Eur Phys J C **33**, s01, s717–s719 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1626-3

EPJ C direct
electronic only

Measurement of heavy quark forward-backward asymmetries using a lepton tag in hadronic Z decays

Latest results from OPAL and DELPHI

T. Krämer

DESY/Universität Hamburg, Notkestr. 85, 22603 Hamburg, Germany, e-mail: `thomas.kraemer@desy.de`

Received: 14 October 2003 / Accepted: 14 January 2004 /

Abstract. Measurements of the b and c quark forward-backward asymmetries performed at LEP are presented, focusing on the latest results from OPAL and DELPHI.

PACS. 12.15.Mm Neutral currents – 13.38.Dg Decays of Z bosons – 13.66.Jn Precision measurements in e-e+ interactions – 14.70.Hp Z bosons

1 Introduction

The measurement of the forward-backward asymmetries of heavy quarks, $A_{\mathrm{FB}}^{\mathrm{q\overline{q}}}$ (q=b,c), in $\mathrm{e^+e^-} \to \mathrm{q\overline{q}}$ events provides an important test of the Standard Model. The $\mathrm{b\overline{b}}$ forward-backward asymmetry provides one of the most precise determinations of the effective electroweak mixing angle for leptons $\sin^2\theta_{\mathrm{eff}}^{\ell}$. This is of particular interest in view of the nearly three standard deviation difference between the average values of $\sin^2\theta_{\mathrm{eff}}^{\ell}$ derived from quark forward-backward asymmetries at LEP on the one hand and from lepton forward-backward asymmetries at LEP and the left-right asymmetry at SLD on the other [1].

The parity violating couplings of the Z to fermions results in an asymmetry $A_{\mathrm{FB}}^{\mathrm{q\overline{q}}}$ in the differential cross-section for b and c quark production:

$$\frac{\mathrm{d}\sigma_{\mathrm{q\overline{q}}}}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3}A_{\mathrm{FB}}^{\mathrm{q\overline{q}}}\cos\theta\,, \tag{1}$$

where θ is the angle between the directions of the incoming electron and outgoing quark, and where initial and final state radiation, quark mass effects and higher order terms have been neglected. At the Z pole, the pole asymmetries $A_{\mathrm{FB}}^{0,\,\mathrm{q}}$ are given by $A_{\mathrm{FB}}^{0,\,\mathrm{q}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{q}}$ where the coupling parameters of the Z to electrons and quarks, $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_{\mathrm{q}}$, depend on the effective vector and axial vector couplings of the Z. Within the context of the Standard Model, these depend on the effective electroweak mixing angle $\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}}$ and are sensitive to the Higgs mass. The values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}}$ are all close to 1/4, with the result that the value of the asymmetry parameter for electrons, $\mathcal{A}_{\mathrm{e}}$, is small, and varies rapidly with $\sin^2\theta_{\mathrm{eff}}^{\ell}$, but the value of $\mathcal{A}_{\mathrm{b}}$ is large, approximately 0.94, and varies only slowly with $\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}}$. This results in a relatively large forward-backward asymmetry for $\mathrm{b\overline{b}}$ events, which is then very sensitive to $\sin^2\theta_{\mathrm{eff}}^{\ell}$ via $\mathcal{A}_{\mathrm{e}}$.

Two new simultaneous measurements of the b and c quark asymmetries using semileptonic decays were submitted to this conference, from OPAL [2] and DELPHI [3]. These measurements are discussed in more detail below. Similar analyses have been performed recently by ALEPH [4] and also by L3 [5]. For an overview over all heavy flavour forward-backward asymmetry measurements see [6].

2 The two new analyses

The basic outlines of the OPAL and DELPHI analyses are quite similar, therefore the two measurements will be described in parallel below, noting any differences.

While OPAL presents a new measurement using its entire Z data sample (all LEP 1 data and the LEP 2 calibration data, recorded from 1996 to 2000), DELPHI just performed a new analysis for the 1993–1995 data sample and does a combination with earlier results from 1990–1992 data.

Both experiments (and also L3 and ALEPH) measure the asymmetries at three different centre-of-mass energies. The bulk of the data was taken very close to the Z resonance ($\sqrt{(}s) \approx 91.25$ GeV). Some events were recorded at centre-of-mass energies approximately 1.8 GeV above and below the Z peak, referred to as off-peak points.

To select only $\mathrm{e^+e^-} \to \mathrm{q\overline{q}}$ events a multi hadronic event selection is made. A good estimate of the $\mathrm{q\overline{q}}$ flight direction is the event thrust axis. To distinguish primary quarks from antiquarks, semileptonic decays of the hadrons produced after fragmentation are used, by reconstructing the lepton charge and separating the different event flavours. Semileptonic decays are identified by searching for electrons and muons in the final state.

Lepton candidates are required to have at least a momentum of 2 GeV (2.5 GeV for muons in DELPHI). Muons are identified by requesting a spatial match between a track reconstructed in the central tracking detectors and a track segment found in the external μ chambers. Applying a soft $\mathrm{d}E/\mathrm{d}x$-cut reduces the background contribution from kaons.

Electrons are identified using a neural network algorithm. The identification relies on ionisation energy loss ($\mathrm{d}E/\mathrm{d}x$) measured in the tracking chamber, together with spatial and energy-momentum (E/p) matching between tracking and calorimetry. DELPHI in addition uses the shower shape of the particle in the calorimeter.

In both analyses, only leptons from the decay of a b or c hadron in a primary $\mathrm{b\overline{b}}$ or $\mathrm{c\overline{c}}$ event are considered as signal. Any other genuine electron or muon, and any hadron misidentified as a lepton, is considered as background. The relationship between the lepton charge and the primary quark or antiquark from which it originated is vital for the asymmetry measurements. According to the sign correlation between primary quark and lepton candidates, the lepton candidates can be categorised into 4 groups:

1. leptons coming directly from the weak decay of b hadrons ($\mathrm{b} \to \ell^-$); electrons and muons from leptonic τ decays where the τ lepton comes from a direct b decay ($\mathrm{b} \to \tau^- \to \ell^-$), and cascade decays ($\mathrm{b} \to \overline{\mathrm{c}} \to \ell^-$), have the same sign correlation as the $\mathrm{b} \to \ell^-$ events.
2. Cascade decays, $\mathrm{b} \to \mathrm{c} \to \ell^+$, which have the opposite sign correlation as group 1.
3. Leptons from the decay of c hadrons produced in $\mathrm{c\overline{c}}$ events, $\mathrm{c} \to \ell^+$, have the opposite sign correlation to direct $\mathrm{b} \to \ell^-$ decays.
4. All other events are classified as background.

A neutral B meson may have mixed before decay, so that a primary b quark decays as a b antiquark, or vice versa. This is quantified by the average mixing parameter, $\overline{\chi}$, which is the probability that a produced b hadron decays as its antiparticle. Leptons from these mixed mesons are classified according to the decaying b quark, and contribute to the asymmetry with the wrong sign for their category, causing a reduction in the observed $\mathrm{b\overline{b}}$ asymmetry by a factor of $(1-2\overline{\chi})$.

In order to extract the b and c quark asymmetries from the data using a fit, there has to be a procedure to separate lepton candidates coming from each of these four groups.

OPAL quark flavour separation

Two neural networks denoted NETb and NETc were used to separate $\mathrm{b} \to \ell^-$ and $\mathrm{c} \to \ell^+$ decays from each other, from the cascade decays, $\mathrm{b} \to \mathrm{c} \to \ell^+$ (which dilute the observed forward-backward asymmetries) and $\mathrm{b} \to \overline{\mathrm{c}} \to \ell^-$, and from backgrounds. Several of the network input variables refer to the jet containing the lepton track. The same tracks and clusters used to define the event thrust axis were combined into jets using a cone algorithm.

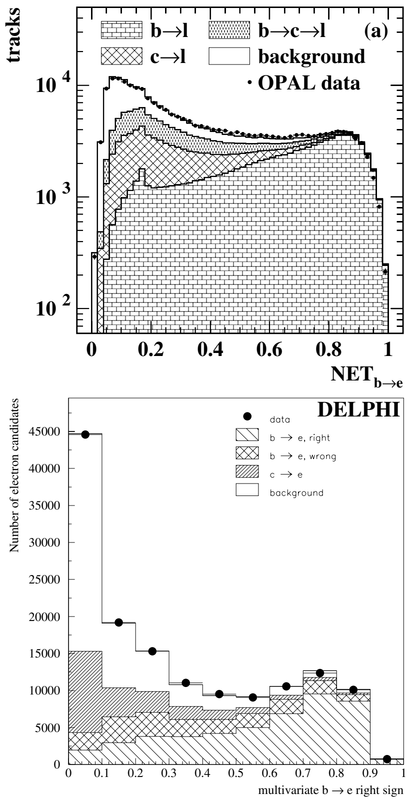

Fig. 1. The output of the OPAL neural network designed to select $\mathrm{b} \to \mathrm{e}$ decays (*top*) and DELPHI likelihood ratio $\mathcal{P}_{b_1}$ (*bottom*) distributions for electrons. The data are shown by the points with error bars, and the expected contributions from different lepton sources by the hatched histograms

The first network, NETb, was trained to distinguish between $\mathrm{b} \to \ell^-$ events and all other categories. The input variables were the momentum p and transverse momentum (relative to the axis of the jet containing the lepton) p_t of the lepton candidate, the energy of the lepton subjet, $E_{\mathrm{sub-jet}}$, the total visible energy of the jet, $E_{\mathrm{jet}}^{\mathrm{vis}}$, and the scalar sum of the transverse momentum of all tracks within the jet, $(\sum p_t)_{\mathrm{jet}}$. Separate networks were trained for electrons and muons. For the electron nets, two extra variables were included, namely the outputs of the electron and conversion neural networks.

The second network, NETc, was trained to distinguish $\mathrm{c} \to \ell^+$ events from all other categories, including $\mathrm{b} \to \ell^-$. The network used all the NETb variables, together with the following three quantities: the decay length significances, $(L/\sigma_L)_{1,2}$, of secondary vertices in the jet containing the lepton (jet 1) and in the most energetic of the other jets in the event (jet 2), and the impact parameter significance of the lepton with respect to the primary vertex, d/σ_d.

The values of the asymmetries and $\overline{\chi}$ were determined using a simultaneous fit to the observed numbers of single lepton events as a function of $\cos\theta_{\mathrm{T}}$, NETb and NETc, and the numbers of dilepton events as a function of $\cos\theta_{\mathrm{T}}$, using a binned maximum likelihood fit.

DELPHI quark flavour separation

The observables entering a multivariate discriminant, which is used for flavour separation, were chosen to be:

- Lepton transverse (p_{T}) and longitudinal (p_{L}) momenta;
- The event b-tagging variable, η_{EVT} combining:
  - The jet lifetime probability, constructed from the positively signed impact parameters of all tracks included in a jet;
  - The effective mass of the system of particles assigned to the secondary vertex;
  - The rapidity of tracks associated to the secondary vertex with respect to the jet direction;
  - the fraction of the jet energy carried by charged particles from the secondary vertex.
- The product of the lepton charge times the jet charge of the opposite hemisphere, $Q_\ell \times Q_{opp}$.

The probabilities $p_k^{p_{\mathrm{T}},p_{\mathrm{L}}}$ and $p_k^{\mathrm{btag,jet-ch}}$ of observing a set of $(p_{\mathrm{T}}, p_{\mathrm{L}})$ and $(\eta_{EVT}, Q_\ell \times Q_{opp})$ values for a lepton from the class k were computed. A likelihood ratio $\mathcal{P}_k$ was built to estimate the probability corresponding to a given set of values within a class:

$$\mathcal{P}_k = \frac{N_k p_k^{p_{\mathrm{T}},p_{\mathrm{L}}} p_k^{\mathrm{btag,jet-ch}}}{\Sigma_{k'} N_{k'} p_{k'}^{p_{\mathrm{T}},p_{\mathrm{L}}} p_{k'}^{\mathrm{btag,jet-ch}}}$$

where N_k ($N_{k'}$) is the total number of leptons from the class k (k'). The scaling of the likelihood ratio by N_k takes into account the relative weights of each class. Neglecting some of the correlations between the observables, such a definition identifies $\mathcal{P}_k$ as the fraction of lepton candidates with a given set of $p_{\mathrm{T}}, p_{\mathrm{L}}, \eta_{EVT}$ and $Q_\ell \times Q_{opp}$ belonging to the class k.

A binned minimum χ^2 fit was used to extract the asymmetries $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$ and $A_{\mathrm{FB}}^{\mathrm{c\bar{c}}}$ from a three dimensional distribution in $\cos\theta_{\mathrm{T}}$ vs. $(\mathcal{P}_1 - \mathcal{P}_2)$ vs. $\mathcal{P}_3$ of the data sample.

In Fig. 1, the separation power of the OPAL and DELPHI quark flavour separation techniques is shown, together with a data Monte Carlo comparison for the $\mathrm{b} \to \ell^-$ channel. In both cases, the separation between signal and background and the data-Monte Carlo agreement is very good.

3 Results

The results for the $A_{\mathrm{FB}}^{\mathrm{q\bar{q}}}$ measurements at the three energy points are corrected to the primary quark level. Using the ZFITTER prediction for the dependence of $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$ and $A_{\mathrm{FB}}^{\mathrm{c\bar{c}}}$ on $\sqrt{s}$, the measurements are shifted to m_{Z} (91.19 GeV), averaged and corrected for initial state radiation, γ exchange, $\gamma - Z$ interference and quark mass effects for each experiment separately. The results for the pole asymmetries for all LEP experiments are shown in Table 1.

The results from the lepton measurements are consistent among themselves and in good agreement with the LEP averages. The LEP averages favour a high Higgs mass.

$$A_{\mathrm{FB}}^{0,\mathrm{b}} = 9.97 \pm 0.16\ \%$$
$$A_{\mathrm{FB}}^{0,\mathrm{c}} = 7.06 \pm 0.35\ \%$$

As can be seen from Table 1 the uncertainties for all measurements are dominated by statistics. The most important contributions to the systematic error for the b asymmetry are the semileptonic decay modes of the b and c hadrons, the modelling of the quark flavour separation and the mixing parameter $\overline{\chi}$. In case of the c asymmetry the systematic error is governed by the semileptonic branching ratios and the modelling of the flavour separation variables. An exception is the DELPHI analysis, where the background asymmetry is by far the biggest contribution.

Table 1. Pole forward-backward asymmetries in % from the lepton measurements for all four LEP experiments

	$A_{\mathrm{FB}}^{0,\mathrm{b}}$	stat.	syst.	$A_{\mathrm{FB}}^{0,\mathrm{c}}$	stat.	syst.
ALEPH*	10.09	±0.38	±0.17	7.33	±0.53	±0.36
DELPHI*	10.31	±0.51	±0.24	7.24	±0.84	±0.62
L3	10.07*	±0.60	±0.35	8.32***	±3.01	±1.07
OPAL**	9.83	±0.38	±0.18	6.42	±0.51	±0.37

Data used: *1991-1995, **1990-2000, ***1990-1991

4 Discussion

The LEP heavy flavour forward-backward asymmetry measurements have gained sensitivity over the entire LEP era, with new improved analyses getting the maximum possible information from the data. However, there is now little scope for further reduction in the uncertainties, and all analyses have been finalised. In terms of the Standard Model, the heavy flavour forward-backward asymmetries can be interpreted as measurements of the weak mixing angle. Motivated by the almost three standard deviation discrepancy between $\sin^2\theta_{\mathrm{eff}}^{\ell}$, extracted from A_{LR} and $A_{\mathrm{FB}}^{0,\mathrm{b}}$, much effort has been invested in improving and checking the b quark asymmetry analyses in particular, where the uncertainty is still dominated by statistics. This discrepancy, which is not changed by the latest analyses presented here, will most likely be left as a legacy from the LEP/SLD era—a statistical fluctuation, or perhaps a hint of new physics?

Acknowledgements. The author thanks the members of the LEP/SLD heavy flavour electroweak working group for the averages presented here and R. Hawkings, P. Wells and D. Zer-Zion for many useful discussions.

References

1. The LEP Collaborations, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group: CERN-EP/2002-091, hep-ex/0212036, 2002
2. G. Abbiendi et al.: CERN-EP-2003-039, accepted by Phys. Lett. B (2003)
3. P. Antilogus et al.: DELPHI note No. 2003-058-CONF-678, 2003
4. A. Heister et al.: Eur. Phys. J. C **24**, 177 (2002)
5. M. Acciarri et al.: Phys. Lett. B **448**, 152 (1999); O. Adriani et al.: Phys. Lett. B **292**, 454 (1992)
6. M. Elsing, these proceedings.