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Direct Measurement of A_b and A_c at the Z^0 Pole Using a Lepton Tag

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The parity violation parameters A_b and A_c of the $Zb\bar{b}$ and $Zc\bar{c}$ couplings have been measured directly, using the polar angle dependence of the Z^0 -pole polarized cross sections. Bottom and charmed hadrons were tagged via semileptonic decays. Both the muon and electron identification algorithms take advantage of new multivariate techniques, incorporating for the first time information from the SLD Čerenkov Ring Imaging Detector. Based on the 1993–1995 SLD sample of 150 000 Z^0 decays produced with highly polarized electron beams, we measure $A_b = 0.910 \pm 0.068(\text{stat}) \pm 0.037(\text{syst})$, $A_c = 0.642 \pm 0.110(\text{stat}) \pm 0.063(\text{syst})$.

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Parity violation in the $Zf\bar{f}$ coupling can be measured via the observables $A_f = 2v_f a_f / (v_f^2 + a_f^2)$, where v_f and a_f represent the vector and axial vector couplings to fermion f . The Born-level differential cross section for the process $e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$ is

$$d\sigma_f/dz \propto (1 - A_e P_e)(1 + z^2) + 2A_f(A_e - P_e)z, \quad (1)$$

where P_e is the e^- beam longitudinal polarization [$P_e > 0$ for right-handed (R) polarization] and $z = \cos\theta$ is the polar angle of the outgoing fermion with respect to the incident electron.

In the presence of e^- beam polarization, it is possible to construct the left-right forward-backward asymmetry

$$\begin{aligned} \tilde{A}_{FB}^f(z) &\equiv \frac{[\sigma_L^f(z) - \sigma_L^f(-z)] - [\sigma_R^f(z) - \sigma_R^f(-z)]}{[\sigma_L^f(z) + \sigma_L^f(-z)] + [\sigma_R^f(z) + \sigma_R^f(-z)]} \\ &= |P_e| A_f \frac{2z}{1 + z^2}, \end{aligned} \quad (2)$$

for which the dependence on the initial state coupling parameter A_e disappears, allowing a direct measurement of the final state coupling parameters A_f . Thus electron beam polarization permits a unique measurement of A_f , independent of that inferred from the unpolarized forward-backward asymmetry [1] which measures the combination $A_e A_f$. In addition, the quantity A_b is largely independent of propagator effects that mod-

ify the effective weak mixing angle, and so is complementary to other electroweak measurements at the Z^0 pole.

To obtain the most precise measurement of A_b it is important to employ several independent methods. In this Letter, we present a simultaneous direct measurement of A_b and A_c based on identified leptons from semileptonic heavy hadron decay, which complements other direct measurements of A_b performed at SLD [SLC (SLAC Linear Collider) Large Detector] [2,3].

The lepton total and transverse momenta (with respect to the nearest jet) are used to assign, for each identified lepton (l), the probabilities for each of the possible production processes: $Z^0 \rightarrow b\bar{b}$, $b \rightarrow l$; $Z^0 \rightarrow b\bar{b}$, $\bar{b} \rightarrow \bar{c} \rightarrow l$; $Z^0 \rightarrow b\bar{b}$, $b \rightarrow \bar{c} \rightarrow l$; $Z^0 \rightarrow c\bar{c}$, $\bar{c} \rightarrow l$; and background (leptons from light hadron decays, photon conversions, and misidentified hadrons). The lepton charge (Q) provides quark-antiquark discrimination, while the angle θ_{jet} with respect to the beam line of the jet nearest to the lepton approximates the underlying quark (b, c) direction. This study makes use of electron and muon identification algorithms which have been improved relative to those used in our analysis of the 1993 data sample [4], and have been applied to the entire 1993–1995 data sample.

The SLAC Linear Collider (SLC) and its operation with a polarized electron beam have been described elsewhere [5]. The SLD Large Detector (SLD) [6] recorded an integrated luminosity of 3.6 pb^{-1} (1.8 pb^{-1}) during the

1994–1995 (1993) running period with a luminosity-weighted electron beam polarization of $|P_e| = 0.772 \pm 0.005$ ($|P_e| = 0.630 \pm 0.011$), at a mean center of mass energy of 91.27 GeV.

Charged particle tracks are reconstructed in the Central Drift Chamber (CDC) and the charge-coupled-device (CCD)-based vertex detector in a uniform axial magnetic field of 0.6 T. The combined momentum resolution in the plane perpendicular to the beam axis is $\delta p_\perp/p_\perp = \sqrt{(0.01)^2 + [0.0026p_\perp/(\text{GeV}/c)]^2}$. The Čerenkov Ring Imaging Detector (CRID) measures the velocities of charged tracks using the angle of Čerenkov photons emitted in liquid and gaseous radiators and has been included in both the electron and the muon identification (limited to $|\cos\theta| < 0.68$). Electrons are well separated from pions in the region between 2 and 5 GeV/ c ; pion (kaon) rejection also considerably reduces backgrounds to the muon sample in the region $2 < p < 5$ ($2 < p < 15$) GeV/ c . The Liquid Argon Calorimeter (LAC) measures the energy and shower profile of charged and neutral particles with an electromagnetic energy resolution of $\sigma_E/E = 15\%/\sqrt{E(\text{GeV})}$ and is used in the electron identification. The Warm Iron Calorimeter (WIC) detects charged particles that penetrate the 3.5 interaction lengths of the LAC and magnet coil.

A requirement of at least 15 GeV of energy in the LAC and at least six tracks with $p_\perp > 250$ MeV/ c selects approximately 130 000 hadronic Z^0 decays from the 1993–1995 sample, the negligible background. Jets are formed using the JADE Collaboration algorithm [7] with parameter $y_{\text{cut}} = 0.005$, based on calorimeter energy cluster information. The jet axis approximates the heavy quark direction (with an angular resolution of ~ 30 mrad for $b\bar{b}$ events). For events with identified electrons, no attempt is made to remove the electron cluster in the jet axis determination.

Electrons are identified [8] with both LAC and CRID information for CDC tracks with $p > 2$ GeV/ c in the angular range $|\cos\theta| < 0.72$. Calorimeter information is used to construct discriminating variables, which are used, along with the CRID e - π separation information, as input variables to a single output neural network [8], trained on the corresponding SLD Monte Carlo (MC) quantities. The efficiency (purity) for electron identification is 62% (70%) for electrons with $p > 2$ GeV/ c . This electron purity estimate includes electrons from photon conversions as signal. The efficiency has been verified in the data using tracks from tagged photon conversions. As pion misidentification contributes the largest part of the electron sample background, the simulation has been verified using charged pions from reconstructed $K_s^0 \rightarrow \pi^+\pi^-$ decays. The fraction of such pions misidentified as electrons is $(1.23 \pm 0.15)\%$, consistent with the MC expectation of $(1.36 \pm 0.07)\%$. Electrons from photon conversions are identified and removed from the analysis sample with 70% efficiency. The remaining photon conversion background comprises 14% of the sample but is

clustered at low momentum, away from most of the signal region.

Muon identification [9] is performed for tracks with $p > 2$ GeV/ c in the angular range $|\cos\theta| < 0.70$, although the muon identification efficiency falls off rapidly for $|\cos\theta| > 0.60$, due to a decrease in the WIC acceptance at the edge of the barrel. CDC tracks are extrapolated along with the associated error matrices, including multiple scattering, and matched with hit patterns in the WIC. For $|\cos\theta| < 0.60$, 87% of the simulated muon tracks have successful matching in the WIC. The CRID $K - \mu$ separation alone rejects 51% of the remaining K and p , with 2% signal loss, while for $p < 6$ GeV/ c the π - μ separation rejects 37% of π , with 5% signal loss. The purity of the final muon sample is improved by requiring that the candidate muons fully penetrate the WIC, and by applying further cuts on the number of hits in the WIC and on the χ^2 of the fit of the track in the WIC and the χ^2 of the CDC/WIC matching. MC studies show that the remaining pion punch-through background is negligible. The simulated prompt muon identification efficiency is 81%, with a purity of 68%, for $|\cos\theta| < 0.60$. The background is due to misidentification (8% of muon candidates) and to muons from light hadron decays (24%). In a sample of pions from K_s^0 decays, 0.3% of pions with $p > 2$ GeV/ c were identified as muons, consistent with the detector simulation.

The likelihood that a measured lepton comes from one of the various physics sources relies directly on MC simulation of semileptonic decays of heavy quarks in Z^0 decays. Z^0 decays are generated via JETSET 7.4 [10]. The B hadron decay model was tuned to reproduce existing data from other experiments, as follows. Semileptonic decays of B mesons are generated according to the ISGW (Isgur Scora Grinstein Wise) formalism [11] with a 23% D^{**} fraction, while semileptonic decays of D mesons are simulated according to the 1994 Particle Data Group branching ratios [12]. Experimental constraints are provided by the $B \rightarrow l$ and $B \rightarrow D$ inclusive momentum spectra measured by CLEO [13,14] and the $D \rightarrow l$ momentum spectrum measured by DELCO [15]. The detailed simulation of the SLD detector response has been realized using GEANT [16] and has been checked extensively against Z^0 data.

Separation between the various lepton sources is accomplished using the total momentum (p) and transverse momentum (p_t) relative to the nearest jet. The p and p_t distributions of muon and electron candidates are shown in Fig. 1, for data and for various sources from MC, with leptons from direct b quark decay dominating at high total and transverse momenta. The disagreement in the electron distribution between data and MC at low transverse momenta is accounted for in the systematic errors.

A maximum likelihood analysis of all hadronic Z^0 events containing leptons is used to determine A_b and A_c simultaneously. The likelihood function contains the following probability term for each lepton in the data:

$$\begin{aligned}
P(p, p_t, P_e, z; A_b, A_c) \propto & \{(1 + z^2)(1 - A_e P_e) - 2Q(A_e - P_e) \\
& \times [(f_b(1 - 2\bar{\chi}_b) - f_{bc}(1 - 2\bar{\chi}_{bc}) + f_{b\bar{c}}(1 - 2\bar{\chi}_{b\bar{c}}))(1 - \Delta_{\text{QCD}}^b(z))A_b \\
& + f_c(1 - \Delta_{\text{QCD}}^c(z))A_c + f_{bkg}A_{bkg}]z\}, \quad (3)
\end{aligned}$$

where $z = \cos\theta_{\text{jet}}$. The lepton source fractions $f_b, f_{bc}, f_{b\bar{c}}, f_c,$ and f_{bkg} , where bc ($b\bar{c}$) refers to $b \rightarrow c \rightarrow \bar{l}$ ($b \rightarrow \bar{c} \rightarrow l$), are functions of p and p_t and are derived by counting leptons in the MC with p and p_t similar to each lepton in the data. Correction factors $(1 - 2\bar{\chi}_x)$ are applied to b -quark lepton sources to account for asymmetry dilution due to $B^0\bar{B}^0$ mixing, with $\bar{\chi}_b$ taken from LEP measurements of the average mixing in $Z^0 \rightarrow b\bar{b}, b(\bar{b}) \rightarrow l(\bar{l})$ events [1]. The differences $\bar{\chi}_b - \bar{\chi}_{bc}$ and $\bar{\chi}_b - \bar{\chi}_{b\bar{c}}$ are determined from the SLD MC. The asymmetry in the background A_{bkg} is parametrized as a function of p and p_t and is estimated from tracks in the data not identified as leptons.

A $\cos\theta$ -dependent correction factor $(1 - \Delta_{\text{QCD}}^f(z))$ is included in the theoretical asymmetry function to incorporate the effects of gluon radiation. The quantity $\Delta_{\text{QCD}}^f(z)$ has been calculated at $O(\alpha_s^2)$ for massive final state quarks [17], and, for $|z| < 0.7$, correcting for this effect increases the measured asymmetry by $\sim 3\%$. However, the use of cuts and weighting in the analysis of the lepton sample and the use of the jet axis to estimate the heavy quark direction lead to biases which favor $q\bar{q}$ events with respect to $q\bar{q}g$ events. Thus the correction to be applied is less than that of Ref. [17]. The effects of these biases have been studied with a MC simulation and decrease the theoretical QCD correction for the muon analysis by $37 \pm 4\%$ ($27 \pm 8\%$) for A_b (A_c) and for the

electrons by $17 \pm 5\%$ ($44 \pm 9\%$) for A_b (A_c). Effects due to QCD radiation of $O(\alpha_s^2)$, which are dominated by gluon splitting, lead to an additional correction of order $+0.5\%$ for electrons and $+1.0\%$ for muons [18].

A list of systematic errors is shown in Table I. When possible, systematic errors have been evaluated consistently with the LEP Electroweak Working Group [1,19] criteria. The background levels have been studied with the MC, but also with a data sample of pure pions from K_s^0 decays. The asymmetry of the background has been varied by $\pm 40\%$ of itself. Uncertainty in the jet axis simulation can affect the asymmetry measurement by distorting the lepton p_t spectrum and, to a lesser extent, the jet direction. The resulting systematic error has been studied by comparing the back-to-back direction of jets for data and MC in two jet events. The electron sample is more sensitive to such effects since both jet finding and electron identification algorithm rely on the same calorimeter response. The precision of the B^\pm and B^0 lepton spectra is directly related to the uncertainty in the D^{**} branching fraction reported by the CLEO Collaboration [13]. The systematic error due to uncertainties in the D lepton spectrum has been estimated by constraining the ACCMM model [20] to the DELCO $D \rightarrow l$ data [15]. The systematic error due to the QCD correction includes uncertainties in the second order QCD calculations for hard gluon emission and gluon splitting, in the value of α_s , and in the bias due to event selection criteria.

This analysis is independent of tracking efficiency, unless such efficiency depends on p, p_t or is not symmetric in $\cos\theta$. The extent of this p and p_t dependence has been constrained by reweighting MC tracks by the ratio of the number of tracks in data and MC as a function of p and p_t . The extracted value of A_f is much less sensitive to potential differences in the relative efficiency for selecting leptons between the forward and backward hemispheres than are the values of A_f extracted from the unpolarized forward-backward asymmetry. The relative suppression factor is greater than $1/A_e^2 \sim 50$ for any value of $|z|$.

The results obtained for the 1993–1995 data are shown in Table II, where the combined result takes into account the systematic correlations between the muon and electron analyses. The correlation coefficients between the values of A_b and A_c are 0.16 for muons and 0.43 for electrons. These results supersede the previously published lepton tag results obtained with the 1993 data sample [4].

The value obtained for A_b from leptons can be combined with already published results from measurements performed at the SLC/SLD with a momentum weighted track charge method [2] [$A_b = 0.911 \pm 0.045(\text{stat}) \pm$

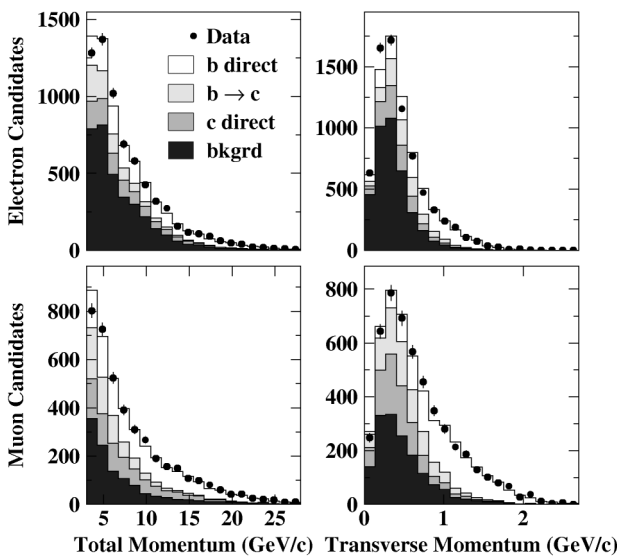


FIG. 1. Distributions of total and transverse momenta with respect to the nearest jet for identified muons and electrons in the data (points) and the MC prediction (histograms).

TABLE I. Systematic errors.

Source	Parameter variation	$\delta A_b(\mu)$	$\delta A_b(e)$	$\delta A_c(\mu)$	$\delta A_c(e)$
Monte Carlo statistics		± 0.005	± 0.020	± 0.014	± 0.037
Track efficiency	MC-data multiplicity match	± 0.006	± 0.004	± 0.002	± 0.002
Jet axis simulation	10 mrad smearing	± 0.020	± 0.030	± 0.011	± 0.064
Background level	$\pm 10\%$ relative	± 0.013	± 0.016	± 0.029	± 0.025
Background asymmetry	$\pm 40\%$ relative	∓ 0.005	∓ 0.007	± 0.015	± 0.087
$\mathcal{B}(Z^0 \rightarrow b\bar{b})$	$R_b = 0.2170 \pm 0.0009$	∓ 0.001	< 0.001	± 0.001	< 0.001
$\mathcal{B}(Z^0 \rightarrow c\bar{c})$	$R_c = 0.1733 \pm 0.0048$	± 0.002	± 0.001	∓ 0.014	∓ 0.018
$\mathcal{B}(b \rightarrow l)$	$(11.12 \pm 0.20)\%$	∓ 0.006	∓ 0.005	± 0.008	± 0.010
$\mathcal{B}(\bar{b} \rightarrow \bar{c} \rightarrow l)$	$(8.03 \pm 0.33)\%$	± 0.003	± 0.004	∓ 0.013	∓ 0.013
$\mathcal{B}(b \rightarrow \bar{c} \rightarrow l)$	$(1.3 \pm 0.5)\%$	± 0.002	± 0.003	± 0.032	± 0.024
$\mathcal{B}(b \rightarrow \tau \rightarrow l)$	$(0.461 \pm 0.079)\%$	< 0.001	< 0.001	± 0.006	± 0.005
$\mathcal{B}(b \rightarrow J/\psi \rightarrow l)$	$(0.07 \pm 0.02)\%$	± 0.003	± 0.004	± 0.001	± 0.001
$\mathcal{B}(\bar{c} \rightarrow l)$	$(9.8 \pm 0.5)\%$	± 0.004	± 0.003	∓ 0.026	∓ 0.026
B lept. spect.- D^{**} fr.	$(23 \pm 10)\%, B^+, B^0; (32 \pm 20)\%, B_s$	± 0.005	± 0.013	± 0.008	± 0.027
D lept. spect.	$ACMM1^{(+ACMM2)}_{(-ACMM3)}$ [20]	± 0.010	± 0.010	± 0.005	± 0.025
B_s fraction in $b\bar{b}$ event	0.115 ± 0.050	± 0.008	± 0.010	∓ 0.007	∓ 0.021
Λ_B fraction in $b\bar{b}$ event	0.072 ± 0.020	± 0.005	± 0.008	∓ 0.003	∓ 0.015
b fragmentation	$\epsilon_b = 0.0045 - 0.0075$	< 0.001	± 0.001	± 0.005	± 0.001
c fragmentation	$\epsilon_c = 0.045 - 0.070$	∓ 0.009	∓ 0.008	± 0.016	± 0.012
Polarization	$\langle P_e \rangle = \frac{77.23 \pm 0.52(94,95)}{63.0 \pm 1.1(93)}$	∓ 0.007	∓ 0.009	∓ 0.006	∓ 0.005
Gluon splitting	$b\bar{b} 2.38 \pm 0.48, c\bar{c} 0.31 \pm 0.11$	± 0.007	± 0.004	± 0.002	± 0.001
Other QCD uncertainties	Δ_{QCD} uncertainties	± 0.004	± 0.003	± 0.002	± 0.010
B mixing χ_b	$\chi = 0.1214 \pm 0.0043$	± 0.010	± 0.014	< 0.001	< 0.001
B mixing $\chi_{bc-b\bar{c}}$	$\chi = 0.1214$ in $B \rightarrow l$ and $B \rightarrow D \rightarrow l$	< 0.001	± 0.001	± 0.009	± 0.005
Total systematic		0.035	0.050	0.064	0.134

0.045(syst)] and with a K^\pm tag [3] [$A_b = 0.855 \pm 0.088(\text{stat}) \pm 0.102(\text{syst})$]. The resulting SLD average

$$A_b = 0.905 \pm 0.051,$$

obtained using the data collected in 1993–1995, is consistent with the SM prediction $A_b = 0.935$ and in agreement with recent preliminary results from LEP and SLD [1].

In conclusion, we have measured the extent of parity violation in the coupling of Z^0 bosons to b and c quarks by using identified charged leptons from semileptonic decays. The analysis presented in this Letter takes advantage of a new sample of 100 000 Z^0 decays collected in 1994–1995 and employs a new method of charged lepton identification which incorporates information from the CRID. The resulting 1993–1995 measurement represents a substantial increase in accuracy relative to results based on the 1993 data sample alone [4].

TABLE II. SLD 1993–1995 A_b and A_c lepton measurements.

	$A_b(\pm \text{stat} \pm \text{syst})$	$A_c(\pm \text{stat} \pm \text{syst})$
Muons	$0.943 \pm 0.090 \pm 0.035$	$0.655 \pm 0.128 \pm 0.064$
Electrons	$0.864 \pm 0.102 \pm 0.050$	$0.581 \pm 0.199 \pm 0.134$
Combined	$0.910 \pm 0.068 \pm 0.037$	$0.642 \pm 0.110 \pm 0.063$

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