THE LEFT-RIGHT FORWARD-BACKWARD ASYMMETRY OF HEAVY QUARKS MEASURED WITH JET CHARGE AND WITH LEPTONS AT THE SLD*

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ABSTRACT

We present direct measurements of the left-right asymmetry of b- and c-quarks from the decay of Z0 bosons produced in the annihilation of longitudinally polarized electrons and unpolarized positrons. Two complementary techniques are presented: 1) Z0 → bb̄ decays are tagged using track impact parameters with b̄b̄ discrimination provided by momentum-weighted track charge; 2) Semileptonic b-decays are tagged using high p and pT muons and electrons. The preliminary results from our 1993 data sample are: 

\[ \Delta F^b = 0.93 \pm 0.13 \pm 0.13 \]

for the jet charge and 

\[ \Delta F^b = 0.93 \pm 0.14 \pm 0.09, \]

and 

\[ \Delta F^c = 0.40 \pm 0.23 \pm 0.20 \]

for the leptons, where the first error is statistical and the second systematic.

1. Introduction

Measurements of the fermion asymmetries at the Z0 provide direct probes of the parity violating left-right asymmetry 

\[ A_f = 2ν_f a_f / [ (ν_f^2 + a_f^2) ] \]

and hence provide a sensitive test of Standard Model predictions. The left-right forward-backward asymmetry \( \Delta F^b \) isolates the \( A_f \) term by taking advantage of the electron beam polarization:

\[ \Delta F^b (y = \cos θ) = \frac{(σ_L(y) - σ_L(-y)) - (σ_R(y) + σ_R(-y))}{(σ_L(y) + σ_R(-y)) + (σ_R(y) + σ_R(-y))} = P_e A_f \frac{2y}{1 + y^2} \]  

(1)

where σ is the differential cross section for \( e^+e^- \rightarrow Z \rightarrow f\bar{f} \) and L (R) refers to left (right) incident electron helicity, with \( P_e < 0 \) (\( P_e > 0 \)).

We present preliminary measurements of \( A_b \) and \( A_c \) from a sample of 50,000 Z0 decays observed at \( \sqrt{s} = 91.26 \) GeV, with an average longitudinal electron polarization of 63.0 ± 1.1%.³ The SLD detector is described elsewhere.⁴⁶

2. Track-Charge Analysis

Hadronic Z0 decays are selected by requiring that at least 7 well reconstructed tracks within \( \cos θ < 0.80 \) carry a large visible energy \( E_{vis} > 18 \) GeV. The dominant contribution to the residual background, \( Z^0 \rightarrow t\bar{t} \) events, is estimated to be less than 0.2% of the sample. Details of the impact parameter b-tag are given in Ref. 5.

The jet charge \( Q_p \) can be written:

\[ Q_p = \sum_{tracks} Q_i \hat{p}_i \cdot \hat{r} \text{\,}^{\hat{r}^{-1}} \]  

(2)

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where \( \hat{t} \) is a unit vector in the direction of the thrust axis. To determine \( A_b \), the sign of \( \hat{t} \)
measured by calorimetry in tagged events is chosen such the \( Q_p \) is negative. \( \hat{t} \) is then used as the estimate of the \( b \)-quark direction where a \( \kappa \) of 0.5 is chosen to maximize the correct-sign probability. The result is shown in Fig. 1.

![Fig. 1. Signed cos(\theta_F) distribution for tagged events produced with left- and right-handed beams, illustrating the significant effect of polarization on the forward-backward asymmetry.](image)

To determine \( A_b \), the double asymmetry \( A_{FB}^b(\cos \theta_F) \) is formed for each bin in \( \cos \theta_F \) and corrected for bin-dependent \( Q_p \) resolution and thrust axis smearing. In addition a first-order QCD correction\(^{7,8} \) (2–5%) is applied. A linear fit through points representing each bin plotted as data verses Monte Carlo produces a slope equal to a measurement of \( P_eA_b \) (see Fig. 2).

The dominant systematic error arises from a lack of a satisfactory explanation for variation in the measured value of \( A_b \) when the tag requirement is varied from 2 tracks at

| Contribution                  | % Error |
|-------------------------------|---------|
| Physics                       |         |
| \( B \)-Decay Model           | 7       |
| \( b \) Fragmentation         | 2       |
| \( B-\bar{B} \) mixing        | 1       |
| Polarization                  | 2       |
| Detector and Tag              |         |
| Tracking Efficiency           | 4       |
| Thrust Axis Resolution        | 2       |
| Tag Modeling                  | 10      |
| Monte Carlo Statistics        | 5       |
| Total (Quadrature Sum)        | 14      |

![Table 1. Relative systematic errors on \( A_b \) for the track-charge analysis.](image)
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+2σ impact parameter to 4 tracks at +4σ. Table 1 summarizes our estimates of these and other errors, which are combined in quadrature for our preliminary result:

\[ A_b = 0.93 \pm 0.13 \text{ (stat)} \pm 0.13 \text{ (sys)} \]  

(3)

3. Lepton Analysis

Electrons are identified by extrapolating charged tracks to the barrel liquid argon calorimeter (LAC) and analyzing the energy deposited in nearby towers. The energy is required to match the momentum of the track and follow the longitudinal profile of an immediate electromagnetic shower. The efficiency for identifying electrons in hadronic Z^0 events is 55% within acceptance. Above 2 GeV, pion misidentification is less than 0.8%. Ninety percent of electron candidates from gamma conversions are identified and removed by searching for a match with a second track consistent with the decay of a massless particle outside a radius of 2 cm.

Muons are identified by matching charged tracks to hits in the 18 active layers of the warm iron calorimeter. Muons candidates are also required to have at least two hits in the last four active layers, forcing the track to penetrate at least 7.3 interaction lengths. Above 3 GeV efficiency is 85% and pion misidentification is below 0.3%.^6

Muons Electrons

|            | Muons candidates | Electrons candidates |
|------------|------------------|----------------------|
|           | SLD Preliminary  | SLD Preliminary      |
|           |                   |                      |
|           |                   |                      |
|           |                   |                      |

Fig. 3. Spectra of tagged lepton candidates projected onto \( p \) and \( p_T \) with Monte Carlo estimations of contributions from signal and background sources.

Jets are identified using LAC energy clusters and the JADE^9 algorithm with \( \gamma_{cut} = 0.005 \). The jet angular resolution is approximately 20 millirad. Event selection is a slightly looser version of the one used for the jet charge.

To determine the best estimates of \( A_b \) and \( A_c \), we use the following probability function:

\[ p_i(A_b, A_c) = 1 + \cos^2 \theta + 2PA \cos \theta \]

\[ A = w_b A_b (1 - 2 \chi) [1 + \Delta_{QCD}^b(\theta)] - w_c A_c [1 + \Delta_{QCD}^c(\theta)] + w_h A_h \]

(4)

where \( \Delta_{QCD} \) are the \( \theta \)-dependent first-order QCD corrections^7,8 and \( A_h \) is the \( p \) and \( p_T \)
dependent asymmetry of all non-lepton charged tracks. The weights \( w_b, w_c, \) and \( w_h \) are the \( p \) and \( p_T \) dependent amount each lepton is affected by \( b \)-quark, \( c \)-quark, or hadron asymmetries. Each weight is derived from the Monte Carlo by tabulating the fraction of the leptons at a particular \( p \) and \( p_T \) that come from one of six relevant sources:

\[
\begin{align*}
    w_b(p, p_T) &= f_{b \to l} - f_{b \to c \to l} + f_{b \to \bar{c} \to l} \\
    w_c(p, p_T) &= f_{c \to l} \\
    w_h(p, p_T) &= f_{\text{hadron}} + f_{\text{mis-id}}
\end{align*}
\]

To determine \( f \), the subset of 50 leptons in the Monte Carlo closest in \( \ln p_T \) and \( p_T \) to each lepton in the data is identified and the various sources tallied.

The results of the maximum likelihood fit are:

- **Muons:**
  \[ A_b = 0.94 \pm 0.20 \pm 0.10 \quad A_c = 0.42 \pm 0.29 \pm 0.18 \]
- **Electrons:**
  \[ A_b = 0.92 \pm 0.19 \pm 0.12 \quad A_c = 0.37 \pm 0.37 \pm 0.31 \]
- **Combined:**
  \[ A_b = 0.93 \pm 0.14 \pm 0.09 \quad A_c = 0.40 \pm 0.23 \pm 0.20 \]

where the first error is statistical and the second systematic (see Table 2). The statistical correlation between \( A_b \) and \( A_c \) is 0.03 for muons and 0.29 for electrons.

Table 2. The absolute systematic errors for \( A_b \) and \( A_c \) measured using maximum likelihood.

| Source                              | \( A_b \) Muons | \( A_b \) Electrons | \( A_c \) Muons | \( A_c \) Electrons |
|-------------------------------------|-----------------|--------------------|-----------------|--------------------|
| Tracking Efficiency                 | 0.013           | 0.016              | 0.013           | 0.004              |
| Jet Axis Simulation                 | 0.060           | 0.045              | 0.061           | 0.130              |
| Background Level                    | 0.019           | 0.008              | 0.028           | 0.014              |
| B mixing                            | 0.027           | 0.025              | —               | —                  |
| Method of determining \( w \)       | 0.040           | 0.083              | 0.082           | 0.185              |
| \( \Gamma (Z' \to bb) \)            | 0.005           | 0.002              | 0.001           | 0.003              |
| \( \Gamma (Z' \to cc) \)            | 0.007           | 0.002              | 0.027           | 0.033              |
| \( B^+ , B^- \) Lepton Spectrum     | 0.022           | 0.046              | 0.116           | 0.140              |
| \( \Lambda_b \) Lepton Spectrum     | 0.032           | 0.018              | 0.046           | 0.054              |
| \( D \) Lepton Spectrum             | 0.008           | 0.012              | 0.023           | 0.026              |
| \( b \) Fragmentation               | 0.022           | 0.020              | 0.037           | 0.098              |
| \( c \) Fragmentation               | 0.011           | 0.015              | 0.012           | 0.011              |
| Background Asymmetry                | 0.006           | 0.011              | 0.027           | 0.087              |
| Polarization                        | 0.018           | 0.018              | 0.008           | 0.007              |
| Second Order QCD                    | 0.008           | 0.008              | 0.040           | 0.040              |
| Total (Quadrature Sum)              | 0.096           | 0.117              | 0.179           | 0.308              |

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