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New Measurement of A_b at the Z^0 Resonance using a Vertex-Charge Technique.*

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Abstract

We present a new preliminary measurement of the parity-violation parameter A_b using a self-calibrating vertex-charge technique. In the 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 $b\bar{b}$ events is selected using the topologically reconstructed mass of B hadrons. From our 1996–1998 data sample of approximately 400,000 hadronic Z^0 decays, we obtain $A_b = 0.897 \pm 0.027(\mathrm{stat})^{+0.036}_{-0.034}(\mathrm{syst})$.

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

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

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 $Zf\bar{f}$ coupling.

From the conventional forward-backward asymmetries formed with an unpolarized electron beam ($P_e = 0$), such as used by the LEP experiments, only the product of parity-violaton 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]

$$\tilde{A}_b \equiv {A_{LRFB}}^b(\xi) = \frac{[\sigma_L^b(\xi) - \sigma_L^b(-\xi)] - [\sigma_R^b(\xi) - \sigma_R^b(-\xi)]}{\sigma_L^b(\xi) + \sigma_L^b(-\xi) + \sigma_R^b(\xi) + \sigma_R^b(-\xi)} = |P_e| A_b \frac{2\xi}{1+\xi^2} \ , \tag{2}$$

where L, R refers to $Z^0 \rightarrow b\bar{b}$ 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 initial state coupling. The quantity $\tilde{A}_b$ 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 paper we present a preliminary direct measurement of A_b from data collected in the SLC Large Detector (SLD) during its 1996–1998 run. We use an inclusive vertex mass tag to select a sample of $Z^0 \rightarrow b\bar{b}$ events, and use the charge of the reconstructed secondary vertex to identify the sign of the charge of the underlying quark. To measure the accuracy of the quark charge assignment, we use a simple self-calibration technique which greatly reduces the model dependence of the result. The result from this analysis is competitive with and complementary to our previous measurements using jet-charge [3], lepton [4] and $K^\pm$ tags[5].

A detailed description of the SLD can be found elsewhere [6]. Charged particles are tracked in the Central Drift Chamber (CDC) in a uniform axial magnetic field of 0.6T. In addition, new a pixel-based CCD vertex detector (VXD3), installed in 1996, provides an accurate measure of particle trajectories close to the beam axis. Recent improvements in the charged particle tracking algorithm have further improved the overall tracking performance. The measured $r\phi$ (rz) track impact parameter resolution now approaches 9μm (11μm) for high momentum tracks, while multiple scattering contributions are 33 μm $/(p_\perp \sin^{3/2}\theta)$ in both projections (z is the coordinate parallel to the beam axis and $p_\perp$ is the momentum in GeV/c perpendicular to the beamline). The momentum resolution of the combined SLD tracking systems is $(\delta p_\perp/p_\perp)^2 = (.01)^2 + (.0026 p_\perp)^2$. 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 ~ 4 μm transverse to the beam axis and ~ 20 μm (for $b\bar{b}$ events) along the beam axis.

Events are classified as hadronic Z^0 decays if they contain: (1) at least seven well-measured tracks (as described in Ref. [6]), (2) a visible charged energy of at least 20 GeV, and (3) have a thrust axis polar angle satisfying $|\cos\theta_{thrust}| < 0.7$. The resulting hadronic sample from the 1996−98 data consists of $\sim 400,000$ events with a non-hadronic background estimated to be $< 0.1\%$. Events classified as having more than three jets by the JADE jet-finding algorithm with $y_{cut} = 0.02$ [7], using reconstructed charged tracks as input, are discarded.

To increase the $Z^0 \rightarrow b\bar{b}$ content of the sample, we select events with reconstructed secondary decay vertices[8]; the inclusive vertexing procedure is based on a 3-dimensional topological algorithm[9]. We calculate the invariant mass of the reconstructed vertex (M_{vtx}), correcting for missing transverse momentum to partially account for neutral particles and tracking inefficiencies. We require that the event contain two vertices well separated from the interaction point, with least one vertex (the "tag" vertex) with $M_{vtx} > 2.0 GeV/c^2$. This results in a sample of 24112 candidate $Z^0 \rightarrow b\bar{b}$ decays. The b-hadron purity and efficiency of this selection are calculated from the data by counting single- and double-tagged events, assuming the Standard Model values for the $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow c\bar{c}$ fractions R_b and R_c[6], and using the Monte Carlo (MC) simulation to predict the charm-hadron efficiency ϵ_c.

The quark and/or antiquark direction is determined by the charge of the reconstructed vertex: e.g., reconstructing a vertex with $Q_{vtx} = +1$ in a given hemisphere indicates the $\bar{b}$ quark was produced in that hemisphere. To improve the accuracy of the vertex charge reconstruction, additional quality tracks which were not used in the original topological vertex finding are "attached" to the toplogical vertex if they pass a set of criteria determined from MC simulation to select primarily B and D decay tracks. These attached tracks are used to improve the vertex charge reconstruction only. All reconstructed vertices with a net charge $Q_{vtx} \neq 0$ are used in this analysis; in the cases where two charged vertices are reconstructed in a single event, the event is discarded from further analysis if both vertices have the same sign. The MC simulation predicts that a reconstructed b-hadron vertex with $M_{vtx} > 2.0$ GeV/c^2 correctly assigns the underlying quark charge with an average probability $< p_b > = (73.0 \pm 0.2)\%$.

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:

$$\rho^i(A_b) = (1 - A_e P_e^i)(1 + (T_z^i)^2) + 2(A_e - P_e^i)T_z^i[A_b f_b^i(2p_b^i - 1)(1 - \Delta^i_{QCD,b}) + A_c f_c^i(2p_c^i - 1)(1 - \Delta^i_{QCD,c}) + A_{bckg}(1 - f_b^i - f_c^i)(2p^i_{bckg} - 1)], \quad (3)$$

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 $Z^0 \rightarrow b\bar{b}(c\bar{c})$ decay, parametrized as a function of the secondary vertex mass, and $\Delta^i_{QCD,b,c}$ are final-state QCD corrections, to be discussed later. A_{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_{vtx} accurately reflects the charge of the respective underlying quark, and are functions of the secondary vertex mass.

In order to reduce dependence on B decay and detector reconstruction modelling, we use a self-calibrating technique to measure p_b directly from the data. Defining N_{++} (N_{+-}) as the number of events with two reconstructed vertices of the same (opposite) sign, one can solve for p_b:

$$p_b = \frac{1}{2}\left(\sqrt{\frac{N_{+-} - N_{++}}{N_{+-} + N_{++}}} + 1\right) \quad (4)$$

where we have assumed both vertices have the same correct-sign probability p_b. In general this is not the case, so we use the MC to determine the mass-dependent shape $p_b(M_{vtx})$ and correct the above equation appropriately. Uncertainties in the mass-dependence of p_b are included in our systematic error estimate (see below). When applied to our MC simulation, this self-calibration technique gives an average correct-sign probability $< p_b(M_{vtx} > 2.0) >= (73.6 \pm 0.5)\%$, in good agreement with the MC "true" value quoted above. The error here is due only to the limited statistics of the self-calibration technique. The same technique applied to the data yields $< p_b(M_{vtx} > 2.0) >= (75.6 \pm 0.9)\%$, and we use this value in the analysis. The MC mass dependence $p_b(M_{vtx})$ is used to extrapolate this value to other masses.

Final-state gluon radiation reduces the observed asymmetry from its Born-level value. This effect is incorporated in our analysis by applying a correction $\Delta_{QCD}(|\cos\theta|)$ to the maximum likelihood function (Eq. 3). This correction is based on the $o(\alpha_s)$ calculation for massive final state quarks of Stav and Olsen [13], which ranges from $\Delta^{SO}_{QCD}(|\cos\theta|) \sim 0.05$ at $|\cos\theta| = 0$ to ~ 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 $Z^0 \to b\bar{b}$ 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, $x_{QCD} = 0.50 \pm 0.25$, such that $\Delta_{QCD} = x_{QCD}\Delta^{SO}_{QCD}$. The effects of $o(\alpha_s^2)$ QCD radiation [14], which are dominated by gluon splitting to $b\bar{b}$, 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 [8] 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_{bckg} is set to zero. After a small (+0.2%) correction [15] for initial state radiation and Z-γ interference, the value of A_b extracted from the fit is $A_b = 0.897 \pm 0.027$ $(stat)$. 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 1. The uncertainty in p_b due to the statistical uncertainties in the data self-calibration technique corresponds to a $+3.4/-3.2\%$ uncertainty in A_b[†]. We have estimated the effects of possible biases in the self-calibration technique by comparing the MC true value of $p_b(M_{vtx})$ with the self-calibrated value of the same quantity determined using the same MC as a trial dataset. We observe no bias, and assign a 1.0% systematic uncertainty in A_b due to our limited MC statistics. The uncertainty in the MC modelling of the M_{vtx} dependence of p_b is included in the tracking efficiency corrections (see below). In addition, while the mean value of the self-calibration parameter p_b is constrained by the data, it has a $\cos\theta$ dependence due to the fall-off of the tracking efficiency at high $\cos\theta$ which must be estimated using the simulation, leading to a 0.6% uncertainty in A_b. We also rely on the MC to correctly model the vertex charge distribution of the light-flavor background (dominantly $Z^0 \to c\bar{c}$) which is subtracted from the raw counts N_{++} and N_{+-}; we conservatively take a $\pm 50\%$ relative uncertainty on this subtraction, which results in a

[†]The error in the self-calibrated p_b is symmetric, but the corresponding error in the event weight (the "analyzing power", $= 2p_b - 1$) is asymmetric.

0.1% uncertainty in A_b.

The extracted value of A_b is sensitive to our estimate of the $Z^0 \to c\bar{c}$ 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 $\Pi_b = (98.6 \pm 0.6)\%$ is dominated by the uncertainties in the charm tagging efficiency ($\epsilon_c = 0.009 \pm 0.001$) and leads to a 0.9% uncertainty in A_b. Details of the estimate of the light and charmed quark efficiencies can be found in Ref. [8].

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. However, without this correction applied, the MC correct-sign probability is $< p_b(M_{vtx} > 2.0) >= (74.4 \pm 0.3)\%$, in better agreement with the data than the lower value obtained with the correction turned on. Moreover, the agreement in the data/MC M_{vtx} spectra is somewhat better without the ad-hoc correction applied. Completely removing this additional correction from the MC results in a 1.0% change in A_b, which is also included as a systematic error. The uncertainty in the beam polarization P_e is taken from a preliminary estimate performed for the SLD A_{LR} analysis[17].

Combining all systematic uncertainties in quadrature yields a total relative systematic uncertainty of $+4.0/-3.8\%$.

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

$$A_b = 0.897 \pm 0.027(\text{stat})^{+0.036}_{-0.034}(\text{syst}). \tag{5}$$

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Table 1: Relative systematic errors on the 1996-98 vertex charge measurement of A_b.

Error Source	**Variation**	$\delta A_b/A_b$
Self-Calibration		
p_b statistics	$\pm 1\sigma$	+3.4/-3.2%
Self-cal bias	MC Statistics	1.0%
$\cos\theta$ shape of p_b	MC Shape *vs* Flat	0.2%
Light Flavor	±50% of correction	0.1%
Analysis		
Tag Composition	$\Pi_b \pm \delta\Pi_b$	0.9%
Detector Modeling	Tracking eff. and resolution corrections on/off	1.0%
Beam Polarization	±0.8%	0.8%
QCD	x_{QCD}, $\alpha_s \pm 0.007$, 2^{nd} order terms	0.8%
Gluon Splitting	±100% of JETSET	0.2%
A_c	0.67 ± 0.05	<0.1%
A_{bckg}	0 ± 0.50	<0.1%
Total		**+4.0/-3.8%**