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HEAVY FLAVOUR PHYSICS RESULTS FROM LEP 1

O. SCHNEIDER

Institut de Physique des Hautes Energies,
Université de Lausanne, CH-1015 Lausanne, Switzerland
e-mail: Olivier.Schneider@iphe.unil.ch

Recent heavy flavour results from the LEP experiments are presented. These include a search for new physics in rare B decays, a new model-independent measurement of the b-quark fragmentation function at the Z peak, updated measurements of $|V_{cb}|$, results on $\Delta\Gamma_s$, searches for B_s^0 oscillations, as well as a new measurement of $\sin(2\beta)$. Many combined results, obtained by dedicated working groups, are also given. The LEP measurements of V_{cb} from $B^0 \to D^{*-}\ell^+\nu$ decays average to $|V_{cb}| = (39.7 \pm 3.0) \times 10^{-3}$, while inclusive measurements yield $|V_{cb}| = (40.8 \pm 2.0) \times 10^{-3}$ dominated by theoretical uncertainties. Charmless semileptonic decays have been observed inclusively, $\mathrm{BR}(b \to u\ell^-\bar{\nu}) = (1.67 \pm 0.55) \times 10^{-3}$, corresponding to $|V_{ub}| = (4.04^{+0.62}_{-0.74}) \times 10^{-3}$. Significant progress has been made in the B_s^0 sector, where the width difference is now close to being measured with a combined result of $\Delta\Gamma_s/\Gamma_s = 0.24^{+0.16}_{-0.12}$ or $\Delta\Gamma_s/\Gamma_s < 0.53$ at 95% CL. However, despite continuing improvements, Δm_s is still unmeasured, with a lower limit of 14.6 ps^{-1} at 95% CL. Improved heavy flavour results are expected from LEP by Summer 2000. The current status of electroweak heavy flavour physics is summarized in another presentation.

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It is not possible to review here all the heavy flavour results produced by the ALEPH, DELPHI, L3 and OPAL experiments based on their LEP 1 data, taken until 1995 at an e^+e^- center-of-mass energy equal or close to the Z mass. Although the peak activity of LEP 1 analysis is behind us, these data are still being analyzed, producing new and improved measurements.

The focus of this presentation is on new or updated b-physics results released since the 1999 Summer Conferences, as well as on the latest averages produced by various LEP heavy flavour working groups.[1] Many of these results can be related to the magnitude of the least well known CKM matrix elements $|V_{cb}|$, $|V_{ub}|$, $|V_{td}|$ and $|V_{ts}|$, which are in turn related to the lengths of the sides of the CKM unitarity triangle. These measurements will be (together with the forthcoming results from the B factories and the Tevatron) important ingredients of future tests of the CKM picture within the Standard Model, where an inconsistency may indeed be an indirect indication of new physics.

New physics may also be responsible for unexpectedly high branching ratios in rare B decays involving flavour-changing neutral currents. For example the branching ratio of the decay $B \to K^-K^-\pi^+$, for which the OPAL collaboration has recently released[2] an upper limit of 1.29×10^{-4} at 90% CL, is predicted to be 10^{-11} at most in the Standard Model (box diagram) but is practically unconstrained in certain supersymmetric models with R-parity violation (tree diagram possible).

1 b-fragmentation studies

Understanding the production of b-hadrons in Z decays is important for many heavy flavour analyses. The b-quark hadronisation can be described in terms of the variable $x_E = E_{b\text{-hadron}}/E_{\text{beam}}$, the fraction of the beam energy retained by the weakly-decaying b-hadron produced in a b jet. Being not known accurately, the distribution of x_E is simulated by the LEP experiments using the JETSET generator together with phenomenological models that relate the energy of the b-hadron with that of the initial b-quark. The most commonly used of these models, from Peterson et al., relies on a single parameter which has merely been tuned to reproduce the experimental spectra of high transverse momentum leptons originating mostly from the decay $b \to c\ell^-\bar{\nu}$. This tuning corresponds to a mean x_E of $\langle x_E \rangle = 0.702 \pm 0.008$, which is the value recommended up to now for heavy flavour analyses at LEP.[3]

The ALEPH collaboration has submitted to this conference a new measurement[4] of the shape of the x_E distribution (see Fig. 1) based on approximately 3000 $B \to D^*l\nu$ decays, where the B meson energy has been estimated in a model-independent way from an identified lepton, a fully reconstructed D^* meson and missing energy information. The energy spectrum is found to be somewhat harder than assumed before, with $\langle x_E \rangle = 0.7198 \pm 0.0045_{\text{stat}} \pm 0.0053_{\text{syst}}$, consistent with a previous ALEPH measurement. This confirms a recent result from SLD,[5] $\langle x_E \rangle = 0.714 \pm 0.005_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.002_{\text{model}}$, which has small model-dependent systematics, although based on an inclusive sample of b-hadrons.

These direct measurements of the shape of the x_E distribution have now sufficient precision to envisage tests of the b-fragmentation model predictions and to discriminate amongst these models for the first time. For example, both ALEPH and SLD data favour the description of Kartvelishvili et al. over the one from Peterson et al.

2 Measurements of $|V_{cb}|$ and $|V_{ub}|$

The study of the $B^0 \to D^{*-}\ell^+\nu$ decay kinematics allows the extraction of $|V_{cb}|$. The differential decay rate as a function of the boost ω of the D^{*-} in the B^0 rest frame is predicted by the Heavy Quark Effective Theory to be

$$\frac{d\Gamma}{d\omega} = \mathcal{K}(\omega)\mathcal{F}^2_{D^*}(\omega)|V_{cb}|^2\,, \tag{1}$$

where $\mathcal{K}(\omega)$ is a known phase-space function and $\mathcal{F}_{D^*}(\omega)$ a single form factor which, in the heavy quark limit, is equal to unity at zero recoil. The interesting observable is thus the decay rate at zero recoil, but since the phase space vanishes at $\omega = 1$, the quantity $\mathcal{F}_{D^*}(1)|V_{cb}|$ must be extracted from an extrapolation of the measured differential rate at $\omega > 1$. At LEP, this extrapolation relies on a specific parametrization[6] of the shape of $\mathcal{F}_{D^*}(\omega)$ in terms of the slope ρ^2 at $\omega = 1$.

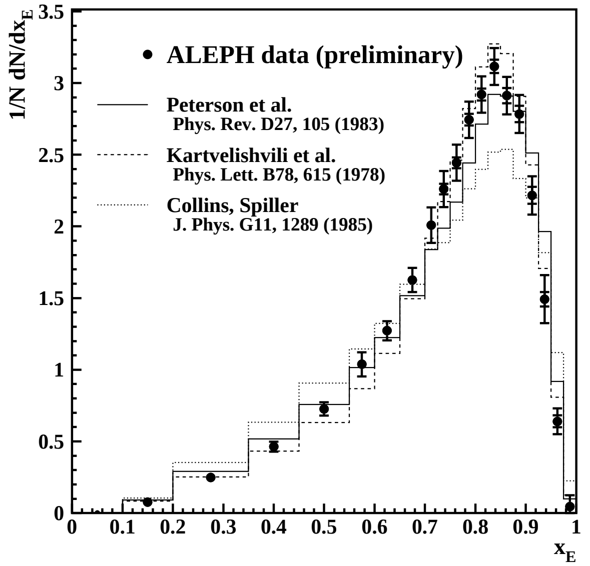

Figure 1: x_E distribution of $B \to D^* l\nu$ mesons measured by ALEPH[4] compared with predictions from various b-fragmentation models fitted to the data.

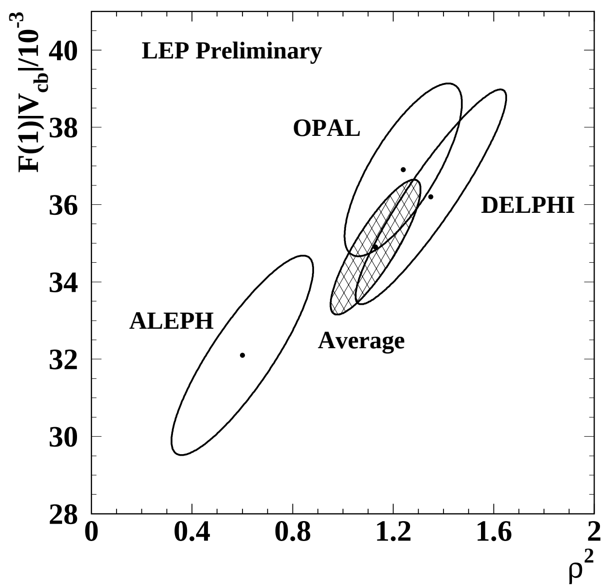

Figure 2: LEP measurements of $\mathcal{F}_{D^*}(1)|V_{cb}|$ and ρ^2 from $B^0 \to D^{*-}\ell^+\nu$ decays, and their average. The error ellipses (39% CL) include systematic uncertainties.

The OPAL collaboration has recently updated their result obtained with fully reconstructed decays and performed a new analysis[7] based on an inclusive D^{*-} reconstruction relying on the identification of the slow pion from the D^{*-} decay. Their new combined result is displayed on Fig. 2, together with earlier and similar measurements from ALEPH and DELPHI. A combination of these results, performed by the LEP V_{cb} working group,[1] takes into account all correlations and yields

$$\mathcal{F}_{D^*}(1)|V_{cb}| = (34.9 \pm 0.7 \pm 1.6) \times 10^{-3} \quad \text{and} \quad \rho^2 = 1.13 \pm 0.08 \pm 0.16 \,. \tag{2}$$

Systematic uncertainties are dominated by the limited knowledge of the D^* recoil spectrum for $B \to D^*\ell\nu X$ background events. With $\mathcal{F}_{D^*}(1) = 0.88 \pm 0.05$ from theoretical calculations taking into account finite quark masses and QCD corrections,[8] this leads to the combined LEP estimate $|V_{cb}| = (39.7 \pm 0.8_{\text{stat}} \pm 1.8_{\text{syst}} \pm 2.2_{\text{theory}}) \times 10^{-3}$ from exclusive decays.

Current theoretical calculations based on heavy quark symmetry relate $|V_{cb}|$ and $|V_{ub}|$ to the inclusive $b \to c\ell^-\bar{\nu}$ and $b \to u\ell^-\bar{\nu}$ decay widths,

$$|V_{cb}| = 0.0411\sqrt{\frac{\text{BR}(b \to c\ell^-\bar{\nu})}{0.105}}\sqrt{\frac{1.55\ \text{ps}}{\tau_b}} \quad \text{and} \quad |V_{ub}| = 0.00445\sqrt{\frac{\text{BR}(b \to u\ell^-\bar{\nu})}{0.002}}\sqrt{\frac{1.55\ \text{ps}}{\tau_b}}\,, \tag{3}$$

with total uncertainties estimated to be $\sim 5\%$.[8] While the measurements of the inclusive $b \to \ell^-$ branching ratio and b-hadron lifetime are well established since several years, with current averages[8] of $\text{BR}(b \to \ell^-) = (10.58 \pm 0.07 \pm 0.17)\%$ and $\tau_b = 1.564 \pm 0.014$ ps, analyses measuring the $b \to u\ell^-\bar{\nu}$ branching ratio are quite recent and unique to LEP. They face the difficulty of dealing with a very large $b \to c\ell^-\bar{\nu}$ background, but have the advantage to be sensitive to the whole lepton spectrum (rather than only to the its end-point where the $b \to c\ell^-\bar{\nu}$ decays are supressed). L3, ALEPH, and DELPHI have now all published evidence for $b \to u\ell^-\bar{\nu}$ transitions, and their measurements average to[8] $\text{BR}(b \to u\ell^-\bar{\nu}) = (1.67 \pm 0.36 \pm 0.37 \pm 0.20) \times 10^{-3}$, where the first uncertainty summarizes statistics and experimental systematics, the second uncertainty reflects the limited knowledge of $b \to c\ell^-\bar{\nu}$ transitions, and the third one results from the modelling of $b \to u\ell^-\bar{\nu}$. Using Eq. 3, the LEP averages from inclusive semileptonic b decays are $|V_{cb}| = (40.8 \pm 0.4_{\text{exp}} \pm 2.0_{\text{theory}}) \times 10^{-3}$ and $|V_{ub}| = (4.04^{+0.62}_{-0.74}) \times 10^{-3}$. The former can be combined[1] with the less precise but consistent LEP estimate from exclusive decays to yield $|V_{cb}| = (40.5 \pm 1.8) \times 10^{-3}$.

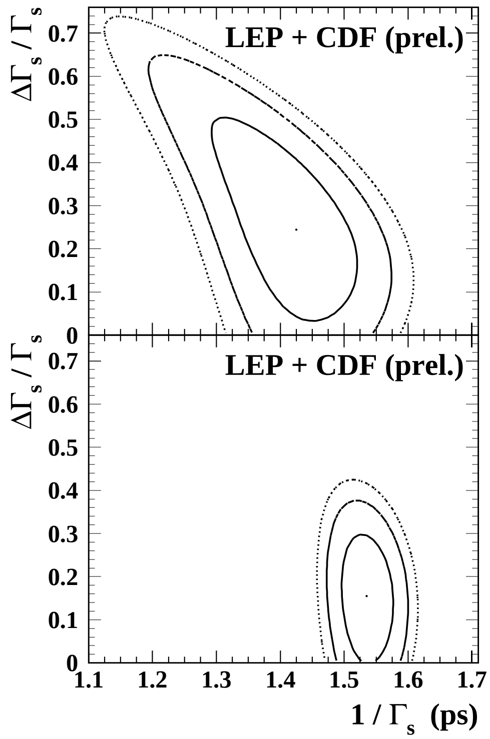

Figure 3: Combined 68%, 95% and 99% CL contours in the plane $(1/\Gamma_s, \Delta\Gamma_s/\Gamma_s)$.[8] The top (bottom) plot is obtained without (with) the constraint $1/\Delta\Gamma_s = \tau_{B^0}$.

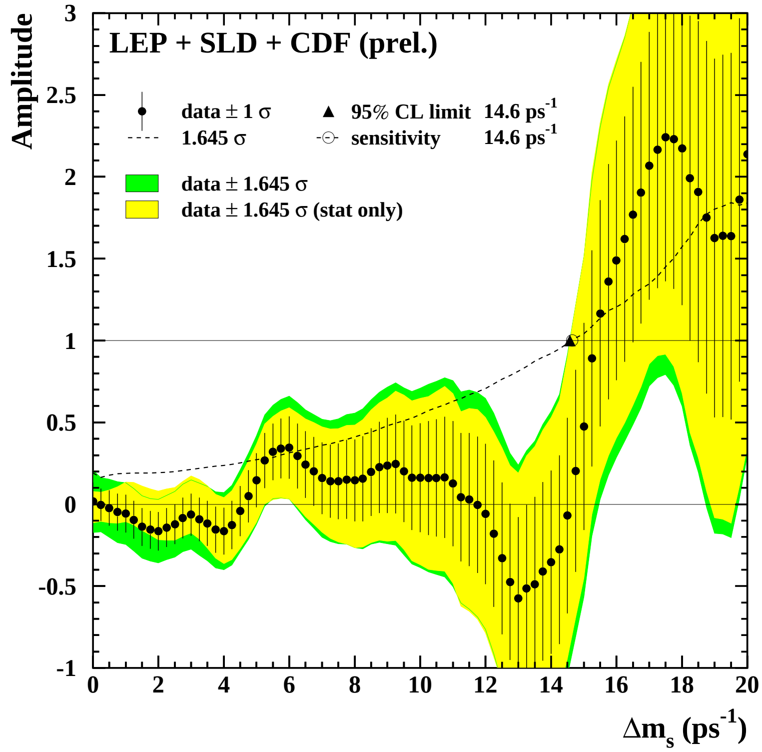

Figure 4: Combined measurements of the B_s^0 oscillation amplitude as a function of Δm_s, obtained by the LEP B oscillations working group.[1] The measurements are dominated by statistical uncertainties. Neighbouring points are statistically correlated.

3 Results on the B_s^0 decay width difference

Information on $\Delta\Gamma_s$, the decay width difference between the two mass eigenstates of the B_s^0–$\bar{B}_s^0$ system, can be obtained by studying the proper time distribution of untagged data samples enriched in B_s^0 mesons. In the case of an inclusive or a semileptonic B_s^0 decay selection, both the short- and long-lived components are present, and the proper time distribution is a superposition of two exponentials with decay constants $\Gamma_s \pm \Delta\Gamma_s/2$. In principle, this provides sensitivity to both Γ_s and $(\Delta\Gamma_s/\Gamma_s)^2$. Ignoring $\Delta\Gamma_s$ and fitting for a single exponential leads to an estimate of Γ_s with a relative bias proportional to $(\Delta\Gamma_s/\Gamma_s)^2$. An alternative approach, which is directly sensitive to first order in $\Delta\Gamma_s/\Gamma_s$, is to determine the lifetime of B_s^0 candidates decaying to CP eigenstates; measurements exist for $B_s^0 \to J/\psi\phi$,[9] and now also for $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$,[10] which are predicted to be mostly CP-even states. Recently, ALEPH has also obtained for the first time an estimate of $\Delta\Gamma_s/\Gamma_s$ directly from a measurement of the $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ branching ratio,[10] under the assumption that these decays practically account for all the CP-even final states.

Figure 3 shows confidence contours in the plane $(1/\Gamma_s, \Delta\Gamma_s/\Gamma_s)$ obtained from a combined likelihood built with all the available information from LEP and CDF, including dedicated $\Delta\Gamma_s$ studies as well as B_s^0 lifetime measurements. The corresponding results for $\Delta\Gamma_s/\Gamma_s$ are[8]

$$\Delta\Gamma_s/\Gamma_s = 0.24^{+0.16}_{-0.12} \quad \text{or} \quad \Delta\Gamma_s/\Gamma_s < 0.53 \quad \text{at 95\% CL} \tag{4}$$

without external constraint, and

$$\Delta\Gamma_s/\Gamma_s = 0.17^{+0.09}_{-0.10} \quad \text{or} \quad \Delta\Gamma_s/\Gamma_s < 0.31 \quad \text{at 95\% CL} \tag{5}$$

when constraining $1/\Gamma_s$ to the current world average of the B^0 lifetime. Such a constraint is well motivated theoretically, since the B^0 and B_s^0 decay widths are predicted to differ by $\sim 1\%$ at most,

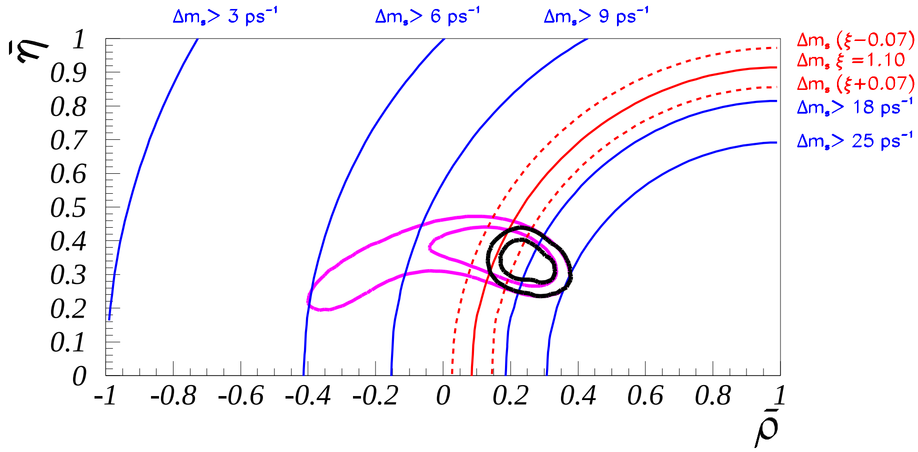

Figure 5: Results of two different CKM fits shown in the $(\bar{\rho}, \bar{\eta})$ plane, using the Wolfenstein parametrization. The two dark closed curves represent the 68% and 95% CL contours obtained using the procedure and assumptions of Caravaglios et al.[14] with $\Delta m_d = 0.484 \pm 0.015$ ps and the Δm_s results of Fig. 4. The two lightest closed curves are the result of the same fit, except that the experimental information on Δm_s is ignored. The circles centered on (1,0) indicate the constraints corresponding to various values of Δm_s, with the hadronic uncertainty indicated as the dashed band.

but the current experimental check of this assumption, $\tau_{B_s^0}/\tau_{B^0} = 0.937 \pm 0.040$,[8] is still of limited precision. These combined results on $\Delta\Gamma_s/\Gamma_s$ are not yet precise enough to test the Standard Model predictions, which typically lie between 5% and 20%.

4 Search for B_s^0 oscillations

B_s^0–$\bar{B}_s^0$ oscillations have been the subject of many studies from ALEPH, DELPHI and OPAL, as well as SLD and CDF. No oscillation signal has been found so far. Because of the limited statistics available, the most sensitive analyses are currently the ones based on inclusive lepton samples, and on samples where a lepton and a D_s meson have been reconstructed in the same jet. However, with larger samples, the most promising approach would be to use fully reconstructed B_s^0 mesons, which have a much better proper time resolution suitable to resolve higher oscillation frequencies.

DELPHI[11] have fully reconstructed 44 B_s^0 candidates in the $\bar{D}^0 K^- \pi^+$, $\bar{D}^0 K^- a_1^+$, $D_s^{(*)-}\pi^+$ and $D_s^{(*)-}a_1^+$, channels, whereas ALEPH have recently reported 50 candidates in the latter two channels. The number of signal events is estimated to be ~ 20 in each experiment, but with a proper time resolution of ~ 0.08 ps, more than two times better compared to more inclusive selections. As a result, these analyses, which have very poor sensitivity by themselves due to the lack of statistics, do nonetheless have a non-negligible impact on the average measurement of the oscillation amplitude $\mathcal{A}$ at high values of Δm_s, the mass difference between the two mass eigenstates of the B_s^0 system.

All results have been combined, including the latest ones from ALEPH[12] released for this conference and based on $D_s^- \ell^+$ correlations and fully reconstructed B_s^0 candidates, to yield the amplitudes $\mathcal{A}$ shown in Fig. 4 as a function of Δm_s. In the combination procedure,[8] the sensitivities of the inclusive lepton analyses, which depend directly on the assumed fraction $f_{B_s^0}$ of B_s^0 mesons in an unbiased sample of weakly-decaying b hadrons, have been rescaled to a common value of $f_{B_s^0} = 0.096 \pm 0.012$. This value is obtained from direct production measurements, measurements of the time-integrated mixing probability $\bar{\chi}$ of b-hadrons at LEP, as well as the new world average of the B^0 oscillation frequency, $\Delta m_d = 0.484 \pm 0.015$ ps. The combined sensitivity for 95% CL exclusion of Δm_s values is found to be 14.6 ps^{-1}, which is also the actual limit below which all values of Δm_s are excluded by the data at 95% CL. No oscillation signal can be claimed based on the deviation from $\mathcal{A} = 0$ seen in Fig. 4 around 17 ps^{-1}: a fast Monte Carlo study[13] shows indeed that statistical fluctuations can produced a more significant deviation (anywhere in the explored range in Δm_s) in $\sim 3\%$ of the samples generated with a very large true value of Δm_s.

The information on $|V_{ts}|$ obtained, in the framework of the Standard Model, from the combined Δm_s limit is hampered by the hadronic uncertainty, as is the case when extracting $|V_{td}|$ from Δm_d.

However, many uncertainties cancel in the frequency ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B^0_s}}{m_{B^0}} \, \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 , \qquad (6)$$

where ξ is currently known to $\sim 6\%$ from lattice QCD. This relation can be used in fits of the CKM matrix, together with the experimental results on Δm_s, Δm_d, $|V_{ub}/V_{cb}|$ and ϵ_K, as well as theoretical inputs and unitarity constraints. Examples of such fits,[14] shown in Fig. 5, illustrate the fact that the combined Δm_s results from Fig. 4 provide, together with the measured value of Δm_d, a significant constraint on the CKM matrix, favouring positive values of the Wolfenstein parameter ρ.

5 CP violation in $B^0 \to J/\psi K^0_S$ decays

ALEPH has recently released a new measurement[15] of the CP asymmetry in $B^0, \bar{B}^0 \to J/\psi K^0_S$ decays,

$$A(t) = \frac{N_{B^0}(t) - N_{\bar{B}^0}(t)}{N_{B^0}(t) + N_{\bar{B}^0}(t)} = -\sin(2\beta)\sin(\Delta m_d\, t) \, , \qquad (7)$$

where $N_{B^0}(t)$ and $N_{\bar{B}^0}(t)$ are the number of events produced as B^0 and $\bar{B}^0$ as a function of the proper time t, and β is one of the angles of the CKM unitarity triangle. From a sample of 23 fully reconstructed candidates, selected with a signal efficiency of $(28 \pm 2)\%$ and an estimated purity of $(71 \pm 12)\%$, ALEPH measures $\sin(2\beta) = 0.93^{+0.64}_{-0.88}(\text{stat})^{+0.36}_{-0.24}(\text{syst})$. The systematic uncertainty is dominated by the limited knowledge of the probability of mistagging the initial state, measured to be $(25 \pm 6)\%$ using $B^{\pm} \to J/\psi K^{\pm}$ events. This $\sin(2\beta)$ result can be combined with previous measurements from OPAL and CDF to yield[15] $\sin(2\beta) = 0.91 \pm 0.35$ or $\sin(2\beta) > 0$ at 98.5% CL, increasing the confidence that CP violation has been observed in the B sector.

Acknowledgments

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