Direct Measurement of Parity Violation in the Coupling of Z^0 Bosons to b Quarks Using a Mass Tag and Momentum-Weighted Track Charge

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We present a direct measurement of the parity-violation parameter A_b using a self-calibrating track-charge technique. In the SLAC Linear Collider Large Detector (SLD) experiment we observe hadronic decays of Z^0 bosons produced in collisions between longitudinally polarized electrons and unpolarized positrons at the SLAC Linear Collider. A sample of $b\overline{b}$ events is selected using the topologically reconstructed mass of B hadrons. From our 1993–1995 sample of approximately 150 000 hadronic Z^0 decays, we obtain $A_b = 0.911 \pm 0.045(\text{stat}) \pm 0.045(\text{syst})$. [S0031-9007(98)06678-2]

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Measurements of b quark production asymmetries at the Z^0 pole determine the extent of parity violation in the $Zb\overline{b}$ coupling. At Born level, the differential cross section for the process $e^+e^- \to Z^0 \to b\overline{b}$ can be expressed as a function of the polar angle θ of the b quark relative to the electron beam direction,

$$\sigma^b(\xi) \equiv d\sigma_b/d\xi \propto (1 - A_e P_e)(1 + \xi^2) + 2A_b(A_e - P_e)\xi , \quad (1)$$

where P_e is the longitudinal polarization of the electron beam, $\xi = \cos\theta$. The parameters $A_f = 2v_f a_f/(v_f^2 + a_f^2)$, ($f = e$ or b) where v_f (a_f) is the vector (axial vector) coupling of the fermion f to the Z^0 boson, express the extent of parity violation in the $Zf\overline{f}$ coupling.

From the conventional forward-backward asymmetries formed with an unpolarized electron beam ($P_e = 0$), such as used by the CERN Lareg Electron-Positron Collider (LEP) experiments, only the product of parity-violation parameters $A_e A_b$ can be measured [1]. For a polarized electron beam, it is possible to measure A_b directly by forming the left-right forward-backward asymmetry [2]

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

where L, R refers to $Z^0 \to b\overline{b}$ 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 initial state coupling. The quantity A_b is largely independent of propagator effects that modify the effective weak mixing angle and thus is complementary to other electroweak asymmetry measurements performed at the Z^0 pole.

In this Letter we present a direct measurement of A_b from data collected in the SLAC Linear Collider (SLC) Large Detector (SLD) between 1993 and 1995. We use an inclusive vertex mass tag to select a sample of $Z^0 \to b\overline{b}$ events, and the net momentum-weighted track charge, first suggested by Field and Feynman [3], to identify the sign of the charge of the underlying quark. The analysis presented in this paper uses an improved track-charge calibration technique which greatly reduces the model dependence of the result.

The operation of the SLC with a polarized electron beam has been described previously [4]. During the 1994–1995 (1993) run, SLD recorded 3.6 pb^{-1} (1.8 pb^{-1}) of e^+e^- annihilation data at a mean center-of-mass energy of 91.28 ± 0.02 GeV, with a mean electron beam longitudinal polarization of $77.2 \pm 0.5\%$ ($63.0 \pm 1.1\%$).

A detailed description of the SLD can be found elsewhere [5]. Charged particles are tracked in the Central Drift Chamber (CDC) in a uniform axial magnetic field of 0.6 T. In addition, a pixel-based charge-coupled device (CCD) vertex detector (VXD) provides an accurate measure of particle trajectories close to the beam axis. The measured $r\phi$ (rz) track impact parameter resolution

approaches 11 μm (37 μm) for high momentum tracks, and is 76 μm (80 μm) at $p_\perp\sqrt{\sin\theta} = 1$ GeV/c, where z is the coordinate parallel to the beam axis and $p_\perp$ is the momentum in GeV/c perpendicular to the beam line. The momentum resolution of the combined SLD tracking systems is $(\delta p_\perp/p_\perp)^2 = (0.01)^2 + (0.0026 p_\perp)^2$. The thrust axis is reconstructed using the liquid argon calorimeter, which covers a range of $|\cos\theta| < 0.98$. The uncertainty in the position of the primary vertex (PV) is 7 μm transverse to the beam axis and 35 μm (52 μm for $b\bar{b}$ events) along the beam axis.

Events are classified as hadronic Z^0 decays if they (1) contain at least seven well-measured tracks (as described in Ref. [5]), (2) contain a visible charged energy of at least 20 GeV, and (3) have a thrust axis polar angle satisfying $|\cos\theta_{\rm thrust}| < 0.7$. The resulting hadronic sample from the 1993–1995 data consists of 76 554 events with a nonhadronic background estimated to be $<0.1\%$. Events classified as having more than three jets by the JADE jet-finding algorithm with $y_{\rm cut} = 0.02$ [6], using reconstructed charged tracks as input, are discarded, leaving 71 951 events in the sample.

To increase the $Z^0 \to b\bar{b}$ content of the sample, a tagging procedure based on the invariant mass of three-dimensional topologically reconstructed secondary decay vertices is applied [7,8]. The mass of the reconstructed vertex is corrected for missing transverse momentum to account partially for neutral particles. The requirement that the event contain at least one secondary vertex with mass greater than 1.6 GeV/c^2 results in a sample of 11 092 candidate $Z^0 \to b\bar{b}$ decays. The purity (91%) and efficiency (65%) are calculated from the data with small correction, based on the Monte Carlo (MC) simulation, applied to account for the *udsc* background.

Using all track-charge quality tracks, as defined in Ref. [9], we form the signed (Q) and unsigned (Q_+) momentum-weighted charge sums

$$Q = -\sum_{\rm tracks} q_j \,{\rm sgn}(\vec{\rm p}_j \cdot \hat{\rm T})\,|(\vec{\rm p}_j \cdot \hat{\rm T})|^\kappa, \qquad (3)$$

$$Q_+ = \sum_{\rm tracks} q_j |(\vec{\rm p}_j \cdot \hat{\rm T})|^\kappa, \qquad (4)$$

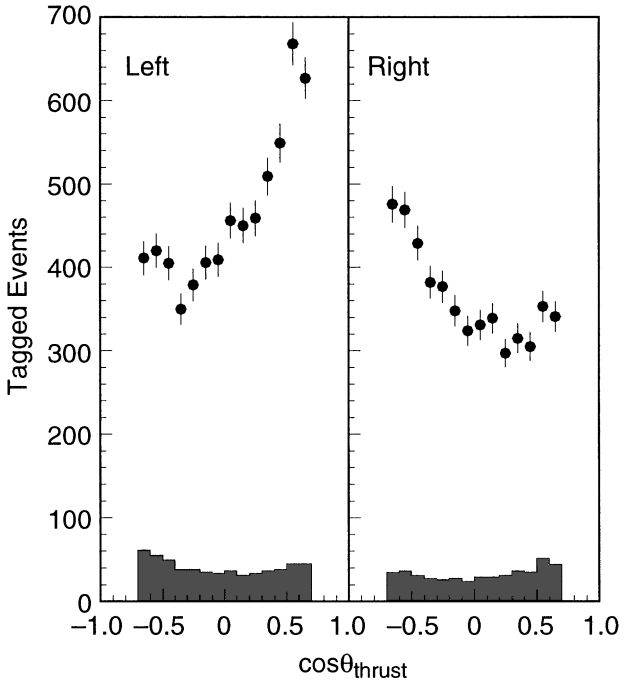

FIG. 1. The polar angle distribution of the signed thrust axis for the b tagged sample. The estimated background is shown by the shaded histogram.

where q_j and $\vec{\rm p}_j$ are the charge and momentum of track j, respectively, and $\hat{\rm T}$ is a unit vector chosen along the direction of the reconstructed thrust axis so that $Q > 0$. The vector $\hat{T}$ is therefore an estimate of the b-quark direction. We use $\kappa = 0.5$ to maximize the analyzing power of the track-charge algorithm for $Z^0 \to b\bar{b}$ events. Figure 1 shows the $T_z = \cos\theta_{\rm thrust}$ distribution of the b-enriched sample separately for left- and right-handed electron beams. Clear forward-backward asymmetries are observed, with respective signs as expected from the cross section formula in Eq. (1).

The value of A_b is extracted via a fit to a maximum likelihood function based on the differential cross section [see Eq. (1)], which provides a somewhat more efficient estimate of A_b than the simple left-right forward-backward asymmetry of Eq. (2):

$$\rho^i(A_b) = (1 - A_e P_e^i)[1 + (T_z^i)^2] + 2(A_e - P_e^i)T_z^i[A_b f_b^i(2p_b^i - 1)(1 - \Delta^i_{{\rm QCD},b}) + A_c f_c^i(2p_c^i - 1)(1 - \Delta^i_{{\rm QCD},c}) + A_{\rm bckg}(1 - f_b^i - f_c^i)(2p^i_{\rm bckg} - 1)], \qquad (5)$$

where P_e^i is the signed polarization of the electron beam for event i, $f^i_{b(c)}$ the probability that the event is a $Z^0 \to b\bar{b}(c\bar{c})$ decay, parametrized as a function of the secondary vertex mass, and $\Delta^i_{{\rm QCD},b,c}$ are final-state QCD corrections, to be discussed later. $A_{\rm bckg}$ is the estimated asymmetry of residual $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ final states. The parameters p are estimates of the probability that the sign of Q accurately reflects the charge of the respective underlying quark, and are functions of $|Q|$, as well as the secondary vertex mass and $|T_z|$.

The analysis presented in our previous publication [9] used a MC simulation to determine p_b and had substantial dependence on the details of the b fragmentation and B decay modeling. In this analysis we measure p_b directly from the data [10]. Defining Q_b ($Q_{\bar{b}}$) to be the unsigned momentum-weighted track-charge sum of the tracks in the thrust hemisphere containing the b ($\bar{b}$) quark, the

quantities

$$Q_{\rm sum} = Q_b + Q_{\overline{b}}, \qquad Q_{\rm dif} = Q_b - Q_{\overline{b}} \tag{6}$$

may be related to the experimental observables defined in Eqs. (3) and (4), respectively: $|Q_{\rm dif}| = |Q|$ and $Q_{\rm sum} = Q_+$. Our MC simulation indicates that the Q_b and $Q_{\overline{b}}$ distributions are approximately Gaussian. In this limit [10],

$$p_b(|Q|) = \frac{1}{1 + e^{-\alpha_b|Q|}}, \tag{7}$$

with

$$\alpha_b = \frac{2q^0_{\rm dif}}{\sigma^2_{\rm dif}} = \frac{2\sqrt{\langle|Q_{\rm dif}|^2\rangle - \sigma^2_{\rm dif}}}{\sigma^2_{\rm dif}}, \tag{8}$$

where $q^0_{\rm dif}$ and $\sigma_{\rm dif}$ are the mean and the width, respectively, of the Gaussian $Q_{\rm dif}$ distribution.

In the absence of a correlation between Q_b and $Q_{\overline{b}}$, $\sigma_{\rm dif} = \sigma_{\rm sum}$, where $\sigma_{\rm sum}$ is the observed width of the Q_+ distribution. Thus α_b can be derived from experimental observables. In the presence of a correlation, $\sigma_{\rm dif} = (1 + \lambda)\sigma_{\rm sum}$, where λ characterizes the strength of the correlation which can be determined from the MC simulation. For JETSET 7.4 [11] with parton shower evolution, string fragmentation, and full detector simulation, λ is found to be 0.027. The effects of light flavor contamination are taken into account by adjusting the observed widths $\sigma^2_{\rm sum}$ and $\langle|Q_{\rm dif}|^2\rangle$, using the magnitude and width of the light-flavor and $c\overline{c}$ contributions estimated from the MC. This correction increases the value of α_b by 2%. The value of α_b measured with the data is in good agreement with the value extracted from the simulation ($\alpha_b^{\rm DATA} = 0.249 \pm 0.013, \alpha_b^{\rm MC} = 0.245 \pm 0.005$).

Final-state gluon radiation reduces the observed asymmetry from its Born-level value. This effect is incorporated in our analysis by applying a correction $\Delta_{\rm QCD}(|\cos\theta|)$ to the maximum likelihood function [Eq. (5)]. This correction is based on the $o(\alpha_s)$ calculation for massive final state quarks of Stav and Olsen [12], which ranges from $\Delta^{\rm SO}_{\rm QCD}(|\cos\theta|) \sim 0.05$ at $|\cos\theta| = 0$ to $\sim$0.01 at $|\cos\theta| = 1$.

However, QCD radiative effects are mitigated by the use of the thrust axis to estimate the b-quark direction, the $Z^0 \to b\overline{b}$ enrichment algorithm, the self-calibration procedure, and the cut on the number of jets. A MC simulation of the analysis chain indicates that these effects can be represented by a $\cos\theta$-independent suppression factor, $x_{\rm QCD} = 0.25 \pm 0.08$, such that $\Delta_{\rm QCD} = x_{\rm QCD}\Delta^{\rm SO}_{\rm QCD}$. The effects of $o(\alpha_s^2)$ QCD radiation [13], which are dominated by gluon splitting to $b\overline{b}$, lead to an additional correction $\delta A_b/A_b = 0.004 \pm 0.002$.

The dependence of the b-tagging efficiency upon the secondary vertex mass is taken from the simulation, with the overall tagging efficiency derived from the single- and double-tagging rates [7] observed in the data. Tagging efficiencies for charm and *uds* events are estimated using the MC simulation, as is the charm correct-signing probability p_c. The value of A_c is set to its standard model value of 0.67, and the value of $A_{\rm bckg}$ is set to zero. After a small (0.2%) correction [14] for initial-state radiation and Z-γ interference, the value of A_b extracted from the fit is $A_b = 0.911 \pm 0.045$(stat). This result is found to be insensitive to the value of the b-tag mass cut.

We have investigated a number of systematic effects which can change the measured value of A_b; these are summarized in Table I. The uncertainty in α_b due to the statistical uncertainties in $\langle|Q_{\rm dif}|^2\rangle$ and $\sigma^2_{\rm sum}$ corresponds to a 3.7% uncertainty in A_b. The uncertainty in the hemisphere correlation parameter λ is estimated [10] by varying fragmentation parameters within JETSET 7.4, and by comparison with the HERWIG 5.7 [15] fragmentation model. The resulting uncertainty in A_b is 1.7%. The sensitivity of the result to the shape of the underlying Q_b distribution is tested by generating various triangular distributions as well as double Gaussian distributions with offset means. The test distributions are constrained to yield a Q_+ distribution consistent with data, and the total uncertainty is found to be 0.8%. In addition, while the mean value of the self-calibration parameter α_b is constrained by the data, it has a $\cos\theta$ dependence due to the falloff of the tracking efficiency at high $\cos\theta$ which must be estimated using the simulation, leading to a 0.4% uncertainty in A_b.

The extracted value of A_b is sensitive to our estimate of the $Z^0 \to c\overline{c}$ background, which tends to reduce the observed asymmetry due to the positive charge of the underlying c quark. The uncertainty in the purity estimate of $(91.1 \pm 0.9)\%$ is dominated by the uncertainties in the charm tagging efficiency ($\epsilon_c = 0.0382 \pm 0.0044$) and charm production fraction ($R_c = 0.1715 \pm 0.0056$) and

TABLE I. Relative systematic errors on the measurement of A_b.

Error source	Variation	$\delta A_b/A_b$
	Self-calibration	
α_b statistics	$\pm 1\sigma$	3.7%
λ_b colleration	JETSET, HERWIG	1.7%
$P(Q_b)$ shape	Different shapes	0.8%
$\cos\theta$ shape of α_b	MC shape vs flat	0.4%
Light flavor	50% of correction	0.4%
	Analysis	
Tag composition	Mostly ϵ_c	1.5%
Detector modeling	Tracking eff. and resolution corrections on/off	1.5%
Beam polarization	$\pm 0.8\%$	0.8%
QCD	$x_{\rm QCD}, \alpha_s \pm 0.007$, 2nd order terms	0.6%
Gluon splitting	$\pm 100\%$ of JETSET 7.4	0.2%
A_c	0.67 ± 0.08	0.8%
$A_{\rm bckg}$	0 ± 0.50	0.1%
A_e	0.1506 ± 0.0028	$\ll 0.1\%$
Total		4.9%

leads to a 1.5% uncertainty in A_b. Details of the estimate of the light and charmed quark efficiencies can be found in Ref. [7].

In order to obtain agreement between the data and the simulation for the rz impact parameter distribution, an *ad hoc* Gaussian smearing of width 20 μm$/\sin\theta$ is added to the MC simulation of the impact parameter. The value of A_b changes by 0.6% when this extra smearing is removed, and is included as a systematic error. In addition, agreement between the data and MC simulation charged track multiplicity distributions is obtained only after the inclusion of additional *ad hoc* tracking inefficiency. This random inefficiency was parametrized as a function of total track momentum, and averages 0.5 charged tracks per event. Removing this additional correction from the MC results in a 1.4% change in A_b, which is also included as a systematic error. Combining all systematic uncertainties in quadrature yields a total relative systematic uncertainty of 4.9%.

In conclusion, we have exploited the highly polarized SLC electron beam to perform a direct measurement of

$$A_b = 0.911 \pm 0.045(\text{stat}) \pm 0.045(\text{syst}), \qquad (9)$$

which is in good agreement with the standard model prediction of 0.935 and with precise measurements of b quark forward-backward asymmetries at LEP [1]. This measurement represents a substantial improvement over our previous result [9] due to a larger event sample, higher electron beam polarization, and the use of the Z^0 data to calibrate the b-tagging efficiency as well as the track-charge algorithm analyzing power.

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