Heavy Flavour Physics at LEP

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1 Introduction

In this lecture I will summarize the LEP results on heavy flavour physics. The topics that will be covered are mainly in the field of beauty physics and can be divided in:

- B physics at the Z° resonance ($\Gamma_{b\bar{b}}$, $A^{fb}_{b\bar{b}}$, χ),
- Beauty signals (B_s , Λ_b , J/ψ),
- B lifetime measurements (τ_b, τ_{B_s}, $\tau_{\Lambda b}$, τ_{B+}, and τ_{B0}).

In the first part I will discuss the measurements of the width $\Gamma_{b\bar{b}}$ and asymmetry $A^{fb}_{b\bar{b}}$ for the process $Z^\circ \rightarrow b\bar{b}$, and a determination of the average mixing parameter χ of the b quark. In the second part evidence for B_s , Λ_b , and J/ψ production in Z° decays will be shown. In the last part I will summarize the measurements of the average b lifetime, and the lifetimes for charged and neutral B hadrons.

It is clear that only the main features of the analysis can be outlined in this paper.[1] For a full account the reader is referred to the literature. Still, I think, the reader will get an impression of what LEP can offer in the field of beauty physics.

2 B Physics at the Z^0 Resonance

An important part of the heavy flavour physics is based on the semi-leptonic decay of the quarks. A Z° decays e.g., into a $b\bar{b}$ or $c\bar{c}$ quark pair, and subsequently one of the quarks decays into a lepton that is identified. These decays can be divided in three categories:

- prompt b decays: $b \rightarrow c + l^-$,
- secondary b decays: $b \rightarrow c \rightarrow s + l^+$,
- prompt c decays: $c \rightarrow s + l^+$.

[1] Both the published results and the new preliminary results from the four LEP experiments will be reviewed. The preliminary results are based on drafts given to me before the SLAC Topical Conference, and I have made no attempt to update them with *preliminary* numbers released afterwards. In case the results were finalised and submitted to a journal, the new numbers are included. In the text I will only refer to published and submitted papers. For most of the preliminary results there are internal ALEPH, DELPHI, L3 or OPAL notes available.

Lepton identification plays an important role in the LEP experiments The general strategy for lepton identification in the LEP experiments is the following: electrons are identified in the electromagnetic calorimeter, using the energy deposition, the shower profile, and the match with the tracks reconstructed in the tracking chambers. Secondly, an electron is identified using the ionisation dE/dx along the track in the central tracking chamber. In Fig. 1 the normalised ionisation dE/dx for electrons - selected in the electromagnetic calorimeter - and background is shown for different momentum intervals.

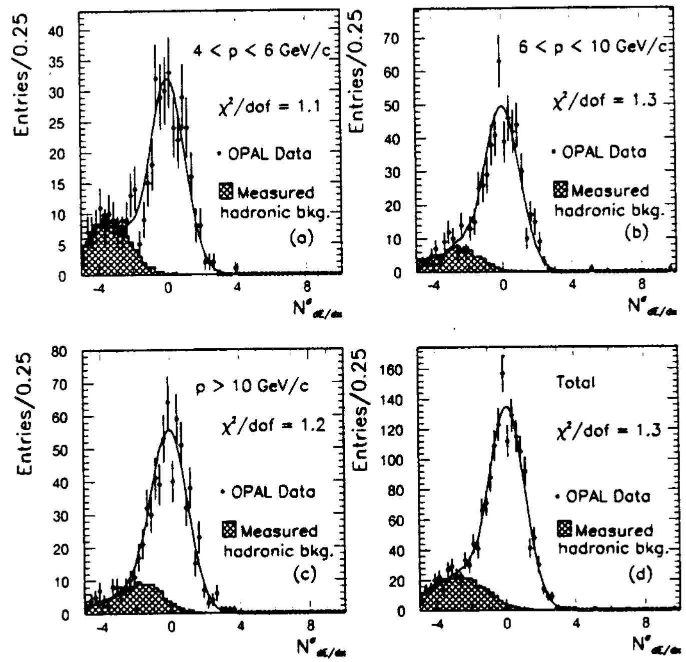

Figure 1: The normalised ionisation dE/dx for electrons and background in the central tracking chamber of OPAL for different momentum intervals.

Muons are identified in the muon chambers and/or in the hadron calorimeter requiring a homogeneous energy deposition compatible with a minimum ionising particle. Misidentification in the case of electrons comes from pion/electron confusion and π^0, γ conversions. For the muons the main background consists of pions and kaons that punch through the iron, and $\pi, K \rightarrow \mu$ decays. Due to the fact that there are two independent methods to identify electrons and muons, efficiencies and purities can be studied very accurately.

Kinematical cuts on the momentum p and transverse momentum p_t of the lepton are used to enrich the sample in heavy quarks. The transverse momentum of a lepton coming from a B hadron is high, due to the high mass of the B hadron. The direction of the B hadron is approximated by the direction of the jet axis in the event. Jets are found and clustered by e.g., the JADE or LUND algorithms, using charged particles and neutral energy. A lepton coming from a b quark has on the average a rather high momentum due to the hard fragmentation function of the b quarks. Usually the Peterson fragmentation function with one free parameter ϵ is used to describe the heavy quarks:

$$f(z) = \frac{A(\epsilon)}{z}\left(1 - \frac{1}{z} - \frac{\epsilon}{(1-z)}\right)^{-2}, \tag{1}$$

where z is defined as $\frac{(E+p_{||})}{(E_0+p_{||0})}$. $A(\epsilon)$ is a normalisation constant, E is the energy of the heavy hadron, $p_{||}$ the longitudinal momentum. The index 0 refers to the initial situation.

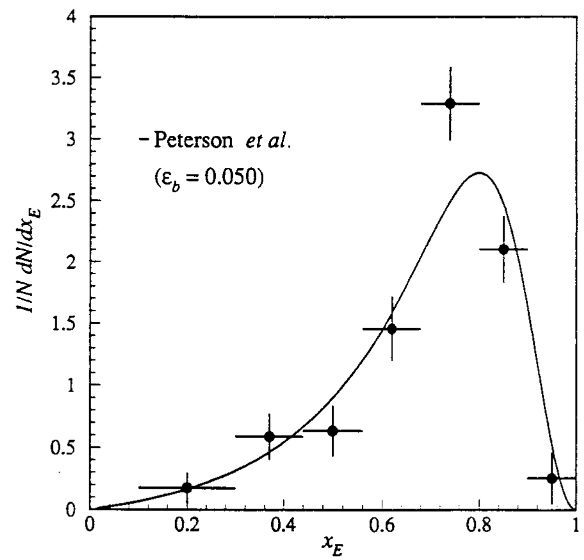

Figure 2: Measured b-quark fragmentation function as a function of x_E by L3. The solid line corresponds to the Peterson fragmentation function with ϵ_b =0.05.

The quantity ϵ can be related to the mean fraction of the energy $< x_b >$ given to the B hadron. At LEP $< x_b >$ is determined to be around 0.70. In Fig. 2 the measured b-quark fragmentation function, and the Peterson fragmentation function are shown as a function of x_E.

2.1 Measurement of $\Gamma_{b\bar{b}}$

Firstly, the results on $\Gamma_{b\bar{b}}$ using leptons will be discussed. Secondly, the results based on other methods will be reviewed. The procedure to determine $\Gamma_{b\bar{b}}$ is more or less the same in the LEP experiments. Starting from the identified leptons a two-dimensional distribution in p and p_t is formed. The p-p_t spectra for prompt b, secondary b, prompt c and background are extracted from the Monte Carlo. The background is fitted from the shape of the distribution in the low p_t region. The fragmentation parameter for b and c quarks is determined from the shape of the momentum distribution selecting events with high p_t. The results[2] for the mean energy fraction $< x_b >$ are listed in Table 1.

Experiment	Leptons	Data Set	$< x_b >$	Ref.
ALEPH	e+μ	90+91	*0.70 ± 0.01 ± 0.02*	[1]
DELPHI	e+μ	90	0.69 ± 0.025 ± 0.01	[2]
L3	e+μ	90	0.686 ± 0.006 ± 0.016	[3]
OPAL	μ	90	0.726 ± 0.007 ± 0.022	[4]

Table 1: Results for the energy fraction $< x_b >$

The LEP measurement of $< x_b >$ is dominated by the systematic error.

The quantity B(b→l)$\Gamma_{b\bar{b}}/\Gamma_h$ is determined by a fit in the full p-p_t plane, or by counting events in the high p_t > 1 GeV/c region. Note that only the product of $\Gamma_{b\bar{b}}/\Gamma_h$ and the semi-leptonic branching ratio B(b→l) is determined.

Experiment	Leptons	Data Set	B(b→l)$\Gamma_{b\bar{b}}/\Gamma_h$	Ref.
ALEPH	e+μ		(see Table 5)	
DELPHI	e+μ	90	0.0221 ± 0.0015	[2]
L3	e+μ	90	0.0249 ± 0.0005 ± 0.0007	[3]
OPAL	μ	90	0.0226 ± 0.0007 ± 0.0013	[4]
OPAL	e	90	0.0238 ± 0.0008 ± 0.0020	[5]

Table 2: Results for $\Gamma_{b\bar{b}}$

In these measurements the systematic error is dominant. If one tries to determine $\Gamma_{b\bar{b}}$ from these numbers one needs - apart from the precisely measured hadronic width (see the talk of C. Hawkes in these Proceedings) - an estimate of the semi-leptonic branching ratio. Here one can use the LEP (see below) or the ARGUS/CLEO [6,7] results. This

[2]New *preliminary* results are in italics. As usual, the first error is statistical, the second systematical. Combined errors, if given, are obtained by summing quadratically both errors.. For *preliminary* numbers I refer only to previous publications.

introduces, however, an additional uncertainty of at least 4%. Further, if ARGUS/CLEO results are used, one assumes that the semi-leptonic branching ratios for B_s, Λ_b, B^0, and B^+ are the same.

The semi-leptonic branching ratio can be determined from the ratio of the lepton and di-lepton spectra at high p_t. The results of the LEP experiments are listed in Table 3. They can - with some caution - be compared with e.g., the CLEO/ARGUS [6,7] value of 0.1055 ± 0.05.

Experiment	Leptons	Data Set	B(b→l)	Ref.
ALEPH	e+μ	90+91	*0.11 ± 0.004 ± 0.004*	
DELPHI	e+μ	90+91	*0.096 ± 0.008 ± 0.010*	
L3	e+μ	90	0.113 ± 0.01 ± 0.006	[3]

Table 3: Results for B(b→l)

Other methods[3] not using leptons, based on the boosted sphericity product (BSP), a multidimensional analysis (MD) based on kinematical variables, or neural networks (NN) are used by the LEP experiments (see Table 4).

Experiment	Method	Data Set	$\Gamma_{b\bar{b}}/\Gamma_h$	Ref.
ALEPH	MD+NN	90+91	*0.214 ± 0.003 ± 0.012*	
DELPHI	BSP	90	0.219 ± 0.014 ± 0.019	[9]
DELPHI	NN	91	0.232 ± 0.005 ± 0.017	[10]

Table 4: Results for $\Gamma_{b\bar{b}}$

The advantage of these methods is that one determines directly $\Gamma_{b\bar{b}}$. The measurements are however dominated by systematic errors, and it will be extremely difficult to reach errors below 5%.

A new approach using leptons is recently proposed by ALEPH. It consists of a fit of the lepton p-p_t spectra, and di-lepton spectra where the di-leptons are splitted up in same and opposite sign leptons in the same and opposite hemispheres. It is clear that in this way a precise determination of $\Gamma_{b\bar{b}}$ and B(b→l) can be obtained, due to the fact that certain systematic errors cancel. The results are shown in Table 5.

Note however that certain parameters as e.g., B(b→l) and $\Gamma_{b\bar{b}}$ are highly correlated. The statistical error on $\Gamma_{b\bar{b}}$ is larger than the error obtained by a fit where only $\Gamma_{b\bar{b}}$ is left free. The systematic error is, as expected, smaller. The transverse and longitudinal momentum distributions for muons are shown in Fig. 3.

[3]DELPHI has also measured $\Gamma_{b\bar{b}}/\Gamma_h = 0.222 \pm 0.032 \pm 0.017$ from the impact parameter distribution [8].

Parameters	ALEPH (90+91)
$\Gamma_{b\bar{b}}/\Gamma_h$	*0.211 ± 0.007 ± 0.008*
$\Gamma_{c\bar{c}}/\Gamma_h$	*0.170 ± 0.010 ± 0.022*
B(b→l)	*0.110 ± 0.004 ± 0.004*
B(c→l)	*0.088 ± 0.003 ± 0.009*
$< x_b >$	*0.70 ± 0.01 ± 0.02*
$< x_c >$	*0.51 ± 0.01 ± 0.02*
χ	*0.137 ± 0.015 ± 0.007*

Table 5: Results from a combined fit of ALEPH

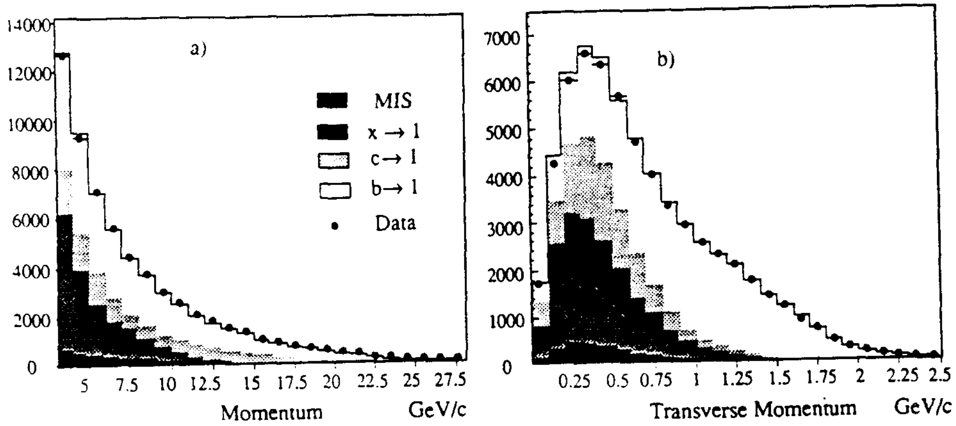

Figure 3: The transverse and longitudinal momentum distribution for muons in ALEPH. The prompt b leptons, prompt c and secondary b leptons, leptons from decays, and misidentified leptons are indicated.

The Standard Model predictions for a top mass of 140 GeV and a Higgs mass of 100 GeV are: $\Gamma_{b\bar{b}}/\Gamma_h = 0.217$ and $\Gamma_{c\bar{c}}/\Gamma_h = 0.171$. The LEP results are in good agreement with these predictions. The highest accuracy on $\Gamma_{b\bar{b}}$ is presently around 4%. There is still a lot of work to do to reach the precision of 1%, and come in the regime where loop effects of the top, Higgs and SUSY particles are expected.

2.2 Measurement of $A_{b\bar{b}}^{fb}$

In the measurement of the forward-backward asymmetry $A_{b\bar{b}}^{fb}$ for b quarks, leptons play an important role, because the prompt leptons reflect the charge of the b or $\bar{b}$ quark. To measure the asymmetry the b quark direction is reconstructed taking the thrust (or sphericity) axis of the event. According to the charge of the lepton the value of cos(thrust) is positively or negatively signed. The angular distribution of the b quark is given by:

$$\frac{d\sigma}{d\cos\theta_b} = 1 + \cos^2\theta_b + \frac{8}{3}A_{b\bar{b}}^{fb}\cos\theta_b. \tag{2}$$

The asymmetry can be determined from the angular distribution, or by simply counting events in the forward and backward hemispheres. The asymmetry can be extracted - as in the case of $\Gamma_{b\bar{b}}$ - by fitting the full p-p_t plane, or by selecting events at high $p_t >$ 1 GeV/c. In the fit one corrects the result for the asymmetry arising from secondary b decays, prompt c decays and the background. The observed asymmetry (uncorrected for the mixing of the B_d and B_s mesons) is given in Table 6. In Fig. 4 the signed cos(thrust) distribution after background subtraction is shown.

Experiment	Leptons	Data Set	$A_{b\bar{b}}^{obs}$	Ref.
ALEPH	e+μ	89-91	0.061 ± 0.013 ± 0.005	[12]
DELPHI	e+μ	90+91	0.094 ± 0.019 ± 0.012	[11]
L3	e+μ	90+91	0.066 ± 0.012 ± 0.015	[13]
OPAL	e+μ	90+91	0.074 ± 0.014 ± 0.007	[14]
Combined			0.069 ± 0.008	

Table 6: Results for $A_{b\bar{b}}^{fb}$

The statistical error is in general larger than the systematic error. If more data are collected the systematic error will still be lowered. If one corrects for mixing, assuming the LEP average $\chi = 0.128 \pm 0.01$ (see Section 2.3), one finds:

$$A_{b\bar{b}}^{fb} = A_{b\bar{b}}^{obs}/(1-2\chi) = 0.093 \pm 0.011 \ (prel.). \tag{3}$$

The Standard Model prediction for the asymmetry is 0.091, assuming a mass of the top quark of 140 GeV and a mass of the Higgs of 100 GeV. The prediction changes by 0.005 for a 50 GeV change in the top mass, or a factor of ten change in the Higgs mass (from 100 to 1000 GeV).

2.3 B^0-$\overline{B}^0$ Mixing at LEP

The B_s and B_d mesons are expected to mix, i.e., to change into their anti-particles. The mixing rate is predicted by the Standard Model. At LEP the average mixing probability

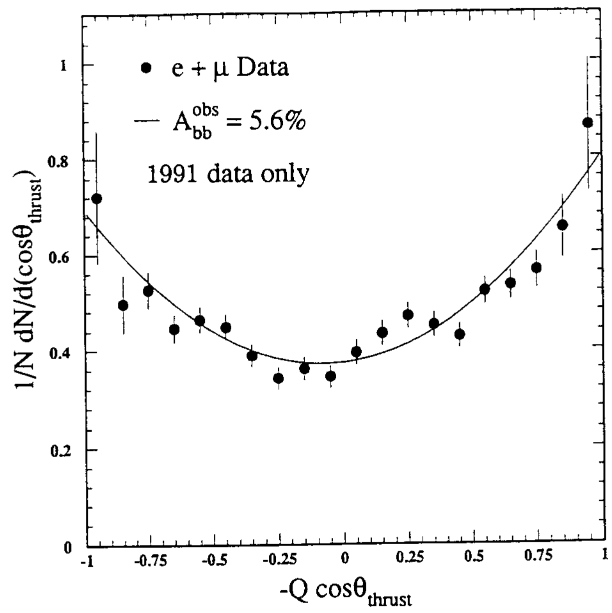

Figure 4: The signed cos(thrust) distribution for muons and electrons after background subtraction by L3.

χ is measured:

$$\chi = f_s\chi_s + f_d\chi_d, \tag{4}$$

where f_s (f_d) is the fraction of B_s (B_d) mesons produced, and χ_s (χ_d) the probability for a B_s (B_d) meson to mix.

The mixing parameter can be determined from the dileptons, or from the lepton combined with the jet charge. In the first case the charge of the dileptons is investigated. If one selects prompt b→l decays in opposite jets and one of the B^0 mesons mixes, it gives rise to a like sign (++ or −−) lepton pair. Therefore the rate of like to unlike sign lepton pairs is fitted as a function of e.g., the minimum p_t of the two leptons, or $p_\otimes = p_{t1}\,p_1 + p_{t2}\,p_2$, or the minimum $p_{comb} = \sqrt{(p/10)^2 + p_t^2}$. All these variables combine the momentum and transverse momentum variables of the leptons in order to obtain an optimal separation between prompt b leptons and others (leptons from secondary, cascade b decays, etc.). The results for the average mixing parameter are shown in Table 7.

In the second method the information of one lepton in combination with the jet charge

Experiment	Leptons	Data Set	χ	Ref.
ALEPH	e+μ	90+91	*0.137 ± 0.015 ± 0.007*	[15]
DELPHI	e+μ	90+91	*0.121 ± 0.042 ± 0.017*	
L3	e+μ	90+91	0.121 ± 0.017 ± 0.006	[16]
OPAL	e+μ	90+91	*0.125 ± 0.015 ± 0.015*	[17]
Combined			*0.128 ± 0.010*	

Table 7: Results for χ

is used. The jet charge is defined as:

$$Q = \frac{\Sigma_i q_i \vec{p_i}.\vec{e_s}}{\Sigma_i \vec{p_i}.\vec{e_s}}, \quad (5)$$

where $\vec{p_i}$ are the three momenta, q_i the charges of the particles and $\vec{e_s}$ is the unit vector of the sphericity (or thrust) axis. The index i loops over all tracks in the forward or backward hemisphere, defined by $\vec{p_i}.\vec{e_s} > 0$ or < 0. The jet charge can distinguish b from $\bar{b}$ quarks on a statistical basis. The sensitivity of the jet charge is, however, different for B_s and B_d mesons. The measured mixing probability χ_q can be written as:

$$\chi_q = 0.72\, f_s\, \chi_s + f_d\, \chi_d. \quad (6)$$

The correction factor 0.72 is estimated by Monte Carlo. The average jet charge of the hemisphere opposite to the lepton, is fitted as a function of p_t of the lepton. The results are shown in Table 8.

Experiment	Leptons	Data Set	χ_q	Ref.
ALEPH	e+μ	90	0.113 ± 0.018 ± 0.027	[18]
DELPHI	μ	90+91	*0.070 ± 0.028 ± 0.024*	
Combined			*0.094 ± 0.024*	

Table 8: Results for χ_q

DELPHI also determined the difference in mixing $\Delta\chi_q$ for jets opposite to the μ^+ and μ^-: $\Delta\chi_q = \frac{\chi_q(\mu^+)-\chi_q(\mu^-)}{2}$ = *0.001 ± 0.028 ± 0.023*. This variable is sensitive to CP violation. Note that in the jet charge measurements the systematic error (coming from the uncertainty on the jet charge distribution) is dominant.

In the dilepton measurements the statistical error is dominant, and a precision of 0.01 is reached. Assuming for $f_s = 0.12$, $f_d = 0.40$ and $\chi_d = 0.16 \pm 0.04$ (measured by ARGUS and CLEO [19]), one obtains χ_s = *0.50 ± 0.08 (LEP) ± 0.13 (χ_d)*. This result is compatible with the expected full mixing of the B_s meson.

3 Beauty Signals

In this part the LEP results will be reviewed for the following exclusive beauty channels:

- Evidence for B_s,
- Evidence for Λ_b,
- J/ψ production.

3.1 Evidence for B_s

Three LEP experiments have evidence for B_s production using the semi-leptonic decay of the B_s into a D_s:

$$B_s \rightarrow D_s^- + l^+ + \nu + X \ .$$

The D_s is reconstructed in two channels, both with a K^+K^- pair and a π in the final state:

$$D_s^- \rightarrow \Phi + \pi^- \text{ and } \Phi \rightarrow K^+K^- \ .$$

Secondly,

$$D_s^- \rightarrow K^{*0} + K^- \text{ and } K^{*0} \rightarrow K^+ + \pi^- \ .$$

To extract the signal the experiments cut around the Φ and K^{*0} masses. To suppress the prompt D_s^- production the lepton is required to have a high tranverse momentum $p_t > 1.2$ GeV/c or a high invariant mass M(D_s^-,l) > 3.0 GeV. Accidental combinations are reduced by a cut on the opening angle cos(ψ)> 0.4 between the K$^+$ and K$^-$ (π^-) in the Φ (K^{*0}) restframe. The first channel has less background due to the narrow width of the Φ. The combinatorial background in the second channel is further reduced by requiring that the dE/dx measurement in the central tracking detector is compatible with a kaon, or by applying a tighter opening angle cut, or by requiring a displaced vertex.

Comparison of the right sign (l$^+$, D_s^- and cc.) and wrong sign lepton D_s combinations shows an excess of events (see Figs. 5, 6 and 7). This can be interpreted as evidence for B_s production.

The main physics backgrounds comes from B(d,u)→ $D_s^- D^+$ where the D^+ decays semi-leptonically. The second background is due to B(d,u)→ D_s^-"K"$l^+\nu$ but this process has a small branching ratio. The number of events *after* background subtraction for the experiments are shown in Table 9. The total background correction is rather small. The branching ratio is defined per lepton: B.R. = f(b→B_s)B($B_s \rightarrow D_s^- l^+ X$) B($D_s^- \rightarrow \Phi\pi^-$).

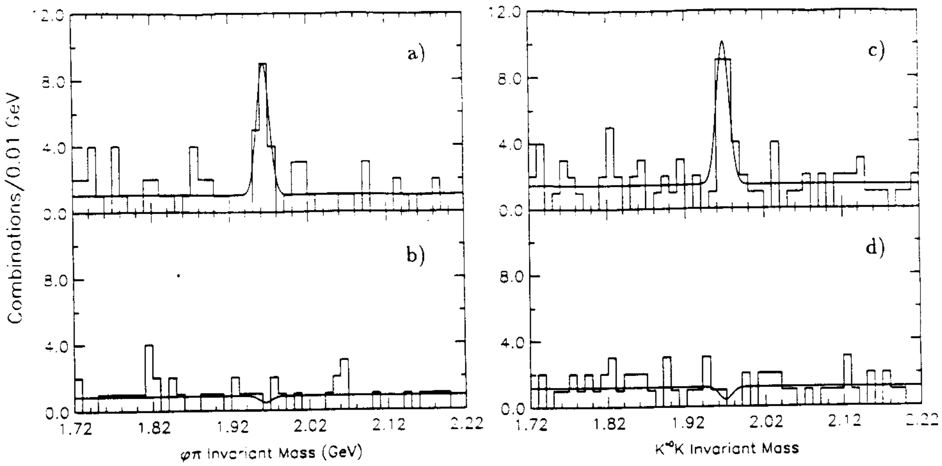

Figure 5: The invariant mass of Φ, π and K, K^{*0} showing a D_s signal for (a, c) opposite, and (b, d) same sign (D_s,lepton) combinations by ALEPH.

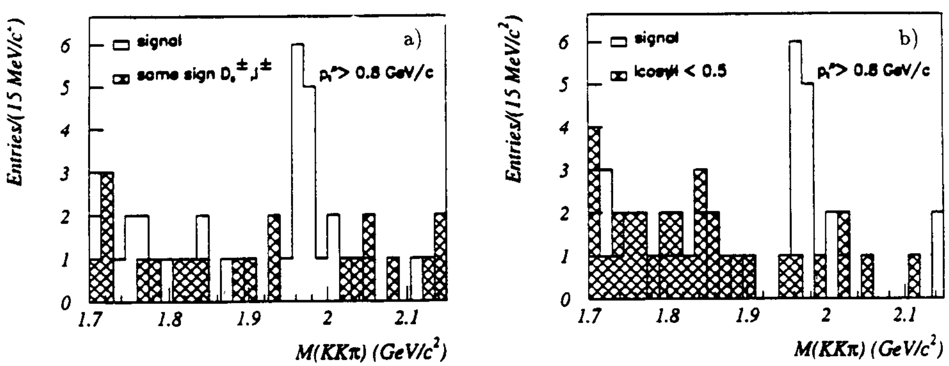

Figure 6: The invariant mass of $K^+, K^-\pi$ showing a D_s signal by DELPHI, (a) for opposite sign and same sign (hatched) (D_s, lepton) combinations, and (b) for events accepted and rejected (hatched) by the opening angle cut.

To conclude there is evidence for B_s production at LEP in both decay channels. Assuming a branching ratio $B(B_s \to D_s^- l^+ X) = 0.09$, and the measured $B(D_s^- \to \Phi\pi^-) = 0.027 \pm 0.07$ one finds: $f(b\to B_s) = 0.18 \pm 0.04$ *(LEP)* $\pm\ 0.04$ *(B.R.)*. This should be compared to the expected fraction of around 0.12.

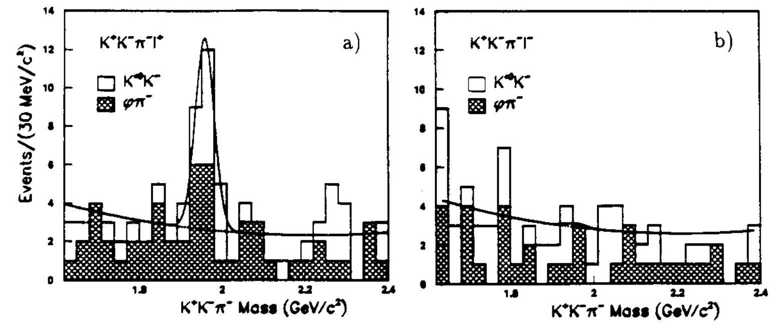

Figure 7: The invariant mass of $K^+, K^-\pi$ showing a D_s signal by OPAL , for (a) opposite, and (b) same sign (D_s, lepton) combinations.

Experiment	Channel	Events	Background	B.R. (10^{-4})	Ref.
ALEPH	A e+μ	$13.7 \pm 4.4 ^{+0.}_{-2.}$	1.8 ± 0.6	combined with B	[20]
ALEPH	B e+μ	$13.1 \pm 5.5 ^{+0.}_{-1.8}$	3.4 ± 1.0	$5.4 \pm 1.4 \pm 1.4$	[20]
DELPHI	A+B μ	$7.5 ^{+3.3}_{-2.6}$	2.0	4.1 ± 1.8	[21]
OPAL	A+B e+μ	*18.3 ± 5.2 ± 0.9*	0.9 ± 0.7	*3.9 ± 1.1 ±0.8*	[22]
Combined		*53 ± 8*		*4.4 ± 1.0*	

Table 9: Results for B_s

3.2 Evidence for Λ_b

There is substantial evidence for Λ_b production using the semi-leptonic decay of the Λ_b into a Λ_c:

$$\Lambda_b \to \Lambda_c^+ + l^- + \nu + X,$$

where the Λ_c decays in the following ways:

- $\Lambda_c \to \Lambda + X$, where the Λ is reconstructed in the decay $\Lambda \to p + \pi^-$.
- or, $\Lambda_c \to p + K^- + \pi^+$.

In the first case the Λ is required to have a decay length greater than 5 cm, and a momentum greater than 3 GeV/c. To suppress the background, some experiments require that the proton should have the proper dE/dx along the track. To enrich the b-quark content of the sample, the lepton is required to have a momentum greater than 5 GeV/c and a transverse momentum greater than 1 GeV/c.

Comparing the right sign (Λ, l^- and cc.) and wrong sign lepton Λ combinations, an excess of events is found (see Fig. 8). The excess of events can be interpreted as Λ_b production.

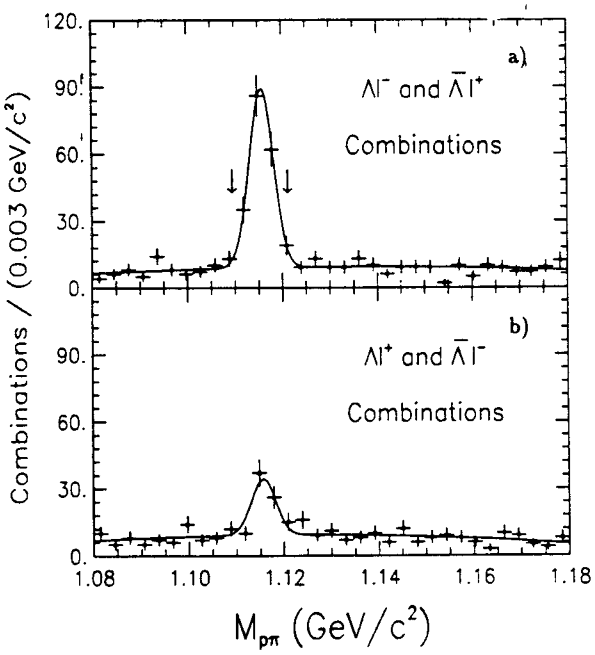

Figure 8: The invariant mass of p, π showing a Λ signal by ALEPH, for (a) right, and (b) wrong sign (Λ, lepton) combinations.

The backgrounds are fairly small. In the case of ALEPH e.g., one estimates 6.7 $\Lambda\, l^-$ combinations due to the decay B(d,u) $\rightarrow \Lambda_c + l^- + \nu + X$. And 4.2 $\Lambda\, l^+$ wrong sign combinations due to the decay b, c $\rightarrow \Lambda_c$ + X, where the Λ_c decays semi-leptonically.

The second channel, analysed by ALEPH, requires the identification of the proton and kaon using the ionisation loss in the time projection chamber. In addition the Λ_c is required to have a momentum above 8 GeV/c, and the invariant mass of the Λ_c and lepton should be above 3.5 GeV.

The number of excess events is shown in Table 10. The branching ratio is defined per lepton: B.R. = f(b$\rightarrow\Lambda_b$)B($\Lambda_b \rightarrow \Lambda_c$ l νX) B($\Lambda_c \rightarrow \Lambda X$). For the second channel the B.R. is defined as: B.R. = f(b$\rightarrow\Lambda_b$)B($\Lambda_b \rightarrow \Lambda_c$ l νX) B ($\Lambda_c \rightarrow pK\pi$).

Experiment	Channel	Events	B.R.(10^{-3})	Ref.
ALEPH	Λ e+μ	*117 ± 18*	*3.8 ± 0.6 ± 1.0*	[23]
DELPHI	Λ μ	*32 ± 10*	*4.0 ± 1.2 ± 0.8*	
OPAL	Λ e+μ	55 ± 9 $^{+0.3}_{-3.1}$	2.9 ± 0.5 ± 0.7	[24]
Combined		*204 ± 22*	*3.4 ± 1.0*	
ALEPH	B e+μ	21 ± 5	0.65 ± 0.15 ± 0.21	[20]

Table 10: Results for Λ_b

To conclude, there is convincing evidence for Λ_b production at LEP in two decay channels. Assuming a branching ratio B($\Lambda_b \rightarrow \Lambda_c\ l^+ X$) = 0.09, and the measured B($\Lambda_c \rightarrow \Lambda$ X) = 0.45 ± 0.15, one finds for the fraction of Λ_b produced at LEP: f(b$\rightarrow\Lambda_b$) = *0.084 ± 0.02 (LEP) ± 0.03 (B.R.).*

3.3 J/ψ Production

Production of J/ψ goes mainly via the following process: Z° $\rightarrow b\bar{b} \rightarrow J/\psi$ + X, where the b ($\bar{b}$) quark produces a J/ψ. The J/ψ is reconstructed from its decay into two leptons. The leptons should have momenta greater than 2 GeV/c and the J/ψ a momentum larger than 5 (10) GeV/c. To suppress the background from double semi-leptonic decay of the b and c quark, one cuts on the missing energy by requiring that the energy in the hemisphere of the J/ψ exceeds 85 percent of the beam energy.

The results[4] for the number of J/ψ events after background subtraction can be found in Table 11. The branching ratio is defined as B(Z° $\rightarrow J/\psi$ X).

L3 measured for the J/ψ the average energy fraction $< x_b >$ = 0.70 ± 0.03 $^{+0.02}_{-0.01}$. This is in good agreement with the results obtained from the lepton spectra (see Table 1). Using the Standard Model value for Z° $\rightarrow b\bar{b}$ = 0.150, one finds for B(B $\rightarrow J/\psi$ X) = *1.37 ± 0.13 %.* This is in agreement with the measurements at lower energies that give a B.R. of 1.12 ± 0.16 [28].

ALEPH and DELPHI have some fully reconstructed B $\rightarrow J/\psi$ X events (see Table 12).

[4]The OPAL numbers are without background subtraction. OPAL used the B($J/\psi \rightarrow l^+l^-$) = 0.069 ± 0.009. The other experiments used the preciser MARK III result of B($J/\psi \rightarrow l^+l^-$) = 0.069 ± 0.00195 ± 0.0015. With this result the B.R. for OPAL becomes 5.3 ± 0.9 ± 0.4 10^{-3}.

Experiment	μ	e	B.R.(10^{-3})	Ref.
ALEPH	*59.7*	*32*	3.81 ± 0.41 ± 0.26	[25]
DELPHI	*44.2*		*4.15 ± 0.75 ± 0.53*	
L3	43	15	4.1 ± 0.7 ± 0.3	[26]
OPAL	42	18	4.5 ± 0.8 ± 0.7	[27]
Combined	*190*	*60*	*4.1 ± 0.4*	

Table 11: Results for J/ψ

Channel	ALEPH	DELPHI
$B^+ \to J/\psi K^+$	*5*	*1*
$B^0 \to J/\psi K^0$	*1*	
$B^0 \to J/\psi K^{*0}$	*1*	*2*
$B^+ \to J/\psi K^+ \pi^- \pi^+$		*2*

Table 12: Results for fully reconstructed B events

ALEPH derives a branching ratio for the first channel: $B^+ \to J/\psi K^+ = 0.22 \pm 0.10 \pm 0.02\%$ [25]. This can be compared with the preciser B.R. measurements of CLEO/ARGUS of 0.077 ± 0.02 % [29].

4 B Lifetime Measurements

In this part the following LEP lifetime measurements will be reviewed:

- Average b lifetime,
- Exclusive b lifetimes.

4.1 Average b Lifetime

The average b lifetime is measured at LEP with leptons and hadrons. This is done on the basis of the signed impact parameter in the RΦ plane. Tracks are extrapolated to the point of closest approach to the production point. The distance to the production point is calculated and signed according to the direction of the track. Most of the experiments profit from a micro-vertex detector, with a typical resolution per point of approximately 8 μm (DELPHI).

The events with leptons (hadrons) are enriched in b quarks by applying a $p_t > 1$ GeV/c and p > 3 GeV/c cut. The lifetime is extracted by fitting the impact parameter distribution, taking into account the composition of the sample (prompt b, secondary b, etc.), the physics function that contains the lifetime, and the resolution function. The results are shown in Table 13.

Experiment		Data Set	τ_b (ps)	Ref.
ALEPH	e+μ	90	1.29 ± 0.06 ± 0.10	[30]
ALEPH	e+μ	91	1.49 ± 0.03 ± 0.06	[31]
DELPHI	μ	90	1.30 ± 0.10 ± 0.08	[8]
DELPHI	h	90	1.27 ± 0.04 ± 0.12	[8]
DELPHI	μ	91	*1.36 ± 0.05 ± 0.05*	
L3	e+μ	90	1.32 ± 0.08 ± 0.09	[32]
OPAL	e+μ	90	1.37 ± 0.07 ± 0.06	[33]
Combined			*1.36 ± 0.05 ± corr.*	

Table 13: Results for τ_b

Adding the 1991 data one observes that the systematic error on the b lifetime is dominant. Most of the systematic error comes from the uncertainties in the b decay scheme. Combining the results of the LEP experiments becomes difficult due to the correlated systematic errors. The LEP experiments have reached a 5% precision, while the theoretical predictions for the average lifetime of the b quark have an uncertainty of approximately 10%.

4.2 Exclusive b Lifetimes

The lifetime of the B producing a J/ψ, the lifetimes of the B_s, Λ_b', B$^+$ and the B^0 are determined at LEP. In the first case the full vertex of the J/ψ is reconstructed from the two leptons, and the decay length is converted into a lifetime.

Experiment	Data Set	τ_b (ps)	Ref.
ALEPH	90+91	$1.35\ ^{+0.19}_{-0.17} \pm 0.05$	[25]
DELPHI	90+91	*$1.34\ ^{+0.30}_{-0.20} \pm 0.20$*	
OPAL	90+91	$1.32\ ^{+0.31}_{-0.25} \pm 0.15$	[27]
Combined		*1.34 ± 0.13*	

Table 14: Results for τ_b

The results (see Table 14) are compatible with the measured average b lifetime.

The lifetime of the B_s is obtained in DELPHI by comparison of the decay length of the reconstructed D_s, and the decay length for events with a D^0. This gives: $\tau_{B_s}/\tau_{B(u,d)} = 0.80 \pm 0.40$ [21].

Fitting the impact parameter of the lepton for the Λ_b events, ALEPH determined the lifetime of the Λ_b: $\tau_{\Lambda b} = 1.12\ ^{+0.29}_{-0.26} \pm 0.16$ ps [34].

DELPHI studied the following B decays:

- $B \to D^0 + l^- + \nu + X$,
- $B \to D^{*+} + l^- + \nu + X$,
- $B \to D^+ + l^- + \nu + X$.

The D particles were fully reconstructed from their decays into charged kaons and pions. Cuts around the mass of the D were put. Further, it was required that the p_t of the lepton exceeded 1 GeV/c, and that the vertex of the D was displaced. From the reconstructed vertex the lifetime was determined. The results [35] are shown in Table 15 and Fig. 9.

Channel	Events	τ_B (ps)
$B \to D^0$	92	$1.27\ ^{+0.22}_{-0.18} \pm 0.15$
$B \to D^{*+}$	61	$1.19\ ^{+0.25}_{-0.19} \pm 0.15$
$B \to D^+$	35	$1.18\ ^{+0.39}_{-0.27} \pm 0.15$
Combined		$1.23\ ^{+0.14}_{-0.13} \pm 0.15$

Table 15: Results for B lifetimes

From the first two channels the lifetimes of the charged and neutral B hadrons are derived. The results are shown in Table 16.

	τ_B (ps)
B^+	$1.30\ ^{+0.33}_{-0.29} \pm 0.15 \pm 0.05$
B^0	$1.17\ ^{+0.29}_{-0.23} \pm 0.15 \pm 0.05$

Table 16: Results for charged and neutral B lifetimes

In addition to the systematic error of 0.15 ps there is a 0.05 ps error, coming from the uncertainty on the amount of D** produced in B decays. Within the errors the lifetimes for neutral and charged B hadrons are equal.

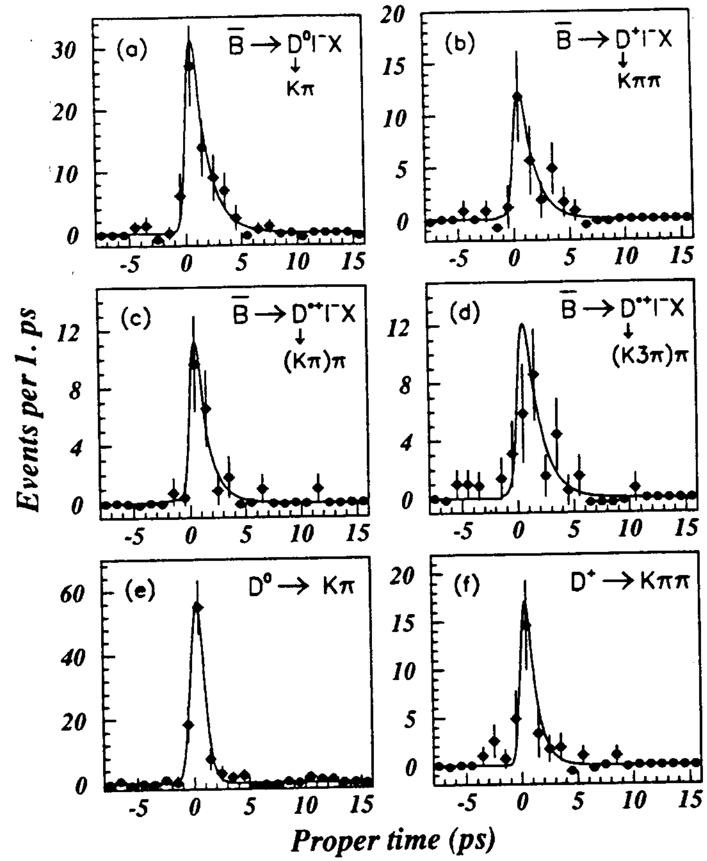

Figure 9: The lifetime distributions for the different B channels (a)-(d), and two D decays modes (e)-(f) by DELPHI.

5 Perspectives

To conclude, I will summarize what was obtained and try to anticipate what LEP will give in the coming years. In the field of beauty physics at the Z° resonance, $\Gamma_{b\bar{b}}$ was determined with a precision of 4%. In the future this error will become smaller using double tag methods, and hopefully the interesting level of a 1% error will be reached. The asymmetry and mixing measurements are still statistics limited. The $A^{fb}_{b\bar{b}}$ will e.g., be determined in the near future with a error below 0.5%, and one can look for top/Higgs/SUSY loop effects.

In the future one expects more beauty signals at LEP for Λ_b , B_s , B^+, and B^0, and some fully reconstructed events. From these signals one will estimate the Λ_b and B_s masses, and determine precisely branching ratios. Possibly, B_s mixing will be observed directly.

Beauty lifetime measurement with higher statistics will be done separately for Λ_b, B_s, B^+, and B^0. LEP will be able to reach a precision below 10%, and test predictions for b lifetime differences.

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