SLAC–PUB–7307
September 1996

Determination of Electroweak Parameters at the SLC*

CONF-960765--55

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Presented at the 28th International Conference on High Energy Physics
Warsaw, Poland
July 25-31, 1996

*Work supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennssee), DE-FG02-95ER40896 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Science and Engineering Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

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Abstract

We present an improved measurement of the left-right cross section asymmetry (A_{LR}) for Z^0 boson production by e^+e^- collisions. The measurement was performed at a center-of-mass energy of 91.28 GeV with the SLD detector at the SLAC Linear Collider (SLC) during the 1994-95 running period. The luminosity-weighted average polarization of the SLC electron beam during this run was measured to be $(77.23 \pm 0.52)\%$. Using a sample of 93,644 hadronic Z^0 decays, we measure the pole asymmetry A^0_{LR} to be $0.1512 \pm 0.0042(\text{stat.}) \pm 0.0011(\text{syst.})$ which is equivalent to an effective weak mixing angle of $\sin^2\theta_W^{\text{eff}} = 0.23100 \pm 0.00054(\text{stat.}) \pm 0.00014(\text{syst.})$. We also present a preliminary direct measurement of the Z^0-lepton coupling asymmetries A_e,A_μ, and A_τ extracted from the differential cross section observed in leptonic Z^0 decays. We combine these results with our previous A_{LR} measurement to obtain a combined determination of the weak mixing angle $\sin^2\theta_W^{\text{eff}} = 0.23061 \pm 0.00047$.

1 Introduction

The left-right cross section asymmetry is defined as $A^0_{LR} \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ where σ_L and σ_R are the e^+e^- production cross sections for Z^0 bosons at the Z pole energy with left-handed and right-handed electrons, respectively. The Standard Model predicts that this quantity depends upon the effective vector (v_e) and axial-vector (a_e) couplings of the Z boson to the electron current,

$$A^0_{LR} = \frac{2v_e a_e}{v_e^2 + a_e^2} \equiv \frac{2(1 - 4\sin^2\theta_W^{\mathrm{eff}})}{1 + (1 - 4\sin^2\theta_W^{\mathrm{eff}})^2}, \qquad (1)$$

where the effective weak mixing angle is defined as $\sin^2\theta_W^{\mathrm{eff}} \equiv (1 - v_e/a_e)/4$. Note that A^0_{LR} is a sensitive function of $\sin^2\theta_W^{\mathrm{eff}}$ and depends upon virtual electroweak radiative corrections including those involving the top quark and Higgs boson, as well as corrections arising from new phenomena. The recent measurement of the top quark mass [1, 2] has greatly enhanced the power of this measurement as a test of the prevailing theory.

The measurement is performed by counting the number of hadronic Z decays observed for each of the two longitudinal polarization states of the incident electron beam. A continual measurement of the electron beam polarization $\mathcal{P}_e$ allows us to form the asymmetry

$$A_{LR}(E_{cm}) = \frac{1}{<\mathcal{P}_e>} \cdot \frac{N_L - N_R}{N_L + N_R} \qquad (2)$$

where $<\mathcal{P}_e>$ is the luminosity-weighted electron beam polarization. The experimental asymmetry A_{LR} must be corrected for small effects arising from initial state radiation, pure photon exchange, and Z-photon interference to extract A^0_{LR}.

2 Electron Polarization at the SLC

At the SLC, longitudinally polarized electrons are produced by photoemission from a strained-lattice GaAs photocathode illuminated by a Ti-Sapphire laser operating at 849 nm.[3] A Pockels cell driven by a pseudo-random sequence at 120 Hz determines the helicity of the incident laser pulse and hence the helicity of the produced electron bunch. Optimization of the cathode design has improved the maximum beam polarization to nearly 80%.

The spin transport of the electrons through the SLC remains unchanged from the 1993 run. The polarization axis of the electron bunch is rotated into the vertical plane before the damping ring, remains oriented vertically during the acceleration phase, and is brought back into the horizontal plane by means of a pair of large amplitude betatron oscillations ("spin bumps") in the SLC North arc.[4] These spin bumps are empirically set to optimize the longitudinal electron polarization at the SLD Interaction Point (IP). The luminosity-weighted e^+e^- center-of-mass energy (E_{cm}) is measured with precision energy spectrometers [5] to be 91.280 ± 0.025 GeV. A detailed description of SLC operations with polarized electrons can be found elsewhere.[6]

3 The Compton Polarimeter

The longitudinal electron beam polarization ($\mathcal{P}_e$) is measured by a Compton scattering polarimeter located 33 meters downstream of the IP. A circularly polarized 2.33 eV photon beam produced by a frequency doubled Nd:YAG laser is scattered off the exiting 45.6 GeV electron bunch just before the beam enters the first set of dipole magnets of the SLC South arc heading towards the electron beam dump. These magnets act as a spectrometer sweeping the scattered electrons out of the main SLC beam line and into a multichannel threshold Cherenkov detector where the momentum spectrum of the electrons is measured in the interval from 17 to 30 GeV/c.

The counting rate in each detector channel is measured for parallel and anti-parallel combinations of the photon and electron beam helicities. The asymmetry formed from these rates is equal to the product $\mathcal{P}_e\mathcal{P}_\gamma A(E)$ where $\mathcal{P}_\gamma$ is the circular polarization of the laser beam at the electron-photon crossing point and $A(E)$ is the theoretical asymmetry function at the accepted energy E of the scattered electrons.

Polarimeter data are acquired continuously during the operation of the SLC. A statistical error of $\sim$ 1% is reached in approximately three minutes, although two thirds of the polarimeter data acquired are used for calibration purposes. We obtain $\mathcal{P}_e$ from the observed asymmetry using the measured value of $\mathcal{P}_\gamma$ and the theoretical asymmetry function (including $\sim$ 1% corrections for detector resolution effects). The systematic uncertainties associated with the polarization measurement, summarized in Table 1, are currently dominated by our ability to measure the linearity of the entire polarimeter system. For the 1994-95 run the total relative systematic uncertainty is estimated to be $\delta\mathcal{P}_e/\mathcal{P}_e = 0.67\%$.

In our previous measurement based on data acquired in 1993,[8] it was noted that the polarization measured by the Compton polarimeter does not exactly correspond to the polarization of the electrons producing Z bosons at the SLD. While the Compton polarimeter measures the polarization of the entire electron bunch, chromatic aberrations in the SLC final focus optics reduce the luminosity generated from the off-energy beam tails. Because of the energy-dependent spin precession experienced by the electrons in the SLC North arc, these off-energy beam tails have a systematically lower net longitudinal polarization than the beam core.

During the 1994-95 run, a number of measures were taken to control this effect, both in the operation of the SLC and in monitoring procedures, which have significantly reduced both the relative size of this effect and the associated uncertainty from $(1.7 \pm 1.1)\%$ to $(0.20 \pm 0.14)\%$. At this level, the spin precession of the electron bunch in the final focus quadrupole triplet must also be taken into account, and the net correction is included as an additional systematic uncertainty on the beam polarization measurement listed in Table 1. In addition, depolarization due to the collision process itself was directly measured and found to be negligible.

Table 1: Polarimeter Systematic Uncertainties

Systematic Uncertainty	$\delta\mathcal{P}_e/\mathcal{P}_e(\%)$
Laser Polarization	0.20
Detector Linearity	0.50
Detector Calibration	0.29
Electronic Noise	0.20
Compton - IP Difference	0.17
Total Uncertainty	0.67

4 Event Selection

The e^+e^- collisions are measured by the SLD detector which has been described elsewhere.[9] The triggering of the SLD relies upon a combination of calorimeter and tracking information, and the event selection is based upon energy clusters reconstructed in the Liquid Argon Calorimeter (LAC),[10] and charged tracks reconstructed in the Central Drift Chamber (CDC).[11] Cuts on minimum calorimeter energy and maximum calorimeter energy imbalance are used to remove two-photon and beam related backgrounds, while a cut on minimum track multiplicity is used to remove e^+e^- final states. These processes have a different left-right production asymmetry than the hadronic Z decays that we are interested in, and we apply a small correction to account for any residual background contamination in our sample. The background in our event sample is estimated to be $(0.08 \pm 0.08)\%$ for e^+e^- final states and $(0.03 \pm 0.03)\%$ for the remainder. Although they are not backgrounds, the other two leptonic final states are also selected with very poor efficiency: $\sim 7\%$ for $\tau^+\tau^-$, $\sim 0\%$ for $\mu^+\mu^-$. We are left with a very pure sample of hadronic Z decays with an estimated total efficiency of $(89 \pm 1)\%$.

5 Measurement of $\mathrm{A_{LR}}$

A total of 93,644 events satisfy the selection criteria. We find that 52,179 (N_L) and 41,465 (N_R) are produced from the left-handed and right-handed electron helicity state respectively, leading to a measured asymmetry $A_m = 0.11441 \pm 0.00325$. After dividing by the luminosity weighted beam polarization, measured to be $< \mathcal{P}_e >= (77.23 \pm 0.52)\%$, and applying a correction of $\delta A_{LR}/A_{LR} = (0.240 \pm 0.055)\%$ to account for the residual background and other small beam asymmetries, we find the left right asymmetry at $E_{cm} = 91.28$ GeV to be

$$A_{LR} = 0.1485 \pm 0.0042(\text{stat.}) \pm 0.0010(\text{syst.}).$$

Correcting this result for electroweak interference and initial state radiation, we find the pole asymmetry A^0_{LR} to be

$$A^0_{LR} = 0.1512 \pm 0.0042(\text{stat.}) \pm 0.0011(\text{syst.}),$$

which can be combined with our previous results [7, 8] to yield a cumulative value of

$$A^0_{LR} = 0.1543 \pm 0.0039$$

$$\sin^2 \theta_W^{\rm eff} \;=\; 0.23060 \pm 0.00050.$$

6 Lepton Asymmetries

While not nearly as precise as the hadronic A_{LR} measurement just presented, additional information about the electroweak couplings can be extracted by considering the leptonic decays of the Z^0 boson. The polarized differential cross section for the process $Z^0 \to l^+l^-$ can be written as

$$\frac{d\sigma}{d\Omega} \propto (1 - \mathcal{P}_e A_e)(1 + \cos^2\theta) + 2(A_e - \mathcal{P}_e)A_l \cos\theta,$$

where $\cos\theta$ is the production angle between the incoming electron and outgoing lepton and A_l is identical to the coupling asymmetry defined in Equation 1 for a lepton of type l. The e^+e^- final states have a more complicated form owing to the additional t-channel photon exchange amplitude, and the analysis of these events will not be presented here. For the remaining $\mu^+\mu^-$ and $\tau^+\tau^-$ events, the quantities A_e, A_μ, and A_τ can be extracted by performing an unbinned likelihood fit to the observed data within a fiducial tracking region of $|\cos\theta| < 0.7$.

Events are selected with a number of tracking and calorimetric cuts to reject e^+e^-, two photon, and hadronic final states. A total of 3,788 $\mu^+\mu^-$ events are selected with an estimated efficiency of 95% in the fiducial tracking region, and an estimated background contamination of 0.4% primarily from the tau final states. A sample of 3,748 $\tau^+\tau^-$ events are selected with a slightly lower efficiency of 89% in the fiducial region and a slightly higher estimated background of 4% mostly from the $\mu^+\mu^-$ final states, along with $\sim 1\%$ e^+e^- contamination. These events have been selected from the combined 1993-95 SLD data set. A number of systematic uncertainties related to the background determination, angular acceptance estimate, and electroweak interference correction have been considered and all found to be negligible compared to the statistical error of each measurement. The results, shown in Table 2, are competitive with the forward-backward asymmetry measurements performed by a single LEP experiment with a factor of ~ 20 more data. This analysis is not complete, and the results from the lepton final states presented in Table 2 are preliminary.

Also listed in Table 2 are two other measurements of A_e performed by the SLD collaboration, which are included for completeness. The first, A_e(bhabha), is an old measurement of the e^+e^- final states based on 1992-93 data only.[12] The second, Q_{LR}, is a measurement of the left-right asymmetry in the inclusive hadronic charge flow.[13] Since the uncertainty in each of the measurements listed in Table 2 is dominated by statistics, the correlated systematic uncertainty due to the electron polarization measurement is negligible and can be safely ignored. Statistical correlations between the various analyses have been estimated to be no larger than $\sim 7\%$ and can also be safely ignored.

Table 2: Lepton Asymmetry Measurements

Method	*Result*
Leptonic	$A_e = 0.148 \pm 0.016$
Final States	$A_\mu = 0.102 \pm 0.033$
(*Preliminary*)	$A_\tau = 0.190 \pm 0.034$
A_e(bhabha)	$A_e = 0.202 \pm 0.038$
Q_{LR}	$A_e = 0.162 \pm 0.043$
A_{LR}	$A_e = 0.1543 \pm 0.0039$
Combined	$A_l = 0.1542 \pm 0.0037$

7 Conclusions

We note that the measurement of A_{LR} presented here represents the single most precise determination of $\sin^2\theta_W^{\rm eff}$ by a single experiment. If we assume the universality of the lepton current coupling parameters, we can include the preliminary results from the lepton final states to produce a slightly improved combined SLD result of

$$A_e = 0.1542 \pm 0.0037$$

$$\sin^2\theta_W^{\rm eff} = 0.23061 \pm 0.00047.$$

It should be noted that the uncertainty on this result is dominated by statistics. The SLD has been approved to run into the year 1998, and we expect to be able to reduce the uncertainty on $\sin^2\theta_W^{\rm eff}$ by another factor of two.

Acknowledgments

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf.

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