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HEAVY QUARK ASYMMETRIES AT LEP

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Abstract

Measurements of b and c quark asymmetries using data collected at LEP 1 are described. The relative merits of each of the individual techniques used is emphasised as is the most profitable way of combining them. Effects of radiative corrections are discussed, together with the impact of these measurements on global electroweak fits used to estimate the expected mass of the Higgs boson.

1 Motivation for Measuring Quark Asymmetries

The accurate determination of the forward-backward asymmetries, A_{FB}, of quarks serves to test the structure of Standard Model (SM)[1] couplings to fermions. They also probe radiative corrections to the SM and consequently allow greater precision when predicting unknown parameters of the model. These are increasingly used to constrain uncertainties on the mass of the Higgs boson[2].

Global fits to electroweak data assume the SM structure of Z couplings to leptons (e, $\mu\,\tau$) and both up (u, c) and down-type (d, s, b) quarks. Given recent, highly accurate, lepton measurements from the τ polarisation[3] and purely leptonic forward-backward asymmetries[2], a similar precision in the quark sector is needed to confirm the internal consistency of the model.

The suite of complimentary measurements described here provide such a precision for both up and down-type quark families. Performing these measurements at LEP 1 offers several advantages. The sensitivity of initial state couplings to the effective weak mixing angle, $\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}$, is compounded by large, measurable asymmetries from quark final states close to the Z. Heavy quark asymmetries in particular are especially favourable, as flavour and direction of the final state quark can be tagged with greater ease than is the case with lighter quarks.

2 Definitions and Experimental Issues

In the SM, the differential cross-section for the process $e^+\,e^- \to f^+\,f^-$ can be written as :

$$\frac{1}{\sigma}\,\frac{\mathrm{d}\,\sigma^f}{\mathrm{d}\,cos\,\theta} \;=\; \frac{3}{8}\,(1+cos^2\theta) \;+\; A_{\mathrm{FB}}^f\,cos\,\theta \tag{1}$$

where A_{FB}^f defined to be the forward-backward asymmetry for fermion flavour, f. It can be expressed as :

$$A_{\mathrm{FB}}^f \;=\; \frac{3}{4}\,\mathcal{A}_e\,\mathcal{A}_f \tag{2}$$

where $\mathcal{A}_f$ is the polarisation of the fermion concerned :

$$\mathcal{A}_f \;=\; \frac{2x}{1+x^2} \;=\; 1\,-\,\frac{2q}{I_3^f}\,(\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} \,+\, \mathcal{C}_f) \tag{3}$$

where x is the ratio of the vector and axial couplings of the fermion to the Z. This final form, separates the terms containing sensitivity to parameters of the SM, such as (m_{t}, m_{H}) through $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$, from vertex corrections in $\mathcal{C}_f$. The latter are typically of the order of $\sim 1\%$ for b quarks[4].

For hadronic decays of quarks, the precise direction of the final state fermion is not accessible experimentally, and so the direction of the thrust axis is usually signed according to methods of correlating the charge of the quark its final decay products. Asymmetries are of the order of $\sim 10\%$ for b and c quarks but are diluted by several effects. These are caused primarily by the correlation method mistagging the quark charge, or by $B^0\bar{B}^0$ mixing or cancellations between other quark backgrounds.

Consequently, the methods of measurement described here represent different compromises between rates of charge mistag, and the efficiency+purity of the flavour tagging procedure. With the increasing sophistication of analyses, several methods of tagging the charge and flavour of decaying quarks are available. These are applied either singly or in combinations.

Minor complications arise when interpretating the results of these analyses, in the form of corrections to pure electroweak predictions of heavy quark asymmetries. For example, quark mass corrections to the electroweak process are generally small, *eg.* representing shifts of 0.05% in the calculation of A_{FB}^b, and are well understood theoretically[4]. Larger and more problematic corrections arise from hard gluon emission in the final state. These so-called QCD corrections are mass, flavour and analysis dependent and so their treatment and associated uncertainties must be handled with care.

3 Latest Techniques for Measuring A_{FB}^b

3.1 Semileptonic Decays of Heavy Quarks

The "classical" method of measuring heavy quark asymmetries relies on differences in the momentum and transverse momentum, (p, p_{T}), spectra of leptons arising from semileptonic b and c quark decays. This method benefits from an unambiguous charge and flavour tag in the case of unmixed b and c hadrons. It however suffers from several disadvantages when used on a more general sample.

The methods reliance on a pair of correlated inputs, such as lepton (p, p_T)alone, leads to a dependence of the method on the precise values of the branching ratios, $\mathrm{BR}(b \to l)$ and $\mathrm{BR}(b \to c \to l)$, semileptonic decay modelling and c branching fractions assumed in Monte Carlo simulations. Some uncertainties are constrained by full use of measurements from lower energy experiments, according to the prescription detailed in[2]. However, the extrapolation of such measurements to LEP energies, and into the different environment of a fragmented jet containing a b-hadron, leaves residual systematic uncertainties. As the purity of the sample, and its charge mistag, are determined by Monte Carlo simulation alone these residual uncertainties are correlated between the 4 LEP experiments.

The relatively small value of the $(b \to l)$ branching fraction means that an overall b tagging efficiency of the order of $\sim 13\%$ is typically achieved with reasonable purities of eg. $\sim 80\%$ in the case of[5]. Effects of $B^0 \bar{B}^0$ mixing, "cascade" b decays $(b \to c \to l)$, backgrounds from c decays $(c \to l)$ and other light quark sources, including detector misidentification, all serve to dilute the otherwise excellent mistag rate.

The systematic impact of such effects can be severely reduced by fitting simultaneously for the the time-integrated mixing parameter, $\bar{\chi}^{1)}$, together with the b and c asymmetries in a "global" fit. Otherwise both $\bar{\chi}$ and A_{FB}^c are inputs to the determination of A_{FB}^b. Their values and uncertainties are either fixed by experiment or, in the case of A_{FB}^c, set to their SM expectation and the dependence on A_{FB}^bused as input to subsequent electroweak (EW) fits[2]. Uncertainties can be further minimised by adding input information which discriminates between b and c events. In such analyses[6, 7] information coming from lifetime tags, using silicon vertex detectors (VDET's), and event shapes amplify the discrimination from semileptonic (p, p_T)spectra.

The LEP experiments make use of such additional inputs, and extra fit quantities, to varying degrees as is summarised in Table 1. Analyses which make use of the classical semileptonic (p, p_T)spectra, and complement

Inputs	lepton (p, p_T)	lifetime	jet shapes	$\bar{\chi}$
Expt.	**ADLO**	**DO**	**DO**	**DL**
Outputs	A_{FB}^b	$\bar{\chi}$	A_{FB}^c	
Expt.	**ADLO**	**AO**	**DO**	

Table 1: *Additional inputs and fit parameters for the semileptonic decay measurements of $A_{\mathrm{FB}}^b$from the 4* LEP *collaborations* ALEPH, DELPHI, L3 *and* OPAL (ADLO).

it with lifetime tags in this way, are the most powerful, statistically and with greater systematic control. For example, the OPAL measurement[7] uses lepton $(p, p_\mathrm{T})$and event-shape information as inputs to a neural net (NN) b tagging algorithm. In addition, it utilises a largely orthogonal c tag, based on lifetime information of jets in the event, combined with the impact parameter significance and detector identification criteria of the lepton. The output of these two neural nets is shown in Figure 1 where the strong separation between sources of leptons in hadronic events is clearly evident. The separation between b and c lepton sources, and the more limited distinction between those and other background sources, enables both an precise determination of A_{FB}^b, $\bar{\chi}$ and the most accurate measurement of $A_{\mathrm{FB}}^c$from the same sample of events. The net gain of such a method is an approximate $\sim 25\%$ improvement in the statistical sensitivity of $A_{\mathrm{FB}}^b$and a $\sim 25\%$ improvement in that of A_{FB}^c. A summary of the current results for A_{FB}^b from semileptonic measurements at LEP is given in Table 2.

Semileptonic Measurements of A_{FB}^b				
Experiment	A_{FB}^b	stat.	syst.	total
ALEPH	0.0965	± 0.0044	± 0.0026	± 0.0051
DELPHI	0.0979	± 0.0065	± 0.0029	± 0.0071
L3	0.0963	± 0.0065	± 0.0035	± 0.0074
OPAL	0.0910	± 0.0044	± 0.0020	± 0.0048
Lifetime and Jetcharge Measurements of A_{FB}^b				
Experiment	A_{FB}^b	stat.	syst.	total
ALEPH	0.1040	± 0.0040	± 0.0032	± 0.0051
DELPHI	0.0979	± 0.0047	± 0.0021	± 0.0051
L3	0.0855	± 0.0118	± 0.0056	± 0.0131
OPAL	0.1004	± 0.0052	± 0.0044	± 0.0068

Table 2: *Summary of latest measurements of $A_{\mathrm{FB}}^b$from the 4* LEP *experiments.*

$^{1)}\bar{\chi}$ is defined to be the probability that a B meson has oscillated to a $\bar{B}$ meson by the time of its decay.
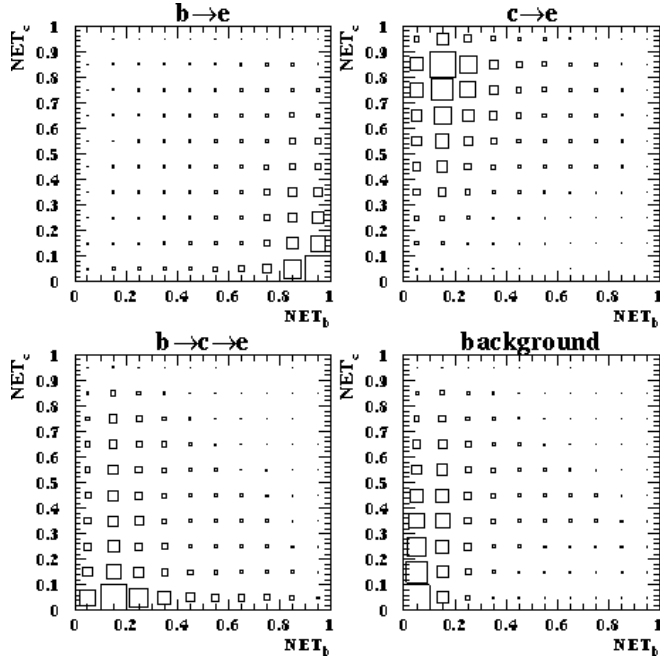
Figure 1: *Two-dimensional summary plot of the c tag neural net output vs. that of the b tag* NN *output for each of the expected lepton sources in the* OPAL *semileptonic asymmetry analysis. The areas of displayed pixels is proportional to the bin contents.*

3.2   Lifetime Tagging and Jetcharge Measurements

An alternative, complementary technique to measure A_{FB}^{b} is based on lifetime information from silicon vertex detectors. This is then combined with a fully inclusive charge correlation method, referred to as the "jetcharge" technique. This method was initially pioneered using samples of untagged hadronic events containing all types of quark flavours accessible at these energies[18]. As a consequence of the low semileptonic branching ratios, such inclusive measurements are almost entirely uncorrelated from semileptonic measurements and so can either be combined or used as a cross-check for consistency of measurements between different methods.

The jetcharge method is based upon the correlation between leading particles in a jet, with that of the parent quark. A hemisphere based jetcharge estimator is formed using a summation over particle charges, q, weighted by their momentum, $\vec{p}$:

$$Q_{\mathrm{F}} \; = \; \frac{\sum_{i}^{\vec{p_i}\cdot\vec{T}>0} \mid \vec{p_i} \cdot \vec{T} \mid^{\kappa} \; q_i}{\sum_{i}^{\vec{p_i}\cdot\vec{T}>0} \mid \vec{p_i} \cdot \vec{T} \mid^{\kappa}} , \qquad (4)$$

and analogously for Q_{B}. The κ parameter is used to optimise the measurement sensitivity. The charge flow between hemispheres, namely $Q_{\mathrm{FB}} = Q_{\mathrm{F}} - Q_{\mathrm{B}}$ is then used to sign the direction of the thrust axis. Currently all LEP collaborations use this method, and the above formalism.

The method benefits from many of the systematic studies performed in untagged samples[18], especially to understand the degree of charge correlation between hemispheres in background events and their light quark parents. The recent A_{FB}^{b} analysis carried out by DELPHI also illustrates this method[10]. In addition to jetcharge information, OPAL makes uses of a weighted vertex charge method[12]. This quantity is a weighted sum of the charges of tracks in a jet which contains a tagged secondary vertex, *ie* :

$$q_{\mathrm{vtx}} \; = \; \sum_{\mathrm{tracks}=i} \omega_i \, q_i \qquad (5)$$

where q_i is the charge of each track,i and ω_i is related to the probability that the tracks comes from the secondary vertex relative to that it came from the primary. The latter probabilities are determined using impact parameter, momentum and multiplicity information. An estimate of the accuracy of the q_{vtx} charge estimator is derived from its variance.

Selecting hemispheres with $\mid q_{\mathrm{vtx}} \mid > 1.4 \times \sigma_{\mathrm{q}} + 0.2$ largely removes neutral B^{0} mesons, and those with poorly measured vertex charges. This also leads to a severe reduction in the size of the event sample, leaving only $\sim 13,000$ events out of a total, untagged input of roughly 4 million hadronic events. Hence, the contribution of the vertex charge measurement, when combined with the jetcharge determination of A_{FB}^{b}, is relatively low.

More significant improvements in statistical precision and control of systematic uncertainties can be obtained from the variety of new techniques summarised in Table 3. Experiments make use of these techniques to varying

Expt.	Improvement
A L	Fit data as a function of tag purity.
A L	Increase acceptance beyond central region.
ADLO	Fit asymmetry as a function of angle.
A	Fit data using range of κ values.
ADO	Extract b quark mistag factor from data.
AD	Extract lighter quark mistags from data.

Table 3: *Recent improvements to the lifetime and jetcharge method for measuring A^b_{FB} from the 4 LEP collaborations ALEPH, DELPHI, L3 and OPAL (ADLO).*

degrees, the most significant of which being the improvement in statistical sensitivity gained by fitting to the asymmetry as a function of angle. With increased statistical precision, comes the need for improved systematic control. The most important of these being the extraction of the charge mistag factor for b quark from data. ALEPH, DELPHI and OPAL now perform this extraction while ALEPH also extracts it as a function of the polar angle of the thrust axis. This takes into account particle losses close to the edge of detector acceptance.

The output distributions from the ALEPH measurement are shown in Figure 2. The asymmetry measurement
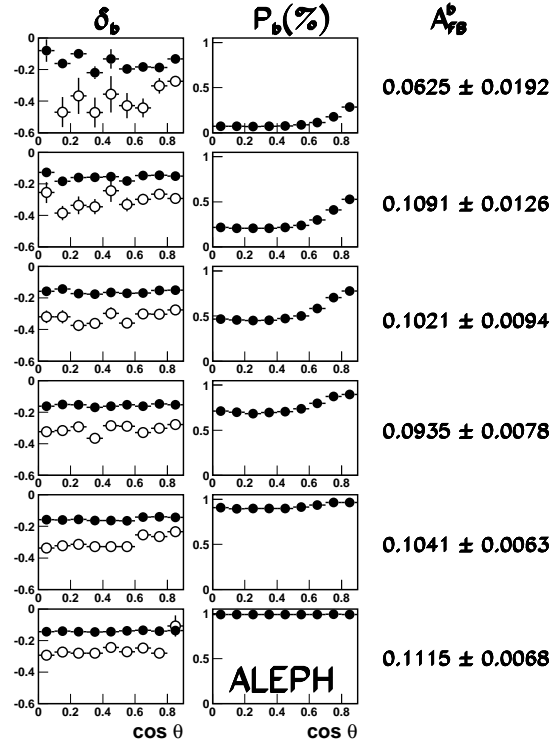

Figure 2: *Extracted fit variables from the ALEPH lifetime+jetcharge measurement of A^b_{FB}. Columns represent the b charge mistag factor and sample b purity as a function of angle in samples with increasing b purity. Filled and open circles represent κ values of 0.5 and 2.0 in equation (4) respectively.*

is made separately in each bin of polar angle, κ and b sample purity before being combined. Some points of interest in such new analyses include the increased statistical power arising from the bins at low angles, even those where the thrust axis lies outside the VDET acceptance. The large value of the asymmetry in these regions compensating for the low tagging efficiencies. The increase in sample b purity at large $cos\,\theta$ for high b purity samples, is due to the loss of tracks at the edge of the VDET acceptance. This affects b events the least, as more tracks with large p_T to the thrust axis continue to tag the event. This is true to a much lesser extent for lighter quark flavours.

Measurements of the b asymmetry using the lifetime and jetcharge method are also summarised in Table 2. It is interesting to note that such measurements, whilst providing similar sensitivity to A_{FB}^b as semileptonic b decays, as yet do not provide the possibility of analogous measurements of A_{FB}^c.

4 Latest Techniques for Measuring the c Asymmetry

In contrast to the incremental progress in the field of b asymmetries, measurements of the corresponding quantity in c decays have improved dramatically in recent years. Of the 4 LEP collaborations, DELPHI, L3 and OPAL have determined the c asymmetry as an output of global semileptonic fits to b and c decays[6, 8, 7] whereas ALEPH, DELPHI and OPAL have performed the same measurement using fully reconstructed samples of D meson decays[13, 14, 15]. As semileptonic measurements are discussed in Section 3.1, only the latter are described here.

The method of exclusively reconstructing D decays aim to use as many channels as possible by reconstructing the D^0 through its decay to $K^-\pi^+$. The D^0 is generally reconstructed[13] by taking all 2 and 4 track combinations and a π^0 candidate with zero total charge. Those combinations with odd charges are then used to form possible D^+ candidates. Each experiment reconstructs a different subset out of a total of 9 different decay modes. The dominant channels however are the $D^+ \to K^-\pi^+\pi^+$ and D^{*+} modes, with all modes offering some statistical power. Similarly, each experiment has different selection criteria in each mode, depending on the momentum and particle identification resolutions of the detectors.

These differences lead to widely varying efficiencies and signal-to-background ratios. For example, the DELPHI mass difference distributions for 4 of the 8 selected modes are shown in Figure 3. An important
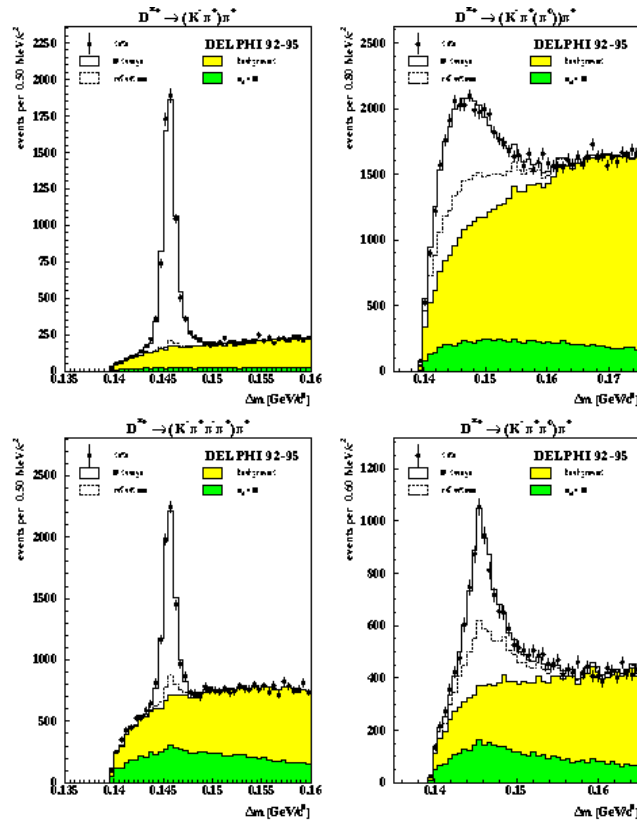

Figure 3: *Difference distributions between the mass of the D^{*+} and the D^0 candidate for different decay modes.*

advantage of such measurements is the ability to determine the background asymmetry, $A_{\mathrm{FB}}^{\mathrm{bkg}}$, from data, mode-by-mode using information from sidebands.

A major difficulty is encountered when trying to correct for the substantial fraction of events due to $B^0 \to D$ decays for $B^0 - \bar{B}^0$ mixing. Each D mode is corrected using an "effective" $\bar{\chi}$ depending on the expected fractions of B_{d}^0 and B_{s}^0 decays contributing to the mode concerned. These effective factors are determined from[16] using Monte Carlo simulation and so give rise to systematic uncertainties. The observed asymmetry, $A_{\mathrm{FB}}^{\mathrm{obs}}$, is then

found using :

$$A_{\mathrm{FB}}^{\mathrm{obs}} = f_{\mathrm{sig}}f_c A_{\mathrm{FB}}^c + f_{\mathrm{sig}}(1 - f_c)A_{\mathrm{FB}}^b + (1 - f_{\mathrm{sig}})A_{\mathrm{FB}}^{\mathrm{bkg}} \qquad (6)$$

where f_{sig} is the fraction of signal of signal+background events and f_c is the fraction of events containing a true D meson which are due to c quark events. As far as possible, the sample c purities, f_c, are determined from data using lifetime, mass and event-shape information in both hemispheres of events containing a D tag.

Each experiment makes use of lifetime information, with both DELPHI and OPAL using the D momentum and jet-shape information respectively in addition, so as to disentangle the substantial contamination from b decays. The DELPHI experiment does so in the context of a simultaneous fit to both b and c asymmetries. However, besides constraining systematic uncertainties, the precision available of A_{FB}^b is negligible compared to methods discussed previously.

The c asymmetry measurements described here are summarised in Table 4 and indicate that, despite complex systematics, such measurements remain primarily limited by the low efficiencies and purities of the D meson reconstruction. Systematic errors vary widely, with the time-dependence of the background asymmetry

Semileptonic Measurements of A_{FB}^c				
Experiment	A_{FB}^b	stat.	syst.	total
DELPHI	0.0770	±0.0113	±0.0071	±0.0133
L3	0.0784	±0.0370	±0.0250	±0.0446
OPAL	0.0595	±0.0059	±0.0053	±0.0079
Exclusive D Tag Measurements of A_{FB}^c				
Experiment	A_{FB}^b	stat.	syst.	total
ALEPH	0.0630	±0.0090	±0.0030	±0.0095
DELPHI	0.0658	±0.0093	±0.0042	±0.0102
OPAL	0.0630	±0.0120	±0.0055	±0.0132

Table 4: *Summary of latest measurements of A_{FB}^c from the 4 LEP experiments.*

remaining merely one of many dominant sources depending on decay mode and experiment.

5 Radiative Corrections to Asymmetry Measurements

Several small corrections must be made to the b and c asymmetries extracted from the described analyses. In the case of A_{FB}^b, QED corrections for ISR and FSR are relatively minor, amounting to -0.0041 and -0.00002 respectively. Similarly, corrections for pure γ exchange and $\gamma - Z$ interference diagrams give rise to a correction of +0.0003. Such corrections, are general in nature and so apply equally to all analyses.

A more difficult set of corrections involves those needed to correct for the presence of hard gluon radiation which can distort the angular distribution of the final state quarks when compared with the pure electroweak process. Estimates of such corrections to heavy quark asymmetries have been computed to first and second order in α_s both numerically[17] and, most recently, analytically[19] in different scenarios for either c, b or massless quarks.

A common procedure for correcting and ascribing systematic uncertainties for the LEP heavy quark asymmetries has been developed[20]. The more recent analytical calculations indicate several discrepancies when compared with the numerical results. These remain to be resolved. Current systematic uncertainties are determined using a procedure of comparing the effects between first and second order in QCD and by switching between massless quarks, and assumptions for the c and b quark masses.

Further difficulties arise when considering the application of such corrections to individual analyses. Theoretical calculations are typically based on the direction of the outgoing quark, whereas the analyses described here use the thrust direction. Further, the sensitivity to hard gluon radiation of data, containing either a lepton of a given (p, p_{T}), a reconstructed D meson or purely inclusive events, varies dramatically. Effects of non-perturbative QCD and higher-order effects during hadronisation must also be evaluated. The latter render QCD corrections both detector *and* analyses dependent, *eg.* event shape selections implying an implicit dependence on the strength of gluon emission. The correction to be applied to a given analysis is derived from :

$$A_{\mathrm{FB}}^{b,c} = (1 - \mathcal{C}_{b,c}\mathcal{S}_{b,c}) \mid_{\mathrm{no\ QCD}} \qquad (7)$$

where $\mathcal{C}_{b,c}$ represents the QCD correction at parton-through-to-hadron level, and $\mathcal{S}_{b,c}$ is the analysis dependent modification. Examples of the magnitude of the QCD corrections at the theoretical and experimental levels are shown in Table 5 for the cases of A_{FB}^b, determined using semileptonic and lifetime+jetcharge analyses[20].

		Lepton Analyses	Lifetime+Jetcharge
$\mathcal{S}_b$	min.	0.52 ± 0.06	0.24 ± 0.46
	max.	0.74 ± 0.07	0.36 ± 0.32
$\mathcal{C}_b$	min.	1.54 ± 0.28	0.71 ± 1.36
	max.	2.19 ± 0.37	1.07 ± 0.96

Table 5: *Summary of QCD corrections to A_{FB}^b for the different analysis methods.*

The constants are evaluated in terms of Monte Carlo simulations, before and after experimental cuts. The hadronisation dependence of corrections is included as a systematic uncertainty by comparing results from both the HERWIG[22] and JETSET[23] models. It is seen from comparing parton and hadron level that the effect of hadronisation is to reduce the magnitude of the QCD correction[2].

It is important to note that the corrections for lifetime+jetcharge measurements are negligible. Significant corrections are observed for both semileptonic, and D tag measurements of both A_{FB}^b and A_{FB}^c. Jetcharge measurements are immune to such corrections as the b-quark charge mistag factor is defined using Monte Carlo with respect to the original $b\bar{b}$ quark pair orientation, prior to gluon or final state photon radiation, parton shower, hadronisation and $B^0\bar{B}^0$ mixing. All these effects are therefore included, by construction, in the analyses, as far as they are properly modelled in the JETSET[23] hadronisation model.

6 Conclusion and Perspectives

With the completion of LEP data-taking at energies close to the Z resonance in 1995, the 4 experiments (ALEPH, DELPHI, L3 and OPAL), have accumulated large samples of hadronic events. From this data, the forward-backward asymmetry of the b quark has emerged as the most sensitive single test of the SM at LEP. The complementary c asymmetry measurements offer additional precison and a new window on couplings in the down-type quark family. The precision from semileptonic measurements of A_{FB}^b is now matched by that of lifetime+jetcharge measurements. The electroweak sensitivity of A_{FB}^c measurements now equals that obtained from combined quark asymmetries measured in untagged samples, highlighting the benficial effect of flavour tagging.

However, in light of these measurements great sensitivity to the couplings of the SM, the continuing discrepancy between electroweak results from LEP and SLD[24] make it essential to understand whether it is due to statistical fluctuations or systematic effects. Separating LEP measurements of A_{FB}^b into those from the two dominant techniques, and conservatively ignoring correlated systematic uncertainties, indicates that there is at most a 1.2σ discrepancy between semileptonic and lifetime+jetcharge measurements. This is insufficient to explain the LEP-SLD discrepancy but indicates that care must be taken when considering common systematics in leptonic decay modelling and fragmentation uncertainties. Further improvements in both b and c asymmetries are possible, as both sets of measurements are still dominated by statistics. For semileptonic analyses, the benefits of using both lifetime and lepton information are emphasised. In the case of the lifetime and jetcharge method, these are most likely to come in the form of improved b tagging efficiencies and extensions of tagging to lower angles. The situation for improvments to measurements of A_{FB}^c is more difficult as the number of available modes is exhausted, and efficient methods of tagging c events remain to be discovered.

At this point, without the prospect of significant, further LEP data-taking at the Z, it is important to focus upon the latest techniques which offer the greatest sensitivity to the couplings of the SM combined with systematic control. The measurements described here obtain combined precisions on the b and c asymmetries of 2.2% and 7.1% respectively. Hence, the goal of acheiving similar precision on the Z couplings to quarks, as that obtained for leptons, has been reached.

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