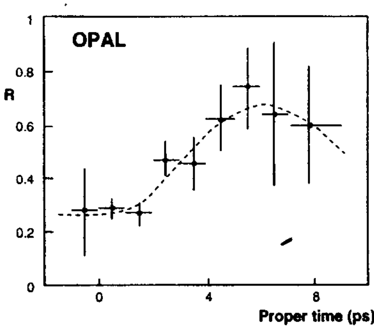

Fig. 22. The proper time distribution for the proportion of like sign objects in the OPAL D*-leptonvs jet charge Δm_d analysis.

10.1 Measurement of Δm_d

All three experiments have now produced excellent results for B_d oscillations and obtained values for x_d which, when averaged over the experiments, yield a more accurate measurement than that obtained from the integrated measurements at the $\Upsilon(4S)$. The quality of the data can be seen in sample results from OPAL,[39] ALEPH,[40] and DELPHI[41] shown in Figs. 22, 23, and 24. All three plots use different analyses; for the OPAL data, Fig. 22, the probe is a D^* with a lepton and the tag is a measure of the jet charge; for ALEPH, Fig. 23, leptons are used for both probe and tag, and for the DELPHI analysis, the probe is a lepton and the tag the jet charge. The values from these and other measurements are given in Fig. 25 which is taken from Stocchi's[42] summary at Beauty '95. The mean value is 0.456 ± 0.020 ps^{-1} to be compared with 0.428 ± 0.050 from the integrated measurement at the $\Upsilon(4S)$. The LEP value corresponds to an x_d value of 0.711 ± 0.044 for the above B_d^0 lifetime.

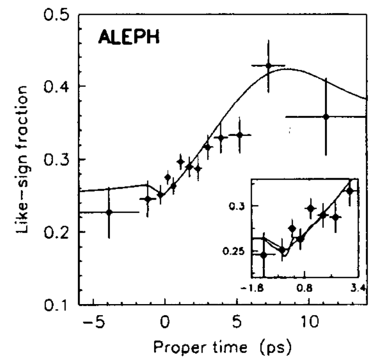

Fig. 23. Like sign fraction as a function of proper time for the ALEPH lepton-lepton Δm_d analysis.

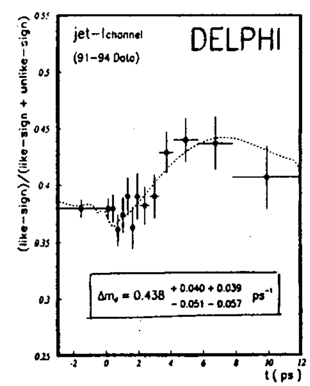

Fig. 24. The proper time distribution for the proportion of like sign objects in the DELPHI lepton vs jet charge Δm_d analysis.

10.2 Lower Limit on Δm_s

The real prize for LEP1, however, would be a definitive measurement of x_s. So far, only lower limits have been given, but these are now reaching values which are in the range expected by theoretical estimation from x_d. These suggest that x_s could be anywhere between a factor of ten to 60 times greater than x_d. The determination of the lower limit at a particular confidence level, and hence, the combination of results from the LEP experiments, is, however, a matter of considerable topical concern and discussion.

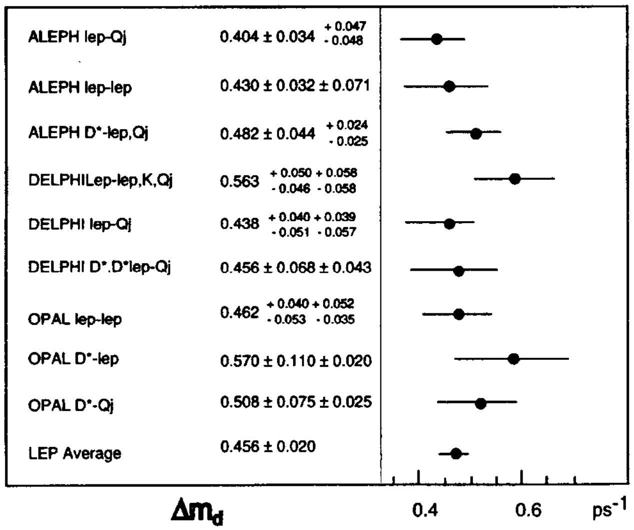

Fig. 25. Current values of Δm_d from the LEP experiments taken from Stocchi's review at Beauty'95.

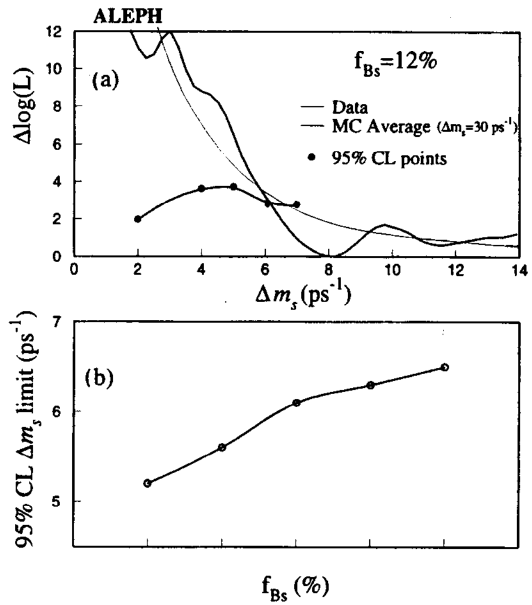

Fig. 26. ALEPH results on the lower limit for Δm_s using the lepton-jet charge technique. The difference in log likelihood is shown in (a) as a function of Δm_s whilst in (b) the sensitivity of the limit to the assumed proportion of B_s mesons is shown.

The method which is most commonly employed is to make an unbinned maximum likelihood fit to the like-sign proper time distributions which have a B_s component and then plot $\Delta\mathcal{L} = (\log\mathcal{L} - \log\mathcal{L}_{min})$ vs Δm_s. If the estimated errors are both correct and Gaussian, then the 95% C.L. is given when $\Delta L = 2$. Problematic is the estimation of the systematic uncertainty. One technique is to use many MC samples for different values of Δm_s in which the experimental uncertainties are parameterized, and a limit taken so that 95% of the samples yield a lower value. This technique can also show if in the real data, a statistical fluctuation had artificially helped to yield a higher limit than could be expected from the sensitivity of the detector and the statistics of the measurement. This is referred to as the "luck" factor, and again there are mixed opinions about whether it is appropriate to quote a high limit which has primarily resulted from a lucky fluctuation.

With these caveats, the present results are quoted in Table 2, although more can be expected for the summer conferences. The best current value comes from the

ALEPH[43] measurement using a lepton on the probe side and jet charge on the tag side; the result is shown in Fig. 26(a). However, when comparing results, it is crucial to know the proportion, f_s, of B_s assumed in the event sample. The best DELPHI[41] result also results from a lepton-jet charge technique, but as they assume a lower value for fs, the results are quite similar. The sensitivity of the limit to the assumed value of f_s for the ALEPH result is shown in Fig. 26(b). An OPAL update is expected imminently.

	f_s	Technique	Δm_s limit, ps^{-1}
ALEPH	0.12	lep-lep	> 5.6
	0.12	lep-Q_{jet}	> 6.1
	0.12	K-lep	> 4.0
DELPHI	0.10	lep-Q_{jet}	>4.2
	0.10	$D_s$lep-Q_{jet}	>1.5
OPAL	0.12	lep-lep	>2.2

Table 2. Lower limits on Δm_s.

So far, no satisfactory method of combining the results has been established. This will probably be necessary if LEP is to have any chance of determining x_s. It is amusing to speculate that many of the likelihoods presently minimize at a Δm_s value around eight. Such a value is well within the capabilities of the LEP detectors so there can be a real hope that by combining results and using all the data, including that from 1995, x_s could be the last major measurement from LEP1.

11 Summary and Outlook

Primarily due to the success of the silicon vertex detectors at tagging the long-lived B states, heavy flavor physics has become a major part of the LEP program. Many results are still statistically limited, and so a doubling or tripling of present statistics would add considerably to our knowledge; they would also help many measurements currently systematically limited as understanding of poorly known branching ratios and decay distributions would continue to improve. However, 1995 is likely to be the last year at which LEP will take any substantial data at the Z, and in 1995, no more than a million hadronic Z decays per experiment can be hoped for.

Nevertheless, important questions remain to be answered. With the increased data, it should become possible to fix finally the semileptonic b-branching ratio; it is almost certainly lower than theoreticians would wish, but a measurement to a few percent would give them a goal. It is also intriguing why this measurement is always found to be higher at LEP than at the Υ (4S). In a similar area, the ratio of the B baryon to the B-meson lifetime would welcome further improvement, although it is now clearly lower than simple predictions. In both of these, we are now aware that the data is not in perfect agreement with expectations, and therefore, further advances in the theory are necessary.

Decays of the Z to b quarks gives a unique opportunity to investigate the Standard Model in the quark sector; in particular, an accurate measurement of the basic Z to b width R_b provides one of the most sensitive tests to radiative corrections in the Standard Model and to possible non-Standard Model effects. The current 2-3σ discrepancy is enticing and the cause of a major effort by the experiments to understand their systematics and learn how to reliably combine results. It is reasonable to expect a further decrease on the overall uncertainty on R_b over the next year.

However, the greatest aim for the LEP program over this final year must be a definitive measurement of x_s, the mixing parameter in the B_s system. With the latest data and an understanding of how to combine results, it should certainly be possible to measure this up to about 12 and maybe to 15, which would be well within the expected range. A definitive measurement would be of major significance to B phenomenology over the next ten years, as, if not measured at LEP, this may have to wait for the LHC.

The final year of heavy flavor physics at the Z could still provide great excitement.

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