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Precision Measurements of the b Forward-Backward Asymmetry at the Z Pole from LEP

W. Liebig
University of Wuppertal, FB8 – Physik, Gaußstr. 20, 42097 Wuppertal, Germany

Abstract

The four LEP experiments have measured the forward-backward asymmetry for the process $e^+e^-\to Z\to b\bar{b}$ at centre-of-mass energies close to m_Z with very high precision. Sophisticated techniques have been developed to reconstruct either the production flavour in exclusive final states like B $\to l^{\pm}$, or the hemisphere charge on a large-size b-enriched sample. The two methods provide largely independent determinations of A_{FB}^b and are briefly presented.

The results yield a very precise determination of the electroweak effective mixing angle $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, probing the Standard Model prediction for the electroweak radiative corrections.

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Precision Measurements of the b Forward-Backward Asymmetry at the Z Pole from LEP

W. Liebig[a*]

[a]University of Wuppertal, FB8 – Physik,
Gaußstr. 20, 42097 Wuppertal, Germany

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1. Introduction

In the process $e^+e^-\to(Z,\gamma)\to b\bar{b}$ observed at LEP, the polar angle distribution of the b quark is forward-backward asymmetric [1]. This asymmetry $A^b_{\rm FB}=(\sigma_{\sf forw.}-\sigma_{\sf backw.})/\sigma_{\sf tot}$ arises from the parity-violating structure of the Z-exchange and its interference with the photon exchange. At centre-of-mass energies close to m_Z, the former is dominant and

$$A^{b,0}_{\rm FB}=\frac{3}{4}\mathcal{A}_e\mathcal{A}_b=\frac{3}{4}\frac{2g_{Ae}g_{Ve}}{g^2_{Ae}+g^2_{Ve}}\frac{2g_{Ab}g_{Vb}}{g^2_{Ab}+g^2_{Vb}}\ . \qquad (1)$$

Higher order electroweak corrections are taken into account by means of an improved Born approximation which relates the coupling ratio to the effective electroweak mixing angle $\sin^2\theta^f_{\rm eff}$. With $\mathcal{A}_b$ being $\approx$ 0.93, the forward-backward asymmetry is basically sensitive to the *leptonic* $\sin^2\theta^{\rm lept}_{\rm eff}$ and can be compared directly to other measurements that determine this quantity, e.g. $A_{\rm LR}$ measured using beam polarisation by SLD [2]. Even long after the LEP 1 running it is therefore of very high interest to provide as precise and reliable asymmetry measurements as possible.

Experimentally, the main task for the b quark asymmetry measurements is to distinguish between the flight directions of the quark and the antiquark. This is achieved by reconstructing the quark charge in one or both of the hemispheres defined by the thrust axis. Two different and largely independent reconstruction methods are applied: one directly sees the clear charge information in case of a weak B decay into a lepton and measures $A^b_{\rm FB}$ and $A^c_{\rm FB}$ simultaneously by means of b-c separation variables. The other approach analyses inclusively all decay types, requiring a flavour-pure data set obtained from b-tagging.

Before the results for $A^b_{\rm FB}$ are discussed, the lepton and the inclusive method and their sophisticated analysis tools will be briefly presented.

2. $A^b_{\rm FB}$ and $A^c_{\rm FB}$ with Leptons

All LEP experiments provide measurements of $A^b_{\rm FB}$ and $A^c_{\rm FB}$ using prompt leptons that are produced with large p and $p_\perp$ in weak B and D meson decays [3–6]. The key feature of all methods is then to distinguish between $b\to l$, $c\to l$, $b\to c\to l$ decays and background using again p, $p_\perp$ either as the direct discriminator or the main ingredient to a lepton ID neural net like the one displayed in Fig. 1. The simultaneous fit in bins of these decay type identifiers and in $\cos\theta$ then yields $A^b_{\rm FB}$ and $A^c_{\rm FB}$. However, analyses are subject to $B-\overline{B}$-mixing and a reliable description of $b\to c\to l$ cascade decays. The latter create

*on behalf of the DELPHI collaboration

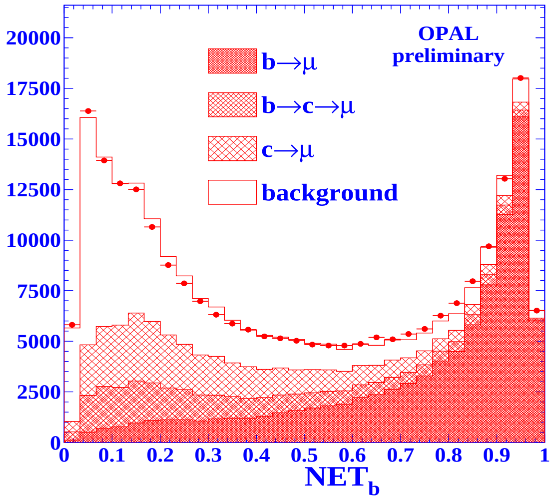

Figure 1. Distribution of the separating variable NET$_b$ used in the OPAL lepton A_{FB} analysis. It enriches $b\!\rightarrow\!\mu$ signal at output values near 1, as illustrated by the Monte Carlo truth information.

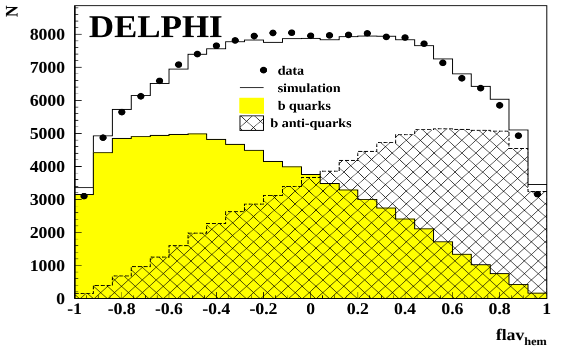

Figure 2. The DELPHI charge tagging neural network output for the data of 1994 in comparison with simulation.

a wrong sign correlation between lepton and initial quark, leading to a double loss in sensitivity. Therefore ALEPH has added an extra NN$_{b\rightarrow c\rightarrow l}$ identification while DELPHI calls in the jet charge of the opposite hemisphere to reduce the number of wrong-sign decays.

3. Inclusive jet charge and new neural net analyses for A^b_{FB}

All four LEP experiments exploit also an inclusive approach to measure A^b_{FB} from a large size b-tagged sample with usually very low backgrounds [7–10]. This allows the use of the jet charge to obtain a correlation to the primary quark charge, however this correlation is diluted by fragmentation and subsequent decays.

3.1. New neural network techniques

ALEPH and DELPHI have improved their techniques by combining more information about B-jets than just the plain jet charge, using neural networks [7,11]. The inputs are in detail:

- jet charges at various weighting powers κ,
- the secondary vertex charge,
- B_x charge tags that weight the charge at the secondary and primary vertex depending on the B hadron hypothesis,
- identified particles (p, K, π),

The output of such a network is displayed for the DELPHI data of 1994 in Fig. 2. In order to be able to discuss later the quality of the two most precise contributions [7,11] to the LEP combined b asymmetry, these measurements are explained in more detail in the following.

3.2. The analyses

ALEPH exploits the proportionality between A^b_{FB} and the average charge flow

$$\langle Q_{\mathsf{F}} - Q_{\mathsf{B}}\rangle = \sum_f \mathcal{P}_f(\theta)\delta_f(\theta)A^f_{\mathrm{FB}}(\theta) \qquad , \qquad (2)$$

using very inclusive hemisphere tags to build $Q_{\mathsf{F}} - Q_{\mathsf{B}}$. DELPHI uses the counting method

$$\frac{N_{\mathsf{F}} - N_{\mathsf{B}}}{N_{\mathsf{F}} + N_{\mathsf{B}}} = \sum_f (2w_f - 1)\mathcal{P}_f A^f_{\mathrm{FB}}(\theta) \qquad (3)$$

with a cut-based selection of hemispheres. The measurements work on b-enriched samples with purities of $\mathcal{P}_b \sim 88\,\%$ (A) and $\mathcal{P}_b \sim 96\,\%$ (D), with both experiments extracting flavour efficiencies from the data. Of utmost importance for being independent from B-physics modelling in the

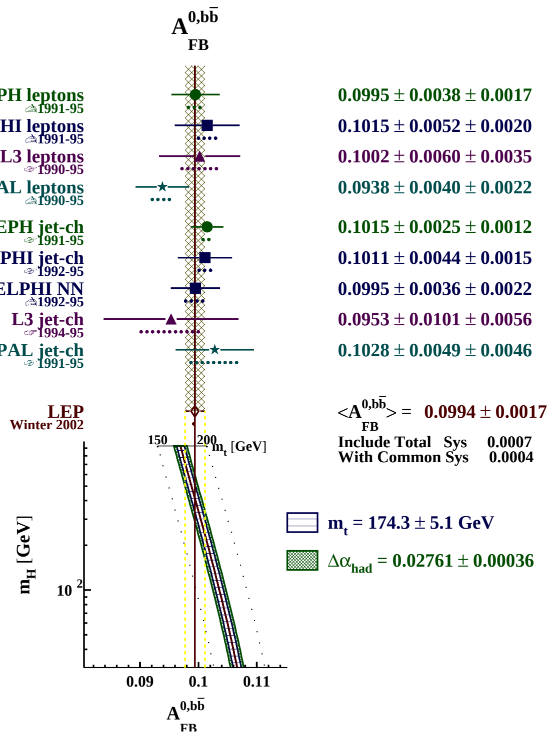

Figure 3. The LEP results for $A_{\mathrm{FB}}^{b,0}$. The average takes into account correlated errors and off-peak measurements.

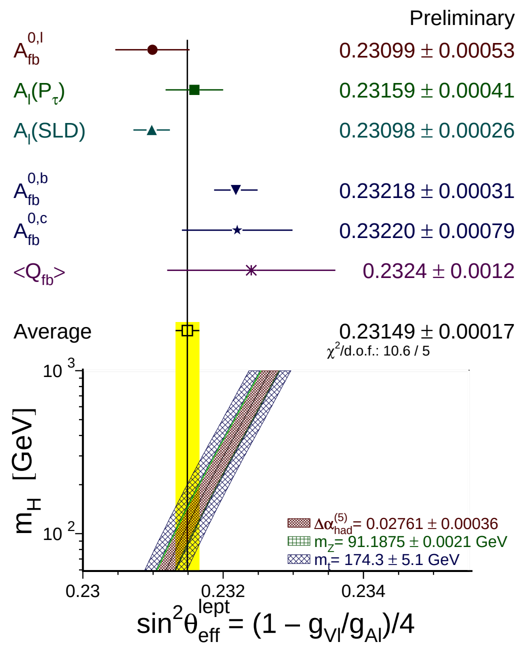

Figure 4. Comparison of several determinations of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ from asymmetries. [12]

simulation is the calibration of the charge correlation to the initial b quark. Therefore ALEPH calibrates the charge separation δ_f by measuring

$$\bar{\delta}^2 = \sigma^2(Q_{\mathsf{FB}}) - \sigma^2(Q_{\mathsf{tot}}) \approx \sum_f \mathcal{P}_f \delta_f^2 \qquad (4)$$

and DELPHI calibrates the probability w_b to identify the quark charge correctly from the numbers of like and unlike sign charged hemisphere pairs. A_{FB}^b is then extracted from a fit to the differential asymmetry.

3.3. Modelling dependence and checks

The remaining corrections that have to be taken from simulation are the individual sensitivity to the QCD correction and the hemisphere correlations. The latter arise mainly from charge conservation and amount to $k_f \sim 10\,\%$ in the correction $[w_b,\, \delta_f] \cdot (1 + k_f)$. The stability versus $\mathcal{P}_b$ has been checked in both experiments. DELPHI, who takes also the charm background contribution from simulation, has verified the c efficiency on data by means of a double hemisphere tag to agree within 20 % with simulation. The charge identification probability for background, w_c, has been checked with opposite hemisphere D^* finding no significant deviation. Also ALEPH has reproduced δ_b by means of high-p_T leptons.

4. Asymmetry results in the light of the Standard Model

The results for the b pole asymmetry $A_{\mathrm{FB}}^{b,0}$ from the four lepton and five inclusive analyses are shown in Fig. 3. They represent the status of winter 2002 and are very consistent with each other. By taking into account correlations and common systematic errors as well as off-peak measurements in cases where available one obtains the LEP combined result of

$$< A_{\mathrm{FB}}^{b,0} >= 0.0994 \pm 0.0017 \quad . \qquad (5)$$

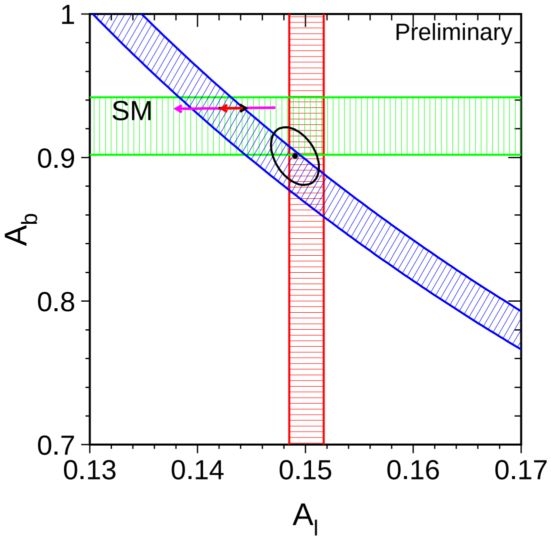

Figure 5. The measurements of the combined LEP+SLD $\mathcal{A}_l$ (vertical band), SLD $\mathcal{A}_b$ (horizontal band) and LEP $A_{\rm FB}^{b,0}$ (diagonal band), compared to the Standard Model expectation (arrow). For more details see [12].

The correlated systematic error arises from mainly physics like QCD correction and light quark fragmentation and turns out to be very small, as quoted in Fig. 3.

According to Eqn. 1 the measurement of $A_{\rm FB}^{b,0}$ can be used together with direct lepton $A_{\rm FB}$ measurements and $A_{\rm LR}$ from SLD to determine $\sin^2\theta_{\rm eff}^{\rm lept}$. This combination is illustrated in Fig. 4 and shows that the lepton and heavy quark results are not very consistent with each other: the probability for the fit is 6%. The electroweak fit however gives no clear hint of a problem in the Standard Model: For example Fig. 5 shows that LEP and SLD are not inconsistent if both $\mathcal{A}_b$ and $\mathcal{A}_l$ are free parameters, there is a region of common overlap. Although this agrees poorly with the Standard Model expectation, a single result like LEP's $A_{\rm FB}^{b,0}$ can still be well compatible.

Via higher order corrections to $\sin^2\theta_{\rm eff}^{\rm lept}$, $A_{\rm FB}^{b,0}$ is sensitive to m_h. Interestingly it is the only quantity that prefers a high higgs mass, thus making the electroweak fit more compatible with the direct exclusion limit on m_h [12,13].

There is just as little ground for a theoretical as there is for an experimental problem: It is the careful work on model-independence and self-calibration methods that has led to continued preliminarity or only very recent publication of the $A_{\rm FB}^b$ results. Additionally, final detector calibrations are only available for a few years, and the tools like the charge neural networks have been developed lately, with feedback from analyses.

5. Concluding remarks

Heavy flavour foward-backward asymmetries have been measured at LEP with various powerful and sophisticated techniques, giving very precise and consistent results. Partly motivated by the fact that their final results will not be superseded by new experiments for many years, they are still very interesting to study and are often dealt with by papers on the electroweak fit in the light of theories beyond the Standard One.

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