SLAC–PUB–6644
LBL–36200
September, 1994
(T/E)

MEASUREMENT OF A_b FROM THE LEFT-RIGHT FORWARD-BACKWARD ASYMMETRY OF b QUARK PRODUCTION IN Z^0 DECAYS USING A MOMENTUM-WEIGHTED TRACK CHARGE TECHNIQUE*

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Submitted to *Physical Review Letters*

*This work was supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-92ER40701 (CIT), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-AC02-76ER00881 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Science and Engineering Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

Abstract

Using an impact parameter tag to select an enriched sample of $Z^0 \to b\bar{b}$ events, and the net momentum-weighted track charge to identify the sign of the charge of the underlying b quark, we have measured the left-right forward-backward asymmetry for b quark production as a function of polar angle. Based on 1.8 pb^{-1} of Z^0 decay data produced with a mean electron beam polarization of $P_e = 63\%$, this yields a direct measurement of the extent of parity violation in the Zbb coupling of $A_b = 0.87 \pm 0.11(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$.

Measurements of fermion production asymmetries at the Z^0 pole provide probes of the combination of vector (v) and axial vector (a) couplings $A_f = 2v_f a_f/(v_f^2 + a_f^2)$, which express the extent of parity violation in the Zff coupling. At Born level, the Z^0 peak differential cross section for producing a final state fermion f at an angle $z = \cos\theta$ from the electron beam direction is

$$\sigma^f(z) \equiv d\sigma_f/dz \propto (1 - A_e P_e)(1 + z^2) + 2A_f(A_e - P_e)z, \tag{1}$$

where P_e is the longitudinal polarization of the electron beam. By manipulating the polarization of the electron beam it is possible to measure the left-right forward-backward asymmetry for b quark production [1]

$$\tilde{A}^b_{FB}(z) = \frac{[\sigma^b_L(z) - \sigma^b_L(-z)] - [\sigma^b_R(z) - \sigma^b_R(-z)]}{\sigma^b_L(z) + \sigma^b_L(-z) + \sigma^b_R(z) + \sigma^b_R(-z)} = |P_e| A_b \frac{2z}{1 + z^2}, \tag{2}$$

where the designation L, R refers to $Z^0 \to b\bar{b}$ decays produced with a predominantly left-handed (negative helicity) or right-handed (positive helicity) electron beam, respectively. The measurement of the double asymmetry eliminates the dependence on the Zee coupling parameter A_e. The quantity A_b is sensitive to radiative effects that correct the Zbb coupling ("vertex corrections"), and is largely independent of propagator effects that modify the effective weak mixing angle ($\delta A_b = -0.63 \cdot \delta \sin^2\theta_W^{\rm eff}$). The measurement of $\tilde{A}^b_{FB}(z)$ is thus complementary to other electroweak asymmetry measurements performed at the Z^0 pole.

In this Letter we present a measurement of $\tilde{A}^b_{FB}(z)$ which relies on an impact parameter tag to select an enriched sample of $Z^0 \to b\bar{b}$ events, while making use of the net momentum-weighted track charge to identify the sign of the charge of the underlying b quark. This result, in conjunction with a parallel analysis based on leptons from semileptonic B hadron decay [2], represents the first direct measurement of the extent of parity violation in the Zbb coupling.

The operation of the SLAC Linear Collider (SLC) with a polarized electron beam has been described previously [3]. During the 1993 run, the SLC Large Detector (SLD) recorded 1.8 pb^{-1} of e^+e^- annihilation data at a mean center-of-mass energy of 91.26 ± 0.02 GeV, with a mean electron beam longitudinal polarization of $63 \pm 1\%$. Charged particles were tracked in the Central Drift Chamber (CDC) [4], which consists of 80 layers of axial or stereo sense wires in a uniform axial magnetic field of 0.6T. In addition, a pixel-based silicon vertex detector (VXD) [5] provides an accurate measure of particle trajectories close to the beam axis. The momentum resolution of the combined CDC and VXD systems is $(\delta p_\perp / p_\perp)^2 = (.01)^2 + (.0026 p_\perp)^2$, where $p_\perp$ is the momentum in GeV/c perpendicular to the beamline. The thrust axis [6] was reconstructed using the Liquid Argon Calorimeter [7], which covers a range of $|\cos\theta| < 0.98$.

The accurate impact parameter measurement provided by the addition of the VXD information to the CDC tracks was used to select a sample enriched in $Z^0 \to b\bar{b}$ events. All impact parameters used in this analysis were for tracks projected into the plane perpendicular to the beam axis, and were measured with respect to the SLC interaction point (IP), derived from fits to Z^0 decays close in time to the event under study [8]. The impact parameter d was derived by applying a sign to the distance of closest approach such that d is positive when the vector from the IP to the point at which the track intersects the associated jet axis [9] makes an acute angle with respect to the track direction. Including the uncertainty on the average IP position, the impact parameter uncertainty σ_d for the overall tracking system approaches 13 μm for high momentum tracks, and is 76 μm at $p_\perp \sqrt{\sin\theta} = 1$ GeV/c.

For the purpose of selecting hadronic events and calculating the momentum-weighted track charge, a loose set of requirements was placed on reconstructed tracks, while stricter requirements were placed on tracks used to select $Z^0 \rightarrow b\bar{b}$ candidates. "Track-charge quality" tracks were required to: i) have $p_\perp \geq 0.15$ GeV/c and $p_{tot} < 50$ GeV/c; ii) have $|\cos\theta| \leq 0.8$; and iii) have the point of closest approach to the beam line be within a cylinder of radius r_0 and half-length l_0 about the IP of $(r_0, l_0) = (2.0, 10.0)$ cm. "Impact parameter quality" tracks were additionally required to: i) have the point of closest approach within $(r_0, l_0) = (0.3, 1.5)$ cm; ii) have at least one VXD hit; iii) have $\sigma_d < 250\mu m$; and iv) not be identified as a decay product of a Λ, K_s^0, or γ-conversion.

Events were classified as hadronic decays of the Z^0 provided that they contained at least 7 track-charge quality tracks, a visible charged energy of at least 20 GeV, and a thrust axis satisfying $|\cos\theta_{thrust}| < 0.7$. The resulting hadronic sample contained 26,759 events, with $< 0.1\%$ non-hadronic background.

A $Z^0 \rightarrow b\bar{b}$ enriched sample of 4032 events was identified by selecting hadronic events with three or more impact parameter quality tracks with normalized impact parameter $d/\sigma_d > 3.0$ [8]. Monte Carlo (MC) studies indicate that this selection algorithm is 61.2% efficient at identifying $Z^0 \rightarrow b\bar{b}$ events, while providing a sample of 90.1% purity.

Using all track-charge quality tracks, we formed the event momentum-weighted charge sum

$$Q = \sum_{tracks} -q_i \cdot \mathrm{sgn}(\vec{p_i} \cdot \hat{T}) |(\vec{p_i} \cdot \hat{T})|^{\kappa}, \tag{3}$$

where q_i and $\vec{p_i}$ are the track charge and momentum, and $\hat{T}$ is the unit vector in the direction of the reconstructed thrust axis. The sign of the vector $\hat{T}$ is chosen so that $Q > 0$, making $\hat{T}$ an estimate of the b quark direction. We have chosen $\kappa = 0.5$ to maximize the analyzing power (AP) of the track charge algorithm for $Z^0 \to b\bar{b}$ events

$$AP = \frac{P_{cor} - P_{inc}}{P_{cor} + P_{inc}} \simeq 37\%, \tag{4}$$

where P_{cor} (P_{inc}) is the probability of assigning the b quark to the correct (incorrect) thrust hemisphere. Figure 1 shows a comparison of the resulting Q distribution between data and MC. Figure 2 shows the $\hat{T}_z$ distribution for the enriched sample, plotted separately for left- and right-handed electron beam. A clear forward-backward asymmetry is observed, with sign as expected from the cross section formula (1).

Events in the enriched sample were divided into bins of width 0.1 in $|\hat{T}_z|$. In each bin, the experimental asymmetry

$$\tilde{A}_i^{\mathrm{obs}} = \frac{[N_i^{L,+} - N_i^{L,-}] - [N_i^{R,+} - N_i^{R,-}]}{N_i^{L,+} + N_i^{L,-} + N_i^{R,+} + N_i^{R,-}} \tag{5}$$

was calculated, where $N_i^{h,\mathrm{s}}$ is the number of events in $|\hat{T}_z|$ bin i produced with beam helicity h, and with estimated b quark hemisphere $\mathrm{s} = \mathrm{sgn}(\hat{T}_z)$.

To determine $\tilde{A}_{FB}^b(z)$, the observed asymmetry must be corrected for the light quark ($udsc$) event contamination of the enriched sample, the dilution of the asymmetry due to the misassignment (4) of the b quark charge, $B^0\overline{B}^0$ mixing, thrust axis resolution smearing, $Z - \gamma$ interference, and the effects of external photon and gluon radiation.

The dilution of the observed asymmetry due to the 10% contamination of light quark events was corrected for bin-by-bin in $|\hat{T}_z|$ according to

$$\tilde{A}_i^{\rm corr} = \frac{\tilde{A}_i^{\rm obs}}{\Pi_i} - \frac{1-\Pi_i}{\Pi_i}\tilde{A}_i^{udsc}, \tag{6}$$

where Π_i is the $Z^0 \to b\bar{b}$ purity in bin i for the enriched sample, estimated from MC assuming the world average branching fraction $R_b = (Z^0 \to b\bar{b})/(Z^0 \to hadrons) = 0.2202 \pm 0.0020$ [10]. $\tilde{A}_i^{udsc} \simeq -0.75\tilde{A}_i^{\rm corr}$ is the expected asymmetry of light quark events, estimated from the subset of reconstructed MC light quark events that pass the $Z^0 \to b\bar{b}$ selection criteria.

The remainder of the corrections listed above were taken into account by the comparison (Figure 3) of $\tilde{A}_i^{\rm corr}$ with the observed asymmetry $\tilde{A}_i^{\rm b,MC}$ for MC $Z^0 \to b\bar{b}$ events which reconstruct in the i^{th} $|\hat{T}_z|$ bin, where the MC sample was generated with the mean electron beam polarization of 63%. The value of the MC parity violation parameter A_b is varied to minimize the χ^2 difference between the data and MC, yielding

$$A_b = 0.87 \pm 0.11({\rm stat.}). \tag{7}$$

with a χ^2 of 8.3 for 6 degrees of freedom.

We have investigated a number of effects that can change the measured value of A_b. The correction for the charge misassignment (4) of the momentum-weighted track charge algorithm, which is implicitly contained in the comparison between $\tilde{A}_i^{\rm corr}$ and $\tilde{A}_i^{\rm b,MC}$, is sensitive to the modeling of the physics of heavy quark fragmentation and decay. To simulate B hadron production and fragmentation, we used the JETSET 6.3 parton shower MC [11], with fragmentation parameters tuned to hadronic e^+e^-

data [12]. Heavy quark fragmentation was simulated via the Petersen function [13], tuned so that $\langle x_b \rangle = E_B/E_{beam} = 0.695 \pm 0.015$ [14] where E_{beam} and E_B are the electron beam energy and the energy of the B hadron after fragmentation, respectively. B hadron semileptonic decay was simulated with the ISGW Model [15], with the fraction of decays producing D^{**} mesons set to 9% [2]. To simulate hadronic decays of B hadrons, the JETSET 6.3 heavy hadron decay simulation [11] was adjusted to reproduce the multiplicity and inclusive particle spectra from B meson decays at the Υ_{4S} [16]. Special care was taken to reproduce the momentum spectra of charmed hadrons from Υ_{4S} decays [17], which greatly constrains the charge flow of B hadron decay into the stable particles that are observed in the SLD. B_s meson decay (12% of MC B hadrons) was simulated by exchanging an s quark for the light spectator quark in the B meson decay model. B baryon decay (9% of MC B hadrons) was simulated via the default JETSET 6.3 model. Varying the properties of B hadron fragmentation and decay within the constraints provided by data indicates an uncertainty of $\delta A_b/A_b = \pm 7\%$ due to the corresponding uncertainty in the AP of the track charge algorithm. The effect of neutral B meson mixing, accounted for by the use of $\overline{\chi} = 0.116 \pm 0.008$ [18] in the MC simulation, leads to a change of $\Delta A_b/A_b = 11 \pm 1\%$.

A number of detector effects can change the track charge algorithm AP (4). Potential differences in the AP between the forward and backward hemispheres, caused for example by geometrical distortion of the tracking system, are suppressed by a factor $A_e/A_b \simeq 0.15$ in the calculation of A_b, and are not a significant source of measurement bias. A comparison between data and MC of the number of charged tracks per hadronic event indicates a $3 \pm 2\%$ excess of tracks in the MC simulation of the SLD, leading to a correction to the measured value of A_b of $+6 \pm 4\%$.

The measured value of A_b depends on the purity of the enriched sample via the correction (6) for light quark contamination. MC studies indicate a $9.3 \pm 0.5\%$ ($0.6 \pm 0.2\%$) contamination of $Z^0 \to c\bar{c}$ ($Z^0 \to uds$) events in the enriched sample [8], with expected asymmetries of $\tilde{A}_i^c \simeq (-0.86 \pm 0.22) \cdot \tilde{A}_i^b$ and $\tilde{A}_i^{uds} \simeq (0.26 \pm 0.26) \cdot \tilde{A}_i^b$. The combined effect of the uncertainties in the light quark fractions and asymmetries on the light quark correction (6) produces a systematic uncertainty of $\delta A_b/A_b = \pm 2\%$, which is dominated by the $\sim$ 25% relative uncertainty on the parameter A_c [10]. We have examined the dependence of A_b upon the criteria used to select the enriched sample, and see no statistically significant effects. As a check, the fraction 0.151 ± 0.002(stat.) of hadronic events selected for the enriched sample is consistent with the MC expectation of $0.147 \pm .006$(syst.) [8].

It is possible to confirm the MC simulation of the track charge algorithm AP by comparing the consistency of the track charge assignment between opposite hemispheres for events in the enriched sample. Calculating Q independently for tracks in each thrust hemisphere, we formed the quantity

$$H = \frac{N_{con} - N_{inc}}{N_{con} + N_{inc}} \simeq (AP_{hem})^2, \tag{8}$$

where N_{con} (N_{inc}) is the number of events with consistent (inconsistent) charge assignment in opposing hemispheres. For the data sample, we find $H = 0.093 \pm 0.016$, while the MC expectation, including the tracking simulation and B meson mixing corrections discussed above, is $H = 0.116 \pm .007$. Taking into account the presence of light quark backgrounds, this corresponds to a difference in the MC and data hemisphere-only analyzing AP of $\Delta AP_{hem}/AP_{hem} = 11 \pm 9\%$, consistent with zero. In addition, we have examined the dependence of A_b upon the value of the momentum weighting exponent κ used in the track charge algorithm; no statistically significant effects were observed.

Radiative effects due to $Z - \gamma$ interference and external radiation account for a $3 \pm 1\%$ correction to A_b, dominated by hard final state gluon radiation. Table 1 presents a summary of the above sources of relative systematic error ($\delta A_b / A_b$), including a contribution of $\pm 6\%$ due to limited MC statistics. Adding all sources of systematic uncertainty in quadrature yields a total relative systematic error of $\pm 11\%$, yielding

$$A_b = 0.87 \pm 0.11(\text{stat.}) \pm 0.09(\text{syst.}). \tag{9}$$

This number is in good agreement with the Standard Model expectation of $A_b = 0.94$ [1], assuming the value $\sin^2 \theta_W^{\text{eff}} = 0.23$.

This result complements that of an independent approach using leptons from semileptonic B decay [2]. Taking into account small correlations between the two techniques yields

$$A_b = 0.89 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.}) \tag{10}$$

for the combined SLD measurement of the extent of parity violation in the Zbb coupling.

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf.

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Figure Captions

Figure 1. Comparison between data (dots) and MC (histogram) of the momentum-weighted tracks charge sum Q for events in the enriched sample. The shaded region shows the expected contribution from light quark ($udsc$) events.

Figure 2. Distribution of tagged events in the polar angle estimate $\hat{T}_z$, for left-handed ($P_e < 0$) and right-handed ($P_e > 0$) events separately. In both plots, a forward-backward asymmetry with sign as expected from the cross section formula (1) is observed.

Figure 3. Light-quark-corrected asymmetry $\tilde{A}^{\rm corr}$ (dots) and expected MC asymmetry $\tilde{A}^{b,MC}$ (histogram) as a function of b quark polar angle estimate $|\hat{T}_z|$. The MC asymmetry was generated with the best-fit parity violation parameter $A_b = 0.87$.

Table 1

Table 1. Contributions to the relative systematic error on A_b.

Source of error	Contribution ($\delta A_b/A_b$)
B Hadron Fragmentation and Decay	$\pm 7\%$
Charged Particle Tracking	$\pm 4\%$
Light Quark Subtraction	$\pm 2\%$
Electron Beam Polarization	$\pm 2\%$
B Meson Mixing	$\pm 1\%$
Radiative Effects	$\pm 1\%$
MC Statistics	$\pm 6\%$
Total	$\pm 11\%$

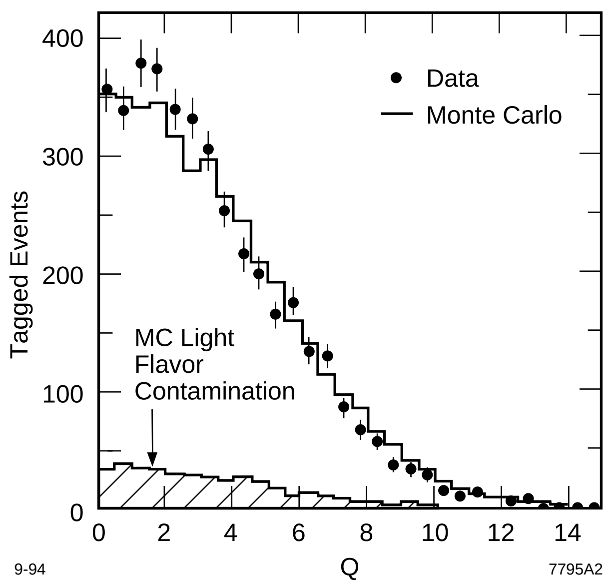
400
300
200
100
0
Tagged Events
Data
Monte Carlo
MC Light
Flavor
Contamination
0
2
4
6
8
10
12
14
Q
9-94
7795A2

Figure 1.

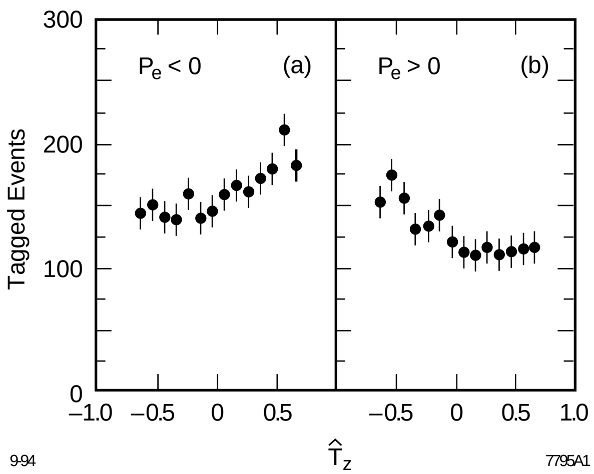
300
200
100
0
Tagged Events
$P_e < 0$
(a)
$P_e > 0$
(b)
–1.0
–0.5
0
0.5
–0.5
0
0.5
1.0
$\hat{T}_z$
9-94
7795A1

Figure 2.

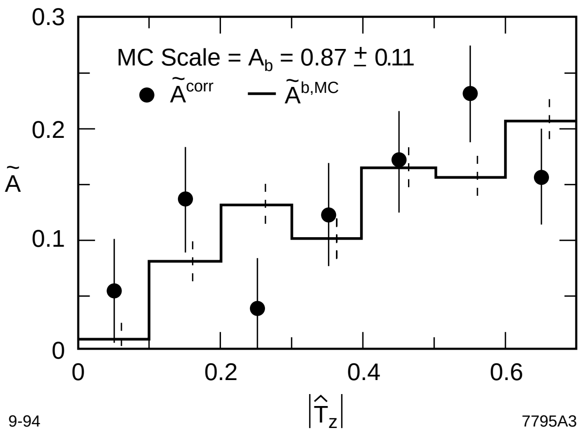
MC Scale = A_b = 0.87 ± 0.11
$\tilde{A}^{corr}$
$\tilde{A}^{b,MC}$
0.3
0.2
0.1
0
$\tilde{A}$
0
0.2
0.4
0.6
$|\hat{T}_z|$
9-94
7795A3

Figure 3.