# HEAVY FLAVOUR PHYSICS AT LEP*

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The production of b hadrons in $e^+e^-$ interactions at the $Z$ pole allows to perform detailed studies of their properties. Almost a million of $Z^0 \to b\bar{b}$ decays have been detected by the four LEP collaborations. In this contribution, some recent results on heavy flavour physics are presented.

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## 1. Introduction

The data collected by the LEP experiments from 1989 to 2000 allows to investigate several aspects of heavy flavour physics. Although recently $b$ factories and experiments at hadron colliders have superseded many LEP results, many others are still competitive and will be for quite some time. In this report, only a small selection of recent results is presented, namely the present status of the $B^0_{\rm s}$ oscillation searches, the most recent measurements of the $b$ quark forward–backward asymmetries at the $Z$ pole, the determination of the $b$ quark fragmentation function, and the measurement of heavy quark production rates in two photon collisions.

## 2. Search for $B^0_{\rm s}$ oscillations

The flavour oscillation frequency in the $B^0_{\rm s}$–$\overline{B}^0_{\rm s}$ system is an important constraint in the determination of the CKM matrix, but it is very difficult to measure due to its high value compared to the current limitations in statistics and experimental resolution.

The probability for a $B^0_{\rm s}$ to oscillate (or not) into the opposite flavour eigenstate is approximately:

$$P(t)_{B^0_{\rm s} \to \overline{B}^0_{\rm s}(B^0_{\rm s})} = \frac{1}{2\tau_s} {\rm e}^{-t/\tau_s} \left[1 \mp A \cos(\Delta m_s t)\right] , \qquad (1)$$

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where $t$ is the proper time at decay, $A \equiv 1$, $\tau_s$ the average $B_s^0$ lifetime and $\Delta m_s$ the mass difference between the mass eigenstates (also called "oscillation frequency"). Experimentally, the effect of the finite proper time resolution and the probability to "mistag" the flavour at production and decay time, must also be taken into account.

Several analysis methods have been applied by the LEP experiments, being usually classified in three categories. Exclusive analyses [1, 2] reconstruct completely specific $B_s^0$ hadronic decay channels and give the highest proper time resolution, but very small data samples; their contribution is most important for high oscillation frequencies. Semi-exclusive analyses [1,3] select $B_s^0$ decays where only some decay particles are reconstructed (*e.g.* $B_s^0 \to D_s \ell \nu$); proper time resolution is worse due to missing particles, like neutrinos, but statistics are higher. Inclusive analyses [1, 3] use broader selection criteria (semileptonic decays, secondary vertices, *etc.*) to allow for much larger statistics at the expense of the signal purity. The mistag probability is dominated by the uncertainties in the determination of the flavour at production, and therefore is similar for all analyses.

In the absence of a measurement, results are expressed by fitting the amplitude $A$ in (1) as a function of a test value $\omega$ of the frequency ("amplitude method" [4]): $A$ is expected to be 1 for $\omega = \Delta m_s$ and 0 for $\omega \ll \Delta m_s$. Values of $\omega$ such that $A + 1.645\sigma_A < 1$ are excluded at 95% C.L. Amplitude spectra for different analyses are easily combined, and in figure 1 the present world combination (based also on preliminary results) is shown [5]. The present

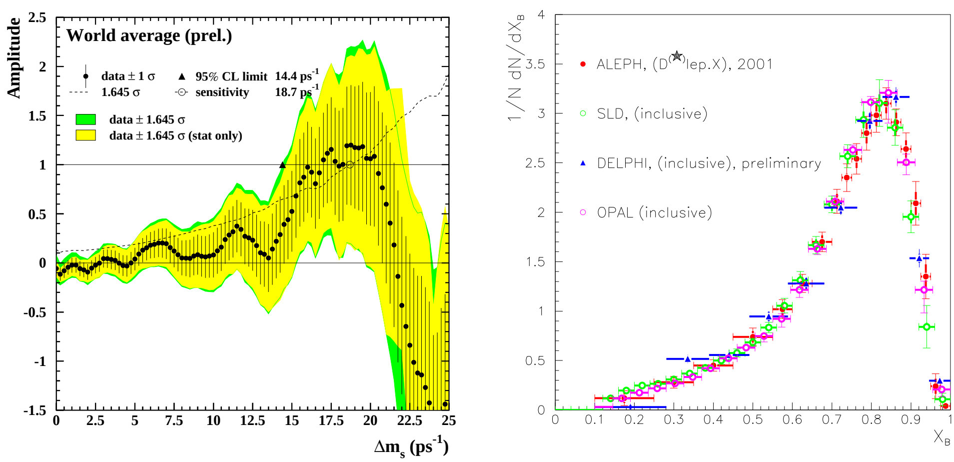


Fig. 1. (left) Combined amplitude spectrum; (right) unfolded $x_B$ distributions for the LEP experiments and SLD.

limit is $\Delta m_s = 14.4\ \mathrm{ps}^{-1}$, and the expected limit for $\Delta m_s = +\infty$ is $18.7\ \mathrm{ps}^{-1}$. Only marginal changes are expected from the final results and only the data of the Tevatron Run II will add significant information, most likely with an actual measurement.

## 3. Heavy quark fragmentation

The hadronization process in $e^+e^-$ collisions is usually described by the convolution of a perturbative part, describing the hard gluon radiation, and a non-perturbative part, called fragmentation function, which is phenomenological in nature and sometimes expressed as a function of $x_b = \frac{E_{\mathrm{hadron}}}{E_{\mathrm{beam}}}$, the hadron energy scaled to the beam energy.

Different measurements were made at LEP, with different techniques. One of them [6] reconstructs semileptonic decays $B \to D^{(*)}\ell\nu$, and the $B$ energy is calculated estimating the neutrino energy from the event missing energy. Other techniques use $b$-tagging and secondary vertex reconstruction algorithms to select an inclusive sample of $Z^0 \to b\bar{b}$ events; the $B$ hadron energy is estimated from the reconstructed particles momenta, weighted with the probability to come from a $B$ decay [7], or using a neural network to combine the discriminating power of several variables [8].

All the experiments have determined the shape of the fragmentation function as a function of $x_b$ (figure 1), and have compared it to existing models [6–8]. The Bowler, Lund and Kartvelishvili models are favoured by the data, while the Peterson *et al.* and Collins models are much less acceptable. The results of all the experiments are consistent:

| | The average values of $x_b$ |
|---|---|
| ALEPH | $0.716 \pm 0.006$ (stat.) $\pm\ 0.006$ (syst.) |
| OPAL | $0.7193 \pm 0.0016$ (stat.)$^{+0.0038}_{-0.0033}$ (syst.) |
| DELPHI | $0.7153 \pm 0.0007$ (stat.)$^{+0.0049}_{-0.0052}$ (syst.) |

A detailed knowledge of the fragmentation function is critical at hadron colliders due the the abundance of the QCD background with $b$ quarks and the presence of $b$ quarks in many interesting processes (*e.g.* $H \to b\bar{b}$).

## 4. Heavy quark asymmetries

A precise measurement of the electroweak mixing angle $\sin^2\theta_W^{\mathrm{eff}}$ comes from the forward–backward asymmetry of quarks in $Z^0 \to q\bar{q}$ decays, different for up- and down-type quarks. Flavour separation can be obtained only for $c$ and $b$ quarks, the latter giving the highest sensitivity to $\sin^2\theta_W^{\mathrm{eff}}$.

Analyses based on the selection of semileptonic $b$ ($c$) decays exploit the correlation between the lepton charge and the particle–antiparticle nature of the quark to set the direction of the $b$ ($c$) quark, approximated by the thrust axis, and derive the asymmetry from the measured angular distribution. Usually, a $b$-tagging variable and the lepton momentum are used to determine the sample composition, and both $b$ and $c$ asymmetries can be extracted from the same fit [9,10]. The flavour composition can be determined from data using double tagging methods. Another possibility is to select inclusively $b$ events and use several charge estimators (*e.g.* charges of jets, secondary vertices, kaons, tracks) to measure the charge asymmetry [11,12].

All LEP and SLD measurements of the $b$ quark asymmetry are in good agreement, but the value of $\sin^2\theta_W^{\rm eff}$ derived from their average has a $2.9\sigma$ discrepancy with the one derived from the SLD measurement of the polarised left–right asymmetry (see figure 2) [13]; this will be an outstanding issue until the coming of new linear colliders.

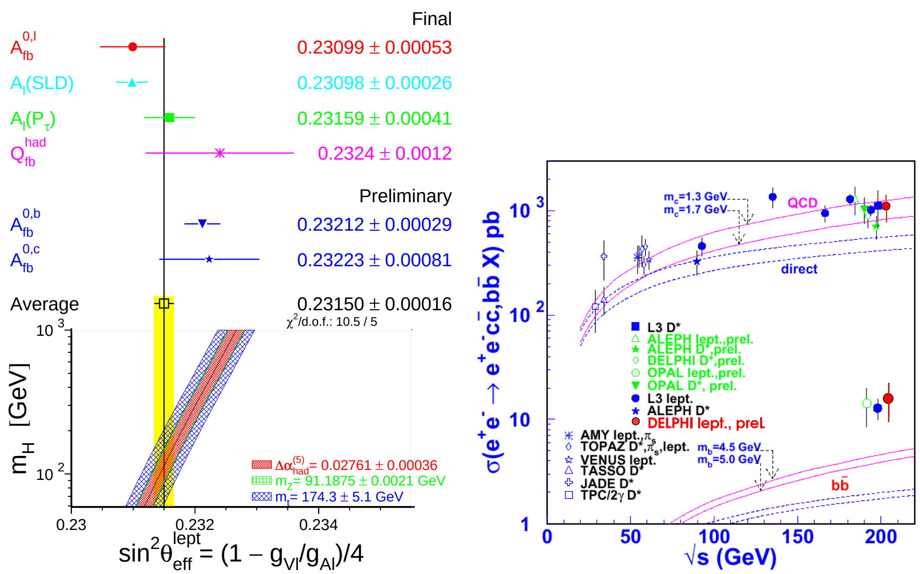


Fig. 2. (left) Measurements of $\sin^2\theta_W^{\rm eff}$ from various asymmetry measurements; (right) published and preliminary results on total open $b$ and $c$ cross-sections in $\gamma\gamma$ events.

## 5. Open $b$ production in $\gamma\gamma$ collisions

The measurement of the total open $c$ and $b$ quark production cross-section in $\gamma\gamma$ events offers the opportunity to test perturbative QCD [14]. At a centre-of-mass energy around 200 GeV, the direct diagram ($\gamma\gamma\to b\bar{b}$) and the single-resolved photon–gluon fusion diagram ($g\gamma\to b\bar{b}$) dominate and contribute with similar weights. The cross-section for $b$ quarks is 1–2 orders of magnitude smaller than for charm due to the smaller electric charge and the larger mass. Different LEP experiments employ similar analysis techniques [15–17], and identify an electron or a muon from a semileptonic $b$ decay and a hadronic jet and measure the lepton momentum transverse to the jet axis; the $b$ content is enhanced by requiring a high visible mass. The distribution of the lepton transverse momentum is compared to the Monte Carlo prediction to extract the production rate. The event fraction due to light quark or open charm $\gamma\gamma$ events are determined in the fit together with the $b$ content, or estimated from other measurements, while contributions from other sources are taken from Monte Carlo simulations. The charge correlation between the kaon and the lepton from the semileptonic decay of heavy quarks has also been exploited to increase the purity of the sample [15].

| | The measured cross section $\sigma(e^+e^- \to e^+e^- b\bar{b}X)$ [pb] |
|---|---|
| L3 | $12.8 \pm 1.7$ (stat.) $\pm\, 2.3$ (syst.) |
| OPAL | $14.2 \pm 2.5$ (stat.)$^{-4.8}_{+5.3}$ (syst.) |
| DELPHI | $14.9 \pm 3.3$ (stat.) $\pm\, 3.4$ (syst.) |

The theoretical prediction from a NLO QCD calculation by Drees *et al.* [14], for a $b$ quark mass of 4.5 GeV/$c^2$, an open $b$ threshold energy of 10.6 GeV and $\sqrt{s} = 194$ GeV is 4.4 pb. This large discrepancy remains unexplained.

## 6. Conclusions

We have shown a small selection of recent results which demonstrate that LEP data still provides a very valuable source of knowledge for $b$ physics even in the era of b factories and hadron colliders. In fact, many LEP results will not be superseded until the advent of linear colliders. Results on $b$ quark forward–backward asymmetry and open $b$ production in $\gamma\gamma$ events show consistent and significant deviations from the expectations and deserve further study. The fragmentation function determination is a critical input to simulation of hadronic interactions, while the limit on $B_{\rm s}^0$ is already a stringent constraint to the CKM matrix determination.

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