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BEAUTY AND CHARM PHYSICS AT LEP

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Invited talk given at the
XXXIVth Rencontres de Moriond
Electroweak Interactions and Unified Theories
Les Arcs, France, March 13-20, 1999

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Recent results in charm and beauty physics at LEP are reported. They allow refined tests of strong and electroweak interactions. The importance of measuring as accurately as possible the apex of the unitarity triangle is emphasized.

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Table 1: Summary of $\bar{n}(g \to Q\bar{Q})$ results (the theoretical value is estimated using $\alpha_S = 0.119 \pm 0.002$, $m_c = 1.5 \pm 0.3$ GeV/c^2 and $m_b = 4.75 \pm 0.25$ GeV/c^2).

Experiment		$\bar{n}(g \to c\bar{c})$ $(\times 10^{-2})$	$\bar{n}(g \to b\bar{b})$ $(\times 10^{-3})$
OPAL published	4	$2.33 \pm 0.50(stat + syst)$	
DELPHI published	6		$2.1 \pm 1.1(stat) \pm 0.9(syst)$
ALEPH published	7		$2.77 \pm 0.42(stat) \pm 0.57(syst)$
DELPHI prelim. (ICHEP'98)	8		$3.3 \pm 1.0(stat) \pm 0.7(syst)$
L3 prelim. (ICHEP'98)	5	$2.22 \pm 0.18(stat) \pm 0.44(syst)$	
OPAL prelim. (new)	3,9	$3.20 \pm 0.21(stat) \pm 0.39(syst)$	$2.15 \pm 0.43(stat) \pm 0.80(syst)$
Theory	1,2	1.5 ± 0.5	2.0 ± 0.3

1 Introduction

With about 5 million c quark jets and 7 million b quark jets recorded by all the four LEP experiments up to 1995, very detailed tests of the strong and electroweak interactions have already been performed. Most of the new results presented here use the full LEP1 statistics and benefit from a better tracking and more sophisticated analysis algorithms than before.

2 Gluon splitting into heavy quark pairs

The probability to produce a heavy quark pair from a gluon in Z hadronic decays is defined as:

$$\bar{n}(g \to Q\bar{Q}) = N(Z \to q\bar{q}g,\ g \to Q\bar{Q})\ /\ N(Z \to \text{hadrons}) \tag{1}$$

where Q is a c or a b quark. The process $g \to Q\bar{Q}$ is considerably suppressed because both the gluon and the quark jet from which it originates must be sufficiently virtual to allow a heavy quark pair to be produced. The probabilities (1) have been calculated within the framework of QCD to leading order in α_S and resumming large leading and next-to-leading logarithmic terms to all orders [1]. Their measurements allow to test QCD and to decrease the systematic uncertainty of important electroweak quantities such as R_c and R_b (where $R_Q = \Gamma(Z \to Q\bar{Q})/\Gamma(Z \to \text{hadrons})$).

A new measurement from OPAL of $\bar{n}(g \to c\bar{c})$ has been performed [3] by selecting three jet events in Z decays and tagging the charm content of the gluon jet by requiring identified electrons, muons or $D^{*\pm}$. The new value supersedes and is higher than a previous OPAL measurement [4], but also higher than in a L3 measurement [5] (see Table 1) and than the theoretical estimate. This should need to be confirmed by other experiments.

The probability for a gluon to split into a $b\bar{b}$ quark pair is expected to be one order of magnitude smaller than for $c\bar{c}$. The analyses benefit from the efficient b tagging methods developed for the R_b measurements. The results presented in Table 1 are in agreement with the expectation.

3 Charm semileptonic branching fraction

The charm semileptonic branching fraction has been measured with a rather large error in low energy experiments [10]. Its uncertainty is an important source of systematic error for the R_b measurement using b semileptonic decays [11] and, to a lesser extent, for the study of the $B^0 - \bar{B}^0$ oscillation based on the lepton-jet charge correlation.

Double tagging methods are used, based on the exclusive reconstruction of a D^{*+} or a D^0 or D^+ meson [a] correlated with an identified lepton ℓ^- in the opposite hemisphere (a similar analysis was also used to measure the multiplicity of D^{*+} in charm quark jets). This D/ℓ^- tag substantially reduces the non-charm background, although at the price of a large reduction of the available statistics. High $c\bar{c}$ purity samples ($\sim 80\%$) can be obtained by selecting energetic D mesons and by rejecting $b\bar{b}$ events from their lifetime information: 16 000 $D^{*\pm}$ are selected in OPAL [12] and 22 000 D in DELPHI [13]. The

[a] Hereafter, charged conjugate states are always implied

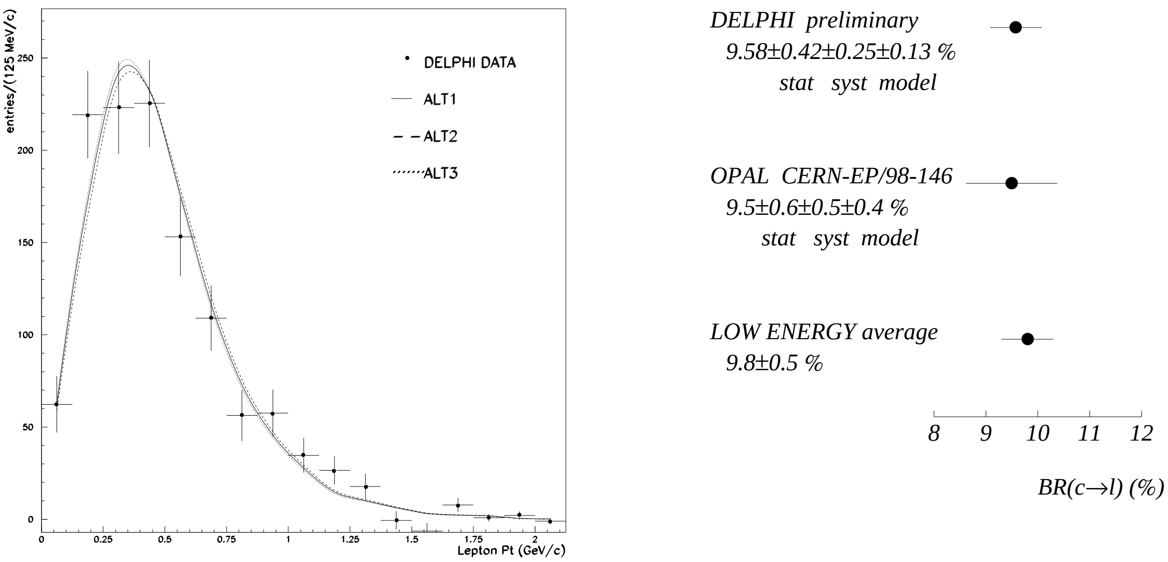

Figure 1: Left: background subtracted transverse momentum spectrum of leptons, compared with the ACCM model. Right: measured charm semileptonic branching fractions.

reconstruction times selection efficiency of electrons or muons of momentum larger than 2 GeV/c is of about 40%, however still with a significant combinatorial background ($s/b \sim 1$). This background is subtracted using events with correlated D^{*+}/ℓ^+ in OPAL and also using the simulation in DELPHI: 850 (1190) D/ℓ^- are finally selected in OPAL (DELPHI). The measured branching fractions at LEP are compatible with the low energy average and are of similar precision (see Fig.1). Note that the model dependence evaluated in DELPHI is significantly smaller than in OPAL.

4 Lifetime of b-hadrons

Compared to the ICHEP'98 conference, new results have been provided by OPAL and ALEPH for the B^+ and B^0 lifetimes, whereas DELPHI has published its b-baryon lifetime [14].

Applying a method developed in DELPHI [15], secondary b-vertices are reconstructed in OPAL [16] and L3 [17] (and also in SLD [18]) using reconstructed charged particles. A dedicated Neural Network helps to achieve a high purity ($\sim$ 95%) b sample in OPAL with 10 500 reconstructed b-vertices. A lower purity ($\sim$ 27%) is obtained in L3, but with a larger number (239 000) of b-vertex candidates. The "excess" B decay length [19] or the impact parameters of all tracks (both relative to the primary interaction vertex) are computed in OPAL and L3, respectively. In OPAL, the b-hadron energy is estimated from the tracks assumed to originate from the b-vertex, thus allowing the b-hadron proper time to be computed. A weighted charge Q_{SV} is then measured at the secondary vertex (and also in the opposite hemisphere in OPAL) in order to distinguish between charged and neutral b-hadrons (see Fig.2). The charged vertices are mainly B^+ (apart 1% of Ξ_b^+), whereas the neutral vertices are a mixture of B^0:B_s^0:Λ_b with the estimated proportions of 0.63:0.24:0.13. Thus the B_s^0 lifetime and the Λ_b fraction give significant systematics to $\tau(B^0)$. Furthermore, the cross-contamination between the charged and neutral vertices induce a correlation of about ~ -0.5 (in OPAL) to -0.8 (in L3) between the fitted $\tau(B^+)$ and $\tau(B^0)$.

Another method, which has different systematics, relies on B semileptonic decays into a reconstructed $\bar{D}^0\ell^+$ ($\sim$ 75% from B^+) or $D^{*-}\ell^+$ ($\sim$ 87% from B^0) in the same hemisphere. ALEPH has re-analysed all its data with an improved tracking and particle identification [20]. Including the 1995 data and adding more D^0 exclusive channels, the amount of exclusive $D\ell$ is about 3400, a factor two better than in a previous analysis. The correlation ~ -0.35 between the fitted $\tau(B^+)$ and $\tau(B^0)$ is partly due to the remaining $B \to \bar{D}\pi\ell^+\nu_\ell$ decays (see Fig.2).

The ratio of B^+ and B^0 lifetimes, and the summary of all measured b-hadron lifetimes, as computed in reference [21], are presented in Fig.3. The ratio $\tau(B_s^0)/\tau(B^0) = 0.95 \pm 0.04$ agrees with the theoretical expectation $\sim 0.99 - 1.01$, the ratio $\tau(B^+)/\tau(B^0) = 1.08 \pm 0.03$ is also compatible with an expectation

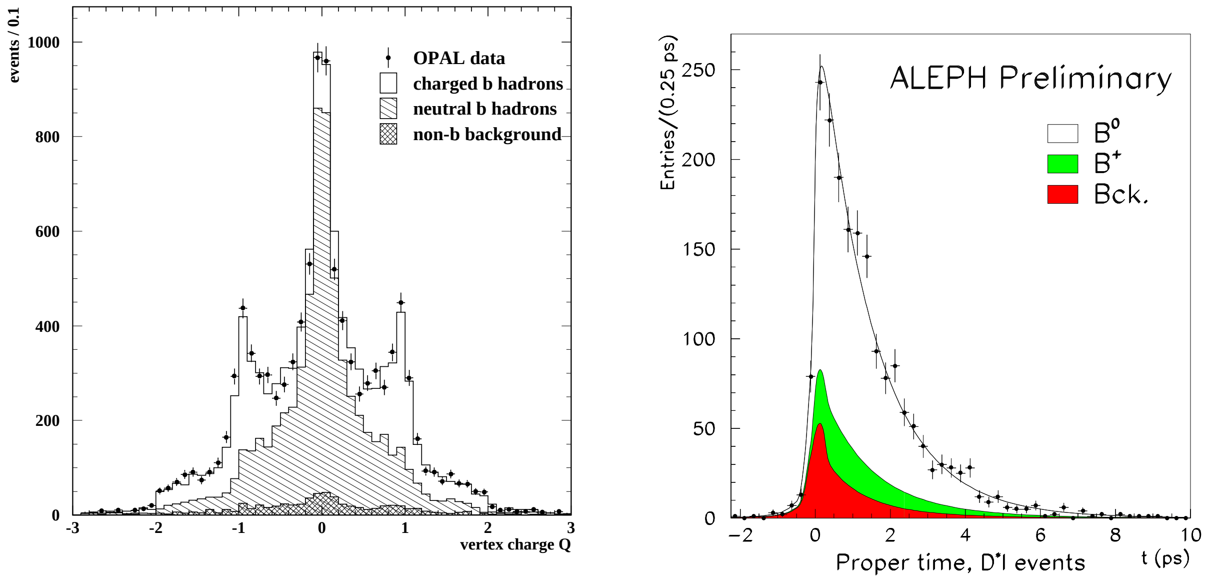

Figure 2: Left: weighted charge at the secondary b-vertices in OPAL. Right: $D^{*+}\ell^-$ proper time in ALEPH.

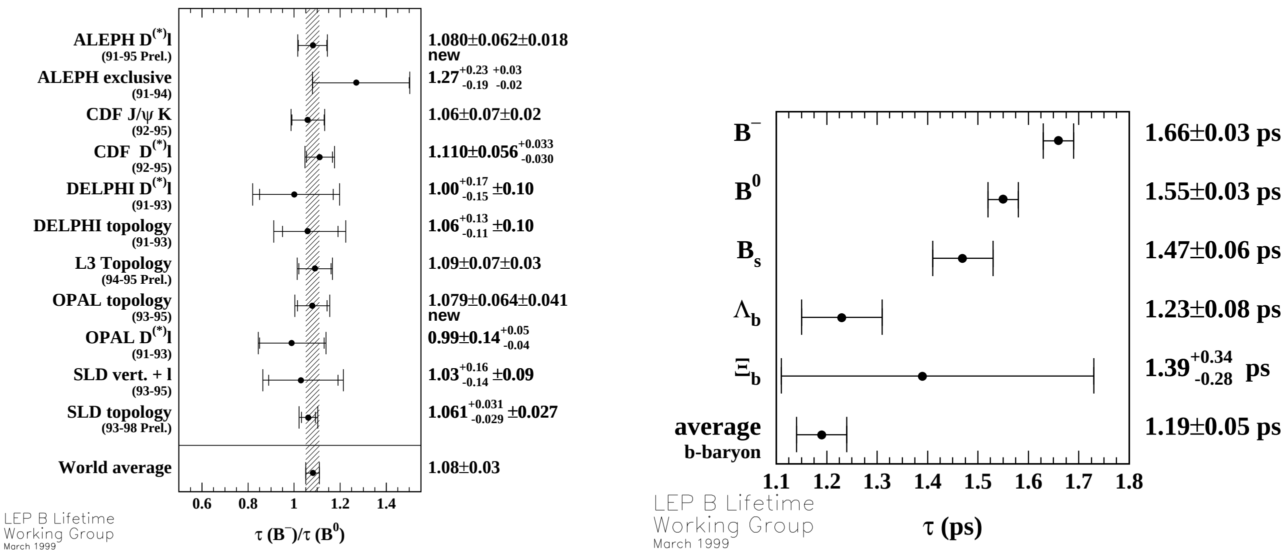

Figure 3: Left: ratio of B^+ and B^0 lifetimes. Right: summary of b-hadron lifetimes measurements.

close to one, however the low value of the ratio $\tau(b - \text{baryon})/\tau(B^0) = 0.77 \pm 0.04$ is not yet clearly well understood [22].

5 Search for CP(T) violation

Similarly to the $K^0 - \bar{K}^0$ system, the weak eigenstates $|B^0\rangle$ and $|\bar{B}^0\rangle$ differ from the mass eigenstates $|B_1\rangle$ and $|B_2\rangle$ [16]:

$$|B_1\rangle = \frac{(1+\epsilon_B)|B^0\rangle + (1-\epsilon_B)|\bar{B}^0\rangle}{\sqrt{2(1+|\epsilon_B|^2)}} \quad \text{and} \quad |B_2\rangle = \frac{(1+\epsilon_B)|B^0\rangle - (1-\epsilon_B)|\bar{B}^0\rangle}{\sqrt{2(1+|\epsilon_B|^2)}} \tag{2}$$

where ϵ_B parametrises indirect CP violation in the b sector. In the Standard Model, $\mathrm{Re}(\epsilon_B)$ is expected to be around 10^{-3}. Limits of a few 10^{-2} have been set to ϵ_B by using semileptonic b-hadron decays. A non-zero value of ϵ_B will also produce a time dependent asymmetry in B^0 and $\bar{B}^0$ decays:

$$A(t) = \frac{\Gamma(B^0 \to \text{anything}) - \Gamma(\bar{B}^0 \to \text{anything})}{\Gamma(B^0 \to \text{anything}) + \Gamma(\bar{B}^0 \to \text{anything})} = a_{\mathrm{CP}} \left[\frac{\Delta m_d\, \tau(B^0)}{2} \sin(\Delta m_d t) - \sin^2\left(\frac{\Delta m_d t}{2}\right) \right] \tag{3}$$

with Δm_d the B^0 oscillation frequency and $a_{\mathrm{CP}} \simeq 4\,\mathrm{Re}(\epsilon_B)$. OPAL has used the same secondary b-vertex reconstruction as for its B lifetime measurements, but without separating the B^0 from the

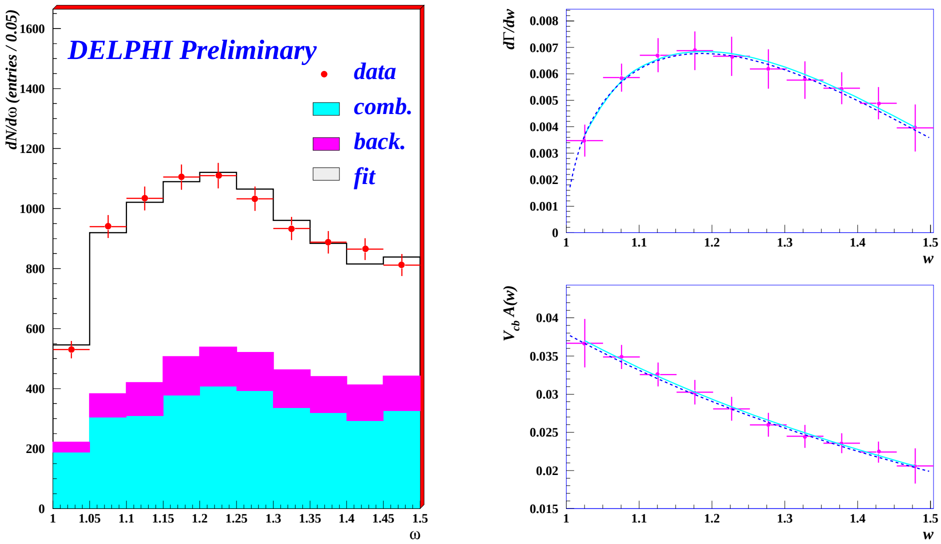

Figure 4: Left: fit to the measured w distributions in DELPHI. Right: unfolded distributions for (top) the differential decay width and (bottom) the form factor.

other b-hadrons. From a large sample of 394 000 selected b-vertices, the following value is obtained [16]:

$$\mathrm{Re}(\epsilon_B) = 0.001 \pm 0.014\ (stat) \pm 0.003\ (syst)$$

which is compatible with zero, in agreement with previous studies in semileptonic b decays. These measurements are not yet precise enough to be sensitive to CP violation.

The relative difference between the b and $\bar{b}$-hadron lifetimes has also been measured for the first time [16]. It is also compatible with zero, in agreement with CPT conservation:

$$\left[\tau(b\ \mathrm{hadron}) - \tau(\bar{b}\ \mathrm{hadron})\right] / \tau(\mathrm{average}) = -0.001 \pm 0.012\ (stat) \pm 0.008\ (syst)\ .$$

6 Measurements of $|\mathrm{V}_{cb}|$

An improved measurement of $|\mathrm{V}_{cb}|$ has been performed in DELPHI using $B^0 \to D^{*-}\ell^+\nu_\ell$ decays [23]. The method relies on a fit to the $\mathrm{d}\Gamma/\mathrm{d}w$ distribution, with

$$w = v_{B^0} \cdot v_{D^*} = \left[m_{B^0}^2 + m_{D^*}^2 - q^2\right] / \left[2\, m_{B^0}\, m_{D^*}\right] \ \text{ and } \ q^2 = (p_{B^0} - p_{D^*})^2 \tag{4}$$

where w is the product of the B^0 and D^* four-velocities and q^2 is the square momentum of the virtual W in the B^0 decay. The w distribution is predicted to be:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}w} = \frac{G_F^2}{48\pi^3}(m_{B^0} - m_{D^*})^2 m_{D^*}^3 \sqrt{w^2-1}\,\mathcal{K}(w)\,\mathcal{F}^2(w)\,|\mathrm{V}_{cb}|^2 \tag{5}$$

where $\mathcal{K}(w)$ is a kinematic term and $\mathcal{F}(w)$ is a form factor. At maximum value of q^2, corresponding to $w = 1$ when the D^{*-} is produced at rest in the B^0 rest frame, the Heavy Quark Effective Theory predicts a value $\mathcal{F}(1) = 0.91 \pm 0.03$ [24]. Different parametrisations of the form factor have been proposed. That from reference [24] depends on only one free parameter and reduces to $\pm 2\%$ the relative uncertainty on $|\mathrm{V}_{cb}|$ due to the form factor parametrisation.

About 6200 $D^{*-} \to \bar{D}^0\pi^-$ from semileptonic B^0 decays have been inclusively reconstructed in DELPHI [23]. The contamination from $D^*\pi\ell^+\nu_\ell$ is estimated to be 12%, whereas $D^*\bar{D}$ and $D^*\tau^+\nu_\tau$ are only about 1% each. Using the constraint $m_\nu = 0$, the experimental resolution is $\sigma(w) = 0.125$ and only 5% of events remain outside the kinematic range $1 < w < 1.50$. The measured w distribution and the unfolded partial decay width and form factors are presented in Fig.4, corresponding to the measured DELPHI value: $|\mathrm{V}_{cb}| = (41.7 \pm 1.5\ (stat.) \pm 1.7\ (syst.exp) \pm 1.4\ (syst.th)) \times 10^{-3}$.

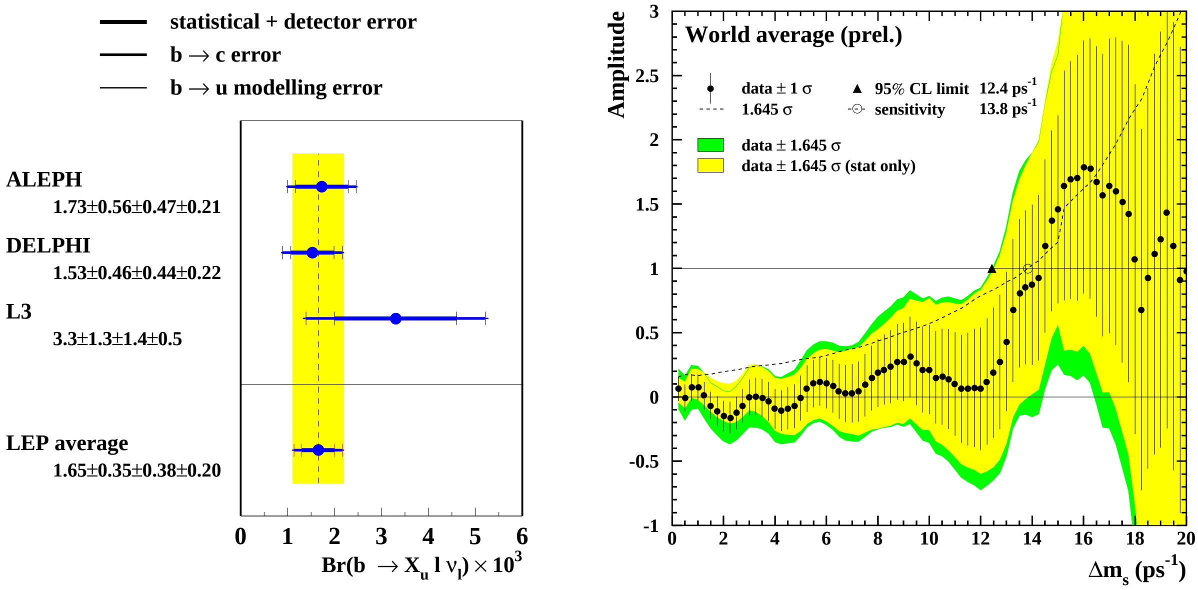

Figure 5: Left: LEP results on $BR(b \to X_u \ell \bar{\nu}_\ell)$. Right: w.a. $B_s^0 - \bar{B}_s^0$ oscillation amplitude as a function of Δm_s.

The average of the exclusive measurements of $|\mathrm{V}_{cb}|$ from LEP and CLEO2 (using $B^0 \to D^{(*)-}\ell^+\nu_\ell$ decays) agrees with the inclusive measurement from CLEO (using $B \to X\ell^+\nu_\ell$ decays), and a global average is inferred, taking the common systematics into account [25]:

$$\begin{aligned}
\text{exclusive :} \quad & |\mathrm{V}_{cb}| = (38.8 \pm 2.1 \pm 1.3\ (theory)) \times 10^{-3} \\
\text{inclusive :} \quad & |\mathrm{V}_{cb}| = (41.0 \pm 1.1 \pm 0.9\ (theory)) \times 10^{-3} \\
\text{global average :} \quad & |\mathrm{V}_{cb}| = (40.4 \pm 1.2) \times 10^{-3}\ .
\end{aligned}$$

Note that in the quoted inclusive measurement, the theoretical errors have been added quadratically (a linear sum would have given an error of ± 1.5 instead of ± 1.2 for the global average).

7 Measurements of $|\mathrm{V}_{ub}|$

No new measurement of $|\mathrm{V}_{ub}|$ at LEP has been reported since the ICHEP'98 conference. The branching fraction $\mathrm{BR}(b \to X_u \ell \bar{\nu}_\ell)$ has been measured from the lepton momentum spectrum and additional b-jet informations using a Neural Network in L3 and ALEPH, and from the reconstructed mass M_{X_u} of the accompanying hadronic system in DELPHI [26]. The LEP average result, as provided by the LEP $|\mathrm{V}_{ub}|$ Working Group, is summarized in Fig.5. Applying Heavy Quark Expansion [27]:

$$\begin{aligned}
|\mathrm{V}_{ub}| &= 0.00465 \left(\frac{\mathrm{BR}(b \to X_u \ell \nu)}{0.002} \frac{1.55}{\tau_b(\mathrm{ps})} \right)^{\frac{1}{2}} (1 \pm 0.039(\mathrm{HQE})) \qquad (6) \\
&= (4.21^{+0.42}_{-0.46}\ (stat + syst.exp)^{+0.52}_{-0.58}(syst.b\ \text{decays}) \pm 0.16(syst.\mathrm{HQE}))\ 10^{-3}\ .
\end{aligned}$$

The LEP $|\mathrm{V}_{ub}/\mathrm{V}_{cb}|$ value can be extracted by using the previous $|\mathrm{V}_{cb}|$ measurement. It is found in agreement with the CLEO inclusive measurement of the endpoint of the lepton momentum spectrum [28] (for this value, the theoretical error has been evaluated according to reference [25]):

$$\begin{aligned}
\text{LEP :} \quad & |\mathrm{V}_{ub}/\mathrm{V}_{cb}| = 0.104 \pm 0.011\ (exp.) \pm 0.015\ (theo.) \\
\text{CLEO :} \quad & |\mathrm{V}_{ub}/\mathrm{V}_{cb}| = 0.080 \pm 0.006\ (exp.) \pm 0.016\ (theo.)
\end{aligned}$$

As the theoretical errors are largely uncorrelated, the average of both results will be used below.

8 Measurements of Δm_d and limit on Δm_s

The averaged $B^0 - \bar{B}^0$ oscillation frequency from LEP, CDF, SLD and $\Upsilon(4(S)$ measurements is [29]:

$$\Delta m_d = 0.471 \pm 0.016\ \mathrm{ps}^{-1}\ .$$

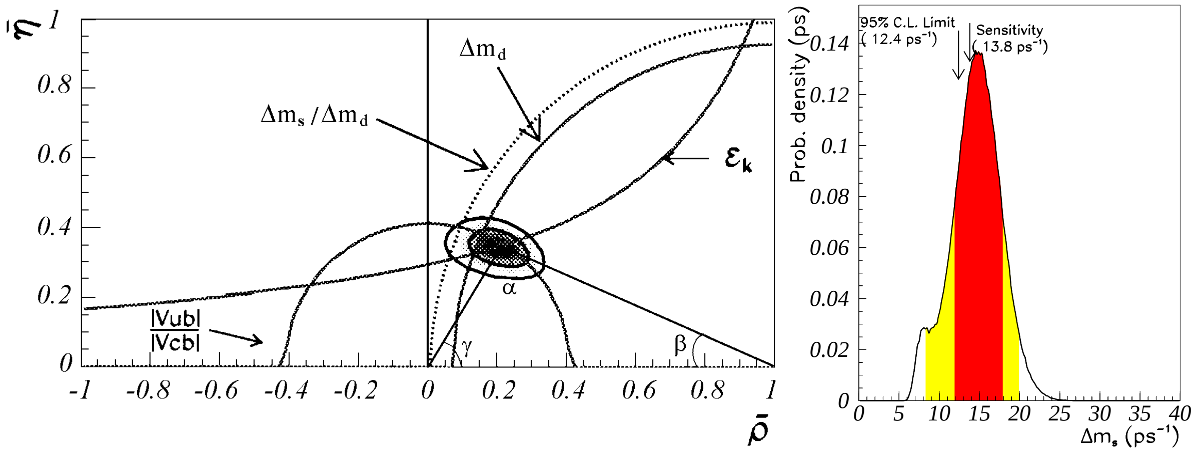

Figure 6: Left: allowed contours at 68% and 95% C.L. for $\bar{\rho}$ and $\bar{\eta}$. (the dotted curve is the 95% C.L. upper limit on Δm_s). Right: Δm_s probability distribution, with (dark grey) 68% and (light grey) 95% C.L. regions.

No experiment has yet directly observed $B_s^0 - \bar{B}_s^0$ temporal oscillations. The following limit has been derived, applying the "amplitude" method to LEP, CDF and SLD data (see Fig.5) [29]:

$$\Delta m_s > 12.4 \text{ ps}^{-1} \text{ at 95\% C.L. for a sensitivity of } 13.8 \text{ ps}^{-1}.$$

A new SLD measurement [18] excludes at 95% C.L. the region Δm_s<5.3 ps^{-1} and 6.0<Δm_s<11.5 ps^{-1} (sensitivity of 6.6 ps^{-1}). LEP alone also excludes Δm_s<11.5 ps^{-1}, but the sensitivity is 12.9 ps^{-1}.

9 Constraints on the unitarity triangle

In the Standard Model of electroweak interactions, the Cabibbo-Kobayashi-Maskawa matrix describes charged current transitions between *down*-type and *up*-type quarks ($d \to W^- u$, etc ...) and CP violation can occur due to a free phase. However, CP violation has only been observed so far in neutral kaon decays and it is of prime interest to observe and measure its predicted value in B decays, where relatively large effects are expected. In the framework of the Wolfenstein parametrisation [30], CP violation in the b sector can be visualized by the "unitarity triangle" in a $\bar{\rho}$–$\bar{\eta}$ plane (defined as in [25]). The $\bar{\rho}$ and $\bar{\eta}$ values of the apex of the triangle can be indirectly predicted by the present experiments and some theoretical inputs. New experiments will tell in the coming years if the measured angles α, β and γ of the triangle are in agreement, or not, with the Standard Model expectation.

Our present knowledge of the unitarity triangle is summarized in Fig.6$_{left}$ where constraints from ϵ_K, $|V_{ub}/V_{cb}|$, Δm_d measurements and the limit on Δm_s are combined to determine the apex of the triangle [25]. It clearly shows that the observed CP violation in the K^0 sector (ϵ_K) agrees well with indirect measurements in the b sector. The $\bar{\rho}$ and $\bar{\eta}$ values are:

$$\bar{\rho} = 0.202^{+0.053}_{-0.059} \ , \quad \bar{\eta} = 0.340 \pm 0.035 \ .$$

The probability for $\bar{\rho}$ to be negative is 1%. The $\bar{\eta}$ value is eight standard deviations away from zero, predicting that indeed a non-flat triangle is expected ! The corresponding angles are expected to be:

$$\sin 2\alpha = -0.26^{+0.29}_{-0.28} \ , \quad \sin 2\beta = 0.725^{+0.050}_{-0.060} \ , \quad \gamma = (59.5^{+8.5}_{-7.5})^\circ \ .$$

A recent CDF measurement of $\sin 2\beta = 0.79 \pm 0.39\ (stat) \pm 0.16\ (syst)$ is in good agreement with this expectation [31], however with a large error.

The Δm_s probability distribution can also be obtained with the same constraints as in Fig.6$_{left}$, but removing now the information from the Δm_s limit (see Fig.6$_{right}$): Δm_s is expected between 12.0 and 17.6 ps^{-1} within one standard deviation and less than 20 ps^{-1} at 95% C.L. The true Δm_s value may be not so far from the present measured limit !

Finally, The KTEV collaboration [32] has presented a new precise measurement of $\mathrm{Re}(\epsilon'_K/\epsilon_K) = (28.0 \pm 3.0\ (stat) \pm 2.8\ (syst))10^{-4}$. This, if confirmed by NA48, could bring a strong constraint on the unitarity triangle as it is simply proportional to $\bar{\eta}$. However large theoretical uncertainties, especially related to QCD and electroweak penguin diagrams, still prevent to use this information [33].

10 Conclusion

Heavy quark physics with LEP1 data is still quite motivating. Impressive experimental progress have improved our understanding of the unitarity triangle, preparing the road to a direct observation of CP violation in B decays. However, despite the good precision achieved now on the CKM matrix elements, theoretical uncertainties are a limitation. Measuring the $B_s^0 - \bar{B}_s^0$ temporal oscillation at LEP or SLD is a challenge, but may be not completely out of reach. New results may also be foreseen in the future on heavy quark spectroscopy, a subject not covered in the present review.

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