B physics at the Z^0 resonance

Richard Hawkings†and Stéphane Willocq‡§

† CERN-EP division, CH 1211 Geneva 23, Switzerland

‡ Physics Department, University of Massachusetts, Amherst, MA 01003, USA

Abstract. B physics results from e^+e^- annihilation at the Z^0 resonance are reviewed. A vast program is summarised, including the study of B^+, B_d^0, B_s^0 and b baryon lifetimes, the time dependence of B_d^0–$\overline{B_d^0}$ and B_s^0–$\overline{B_s^0}$ oscillations, the width difference in the B_s^0–$\overline{B_s^0}$ system, and the measurements of the magnitudes of the CKM matrix elements V_{cb} and V_{ub}.

1. Introduction

The production of b hadrons in e^+e^- annihilation at the Z^0 resonance offers an excellent opportunity to study their properties in detail. The four LEP experiments have each accumulated 0.9 million $Z^0 \to b\overline{b}$ events, and the SLD experiment at the SLAC linear collider has collected a further $120\,000$ $b\overline{b}$ events with a polarised e^- beam and excellent secondary vertex resolution from a pixel-based vertex detector. These data samples have been used to perform a huge program of b physics, including the studies of b hadron lifetimes, B_d^0 and B_s^0 mixing, the B_s^0–$\overline{B_s^0}$ width difference and measurements of the CKM matrix element magnitudes $|V_{cb}|$ and $|V_{ub}|$ described below.

2. b hadron lifetimes

The lifetimes of b hadrons depend both on the strength of the coupling of the b quark to the lighter c and u quarks, and on the dynamics of the b hadron decay. The spectator model prediction that all b hadron lifetimes are equal is modified by effects dependent on the flavour of the light quark(s) in the hadron. These effects can be calculated using Heavy Quark Expansion tools, and the precise measurement of b hadron lifetimes provides an important test of this theory.

Experimentally, the measurement of b hadron lifetimes requires the isolation of a sample of the particle under study (both from other b hadrons and non b background), the reconstruction of the proper decay time of each b hadron, and the detailed understanding of backgrounds and systematic biases. Different approaches have been used, and will be discussed in more detail below.

§ E-mail: `richard.hawkings@cern.ch` and `willocq@physics.umass.edu`

2.1. B^+ and B^0_d lifetimes

The purest samples of B^+ and B^0_d hadrons are obtained via exclusive reconstruction, for example semileptonic decays of the form $B^- \to D^0 \ell^- \bar{\nu}$ and $\bar{B}^0_d \to D^{*+} \ell^- \bar{\nu}$ followed by $D^{*+} \to D^0 \pi^+$. The D^0 can be reconstructed in various exclusive decay modes, for example $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^+$ and $K^0_s \pi^+ \pi^-$. A recent ALEPH analysis [1] obtains 1880 B^0_d and 2856 B^+ candidates at $85\,\%$ and $80\,\%$ purity from their recently reprocessed LEP1 data sample. The sample purities are limited both by combinatorial background (random combinations of tracks faking a D^0 or D^{*+}), and by cross-contamination of the B^+ and B^0_d samples. The latter is caused mainly by decays of the form $B^- \to D^{**0} \ell^- \bar{\nu}$ and $\bar{B}^0_d \to D^{**+} \ell^- \bar{\nu}$, where the orbitally excited D^{**} decays to $D^{*+} \pi$ or $D^0 \pi$. Fully exclusive reconstruction of particular hadronic decay modes, for example $B^- \to D^0 \pi^-$ and $\bar{B}^0_d \to D^{*+} \pi^-$ has also been used by ALEPH [2], but the reconstructed sample sizes are too small to produce competitive lifetime measurements.

Much larger samples of b hadrons can be obtained using vertex-based b tagging, exploiting the silicon microvertex detectors installed in the LEP and SLD experiments. Events with a clear separated secondary vertex can be classified as charged (B^+) or neutral (B^0_d, B^0_s or Λ_b) by reconstructing the charge of the secondary vertex from the associated tracks. This technique results in large high purity B^+ samples, but the B^0_d sample is limited by irreducible contamination from B^0_s and Λ_b. The selection of clear secondary vertices results in a bias towards large b hadron lifetimes, which must be controlled. In the OPAL analysis [3], this is handled using an 'excess decay length' technique, finding the minimum decay length for each event that would still result in it being selected, whilst the higher resolution silicon detectors of DELPHI and especially SLD allow them simply to cut events with small proper times and fit an unbiased exponential beyond the cut [4]. In all these analyses, the charged/neutral separation is enhanced using additional information, for example by reconstructing the flavour (b or $\bar{b}$) of the b hadron in the opposite event hemisphere, or by using identified kaons or protons to suppress B^0_s and Λ_b background. These techniques result in samples of tens of thousands of charged and neutral b decays, even for SLD where the high performance vertex detector more than compensates for the lower initial number of Z^0 compared to LEP.

A third technique to measure the B^0_d lifetime involves exploiting the small energy release in the decay $D^{*+} \to D^0 \pi^+$, which means that in $\bar{B}^0_d \to D^{*+} \ell^- \bar{\nu}$ decays the π^+ is produced with very small transverse momentum with respect to the D^0 direction. The D^0 direction can be reconstructed inclusively by weighting tracks and clusters according to kinematic and vertexing information, without the need to explicitly reconstruct the decay modes of the D^0. $\bar{B}^0_d \to D^{*+} \ell^- \bar{\nu}$ events are selected by looking for charged pions with small transverse momentum and sign opposite to that of the lepton, and the combinatorial background is controlled using events with same sign pions and leptons. Additional background contamination comes from $\bar{B} \to D^{**} \ell^- \bar{\nu}$ decays in the same way as for exclusively reconstructed D^0. Using this technique, DELPHI, L3 and OPAL [5, 6]
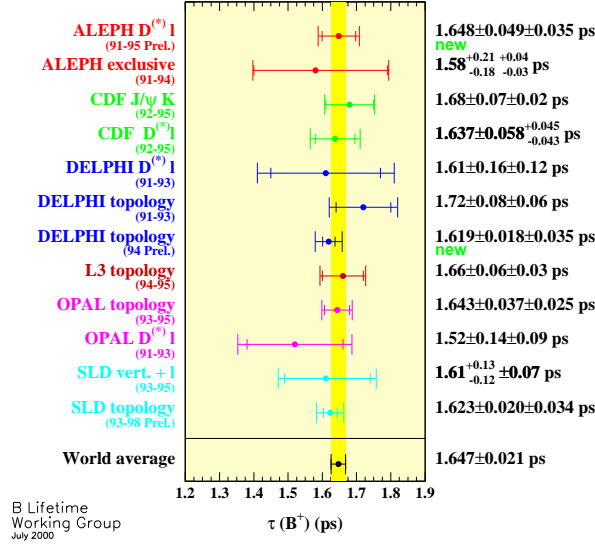
Figure 1. Summary of the B^+ lifetime measurements from LEP, CDF and SLD.
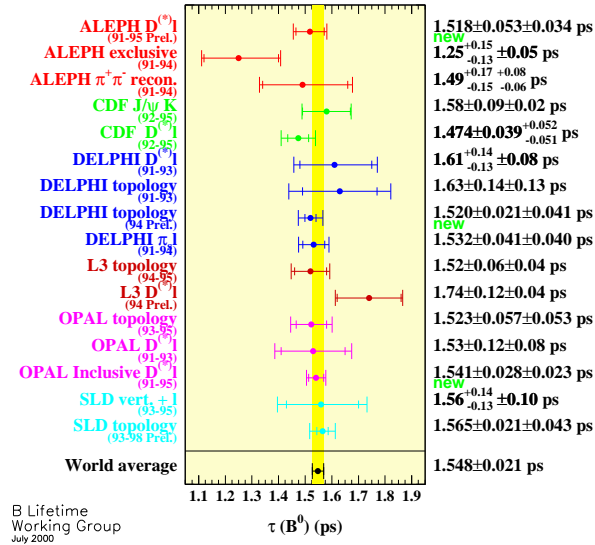

Figure 2. Summary of the B_d^0 lifetime measurements from LEP, CDF and SLD.

have reconstructed samples of around 5000 B_d^0 decays and measured the lifetime.

A summary of all B^+ and B_d^0 lifetime measurements is given in Figures 1 and 2 [7]. The B^+ measurements are dominated by the topological secondary vertex analyses from DELPHI, OPAL and SLD [3, 4] whilst the most accurate B_d^0 measurements come from the OPAL inclusive $\bar{B}_d^0 \to D^{*+}\ell^-\bar{\nu}$ analysis [6] and the DELPHI and SLD topological measurements [4].
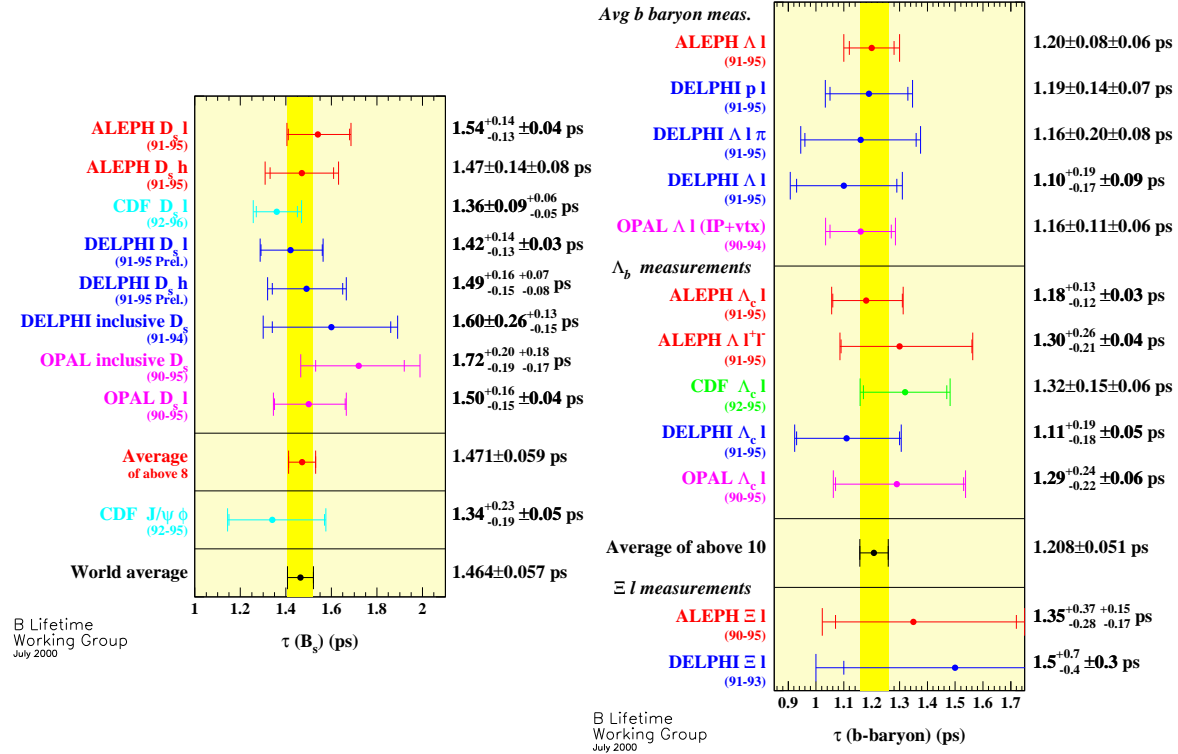
Figure 3. Summary of the B_s^0 and b baryon lifetime measurements from LEP and CDF.

2.2. B_s^0 and Λ_b lifetimes

In $Z^0 \rightarrow b\bar{b}$ decays, only about 10% of b quarks hadronise to form B_s^0 mesons, and a further 10% form b baryons [7]. The smaller numbers of hadrons compared to B^+ and B_d^0 mean that only exclusive reconstruction techniques can be used to isolate pure samples, and these samples are rather small—typically less than a thousand events. The available measurements are summarised in Figure 3 [7]. The most precise B_s^0 lifetime results come from semileptonic $B_s^0 \rightarrow D_s\ell\bar{\nu}$, augmented by more inclusive $B_s^0 \rightarrow D_s X$ hadronic decay analyses with lower purity. The b baryon decay results are split into two groups—those from inclusive $\Lambda\ell$ correlations, and those in which an intermediate charm baryon Λ_c^+ is exclusively reconstructed. The latter is expected to be enhanced in the lightest b-flavoured baryon Λ_b^0. There are also measurements of the Ξ_b lifetime via $\Xi\ell$ correlations, but these are of very limited statistical precision [8].

2.3. Lifetimes summary

The lifetime results can be most usefully compared with theory by studying the lifetime ratios τ_{B^+}/τ_{B^0}, τ_{B_s}/τ_{B^0}, *etc.* These are shown in Figure 4, together with the corresponding theoretical predictions [7]. Whilst the meson lifetime ratios are in excellent agreement, the b baryon lifetime is significantly smaller than expected. The
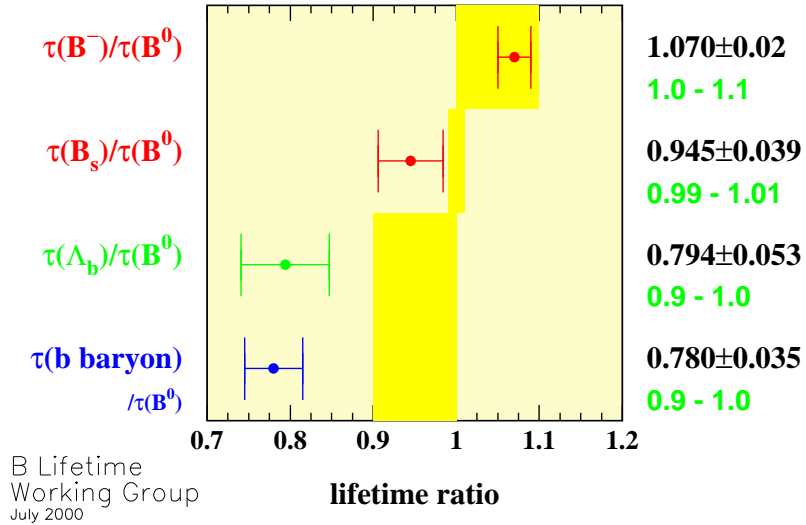
Figure 4. Summary of experimental measurements of lifetime ratios, together with theoretical expectations.

experimental results have been stable for several years, and it remains to be seen whether they can be reconciled with the existing theoretical picture, or are pointing to a more fundamental problem. The LEP and SLD lifetime analyses are now almost complete, so further significant experimental improvement can only be expected from the $\Upsilon(4S)$ B factories (for B$^+$ and B$^0_\mathrm{d}$ only) and Run II of the Tevatron.

3. B mixing

3.1. Introduction

The B$^0_\mathrm{q}$–$\overline{\mathrm{B}^0_\mathrm{q}}$ system consists of B$^0_\mathrm{q}$ and $\overline{\mathrm{B}^0_\mathrm{q}}$ flavour eigenstates, which are superpositions of heavy and light mass eigenstates ($q = d$ and s for B$^0_\mathrm{d}$ and B$^0_\mathrm{s}$ mesons, respectively). The difference in mass Δm_q between these eigenstates leads to B$^0_\mathrm{q} \leftrightarrow \overline{\mathrm{B}^0_\mathrm{q}}$ oscillations with a frequency (see Ref. [9])

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_t^2 F(m_t^2/m_W^2) f_{B_q}^2 B_{B_q} \eta_{QCD} \left|V_{tb}^* V_{tq}\right|^2 , \tag{1}$$

where G_F is the Fermi constant, m_{B_q} is the B$^0_\mathrm{q}$ hadron mass, m_t is the top quark mass, m_W is the W boson mass, F is a function defined in Ref. [10], and η_{QCD} is a perturbative QCD parameter. The parameter B_{B_q} and the decay constant f_{B_q} parameterize hadronic matrix elements. Much of the interest in B mixing stems from the fact that a measurement of the B$^0_\mathrm{d}$ (B$^0_\mathrm{s}$) oscillation frequency allows the magnitude of the CKM matrix element V_{td} (V_{ts}) to be determined, see equation (1). However, this is limited by an uncertainty of about 20% in the product $f_{B_q}\sqrt{B_{B_q}}$ [11]. Uncertainties

are reduced for the ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 = \frac{m_{B_s}}{m_{B_d}} (1.16 \pm 0.05)^2 \left|\frac{V_{ts}}{V_{td}}\right|^2 ,$$

which indicates that the ratio $|V_{ts}/V_{td}|$ can be determined with an uncertainty as small as 5% [11]. In the Wolfenstein parameterization of the CKM matrix, we have $\Delta m_d \propto |V_{td}|^2 \simeq A^2\lambda^6[(1-\rho)^2+\eta^2]$ and $\Delta m_s \propto |V_{ts}|^2 \simeq A^2\lambda^4$, where $\lambda = 0.2224 \pm 0.0020$ and $A = 0.83 \pm 0.03$ [12], but ρ and η are not well known. As a result, studies of B_d^0 and B_s^0 mixing provide one of the strongest constraints on the CKM unitarity triangle parameters ρ and η, thus constraining CP violation in the Standard Model.

Experimental studies require two main ingredients: (i) reconstruction of the B_q^0 decay and its proper time, (ii) determination of the B_q^0 or $\overline{B_q^0}$ flavour at both production and decay to classify the decay as either 'mixed' (if the tags disagree) or 'unmixed' (otherwise). The significance for a B_q^0 oscillation signal can be approximated by [13]

$$S = \sqrt{\frac{N}{2}} \, f(B_q^0) \, [1 - 2\,w] \, e^{-\frac{1}{2}(\Delta m_q \sigma_t)^2}, \tag{2}$$

where N is the total number of decays selected, $f(B_q^0)$ is the fraction of B_q^0 mesons in the selected sample, w is the probability to incorrectly tag a decay as mixed or unmixed (i.e. the mistag rate) and σ_t is the proper time resolution. The proper time resolution depends on both the decay length resolution σ_L and the momentum resolution σ_p according to $\sigma_t^2 = (\sigma_L/\gamma\beta c)^2 + (t\,\sigma_p/p)^2$. Based on the Wolfenstein parameterization, we see that $\Delta m_s/\Delta m_d \simeq 1/\lambda^2$, which is of order of 20 (the other Wolfenstein parameters are of order 1). Therefore, B_s^0 oscillations are expected to be much more rapid than B_d^0 oscillations. The ability to resolve such rapid oscillations thus requires excellent decay length and momentum resolution, and benefits from having a low mistag rate and a high B_s^0 purity.

3.2. B_d^0 mixing

Measurements of the B_d^0 oscillation frequency have been performed by ALEPH, DELPHI, L3, OPAL and SLD (see Ref. [14]). Most of these rely on semileptonic B decays to provide a sample with high B_d^0 purity and excellent decay flavour tag via the charge of the decay lepton: a negatively (positively) charged lepton tags a $\overline{B_d^0}$ (B_d^0) decay. One of the main challenges is to suppress leptons from cascade ($b \rightarrow c \rightarrow l^+$) decays which contribute "wrong-sign" leptons; direct leptons come from ($b \rightarrow l^-$) transitions. Such suppression is usually achieved with a cut on p_T, the momentum of the lepton transverse to the jet axis, or with a combination of variables, e.g. using a neural network algorithm.

Reconstruction methods fall in three general categories. (i) nearly exclusive: a high purity sample is extracted by selecting $B_d^0 \rightarrow D^{(*)-}l^+\nu_l$ decays with subsequent $D^{*-} \rightarrow \overline{D^0}\pi^-$ where $\overline{D^0} \rightarrow K^+\pi^-(\pi^0)$ or $\overline{D^0} \rightarrow K^+\pi^-\pi^+\pi^-$; (ii) D^* inclusive: the previous decay chain can be partially reconstructed with a much higher efficiency by selecting the direct lepton and the slow pion from the D^* decay, and by reconstructing
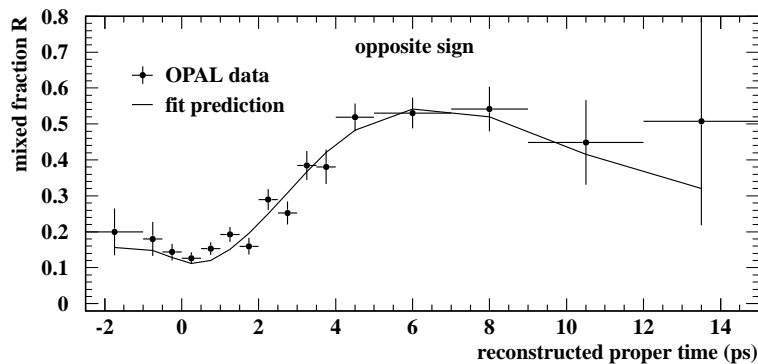
Figure 5. Fraction of events tagged as mixed as a function of reconstructed proper time for the sample with opposite sign lepton and pion tracks.

the D^0 decay inclusively (this is the same method described in Sec. 2.1); (iii) fully inclusive: a lepton with high momentum p and p_T combined with an inclusive B and/or D vertex reconstruction.

The most precise single measurement performed at the Z^0 resonance is the inclusive D^* analysis by OPAL [6]: high statistics samples of same-sign and opposite-sign lepton-pion pairs are selected, with the same-sign pairs serving to constrain the combinatorial background. A clear oscillation signal is observed in the fraction of opposite-sign events tagged as mixed (Fig. 5) and a value of $\Delta m_d = 0.497 \pm 0.024(stat) \pm 0.025(syst)$ ps^{-1} is extracted.

All available measurements have been averaged to extract a world average value of $\Delta m_d = 0.487 \pm 0.014$ ps^{-1} [14]. This average is currently dominated by LEP measurements but will soon be dominated by B Factory measurements, thanks to much higher statistics.

3.3. B$_s^0$ mixing

The study of the time dependence of B$_s^0$ mixing proceeds along the same lines as that of B$_d^0$ mixing described earlier. However, only about 10% of b quarks fragment into B$_s^0$ mesons, as compared with about 40% into B$_d^0$ mesons. Furthermore, the B$_s^0$ oscillation frequency is expected to be much larger than that for B$_d^0$ oscillations. The search for B$_s^0$ oscillations thus presents a major experimental challenge. To address this, sophisticated analyses have been developed with an emphasis on lowering the mistag rate, increasing the B$_s^0$ purity and improving the proper time resolution, all of which affect the sensitivity to B$_s^0$ mixing, see equation (2).

Tagging of the production flavour generally combines a number of different methods. The single most powerful tag exploits the large polarized forward-backward asymmetry in Z$^0 \rightarrow$ b$\overline{\text{b}}$ decays. This tag is available at SLD thanks to the large electron beam polarization ($P_e \simeq 73\%$). A left- (right-) handed incident electron tags the quark produced in the forward hemisphere as a b ($\overline{\text{b}}$) quark. This method yields a mistag rate

of 28% with nearly 100% efficiency. Tags used in all analyses rely on charge information from the event hemisphere opposite that of the B_s^0 candidate: (i) charge of lepton from the direct transition $b \to l^-$, (ii) momentum-weighted jet charge, (iii) secondary vertex charge, (iv) charge of secondary vertex kaon from the dominant transition $b \to c \to s$, (v) charge dipole of secondary vertex (SLD only). Other tags from the same hemisphere as the B_s^0 candidate are also used: (i) unweighted (or weighted) jet charge, and (ii) charge of fragmentation kaon accompanying the B_s^0. These various tags are combined on an event-by-event basis to yield an overall mistag rate of 20-25%, depending on the particular analysis.

The analyses differ in the way the B_s^0 decay is reconstructed and thus in the way the decay flavour is determined. Three general classes can be identified: inclusive, semi-exclusive and fully exclusive. Inclusive analyses benefit from the large available statistics but suffer from low B_s^0 purity, whereas more exclusive analyses benefit from high purity and resolution but suffer from the lack of statistics (this is particularly true for the fully exclusive analyses). Several analyses are discussed below to highlight these differences.

Inclusive analyses have been performed by ALEPH, DELPHI, OPAL and SLD. The charge dipole analysis is an example of fully inclusive method introduced by SLD [15]. It aims to reconstruct the b hadron decay chain topology. This method takes full advantage of the superb decay length resolution of the SLD CCD pixel vertex detector to separate secondary tracks (from the B decay point) from tertiary tracks (from the D decay point). The decay length resolution is parametrized by the sum of two Gaussians with $\sigma_L = 72$ μm (60% fraction) and 265 μm (40%), whereas the momentum resolution is parametrized with $\sigma_p/p = 0.07$ (60%) and 0.21 (40%). A "charge dipole" δQ is defined as the distance between secondary and tertiary vertices signed by the charge difference between them such that $\delta Q > 0$ ($\delta Q < 0$) tags $\bar{B}_d^0(B_d^0)$ decays. The average decay flavour mistag rate is estimated to be 24% and is mostly due to decays producing two charmed hadrons. A sample of 8556 decays is selected with a B_s^0 purity estimated to be 15% (higher than the production rate of 10% due to the fact that only neutral decays are selected).

The most sensitive inclusive analysis was performed by ALEPH [16] and aims to reconstruct semileptonic B decays. In this analysis, the D decay vertex is reconstructed inclusively and a resultant D track is vertexed with the lepton and the b hadron direction (from the jet direction) to form a B decay vertex. Fairly loose cuts are used at the various stages of the analysis to obtain a high statistics sample of 74026 events. The analysis relies on several neural network algorithms to perform the following tasks: production flavour tagging, $b\bar{b}$ event selection, direct lepton selection, and B_s^0 fraction enhancement. To maximize sensitivity to B_s^0 oscillations the analysis incorporates all the information event by event since this helps identify events with increased sensitivity.

Semi-exclusive analyses have been performed by ALEPH, DELPHI, OPAL and SLD. B_s^0 decays are partially reconstructed in the modes $B_s^0 \to D_s^- l^+ \nu_l X$ and $B_s^0 \to D_s^- h^+ X$, where h represents any charged hadron (or system of several hadrons) and the D_s^- meson decay is either fully or partially reconstructed in the modes $D_s^- \to \phi \pi^-$,

$K^{*0}K^-$, K^0K^-, $\phi\pi^-\pi^+\pi^-$, $\phi l^-\overline{\nu_l}$, *etc.*

The most sensitive semi-exclusive analysis performed by DELPHI selects 436 $D_s^- l^+$ events [17]. The small statistics is compensated by the high $B_s^0 \rightarrow D_s^- l^+ \nu_l$ purity, estimated to be $\sim 53\%$, and the good decay length and momentum resolution, $\sigma_L = 200$ μm (82% fraction) and 670 μm (16%), $\sigma_p/p = 0.07$ (82%) and 0.16 (16%). Analyses selecting $D_s^- h^+$ final states benefit from higher statistics but are less sensitive than those selecting $D_s^- l^+$ states because of lower B_s^0 purity and worse proper time resolution.

Finally, fully exclusive analyses have been performed by ALEPH [18] and DELPHI [19] via the modes $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- a_1^+$, $\overline{D^0}K^-\pi^+$, and $\overline{D^0}K^-a_1^+$, where the D_s^- and $\overline{D^0}$ are fully reconstructed. The number of decay candidates is 50 for ALEPH and 44 for DELPHI with signal purities of approximately 40% and 50%, respectively. The main advantage of this method is its excellent proper time resolution with a negligible contribution from momentum resolution $\sim 0.5\%$. As a result, σ_t does not grow with increasing proper time t and thus the oscillation amplitude is not damped as t increases. Due to limited statistics, this method is not competitive with respect to the inclusive and semi-exclusive methods described above. However, this is the method of choice for future studies of B_s^0 oscillations at hadron colliders.

Studies of the time dependence of B_s^0 mixing are carried out with the "amplitude method", which is equivalent to a normalized Fourier transform [13]. The oscillation amplitude A is expected to be $A = 0$ ($A = 1$) for oscillation frequencies sufficiently far from (close to) the true value of Δm_s. All available measurements of the oscillation amplitude at $\Delta m_s = 15$ ps^{-1} are summarized in Figure 6. Also shown are the sensitivities for each analysis to set a 95% C.L. lower limit on Δm_s.

The measured oscillation amplitudes are combined [14], taking statistical and systematic correlations into account, to obtain the world average amplitude spectrum shown in Figure 7. The rise in statistical error as Δm_s increases comes from the fact that an increasingly smaller fraction of the data sample has sufficient proper time resolution to resolve more rapid oscillations; the better the resolution, the smaller the rise. The combined amplitude spectrum excludes mixing ($A = 1$) for $\Delta m_s < 15.0$ ps^{-1} at the 95% C.L., whereas the sensitivity is 18.0 ps^{-1}. The significance of the deviation from $A = 0$ near $\Delta m_s = 17.5$ ps^{-1} was investigated with a parameterized fast Monte Carlo simulation. It was found that, assuming that the true value of Δm_s is large, the probability to observe a deviation of equal or greater significance as that seen in figure 6 anywhere between Δm_s of 0 and 25 ps^{-1} is about 2.5%.

Further progress is still expected from DELPHI and SLD over the next year or so. In the near future, CDF (and presumably D0) is expected to apply the fully exclusive method and observe B_s^0 oscillations with 5σ significance up to Δm_s of 40 ps^{-1}. Beyond this, both BTeV and LHC-b are expected to measure Δm_s with statistical precision of 0.1% or better.
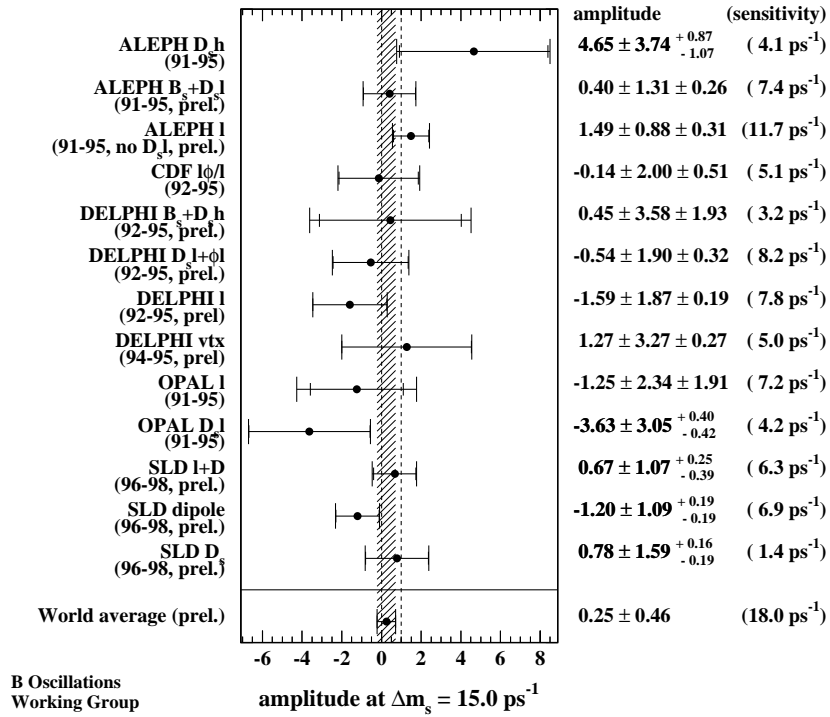
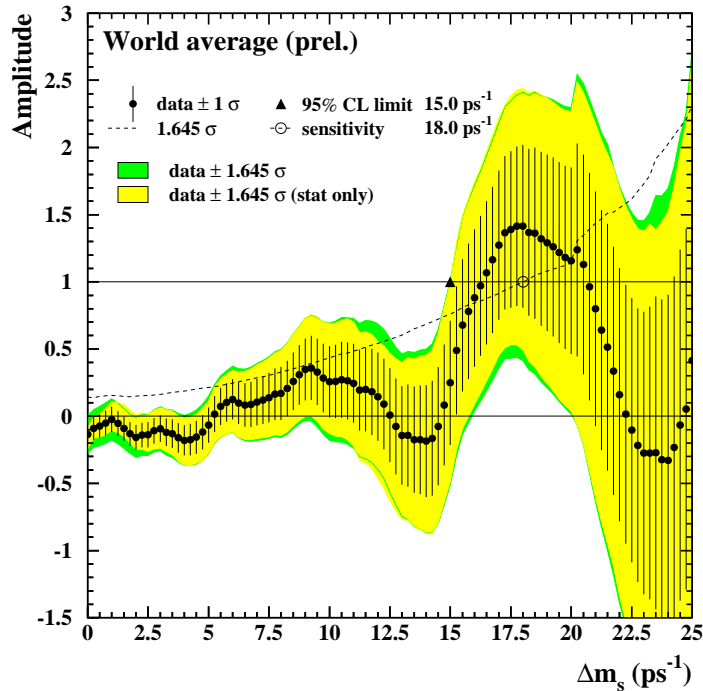**Figure 6.** Measurements of the B_s^0 oscillation amplitude for $\Delta m_s = 15 \text{ ps}^{-1}$.

Figure 7. World average B_s^0 oscillation amplitude as a function of Δm_s.

4. Width difference in B$_s^0$ mesons

As discussed in the previous section, the B$_s^0$–$\overline{\text{B}_s^0}$ system consists of mass eigenstates B$_s^{\text{light}}$ and B$_s^{\text{heavy}}$. Neglecting CP violation, these are also CP eigenstates B$_s^{\text{short}}$(CP=+1) and B$_s^{\text{long}}$(CP=−1) with different decay widths Γ_s^{short} and Γ_s^{long}, since the quark level B$_s^0$ decay process b($\bar{\text{s}}$) $\rightarrow$ c$\bar{\text{c}}$s($\bar{\text{s}}$) gives rise to mainly CP-even final states. The width difference $\Delta\Gamma_s = \Gamma_s^{\text{short}} - \Gamma_s^{\text{long}}$ could be as large as 20 %, and a non-zero value would mean that the B$_s^0$ meson would have two distinct components with different lifetimes $\tau_{\text{B}_s}^{\text{short}} = 1/\Gamma_s^{\text{short}}$ and $\tau_{\text{B}_s}^{\text{long}} = 1/\Gamma_s^{\text{long}}$. The corresponding width difference in the B$_d^0$ meson system is expected to be negligible.

Experimentally, a non-zero value of $\Delta\Gamma_s$ can be searched for in two ways: measuring the lifetime of a CP eigenstate decay mode and comparing the result with the inclusive B$_s^0$ lifetime, or looking for deviations from a single exponential in inclusive (*e.g.* semileptonic) B$_s^0$ decays. The former has a linear sensitivity to $\Delta\Gamma_s$, but is limited by the small branching ratios to CP eigenstates, whilst the latter method has larger statistics but less sensitivity as the dependence on $\Delta\Gamma_s$ is only second order.

Measurements of the first type include a CDF analysis of B$_s^0 \rightarrow$ J/$\psi\phi$ [20] and an ALEPH analysis of B$_s^0 \rightarrow \phi\phi$X resulting from the dominantly CP-even decay B$_s^0 \rightarrow$ D$_s^{(*)+}$D$_s^{(*)-}$ [21]. DELPHI have also measured the B$_s^0$ lifetime in B$_s^0 \rightarrow$ D$_s$X, assumed to contain more CP-even than CP-odd decays [22].

The B$_s^0$ lifetime measurements from semileptonic B$_s^0$ decays (see Section 2.2) also provide a constraint on $\Delta\Gamma_s$ as a function of the average B$_s^0$ width $\Gamma_s = (\Gamma_s^{\text{long}} + \Gamma_s^{\text{short}})/2$, since the semileptonic width Γ_{sl} is expected to be the same for both B$_s^{\text{short}}$ and B$_s^{\text{long}}$. This leads to different semileptonic branching ratios $\Gamma_{\text{sl}}\tau_{\text{B}_s}^{\text{short}}$ and $\Gamma_{\text{sl}}\tau_{\text{B}_s}^{\text{long}}$ for the two states, and hence an unequal mixture of them in the semileptonic decay sample. The sensitivity is enhanced if the average B$_s^0$ lifetime $\tau_{\text{B}_s} = 1/\Gamma_s$ is assumed to be equal to the B$_d^0$ lifetime, which is expected to be true to better than 1 %. Finally, L3 have set a direct limit on $\Delta\Gamma_s$ by studying the proper time distribution in a sample of topologically selected neutral b hadron decays (see section 2.1) and assuming values for the B$_d^0$ and Λ_b lifetimes [23].

The various results from LEP and CDF have been combined to give an overall result of $\Delta\Gamma_s/\Gamma_s = 0.16^{+0.08}_{-0.09}$ or $\Delta\Gamma_s/\Gamma_s < 0.31$ at 95 % CL [7]. If the $\tau_{\text{B}^0} = \tau_{\text{B}_s}$ assumption is removed, the result changes to $\Delta\Gamma_s/\Gamma_s = 0.24^{+0.16}_{-0.12}$ or $\Delta\Gamma_s/\Gamma_s < 0.53$ at 95 % CL. These results are suggestive of a significant non-zero value of $\Delta\Gamma_s$, consistent with the high limit on Δm_s, but are not yet significant enough to draw any definite conclusions.

5. Measurements of $|V_{\text{cb}}|$

The magnitudes of the CKM matrix elements V_{cb} and V_{ub} are fundamental parameters of the Standard Model which can only be determined experimentally, and are of particular interest in the CKM model of CP violation. Their values govern the transition rates of the quark level processes b $\rightarrow$ c$\ell\bar{\nu}$ and b $\rightarrow$ u$\ell\bar{\nu}$. However, the confinement of

quarks within hadrons leads to significant theoretical uncertainties in interpreting the corresponding hadronic decays.

The magnitude of V_{cb} is measured from the differential rate of $\bar{\mathrm{B}}_{\mathrm{d}}^0 \to \mathrm{D}^{*+}\ell^-\bar{\nu}$ decays as a function of the recoil variable ω, defined as the product of the four-velocities of the B and D^{*+} mesons. ω varies from 1 at the point of zero recoil (when the D^{*+} is produced at rest in the B rest frame) to about 1.5. The differential decay rate is given by

$$\frac{d\Gamma}{d\omega} = \frac{1}{\tau_{\mathrm{B}^0}} \frac{d\mathrm{Br}(\mathrm{B}_{\mathrm{d}}^0 \to \mathrm{D}^{*+}\ell\bar{\nu})}{d\omega} = \mathcal{F}^2(\omega)|V_{\mathrm{cb}}|^2\mathcal{K}(\omega)$$

where $\mathcal{F}(\omega)$ is the hadronic form factor, $\mathcal{K}(\omega)$ is a known phase space term and τ_{B^0} is the $\mathrm{B}_{\mathrm{d}}^0$ lifetime [25, 26]. In the heavy quark limit, $\mathcal{F}(\omega)$ corresponds to the Isgur-Wise function and $\mathcal{F}(1) = 1$ [26]. Dispersion relations allow the form of $\mathcal{F}(\omega)$ to be calculated in terms of a single parameter ρ^2 which represents the slope of $\mathcal{F}(\omega)$ at $\omega = 1$ [27]. The value of $\mathcal{F}(1)$ can be calculated using Heavy Quark Efective Theory (HQET); one recent estimate gives $\mathcal{F}(1) = 0.913 \pm 0.042$ [28]. Unfortunately, the phase space term $\mathcal{K}(\omega) \to 0$ as $\omega \to 1$, so the differential decay rate must be measured close to $\omega = 1$ and extrapolated to determine $|V_{\mathrm{cb}}|$.

The signal decay can be reconstructed exclusively, where the D^0 is reconstructed in specific decay modes, or inclusively, as discussed in section 2.1. The recoil ω is reconstructed for each event from the estimated D^{*+} and $\mathrm{B}_{\mathrm{d}}^0$ four-momenta. The unmeasured neutrino is reconstructed from the missing momentum vector in the event, and the $\mathrm{B}_{\mathrm{d}}^0$ flight direction can also be inferred from its reconstructed secondary vertex position, particularly for long-lived $\mathrm{B}_{\mathrm{d}}^0$ decaying far from the primary vertex. The resolution on the reconstructed ω is typically 0.07–0.15, and the reconstruction efficiency is almost flat as a function of ω, allowing a precise extrapolation to $\omega = 1$.

The values of $\mathcal{F}(1)|V_{\mathrm{cb}}|$ and ρ^2 are extracted using likelihood fits to the reconstructed ω spectra, taking into account contributions from signal decays, physics background (mainly from decays of the form $\bar{\mathrm{B}} \to \mathrm{D}^{*+}\mathrm{h}\,\ell^-\bar{\nu}$) and combinatorial background. The combinatorial background is estimated using events from the mass sidebands or having the wrong lepton-pion charge correlation. The physics background has contributions from $\bar{\mathrm{B}} \to \mathrm{D}^{**}\ell^-\bar{\nu}$ decays where the D^{**}decays to $\mathrm{D}^*\pi$ or $\mathrm{D}^*\mathrm{K}$, and possibly also from direct four-body non-resonant $\bar{\mathrm{B}} \to \mathrm{D}^{*+}\mathrm{h}\,\ell^-\bar{\nu}$ decays. Isospin considerations imply that approximately two thirds of these decays involve charged pions, which can be suppressed by looking for additional charged particles consistent with coming from the b decay vertex.

The contribution of $\bar{\mathrm{B}} \to \mathrm{D}^{*+}\mathrm{h}\,\ell^-\bar{\nu}$ events can be calculated from the ALEPH measurement of $\mathrm{Br}(\mathrm{b} \to \mathrm{D}^{*+}\pi^-\ell\bar{\nu}) = (0.473\pm0.095)\,\%$ [29], but the ω spectrum of these events is also important. The decay rates and form factors predicted by the calculation of Leibovich *et al.*[30] have been used, with the free parameters of the calculation constrained by experimental measurements of the ratio $R^{**} = \Gamma(\bar{\mathrm{B}} \to \mathrm{D}_2^*\ell\bar{\nu})/\Gamma(\bar{\mathrm{B}} \to \mathrm{D}_1\ell\bar{\nu}) = 0.37 \pm 0.16$ [7].
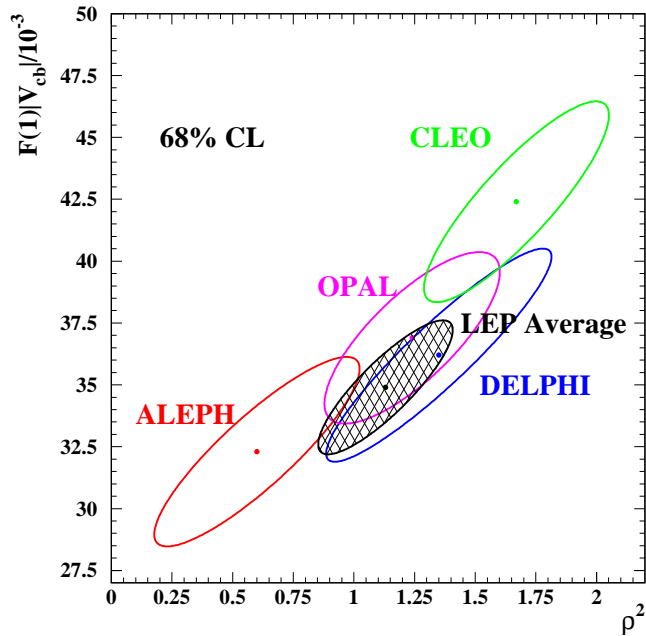
Figure 8. Experimental measurements of $\mathcal{F}(1)|V_{cb}|$ and ρ^2 from ALEPH, DELPHI, OPAL and CLEO.

A recent preliminary DELPHI analysis [31] has searched for mass structure in $\bar{B} \rightarrow D^{*+}\pi^-\ell\bar{\nu}$, $\bar{B} \rightarrow D^0\pi^+\ell\bar{\nu}$ and $\bar{B} \rightarrow D^+\pi^-\ell\bar{\nu}$ decays, by combining charged pions with exclusively reconstructed $D^{(*)}\ell$ combinations. DELPHI measure branching ratios for $\bar{B} \rightarrow D_1\ell\bar{\nu}$ and $\bar{B} \rightarrow D_2^*\ell\bar{\nu}$ consistent with earlier results from ALEPH and CLEO, and also reports first evidence for the production of the broad D_1^* state, $Br(\bar{B} \rightarrow D_1^*\ell\bar{\nu}) = (1.63 \pm 0.55)\,\%$, in agreement with expectations from HQET. Since the understanding of the background from these decays is the largest systematic error on the LEP measurements of $|V_{cb}|$, further results in this area would be extremely beneficial.

The fit results for $\mathcal{F}(1)|V_{cb}|$ and ρ^2 from the ALEPH exclusive [32], DELPHI inclusive [33] and OPAL inclusive and exclusive combined [34] analyses are shown in Figure 8. Some of these results used linear or quadratic parameterisations of the hadronic form factor $\mathcal{F}(\omega)$, and older evaluations of the background from $\bar{B} \rightarrow D^{*+}h\,\ell^-\bar{\nu}$ decays. The central values and uncertainties of all the measurements have been corrected by the LEP V_{cb} working group to use the latest form factor and background evaluations. The combined LEP result, taking into account correlated systematic uncertainties, is

$$\mathcal{F}(1)|V_{cb}| = (34.9 \pm 0.7 \pm 1.6) \times 10^{-3}$$
$$\rho^2 \qquad = 1.12 \pm 0.08 \pm 0.15$$

where the first error is statistical and the second systematic in each case [7].

The recent measurement from CLEO [35] is also shown in Figure 8, and is somewhat higher than the LEP result. Assuming no correlated systematic errors, and correcting to a common form factor parameterisation, the LEP and CLEO $\mathcal{F}(1)|V_{cb}|$ results differ by

2.4 standard deviations. More work is needed to understand the origin of this possible discrepancy.

Using the value $\mathcal{F}(1) = 0.913 \pm 0.042$ [28], the LEP combined result is

$$|V_{cb}| = (38.2 \pm 1.9 \pm 1.8) \times 10^{-3}$$

where the first error is the experimental error on $\mathcal{F}(1)|V_{cb}|$ and the second the theoretical uncertainty on the value of $\mathcal{F}(1)$.

The value of $|V_{cb}|$ can also be extracted from the LEP measurement of the inclusive semileptonic branching ratio $\mathrm{Br(b \to X\ell\bar\nu)} = (10.56 \pm 0.11 \pm 0.18)\%$ [36], after subtracting the contribution from $\mathrm{b \to u\ell\bar\nu}$. Theoretical models can then be used to translate this into a measurement of $|V_{cb}|$ [7], giving $|V_{cb}| = (40.7 \pm 0.5\,(\mathrm{expt}) \pm 2.0\,(\mathrm{theory})) \times 10^{-3}$, in encouraging agreement with the determination from $\bar{\mathrm{B}}_\mathrm{d}^0 \to \mathrm{D}^{*+}\ell^-\bar\nu$ decays. Significant correlations (both experimental and theoretical) exist between these measurements, so no attempt is made to average them at present.

6. Measurements of $|V_{ub}|$

The magnitude of V_{ub} can be measured from the rate of charmless semileptonic b decays $\bar{\mathrm{B}} \to \mathrm{X}_u\ell\bar\nu$, but there is an overwhelming background from charmed semileptonic b decays, due to the smallness of the ratio $(|V_{ub}|/|V_{cb}|)^2 \sim 10^{-2}$. The main challenges of this measurement are therefore to separate a clean sample of charmless decays whilst maintaining a model independent efficiency and good control over the charmed background.

Previous measurements of $|V_{ub}|$ at the $\Upsilon(4S)$ resonance have used either a lepton endpoint technique (selecting events with lepton energies beyond the kinematic limit for $\bar{\mathrm{B}} \to \mathrm{D}\ell\bar\nu$ decays) [37], or the reconstruction of specific exclusive final states ($\bar{\mathrm{B}} \to \pi\ell\bar\nu$ or $\rho\ell\bar\nu$) [38]. The former suffers from significant dependence on the modelling of the lepton energy spectrum, whilst the latter requires an estimate of the decay form factor in a regime where HQET is not applicable.

The experimental environment at LEP allows a rather different and complementary technique to be used, based on inclusive reconstruction of the hadronic system recoiling against the lepton. In most $\bar{\mathrm{B}} \to \mathrm{X}_u\ell\bar\nu$ decays, the invariant mass of this system is significantly below the charm hadron mass, allowing a relatively model independent measurement of the charmless semileptonic branching ratio. Theoretical models can then be used to relate this branching ratio to $|V_{ub}|^2$.

The ALEPH [39] and L3 [40] analyses start by selecting a sample of events with an identified high momentum lepton (electron or muon) emitted with significant transverse momentum with respect to the nearest jet axis. Secondary vertex based b-tagging is used to suppress non-b$\bar{\mathrm{b}}$ event background. Reconstructed particles (tracks and calorimeter clusters) in the jet containing the lepton are then classified as coming from the b hadron decay or fragmentation processes, based on momentum, rapidity and vertexing information. The b decay particles are boosted into the reconstructed b hadron rest

frame, and various kinematic and event shape variables, as well as the invariant mass of the hadronic system, are calculated. Both charged and neutral particles are used, to minimise the dependence on the particular b decay mode. The final selection is typically made using an artificial neural network, trained to separate $\bar{\text{B}} \to \text{X}_u \ell \bar{\nu}$ decays from $\bar{\text{B}} \to \text{X}_c \ell \bar{\nu}$ decays using all available discrimination variables and their correlations.

A somewhat different approach is taken by DELPHI [41]. Here, the selected events are divided into 4 classes, depending on the reconstructed hadronic mass (above or below 1.6 GeV) and an enrichment or depletion in b $\to$ u decays. The enrichment is performed by selecting events with no identified kaons or protons (from charm decays), and by trying to associate the lepton with the secondary vertex of the hadronic system— in $\bar{\text{B}} \to \text{X}_c \ell \bar{\nu}$ decays, the lepton tends to be produced closer to the primary vertex due to the flight distance of the charm hadron before it decays. An excess of events is found in the class with low hadronic mass and $b \to u$ enrichment, consistent with the presence of $\bar{B} \to X_u \ell \bar{\nu}$ decays. The analysis measures the ratio $\text{Br}(\bar{B} \to X_u \ell \bar{\nu})/\text{Br}(\bar{B} \to X_c \ell \bar{\nu})$ using a binned maximum likelihood fit to the number of events and lepton energy spectrum of each class.

The measurements from ALEPH [39], DELPHI [41] and L3 [40] have been combined to give a result of

$$\text{Br}(\bar{\text{B}} \to \text{X}_u \ell \bar{\nu}) = (1.74 \pm 0.37(\text{expt}) \pm 0.38(\text{b} \to \text{c}) \pm 0.21(\text{b} \to \text{u})) \times 10^{-3}$$

where the first error includes statistical and uncorrelated systematic contributions, the second is associated with modelling b $\to$ c decays and the third with modelling b $\to$ u decays [7].

This result can be translated into a value for $|V_{\text{ub}}|$ using the relation [42]

$$|V_{\text{ub}}| = 0.00445 \times \left(\frac{\text{BR(b} \to \text{X}_u \ell \bar{\nu})}{0.002} \frac{1.55\,\text{ps}}{\tau_{\text{b}}} \right)^{\frac{1}{2}}$$
$$\times (1 \pm 0.02(\text{pert}) \pm 0.035(\text{m}_{\text{b}}))$$

where τ_{b} is the inclusive b hadron lifetime and the uncertainties refer to unknown higher order corrections and the value of the b quark mass. Using $\tau_{\text{b}} = 1.564 \pm 0.014\,\text{ps}$ [7] this gives

$$|V_{\text{ub}}| = \left(4.13^{+0.42}_{-0.47}(\text{expt})\,^{+0.43}_{-0.48}(\text{b} \to \text{c})^{+0.24}_{-0.25}(\text{b} \to \text{u}) \pm 0.20(\text{theory}) \right) \times 10^{-3}\,,$$

where the errors correspond to uncorrelated experimental, b $\to$ c, b $\to$ u and theoretical sources respectively. As expected, the largest error comes from the uncertainties in modelling the large background from $\bar{\text{B}} \to \text{X}_c \ell \bar{\nu}$ decays in these analyses.

7. Conclusions

The LEP and SLD experiments have made an enourmous contribution to the knowledge of b physics. The individual b hadron lifetimes have each been measured to 1–4 %, the B^0_{d} oscillation frequency has been measured to 3 % and an impressive lower limit of $15.0\,\text{ps}^{-1}$ has been set on the B^0_{s} oscillation frequency. Limits have also been set on

the $B_s^0 - \bar{B}_s^0$ width difference $\Delta\Gamma_s$. Finally, the CKM element $|V_{cb}|$ has been measured to 7 %, and evidence has been seen for a non-zero value of $|V_{ub}|$. With the exception of the unexpectedly low value of the Λ_b lifetime, all measurements are in impressive and consistent agreement with theoretical expectations and the Standard Model CKM mechanism of CP violation.

References

[1] Barate R *et al* 2000 *Phys. Lett.* B **492** 275
[2] Buskulic D *et al* 1996 *Z. Phys.* C **71** 31
[3] Abbiendi G *et al* 2000 *Eur. Phys. J.* C **12** 609
[4] DELPHI collaboration 2000 A precise measurement of the B^+ and B_d^0 lifetimes with the DELPHI detector 2000 *Preprint* DELPHI 2000-109 CONF 408
    SLD collaboration 1999 Measurement of the B^+ and B_d^0 lifetimes using topological vertexing at SLD *Preprint* SLAC-PUB-8206
[5] Abreu P *et al* 1997 *Z. Phys.* C **74** 19
    L3 collaboration 1998 Measurement of the B_d^0 meson lifetime using the decay $\bar{B}_d^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ *Preprint* L3 note 2142
[6] Abbiendi G *et al* 2000 Measurement of the B_d^0 lifetime and oscillation frequency using $\bar{B}_d^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ decays *Preprint* CERN-EP/2000-090 accepted by *Phys. Lett.* B
[7] ALEPH, DELPHI, L3, OPAL, CDF and SLD Collaborations 2000 Combined results on b-hadron production rates, lifetimes, oscillations and semileptonic decays *Preprint* CERN-EP/2000-96
[8] Buskulic D *et al* 1996 *Phys. Lett.* B **384** 449
    Abreu P *et al* 1995 *Z. Phys.* C **68** 541
[9] Buras A J, Slominski W and Steger H 1984 *Nucl. Phys.* B **345** 369
[10] Inami T and Lim C S 1981 *Prog. Theor. Phys.* **65** 297
[11] Bernard C 2000 Heavy quark physics on the lattice *Preprint* hep-lat/0011064
[12] Faccioli P 2000 CKM matrix: the over-consistent picture of the unitarity triangle *Preprint* hep-ph/0011269
[13] Moser H-G and Roussarie A 1997 *Nucl. Instrum. Methods* A **384** 491
[14] B Oscillations Working Group 2000 `http://www.cern.ch/LEPBOSC/`
[15] Abe K *et al* 2000 Time dependent B_s^0–$\overline{B_s^0}$ mixing using inclusive and semileptonic B decays at SLD *Preprint* SLAC-PUB-8225
[16] ALEPH collaboration 2000 Study of B_s^0 oscillations with inclusive semileptonic decays *Preprint* ALEPH/2000-059
[17] Abreu P *et al* 2000 Measurement of the B_s^0 lifetime and study of B_s^0–$\overline{B_s^0}$ oscillations using $D_s l$ events *Preprint* CERN-EP/2000-043
[18] ALEPH collaboration 2000 Study of B_s^0–$\overline{B_s^0}$ oscillations using fully reconstructed B_s^0 and $D_s^- - l$ events *Preprint* ALEPH/2000-029
[19] Abreu P *et al* 2000 Study of B_s^0–$\overline{B_s^0}$ oscillations and B_s^0 lifetime using hadronic decays of B_s^0 mesons *Preprint* CERN-EP/2000-087
[20] Abe F *et al* 1998 *Phys. Rev.* D **57** 5382
[21] Barate R *et al* 2000 *Phys. Lett.* B **486** 286
[22] Abreu P *et al* 1996 *Z. Phys.* C **71** 11
[23] Acciarri M *et al* 1998 *Phys. Lett.* B **438** 417
[24] See for example, Neubert M 1994 *Phys. Rep.* **245** 259
    Neubert M 1996 *Int. J. Mod. Phys.* A **11** 4173
[25] Shifman M A and Voloshin M B 1988 *Sov. J. Nucl. Phys.* **47** 511
    Neubert M 1991 *Phys. Lett.* B **264** 455
    Neubert M 1994 *Phys. Lett.* B **338** 84

[26] Isgur N and Wise M 1989 *Phys. Lett.* B **232** 113
   Isgur N and Wise M 1990 *Phys. Lett.* B **237** 527
   Falk A F, Georgi H, Grinstein B and Wise M 1990 *Nucl. Phys.* B **343** 1
[27] Caprini I, Lellouch L and Neubert M 1998 *Nucl. Phys.* B **530** 153
[28] The BaBar Physics Book 1998 ed. Harrison P F and Quinn H R *Report* SLAC-R-054, and references therein
[29] Buskulic D *et al* 1997 *Z. Phys.* C **73** 601
[30] Leibovich A, Ligeti Z, Stewart I and Wise M 1998 *Phys. Rev.* D **57** 308
[31] DELPHI collaboration 2000 Narrow and broad excited charmed states in b-hadron semileptonic decays *Preprint* DELPHI 2000-106 CONF-405
[32] Buskulic D *et al* 1997 *Phys. Lett.* B **395** 373
[33] DELPHI collaboration 1999 New precise measurement of V_{cb} *Preprint* DELPHI 99-107 CONF 294
[34] Abbiendi G *et al* 2000 *Phys. Lett.* B **482** 15
[35] CLEO collaboration 2000 Determination of the B $\rightarrow$ D$^{*+}\ell\nu$ Decay Width and $|V_{cb}|$ *Preprint* CLEO CONF 00-03
[36] ALEPH, DELPHI, L3, OPAL and SLD collaborations, LEP electroweak working group and SLD heavy flavour and electroweak working groups 2000 A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model *Preprint* summer 2000 CERN-EP preprint in preparation.
[37] Fulton R *et al* 1990 *Phys. Rev. Lett* **64** 16
   Albrecht H *et al* 1990 *Phys. Lett.* B **234** 409
[38] Alexander J P *et al* 1996 *Phys. Rev. Lett* **77** 5000
   Behrens B H *et al* 2000 *Phys. Rev.* D **61** 052001
[39] Barate R *et al* 1999 *Eur. Phys. J.* C **6** 555
[40] Acciarri M *et al* 1998 *Phys. Lett.* B **436** 174
[41] Abreu P *et al* 2000 *Phys. Lett.* B **478** 14
[42] Uraltsev N 1996 *Int. J. Mod. Phys.* A **11** 515
   Bigi I, Dikeman R D and Uraltsev N 1998 *Eur. Phys. J.* C **4** 453
   Hoang A H, Ligeti Z and Manohar A V 1999 *Phys. Rev. Lett* **82** 277
   Hoang A H, Ligeti Z and Manohar A V 1999 *Phys. Rev.* D **59** 074017