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Direct Measurement of A_b and A_c at the Z^0 Pole Using a Lepton Tag[1]

The SLD Collaboration†
Stanford Linear Accelerator Center,
Stanford University, Stanford, CA 94309

Abstract

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 1993-95 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 $e^+e^- \to Z^0 \to f\bar{f}$ is

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

where P_e is the 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

$$\tilde{A}^f_{FB}(z) = \frac{[\sigma^f_L(z) - \sigma^f_L(-z)] - [\sigma^f_R(z) - \sigma^f_R(-z)]}{[\sigma^f_L(z) + \sigma^f_L(-z)] + [\sigma^f_R(z) + \sigma^f_R(-z)]} = |P_e| A_f \frac{2z}{1+z^2}, \tag{2}$$

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 modify the effective weak mixing angle, and so is complementary to other electroweak measurements performed at the Z^0 pole. In particular the Standard Model (SM) expectation $A_b = 0.935$ has only a very slight dependence on the top quark and Higgs boson masses.

To obtain the most precise measurement of A_b it is important to employ several independent methods. In this paper, we present a simultaneous direct measurement of A_b and A_c based on identified leptons from semileptonic heavy hadron decay. This measurement complements other direct measurements of A_b performed at SLD that uses momentum-weighted track charge [2] and identified kaons [3] to determine the sign of the underlying quark in $b\bar{b}$ events.

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: $Z^0 \to b\bar{b}, b \to l$; $Z^0 \to b\bar{b}, \bar{b} \to \bar{c} \to l$; $Z^0 \to b\bar{b}, b \to \bar{c} \to l$; $Z^0 \to c\bar{c}, \bar{c} \to l$; 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 direction. The parameters A_b and A_c are then extracted by a maximum likelihood fit to the polarized differential cross section, taking into account the effects of hard gluon radiation. Although in this approach the polarized asymmetry (2) is not explicitly formed, the results for A_b and A_c thus obtained maintain their insensitivity to the initial state coupling parameter A_e. 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 1993-95 data sample.

The SLAC Linear Collider (SLC) and its operation with a polarized electron beam has been described elsewhere [5]. The SLC Large Detector (SLD) recorded an integrated luminosity of 3.6 pb^{-1} (1.8 pb^{-1}) during the 1994-95 (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) [6] and the CCD-based vertex detector [7] in a uniform axial magnetic field of 0.6T. The combined momentum resolution in the plane perpendicular to the beam axis is $\delta p_\perp / p_\perp =$

$\sqrt{(.01)^2 + (.0026\ p_\perp/GeV/c)^2}$. The Liquid Argon Calorimeter (LAC) [8] measures the energies and shower profiles of charged and neutral particles and is used in the electron identification. The LAC is segmented into projective towers with separate electromagnetic and hadronic sections. In the barrel LAC, which covers the angular range $|\cos\theta| < 0.82$, the electromagnetic towers have a transverse size of ~ 35 mrad and are divided longitudinally into a front section of 6 radiation lengths and a back section of 15 radiation lengths. The barrel LAC electromagnetic energy resolution is $\sigma_E/E = 15\%/\sqrt{E(GeV)}$.

The Warm Iron Calorimeter (WIC) [9] detects charged particles that penetrate the 3.5 interaction lengths of the LAC and magnet coil. It is composed of sixteen layers of plastic streamer tubes, which provide hit resolution of 0.4 cm and 2.0 cm in the azimuthal and axial directions, respectively. The streamer tubes are interleaved with 2 inch thick plates of iron, for a total thickness of 4 interaction lengths. The Čerenkov Ring Imaging Detector (CRID)[10] measures the velocities of charged tracks using the angles of Čerenkov photons emitted in liquid and gaseous radiators. The CRID information (limited to the barrel region, $|\cos\theta| < 0.68$) has been included in both the electron and the muon identification. Only the gas information is relevant for the momentum range used in this analysis ($p > 2$ GeV/c). 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.

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 1993-95 sample, with negligible background. Jets are formed using the JADE algorithm [11] with parameter $y_{cut} = 0.005$ on calorimeter energy cluster information. The jet axis approximates the b-quark direction in $Z^0 \rightarrow b\bar{b}$ events, with an angular resolution of ~ 30 mrad. For events with identified electrons, no attempt is made to remove the electron cluster in the jet axis determination.

Electrons are identified[12] 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 exploit the characteristics of electromagnetic showers, including transverse and longitudinal shower development shapes, and the comparison of LAC energy and track momentum. These quantities, along with the CRID e-π separation information, are used as input variables to a single output Neural Network[12], trained on the corresponding SLD Monte Carlo (MC) quantities. The efficiency (purity) for electron identification is on average 62% (70%) and over 78% (80%) for electrons with momenta greater than 15 GeV/c. This electron purity estimate includes electrons from photon conversions as signal. 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[13] 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 $\pi - \mu$ 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 WIC hits associated with the extrapolated tracks, on the χ^2 of the CDC/WIC matching and on the χ^2 of the fit of track in the WIC. MC studies show that the remaining pion punch-through background is negligible. Muons from pion and kaon decays and hadronic showers are a significant background, but fall off rapidly with increasing momentum. 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 each of the physics sources ($b \to l$, $b \to c \to l$, $c \to l$, background, etc.) relies directly on MC simulation of semileptonic decays of heavy quarks in Z^0 decays. Z^0 decays are generated via JETSET 7.4[14]. 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 formalism [15] with a 23% D^{**} fraction, while semileptonic decays of D mesons are simulated according to the 1994 Particle Data Group branching ratios [16]. Experimental constraints are provided by the $B \to l$ and $B \to D$ inclusive momentum spectra measured by CLEO [17] [18] and the $D \to l$ momentum spectrum measured by DELCO [19]. The detailed simulation of the SLD detector response has been realized using GEANT [20] 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 muons and electrons 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. At low transverse momenta the disagreement in the electron distribution between data and MC is ascribed to the uncertainty in the jet axis simulation. This is taken into account in the evaluation of the systematic errors as discussed below.

The distribution of the quantity $Q\cos\theta_{jet}$, which approximates the b quark direction, is shown in figure 2 for the identified lepton sample. The experimental asymmetry, with the appropriate sign, can be clearly seen in the separate distributions for left and right handed electron beams. For illustrative purposes this sample includes an additional cut (which is not used for the full analysis) on the lepton p and p_t, $\sqrt{(p(GeV/c)/15.0)^2 + (p_t(GeV/c)/1.0)^2}$ > 1.0, which increases the $b \to l$ purity to 76% for muons and 68% for electrons.

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:

$$\begin{aligned} P\left(p, p_t,\, P_e, z;\, A_b, A_c\right) \propto \quad & \{(1+z^2)(1-A_eP_e) \\ & -2Q(A_e-P_e)\left[(f_b(1-2\bar{\chi}_b) - f_{bc}(1-2\bar{\chi}_{bc})\right. \\ & +f_{b\bar{c}}(1-2\bar{\chi}_{b\bar{c}}))(1-\Delta^b_{QCD}(z))A_b \\ & \left.+f_c(1-\Delta^c_{QCD}(z))A_c + f_{bkg}A_{bkg}\right] z\Big\}\,, \end{aligned} \tag{3}$$

where $z = \cos\theta_{jet}$. The lepton source fractions f_b, f_{bc}, $f_{b\bar{c}}$, f_c, and f_{bkg}, where bc ($b\bar{c}$) refers to

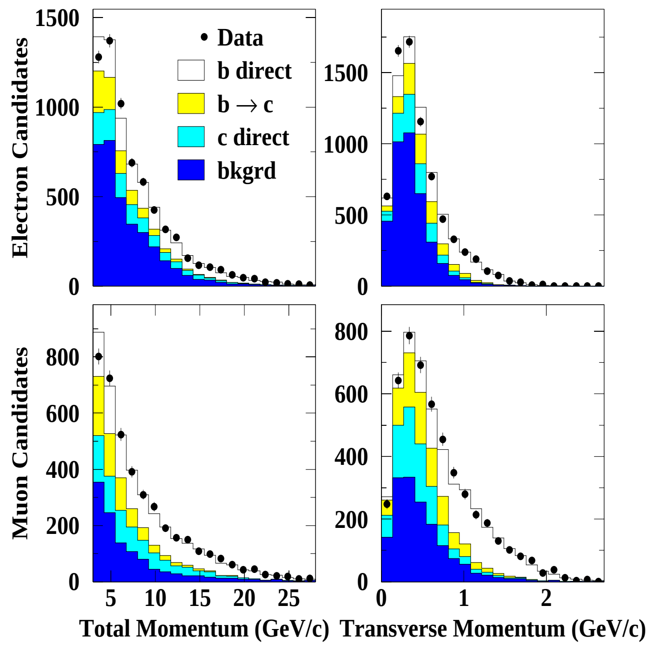

Figure 1: Distributions of total and transverse momenta with respect to the nearest jet for identified muons and electrons in the data (points) and the MC prediction (histograms) for various sources.

$b \to c \to \bar{l}$ ($b \to \bar{c} \to l$), 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 $Z^0 \to b\bar{b}, b(\bar{b}) \to l(\bar{l})$ 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 $(1 - \Delta^f_{QCD}(z))$ is included in the theoretical asymmetry function to incorporate the effects of gluon radiation. The quantity $\Delta^f_{QCD}(z)$ has been calculated at $O(\alpha_s)$ for massive final state quarks by Stav and Olsen [21] and is as large as .05 (.06) for the b (c) quark at $z = 0$. For an unbiased sample of $b\bar{b}$ or $c\bar{c}$ events with $|z| < 0.7$, correcting for this effect increases the measured asymmetry by 3% overall. However, the theoretical calculations have been performed in the limit of perfect efficiency in the reconstruction of events with emission of gluons of any energy. The inefficiency of the detector, the use of cuts and weighting in the identifications and in the analysis of the lepton sample, and the use of the jet axis to estimate the b-quark direction, lead to biases in the use of the lepton sample 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 [21]. The effects of these biases have been studied with a MC simulation of the analysis chain and have been accounted for in the likelihood function, decreasing the theoretical QCD correction by about 30%. 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% and +1.0% for electrons and muons respectively[22][23].

A list of systematic errors is shown in Table 1. When possible, systematic errors have been evaluated consistently with the LEP Electroweak Working Group[24] criteria. The background levels have been studied with the MC, but also with a data sample of pure pions

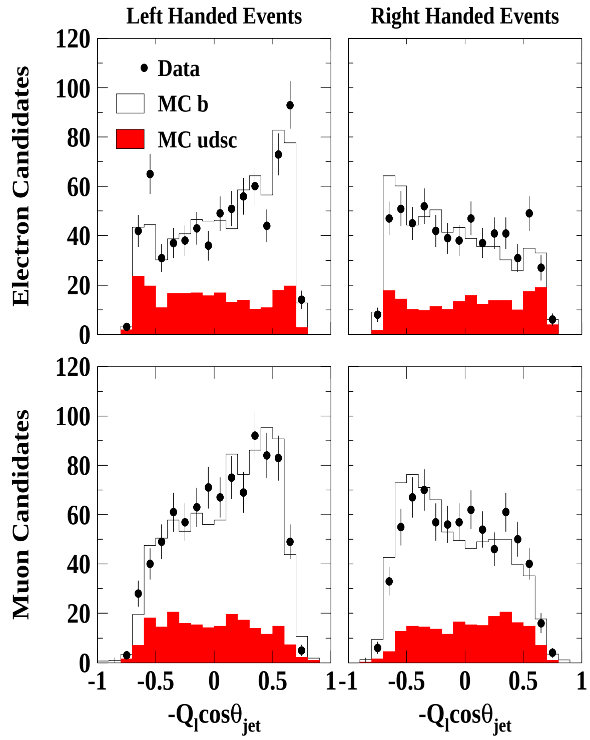

Figure 2: The polar angle distributions of the jet direction, signed by the lepton charge, in a b-enriched sample. The open histogram shows the total MC standard model prediction (assumes $A_b = 0.935$), with the shaded area representing the contribution from sources other than b quarks.

from K_s^0 decays. The asymmetry of the background has been varied by $\pm 40\%$. 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 systematics 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[17]. The systematic error due to uncertainties in the D lepton spectrum has been estimated by constraining the ACCMM model[25][24] to the DELCO $D \rightarrow l$ data[19]. The systematic error due to the QCD correction includes uncertainties in the 2nd 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 in the analysis.

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 dependency has been calculated 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 extacted from the unpolarized forward-backward asymmetry. The relative suppression factor is greater than $1/{A_e}^2 \sim 50$ for any value of $|z|$ and therefore forward-backward asymmetry in the detector acceptance is not a significant source of measurement bias.

Source	Parameter variation	$\delta A_b(\mu)$	$\delta A_b(e)$	$\delta A_c(\mu)$	$\delta A_c(e)$
Monte Carlo statistics		$\pm.005$	$\pm.020$	$\pm.014$	$\pm.037$
Track efficiency	MC-data multiplicity match	$\pm.006$	$\pm.004$	$\pm.002$	$\pm.002$
Jet axis simulation	10 mrad smearing	$\pm.020$	$\pm.030$	$\pm.011$	$\pm.064$
Background level	$\pm10\%$ relative	$\pm.013$	$\pm.016$	$\pm.029$	$\pm.025$
Background asymmetry	$\pm40\%$ relative	$\mp.005$	$\mp.007$	$\pm.015$	$\pm.087$
BR($Z^0 \to b\bar{b}$)	$R_b = .2170 \pm .0009$	$\mp.001$	$<.001$	$\pm.001$	$<.001$
BR($Z^0 \to c\bar{c}$)	$R_c = .1733 \pm .0048$	$\pm.002$	$\pm.001$	$\mp.014$	$\mp.018$
BR($b \to l$)	$(11.12 \pm 0.20)\%$	$\mp.006$	$\mp.005$	$\pm.008$	$\pm.010$
BR($\bar{b} \to \bar{c} \to l$)	$(8.03 \pm 0.33)\%$	$\pm.003$	$\pm.004$	$\mp.013$	$\mp.013$
BR($b \to \bar{c} \to l$)	$(1.3 \pm 0.5)\%$	$\pm.002$	$\pm.003$	$\pm.032$	$\pm.024$
BR($b \to \tau \to l$)	$(0.461 \pm 0.079)\%$	$<.001$	$<.001$	$\pm.006$	$\pm.005$
BR($b \to J/\psi \to l$)	$(0.07 \pm 0.02)\%$	$\pm.003$	$\pm.004$	$\pm.001$	$\pm.001$
BR($\bar{c} \to l$)	$(9.8 \pm 0.5)\%$	$\pm.004$	$\pm.003$	$\mp.026$	$\mp.026$
B lept. spect.	$(23 \pm 10)\%$, $B^{+,0}$;	$\pm.005$	$\pm.013$	$\pm.008$	$\pm.027$
- D^{**} fr.	$(32 \pm 20)\%$, B_s				
D lept. spect.	$ACCMM1\ (^{+ACCMM2}_{-ACCMM3})$ [25]	$\pm.010$	$\pm.010$	$\pm.005$	$\pm.025$
B_s fraction in $b\bar{b}$ event	$.115 \pm .050$	$\pm.008$	$\pm.010$	$\mp.007$	$\mp.021$
Λ_b fraction in $b\bar{b}$ event	$.072 \pm .020$	$\pm.005$	$\pm.008$	$\mp.003$	$\mp.015$
b fragmentation	$\epsilon_b = .0045\text{-}.0075$	$<.001$	$\pm.001$	$\pm.005$	$\pm.001$
c fragmentation	$\epsilon_c = .045\text{-}.070$	$\mp.009$	$\mp.008$	$\pm.016$	$\pm.012$
Polarization	$<P_e>=^{77.23\pm.52(94,95)}_{63.0\pm1.1(93)}$	$\mp.007$	$\mp.009$	$\mp.006$	$\mp.005$
QCD uncertainties	Δ_{QCD} uncertainties	$\pm.008$	$\pm.005$	$\pm.003$	$\pm.010$
B mixing χ_b	$\chi = .1214 \pm .0043$	$\pm.010$	$\pm.014$	$<.001$	$<.001$
B mixing $\chi_{bc-b\bar{c}}$	$\chi = .1214$ in $b \to l$ & $b \to c \to l$	$<.001$	$\pm.001$	$\pm.009$	$\pm.005$
Total Systematic		.035	.050	.064	.134

Table 1: Systematic errors

The results obtained for the 93-95 data are shown in table 2, 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] ($A_b = 0.911 \pm 0.045(\text{stat}) \pm 0.045(\text{syst})$) 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 100000 Z^0 decays collected in 1994-95 and employs a new method of charged lepton identification which incorporates information from the CRID. The resulting 1993-95 values of $A_b = 0.910 \pm 0.068(\text{stat}) \pm$

	A_b(±stat ± syst)	A_c(±stat ± 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	$0.910 \pm 0.068 \pm 0.037$	$0.642 \pm 0.110 \pm 0.063$

Table 2: A_b and A_c lepton measurements for the 1993-95 SLD data.

0.037(syst) and $A_c = 0.642 \pm 0.110$(stat) ± 0.063(syst) represent a substantial increase in accuracy relative to results based on the 1993 data sample alone[4].

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References

[1] The LEP collaborations and the LEP electroweak working group, CERN-EP/99-15 and CERN-PPE/97-154 and references therein.

[2] K. Abe *et al.*, *Phys. Rev. Lett.* **81**, 942 (1998).

[3] K. Abe *et al.*, SLAC-PUB-7959, Nov. 1998 *submitted to Phys. Rev. Lett.*.

[4] K. Abe *et al.*, *Phys. Rev. Lett.* **74**, 2895 (1995).

[5] K. Abe *et al.*, *Phys. Rev. Lett.* **78**, 2075 (1997).

[6] M. Fero *et al.*, *Nucl. Instr. & Meth.* **A367**, 111 (1995).

[7] G. Agnew *et al.*, SLAC-PUB-5906 (1992).

[8] D. Axen *et al.*, *Nucl. Instr. & Meth.* **A328**, 472 (1993).

[9] A. Benvenuti *et al.*, *Nucl. Instr. & Meth.* **A276**, 94 (1989); *Nucl. Instr. & Meth.* **A290**, 353 (1990).

[10] K. Abe *et al.*, *Phys. Rev.* **59**, 1999 (.)

[11] W. Bartel *et al.*, *Z. Phys.* **C33**, 23 (1986).

[12] D. Falciai, Ph.D. Thesis, Universitá di Perugia (1996).

[13] G. Mancinelli, Ph.D. Thesis, Universitá di Perugia (1997).

[14] T. Sjöstrand *et al.*, *Comp. Phys. Comm.* **82**, 74 (1994).

[15] N. Isgur, D. Scora, B. Grinstein, M. Wise, *Phys. Rev.* **D39**, 799 (1989); code provided by P. Kim and CLEO Collaboration.

[16] Review of Particle Properties, *Phys. Rev.* **D50**, 1173 (1994).

[17] B. Barish *et al.*, *Phys. Rev. Lett.* **76**, 1570 (1996); L. Gibbons *et al.*, *Phys. Rev.* **D56**, 2783 (1997).

[18] M. Thulasidas, PhD thesis, Syracuse University (1993).

[19] W. Bacino *et al.*,*Phys. Rev. Lett.* **43**, 1073 (1979).

[20] GEANT 3.21 program, CERN Applications Software Group, CERN Program Library.

[21] A. Djouadi, J. Kühn, and P. Zerwas, Z. Phys **C46**, 411 (1990); G. Altarelli and B. Lampe, Nucl. Phys. **391**, 3 (1993); J.B. Stav and H.A. Olsen, PRD **D52**, 1359 (1995); PRD **D50**, 6775 (1994).

[22] K. Abe *et al.*, SLD Physics Note 66, Feb. 1998.

[23] R. Akers *et al.*, *Z. Phys.* **C67**, 27 (1995);*Z. Phys.* **B353**, 595 (1995); P. Abreu *et al.*, Phys. Lett. **B405**, 202 (1997); R. Barate *et al.*, CERN-EP-98-103, *submitted to Phys. Lett. B.*

[24] Presentation of LEP Electroweak Heavy Flavour Results for Summer 1996 Conferences, LEPHF/96-01/.

[25] G.Altarelli, N.Cabibbo, G.Corbó, L.Maiani, G.Martinelli, *Nucl. Phys.* **B208**, 365 (1982).

†**The SLD Collaboration**

Kenji Abe,[20] Koya Abe,[32] T. Abe,[28] I.Adam,[28] T. Akagi,[28] N. J. Allen,[4] A. Arodzero,[21] W.W. Ash,[28],* D. Aston,[28] K.G. Baird,[16] C. Baltay,[38] H.R. Band,[37] M.B. Barakat,[15] O. Bardon,[18] T.L. Barklow,[28] G. L. Bashindzhagyan,[19] J.M. Bauer,[17] G. Bellodi,[22] R. Ben-David,[38] A.C. Benvenuti,[3] G.M. Bilei,[24] D. Bisello,[23] G. Blaylock,[16] J.R. Bogart,[28] B. Bolen,[17] G.R. Bower,[28] J. E. Brau,[21] M. Breidenbach,[28] W.M. Bugg,[31] D. Burke,[28] T.H. Burnett,[36] P.N. Burrows,[22] R.M. Byrne,[18] A. Calcaterra,[11] D. Calloway,[28] B. Camanzi,[10] M. Carpinelli,[25] R. Cassell,[28] R. Castaldi,[25] A. Castro,[23] M. Cavalli-Sforza,[34] A. Chou,[28] E. Church,[36] H.O. Cohn,[31] J.A. Coller,[5] M.R. Convery,[28] V. Cook,[36] R. Cotton,[4] R.F. Cowan,[18] D.G. Coyne,[34] G. Crawford,[28] C.J.S. Damerell,[26] M. N. Danielson,[7] M. Daoudi,[28] N. de Groot,[28] R. Dell'Orso,[24] P.J. Dervan,[4] R. de Sangro,[11] M. Dima,[9] A. D'Oliveira,[6] D.N. Dong,[18] M. Doser,[28] R. Dubois,[28] B.I. Eisenstein,[12] V. Eschenburg,[17] E. Etzion,[37] S. Fahey,[7] D. Falciai,[11] C. Fan,[7] J.P. Fernandez,[34] M.J. Fero,[18] K.Flood,[16] R. Frey,[21] T. Gillman,[26] G. Gladding,[12] S. Gonzalez,[18] E. R. Goodman,[7] E.L. Hart,[31] J.L. Harton,[9] A. Hasan,[4] K. Hasuko,[32] S. J. Hedges,[5] S.S. Hertzbach,[16] M.D. Hildreth,[28] J. Huber,[21] M.E. Huffer,[28] E.W. Hughes,[28] X.Huynh,[28] H. Hwang,[21] M. Iwasaki,[21] D. J. Jackson,[26] P. Jacques,[27] J.A. Jaros,[28] Z.Y. Jiang,[28] A.S. Johnson,[28] J.R. Johnson,[37] R.A. Johnson,[6] T. Junk,[28] R. Kajikawa,[20] M. Kalelkar,[27] Y. Kamyshkov,[31] H.J. Kang,[27] I. Karliner,[12] H. Kawahara,[28] Y. D. Kim,[29] R. King,[28] M.E. King,[28] R.R. Kofler,[16] N.M. Krishna,[7] R.S. Kroeger,[17] M. Langston,[21] A. Lath,[18] D.W.G. Leith,[28] V. Lia,[18] C.-J. S. Lin,[16] X. Liu,[34] M.X. Liu,[38] M. Loreti,[23] A. Lu,[33] H.L. Lynch,[28] J. Ma,[36] M. Mahjouri,[18] G. Mancinelli,[27] S. Manly,[38] G. Mantovani,[24] T.W. Markiewicz,[28] T. Maruyama,[28] H. Masuda,[28] E. Mazzucato,[10] A.K. McKemey,[4] B.T. Meadows,[6] G. Menegatti,[10] R. Messner,[28] P.M. Mockett,[36] K.C. Moffeit,[28] T.B. Moore,[38] M.Morii,[28] D. Muller,[28] V.Murzin,[19] T. Nagamine,[32] S. Narita,[32] U. Nauenberg,[7] H. Neal,[28] M. Nussbaum,[6],* N.Oishi,[20] D. Onoprienko,[31] L.S. Osborne,[18] R.S. Panvini,[35] H. Park,[21] C. H. Park,[30] T.J. Pavel,[28] I. Peruzzi,[11] M. Piccolo,[11] L. Piemontese,[10] E. Pieroni,[25] K.T. Pitts,[21] R.J. Plano,[27] R. Prepost,[37] C.Y. Prescott,[28] G.D. Punkar,[28] J. Quigley,[18] B.N. Ratcliff,[28] T.W. Reeves,[35] J. Reidy,[17] P.L. Reinertsen,[34] P.E. Rensing,[28] L.S. Rochester,[28] P.C. Rowson,[8] J.J. Russell,[28] O.H. Saxton,[28] T. Schalk,[34] R.H. Schindler,[28] B.A. Schumm,[34] J. Schwiening,[28] S. Sen,[38] V.V. Serbo,[28] M.H. Shaevitz,[8] J.T. Shank,[5] G. Shapiro,[14] D.J. Sherden,[28] K. D. Shmakov,[31] C. Simopoulos,[28] N.B. Sinev,[21] S.R. Smith,[28] M. B. Smy,[9] J.A. Snyder,[38] H. Staengle,[9] A. Stahl,[28] P. Stamer,[27] R. Steiner,[1] H. Steiner,[14] M.G. Strauss,[16] D. Su,[28] F. Suekane,[32] A. Sugiyama,[20] S. Suzuki,[20] M. Swartz,[13] A. Szumilo,[36] T. Takahashi,[28] F.E. Taylor,[18] J. Thom,[28] E. Torrence,[18] N. K. Toumbas,[28] T. Usher,[28] C. Vannini,[25] J. Va'vra,[28] E. Vella,[28] J.P. Venuti,[35] R. Verdier,[18] P.G. Verdini,[25] S.R. Wagner,[28] D. L. Wagner,[7] A.P. Waite,[28] S. Walston,[21] J.Wang,[28] C. Ward,[4] S.J. Watts,[4] A.W. Weidemann,[31] E. R. Weiss,[36] J.S. Whitaker,[5] S.L. White,[31] F.J. Wickens,[26] B. Williams,[7] D.C. Williams,[18] S.H. Williams,[28] S. Willocq,[28] R.J. Wilson,[9] W.J. Wisniewski,[28] J. L. Wittlin,[16] M. Woods,[28] G.B. Word,[35] T.R. Wright,[37] J. Wyss,[23] R.K. Yamamoto,[18] J.M. Yamartino,[18] X. Yang,[21] J. Yashima,[32] S.J. Yellin,[33] C.C. Young,[28] H. Yuta,[2] G. Zapalac,[37] R.W. Zdarko,[28] J. Zhou.[21]

(The SLD Collaboration)

[1]*Adelphi University, Garden City, New York 11530,*
[2]*Aomori University, Aomori, 030 Japan,*
[3]*INFN Sezione di Bologna, I-40126, Bologna Italy,*
[4]*Brunel University, Uxbridge, Middlesex, UB8 3PH United Kingdom,*
[5]*Boston University, Boston, Massachusetts 02215,*
[6]*University of Cincinnati, Cincinnati, Ohio 45221,*
[7]*University of Colorado, Boulder, Colorado 80309,*
[8]*Columbia University, New York, New York 10533,*
[9]*Colorado State University, Ft. Collins, Colorado 80523,*
[10]*INFN Sezione di Ferrara and Universita di Ferrara, I-44100 Ferrara, Italy,*
[11]*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy,*
[12]*University of Illinois, Urbana, Illinois 61801,*
[13]*Johns Hopkins University, Baltimore, Maryland 21153,*
[14]*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720,*
[15]*Louisiana Technical University - Ruston,LA 71272,*
[16]*University of Massachusetts, Amherst, Massachusetts 01003,*
[17]*University of Mississippi, University, Mississippi 38677,*
[18]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,*
[19]*Institute of Nuclear Physics, Moscow State University, 119899, Moscow Russia,*
[20]*Nagoya University, Chikusa-ku, Nagoya 464 Japan,*
[21]*University of Oregon, Eugene, Oregon 97403,*
[22]*Oxford University, Oxford, OX1 3RH, United Kingdom,*
[23]*INFN Sezione di Padova and Universita di Padova I-35100, Padova, Italy,*
[24]*INFN Sezione di Perugia and Universita di Perugia, I-06100 Perugia, Italy,*
[25]*INFN Sezione di Pisa and Universita di Pisa, I-56010 Pisa, Italy,*
[26]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom,*
[27]*Rutgers University, Piscataway, New Jersey 08855,*
[28]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309,*
[29]*Sogang University, Seoul, Korea,*
[30]*Soongsil University, Seoul, Korea 156-743,*
[31]*University of Tennessee, Knoxville, Tennessee 37996,*
[32]*Tohoku University, Sendai 980, Japan,*
[33]*University of California at Santa Barbara, Santa Barbara, California 93106,*
[34]*University of California at Santa Cruz, Santa Cruz, California 95064,*
[35]*Vanderbilt University, Nashville,Tennessee 37235,*
[36]*University of Washington, Seattle, Washington 98105,*
[37]*University of Wisconsin, Madison,Wisconsin 53706,*
[38]*Yale University, New Haven, Connecticut 06511.*

* Deceased.