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P R E L I M I N A R Y

Measurement of the Forward-Backward Asymmetries in $Z \to b\bar{b}$ and $Z \to c\bar{c}$ Decays with Leptons

The ALEPH Collaboration

Abstract

The full sample of hadronic Z decays collected at the Z pole with the ALEPH detector is analysed in order to measure the forward-backward asymmetries in $Z \to b\bar{b}$ and $Z \to c\bar{c}$ events. The quark's electric charge is tagged by the charges of electrons and muons produced in c and b semileptonic decays. An attempt has been made to optimise both the flavour and $b \to l/b \to c \to l$ process separation. The b and c quark asymmetries at $\sqrt{s} = M_Z$ are measured simultaneously, and are determined to be : $A^b_{FB} = 0.0949 \pm 0.0040 \pm 0.0023$ and $A^c_{FB} = 0.0562 \pm 0.0053 \pm 0.0036$. In the framework of the Standard Model, these correspond to a value of the effective weak mixing angle of $\sin^2\theta^{eff}_W = 0.23228 \pm 0.00076$. These results are preliminary.

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1 Introduction

Benefitting from upgraded track reconstruction and improved particle identification, the recently reprocessed 4.1 million hadronic Z decays recorded with the ALEPH detector offer the opportunity to test Standard Model electroweak radiative corrections with an improved precision. The forward-backward asymmetries in heavy flavour decays of the Z boson are of special interest since they represent the highest experimental sensitivity at LEP to electroweak parameters.

The analysis presented in this note is aimed at refining the ALEPH measurement of the c and b asymmetries, using leptons issued from the semileptonic decays of heavy hadrons [1].

The measurement of $\mathrm{A}_{\mathrm{FB}}^{b}$ ($\mathrm{A}_{\mathrm{FB}}^{c}$) requires selection of $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ ($\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$) events and to identify the electric charge of the initial quarks. The latter is realized through the identification of electrons and muons originating from semileptonic decays of B hadrons. The selection of $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ events is performed by means of two multivariate analyses, aimed at improving the flavour separation within the lepton candidates sample. In addition, special attention has been directed towards the separation of the processes $\mathrm{b} \rightarrow \mathrm{l}$ and $\mathrm{b} \rightarrow \mathrm{c} \rightarrow \mathrm{l}$, the latter being the major source of dilution of the statistical significance of $\mathrm{A}_{\mathrm{FB}}^{b}$ measurement.

The $\mathrm{A}_{\mathrm{FB}}^{b}$ and $\mathrm{A}_{\mathrm{FB}}^{c}$ measurements are performed simultaneously in a fit to the polar angle distribution of events containing at least one identified lepton candidate in the parameter space of the three variables controlling the flavour and processes separation.

2 Event Selection

The sample of $\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$ events is selected as described in [2], using data collected by ALEPH in the years 1991-1995. This preliminary analysis uses a total of approximately four million hadronic Z decays, selected at the center-of-mass energy $\sqrt{s} = M_Z$. Within this sample, electrons and muons are identified according to the procedure described in [2]. However, in order to increase the statistics of the sample, electron candidates are required to have a momentum p greater than 2 GeV/c, while muon candidates are required to have $p > 2.5$ GeV/c. Futhermore, in addition to the dE/dx information from the TPC (Time Projection Chamber), the TPC pad dE/dx is also used to identify electrons [3]. A total of 535,047 lepton candidates are selected.

3 Principles of the Method

Measurement of $\mathrm{A}_{\mathrm{FB}}^{b}$ and $\mathrm{A}_{\mathrm{FB}}^{c}$ requires an estimate of the quark-antiquark direction. It is determined from the polar angle of the reconstructed thrust axis of the event. The tag of the initial quark charge is obtained from the charge of the lepton (a negative charged lepton signs a b or a $\bar{c}$ quark, in the absence of mixing and cascade decays).
The signal events are $b \rightarrow l^-$ ($\bar{b} \rightarrow l^+$) and $c \rightarrow l^+$ ($\bar{c} \rightarrow l^-$) respectively for $\mathrm{A}_{\mathrm{FB}}^{b}$ and $\mathrm{A}_{\mathrm{FB}}^{c}$. The relevant point for the c and b asymmetry measurements is the isolation of these processes from each other and from all other contributions. The method of the measurement consists of, firstly, separating the quark flavours in the lepton candidate sample. Flavour separation is achieved by means of two multivariate quantities, denoted N_b and N_{uds}, respectively to tag $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow$ uds events. As shown in Figure 1, $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$, $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ and $\mathrm{Z} \rightarrow$ uds fill different regions in the plane (N_b,N_{uds}).

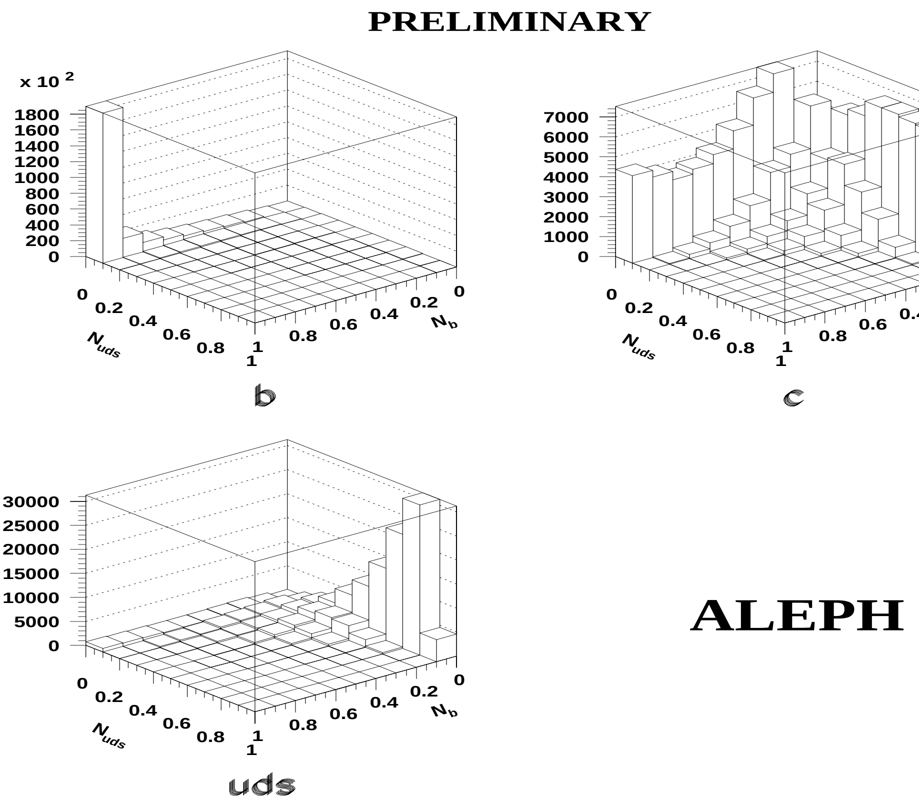

Figure 1: The distribution of the b, c and uds events in the plane of the two multivariate quantities (N_b,N_{uds}).

The variables used to form the multivariate quantities are described in the following section. An accurate A_b measurement requires furthermore to separate $b \to l$ and $b \to c \to l$, both supporting the asymmetry A_b, except for the sign flip. A dedicated multivariate analysis is also used for this purpose.

3.1 The flavour separation

Two multivariate analyses using neural networks have been conducted to tag both $Z \to b\bar{b}$ and $Z \to$ uds events. The goal is to combine the most discrimating event characteristics, taking into account their correlations.

3.1.1 b-tagging

To isolate b events, the following set of variables are considered and some of their distributions is plotted in the Figure 2:

- P_E, the lifetime probability of the event, built with an impact parameter-based algorithm [5];
- p, the lepton momentum;
- $p_\perp$, the transverse momentum with respect to the nearest jet axis, lepton excluded;
- $\not{E}$, the missing energy of the event;
- $\sum\limits_i p^2_{\perp i}$, where $p_{\perp i}$ is the transverse momentum of the i^{th} track of the most energetic jet in the event;

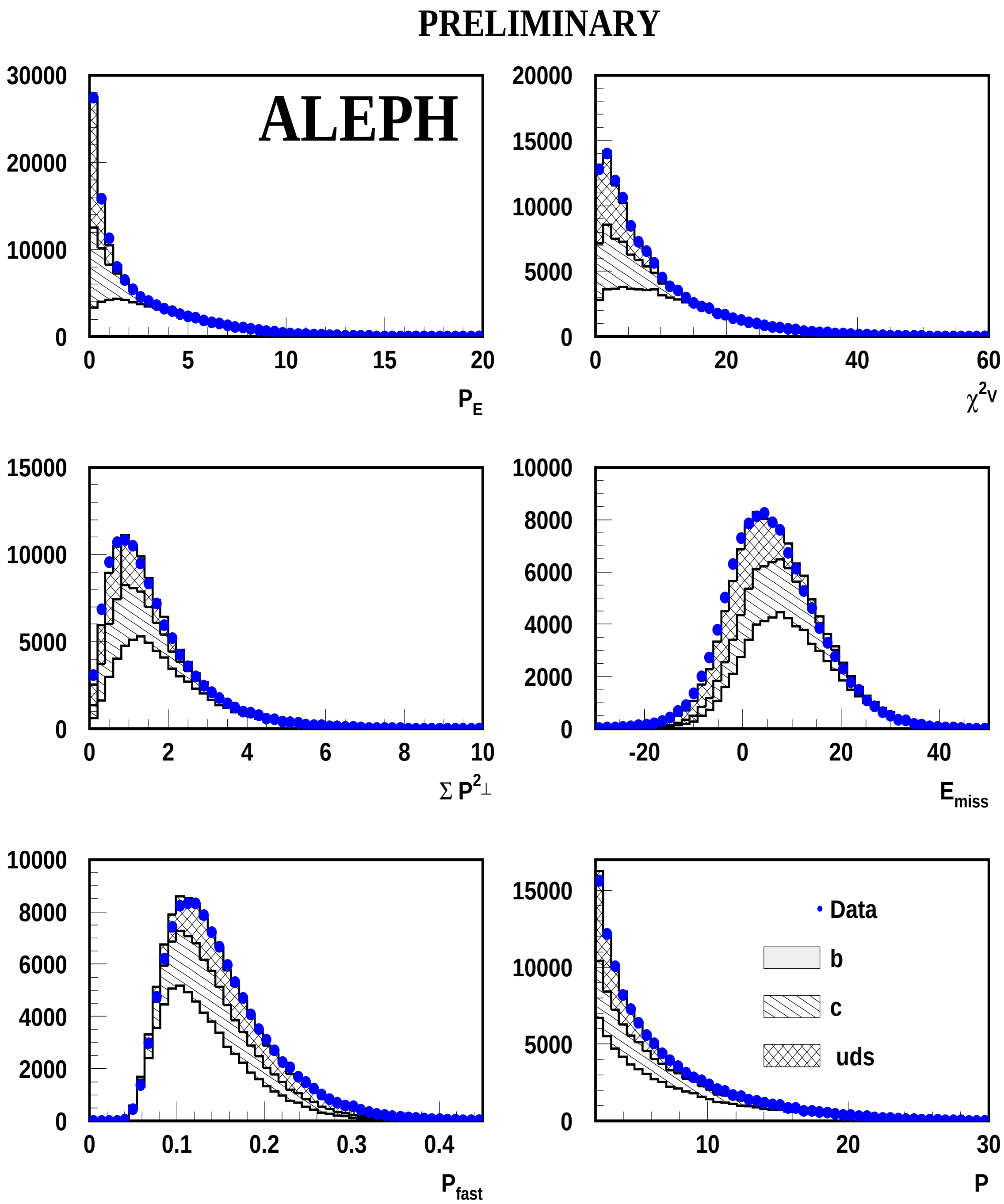

Figure 2: Distributions of the most discriminating variables used in the construction of the combined variables N_b and N_{uds}.

- $\frac{d}{\sigma_d}$, the lepton's impact parameter significance.

The long lifetime of B hadrons (which affects P_E,$\frac{d}{\sigma_d}$), the high mass of the b quarks (entering through $\sum_i p^2_{\perp i}$, which measures the width and the multiplicities of the most energetic jet) and the related kinematical lepton properties (p,$p_\perp$) are used to construct the quantity N_b. Its distribution is shown Figure 3.

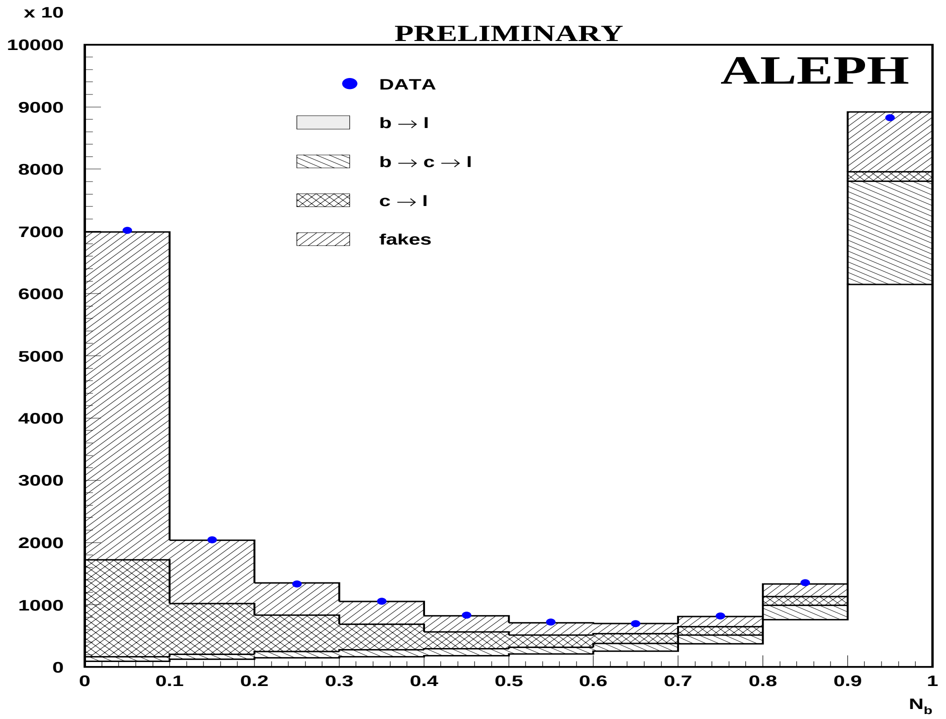

Figure 3: The distribution of the combined variable N_b.

3.1.2 Light quarks tagging

Following the same strategy of combining the information using a neural network, four variables are considered to tag Z → uds events in the lepton candidate sample :

- χ^2_V, the probability for a secondary vertex to be found in the event;
- E_{vis}, the visible energy of the event;
- p_{fast}, the momentum of the fastest particle of the event;
- $p^2_{\perp\pi_s}$, the transverse momentum of the π_s candidate [1] with respect to the nearest jet axis.

The search for secondary vertices in the event, the $p^2_{\perp\pi_s}$ and the visible energy of the event serves to reject b events and c events. The visible energy is useful when an energetic neutrino is produced in a semileptonic heavy hadron decay. p_{fast} is specifically designed for uds tagging; the fastest particle of the event being often directly issued from the initial light quark. χ^2_V and p_{fast} are shown Figure 2. These four quantities are combined with the help of a neural network to form the discriminating variable N_{uds} plotted Figure 4.

[1] The π_s candidate is issued from the decay $D^{**} \rightarrow D^{*}\pi_s$.

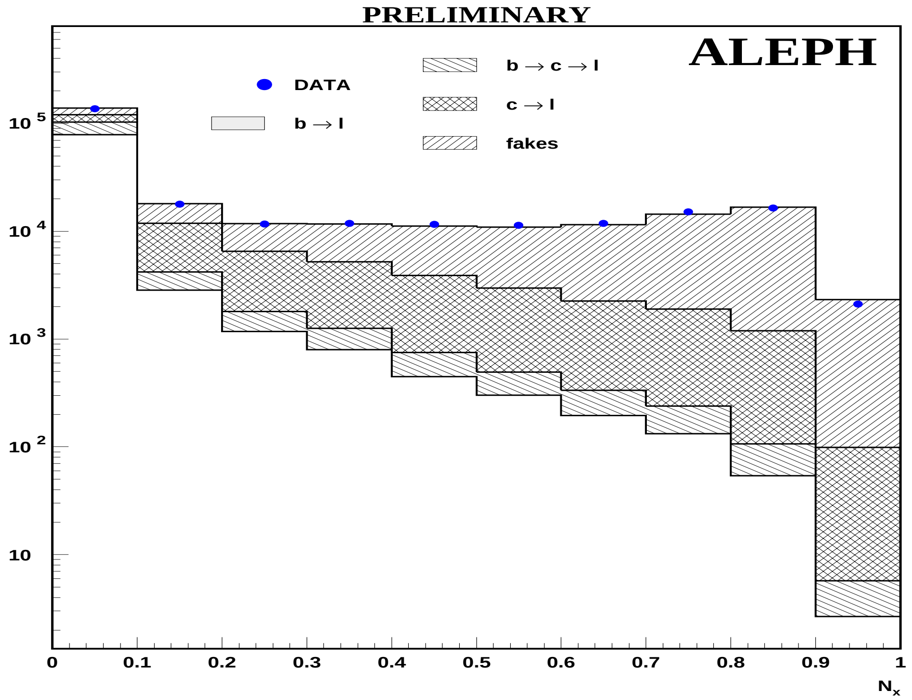

Figure 4: The distribution of the combined variable N_{uds}.

3.2 b → l and b → c → l separation

Assuming flavour separation is perfectly realised, the statistical uncertainty on $\mathrm{A}^b_{\mathrm{FB}}$ evolves, to a first approximation, as the inverse of the difference $(f_{\mathrm{b}\to\mathrm{l}} - f_{\mathrm{b}\to\mathrm{c}\to\mathrm{l}})$ where $f_{\mathrm{b}\to\mathrm{l}}$ is the fraction of b → l events in the sample. This consideration emphasises the importance of achieving the best possible separation between these two processes. In ALEPH, only the kinematical properties of the b lepton have been used so far in that respect. The separation is improved upon here by considering the properties of the B hadron jet to which the lepton candidate belongs. The decays $B \to l\nu D$ and $B \to WD(D \to l\nu X)$ [2] lead to significantly different jet topologies (multiplicities, invariant mass, jet opening *etc* ...)

3.2.1 Jet clustering

Jet-finding with the JADE algorithm is used to associate the tracks to the initial parton, while the properties relevant for our purpose are linked to the primary B hadron. A different approach of clustering, first developed at LEP by OPAL [4] and based on a geometrical association of tracks, is therefore chosen to measure lepton jet properties. The purities in terms of B tracks and measured B energy of the subsequent jet are found to be improved with respect to that found with JADE.

3.2.2 Jet properties

The boost experienced by the B tends to dilute some of the topological differences underlined above between the b → l and b → c → l. It is therefore more relevant to study the separation by boosting back the tracks of the jet, without considering the neutrino (this frame will be referred to as the (lD) frame in the following). In the (lD) frame, two hemispheres are

[2] D refers to as pseudoscalar D^0 or D^+, vector D^* and orbitally excited $L = 1$ D^{**}.

defined according to the plane orthogonal to the lepton direction. Three variables are then constructed for b → l / b → c → l separation :

- E_{CM1} is defined as the sum of energies of the tracks belonging to the lepton hemisphere, excluding the lepton itself. Except for fragmentation tracks, the D and the l issued from the decay $B \rightarrow Dl\nu$ are by definition produced back to back in the (lD) frame. On the contrary, the lepton originating from the cascade decay $B \rightarrow WD(D \rightarrow Xl\nu)$ should be found close in phase space with the X system. A low value of E_{CM1} is therefore more especially characteristic of a b → l decay.

- $P_{lt} = \frac{|P_+ - P_-|}{P_+ + P_-}$ where P_+ is the sum of the parallel momenta of the jet tracks with respect to the lepton direction. P_{lt} acts on the fact that two "directions of hadronization" are experienced in most of the b → c → l decays (the c quark and the W decay). A high value of P_{lt} is thus more likely for the b → l events.

- $E_{jet} = \sum_i E_i$, where E_i is the energy of the i^{th} track of the jet.

3.2.3 Lepton kinematical properties

The high mass of the B hadron results in a large momentum and transverse momentum of the primary lepton. These well-known characteristics have been used, together with the jet properties, to achieve an improved b → l / b → c → l separation. In addition, the energy of the lepton candidate in the (lD) rest frame, its impact parameter significance defined as $\frac{d}{\sigma_d}$ and the missing energy of the event $\not{E}$ are also used as inputs. Figure 5 displays the distributions of the four most discrimating variables used for b → l / b → c → l separation.

3.2.4 Combination of the discriminating variables

A variable, denoted as N_{bl}, is built from the set of the eight discriminating variables defined above. Figure 6 shows the distribution of N_{bl} in a sample enriched in b events. The b → l / b → c → l separation is significantly improved with respect to what can be achieved with $p_\perp$ alone and the related improvement in the $\mathrm{A}^b_{\mathrm{FB}}$ statistical uncertainty is estimated to be approximately 10%.

4 The Fitting Method

The asymmetries are extracted from a fit of a binned Log likelihood to the distribution of events in the space $(N_b, N_{uds}, N_{bl}, x)$, where x is the signed quantity $-Qcos(\theta_{thrust})$.
The total Log likelihood is

$$-\ln\mathcal{L} = -\sum_{i=1}^{N_1}\sum_{j=1}^{N_2}\sum_{k=1}^{N_3}\sum_{l=1}^{N_4} n_{ijkl}(\ln f_{ijkl}) \qquad (1)$$

where (N_1,N_2,N_3,N_4) = (10,10,10,20) are the number of bins for each dimension $(N_b, N_{uds}, N_{bl}, x)$, n_{ijkl} is the number of lepton candidates in the data sample in the bin

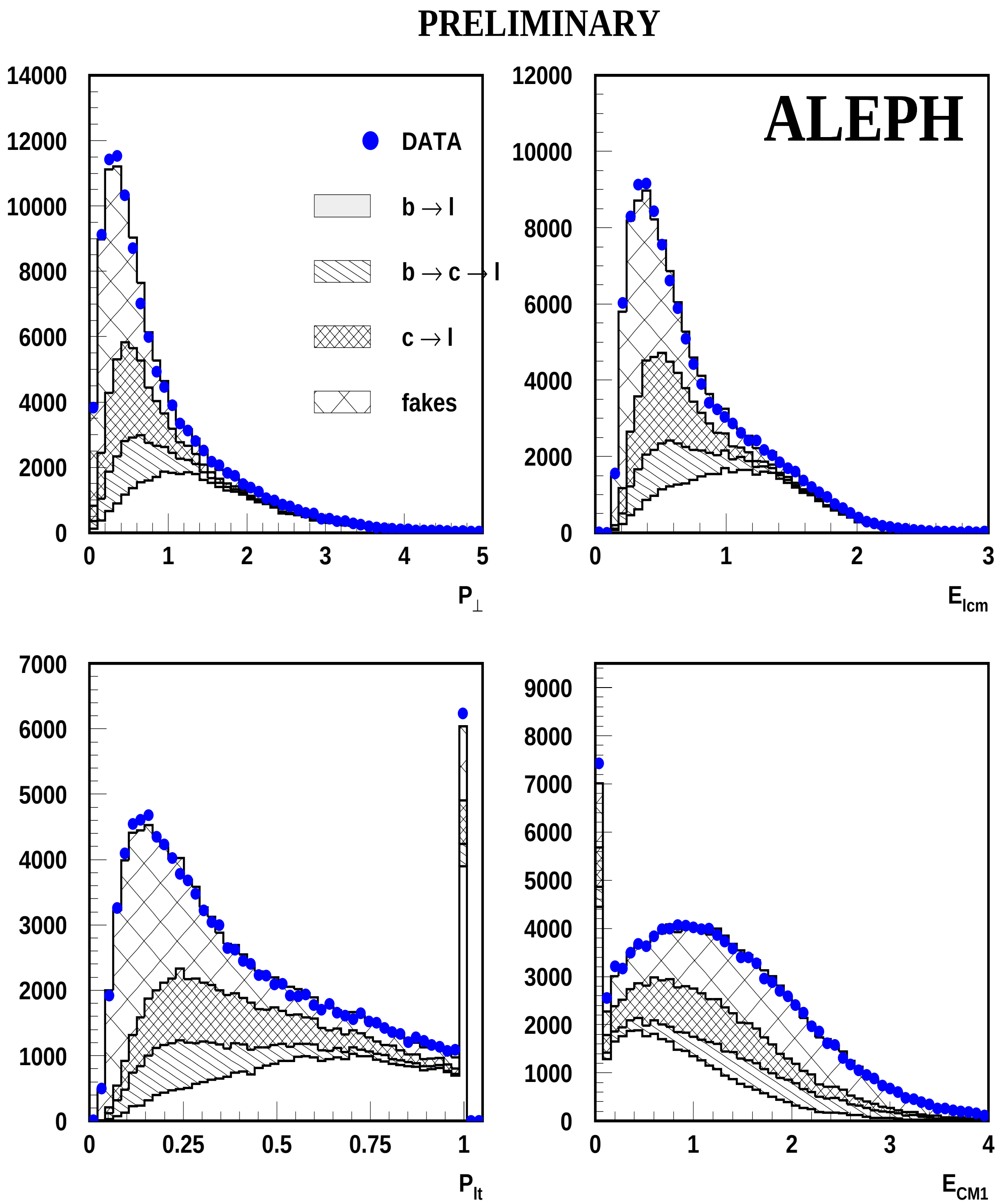

Figure 5: Distributions in data and MC events of the four most discriminating quantities used in the construction of the combined variable N_{bl}.

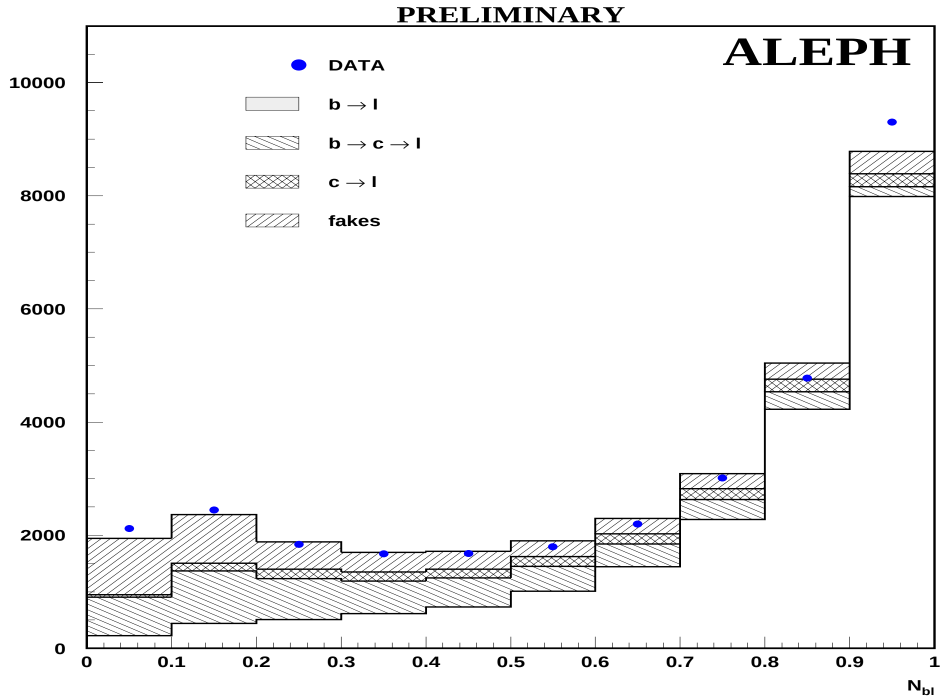

Figure 6: The distribution of the combined variable N_{bl} in an enriched sample of b events.

(i, j, k, l) and f_{ijkl} the expected number of events. f_{ijkl} is written as :

$$\begin{aligned}
f_{ijkl} &= (F^{\text{r.s.}}_{b\to\ell})_{ijkl}\left(\int(1+x^2+\frac{8}{3}\mathrm{A}^b_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})\,x)dx\right)_l \\
&+ (F^{\text{w.s.}}_{b\to\ell})_{ijkl}\left(\int(1+x^2-\frac{8}{3}\mathrm{A}^b_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})\,x)dx\right)_l \\
&+ (F^{\text{asym}}_{b\to\text{bkg}})_{ijkl}\left(\int(1+x^2+\frac{8}{3}\mathrm{A}^b_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})(2\eta_b-1)\,x)dx\right)_l \\
&+ (F_{c\to\ell})_{ijkl}\left(\int(1+x^2-\frac{8}{3}\mathrm{A}^c_{\mathrm{FB}}\,x)dx\right)_l \\
&+ (F^{\text{asym}}_{c\to\text{bkg}})_{ijkl}\left(\int(1+x^2-\frac{8}{3}\mathrm{A}^c_{\mathrm{FB}}(2\eta_c-1)\,x)dx\right)_l \\
&+ (F^{\text{asym}}_{s\to\text{bkg}})_{ijkl}\left(\int(1+x^2+\frac{8}{3}\mathrm{A}^s_{\mathrm{FB}}(2\eta_s-1)\,x)dx\right)_l \\
&+ (F^{\text{asym}}_{d\to\text{bkg}})_{ijkl}\left(\int(1+x^2+\frac{8}{3}\mathrm{A}^d_{\mathrm{FB}}(2\eta_d-1)\,x)dx\right)_l \\
&+ (F^{\text{asym}}_{u\to\text{bkg}})_{ijkl}\left(\int(1+x^2-\frac{8}{3}\mathrm{A}^u_{\mathrm{FB}}(2\eta_u-1)\,x)dx\right)_l \\
&+ (F^{\text{sym}}_{\text{bkg}})_{ijkl}\left(\int_l(1+x^2)dx\right)_l
\end{aligned}$$

The fractions, $F_{process}$, are determined from simulated events. The quantities η_q are the original quark charge correlation probabilities for the background components. The use of the lifetime information in the flavour separation makes the $\mathrm{A}^b_{\mathrm{FB}}$ measurement sensitive, not only to the integrated value of the $B^0\bar{B}^0$ mixing $\bar{\chi}$, but also to the frequency of the $B^0_d\bar{B}^0_d$ oscillations (accounted for by the quantity $\bar{\chi}_{ijkl}$).

5 Systematics Studies

The systematic errors and associated uncertainties considered so far are reported Table 1. The main systematic effects are discussed below.

5.1 Heavy quark production and semileptonic decay modelling

The branching ratios of the prompt leptons in heavy flavours decays together with the partial width $\mathrm{R_b}$ and R_c enter in the evaluation of the quantities $F_{process}$. Their values are varied within their uncertainties to assign the related systematic errors.
The lepton energy spectrum is reweighted to match the experimental measurements of Cleo, Delco and Mark III. The assignment of the systematic uncertainties is explained in Reference [6].

5.2 b and c fragmentation

The c and b fragmentation into hadrons is modelled by the Peterson function [7]. The values of the relevant parameters ϵ_{c} and ϵ_{b} are varied to reproduce the uncertainties on X_C and X_B [3].

5.3 Lepton identification and misidentification of hadrons

The assignment of the uncertainties related to lepton identification is studied in data and follows the technique defined in Reference [2]. Special care has been taken to control the identification of low momenta muons ($p \leq 3$ GeV/c) considered in this measurement.

5.4 The background charge correlation

In the background component, some high momenta particles (misidentified K and π mesons) may carry information about the original quark charge. It is then useful to define the probability that a fake lepton candidate carries the correct charge correlation with the original quark. This probability is denoted by η and is computed from simulated events as a function of the particle momentum. A 20 % overall uncertainty is assigned to this asymmetric component of the background.

5.5 Lifetime and B physics

The topological branching fractions, the lifetime and the relative production rates of b-hadrons have been varied within their uncertainties to study the induced systematic error. At the same time, to improve the data-Monte Carlo agreement of the significance distribution for the light quarks events, a smearing from impact parameters is implemented. The full change implied by the smearing procedure is assigned as a sytematic uncertainty. This study has been performed using a simpler analysis, involving only the lifetime probability P_E in the b-tagging [8]. The quoted uncertainty is hence assumed to be conservative.

5.6 $B \to D^{**}$

The lepton energy spectrum is sensitive to the presence of a D^{**} in the B decays. It is also true when considering the jet properties. A change of the fraction of D^{**} in B decays according to the experimental uncertainty of the measurement is applied to estimate this systematic effect. This uncertainty is correlated to the $b \to l$ modelling uncertainty.

[3] X_C (X_B) is the fraction of the beam energy carried by the primary c (b) hadron.

Error sources	$\Delta(A_{FB}^{b})$	$\Delta(A_{FB}^{c})$
$BR(b \to l)$	∓ 0.036	± 0.037
$BR(b \to c \to l)$	± 0.013	∓ 0.033
$BR(c \to l)$	± 0.026	∓ 0.167
$BR(b \to \bar{c} \to l)$	± 0.036	± 0.097
$BR(b \to \tau \to l)$	± 0.001	∓ 0.020
$BR(b \to u)$	∓ 0.003	∓ 0.005
$BR(b \to D^{**})$	± 0.11	± 0.12
ϵ_b	∓ 0.011	± 0.031
ϵ_c	∓ 0.040	± 0.046
R_b	∓ 0.004	± 0.006
R_c	± 0.018	∓ 0.082
Gluon splitting ($b\bar{b}$)	± 0.012	± 0.006
Gluon splitting ($c\bar{c}$)	± 0.009	∓ 0.011
Electron id	∓ 0.004	∓ 0.007
Muon id	$< 10^{-3}$	∓ 0.011
γ conversions	± 0.028	± 0.064
Electron bkg	± 0.004	± 0.020
Punch–through	± 0.019	± 0.078
Muon id (low p)	± 0.008	± 0.001
$b \to l$ model	${}^{-0.053}_{+0.090}$	${}^{-0.077}_{+0.100}$
$c \to l$ model	${}^{+0.057}_{-0.050}$	${}^{-0.076}_{+0.044}$
$b \to c \to l$ model	${}^{+0.004}_{-0.003}$	${}^{-0.015}_{+0.014}$
$p_{\perp}$ charm	∓ 0.001	∓ 0.019
Bkg charge correlation	± 0.005	∓ 0.082
A_{FB}^{s}	∓ 0.003	± 0.038
A_{FB}^{d}	$< 10^{-3}$	± 0.026
A_{FB}^{u}	$< 10^{-3}$	± 0.008
mixing	± 0.132	± 0.002
d smearing	± 0.013	∓ 0.072
B lifetimes	$< 10^{-3}$	∓ 0.005
B fractions	∓ 0.005	± 0.015
B charged tracks multiplicity	± 0.088	∓ 0.177
TOTAL	± 0.228	± 0.357

Table 1: Systematic uncertainties in units of 10^{-2}.

5.7 Mixing

The probability that a neutral B meson has oscillated is determined in any bin of the analysis from simulated events. The ALEPH measurement of the time-integrated mixing parameter is used to reweight the Monte Carlo and to take into account properly correlated uncertainties with the modelling.

6 The Fit Results and the Extraction of $\sin^2\theta_W^{eff}$

Figure 7 displays the observed angular distribution at peak energy in the b-enhanced region and the result of the fit.

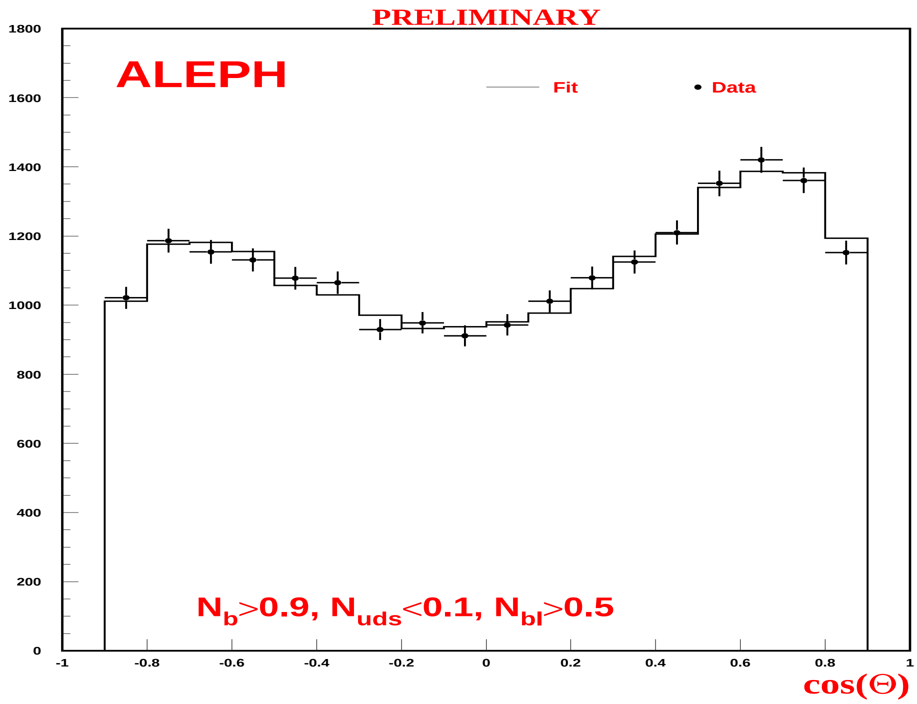

Figure 7: Observed angular distribution in the b-enhanced region. The histogram illustrates the result of the fit.

The b and c asymmetries at peak energy are measured to be :

$$\begin{aligned} \mathrm{A}_{\mathrm{FB}}^{b} &= 0.0949 \pm 0.0040\ (stat.)\ \pm 0.0023\ (syst.) \\ \mathrm{A}_{\mathrm{FB}}^{c} &= 0.0562 \pm 0.0053\ (stat.)\ \pm 0.0036\ (syst.) \end{aligned}$$

The statistical correlation between measurements is found to be 10%. The dependance of $\mathrm{A}_{\mathrm{FB}}^{b}$ and $\mathrm{A}_{\mathrm{FB}}^{c}$ upon the Standard Model electroweak radiative corrections is related to the value of $\sin^2\theta_W^{eff}$. The procedure to unfold QED and QCD effects from the measured b and c asymmetries and the center-of-mass energy dependence of the measurement is described in Reference [6]. The values of the QCD corrections are taken to be 0.024 ± 0.014 and 0.014 ± 0.010, respectively for b and c [9]. It results in the following measurement of the electroweak mixing angle :

$$\sin^2\theta_W^{eff} = 0.23228 \pm 0.00076$$

7 Conclusion

In a data sample of 3.9 million hadronic Z decays recorded at the Z peak with the ALEPH detector at LEP, a simultaneous measurement of the c and b asymmetries is performed by means of leptons originating from the semileptonic decays of heavy flavoured hadrons. The data are analysed as a function of the polar angle of the thrust axis in a space of discriminating variables aimed to separate lepton candidates according to the event flavour and process origin. The c and b asymmetries are measured to be :

$$\mathrm{A}_{\mathrm{FB}}^{b} = 0.0949 \pm 0.0040\ (stat.)\ \pm 0.0023\ (syst.)$$
$$\mathrm{A}_{\mathrm{FB}}^{c} = 0.0562 \pm 0.0053\ (stat.)\ \pm 0.0036\ (syst.)$$

The electroweak mixing angle is derived from these measurements and is determined to be :

$$\sin^2\theta_W^{eff} = 0.23228 \pm 0.00076$$

These results are preliminary.

References

[1] ALEPH Collaboration, D. Buskulic *et al.*, Phys. Lett. **B384** (1996) 414.

[2] ALEPH Collaboration, D. Buskulic *et al.*, Nucl. Instr. Methods **A346** (1994) 461.

[3] ALEPH Collaboration, D. Decamp *et al.*, Nucl. Instr. Methods **A294** (1990) 121.

[4] OPAL Collaboration, R. Akers *et al.*, Z. Phys. **C63** (1994) 197.

[5] ALEPH Collaboration, D. Buskulic *et al.*, Phys. Lett. **B313** (1993) 535.

[6] The LEP Electroweak Working Group for the LEP Experiments, "Combining Heavy Flavour Electroweak Measurements at LEP", Nucl. Instr. Methods **A378** (1996) 101.

[7] C. Peterson *et al.*, Phys. Rev. **D27** (1983) 105.

[8] "Asimmetria avanti-indetro dei quark pesanti in interazioni e+e- al LEP (esperimento ALEPH)", A. Tricomi, PhD Thesis, February 1998, Catania.

[9] Private communication.