b-QUARK PHYSICS AT LEP*

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(Received March 5, 2001)

A summary of important LEP measurements in the b-quark physics is presented. The following topics are reviewed: b-fragmentation, the spectroscopy and lifetimes of beauty hadrons, B^0–$\overline{B}^0$ oscillations and the extraction of the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$.

PACS numbers: 14.65.Fy, 13.25.Hw, 13.20.He

1. Introduction

In the period 1989–1995 the LEP collider [1] was operated at center-of-mass energies around the Z^0 resonance (so called LEP I programme). Each of the four LEP experiments: ALEPH, DELPHI, L3 and OPAL [2], collected around 4.2 million of hadronic events. The fraction of these which are $b\bar{b}$ is high: $R_b = \Gamma_{b\bar{b}}/\Gamma_{\rm had} \approx 22\%$. Moreover, contrary to "B-factories" operating at the $\Upsilon(4S)$, at LEP there was sufficient energy to produce all b-hadrons, including b-baryons, B_s^0 and other hadrons with higher spin and orbital momentum.

Thanks to the relatively long lifetime of the beauty quark (≈ 1.5 ps), the $b\bar{b}$ events could be singled out by the presence of displaced secondary vertices, tracks with a significant impact parameter or a high rapidity, and a high transverse momentum of the leptons with respect to the jet axis ($p_{\rm T}$). The typical purity (efficiency) of this so-called *b-tagging* was 60 (90)%, respectively [3, 4]. This method, applied separately to both hemispheres, allowed to obtain accurate measurements of the relative width of the Z^0 into b-quarks were obtained. The combined result, $R_b = 0.21653 \pm 0.00069$ [5], corresponds to a precision of 0.3% and is in agreement with the expectation from the standard model.

* Presented at the Cracow Epiphany Conference on b Physics and CP Violation, Cracow, Poland, January 5–7, 2001.

The enriched $b\bar{b}$ samples allowed to perform many valuable tests of quantum chromodynamics (QCD). In particular, clear effects due to the b-quark mass running were observed. Comparing with the determinations at the $\Upsilon(4S)$ energies: $m_b(\Upsilon(4S)) \approx 4.2\,\mathrm{GeV}$, the measurements of ALEPH [6] and DELPHI [7] of the running b-quark mass at the Z^0 pole yielded the average of $m_b(Z^0) = (2.96 \pm 0.36)$ GeV. This value is consistent with the one predicted from QCD.

The b-tagging is also absolutely crucial for many other LEP studies, like the search for the Higgs boson, as discussed by Martinez-Rivero [8] at this conference.

2. *b*-fragmentation studies

The hadronization of beauty quarks into physical states can be studied by the measurement of the energy spectra of b-hadrons which are commonly described in terms of the fraction, $x_B = E_B/E_{\mathrm{beam}} = 2E_B/\sqrt{s}$, of the beam energy retained by the weakly-decaying b-hadron (E_B denotes the energy of beauty hadron and $\sqrt{s}$ is the center-of-mass energy). The predicted distribution of the energy of b-hadrons depends upon a convolution of perturbative QCD and the hadronization process itself. The nature of the latter is non-perturbative and is described by the phenomenological models.

The first studies [9–12] used the momentum spectrum of the lepton from semileptonic decays of b-hadrons. They resulted in the mean value of x_B of approximately 0.7. More recent analyses of ALEPH [13,14] were based on semileptonic decays $B \to l\,\bar{\nu}_l D^{(*)}(X)$[1]. The charmed mesons were reconstructed through the decay modes $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+(\pi^0)$, $K^-\pi^+\pi^+\pi^-$, $K^0_s\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$. The neutrino energy was estimated from the missing energy in the lepton hemisphere. The energy spectrum of B mesons was obtained for approximately 3000 decays $B \to l\bar{\nu}_l D^{(*)}(X)$. For the most recent measurement it yielded the value of $\langle x_B \rangle = 0.7499 \pm 0.0065 \pm 0.0069$ [14] which points towards a harder b-fragmentation to compare with earlier studies. The SLD experiment [15] used a sample of 4200 inclusively reconstructed B hadrons and yielded $\langle x_B \rangle = 0.710 \pm 0.003 \pm 0.006$. Both ALEPH and SLD, had compared the measured energy spectra with the predictions of different fragmentation models. The results are not fully consistent but seem to favour the parametrizations of Kartvelishvili [16] and Peterson [17].

[1] The charge-conjugate states are always implicitly considered.

3. Spectroscopy and production rates of beauty hadrons

Before the LEP start-up, only the non-strange pseudo-scalars B_d^0 and B^+ and vector meson B^* were observed. The LEP studies confirmed the observation of the B^*, yielded evidence for the pseudoscalar, strange state B_s^0 and orbitally excited B^{**}, providing also hints for the presence of B_s^{**} and radially excited states $B^{(*)'}$. As far as the b-baryons are concerned, LEP confirmed unambiguously the existence of the Λ_b, observed the Ξ_b^- and possibly the Σ_b and the Σ_b^*.

The experimental studies about the b-hadron spectroscopy were based on the inclusive reconstruction of beauty hadrons. Four-momenta of b-hadrons were reconstructed with the help of either a rapidity algorithm [18], or as a sum of four-momenta of tracks attributed to the secondary vertex [19]. In the rapidity approach, particles with rapidities above certain value, typically around 1.5, are considered to be the products of b-hadron's decay. This allowed to reconstruct the four momenta of b-hadrons with the energy (angular) resolution of 7% (15 mrad), respectively.

The mass of the B_s^0 meson was determined first from ALEPH [20], DELPHI [21] and OPAL [22] using six fully reconstructed decays to $D_s\pi$, $D_s a_1$ and $J/\psi\phi$. A bigger sample of 32 ± 6 decays $B_s^0 \to J/\psi\phi$ was collected by the CDF [23]. The average mass [24] of the B_s^0 is (5369.6 ± 2.4) MeV.

Using the samples of inclusively reconstructed B hadrons, all four LEP collaborations [18,25–27] had confirmed the first observations of the vector meson B^*, reported by CLEO [28] and CUSB [29]. As the mass splitting between the B^* and B is significantly smaller than the pion's mass, only the electromagnetic decays $B^* \to B\gamma$ are allowed. At LEP, the photons were directly detected by L3. The other three experiments reconstructed $\gamma \to e^+e^-$ conversions. The world average [24] of the B^*–B hyperfine splitting (*cf.* Fig. 1(Aa)) yielded: $\Delta M(B^*\text{–}B) = (45.78 \pm 0.35)$ MeV. The B^* and B yields have been measured by all LEP collaborations [18,25–27] and found to be consistent with the statistical spin composition:

$$\frac{\sigma_{B^*}}{\sigma_B + \sigma_{B^*}} = 0.748 \pm 0.004\,.$$

The LEP experiments [25,30–32] gave the first experimental evidence for orbitally excited B^{**} mesons by combining single charged pions with B mesons reconstructed inclusively. A broad maximum was observed in the spectrum of the Q-value of $B^{(*)}\pi$ pairs (*cf.* Fig. 1(Bb)). In addition, ALEPH [33] had observed a similar resonant structure by using the sample of 404 fully reconstructed charged and neutral B mesons. The shape of the maximum observed by this two approaches was well described by the mixture of two broad and two narrow states, as expected by the Heavy Quark Effective Theory (HQET) [34]. However, the detailed decomposition

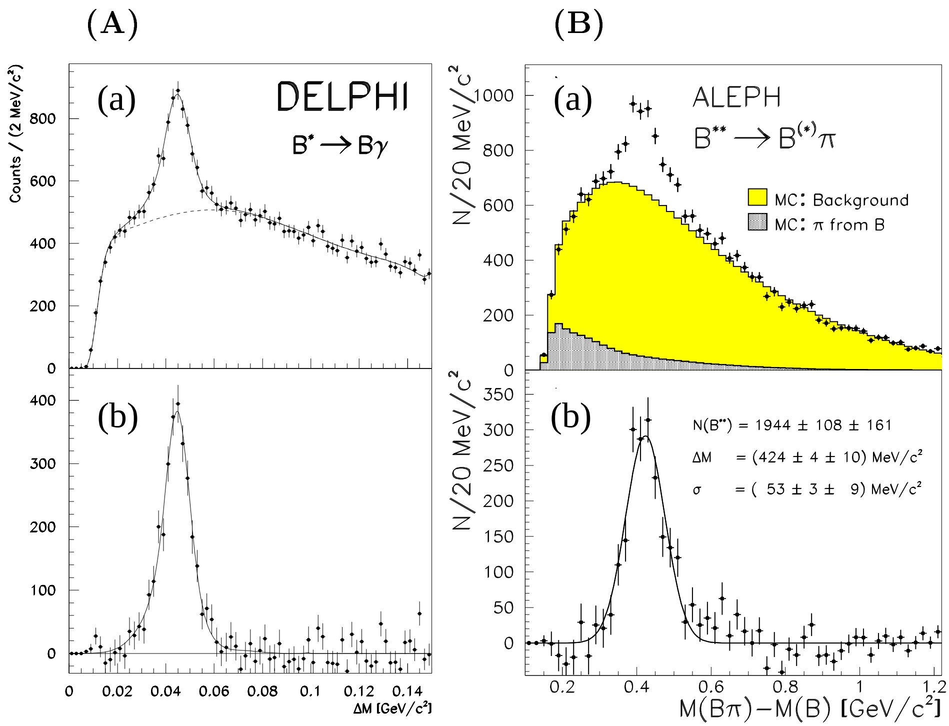

Fig. 1. The distribution of the mass difference $\Delta M(B^*{-}B)$ (plot (A)) and $\Delta M(B^{**}{-}B)$ (plot (B)) before (plots (a)) and after (plots (b)) background subtraction. The data are represented by points with error bars. The curves on plots (b) show the results of the fit using a Gaussian distribution for the signal.

into individual resonances is not possible yet. The world average [24] of the mass of the B^{**} states is (5697 ± 9) MeV and the production rate is

$$f_{B^{**}} = \frac{\mathcal{B}(b \to B^{**}_{u,d})}{\mathcal{B}(b \to B_{u,d})} = (30 \pm 10)\% \,.$$

Four events of fully reconstructed decays $\Lambda_b \to \Lambda_c \pi(a_1)$ were observed both by ALEPH [35] and DELPHI [36]. The most precise mass measurement of the Λ_b was performed by CDF [37]. The average mass of the Λ_b is $m_{\Lambda_b} = (5624 \pm 9)$ MeV. The Ξ_b^- baryon was observed inclusively by ALEPH [38] and DELPHI [39] as an excess of the same sign pairs Ξ^--l^-. However, this partial reconstruction did not allow for the mass determination. The observation of the decays $\Sigma_b^{(*)} \to \Lambda_b \pi$ was reported only by DELPHI [40] and needs confirmation.

The production rates of pseudo-scalar b-mesons and generic b-baryon were measured at LEP and CDF. The average results [41, 42] yielded:

$$f_{B_d^0} = f_{B^+} = (40.3 \pm 1.2)\%,\ f_{B_s^0} = (9.4 \pm 2.2)\%,\ f_{b\text{-baryon}} = (10.1 \pm 1.7)\%. \tag{1}$$

All results concerning the masses and production rates of beauty hadrons are in good agreement with the theoretical predictions, in particular with those given by HQET [34].

4. Lifetimes of beauty hadrons

The lifetimes of beauty hadrons depend on the magnitude of the CKM matrix elements $|V_{cb}|$ and on the dynamics of the decays of beauty hadrons. According to the spectator model, the lifetimes of all b-hadrons are equal. This prediction is modified after taking into account the effects resulting from the presence of the light quark (diquark) inside the beauty hadrons. In the framework of Heavy Quark Expansion these effects can be estimated as an expansion in powers of $1/m_b$. It leads to the following predictions [43]:

$$\frac{\tau(B^+)}{\tau(B_d^0)} = 1 + 0.05\left(\frac{f_B}{200\,\mathrm{MeV}}\right)^2,\ \frac{\tau(B_s^0)}{\tau(B_d^0)} = 1 \pm \mathcal{O}(1\%),\ \frac{\tau(\Lambda_b)}{\tau(B_d^0)} = (0.9 - 0.95)\,, \tag{2}$$

where $f_B \approx 200\,\mathrm{MeV}$ is the pseudo-scalar decay constant. The LEP experiments, together with SLD and CDF, provided precise measurements of b-hadrons lifetimes which allowed to test quantitatively the relations given in Eq. (2).

The lifetimes of beauty hadrons were measured using four basic techniques. In the first, so-called *topological* method, the b-decay vertices were reconstructed inclusively and the charge of the b-hadron was determined from the total charge of the tracks associated to vertex. This approach provided a large sample of events (~ 74000 of B^+ and B_d^0) at the price of a reduced purity ($\approx 67\%$) and a substantial model dependence. The second, *semileptonic* technique exploited the partial reconstruction of semileptonic decays like $B^+ \to \bar{D}^0 l^+ \nu_l X$ and $B_d^0 \to \bar{D}^{(*)-} l^+ \nu_l X$. High p and p_{T} leptons were identified and the charm hadron of the appropriate charge was partially or fully reconstructed. This method provided samples of a reasonably high statistics and purity (ALEPH [44]: 3700 events of B^+ and B_d^0, purity $\approx 85\%$). It required, however, the accurate determination of the missing four-momentum in order to estimate the four-momentum of neutrino. The third approach involved the full reconstruction of b-hadrons in hadronic decays. Their momenta were well determined, since there were no missing particles. Finally, some lifetime measurements were based on the impact parameters of tracks from the decays of beauty hadrons, in particular leptons.

The best measurements of B_d^0 and B^+ lifetimes were performed by LEP experiments and SLD using the topological and semileptonic methods. In the topological approach the purity of B_d^0 sample was limited by irreducible contamination of B_s^0 and Λ_b. The main source of systematic uncertainties in the semileptonic method was due to the presence of the physical background $B \to \overline{D}^{**} l^+ \nu_l$. For B^+, the most accurate measurements were obtained by DELPHI [45], OPAL [46] and SLD [47], using topological approach and by ALEPH [44] using D^*-l pairs. The average value of the B_d^0 lifetime is determined mostly by D^*-l measurements of ALEPH [44], DELPHI [48] and OPAL [49] and by topological results of DELPHI [45] and SLD [47]. The most accurate measurements of the B_s^0 lifetime were based on the study of D_s-l pairs (ALEPH [50], CDF [51] and DELPHI [52]) coming from the decay $B_s^0 \to \overline{D}_s l^+ \nu_l X$ and D_s-hadron pairs (ALEPH [53] and DELPHI [54]) from $B_s^0 \to \overline{D}_s h X$.

The results concerning beauty baryons were commonly given as lifetimes of "generic b-baryon" and Λ_b. In the first case the signal enrichment was obtained by the reconstruction of Λ^0-l (*e.g.* ALEPH [55], impact parameter technique) and p-l (DELPHI [56]) pairs. The sample is composed mostly of the Λ_b, but the contribution for Ξ_b^-, Ω_b *etc.* is not negligible ($\approx$ 15%). For Λ_c-l pairs (ALEPH [55], DELPHI [56]) the Λ_b

$\tau_{B_d^0} = (1.548 \pm 0.021)\,\mathrm{ps}$

$\tau_{B^+} = (1.647 \pm 0.021)\,\mathrm{ps}$

$\tau_{B_s^0} = (1.464 \pm 0.057)\,\mathrm{ps}$

$\tau_{b\text{-baryon}} = (1.208 \pm 0.051)\,\mathrm{ps}$

$\tau_{\Lambda_b} = (1.229^{+0.081}_{-0.079})\,\mathrm{ps}$

$\tau_{\Xi_b^-} = (1.39^{+0.34}_{-0.28})\,\mathrm{ps}$

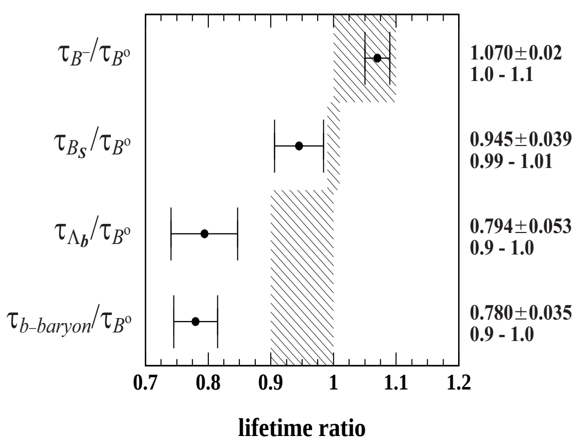

Fig. 2. Average values of lifetimes of beauty hadrons together with their ratios and theoretical expectations.

lifetime is determined as the yield of other b-baryons states can be safely neglected. One of the main sources of systematic uncertainties in the determination of b-baryon lifetimes comes from the Λ_b polarization. The latter modifies the angular distributions of the Λ_b's decay products. The polarization was measured using the average values of lepton and neutrino energies in the samples containing the Λ^0-l final state. The average of measurements from ALEPH [57], DELPHI [58] and OPAL [59] yielded $\mathcal{P}(\Lambda_b) = -0.45^{+0.17}_{-0.15} \pm 0.08$. ALEPH [38] and DELPHI [39] performed also the first measurements of the Ξ_b^- lifetime using Ξ^--l^- pairs. They were, however, of very limited statistical accuracy.

The average values of lifetimes of beauty hadrons, as given by the LEP B Lifetimes Working Group [42, 60], are presented in Fig. 2. As far as b-mesons are concerned, the lifetime ratios are in good agreement with the theoretical expectations, *cf.* Eq. (2) and Fig. 2. The lifetimes of b-baryons and the Λ_b are significantly smaller than expected once. This discrepancy was discussed in numerous theoretical papers [43, 61]. It may indicate a potential problem in the operator product expansion and the assumption of the quark–hadron duality. The experimental accuracy of $\tau_{B_d^0}$ and τ_{B^+} will improve soon on the basis of new results from the B-factories. The same is expected for the B_s and Λ_b from TEVATRON.

5. The branching fraction for semileptonic decays $\mathcal{B}(b \to lX)$

Measurements of the branching fraction for semileptonic decays of beauty hadrons provide important information about the dynamics of heavy quark decays and allow to determine the size of the $|V_{cb}|$ CKM matrix element. The "direct" $b \to l$ signal was separated experimentally from other components like the cascade $b \to c(\bar{c}) \to \bar{l}(l)$ and the $c \to \bar{l}$ transitions using the harder p and p_{T} distributions of the lepton from prompt b-decays. The decay topology, the charge correlation between the b-quark and the lepton and double b-tagged events where both b-hadrons decayed semileptonically [62–64] were also exploited to suppress the backgrounds. The precision of all these methods was limited by the model dependence in the description of the signal and background spectra. The LEP average of the semileptonic branching fraction [65] yielded $\mathcal{B}(b \to lX) = (10.56 \pm 0.11 \pm 0.18)\%$ and was consistent with the value measured by the CLEO collaboration [66] as $\mathcal{B}(b \to lX) = (10.49 \pm 0.17 \pm 0.43)\%$. To account for the different beauty hadron species produced, the LEP results were rescaled by $1/2(\tau_{B_d^0} + \tau_{B^+})/\tau_b$ where τ_b denotes the average lifetime of beauty hadrons[2].

[2] $\tau_b = f_{B_d^0}\, \tau_{B_d^0} + f_{B^+}\, \tau_{B^+} + f_{B_s^0}\, \tau_{B_s^0} + f_{b\text{-baryon}}\, \tau_{b\text{-baryon}}$.

Once the total decay width is fixed, the yields of semileptonic, double charmed and charmless decays are correlated. Therefore it is appropriate to analyse the results concerning the $\mathcal{B}(b \to lX)$ in relation with the average number of charm hadrons in B-decays $\langle n_c \rangle$. The average of LEP measurements, $n_c = 1.171 \pm 0.040$, is consistent with the results of CLEO ($n_c = 1.159 \pm 0.049$) [65]. The measured values of $\mathcal{B}(b \to lX)$ and n_c are consistent with theoretical predictions.

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

The elements $|V_{cb}|$ and $|V_{ub}|$ of the CKM matrix are fundamental parameters of the standard model that can be determined in $b \to cl^-\bar{\nu}$ and $b \to ul^-\bar{\nu}$ decays. Experimentally, the semileptonic width is obtained from the average lifetime of b-hadrons and the semileptonic branching ratio:

$$\Gamma(B \to X_{c(u)} l \bar{\nu}_l) = \frac{\mathrm{BR}(B \to X_{c(u)} l \bar{\nu}_l)}{\tau_b}\,, \tag{3}$$

which leads to the following formulae for the $|V_{cb}|$ and $|V_{ub}|$:

$$|V_{cb}| = 0.0411 \sqrt{\frac{\mathrm{BR}(B \to X_c l \bar{\nu}_l)}{0.105}} \sqrt{\frac{1.55\,\mathrm{ps}}{\tau_b[\mathrm{ps}]}} \times (1 \pm 0.04)\,, \tag{4}$$

$$|V_{ub}| = 0.00445 \sqrt{\frac{\mathrm{BR}(b \to X_u l \bar{\nu}_l)}{0.002}} \sqrt{\frac{1.55\,\mathrm{ps}}{\tau_b[\mathrm{ps}]}} \times (1 \pm 0.05)\,. \tag{5}$$

This way of extraction of the $|V_{cb}|$ is commonly known as the inclusive method. In the so-called exclusive approach, the magnitude of the $|V_{cb}|$ was extracted from the measurement of the differential partial width of the decay $\overline{B}{}^0_d \to D^{*+} l^- \bar{\nu}$ as a function of ω *i.e.* the product of four-velocities of the B and D^* mesons:

$$\omega = v_B\, v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}, \qquad q^2 = (p_B - p_{D^*})^2. \tag{6}$$

The variable ω ranges from one in the point of zero recoil, when the D^{*+} is produced at rest in the $\overline{B}{}^0_d$ rest frame, to about 1.5. The differential decay rate is predicted to be

$$\frac{d\Gamma}{d\omega} = \mathcal{K}(\omega)\, \mathcal{F}^2_{D^*}(\omega)\; |V_{cb}|^2\,, \tag{7}$$

where $\mathcal{K}(\omega)$ is a known phase-space function and $\mathcal{F}_{D^*}(\omega)$ denotes the hadronic form-factor. In the heavy quark limit ($m_b \to \infty$), the form-factor coincides with the Isgur–Wise function and its magnitude at zero-recoil can be estimated using HQET [34] to be $\mathcal{F}_{D^*}(\omega = 1) = 1$. This value is modified to 0.88 ± 0.05 [42] after taking into account the effects of a finite quark mass and QCD corrections. The Isgur–Wise form-factor is approximated with the expansion around $\omega = 1$ with the parameter $\hat{\rho}$, interpreted as the slope of $\mathcal{F}_{D^*}$ at zero recoil. As the phase space function vanishes in the limit of zero-recoil, the differential decay rate has been measured close to $\omega = 1$ and extrapolated to determine the product $\mathcal{F}_{D^*}(1)\,|V_{cb}|$.

The D^{*+} mesons were observed in the decays to $D^0\pi^+$. Due to the limited phase space available in this decay, the charged pion, denoted below as π^*, was produced almost at rest in the D^* rest frame. The D^0 was reconstructed either exclusively, in particular decay modes $K^-\pi^+(\pi^0)$, $K^-\pi^+\pi^+\pi^-$ and $K^0_s\pi^+\pi^-$ (ALEPH [67] and OPAL [68]), or inclusively, by looking for generic secondary vertices consistent with the hypothesis of the D^0 decay, inside the jet containing the lepton and charged pion (DELPHI [69], OPAL [68]). The values of $\mathcal{F}_{D^*}(1)\,|V_{cb}|$ and $\hat{\rho}^2$ were extracted by a maximum likelihood

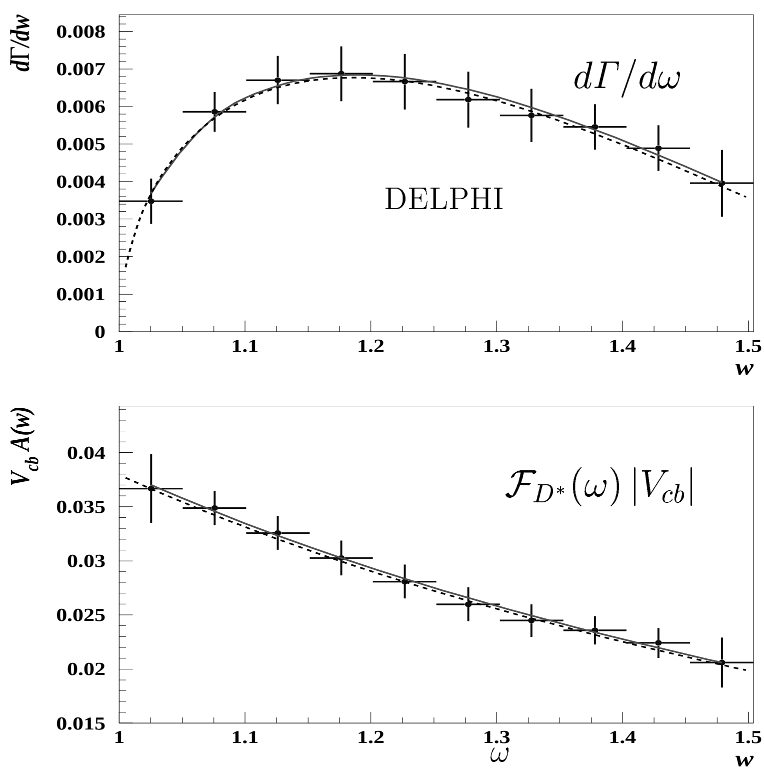

Fig. 3. The differential decay width (upper plot) and the product of the decay form-factor $\mathcal{F}_{D^*}(\omega)$ and the $|V_{cb}|$ (lower plot) of the decay $\overline{B}{}^0_d \to D^{*+}l^-\bar{\nu}$ as a function of the variable ω. The dotted (continuous) line shows the results of a fit to the data histogram neglecting (including) the statistical correlations among the bins.

fit to the reconstructed ω spectra (see Fig. 3). The fit took into account the combinatorial and physics backgrounds. The first was estimated using events with wrong-sign l^{-}-π^{*-} charge correlation and from the mass sidebands. The latter was due to the presence of the decays $\overline{B}_d^0 \to D^{**+} l^- \bar{\nu}_l$ where the D^{**+} decays to $D^*\pi$ or D^*K and possibly also from non-resonant $\overline{B}_d^0 \to D^{*+} h l^- \bar{\nu}_l$ decays. The average of LEP results yielded

$$\begin{aligned} \mathcal{F}_{D^*}(\omega)\,|V_{cb}| &= 34.5 \pm 0.7 \pm 1.5 \times 10^{-3}\,, \\ \hat{\rho}^2 &= 1.01 \pm 0.08 \pm 0.16\,. \end{aligned}$$

The recent study of CLEO [70] gave somewhat higher value of $\mathcal{F}_{D^*}(\omega)\,|V_{cb}| = 42.4 \pm 1.8 \pm 1.9 \times 10^{-3}$. The results for $|V_{cb}|$, extracted by the LEP $|V_{cb}|$ Working Group [71], using both inclusive and exclusive methods, are

$$|V_{cb}|^{\text{inclusive}} = 40.7 \pm 0.5 \pm 2.0) \times 10^{-3}\,, \quad |V_{cb}|^{\text{exclusive}} = (39.8 \pm 1.8 \pm 2.2) \times 10^{-3}\,,$$

$$|V_{cb}|^{\text{LEP average}} = (40.4 \pm 1.8) \times 10^{-3}.$$

The magnitude of the $|V_{ub}|$ was determined first by CLEO [72] and ARGUS [73] from the yield of leptons with momenta above the kinematical limit for $b \to X_c l \bar{\nu}_l$ decays. In addition, the CLEO [74] collaboration measured the $|V_{ub}|$ from the exclusive decays $B \to \pi l \bar{\nu}_l$ and $B \to \rho l \bar{\nu}_l$. The drawback of the first two approaches is their strong model dependence. At LEP the extraction of the $|V_{ub}|$ was recently performed by ALEPH [75], DELPHI [76] and L3 [77] from the study of properties of the hadronic system recoiling against the lepton. The main difficulty of this method was the isolation of the $b \to u$ transitions from the dominant $b \to c$, which yield was around 50 times bigger. The discrimination between $b \to c$ and $b \to u$ is based on the differences in the invariant mass of the system accompanying the lepton, in kaon content and in the decay vertex topology and multiplicity.

The combination of LEP measurements yielded the value of the semileptonic branching ratio for the $b \to u$ transition of $\mathrm{BR}(b \to X_u l^- \bar{\nu}_l) = (1.74 \pm 0.57) \times 10^{-3}$. Using Eq. (5), this result can be translated into a value for the $|V_{ub}|$ provided by the LEP $|V_{ub}|$ Working Group:

$$|V_{ub}|^{\text{LEP average}} = (4.13^{+0.63}_{-0.75}) \times 10^{-3}\,,$$

which is consistent with the recent CLEO determination [74]: $|V_{ub}|^{\text{CLEO}} = (3.25^{+0.61}_{-0.64}) \times 10^{-3}$. The systematic uncertainties associated with modelling $b \to u$ and $b \to c$ transitions are 10% (17%) for LEP (CLEO) results, respectively. They are, however, mostly uncorrelated.

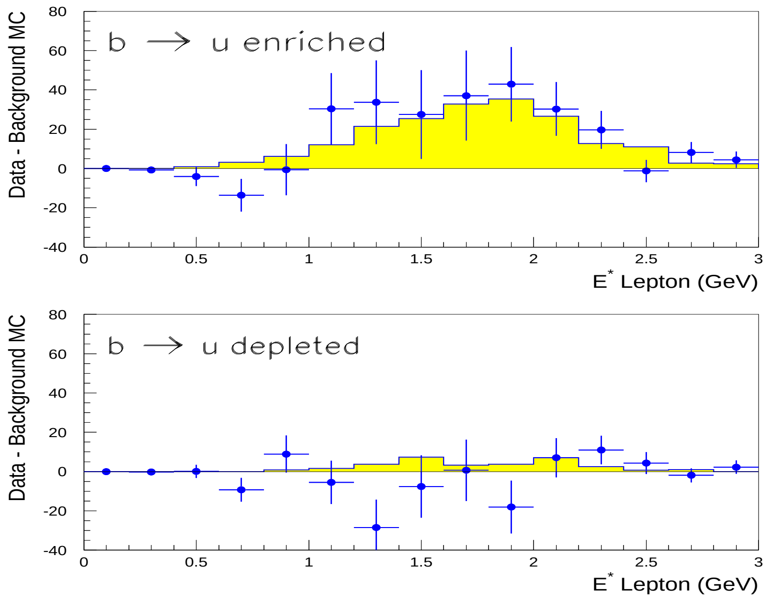

Fig. 4. Background subtracted energy spectrum of leptons E_l^*, measured in the B meson rest frame, as obtained by the DELPHI for the $b \to u$ enriched (upper plot) and $b \to u$ depleted (lower plot) samples. The shaded histograms show the expected E_l^* distribution for the signal of $b \to u$ semileptonic decays normalized to the fitted value of $|V_{ub}|/|V_{cb}|$.

7. B^0–$\overline{B}^0$ oscillations

LEP did the first observation of time-dependent B_d^0–$\overline{B}_d^0$ oscillations (ALEPH [79]). The probability that a primary $B_{d(s)}^0$ has oscillated to a $\overline{B}_{d(s)}^0$ is given by:

$$\mathcal{P}\left(B_q^0 \to B_q^0\left(\overline{B}_q^0\right)\right)(t) = \frac{1}{2\tau_q}\,\mathrm{e}^{-\frac{t}{\tau_q}}\left[1 \pm \cos(\Delta m_q t)\right], \qquad (8)$$

where $\Delta m_{d(s)}$ is the mass splitting of the two mass eigenstates. The B_s^0–$\overline{B}_s^0$ oscillations are expected to be more than twenty times faster than those with B_d^0–$\overline{B}_d^0$.

To observe time-dependent B^0–$\overline{B}^0$ oscillations both the production and decay flavour had to be tagged and the proper time must be accurately measured. For the B_d^0–$\overline{B}_d^0$ system, the B flavour at the decay time can be tagged by the charge of the lepton, kaon or D^* meson attributed to the

B-decay products or by the *jet (hemisphere) charge*. The latter is the momenta weighted charge of particles belonging to a jet (hemisphere). The B flavour at the production time can be established either from the tracks belonging to the same hemisphere as the B candidate (*same-side tag*) or the opposite hemisphere tracks (*opposite-side tag*) can be used. The basic *same side tag* is the charge of a track from the primary vertex. It is correlated with the production state of the B if that track is the first particle in the fragmentation chain or a decay product of a B^{**} meson. The charge of a lepton from $b \to l^-$ or of a kaon from $b \to c \to s$ or the *hemisphere charge* can be used as *opposite-side tags*. The oscillations were studied by performing a maximum likelihood fit to the distributions of fractions of events tagged as mixed and unmixed as a function of the proper time. Fig. 5(a) shows the B_d^0 oscillations. Here both the production and decay flavour were tagged by leptons. The like-sign di-leptons were a signature of an oscillation.

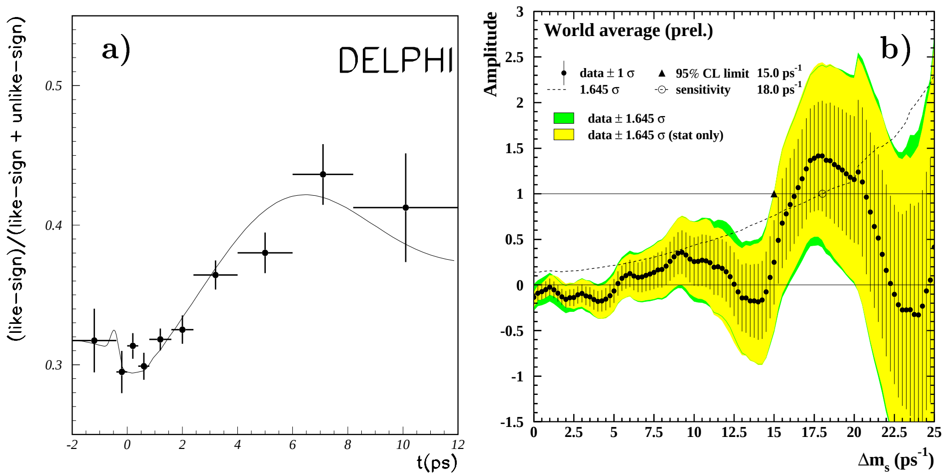

Fig. 5. (a) Fraction of events in which the oscillation B_d^0–$\overline{B}_d^0$ took place as a function of the reconstructed proper time; (b) combined measurements of the B_s^0 oscillation amplitude as a function of Δm_s.

The 26 individual measurements of mass difference Δm_d provided by LEP, SLD and CDF were averaged by the LEP B Oscillations Working Group [41, 42] to be

$$\Delta m_d = (0.487 \pm 0.014)\ \mathrm{ps}^{-1}.$$

Among the recent measurements, the most accurate was performed by OPAL [49]. It was based on inclusive reconstruction of $B_d^0 \to D^{*+} l^- \bar{\nu}_l$ decays. The B_d^0 decay vertex was reconstructed by intersecting the lepton with the soft pion from the decay $D^{*+} \to D^0\pi^*$. The flavour at the production (decay) time was tagged using the jet charge (lepton's charge), respectively. The present average is dominated by LEP results. However, it is worthwhile to stress that the preliminary results of B_d^0–$\overline{B}_d^0$ oscillations obtained at B-factories [80] are not yet included.

Up to now, no experiment was able to show evidence for the fast B_s^0–$\overline{B}_s^0$ oscillations. The experimental results are thus presented as lower limits of the oscillation frequency Δm_s. The B_s^0 oscillations were searched for using fully reconstructed decays, $D_s^- l^+$ final states and inclusive methods. Analyses of fully reconstructed B_s^0 have been performed in the channels $B_s^0 \to D_s^{(*)}\pi^+$, $D_s^{(*)}a_1^+$, $\overline{D}^0 K^-\pi^+$ and $\overline{D}^0 K^- a_1^+$ by ALEPH [81] and DELPHI [82]. The sample collected by DELPHI was composed of 44 decays with an estimated B_s^0 purity of around 50%. Due to the excellent decay length resolution, this sample has a good sensitivity in the region of high Δm_s. Analyses of D_s-l final states have a similar B_s^0 purity but worse proper time resolution. They lead to the samples of a few hundred events (ALEPH [81], DELPHI [52]). The highest sensitivity was achieved using the analyses of inclusive leptons. These studies provide around 50000 candidates with a B_s^0 purity of around 10% (ALEPH [83]). Moreover, the SLD collaboration [84] studied the B_s^0–$\overline{B}_s^0$ oscillations using topologically reconstructed vertices of heavy quark decays.

To combine results of the different experiments and methods a specific *amplitude method* was put forward. The mixing probability, as given by Eq. (8), was modified by multiplying the oscillating term by the amplitude $\mathcal{A}$. Thus, for each fixed value of Δm_s, the data were fitted to a function proportional to $1 \pm \mathcal{A}\cos(\Delta m_s t)$. This corresponds to Fourier analysis of oscillation data with the amplitude studied as a function of the oscillation frequency. The oscillation amplitude was expected to be $\mathcal{A} = 0$ ($\mathcal{A} = 1$) for frequencies which are far from (close to), respectively, the true value of Δm_s. The measured oscillation amplitudes were combined [41] to provide the world average of amplitude spectrum presented in Fig. 5(b). A value of Δm_s could be excluded at 95% C.L., corresponding to a value of the amplitude such that: $\mathcal{A} + 1.645\,\sigma_{\mathcal{A}} \leq 1$. The amplitude spectrum, combined from LEP, SLD and CDF measurements, excludes mixing for

$$\Delta m_s > 15.0 \text{ ps}^{-1}\,, \qquad \text{LEP}: \quad \Delta m_s > 11.8 \text{ ps}^{-1}\,.$$

The sensitivity, defined as the expected limit in Δm_s at 95% C.L. corresponds to:

$$\Delta m_s^{\text{sens}} = 18.0 \text{ ps}^{-1}\,, \qquad \text{LEP}: \quad \Delta m_s^{\text{sens}} = 14.5 \text{ ps}^{-1}\,.$$

The amplitude spectrum exceeds value one in the range of oscillation frequencies between 15 and 20 ps^{-1}, reaching a maximum at $\Delta m_s = 17.8 \text{ ps}^{-1}$.

This is interpreted as a hint of B_s^0–$\overline{B}_s^0$ oscillations. The deviation of the measured amplitude from $\mathcal{A} = 0$ is about 2.5 standard deviations. SLD and LEP experiments will provide improved limits on Δm_s over this year. New results are also expected from CDF and, presumably D0, after the start of next run at TEVATRON in March 2001. Altogether it does not seem unlikely that a signal for B_s^0 oscillations at more than three standard deviations can be obtained. More detailed information about neutral B mesons oscillation can be found in Refs. [41,42] and [85–87].

For the strange-beauty mesons, the width difference $\Delta\Gamma_s = \Gamma_s^H$–$\Gamma_s^L$ between the two mass and CP eigenstates[3] B_s^L and B_s^H is expected to be non-negligible reaching the value of around 20%. Experimentally the Δm_s can be determined either by observing two different exponentials in the lifetime plots of B_s^0 or by measuring the lifetime of a CP eigenstate (*e.g.* $B_s^0 \to J/\psi\phi$) and comparing the estimated value with the average of the $\tau_{B_s^0}$. Assuming that $\tau_{B_d^0} = \tau_{B_s^0}$, the combination of results from LEP and CDF yielded $\Delta\Gamma_s/\Gamma_s = 0.16^{+0.08}_{-0.09}$ or $\Delta\Gamma_s/\Gamma_s < 0.31$ (95% C.L.) [42]. The results change to $\Delta\Gamma_s/\Gamma_s = 0.24^{+0.16}_{-0.12}$ or $\Delta\Gamma_s/\Gamma_s < 0.53$ (95% C.L.) if the assumption of equal B_d^0 and B_s^0 lifetimes is relaxed. These results are in qualitative agreement with theoretical expectations. However, they do not allow yet to draw a conclusion that the width difference $\Delta\Gamma_s$ is non-zero.

8. Summary

The LEP measurements provided a dominant contribution in many domains of the b-quark physics. Among the major achievements are the determinations of lifetimes of individual b-hadrons which have been measured with an accuracy of (1.5–6)%, the results concerning the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ and the measurement of the oscillation frequency for B_d^0–$\overline{B}_d^0$ mesons together with the stringent limit on Δm_s. Last but not least, LEP studies had improved significantly the knowledge of spectroscopic features of b-hadrons.

The LEP measurements of $|V_{cb}|$, $|V_{ub}|$, Δm_d and Δm_s, together with constraints from the ε_K parameter, had large impact on the determination of the parameters of the unitary triangle (*cf.* Fig. 6) leading to the values [86]:

$$\bar{\rho} = 0.206 \pm 0.043, \quad \bar{\eta} = 0.339 \pm 0.044, \quad \gamma = (58.5 \pm 6.9)^\circ,$$

$$\sin 2\alpha = -0.28 \pm 0.27, \quad \sin 2\beta = 0.723 \pm 0.069.$$

[3] Neglecting CP violation.

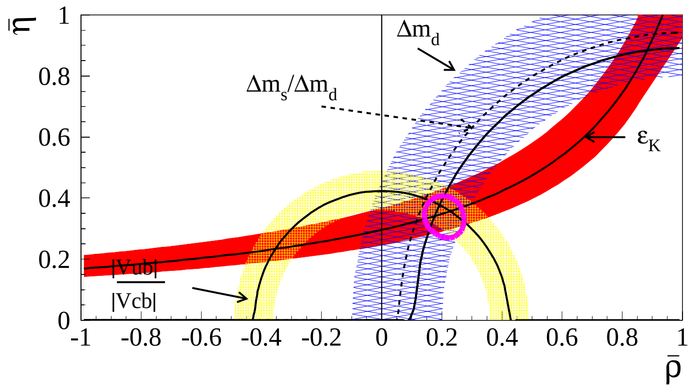

Fig. 6. Selected regions in the $\bar{\rho}$-$\bar{\eta}$ plane. The continuous curves represent the constraints resulting from the measurements of $|V_{ub}|\,/\,|V_{cb}|$, Δm_d, and ε_K. The dotted curve corresponds to the 95% C.L. limit on the $\Delta m_s/\Delta m_d$. The bands surrounding the $|V_{ub}|\,/\,|V_{cb}|$, ε_K and $\Delta m_s/\Delta m_d$ curves represent the respective contours of 68% C.L. The allowed region (contour at 68% C.L.) in shown as a circle surrounding the region where the continuous and dotted lines cross.

I would like to express my gratitude to the organizers of the Conference for the invitation and a very pleasant atmosphere. The effort of all colleagues of the LEP collaborations is also gratefully acknowledged. Special thanks are due to P. Kluit and A. Stocchi for careful reading of the manuscript. This work was partially supported by the Polish State Committee for Scientific Research (KBN) grant 2 P03B 111 16 and SPUB-M/CERN/P-03/DZ 297/2000.

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