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RECENT RESULTS ON B PHYSICS FROM LEP

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Abstract

In this note [1] I will present some of the most recent results on B properties based on the full LEP1 statistics ($\approx 4 \div 4.5$ M hadronic Z^0 decays each LEP experiment). The selection of the topics follows in a way my personal experience and taste. Acknowledgments are due to LEP Collaborations for providing the data and to the various LEP Heavy Flavour Working Groups for combining the experimental results in the appropriate manner.

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[1] A condensed version of this note will appear in the Proceedings of the IVth Rencontres du Vietnam, Physics at Extreme Energies (Particle Physics and Astrophysics), Hanoi (July 19–25, 2000), Vietnam.

1 Measurements of the CKM elements $|V_{cb}|$ and $|V_{ub}|$.

In the Standard Model the CKM elements are free parameters, constrained only by the requirement that the matrix has to be unitary. Thus they need to be measured by the experiments.

1.1 Measurements of $|V_{cb}|$

$|V_{cb}|$ has been extracted at LEP in a variety of ways but the most accurate ones are the exclusive "zero–recoil" in the decay $\bar{B}^0_d \to D^{*+} l^- \bar{\nu}_l$ and the inclusive method from the semileptonic decay width of b–decays.

Introducing the kinematics for the exclusive decay $\bar{B}^0_d \to D^{*+} l^- \bar{\nu}_l$:

$$\omega = v_B \cdot v_{D*} = \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}}; \quad 1 < \omega < 1.5 \tag{1}$$

$$q^2 = (p_B - p_{D*})^2 \tag{2}$$

(ω = 1 means that the $D^{*+}$is produced at rest in the $\bar{B}^0_d$ rest frame), the HQET predicted rate is:

$$\frac{d\Gamma}{d\omega} = \mathcal{K}(\omega)\mathcal{F}^2_{D*}(\omega)|V_{cb}|^2 \tag{3}$$

where $\mathcal{K}(\omega)$ is a known phase space factor and $\mathcal{F}_{D*}(\omega)$ represents the hadronic form factor for the $\bar{B}^0_d \to D^{*+} l^- \bar{\nu}_l$ decay. For $m_b = \infty$ HQET predicts (at zero recoil, ω = 1) $\mathcal{F}_{D*}(1)$ = 1 but finite quark mass and QCD corrections give $\mathcal{F}_{D*}(1) = 0.88 \pm 0.05$ (value used by the LEP $|V_{cb}|$ Working Group).

$\mathcal{K}(\omega) \to 0$ for $\omega \to 1$ then the extrapolation accuracy relies on achieving a reasonable and constant reconstruction efficiency at $\omega \approx 1$; moreover there are on the market several parameterizations for $\mathcal{F}_{D*}(\omega)$. [2]

ALEPH, DELPHI and OPAL have used this method: the 3 measurements are obtained using slightly different methods and inputs: the LEP $|V_{cb}|$ Working Group has brought them on the same footing before combining. The results [3] of the extrapolation (ρ is the slope at $\omega \approx 1$) and their combination is reported in Fig. 1. The dominant systematic error is from $\bar{B}^0_d \to D^{**} l^- \bar{\nu}_l$ (mainly from its shape). There is hope to reduce it in the future with smaller theoretical uncertainty and more experimental constraints.

[2] The LEP $|V_{cb}|$ Working Group has used that of Caprini *et al* [1].
[3] The results presented in this note have been updated, whenever possible, to include the Osaka results.

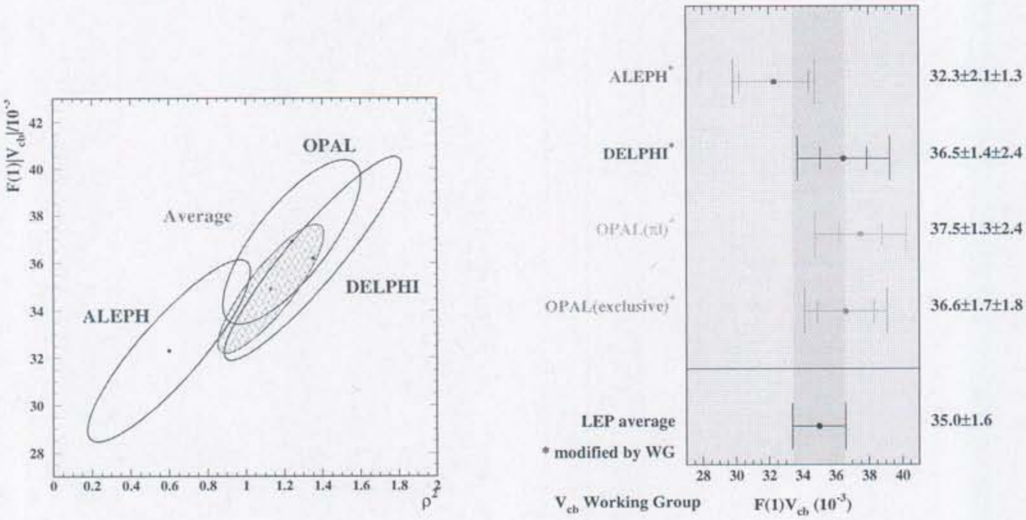

Figure 1: Extrapolations at "zero–recoil" ($\omega = 1$) and combination of the exclusive $\mathcal{F}(1)$*$|\mathrm{V_{cb}}|$ results.

$|\mathrm{V_{cb}}|$ has also been obtained at LEP from inclusive b $\to \ell$ decays. For a free b–quark decay:

$$\Gamma(b \to c\ell^- \bar{\nu}) = \frac{G_F^2 m_b^5}{192\pi^3} |\mathrm{V_{cb}}|^2 \times \mathrm{phase-space\ \ factor} \tag{4}$$

and assuming the same semileptonic decay width for all b–hadrons:

$$\Gamma(b \to c\ell^- \bar{\nu}) = BR(X_b \to X_c \ell^- \bar{\nu})/\tau_b^{incl} \tag{5}$$

The LEP $|\mathrm{V_{cb}}|$ Working Group has modified this expression using the following Heavy Quark Expansion (HQE) [2] which has an expected 5% theoretical uncertainty:

$$|\mathrm{V_{cb}}| = 0.0411 \sqrt{\frac{BR(X_b \to X_c \ell^- \bar{\nu})}{0.105}} \sqrt{\frac{1.55\ ps}{\tau_b^{incl}}} \tag{6}$$

From the average LEP BR(b $\to \ell^- \bar{\nu}$X) = (10.56 $\pm$0.11 $\pm$0.18)% obtained with a global fit to the c and b sectors at the Z^0 pole (subtraction of the BR(b $\to \ell^- \bar{\nu} \mathrm{X}_u$) is needed) and the inclusive lifetime τ_b^{incl} = 1.564 $\pm$ 0.014 ps from PDG, LEP has obtained: $|\mathrm{V_{cb}}|^{\ incl} = (40.70\ \pm\ 0.50\ \pm\ 2.00(th)) \times 10^{-3}$.

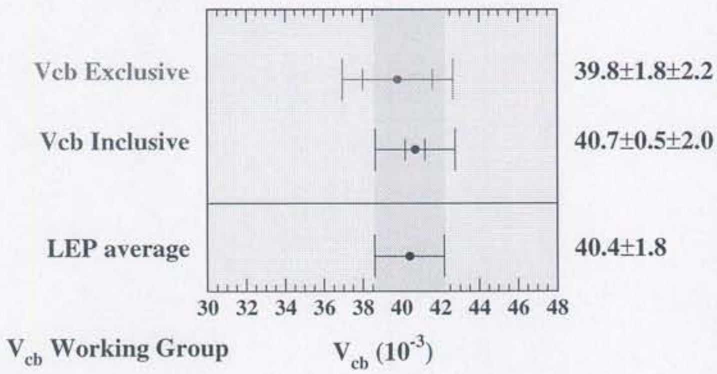

Figure 2: Combination of the exclusive and inclusive LEP results on $|V_{cb}|$.

This result (see Fig. 2) is more precise and compatible with the average $|V_{cb}|^{exclusive}$ = $(39.8 \pm 1.8 \pm 2.2) \times 10^{-3}$. Properly taking into account the correlated systematic errors the combined LEP value turns out to be: $|V_{cb}| = (40.4 \pm 1.8) \times 10^{-3}$.

1.2 Measurements of $|V_{ub}|$ from inclusive charmless b semileptonic decays

CLEO and ARGUS have both seen excesses in the end–point of the lepton spectra in B decays, attributed to charmless decay (CLEO has also reported measurement in the exclusive $B \to (\pi, \rho, \omega)\, \ell\bar{\nu}$ channels). However both approaches strongly depend on models to extract BR. LEP has a unique feature: the b–hadron system is boosted and the two initial quark states can be separated (detecting secondary vertices); thus the momentum range is not restricted to the end–point only. The most serious limitation arises from the very large background from $b \to X_c \ell\bar{\nu}$, the main difference between the two being represented by a larger recoiling mass for a charmed state if compared to a charmless system (typically M_{rec} below the D mass for a charmless decay).

ALEPH and L3 have used several kinematical variables and neural network analyses to enhance the $b \to X_u$ content; they are then sensitive to the uncertainties of the b fragmentation function. DELPHI has fitted directly $|V_{ub}|/|V_{cb}|$ on the lepton energy after enriching in $b \to u$ decays with a mass cut.

Step one of the measurement consists in obtaining and properly averaging the measurements of BR(b $\to$ $X_u \ell \bar{\nu}$) (BR(b $\to$ $X_u \ell \bar{\nu}$) = (1.74 $\pm$ 0.57) $\times$ 10^{-3}); step two in extracting $|V_{ub}|$ with the HQE expansion (4% theoretical uncertainty expected):

$$|V_{ub}| = 0.00445\sqrt{\frac{BR(X_b \to X_u \ell^- \bar{\nu})}{0.002}}\sqrt{\frac{1.55\ ps}{\tau_b^{incl}}} \tag{7}$$

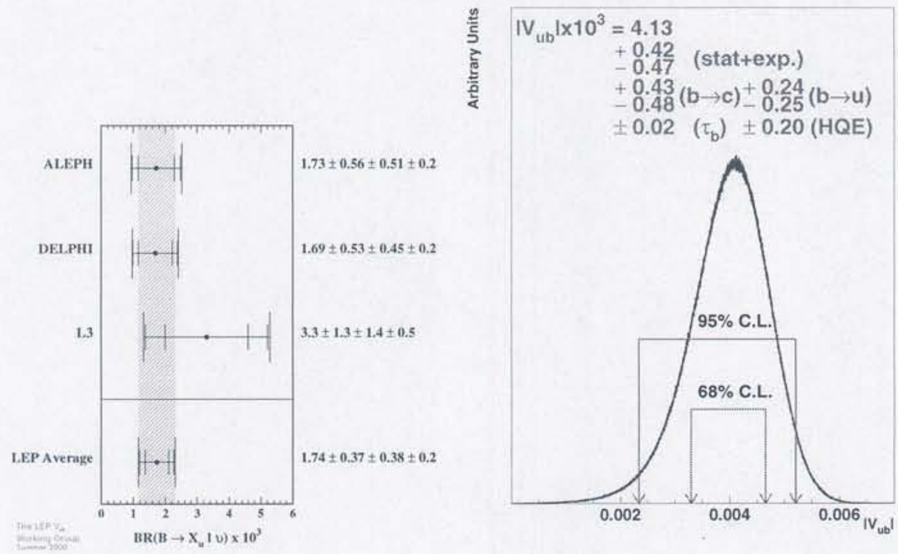

Figure 3: Combination of the LEP $|V_{ub}|$ results.

The combined LEP average (Fig. 3) is: $|V_{ub}|$ = (4.13 $^{+0.63}_{-0.75}$) $\times$ 10^{-3}.

2 B^0–$\bar{B}^0$oscillations.

Starting with a B_q^0 meson produced at time t = 0, the probability to observe a B_q^0 or a $\overline{B_q^0}$ decaying at proper time t can be written, neglecting effects from CP violation:

$$\mathcal{P}_{B_q^0 \to B_q^0, \overline{B_q^0}}(t) = \frac{1}{2} e^{-t/\tau_q}(1 \pm \cos \Delta m_q t) \quad \Delta m_q = m_{B_1^0} - m_{B_2^0} \tag{8}$$

An oscillation study thus implies the measurement of the decay proper time, the knowledge of both $B_{s(d)}$ or $\overline{B}_{s(d)}$ at t = t^0 (decay tag) and $B_{s(d)}$ or $\overline{B}_{s(d)}$ at t = 0 (production tag). The B_d^0 oscillations have been seen, well understood and measured (Fig. 4), with a world average of Δm_d = (0.487 $\pm$ 0.014) ps^{-1}, and then they will not be covered here any more.

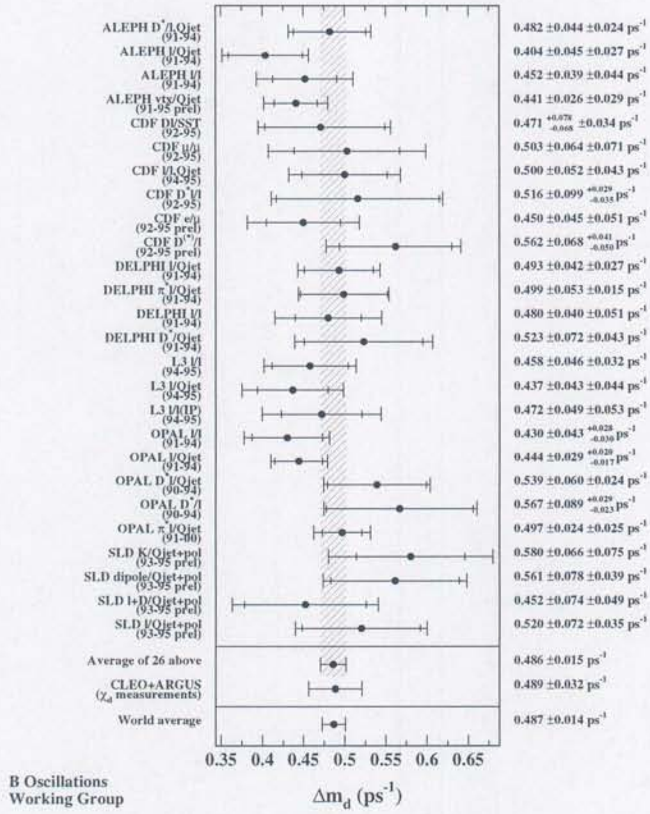

Figure 4: Δm_d measurements and their averages.

Since $\Delta m_d \propto |V_{td}|^2$ and $\Delta m_s \propto |V_{ts}|^2$ the expectation is $\Delta m_s \approx 1/sin^2\theta_{Cabibbo}\,\Delta m_d \simeq \mathcal{O}(10)\ ps^{-1}$.

Let us consider the "resolution" of a Δm_s measurement:

$$\sigma_A = \frac{1}{\sqrt{N} f_{B_s}(2\epsilon - 1) e^{-(\Delta m_s \sigma_t)^2/2}} \tag{9}$$

where N is total number of events in the sample, $f_{\bar{B}_s^0}$ the fraction of events due to $\bar{B}_s^0$ decays and ϵ the tagging purity, defined as:

$$\epsilon = \frac{N_{right}}{N_{right} + N_{wrong}} \tag{10}$$

(N_{right}(N_{wrong}): number of correctly (incorrectly) tagged events) and finally σ_t is the proper time resolution:

$$\sigma_t = \sqrt{\sigma_L^2 + \sigma_P^2 t^2} \tag{11}$$

The importance of reaching good resolution on both length and time can be judged from the cartoon of Fig. 5 where one sees that degrading their resolutions the oscillation amplitude essentially vanishes.

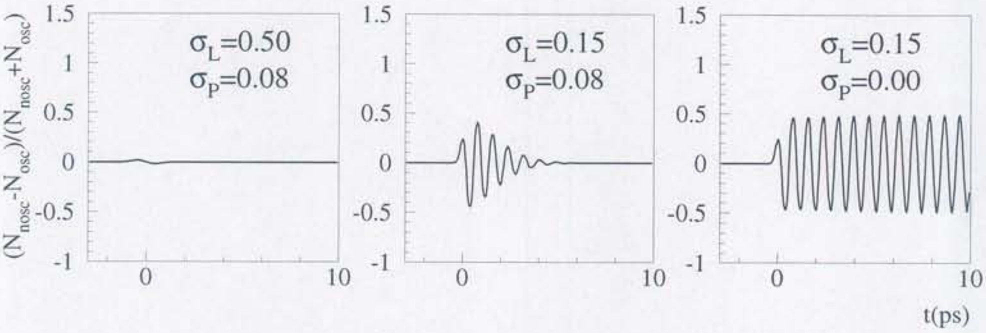

Figure 5: This schematic behaviour has been prepared with $\Delta m_s = 8\ ps^{-1}$.

B_s oscillations have been extensively studied at LEP (ALEPH, DELPHI and OPAL), SLC (SLD) and Tevatron (CDF). Space limitation does not allow me to enter here into the details of the many different analyses. I will simply report some features of the various LEP analyses:

- Inclusive lepton (ALEPH, DELPHI, OPAL): high p_T lepton, inclusive vertex reconstruction, global tagging, $N \simeq$ few $\times$ 10000, $f_{\bar{B}_s^0} \simeq 10\%$, $\epsilon \simeq 70\%$, $\sigma_t(t < 1\ ps) \simeq 0.27$ ps.
- $D_s^{\pm}\ell^{\mp}$ (ALEPH, DELPHI): high p_T lepton, good vertexing, D_s completely reconstructed, global tagging, $N \simeq$ 300–400, $f_{\bar{B}_s^0} \simeq 60\%$, $\epsilon \simeq 78\%$, $\sigma_t(t < 1\ ps) \simeq 0.18$ ps. Since this method has a limited statistics, it is vital to reconstruct as many D_s^+ decay modes as possible: $D_s^+ \to \phi\pi^+, \phi\pi^+\pi^0$, $\phi\pi^+\pi^-\pi^+$, $\overline{K^{0*}}K^+$, $\overline{K^{0*}}K^{*+}$, $K_S^0K^+$, $\phi e^+\nu_e$, $\phi\mu^+\nu_\mu$.
- Exclusive $\bar{B}_s^0$ (ALEPH, DELPHI): this method, proposed by DELPHI in Moriond 1998, relies on the fact that, since:

$$\sigma_A \propto \frac{1}{e^{-(\Delta m_s \sigma_t)^2/2}} \quad \sigma_t = \sqrt{\sigma_L + (\sigma_P/P)^2 t^2} \tag{12}$$

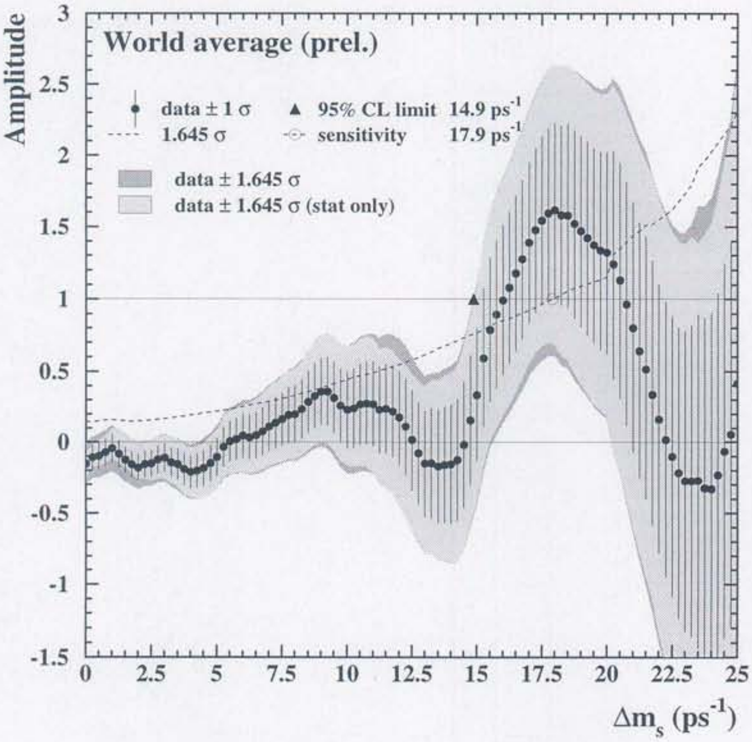

Figure 6: Amplitude analysis vs Δm_s. LEP alone sets a 95% CL lower limit of $11.5\ ps^{-1}$ with a sensitivity of $14.4\ ps^{-1}$.

to improve σ_A at high Δm_s one needs very good σ_t. An exclusive $\bar{B}_s^0$ analysis has essentially $\sigma_P/P \simeq 0$. ALEPH has presented in Moriond 2000 an exclusive $D_s a_1$ and $D_s\pi$ analysis. Although this analysis alone has a modest sensitivity and limit, it gives a significant contribution for high Δm_s values ($> 10\ ps^{-1}$).

The amplitude method [3] is used to combine results from the different analyses and to set lower limits on Δm_s. This method consists essentially in replacing the oscillation term with:

$$1 \pm \cos(\Delta m_s t) \rightarrow 1 \pm \mathcal{A}\cos(\Delta m_s t) \tag{13}$$

One then expects $\mathcal{A}$ = 0 at a frequency below the true Δm_s and $\mathcal{A}$ = 1 at the true frequency Δm_s. The analysis fits for $\mathcal{A}$ (for a fixed Δm_s) and excludes the corresponding frequency at 95% CL if $\mathcal{A} + 1.645\ \sigma_{\mathcal{A}} < 1$.

As of today the summary of the amplitude analysis is given in Fig. 6.

3 Constraints on the CKM matrix elements and related.

There is an experimental hierarchy among the CKM matrix elements of the popular Wolfenstein parametrization in terms of λ, A, ρ and η.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1\text{-}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1\text{-}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & \text{-}A\lambda^2 & 1 \end{pmatrix} \quad (14)$$

λ is very well known ($\lambda = 0.2196 \pm 0.0023$ from K_{e3} decays). $|V_{cb}| = A\lambda^2$: from the value of $|V_{cb}|$ reported above in (1.1) one derives A = 0.838 ± 0.041. Thus ρ and η are the most uncertain parameters.

The constraints imposed by the different LEP and non–LEP parameters on the unitary triangle is summarized in the following table:

Measurement	$V_{CKM}\times$other	Constraint
$b \to u/b \to c$	$\|V_{ub}/V_{cb}\|^2$	$\bar{\rho}^2 + \bar{\eta}^2$
Δm_d	$\|V_{td}\|^2 f_{B_d}^2 B_{B_d} f(m_t)$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\|\frac{V_{td}}{V_{ts}}\right\|^2 \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
ϵ_K	$f(A, \bar{\eta}, \bar{\rho}, B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$

where $\bar{\rho}(\bar{\eta}) = \rho(\eta)(1 - \lambda^2/2)$.

LEP has given a tremendous improvement in reducing the allowed regions [4] of the unitary triangle (see Fig. 7).

The allowed region corresponds to $\bar{\rho} = 0.202 \pm 0.048$ and $\bar{\eta} = 0.340 \pm 0.047$. These give indirect measurements of sin2β and sin2α (sin2β = 0.716 ± 0.007 and sin2α = -0.26 $\pm$ 0.28) which are useful to test if direct measurements of the same quantities could give any hint for new physics. Direct determinations of sin2β are available now. The most precise comes from CDF (but there are also measurements from ALEPH and OPAL): sin2β = 0.91 ± 0.35 which is not yet precise enough to really indicate, if compared with its indirect measurement, something new.

The third angle is also indirectly measured as $\gamma = (59.3 \pm 7.3)^o$. Hadronic B decays can give constraints on γ (like $\sin^2\gamma < R_1 = \frac{Br(B^0(\bar{B}^0)\to\pi^\pm K^\mp)}{Br(B^\pm\to\pi^\pm K^0)}$ if $R_1 < 1$). A new fit with several B decay modes gives γ=$(113\ ^{+25}_{-23})^o$ but there are still controversies on the hadronic uncertainties to attach to this determination.

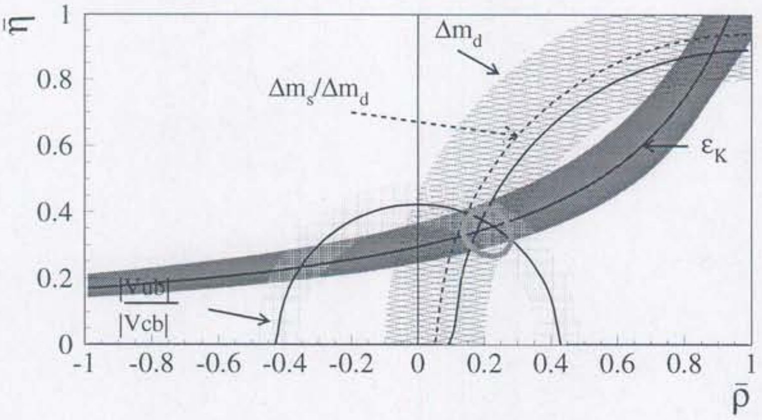

Figure 7: Allowed regions in the unitary triangle. The bands show the contributions of the different parameters.

4 Measurements of $\Delta\Gamma_s/\Gamma_s$.

B_s mixing (if it exists) implies two mass eigenstates. In analogy with the K^0 system one can define $B_s^{heavy} \equiv B_s^{long}$, the CP–odd state and $B_s^{light} \equiv B_s^{short}$, the CP–even state. Introducing $\Gamma_S = (\Gamma_s^{long} + \Gamma_s^{short})/2$ and $\Delta\Gamma_S = \Gamma_s^{short} - \Gamma_s^{long}$ lattice NLO [5] predicts $\Delta\Gamma_s/\Gamma_s = 0.16 \pm 0.03 \pm 0.04$.

Note that $\Delta\Gamma_s$ and Δm_s are correlated since $\frac{\Delta\Gamma_s}{\Delta m_s} \approx \frac{3}{2}\,\pi\,\frac{m_b^2}{m_t^2}$, thus in principle the measurement of $\Delta\Gamma_s$ could help in measuring Δm_s if the $\bar{B}_s^0$ oscillation is too fast (but here the theory is still uncertain).

Several methods have been applied to determine $\Delta\Gamma_s$: a double exponential lifetime fit for a mixture of CP eigenstates (inclusive, semileptonic, D_s–hadron) (L3, DELPHI) (this analysis has a quadratic sensitivity to $\Delta\Gamma_s$), single CP eigenstates ($\phi\phi$, $J/\psi\phi$) (ALEPH, CDF) (this has a linear sensitivity to $\Delta\Gamma_s$ but small statistics) and finally ALEPH has provided the BR($B_s^{short} \to D_s^* D_s^*$) = $\Delta\Gamma_s/(\Delta\Gamma_s + \Gamma_s/2)$

A constraint is often used to improve the fit (since τ_{B_s} has apparently no meaning):

$$\frac{1}{\Gamma_s} = \frac{1}{\Gamma_d} = \tau_{B_d} = (1.562 \pm 0.029)\ ps \tag{15}$$

The theoretical motivation for this constraint is that Γ_s is expected to be equal to Γ_d within $> 1\%$; furthermore $\Delta\Gamma_d$ is negligible.

ALEPH has measured the B_s^{short} lifetime using $B_s \to D_s^*\ D_s^* \to \phi\phi X$ which is predominantly a CP–even decay. They find $\tau(B_s^{short})$ = 1.27 $\pm$ 0.33 $\pm$ 0.07 ps which corresponds to $\Delta\Gamma_s/\Gamma_s = 0.45\ ^{+0.80}_{-0.49}$.

The combination of the various results consists in constructing the bi–dimensional global likelihood as a function of $\Delta\Gamma_s/\Gamma_s$ and $1/\Gamma_s$. Using all $B_s \to D_s^- \ell^+ \nu X$ lifetime measurements, the DELPHI $B_s \to D_s^-\ h^+\ X$ study, the ALEPH $B_s \to \phi\phi X$ study and the CDF $B_s \to J/\psi\phi$ lifetime, with the additional lifetime constraint, one obtains (see Fig. 8) $\Delta\Gamma_s/\Gamma_s = 0.16\ ^{+0.08}_{-0.09}$, ($< 0.31$ at 95% CL).

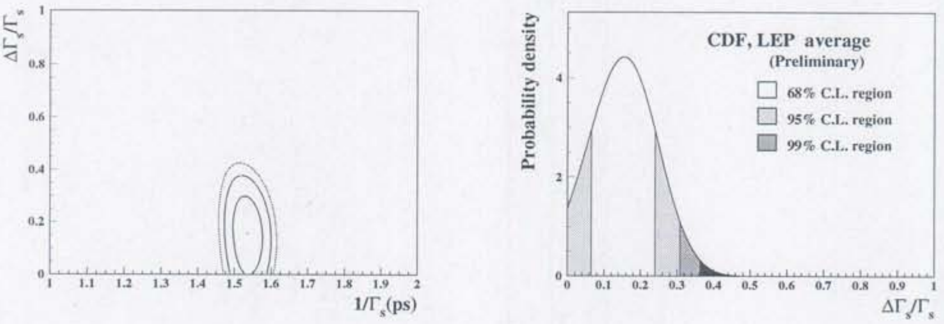

Figure 8: Bi–dimensional global likelihood function and probability density distribution for $\Delta\Gamma_s/\Gamma_s$.

5 Summary and outlook.

A lot of work on B physics has been done at LEP in the last few years; LEP1 is still very active and many results are going to be published soon. The next major steps will come from B factories and from Tevatron run II.

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