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Measurement of the $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$ Forward-Backward Asymmetry Using Leptons

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Abstract

The forward-backward charge asymmetry in the process $e^+e^- \rightarrow b\bar{b}$ is measured using samples of hadronic Z^0 events containing prompt muons or electrons, collected by the L3 experiment in the years 1993 to 1995. The measurements are combined with previous L3 measurements based on data collected in the years 1990 to 1992 to yield the preliminary result:

$$A_b^{FB} = 0.0947 \pm 0.0063(stat.) \pm 0.0039(sys.)\,,$$

from a total sample of 3.3 million hadronic Z^0 decays with a mean center-of-mass energy of 91.26 GeV.

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Introduction

In the process $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$, the distribution of the quark production angle θ_b relative to the electron beam direction can be parametrised by:

$$\frac{d\sigma}{d\,cos\theta_b} \propto \frac{3}{8}(1+cos^2\theta_b) + A_b^{FB} cos\theta_b.$$

Within the Standard Model [1] at lowest order, for $\sqrt{s} = M_Z$, the forward-backward asymmetry A_b^{FB} is related to the vector v_f and axial-vector a_f couplings of fermions to the Z^0 boson by:

$$A_b^{FB} = \frac{3}{4}\frac{2v_e a_e}{v_e^2+a_e^2}\frac{2v_b a_b}{v_b^2+a_b^2}$$

Higher order corrections modify this lowest order relation. These effects are accounted for by replacing the couplings v_f,a_f with modified effective couplings $\bar{v}_f$,$\bar{a}_f$, which are related by:

$$\frac{\bar{v}_f}{\bar{a}_f} = 1 - 4|q_f|sin^2\bar{\theta}_W,$$

where q_f is the fermion charge and $\bar{\theta}_W$ is the effective electroweak mixing angle.

The high sensitivity to $sin^2\bar{\theta}_W$ of the down type quark asymmetries and the comparative ease of selecting pure $Z \rightarrow b\bar{b}$ samples make A_b^{FB} measurements excellent tests of the Standard Model. Due to mixing in the $B^0\bar{B}^0$ system where a B_d^0 or B_s^0 oscillates into its anti-particle the observed asymmetry is diluted by a factor $1/(1-2\chi_b)$.

Electrons and muons from the semileptonic decays of b quarks are used to select events coming from $Z \rightarrow b\bar{b}$. The large mass and hard fragmentation of the b-quark results in prompt leptons from b-quark decay having large momentum and transverse momentum p_t with respect to the quark direction; the p_t reflects the momentum distribution in the centre-of-mass frame of the heavy hadron. Thus a high p,p_t lepton within a jet provides both b-flavour enhancement and charge information, from the correlation of the lepton charge, q, with the quark charge. The quark direction estimator is obtained from the event thrust axis. The observable $-q\,cos\theta_{thrust}$, where the thrust direction is oriented into the hemisphere containing the lepton, provides an estimate of the direction of the b-quark. Prompt leptons constitute roughly 1% of all charged particles produced in hadronic events. Thus both effective background rejection and lepton selection are required.

In this paper, a measurement of A_b^{FB} with the L3 detector using events collected at center-of-mass energies, $\sqrt{s}$, close to the Z^0 pole energy during the data taking periods of 1993-1995 is presented. The data sample consists of 2.3 million hadronic events with mean energy 91.24 GeV. This measurement is combined with previous L3 A_b^{FB} results [2, 3] using data from the 1990-1992 running periods, corresponding to 1.04 million hadronic events.

Detector description and event selection

A detailed description of the L3 detector is provided in reference [4,5]. The trigger requirements and the selection criteria for hadronic events containing electrons or muons have been described previously [6, 7]. Muons are identified and measured in the muon chamber system. We require that a muon track consists of track segments in at least two of the three layers of muon chambers, and that the muon track points back to the interaction region. Electrons are identified using the electromagnetic and hadronic calorimeters, as well as the central tracking chamber. Only electrons in the barrel region $|cos\theta| < 0.69$ have been considered for this analysis. Requiring less than 3 GeV to be deposited in a cone of half angle 7° behind the electromagnetic cluster rejects hadrons which fulfil the electron shower shape and energy criteria in the electromagnetic calorimeter. Photons are rejected by requiring a track in the central tracking chamber to be matched with the electromagnetic cluster. The track curvature in the central tracking chamber determines the charge of the electron. The electron selection, in particular the shower shape criteria, implies an isolation requirement on identified electrons. This results in a lower efficiency for electrons than for muons.

The momentum of muon candidates is required to be greater than 4 GeV, while the electrons candidates are required to have momentum greater than 3 GeV. Requirements on the transverse momentum p_t of the leptons are used to further enhance the $b\bar{b}$ purity. The transverse momentum is defined with respect to the nearest jet, where the measured energy of the lepton is excluded from the jet. If there is no jet with an energy greater than 6 GeV remaining in the same hemisphere as the lepton, then p_t is calculated relative to the thrust axis of the event. In events containing more than one lepton candidate only the highest p_t lepton is used in the analysis.

After hadron selection and detector quality requirements the total number of hadronic events selected is 2.3 million, at a mean center-of-mass energy of 91.24 GeV. Of these, the number with prompt lepton candidates selected is 79417, comprising 55597 with muon candidates and 23820 with electron candidates.

Event simulation

The JETSET 7.3 Monte Carlo program [8] was used to generate event samples, simulating the fragmentation and decay of hadronic events. The events were passed through the full L3 detector simulation [9], which includes the effects of experimental resolution, energy loss, multiple scattering, interactions and decays in the detector materials.

Relevant electroweak parameters, fragmentation parameters, semileptonic decay models, and branching ratios were re-tuned to their current best values and the uncertainties on these parameters were used to determine the systematic uncertainties on the results. The parameter values and uncertainties used follow the recommendations developed by the LEP Electroweak Working Group on Heavy Flavours [10].

Table 1 summarises the parameter values and uncertainties used. The scaled energy ($x_E = 2E_{hadron}/\sqrt{s}$) distributions of the weakly decaying heavy hadrons are modelled using the Peterson fragmentation function [11]. The shape determining Peterson parameters ϵ_b,ϵ_c for b and c hadrons were adjusted to attain the recommended mean scaled energies $\langle \mathrm{x}_E(\mathrm{b})\rangle$ and $\langle \mathrm{x}_E(\mathrm{c})\rangle$. The JETSET lepton momentum spectra are re-weighted using the lepton momentum in the rest frame of the weakly decaying heavy hadron. For $b \to l$ decays the ACCMM model [12] with Fermi momentum $p_f = 298$ MeV and produced quark mass 1673 MeV is used for the center-point and the ISGW model [13] with 11% D^{**} and 32% D^{**} (ISGW**) are used as upper and lower points. For $c \to l$ decays the ACCMM model is used as a convenient functional form, with parameters for the center-point and variations (CL1,CL2,CL3) chosen from fits to DELCO [14] and MARK III [15] data. For the $b \to c \to l$ decay chain, the $b \to D$ spectrum measured by CLEO [16] is combined with the $c \to l$ spectrum corrected by the procedure described above.

Monte Carlo events with single leptons, or the highest p_t lepton in multi-lepton events, are

Electroweak Parameters	
R_b	0.216 ± 0.005
R_c	0.169 ± 0.005
A_c^{FB}	0.067 ± 0.015

Fragmentation	
$\langle x_E(b)\rangle$	0.702 ± 0.008
$\langle x_E(c)\rangle$	0.484 ± 0.008

Branching Ratios	
$Br(b \to l)$	0.105 ± 0.005
$Br(b \to c \to l^+)$	0.080 ± 0.005
$Br(b \to \bar{c} \to l^-)$	0.013 ± 0.005
$Br(b \to \tau \to l)$	0.0045 ± 0.0008
$Br(c \to l)$	0.098 ± 0.005
$Br(b \to J/\psi \to ll)$	0.0007 ± 0.0002

Semileptonic Decay models	
$b \to l$ model	ACCMM (+ISGW,-ISGW**)
$c \to l$ model	CL1 (+CL2,-CL3)
$b \to D$ model	see text

Table 1: Central values and variations of parameters used; the abbreviations are explained in the text.

Category (k)	μ	e	A_k
$b \to l^-$	62.7	74.7	A_b
$b \to c \to l^+$	7.5	5.8	$-A_b$
$b \to \tau \to l^-$	0.9	1.1	A_b
$b \to \bar{c} \to l^-$	1.1	0.6	A_b
$c \to l^+$	10.0	6.1	$-A_c$
background	17.8	11.7	A_{bkg}

Table 2: Monte Carlo estimates of the composition (%) in the single lepton data sample, and their asymmetry contributions.

classified into six categories: $b \to l$, $b \to c \to l$, $b \to \tau \to l$, $b \to \bar{c} \to l$, $c \to l$ and background. The background includes leptons from π and K decays, Dalitz decays, photon conversions and misidentified hadrons. Examples of the causes of misidentifying hadrons as leptons are $\pi - \gamma$ overlaps for electrons and punchthrough for muons. The Monte Carlo estimate of the sample compositions are shown in table 2 together with the asymmetry contribution of each source.

Fitting Method

The observed asymmetry A_b^{obs} is extracted using an unbinned maximum likelihood fit to the p and p_t distributions, where we assume no $B^0\bar{B}^0$ mixing. The likelihood function has the form:

$$\mathcal{L} = \prod_{i=1}^{N_{data}} \sum_{k=1}^{6} f_k(i).[\frac{3}{8}(1 + cos^2\theta_i) + A_k\, cos\theta_i].$$

For each data lepton i the fractions in each category k, $f_k(i)$, are determined from the number and type of Monte Carlo leptons found within a rectangular box centred on the data lepton in the p-p_t plane. The box dimensions are increased until a minimum of 30 Monte Carlo leptons are included in the box. The six categories are listed in table 2 together with their associated asymmetries A_k. The estimate of the b-quark direction $cos\theta_i$ is obtained from the observable $-qcos\theta_{thrust}$, where the thrust direction is oriented into the hemisphere containing the lepton, of charge q.

Preliminary Results

The observed asymmetry is corrected for the effects of mixing using the value $\chi_b = 0.120$. Separate fits for muons and electrons are performed. Estimates of the charge confusion for muons and electrons are made and corrections are applied. The error on the charge confusion estimate is included as a contribution to the systematic error.

The A_b^{FB} results from the 1993-1995 data sample at energies close to the peak energy $\sqrt{s} = M_Z$ with $\langle\sqrt{s}\rangle = 91.24$ is:

$$A_b^{FB} = 0.0973 \pm 0.0078(stat.) \pm 0.0045(sys.).$$

A breakdown of the systematic uncertainties is provided in table 3, and includes dependencies on other Electroweak parameters.

Effects of reconstruction uncertainties in the simulation of the lepton momentum and in the jet direction determination are estimated by smearing the lepton momentum by 10% and the angle between the lepton and the nearest jet by 1°. Monte Carlo studies show the background asymmetry A_{bkg} to be consistent with zero, we vary this by ±1% as an estimate of the uncertainty in this quantity.

After combination with the 1990-1992 A_b^{FB} results [2] the total sample of 3.3 million hadronic Z^0 decays, with $\langle\sqrt{s}\,\rangle = 91.26$ and $\chi_b = 0.120$, yields:

$$A_b^{FB} = 0.0947 \pm 0.0063(stat.) \pm 0.0039(sys.).$$

Contribution	Value	Variation	$\Delta A_{b\bar{b}}$ $\times 10^2$
R_b	0.2160	$\pm$ 0.0050	$\mp$ 0.055
R_c	0.1690	$\pm$ 0.0050	$\pm$ 0.043
A_c^{FB}	0.0670	$\pm$ 0.0150	$\pm$ 0.208
Electroweak Parameters			0.219
$\langle x_E(b) \rangle$	0.7020	$\pm$ 0.0080	$\pm$ 0.005
$\langle x_E(c) \rangle$	0.4840	$\pm$ 0.0080	$\pm$ 0.022
$Br(b \to l)$	0.1050	$\pm$ 0.0050	$\mp$ 0.160
$Br(b \to c \to l^+)$	0.0800	$\pm$ 0.0050	$\pm$ 0.065
$Br(b \to \bar{c} \to l^-)$	0.0130	$\pm$ 0.0050	$\mp$ 0.027
$Br(b \to \tau \to l)$	0.0045	$\pm$ 0.0008	$\mp$ 0.009
$Br(c \to l)$	0.0980	$\pm$ 0.0050	$\pm$ 0.073
$Br(b \to J/\psi \to ll)$	0.0007	$\pm$ 0.0002	$\pm$ 0.030
Fragmentation and Branching Ratios			0.193
$b \to l$ model			$\mp$ 0.060
$c \to l$ model			$\pm$ 0.152
$b \to D$ model			$\mp$ 0.029
Decay models			0.166
background fraction	1.0000	$\pm$ 0.1000	$\pm$ 0.063
background asymmetry	0.0000	$\pm$ 0.0100	$\mp$ 0.219
Background effects			0.228
charge confusion correction			$\pm$ 0.017
lepton-jet angle smearing		1°	$\pm$ 0.142
lepton momentum smearing		10%	$\pm$ 0.115
Detector effects			0.184
Total systematic			0.446

Table 3: Combined systematic uncertainties for muons and electrons collected during the 1993-95 peak running periods, $\langle \sqrt{s} \rangle = 91.24$.

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