B physics at LEP

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Abstract

A personal and extremely brief description is given of some areas of B physics where LEP has made a significant contribution.

1 Introduction

The LEP accelerator at CERN, with its experiments ALEPH, DELPHI, L3 and OPAL, has provided a wealth of experimental data over the years, especially in the field of B physics.

Since the Z^0 boson is produced at rest in a collider like LEP, the two quarks produced in the decay are emitted back-to-back, giving two well separated jets. Thanks to the large mass of the Z^0, the B hadrons are also given a substantial boost, thus they fly on average 2 mm before decaying. This, together with the fact that the development of silicon microvertex detecors took place about at the time when LEP was starting up, has placed the LEP experiments in leading positions in key areas of B physics.

Over the years from 1989 until 1995, when LEP was tuned towards higher energies, the four experiments collected about 1.6 million B hadron events each.

This talk will describe some of the b physics areas where LEP experiments have played, and largely still plays, an important rôle. Given the limited space, the description will necessarily be incomplete.

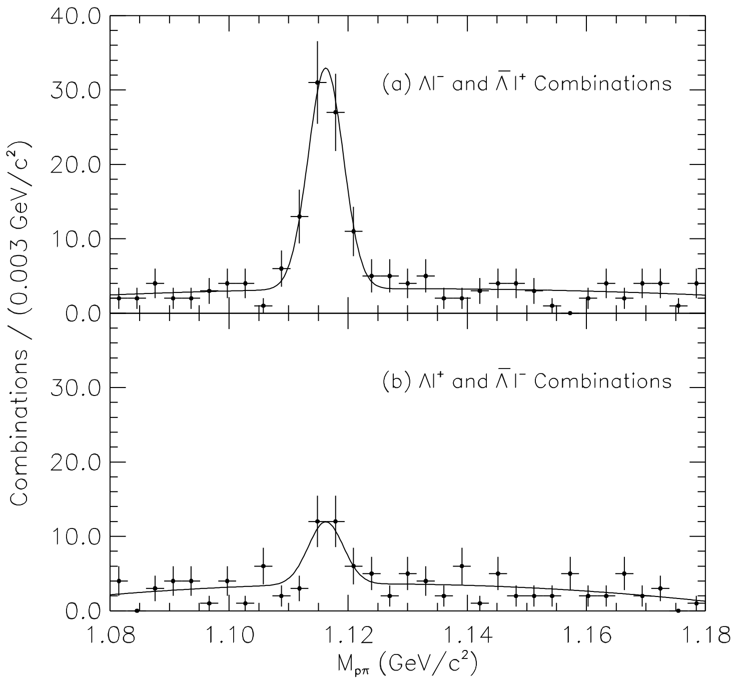


Figure 1: ALEPH's first sighting of the Λ_b.

2 B baryons

In 1991 the first convincing signal of the Λ_b baryon was first seen by ALEPH [1] (fig. 1, left) when combining Λ with a high-p_T lepton of proper charge. Since then the Λ_b has been extensively studied, and *e.g.* the current world average for the Λ_b lifetime is 1.229 ± 0.08 ps, a remarkable precision. In 1993 DELPHI managed to see the first sign of the beauty strange Ξ_b baryon by combining $\Xi \to \Lambda\pi^-$ candidates with a high-p_T lepton [2]. This has later been complemented in a new analysis, yielding $\tau(\Xi_b^{0,-}) = 1.48^{+0.40}_{-0.31} \pm 0.12$ ps [3]. The HFAG world average (Winter 2004) is $\tau(\Xi_b^{0,-}) = 1.39^{+0.34}_{-0.28}$ ps [4], without the new DELPHI result.

3 B hadron lifetimes

B lifetime measurements are an important handle on B decay dynamics. Calculations of B hadron lifetimes involve not only the straight-forward spectator

Ratio	Experiments	Prediction, range
$\tau(B)/\tau(B^0)$	1.086 ± 0.017	1.0 — 1.1
$\tau(B_s)/\tau(B^0)$	0.951 ± 0.038	0.99 — 1.01
$\tau(\Lambda_b)/\tau(B^0)$	0.800 ± 0.052	0.9 — 1.0
$\tau(b\ baryon)/\tau(B^0)$	0.786 ± 0.034	0.9 — 1.0

Table 1: Comparison between B lifetime ratios and theoretical predictions, from HFAG winter 2004.

diagram, but also interference between spectator and decay products in case they contain identical quarks, W exchange diagrams and also in some cases annihilation diagrams.

The current (Winter 2004) world average B lifetimes are [4]:

$$\begin{aligned} \tau(B_d^0) &= (1.536 \pm 0.014)ps \\ \tau(B^+) &= (1.671 \pm 0.018)ps \\ \tau(B_s^0) &= (1.461 \pm 0.057)ps \\ \tau(\Lambda_B) &= (1.229 \pm 0.080)ps \\ \tau(b\ baryon) &= (1.208 \pm 0.051)ps \end{aligned}$$

Comparing the B lifetime measurements with theory, table 1, it is clear that theory fails to predict the magnitude of the ratios between the different B hadrons, although the hierarchy is about right.

4 CKM parameters

In the Standard Model, weak and mass eigenstates are different and the CKM matrix has been introduced to parametrize this transformation. This matrix can be parametrized using three real numbers and one phase which cannot be transformed away. This phase leads to CP violation in the weak decay. Several parametrizations exist, and one commonly used is the one proposed by Wolfenstein, which can be expressed as

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \quad (1)$$

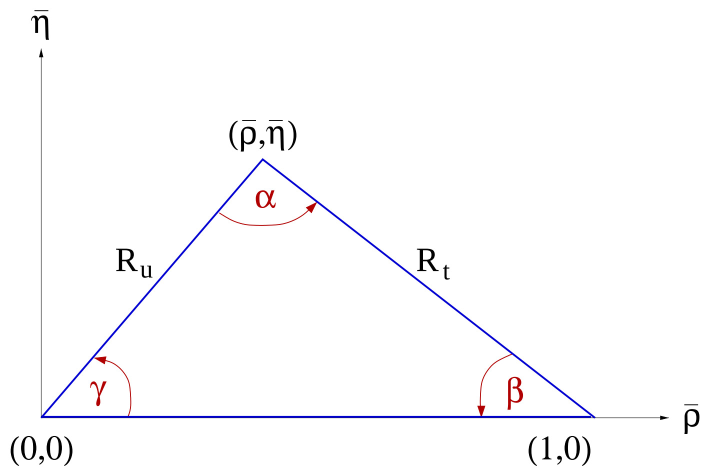


Figure 2: The Unitary Triangle in the $(\overline{\rho}, \overline{\eta})$ plane.

$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where η is the CP violating phase.

From the unitarity of the CKM matrix one can see that

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0 \tag{2}$$

which, by defining $\overline{\rho} = \rho(1 - \frac{\lambda^2}{2})$ and $\overline{\eta} = \eta(1 - \frac{\lambda^2}{2})$ can be expressed graphically as a triangle with corners at (0,0), (1,0) and $(\overline{\rho}, \overline{\eta})$, see fig. 2.

LEP experiments have contributed in constraining the Unitary Triangle doing measurements of

- V_{ub} in semileptonic decays,
- V_{cb} in inclusive and exclusive semileptonic b-decays,
- Δm_d from time dependent B^0 oscillations, and
- limits on Δm_d.

Examples of some of the later results in these areas will be given below.

4.1 V_{ub} and V_{cb}

The length of the left-hand-side of the Unitary Triangle (fig. 2) is given by

$$R_u = \frac{(1-\lambda^2)|V_{ub}|}{\lambda|V_{cb}|}. \quad (3)$$

$|V_{ub}|$ has been measured at LEP using inclusive spectra in $b \rightarrow u$ enriched semileptonic decays. However, the LEP measurements have already been superseeded by more precise measurements from BaBar and Belle.

In measurements of $|V_{cb}|$ using $\overline{B_d^0} \rightarrow D^{*+}l^-\overline{\nu_l}$ LEP is still competitive, though. The differential cross section for this decay can be written

$$\frac{d\Gamma(\overline{B} \rightarrow D^* l^- \overline{\nu})}{d\omega} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 F^2(\omega)K(\omega). \quad (4)$$

Here ω is defined as the product of the 4-velocities of the B and the D^* mesons:

$$\omega = v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}} \quad (5)$$

where q^2 is the mass of the charged lepton-neutrino system. $F(\omega)$ is a form factor and $K(\omega)$ is a kinematical factor. At $q^2 = q^2_{max}$, corresponding to $\omega = 1$, the D^* is produced at rest in the B rest frame and HQET can be used to obtain the value for the form factor $F(\omega = 1)$.

Expanding the form factor around $\omega = 1$ one can write:

$$F(\omega) = F(1)[1 - \rho^2(\omega - 1) + O(\omega - 1)^2]. \quad (6)$$

Experimentally one fits simultaneously $F(1) \cdot |V_{cb}|$ and ρ^2, from the shape of a distribution like in fig. 3, left, in this case yielding a value of $F(1) \cdot |V_{cb}| = (37.7 \pm 1.1 \pm 1.9) \cdot 10^{-3}$ and $\rho^2 = 1.39 \pm 0.10 \pm 0.33$ [5]. A summary of the spring 2004 world data can be seen in fig 3, right [6]. The world averages are $F(1) \cdot |V_{cb}| = (36.5 \pm 0.8) \cdot 10^{-3}$ and $\rho^2 = 1.47 \pm 0.13$.

4.2 Oscillations

B^0 states can oscillate into $\overline{B^0}$ states and vice versa through box diagrams shown in fig. 4. The oscillation frequency Δm_q is proportional to $|V_{tq}|^2$:

$$\Delta m_q = \frac{G_F^2}{6\pi^2}\eta_B S(m_t^2/m_W^2) m_t^2 m_{B_q} B_{B_q} f_{B_q}^2 |V_{tb}|^2 |V_{tq}|^2. \quad (7)$$

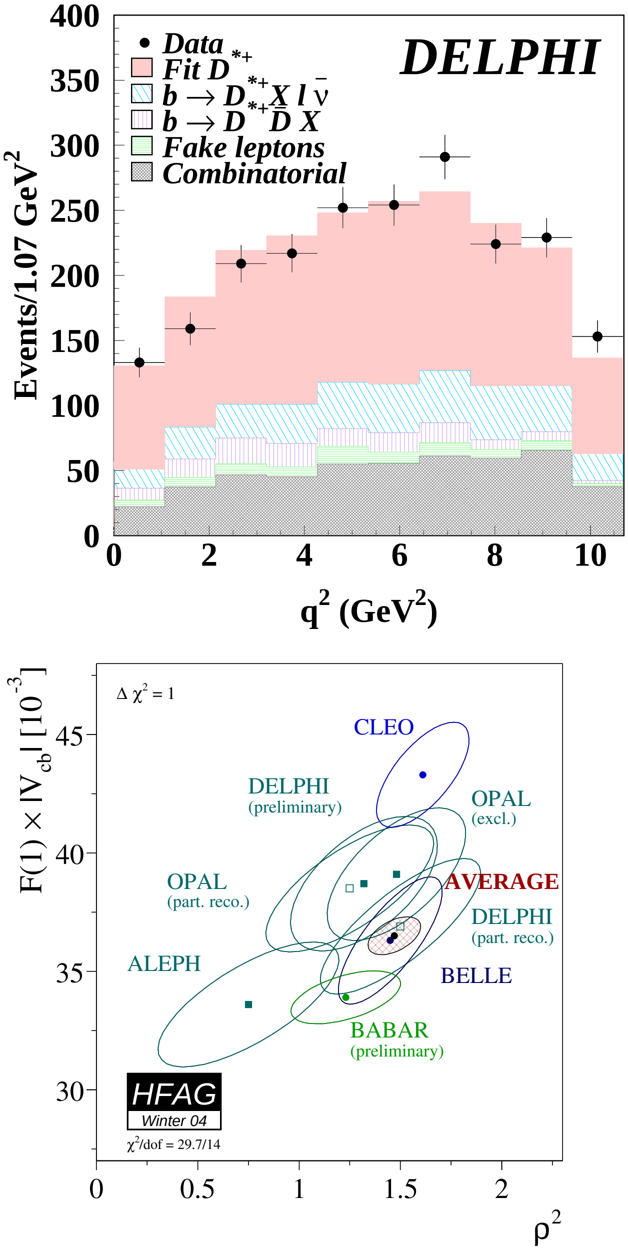


Figure 3: Left: Example of an experimental q^2 distribution (DELPHI) [5]. Right: World data on $F(1) \cdot |V_{cb}|$ and ρ^2 [6].

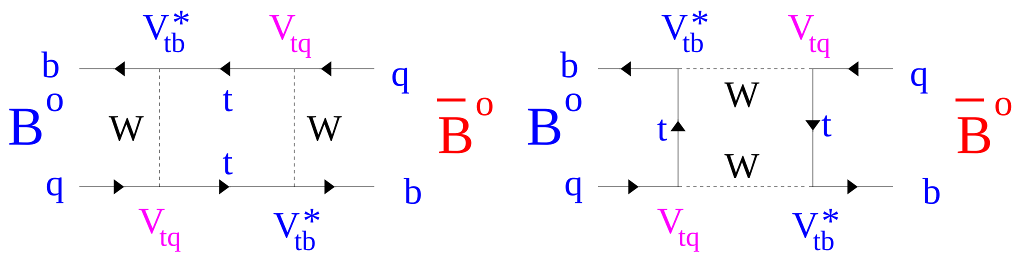


Figure 4: $B - \overline{B}$ mixing diagrams.

Here G_F is the Fermi coupling constant, and $S(m_t^2/m_W^2)$ can be calculated from the box diagram, fig. 4. η_B is a correction factor obtained at next to leading order in perturbative QCD with a relatively small error. The largest theoretical uncertainties come from the non-perturbative QCD corrections $f_{B_q}^2$ and B_{B_q}. However, these uncertainties largely cancels when looking instead at the ratio $|\Delta m_d|/|\Delta m_s|$. This quantity measures the length of the right-hand-side of the Unitary Triangle (fig. 2)

$$R_t = \frac{|V_{td}|}{\lambda |V_{ts}|}. \tag{8}$$

4.2.1 B_d^0 oscillation

Experimentally B_d^0 oscillation is measured as follows. The flavour of the B_d^0 at production is tagged by looking at the flavour of the B in the opposite hemisphere, assuming there is no oscillation there (*e.g.* by using a charged B meson for tagging). The flavour of the B_d^0 at decay is found by looking at the decay products, and finally the decay time is measured from the displacement of the decay vertex w.r.t. the production vertex. A fit is then made using the likelihood function:

$$\Pr(B_d^0 \to \overline{B_d^0})(t) = \frac{1}{2} e^{-t/\tau(B_d^0)} (1 - \cos \Delta m_d t), \tag{9}$$

where $\tau(B_d^0)$ is the proper lifetime of a given B_d^0, and Δm_d is the sought oscillation frequency. ALEPH was the first experiment to perform this direct measurement of Δm_d, in 1993. Since then a large number of analyses have been performed by all LEP collaborations, as well as others. The "final" LEP average is $\Delta m_d = 0.494 \pm 0.014 ps^{-1}$, whereas the world average

$$\Delta m_d = 0.502 \pm 0.007 ps^{-1}$$

is now dominated by the B factories [4].

4.2.2 B_s^0 oscillation

From equations (1) and (7) it can be seen that

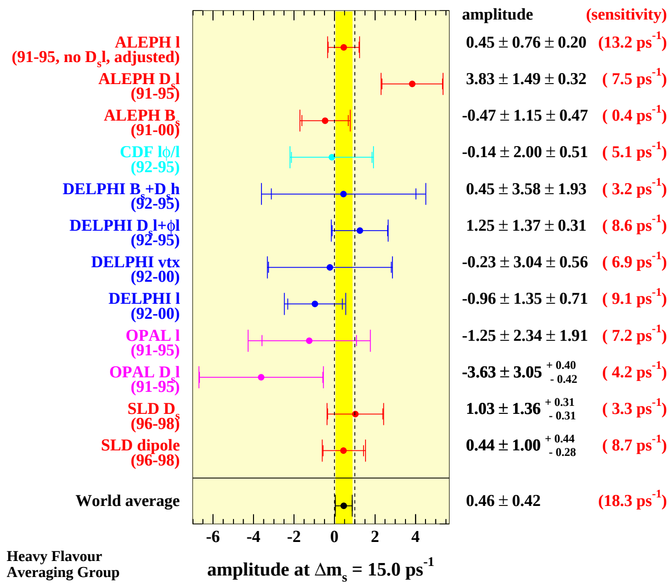
$$\frac{\Delta m_d}{\Delta m_s} \sim \lambda^2 \sim 0.05, \tag{10}$$

hence the oscillation time in the B_s^0 system is much shorter than for the B_d^0. Furthermore the B_s^0 production rate is rather low. Therefore one has changed the analysis technique in order to be able to combine measurements from several channels and/or experiments, in order to achieve maximum sensitivity. This is done by modifying the likelihood of eq. (9) by adding an amplitude A, thus:

$$\Pr(B_s^0 \rightarrow \overline{B_s^0})(t) = \frac{1}{2} e^{-t/\tau(B_s^0)}(1 - A \cos \Delta m_s t). \tag{11}$$

The amplitude A is then measured at fixed values of Δm_s, and then averaged over all channels/experiments, fig. 5 left. The amplitude measurements are then plotted as a function of Δm_s, see fig. 5, right. A true oscillation signal would show up as a significant peak compatible with $A = 1$. The dashed curve corresponds to the size of the error, thus it crosses $A = 1$ at the sensitivity limit. In the absence of a clear signal a lower limit for Δm_s is inferred at the point where $A + \sigma(A) = 1$. Note that the errors have been multiplied by 1.645 in order to extract directly the 95% confidence level values. As shown in the figure the winter 2004 world average lower limit was $\Delta m_s < 14.5$ ps^{-1} at 95% confidence level and the sensitivity limit was 18.3 ps^{-1} [4]. The peak around 18 ps^{-1} is only about 1.7 σ, so no claim for a measurement has been made. The limit obtained from LEP measurements alone was $\Delta m_s < 11.5$ ps^{-1} at 95% confidence level and the sensitivity 16.9 ps^{-1} [4].

Over the years there has been an impressive increase in the Δm_s sensitivity, from about 6 ps^{-1} in 1995 when LEP I had just finished datataking, to the present sensitivity. A large part of this increase is due to improved analyses tools and better understanding of data.



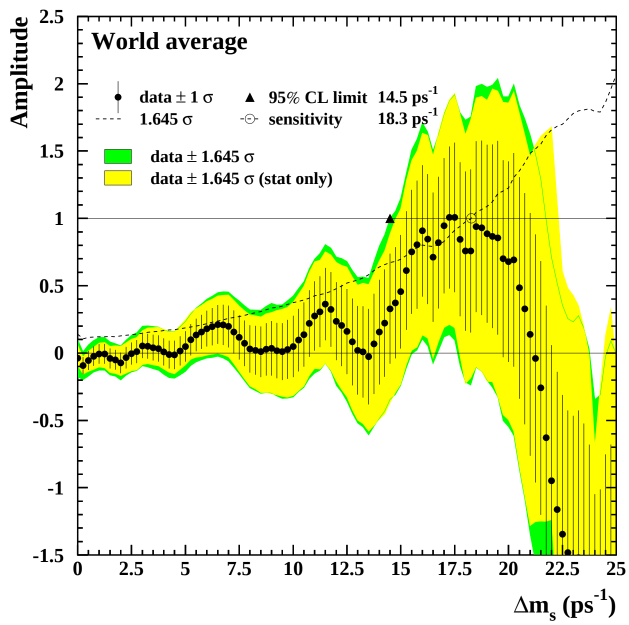


Figure 5: Left: Average oscillation amplitude at $\Delta m_s = 15.0\text{ps}^{-1}$. Right: Amplitude vs. Δm_s, world average as of spring 2004.

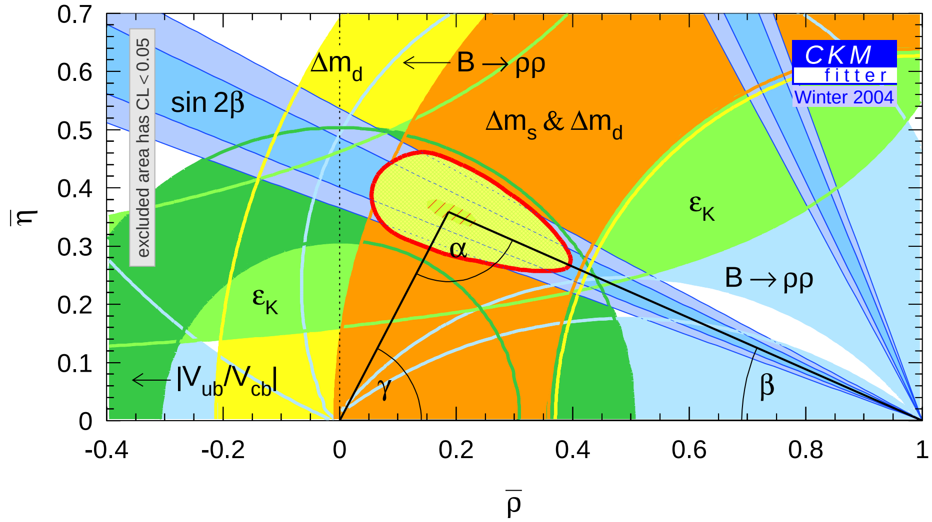


Figure 6: Unitary triangle fit to world data.

4.3 Unitary triangle fit

For completeness, the current unitary triangle fit to world data is given in figure 6 [7]. The 95% confidence level contour is outlined[1].

5 Fragmentation functions

The development of a $b\bar{b}$ quark pair into stable particles that enter a detector, can be loosely split into three stages: In the first ('perturbative') stage, the b-quarks radiate gluons which in turn may split into $q\bar{q}$ or gg pairs. The second stage concerns the fragmentation of the quarks into colourless hadronic states and is not calculable within perturbation theory. This stage must therefore be phenomenologically modelled along with the third phase, which describes the prompt decay of excited states and of longer-lived weakly decaying states into stable particles.

Various models of the fragmentation process have been incorporated into simulation packages in the past with varying degrees of success in accurately reproducing the data. In practice these models are implemented via a *frag-*

[1]this fit includes the $\sin 2\beta$ average of HFAG.

mentation function $D_b^B(v)$ (parameterised in terms of some kinematical variable v) which can be interpreted as the probability density function that a hadron B, containing the origional quark b, is produced with a given value v. In order to accurately reproduce the data the fragmentation function must be correct in shape and also have parameters that are tuned to the data.

The exact definition of v varies from model-to-model. For models relevant to b-quark fragmentation from Z^0 decay, the choice of fragmentation variable v falls into one of two broad categories commonly labelled as z and x where:

- z is a fraction normalised to kinematical properties of the parent b-quark before modelling of the fragmentation process begins.
- x is a fraction normalised to the electron/positron beam energy i.e. $m(Z^0)/2$.

From a phenomenological point of view, z is the relevant choice of variable for a parameterisation implemented in an event generator algorithm. However, because z depends explicitly on the properties of the parent b-quark, it is not a quantity that can be directly measured by experiments. For this reason all existing measurements of $D_b^B(v)$ are based on the reconstruction of x.

The fragmentation variable, for the case of an initial b and $\bar{b}$ quark system in the absence of gluon radiation, is defined as

$$z = \frac{(E + p_{||})_B}{(E + p)_b}. \tag{12}$$

Here, $p_{||}$ represents the hadron momentum in the direction of the b-quark and $(E + p)_b$ is the sum of the energy and momentum of the b-quark just before fragmentation begins.

The x fragmentation variable is defined to be,

$$x_B = \frac{2E_B}{\sqrt{s}} \tag{13}$$

where E_B is the b-hadron energy and $\sqrt{s}$ is the center-of-mass energy, which are both quantities that can in principle be directly reconstructed in the detector. When discussing x_B, it is necessary to be clear about exactly which b-hadron is being considered. The *primary b-hadron* is the state created directly after the hadronisation phase, whereas the *weak b-hadron* is the state that finally decays somewhere in the detector.

From the wealth of measurements and model comparisons regarding b fragmentation functions that have been measured by the LEP collaborations, only the mean x_B values will be shown here:

$$\begin{aligned}
\text{ALEPH[8]}: \quad & < x_B^{weak} > &=& \quad 0.716 \pm 0.006 \pm 0.006 \\
\text{DELPHI(prel.)[9]}: \quad & < x_B^{weak} > &=& \quad 0.7153 \pm 0.0007^{+0.0049}_{-0.0052} \\
\text{OPAL[10]}: \quad & < x_B^{weak} > &=& \quad 0.7193 \pm 0.0016^{+0.0036}_{-0.0031} \\
\text{SLD[11]}: \quad & < x_B^{weak} > &=& \quad 0.709 \pm 0.003 \pm 0.004
\end{aligned}$$

The smallness of the statistical error in the DELPHI measurement is striking, but it is also worth noting that the spread between the measurements is greater than what is to be expected from the errors given.

6 Concluding remarks

LEP was a very powerful instrument in measuring a large number variables in many areas of B physics, out of which only a handful have been mentioned here. Despite the fact that the bulk of the data was taken before 1996, there still remains a handful publications with B physics results to be published within the coming months. However, it is clear that the B physics area will soon be completely dominated by results from the B factories and the Tevatron, until the startup of the LHC.

7 Acknowledgements

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