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 which have been improved relative to those used in 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

\[
d\sigma_f / dz \propto (1 - A_c P_e)(1 + z^2) + 2A_f (A_e - P_e)z ,
\]

where \( P_e \) is the \( e^- \) beam longitudinal polarization \([P_e \geq 0]\) 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

\[
A_{FB}^f(z) \equiv \frac{[\sigma_L(z) - \sigma_L(-z)] - [\sigma_R(z) - \sigma_R(-z)]}{[\sigma_L(z) + \sigma_L(-z)] + [\sigma_R(z) + \sigma_R(-z)]} = \frac{|P_e| A_f}{2z} \frac{2z}{1 + z^2} ,
\]

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 \( A_c A_f \). In addition, the quantity \( A_b \) is largely independent of propagator effects that mod-
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 \(\delta p_{\perp}/p_{\perp} = \sqrt{(0.01)^2 + (0.0026p_{\perp}/(GeV/c))^2}\). 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 included in both the electron and the muon identification.

For events containing leptons is used to determine \(A_0\) and \(A_\beta\) simultaneously. The likelihood function contains the following probability term for each lepton in the data:

\[
\frac{1}{\sqrt{2\pi \sigma_e^2}} \exp \left( -\frac{(E - \mu)^2}{2\sigma_e^2} \right)
\]

for \(p > 2\) 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 \(e-\pi\) 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 well. 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 \(K^0 \rightarrow \pi^+ \pi^-\) 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 \(\pi-\mu\) separation rejects 37% of the \(\pi\), 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 \(\chi^2\) of the track in the WIC and the \(\chi^2\) 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 \(K^0\) 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 \textsc{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 systematic errors.

A maximum likelihood analysis of all hadronic \(Z^0\) events containing leptons is used to determine \(A_0\) and \(A_\beta\), simultaneously. The likelihood function contains the following probability term for each lepton in the data:
where $z = \cos \theta_{\text{jet}}$. The lepton source fractions $f_b$, $f_{bc}$, $f_{b\pi}$, $f_c$, and $f_{bkg}$, where $bc$ ($b\pi$) refers to $b \rightarrow c \rightarrow \bar{t}$ ($b \rightarrow \pi \rightarrow l$), are functions of $p$ and $p_t$ and are derived by counting leptons in the MC with $p > 6$ GeV/$c$ and $p_t > 3$ GeV/$c$, and the use of the jet axis to estimate the lepton sample and the use of the jet axis to estimate the lepton source fractions $A_b$, $A_c$, and $A_{bkg}$, which 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 QCD radiation. The quantity $\Delta_{\text{QCD}}^{f}(z)$ has been calculated at $O(\alpha_s)$ 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 $q\overline{q}$ events with respect to $q\overline{q}g$ 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 $A_b$ ($A_c$).

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 $A_f$ from leptons can be combined with already published results from measurements performed at the SLC/SLD with a momentum weighted track charge method [2] $[A_b = 0.911 \pm 0.045(\text{stat}) \pm 0.042(\text{syst})]$.
0.088 with recent preliminary results from LEP and SLD [1].

The analysis presented in this Letter takes advantage of a new sample of 100,000 $Z^0$ decays. 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].

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*Deceased.


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


