A\textsuperscript{b}_{FB} STATUS OF RESULTS

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The status of results on forward-backward asymmetry in Z → bb decays is reviewed. A comparison of LEP measurements, with emphasis on the final ALEPH measurement with leptons, and a critical discussion of average from heavy flavour electroweak combination is presented.

1 Introduction

The high efficiency and purity with which b-quarks can be tagged allow precise measurements of the forward-backward asymmetry in Z → bb decays, A\textsuperscript{b}_{FB}, defined as

\[ A_{FB}^{b} = \frac{\sigma_{F} - \sigma_{B}}{\sigma_{F} + \sigma_{B}}, \]

where the cross sections are integrated over the full forward (F) and backward (B) hemisphere. This asymmetry is the observable with the highest sensitivity to \(\sin^{2}\theta_{\text{eff}}^{W}\) at LEP and thus an important test of the Standard Model.

Most experiments measure \(A_{FB}^{b}\) from a fit to the differential cross section with respect to the scattering angle:

\[ \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1 + \cos^{2}\theta) + A_{FB}^{b}\cos\theta. \]

This is statistically more powerful than using Equation 1 and is independent of non-uniform angular acceptance. The scattering angle \(\theta\) is measured using the thrust axis of the event, oriented along the antiquark-quark direction. Therefore to measure the b forward-backward asymmetry the quark flavour needs to be tagged and the quark has to be separated from the antiquark. Several methods have being exploited by the four LEP collaborations.

Leptons issued by direct \(b \rightarrow \ell\) decays provide both flavour and charge tag. Thanks to the hard fragmentation and high mass of b-quarks they are characterised by large total and transverse momenta, \(p\) and \(p_{\perp}\), and their charge is correlated to the decaying quark charge. However the quark charge at production is the relevant quantity for the asymmetry measurement, so corrections are required for the effects of \(B^{0} - \bar{B}^{0}\) mixing.

Lifetime based taggings are also used to select high purity samples of b-quarks, the quark charge then being estimated by jet- and vertex-based charge taggings.

Any analysis measures the asymmetry in the selected sample as given by:

\[ A_{FB}^{\text{meas}} = \sum_{q} (2\omega_{q} - 1)\eta_{q}A_{FB}^{q}, \]
Table 1: Sample composition for $p_\perp > 1.25$ GeV in the ALEPH lepton sample. The correlation between the lepton charge and the decaying quark charge is also shown.

| Lepton source          | fraction ($p_\perp > 1.25$ GeV) | charge correlation |
|------------------------|----------------------------------|--------------------|
| $b \rightarrow \ell, b \rightarrow \bar{c} \rightarrow \ell$ | 0.795                           | 1                  |
| $b \rightarrow c \rightarrow \ell$                            | 0.046                           | $-1$               |
| $c \rightarrow \ell$                                           | 0.048                           | 1                  |
| background             | 0.111                           | weak               |

where $\eta_q$ is the fraction of $Z \rightarrow q\bar{q}$ events in the sample and $\omega_q$ is the probability to correctly tag the quark charge. These are usually estimated on Monte Carlo simulated events and depend on many parameters used to tune the simulation to the real data. Some of these physics inputs are also measured using data collected at the Z peak and therefore have common systematics between them and with the asymmetry. The four LEP collaborations and SLD have agreed on a common list of these physical quantities and on an averaging procedure to take into account correlations, resulting in a simultaneous fit of the most important heavy flavour electroweak observables.

The only new result on $A_{FB}^b$ at this conference is the final ALEPH result with leptons, therefore emphasis is given here to LEP measurements using leptons. A review of the results obtained with jet-charge based measurements can be found elsewhere. The impact on the heavy flavour electroweak combination of the new ALEPH measurement is also discussed in detail.

2 $A_{FB}^b$ measurement with leptons

As pointed out before, leptons are a powerful tool for tagging b quarks/antiquarks. However high momentum leptons are also produced in $c \rightarrow \ell$ decays, even if with a lower transverse momentum, as this is limited by half the quark mass. Both $b$- and $c$-quarks decays in electrons or muons with a branching ratios of about 10%. These leptons always have the same charge sign as the decaying quark, but for charm decays an antifermion is produced out of a fermion. Because of this fermion/antifermion flip, cascade decays $b \rightarrow c \rightarrow \ell$ have opposite forward-backward asymmetry with respect to direct $b \rightarrow \ell$ decays. The same holds for $c \rightarrow \ell$ decays, since $A_{FB}^c$ has the same sign as $A_{FB}^b$. Therefore the measured $A_{FB}^b$ shows a large sensitivity to the sample composition. In addition the asymmetry in $b$ events is also diluted because of $B^0 - \bar{B}^0$ mixing by a factor $1 - 2\bar{\chi}$, where

$$\bar{\chi} = \chi_d f_{B_d^0} \frac{BR(B_d^0 \rightarrow \ell)}{BR(b \rightarrow \ell)} + \chi_s f_{B_s^0} \frac{BR(B_s^0 \rightarrow \ell)}{BR(b \rightarrow \ell)}$$

is the integrated mixing parameter ($f_{B_d^0}$ and $f_{B_s^0}$ are the production fractions of $B_d^0$ and $B_s^0$).

I will discuss in the following how the flavours and direct/cascade decays are separated and how $\bar{\chi}$ is measured from the data themselves.

2.1 Multivariate analysis

In an analysis based simply on lepton total and transverse momentum, $A_{FB}^b$ can be measured on a sample enriched in $b \rightarrow \ell$ decays by a cut on the lepton transverse momentum. As an example, Table shows the sample composition for the ALEPH lepton sample, requiring a lepton transverse momentum greater than 1.25 GeV, and the correlation between the lepton charge and the quark charge at decay time. On the contrary $c \rightarrow \ell$ decays can be only poorly separated on a statistical basis from $b \rightarrow c \rightarrow \ell$ decays using these variables.
To enhance the sensitivity on both $A^b_{FB}$ and $A^c_{FB}$, ALEPH, DELPHI and OPAL use multivariate analyses, which allow to improve the separation between the different contributions to the lepton sample.

To distinguish the event quark flavour, in addition to the lepton $p$ and $p_\perp$ ALEPH uses information from:

- lifetime tags based on the transverse impact parameter of tracks and on inclusively reconstructed secondary vertices;
- missing energy due to neutrinos produced in semileptonic quark decays;
- quark-mass related tags: sum of transverse momentum of tracks in the most energetic jet of the event and momentum of the highest momentum particle of the event;
- a $D^{*\pm}$ tag based on the soft pion issued in $D^{*\pm} \to D^0\pi^{\pm}$ decays.

All these variables are combined in a neural network trained to separate $b$ from uds events. Because of the limited acceptance of the vertex detector, the discriminating power of the above variables (the lifetime tag ones in particular) depends on the thrust $|\cos \theta|$ and therefore this variable is also used in the neural network as a control variable. The distributions of the two neural network outputs, called $N_b$ and $N_{uds}$, are shown in Figure 1. Since $Z \to c\bar{c}$ events have intermediate properties a good discrimination of all the three flavours is obtained in the plane $(N_b, N_{uds})$.

In order to separate $b \to \ell$ and $b \to c \to \ell$ decays the discriminating power of lepton $p$ and $p_\perp$ is improved using the different properties of the lepton jet in direct and cascade decays. Several variables are built to distinguish whether in the jet, lepton excluded, only D decay products or both D and “virtual” W decay products are present. These variables are then combined with the lepton kinematic properties in a neural network, which output is called $N_{bl}$. Figure 2

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The determination of $A^b_{FB}$ also profit from a better measurement of $A^c_{FB}$, because of its dependence on it.

Here uds events are referred all together as a single “light-quark” flavour, since in this context their properties do not differ significantly.
Figure 2: Distribution in bins of \((N_b, N_{bl})\) in the \textit{Aleph} Monte Carlo simulation.

shows the distribution of the different processes in bins of \(N_{bl}\) versus \(N_b\) in a simulated sample enriched in \(b\) and \(c\) content by a cut on the \(N_{uds}\) variable. The three main sources of leptons are clearly well separated. The binning of the neural network outputs is chosen as to ensure an almost equal occupancy of the different bins, in order to minimise statistical fluctuations in the simulated sample.

The use of lepton jet variables to enhance the separation of direct from cascade decays has been pioneered by \textit{OPAL}. In their analysis two neural networks, respectively for \(b \rightarrow \ell\) and \(c \rightarrow \ell\) decays, are built combining these variables with lepton \(p\) and \(p_{\perp}\), a mass tag and two lifetime tags (one based on the impact parameter of the tracks belonging to the lepton jet and the other most energetic jet in the event, the other based on the lepton impact parameter). The latest are actually used only as anti-\(b\) tag in the \(c\) neural network, since the \(b\) one is aimed at separating \(b \rightarrow \ell\) from both lighter quarks decays and \(b \rightarrow c \rightarrow \ell\) decays. As a consequence in the plane defined by the two neural network outputs, the \(b \rightarrow c \rightarrow \ell\) decays are not well separated from the background due to \(uds\) and \(c\) events, with some loss of information on \(A_{FB}^{B}\).

On the other hand, the separation of \(c \rightarrow \ell\) decays from other sources of leptons (either true or

\(^{\text{A Monte Carlo sample of about 8 million hadronic Z decays is used, as well as two dedicated heavy flavour}}\)
\(^{\text{samples of 5 million Z \rightarrow bb decays and 2.4 million Z \rightarrow c\bar{c} decays. These figures must be compared with a full}}\)
\(^{\text{LEP1 statistics of about 4 millions hadronic Z decays. With the chosen binning the effect of statistical fluctuations}}\)
\(^{\text{in the simulated sample is found to be negligible.}}\)
fake) should be optimal, since a dedicated neural network is designed for this purpose.

**DELPHI** used a lifetime tag to better separate b-quarks and c-quarks and the correlation between the lepton charge and the jet-charge in the opposite hemisphere to enhance the separation of $b \to \ell$ to $b \to c \to \ell$ decays. This correlation is negative for $b \to \ell$ decays and positive for $b \to c \to \ell$ decays. The sign is reverted if the lepton comes from a neutral B meson which undergoes $B^0 - \bar{B}^0$ mixing. However in both cases using the jet-charge helps in tagging the correct quark charge at production time. The drawback is the consequent large statistical and systematic correlation with the jet-charge based measurements. Figure 3 shows the distributions of the discriminating variables in the muon sample.

### 2.2 Mixing measurement

The integrated mixing parameter $\bar{\chi}$ (Equation 3) is measured using dileptons events. If both leptons are produced by $b \to \ell$ decays, the measured fraction of like-sign dilepton events is proportional to $2\bar{\chi}(1 - \bar{\chi})$, allowing to extract $\bar{\chi}$. Background due to other processes and misidentified hadrons has to be taken into account too, but requiring both leptons to have a large $p_\perp$ or, even better, a $(b \to \ell)$-like neural network output, it is reduced at the 15% level.

The new **ALEPH** result for $\bar{\chi}$ is

$$\bar{\chi} = 0.1196 \pm 0.0049 \, \text{(stat.)} +0.0043 \, -0.0050 \, \text{(syst.)}. $$

The largest contribution to the systematic error is due to the modelling of semileptonic decays. It must be pointed out that the previous **ALEPH** result $\bar{\chi} = 0.1246 \pm 0.0051 \, \text{(stat.)} \pm 0.0052 \, \text{(syst.)}$, would be $\bar{\chi} = 0.1193$ if the latest measured values of the branching ratios $\text{BR}(b \to \ell)$, $\text{BR}(b \to c \to \ell)$ and $\text{BR}(c \to \ell)$ were taken into account, therefore the new result is fully compatible with the old one.
3 Results

The asymmetry is measured separately at each centre-of-mass energy point. The final ALEPH results are shown in Figure 4. These asymmetry measurements performed at peak and off-peak energies are extrapolated to \( M_Z \). Then the QED, QCD and \( Z - \gamma \) interference corrections are applied to obtain the pole asymmetry:

\[
A^0_{FB} = 0.0998 \pm 0.0040 \text{ (stat.)} \pm 0.0017 \text{ (syst.)}.
\]

Systematic uncertainties are shown in Table 2. The main systematic error is due to the uncertainty on the mixing parameter. This is mostly statistical, since the sources of systematic error are common and partially cancel out.

This measurement is combined with the inclusive ALEPH result and with the results of the other LEP experiments. The \( b \) forward-backward asymmetry is fitted together with the most relevant electroweak heavy-flavour observables and with the most important input parameters, taking into account the common systematics and the statistical correlation. Figure 5 shows the

| Error sources                  | \( \Delta(A^0_{FB}) \) |
|-------------------------------|-----------------|
| Semileptonic branching ratios | 0.034           |
| Lepton modelling              | 0.090           |
| Detector simulation           | 0.015           |
| Background asymmetries        | 0.002           |
| B and D physics               | 0.032           |
| Mixing                        | 0.132           |
| Total                         | 0.169           |
most precise $A_{FB}^{0,b}$ measurements included in the fit. The combination yields

$$A_{FB}^{0,b} = 0.0994 \pm 0.0017.$$  

The main error source is statistics, and the small systematic error is mostly uncorrelated between the different experiments, as shown in Table 3. All results, either using leptons or inclusive methods, are consistent between the four LEP collaborations.

With respect to the summer 2001 preliminary result\footnote{The combination procedure already took into account the changes in the branching ratios values with respect to the time the previous $\bar{\chi}$ measurement was published, so the $\bar{\chi}$ value used in the fit is unchanged with respect to summer 2001.}, $A_{FB}^{0,b} = 0.0990 \pm 0.0017$, the average has changed by a quarter of a sigma because of the final ALEPH result. As we have shown before, this change is not due to the new measurement of the mixing parameter $\bar{\chi}$.\footnote{The combination procedure already took into account the changes in the branching ratios values with respect to the time the previous $\bar{\chi}$ measurement was published, so the $\bar{\chi}$ value used in the fit is unchanged with respect to summer 2001.} The ALEPH measured $A_{FB}^{b}$ and to a less extent the other LEP measurements, have changed because of the final ALEPH measurement of $A_{FB}^{c}$. With respect to the preliminary result\footnote{The combination procedure already took into account the changes in the branching ratios values with respect to the time the previous $\bar{\chi}$ measurement was published, so the $\bar{\chi}$ value used in the fit is unchanged with respect to summer 2001.}, off-peak energies measurements have been performed and a problem due the too large number of bins in which the analysis was performed has been fixed. This measurement, $A_{FB}^{0,c} = 0.0732 \pm 0.0053$ (stat.) $\pm 0.0037$ (syst.), is today the most precise LEP result on $A_{FB}^{0,c}$. 

Figure 5: $A_{FB}^{0,b}$ measurements used in the heavy flavour combination. The $A_{FB}^{0,b}$ measurements with D-mesons contribute only very little weight and are not shown in the plot. The values shown are corrected to the same input parameters (including the other fitted observables which are fixed to the results of the full fit).
Table 3: Sources of uncertainty on $A_{FB}^{0,b}$ average. Numbers are given in units of $10^{-2}$

| Error sources         | $\Delta(A_{FB}^{0,b})$ |
|-----------------------|------------------------|
| Statistics            | 0.16                   |
| Internal systematics   | 0.06                   |
| Common systematics     | 0.04                   |
| Total Systematics      | 0.07                   |
| Total                 | 0.17                   |

4 Conclusions

The status of $A_{FB}^{b}$ measurements has been discussed with particular emphasis on the final ALEPH measurement with leptons

$$A_{FB}^{0,b} = 0.0998 \pm 0.0040 \text{ (stat.)} \pm 0.0017 \text{ (syst.)}.$$  

Using this new result the heavy flavour electroweak combination yields

$$A_{FB}^{0,b} = 0.0994 \pm 0.0017.$$  

All results, either using leptons or inclusive methods, are consistent between the four LEP collaborations.

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