B physics at LEP: selected topics

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B PHYSICS AT LEP
SELECTED TOPICS

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Invited talk at the XVIII International Workshop on High Energy
Physics and Field Theory, Protvino-Russia, 24-30 June 1995

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Abstract

Four selected topics on B Physics at LEP are reviewed. These topics cover $Z \to b\bar{b}$ partial width, b hadron lifetimes, $B^0 - \bar{B}^0$ mixing and the CKM matrix element V_{cb}. The latest results from the four LEP experiments are presented and discussed.

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1 Introduction

Since it started in summer 1989 LEP has provided, in addition to the very precise tests of the standard model of electroweak interactions, a set of remarkably new results in B physics. The four LEP experiments, ALEPH, DELPHI, L3 and OPAL have collected a total of 12 million hadronic Z^0 by the end of 1994. This impressive number of events has led to an interesting and exciting developpement in B physics at LEP. Four selected topics in this field are presented in this contribution. They cover $Z \to b\bar{b}$ partial width, b hadron lifetimes, $B^0 - \bar{B}^0$ mixing and the CKM matrix element V_{cb}.

In this article I have used updated values.

2 The measurement of $R_b = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$

In the standard model of electroweak interactions the $Z \to b\bar{b}$ width receives a specific vertex correction involving the top quark mass and is independent of the Higgs mass. This correction is suppressed for the other quark final states. Therefore the measurement of the ratio $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to \text{hadrons})$ is of particular interest since it is an observable sensitive to the top quark mass.

Experimentally the procedure to measure R_b is simple in principle, one counts, around the Z peak, the number of $e^+e^- \to hadrons$ events, tags $e^+e^- \to b\bar{b}$ events by some means with known efficiency and extracts R_b.

Three methods have been used at LEP to measure R_b:

- Inclusive semileptonic b hadrons decays where $b\bar{b}$ events are selected using the p and $p_\perp$ distributions of the lepton.
- Event shape method where $b\bar{b}$ events are selected based on their specific spherical decay shape using kinematic variables with the help of a neural network.
- lifetime tagging exploits the relatively long b hadron decay length (few millimeters) compared to the other hadrons, to select $b\bar{b}$ events. This task which consists of tagging displaced vertices is facilitated by the use of a micro vertex detector. This method is the most powerful among the three, it can achieve $b\bar{b}$ purity of 90% for 40% efficiency which is to be compared to 10% efficiency for the same purity using the inclusive semileptonic tag.

In these analyses the knowledge of the $b\bar{b}$ tagging efficiency is an important issue. To have a better control on this important parameter, a double tagging technique, where the two hemispheres of a selected event are used seperatly, is applied. With this technique systematic errors associated with uncertainties in b hadron production and decay are eliminated but on the other hand one needs to know the correlations

Experiment	method	R_b ($R_c = 0.171$)
ALEPH [1]	lepton fit	0.2190 ± 0.0060(stat) ± 0.0050(syst)
ALEPH [2]	event shape	0.2280 ± 0.0050(stat) ± 0.0050(syst)
ALEPH [3]	lifetime tag	0.2192 ± 0.0022(stat) ± 0.0026(syst)
DELPHI [4]	lifetime + lepton	0.2231 ± 0.0029(stat) ± 0.0035(syst)
DELPHI [4]	multivariate	0.2186 ± 0.0032(stat) ± 0.0022(syst)
DELPHI [4]	lifetime tagg	0.2216 ± 0.0017(stat) ± 0.0027(syst)
L3 [5]	lepton fit	0.2187 ± 0.0081(stat) ± 0.0080(syst)
L3 [6]	event shape	0.2220 ± 0.0030(stat) ± 0.0070(syst)
OPAL [7]	lepton fit	0.2220 ± 0.0110(stat) ± 0.0070(syst)
OPAL [8]	lifetime tag	0.2171 ± 0.0021(stat) ± 0.0021(syst)
LEP average	all	0.2198 ± 0.0016
Standard Model		0.2157 ($m_t = 179$ GeV/c^2)

Table 1: Summary of the R_b measurements at LEP

between the two hemispheres. Apart from the efficiency, another important parameter to keep under control is the bakground level (mainly charm).

The measured value of R_b depends on the value of $R_c(\Gamma(Z^0 \rightarrow c\bar{c})/\Gamma(Z^0 \rightarrow \text{hadrons}))$ and the two are highly correlated. The measurements of R_b from the 4 LEP experiments (assuming the standard model value for $R_c = 0.171$) are summarized in table 1. The average value of R_b is 2.5 σ above the value predicted by the standard model for a top quark mass of $m_t = 179$ GeV/c^2. This is an important result since it represents the only observed deviation from the standard model. To have more confidence on this result, R_b needs to be measured with a much better accuracy. Since half the error on R_b is systematic, more work is needed to have a better control of the systematics.

3 Measurements of b hadron lifetimes

In the spectator model [9] all hadrons with a particular heavy quark Q are predicted to have equal lifetime. This simple picture is based on the assumption that heavy hadron decays are governed by the decay of the heavy quark independently of the light constituant quark(s). Experimental results in the charm sector [10] ($\tau_{D^+} \simeq 2.6\ \tau_{D^0} \simeq 2.2\ \tau_{D_s^+} \simeq 5\ \tau_{\Lambda_c^+}$) show important deviations from this picture. These deviations are understood to arise from non-spectator decays such as W-exchange, W-annihilations or destructive interference between colour-supressed and colour-allowed decay amplitudes giving the same final state. Quantitatively these corrections induce differences between the total decay widths of the ordrer $1/m_Q^2$. In the beauty sector due to larger b quark mass non-spectator effects should be smaller than in the charm sector. As for charmed hadrons the predicted hierarchy between b hadron lifetimes is: $\tau_{B^+} > \tau_{B_d^0} \approx \tau_{B_s^0} > \tau_{\Lambda_b}$. More precisely the following ratios are predicted [11]:

$$\begin{aligned} \tau_{B^+}/\tau_{B_d^0} &= 1.0 + 0.05(\frac{f_B}{200\text{MeV}})^2 \\ \tau_{B_s^0}/\tau_{B_d^0} &= 1.0 \\ \tau_{\Lambda_b}/\tau_{B_d^0} &\approx 0.9 \end{aligned} \tag{1}$$

An experimental verification of these theoretical predictions is important as it tests the significance of non-perturbative corrections in b hadron decays.

3.1 Experimental techniques

Two main techniques are used to measure the b hadron lifetimes at LEP :

- The impact parameter method (developped in the early experiments at PEP and PETRA as an alternative to poor b vertexing precision) is used mainly for inclusive b hadron lifetime measurements and in cases where the b hadron decay length cannot be reconstructed. For semileptonic b hadron decays the impact parameter of the lepton with respect to the primary vertex (interaction point) is directly related to the proper decay time of the b hadron.
- The decay length method is mainly used for exclusive b hadrons lifetime measurements. In this method the proper time of the b hadron decay is given by:

  $$t_b = \frac{l_b\, m_b}{P_b} \tag{2}$$

  Where l_b, m_b and P_b are the reconstructed b hadron decay length, mass and momentum respectively. The b hadron decay length is measured with a precision of 300 μm using the high resolution vertex detector. The mass and the momentum of the b hadron are determined from its reconstructed decay products and with the help of missing neutrino energy in the case of semileptonic b hadron decays. The typical resolution on the proper time t_b with this method is 10-20 %.

3.2 Inclusive b hadron lifetime

The most accurate measurements of the average b hadron lifetime at LEP were performed using :

Experiment	method	$\langle\tau_b\rangle$ (ps)
ALEPH [12]	$e\mu$	1.533 ± 0.013(stat) $\pm$ 0.022(syst)
DELPHI [13]	$e\mu$	1.542 ± 0.021(stat) $\pm$ 0.045(syst)
DELPHI [16]	inclu. had.	1.600 ± 0.010(stat) $\pm$ 0.028(syst)
L3 [14]	$e\mu$	1.535 ± 0.035(stat) $\pm$ 0.028(syst)
OPAL [15]	$e\mu$	1.523 ± 0.034(stat) $\pm$ 0.038(syst)
LEP average (1)	$e\mu$	1.533 ± 0.019
LEP average (2)	all	1.550 ± 0.016

Table 2: Summary of the inclusive b hadron lifetime measurements at LEP

- Impact parameter of high p_T leptons from semileptonic b hadron decays.
- Vertex topology in hadronic b decays.

The impact parameter method [12] [13] [14] [15], uses the Monte Carlo to estimate the background fraction and composition. The average b hadron lifetime is extracted by an unbinned maximun likelihood fit to the impact parameter distribution of the lepton candidates.

The second method [16] uses displaced multiprong vertices, in a b hadron enriched sample, to reconstruct b hadron decay point. In this method the average b hadron lifetime is extracted from the reconstructed decay length distribution using a physics function, estimated from the Monte Carlo, which relates the b hadron decay length to its proper decay time.

The measurements of the average b hadron lifetime from the 4 LEP experiments and their average are summarized in table 2. The lifetime measured by DELPHI with the second method is about 2 σ higher than the lifetime measured from inclusive b hadron semileptonic decays. This difference is not yet understood. Systematics in these measurements may have been underestimated.

3.3 Exclusive b hadron lifetimes

3.3.1 B^+ and B_d^0 lifetimes

Three methods have been used at LEP to mesure the B^+ and B_d^0 lifetimes.

- Fully reconstructed B^+ and B_d^0 decays.
- Partially reconstructed $B \to \bar{D}^{(*)}\ell\nu X$ decays.
- Topological secondary vertex reconstruction.

a) Fully reconstructed B^+ and B_d^0 decays:

ALEPH has recontructed a total of 94 B^+ and 121 B_d^0 events in different decay channels [17]:

- $B^+ \to \bar{D}^0\pi^+$, $\bar{D}^0 a_1^+$, $(J/\psi,\ \psi(2s))K^+$, $(J/\psi,\ \psi(2s))K^{*+}$
- $B^0 \to D^-\pi^+$, $D^{*-}\pi^+$, $D^{*-}\rho^+$, $D^{*-}a_1^+$, $(J/\psi,\ \psi(2s))K_s^0$, $(J/\psi,\ \psi(2s))K^{*0}$

This method has two advantages: the reconstructed B events are almost background free and their proper times are measured with a very good accuracy. Consequently the B^+ and B_d^0 lifetime measurements have a low systematic uncertainty but due to the limited number of reconstructed events the statistical accuracy is limited.

b) Partially reconstructed $B \to \bar{D}^{(*)}\ell\nu X$ decays:

In this method B^+ and B_d^0 are identified using $D^{(*)}$-lepton correlations. Events with $D^{(*)-}\ \ell^+$ are dominantly from B_d^0 decay and events with $\bar{D}^0\ \ell^+$ (excluding $D^{*-} \to \bar{D}^0\pi^-$) are dominantly from B^+ decay. This simple discrimination criterion between B^+ and B_d^0 gets complicated by higher excited charm states contributions namely $B \to D^{**}\ell\nu$, $D^{**} \to D^{(*)}\pi$ which accounts for about 30% of the semileptonic B decays. In these decays $D^{(*)-}\ \ell^+$ receive contributions from B^+ and $\bar{D}^0\ \ell^+$ from B_d^0. Kinematical and topological rejection criteria are used to reduce this misassociation and corrections are applied to take into account the remaining contamination. The B^+ and B_d^0 lifetimes are extracted from their proper time distribution reconstructed as explained in section 3.1. This method has been used by ALEPH [17], DELPHI [18] and OPAL [19] collaborations. For the measurement of B_d^0 lifetime ALEPH has also used partially recontructed $B_d^0 \to \pi_B^+ X D^{*-}$; $D^{*-} \to \pi_{D^*}^- \bar{D}^0$ decays where only $\pi_B^+\pi_{D^*}^-$ pairs where reconstructed.

c) Topological secondary vertex reconstruction:

Inclusive secondary vertex reconstruction similar to the average b hadron lifetime measurement has been used by DELPHI [20] to measure B^+ and B_d^0 lifetimes. The separation between B^+ and neutral b hadron states is based on the net charge of the tracks at the decay vertex. This method benefits from large statistic and systematic uncertainties due to incorrect assignement of tracks to the decay vertex seem to be well controlled. This method has provided the most accurate measurement of the B^+ lifetime. The B^0 lifetime is extracted from the selected b hadron component using independent mesurements of the Λ_b and B_s^0 fractions and lifetimes.

The measurements of the B_d^0 and $B^\pm$ lifetimes, are summarized in tables 3 and 4.

3.3.2 B_s^0 lifetime

The B_s^0 lifetime has been measured at LEP using partial reconstruction of the semileptonic decay $B_s^0 \to D_s^+\ell^-\bar{\nu}$ and the hadronic decay $B_s^0 \to D_s^+\ hadron$ [21] [22] [23] [24]. The D_s^+ candidates were reconstructed in $\phi\pi^+$ and $\bar{K}^{*0}K^+$ decay

Experiment	method	$\tau_{B_d^0}$ (ps)
ALEPH [17]	full. recons.	$1.25^{+0.15}_{-0.13}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ *
ALEPH [17]	$D^*\ell$	$1.61 \pm 0.07(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ *
ALEPH [17]	$\pi^+_B \pi^-_{D^*}$	$1.49^{+0.17}_{-0.15}(\mathrm{stat})^{+0.08}_{-0.06}(\mathrm{syst})$ *
DELPHI [20]	inclu. vertex recons.	$1.63 \pm 0.14(\mathrm{stat}) \pm 0.13(\mathrm{syst})$
DELPHI [18]	$D^*\ell$	$1.61^{+0.14}_{-0.13}(\mathrm{stat}) \pm 0.08(\mathrm{syst})$
OPAL [19]	$D^*\ell$	$1.53 \pm 0.12(\mathrm{stat}) \pm 0.08(\mathrm{syst})$
LEP average	all	1.555 ± 0.059

Table 3: Summary of the B_d^0 lifetime measurements at LEP. Values quoted with a * are preliminary results

Experiment	method	τ_{B^+} (ps)
ALEPH [17]	full. recons.	$1.58^{+0.21}_{-0.18}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ *
ALEPH [17]	$D^*\ell$	$1.58 \pm 0.09(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ *
DELPHI [20]	inclu. vertex recons.	$1.72 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst})$
DELPHI [18]	$D^*\ell$	$1.61 \pm 0.16(\mathrm{stat}) \pm 0.12(\mathrm{syst})$
OPAL [19]	$D^*\ell$	$1.52 \pm 0.14(\mathrm{stat}) \pm 0.09(\mathrm{syst})$
LEP average	all	1.631 ± 0.060

Table 4: Summary of the B^+ lifetime measurements at LEP. Values quoted with a * are preliminary results

channels. Candidates B_s^0 are identified using $D_s^+ \ell^-$ and D_s^+ *hadron*$^-$ charge correlation. Apart from these two channels, DELPHI has used two other complementary methods ($\phi \ell^\pm$ and inclusive D_s^+) to measure the B_s^0 lifetime. In hadronic and inclusive channels the systematic errors are large compared to the semileptonic channel due mainly to the estimation of the background.

The measurements of the B_s^0 lifetime with these different methods are summarized in table 5.

3.3.3 *b* baryon lifetime

For Λ_b, mainly two methods have been used by the LEP collaborations to select Λ_b candidates. The two methods search for semileptonic Λ_b decay through the charge correlation between a lepton and a fully reconstructed baryon Λ or Λ_c [25] [26] [27] [28] namely $\Lambda \ell^-$ or $\Lambda_c^+ \ell^-$. These right-sign combinations are expected to be dominantly from $\Lambda_b \to \Lambda_c^+ \ell^- \bar{\nu} X$. A small fraction of $\Lambda \ell^-$ combinations is expected to come also from Ξ_b semileptonic decays. Assuming that Λ_b is the dominant source of b baryons at the Z resonance $\Lambda \ell^-$ combinations can be considered as mainly sensitive to Λ_b semileptonic decays.

Experiment	method	$\tau_{B_s^0}$ (ps)
ALEPH [21]	D_s *hadron*	$1.61^{+0.30}_{-0.29}(\text{stat})^{+0.18}_{-0.16}(\text{syst})$
ALEPH [22]	$D_s\ell$	$1.64^{+0.16}_{-0.14}(\text{stat}) \pm 0.04(\text{syst})$
DELPHI [23]	D_s *hadron*	$1.57^{+0.45}_{-0.37}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$
DELPHI [23]	$D_s\ell$	$1.54^{+0.31}_{-0.27}(\text{stat}) \pm 0.06(\text{syst})$
DELPHI [23]	D_s inclu.	$1.61^{+0.34}_{-0.29}(\text{stat})^{+0.18}_{-0.13}(\text{syst})$
DELPHI [23]	$\phi\ell$	$1.45^{+0.20}_{-0.23}(\text{stat})^{+0.32}_{-0.16}(\text{syst})$
OPAL [24]	$D_s\ell$	$1.54^{+0.25}_{-0.21}(\text{stat}) \pm 0.06(\text{syst})$
LEP average	all	1.591 ± 0.106

Table 5: Summary of the B_s^0 lifetime measurements at LEP.

Experiment	method	τ_{Λ_b} (ps)
ALEPH [25]	$\Lambda_c^+\ell^-$	$1.24^{+0.15}_{-0.14}(\text{stat}) \pm 0.05(\text{syst})$ *
ALEPH [25]	$\Lambda\ell^-$	$1.21 \pm 0.09(\text{stat}) \pm 0.07(\text{syst})$ *
DELPHI [26]	$\Lambda_c^+\ell^-$	$1.26^{+0.26}_{-0.22}(\text{stat})^{+0.03}_{-0.05}(\text{syst})$
DELPHI [26]	$\Lambda\ell^-$	$1.10^{+0.16}_{-0.14}(\text{stat})^{+0.05}_{-0.08}(\text{syst})$
OPAL [27]	$\Lambda_c^+\ell^-$	$1.14^{+0.22}_{-0.19}(\text{stat}) \pm 0.07(\text{syst})$
OPAL [28]	$\Lambda\ell^-$	$1.16 \pm 0.11(\text{stat}) \pm 0.06(\text{syst})$
LEP average	all	1.184 ± 0.065

Table 6: Summary of the Λ_b lifetime measurements at LEP. Values quoted with a * are preliminary results

The two lifetime measurement techniques discussed in 3.1 were used to determine the Λ_b lifetime. For $\Lambda_c^+\ell^-$ combinations the decay length method has been used and for $\Lambda\ell^-$ combinations ALEPH and OPAL used the impact parameter method while DELPHI requiring an additional pion used the decay length method.

The Λ_b lifetime measurements are summarized in table 6.

3.4 conclusion on b hadron lifetimes

A summary of the exclusive b hadron lifetimes is presented in Figure 1 with a comparison to the inclusive measurement. As can be seen the pattern of measured lifetimes $\tau_{B^+} > \tau_{B_d^0} \approx \tau_{B_s^0} > \tau_{\Lambda_b}$ follows the theoretical predictions outlined in section 3 however, the ratio of Λ_b and B_d^0 lifetimes which is 0.761 ± 0.051 is 2.7 σ smaller than the theoretical estimation of 0.9 [11]. This discrepancy with the theoretical prediction remains to be understood. Assuming the relative production of b hadrons B^+, B_d^0, B_s^0, Λ_b at the Z resonance to be : 0.39 : 0.39 : 0.12 : 0.10, the average b hadrons lifetime calculated from exclusive measurements is 1.552 ± 0.036 ps, in good

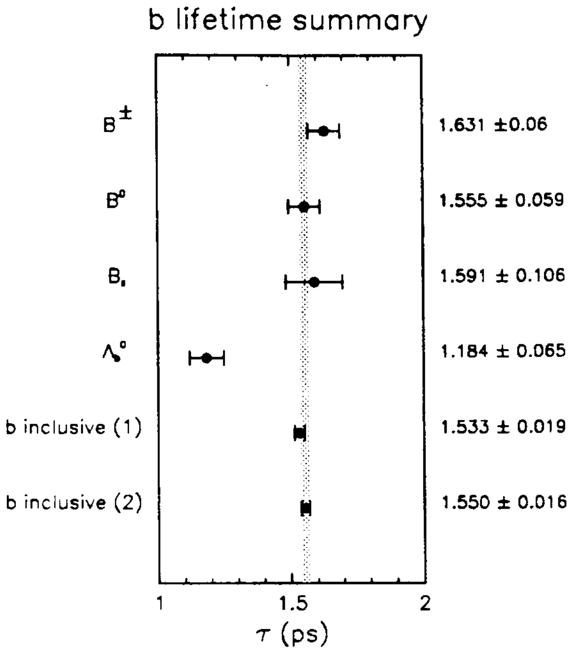

Figure 1: Summary of the exclusive b hadron lifetimes measurements at LEP with a comparison to the inclusive measurement.

agreement with inclusive b hadron lifetime value 1.533±0.019 ps (or 1.550±0.016 ps).

4 $B^0 - \bar{B}^0$ mixing

As in the $K^0\bar{K}^0$ system, neutral B mesons with mass eigenstates B_1 and B_2 are linear combinations of flavour eigenstates B^0 and $\bar{B}^0$. Neglecting CP violation one obtains:

$$\begin{aligned} B_1 &= \frac{1}{\sqrt{2}}(B^0 + \bar{B}^0) \\ B_2 &= \frac{1}{\sqrt{2}}(B^0 - \bar{B}^0) \end{aligned} \tag{3}$$

This feature leads to the phenomena of $B^0 - \bar{B}^0$ mixing. The probability that the state, initially produced as B^0 mixes into $\bar{B}^0$ at time t is (neglecting CP violation) given by:

$$P(B^0 \to \bar{B}^0, t) = e^{-\Gamma t}[1 - cos(\Delta m\ t)] \tag{4}$$

where Γ is the decay width of B_1 and B_2 states and Δm their mass difference. This oscillatory behaviour, with frequency Δm, of the $B^0 - \bar{B}^0$ mixing probability proceeds via second order weak interaction as described by the Box-diagrams shown in figure 2.

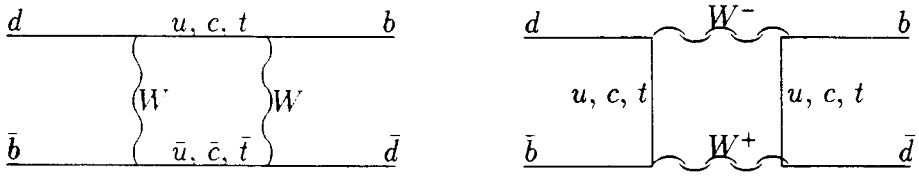

Figure 2: Box-diagrams: oscillation between B_d^0 et $\bar{B}_d^0$ states.

The integrated probability χ that a B^0 mixes to $\bar{B}^0$ is given by:

$$\chi = \frac{1}{2}\frac{(\Delta m/\Gamma)^2}{1+(\Delta m/\Gamma)^2} \tag{5}$$

The first evidence of $B^0 - \bar{B}^0$ mixing was found by UA1 [29]. This experiment could not distinguish between B_s^0 and B_d^0 and has measured an average mixing $\bar{\chi} = f_s\chi_s + f_d\chi_d$, where χ_s and χ_d are respectively the time integrated probability of B_s^0 and B_d^0, f_s and f_d are their relative abundance. Evidence of $B_d^0 - \bar{B}_d^0$ mixing was first reported by ARGUS [30] and confirmed by CLEO [31].

The theoretical prediction of the oscillation frequencies Δm_d for B_d^0 and Δm_s for B_s^0 are derived from calculations of the Box-diagrams contributions where the top quark exchange dominates:

$$\Delta m_{d,s} = \frac{G_F^2}{6\pi^2} m_{B_{d,s}} m_t^2 F(\frac{m_t^2}{m_W^2}) \eta B_{B_{d,s}} f_{B_{d,s}}^2 |V_{tb}^* V_{td,s}|^2 \tag{6}$$

G_F is the Fermi coupling constant, m_t is the top quark mass, F is a function which depends on m_t and m_W. η is a QCD correction factor, B_{B_d} is the so called bag-factor and f_{B_d} the B_d^0 decay constant. The largest theoretical uncertainty on $\Delta m_{d,s}$ comes from the product $B_{B_{d,s}} f_{B_{d,s}}^2$.

The dependence on the top quark mass drops out in the ratio $\Delta m_s/\Delta m_d$:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}\eta_{B_s} B_{B_s} f_{B_s}^2}{m_{B_d}\eta_{B_d} B_{B_d} f_{B_d}^2} |\frac{V_{ts}}{V_{td}}|^2 \tag{7}$$

From the allowed range of $|V_{ts}/V_{td}|$ within the CKM matrix, a recent theoretical estimation [44] shows that $\Delta m_s/\Delta m_d$ lies at 95% $C.L.$ within:

$$10.5(\frac{\xi}{1.16})^2 \leq \frac{\Delta m_s}{\Delta m_d} \leq 77.7(\frac{\xi}{1.16})^2 \tag{8}$$

where $\xi = (f_{B_s}\sqrt{B_{B_s}})/(f_{B_d}\sqrt{B_{B_d}}) = 1.16 \pm 0.1$.

This large allowed range which reflects the poor knowledge of $|V_{ts}/V_{td}|$, shows also that for $B_s^0 - \bar{B}_s^0$ the oscillation frequency is at least 10 times higher than for $B_d^0 - \bar{B}_d^0$.

Experiment	method	$\bar{\chi}$ in %
ALEPH [33]	dilepton tagging	$10.6 \pm 0.7(\text{stat}) \pm 0.9(\text{syst})$ *
DELPHI [34]	dilepton tagging	$15.4 \pm 2.0(\text{stat}) \pm 1.5(\text{syst})$
L3 [35]	dilepton tagging	$12.3 \pm 1.2(\text{stat}) \pm 0.8(\text{syst})$
OPAL [36]	dilepton tagging	$14.4 \pm 2.2(\text{stat}) \pm 0.7(\text{syst})$
LEP average		11.5 ± 0.6

Table 7: Summary of the time integrated $B^0 - \bar{B}^0$ mixing. The value quoted with a * is a preliminary result.

4.1 Time integrated mixing

The measurement of $B^0 - \bar{B}^0$ mixing requires indentification of the particle/antiparticle state both at its production and at its decay. The experimental technique commonly used to measure the time integrated mixing χ is the dilepton tag method. In $b\bar{b}$ events where both b hadrons decay semileptonically, like-sign lepton pair is a signature of mixing. The fraction of the like-sign (mixed) events is given by:

$$R = \frac{N_{\pm\pm}}{N_{\pm\pm} + N_{\pm\mp}} \tag{9}$$

The main background affecting R comes from cascade decay $b \rightarrow c \rightarrow \ell$.

At the $\Upsilon(4s)$ χ_d is related to R by $\chi_d = (1 + \lambda)R$, where $\lambda = 1.13 \pm 0.19$ is a correction for the contribution of B^+B^- events to the like-sign fraction. The average value of χ_d measured by experiments running at the $\Upsilon(4s)$ is [32] $\chi_d = 0.168 \pm 0.024$. This corresponds to $\Delta m_d / \Gamma_d = 0.711 \pm 0.077$ which, using the LEP average value $\tau_{B^0} = 1.555 \pm 0.059$ ps corresponds to $\Delta m_d = 0.457 \pm 0.049 \pm 0.018$ ps^{-1}.

At LEP both B_s^0 and B_d^0 are produced, consequently the measured time integrated mixing is $\bar{\chi} = f_s \chi_s + f_d \chi_d$. Since $b\bar{b}$ pairs are produced incoherently $\bar{\chi}$ is related to R by $R \approx 2\bar{\chi}(1 - \bar{\chi})$. The measurement of $\bar{\chi}$ at LEP has been performed mainly by the dilepton method. ALEPH and DELPHI have also used the jet charge method but this techniques leads to a slightly different sensitivity to B_s^0 and B_d^0.

The measurements of $\bar{\chi}$ from the LEP experiments are summarized in table 7. The LEP average value is $\bar{\chi} = 0.115 \pm 0.006$. Assuming $f_s = 0.12$ and $f_d = 0.39$, this value gives $\chi_s > 0.30$ at 95% *C.L.*, which corresponds to $\Delta m_s / \Gamma_s > 1.22$ at 95% *C.L.* and using $\Delta m_d = 0.457 \pm 0.049 \pm 0.018$ ps^{-1} and $\tau_{B_s} = 1.591 \pm 0.106$ ps translates to $\Delta m_s / \Delta m_d > 1.7(\pm 0.2)$ at 95% *C.L.* which is much smaller than the expected lower limit from theoretical prediction. This poor limit reflects the fact that time integrated mixing has no senitivity to high $\Delta m_s / \Gamma_s$ since for $\chi_s = 0.5$, $(\Delta m_s / \Gamma_s) \rightarrow \infty$. To explore the domain above the expected low theoretical limit of $\Delta m_s / \Delta m_d$ (see equation 8) one needs time dependent mixing measurements.

4.2 Time dependent mixing measurements

The time dependent mixing measurement looks for the characteristic oscillatory behaviour of the mixing which allows the measurement of the frequency Δm directly. The measurement requires a good resolution on the proper time of B^0, especially for B_s^0 where the oscillation frequency is expected to be high and as in the time integrated mixing, the particle/antiparticle state has to be tagged at both its production and decay times.

The technique used at LEP to measure the time dependent mixing is as follows: The selected $b\bar{b}$ event candidate is divided into two hemispheres, one hemisphere is used to tag the production flavour and the other to measure the decay flavour and its proper time. The charge correlation between the two hemispheres is used then to tag mixed and unmixed events.

4.2.1 $B_d^0 - \bar{B}_d^0$ oscillation

Conditions for observing $B_d^0 - \bar{B}_d^0$ oscillation are favourable at LEP for two reasons: the relative abudance of B_d^0 among b hadrons is high ($f_d \approx 0.39$) and its oscillation frequency Δm_d is low (1 oscillation period $\approx 9 \times \tau_{B_d^0}$). The amplitude of the oscillation is however reduced due mainly to proper time resolution, charge mistag and background contamination.

The first measurement of the time dependent $B_d^0 - \bar{B}_d^0$ mixing was reported by ALEPH [37]. Since then several results have been reported by LEP experiments. They are based mainly on three methods : $D^{*+}l^-$ (with or without jet-charge), dilepton and lepton and jet-charge. The last two are sensitive to $B_s^0 - \bar{B}_s^0$ as well, in this case, maximal B_s^0 mixing is assumed for Δm_d measurement. Figure 3 shows the variation of mixed event candidates with the B_d^0 decay proper time measured with the dilepton method by ALEPH.

The latest measurements of Δm_d [38] [39] [40] [41] are summarized in table 8. The LEP average value is $\Delta m_d = 0.456 \pm 0.020$ ps^{-1} which correponds to $\Delta m_d = (3.00 \pm 0.13)10^{-4}$ eV.

4.2.2 $B_s^0 - \bar{B}_s^0$ oscillation

Compared to B_d^0, the measurement of $B_s^0 - \bar{B}_s^0$ oscillation suffers from two limitations: the B_s^0 relative production at LEP is more than three time smaller than B_d^0 ($f_s \approx 0.12$) and its oscillation frequency is much higher. From the expected Δm_s range using Δm_d value and theoretical predictions, one oscillation period $\approx [0.1, 1] \times \tau_{B_s^0}$. Further the significance of the oscillation is reduced by the mixed or unmixed mistag rate, background contamination and proper time resolution. These considerations show how difficult a task it is to search for $B_s^0 - \bar{B}_s^0$ oscillations.

Four methods have been used at LEP to search for $B_s^0 - \bar{B}_s^0$ oscillations : dilepton, lepton and jet-charge methods mentioned above, lepton-kaon and jet-charge, and $D_s^- l^+$ correlations. The results of these analyses are summarized in table 9, they all

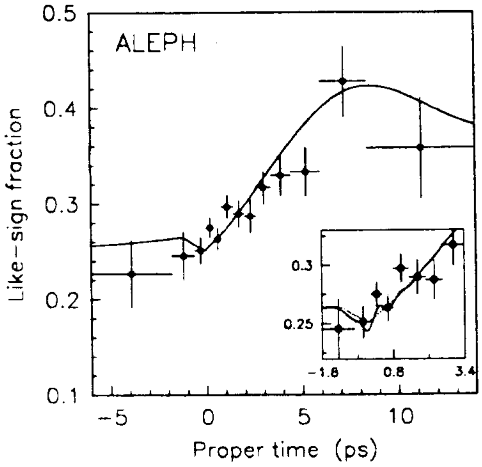

Figure 3: The like-sign fraction as function of reconstructed proper time with Δm_d fit (assuming maximal B_s^0 mixing) superimposed. The insert shows the result of the fit with Δm_s as free parameter.

Experiment	method	Δm_d in ps^{-1}
ALEPH [38]	$D^{*+}\ell^-, Q_j$	$0.482 \pm 0.044(\text{stat}) \pm 0.025(\text{syst})$ *
ALEPH [38]	ℓ, Q_j	$0.404 \pm 0.034(\text{stat}) \pm 0.049(\text{syst})$ *
ALEPH [38]	$\ell^+\ell^+$	$0.430 \pm 0.032(\text{stat}) \pm 0.071(\text{syst})$ *
DELPHI [39]	$D^{*+} + D^{*+}\ell^-, Q_j$	$0.421 \pm 0.064(\text{stat}) \pm 0.042(\text{syst})$ *
DELPHI [39]	$\ell^+K^+Q_j$	$0.563^{+0.050}_{-0.046}(\text{stat}) \pm 0.058(\text{syst})$ *
DELPHI [39]	ℓ, Q_j	$0.438^{+0.040}_{-0.051}(\text{stat})^{+0.039}_{-0.057}(\text{syst})$ *
DELPHI [39]	$\ell^+\ell^+$	$0.420 \pm 0.080(\text{stat})^{+0.080}_{-0.070}(\text{syst})$ *
OPAL [40]	$D^{*+}\ell^-, Q_j$	$0.539 \pm 0.060(\text{stat}) \pm 0.024(\text{syst})$ *
OPAL [40]	$D^{*+}\ell^-$	$0.570 \pm 0.110(\text{stat}) \pm 0.020(\text{syst})$
OPAL [41]	ℓ, Q_j	$0.439^{+0.030}_{-0.029}(\text{stat})^{+0.020}_{-0.019}(\text{syst})$ *
OPAL [41]	$\ell^+\ell^+$	$0.462^{+0.040}_{-0.053}(\text{stat})^{+0.052}_{-0.035}(\text{syst})$
LEP average	all	0.456 ± 0.020

Table 8: Summary of Δm_d measurements at LEP. Values quoted with a * are preliminary results

exclude low values of Δm_s. The limit on Δm_s is extracted from the dependence on Δm_s of the Log-likelihood fit of the selected data sample relative to its minimum. The limit is set from the intersection between the data Log-likelihood curve and the expected log-likelihood value (using a fast Monte Carlo simulation), for different Δm_s, for which the B_s^0 mixing has not occured in 95 % of the sample. For

Experiment	method	Δm_s limit (95% C.L.)
ALEPH [45]	lepton-jet	6.1 ps^{-1} ($f_s = 0.12$)
		5.6 ps^{-1} ($f_s = 0.10$)
ALEPH [38]	dilepton	5.6 ps^{-1} ($f_s = 0.12 \pm 0.3$)*
ALEPH [46]	lepton-K-jet	4.0 ps^{-1} ($f_s = 0.12 \pm 0.3$)*
DELPHI [39]	lepton-jet	4.2 ps^{-1} ($f_s = 0.10 \pm 0.3$)*
DELPHI [47]	D_s-lepton	1.5 ps^{-1}
OPAL [41]	lepton-jet	3.3 ps^{-1} ($f_s = 0.12 \pm 0.4$)*
OPAL [41]	dilepton	2.2 ps^{-1} ($f_s = 0.12 \pm 0.4$)

Table 9: Summary of Δm_s limits at LEP. Values quoted with a * are preliminary results

illustration, figure 4 shows the limit on Δm_s from the dilepton analysis by ALEPH.

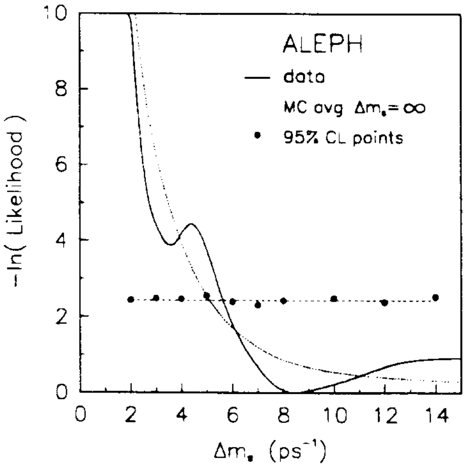

Figure 4: The negative log-likelihood fit for the data (relative to the point of maximum like-lihood), as a function of Δm_s. The points show the value of log-likelihood below which 95 % of Monte Carlo samples lie at a given value of Δm_s.

Using the LEP average value $\tau_{B_s^0} = 1.591 \pm 0.106$ ps the limit $\Delta m_s > 6.1$ ps^{-1} which corresponds to $\Delta m_s/\Gamma_s > 9.7(\pm 0.6)$. Using the LEP average value $\Delta m_d = 0.456 \pm 0.020$ ps^{-1}, one obtains $\Delta m_s/\Delta m_d > 13.4(\pm 0.6)$ which, using the theoretical estimation of $(m_{B_s}\ \eta_{B_s}\ B_{B_s} f^2_{B_s})/(m_{B_d}\ \eta_{B_d}\ B_{B_d}\ f^2_{B_d})$ [44], yields :

$$|\frac{V_{ts}}{V_{td}}| > 3.1(\pm 0.25) \qquad (10)$$

which is the best existing limit.

5 The measurement of $|V_{\rm cb}|$

The magnitude of the *CKM* matrix element $|V_{\rm cb}|$ can be determined either from inclusive semileptonic B decays or from exclusive channels such as $\overline{B^0} \to D^{*+} l^- \overline{\nu_l}$. These two methods have both been exploited at LEP and at experiments running at the $\Upsilon(4s)$.

In the inclusive method $|V_{\rm cb}|$ is determined from the inclusive b hadrons semileptonic width $\Gamma(B \to X\ell\nu)$ via the equation:

$$F_c |V_{\rm cb}|^2 + F_u |V_{\rm ub}|^2 = \frac{192\pi^3}{G_F^2 m^5} \Gamma(B \to X\ell\nu) \tag{11}$$

where F_c and F_u are coefficients which include phase space and *QCD* corrections. Although statistically not limited, the inclusive method suffers from large theoretical uncertainties of the order of 10 % due mainly to the unknown higher order corrections in the expansion for the semileptonic width in $\alpha_s(m_b)$ [48]. [1].

The dermination of $|V_{\rm cb}|$ from exclusive decay such as $\overline{B^0} \to D^{*+} l^- \overline{\nu_l}$ has less theoretical limitations compared to the inclusive method. In the framework of the heavy quark effective theory (HQET) [50], this decay mode can be expressed, to the leading order, in terms of only one form factor, the Isgur-Wise function. Although HQET cannot predict the shape of this function, for decays close to zero recoil (decays of maximum q^2)[2], it is absolutely normalized up to corrections of order $1/m_b^2$ [52]. This normalization provides a reliable determination of $|V_{\rm cb}|$.

The strategy, commonly used [51], to extract $|V_{\rm cb}|$ from the decay $\overline{B^0} \to D^{*+} l^- \overline{\nu_l}$, is to fit its measured differential decay rate and to extrapolate it up to the point of maximum q^2:

$$\begin{aligned} \frac{d\Gamma}{d\omega} &= \frac{1}{\tau_{B^0}} \frac{dBr(\overline{B^0} \to D^{*+} \ell^- \overline{\nu_\ell})}{d\omega} \\ &= G(\omega)\, \mathcal{F}^2(\omega)\, |V_{\rm cb}|^2 \end{aligned} \tag{12}$$

where $\omega = v_{B^0} \cdot v_{D^*} = (m_B^2 + m_{D^*}^2 - q^2)/2m_B m_{D^*}$, $G(\omega)$ is a known phase space function and $\mathcal{F}(\omega)$ is a universal form factor with unknown shape. At $\omega = 1$ (maximum q^2) $G(\omega) \approx 0$ and $\mathcal{F}(\omega) \cdot |V_{\rm cb}|$ is determined by extrapolation.

The first measurements of $|V_{\rm cb}|$ with this method were performed by ARGUS and CLEO experiments [53, 54]. At LEP, ALEPH used the same method and reported the first measurement of $|V_{\rm cb}|$ in [55]. ALEPH has reconstructed a sample of 410 $\overline{B^0} \to D^{*+} \ell^- \overline{\nu_\ell}$ candidates from which the differential decay rate $d\Gamma(\overline{B^0} \to D^{*+} \ell^- \overline{\nu_l})/d\omega$ was reconstructed. The ω variable was reconstructed from the $D^{*+}\ell^-$ system with a resolution of 14 % of the allowed range. Figure 5 shows the reconstructed $\mathcal{F}(\omega) \cdot |V_{\rm cb}|$ distribution with a fit superimposed using a linear $\mathcal{F}(\omega)$ shape

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[1] Some theorists [49] claim that the theoretical uncertainty does not exceed 5%

[2] The q^2 is the mass squared of the virtual W, *i.e.* for the decay $\overline{B^0} \to D^{*+} l^- \overline{\nu_l}$, the mass squared of the (l, ν) pair.

with a slope a^2. The fit yields the following result:

$$\begin{aligned} \mathcal{F}(1)\cdot|V_{\mathrm{cb}}| &= (3.14 \pm 0.23_{\mathrm{stat}} \pm 0.25_{\mathrm{syst}}) \times 10^{-2} \\ a^2 &= 0.39 \pm 0.21_{\mathrm{stat}} \pm 0.12_{\mathrm{syst}} \end{aligned} \tag{13}$$

The systematic error is mainly due to the error on the relative abundance of B_d^0 in b hadronic events, the relative proportion of non resonant B^0 decays and the fitting method.

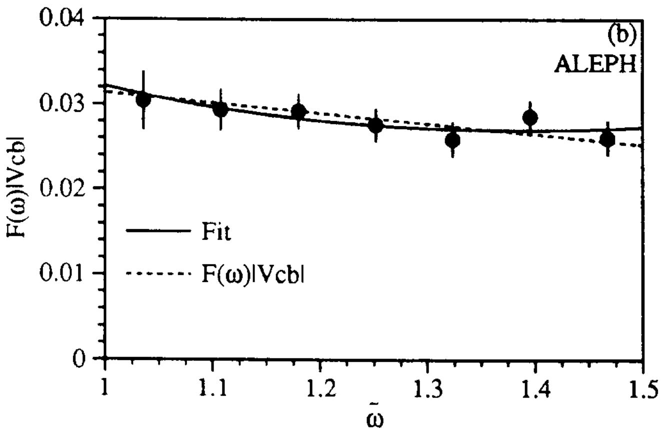

Figure 5: The product $\mathcal{F}(\omega)\cdot|V_{\mathrm{cb}}|$ as a function of ω. The value of $\mathcal{F}(\omega=1)\cdot|V_{\mathrm{cb}}|$ corresponds to the intercept of this curve.

This result is to be compared to the latest CLEO result [54] :

$$\begin{aligned} \mathcal{F}(1)\cdot|V_{\mathrm{cb}}| &= (3.51 \pm 0.19_{\mathrm{stat}} \pm 0.19_{\mathrm{syst}}) \times 10^{-2} \\ a^2 &= 0.84 \pm 0.13_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}} \end{aligned} \tag{14}$$

Using $\mathcal{F}(1) = 0.91 \pm 0.04$ [56], the result for $|V_{\mathrm{cb}}|$ from ALEPH is:

$$|V_{\mathrm{cb}}| = (3.45 \pm 0.25_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.15_{\mathrm{theory}}) \times 10^{-2} \tag{15}$$

6 Conclusions

LEP has provided numerous interesting new results in B physics. Among these results :

- R_{b} has been measured with a relative precision of $< 1\%$ and showed a discripency of 2.5 σ with respect to the standard model prediction. This is the only deviation observed from the standard model. It is yet to be understood and interpreted.

- b hadron lifetimes have been measured with good precision. The hierarchy among b hadron lifetimes agrees with theoretical prediction although $\tau_{\Lambda_b}/\tau_{B^0}$ is 2 σ lower than expected.
- $B_d^0 - \bar{B}_d^0$ time dependent oscillations have been measured for the first time at LEP and its oscillation frequency Δm_d measured with good precision. For $B_s^0 - \bar{B}_s^0$ oscillations a direct limit $\Delta m_s > 6.1$ ps^{-1} has been set for the first time.
- The CKM matrix element $|V_{\mathrm{cb}}|$ has been measured at LEP by ALEPH with a relative error of 10 % and it agrees with the values measured by ARGUS and CLEO.

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