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Polarized Bhabha Scattering and a Precision Measurement of the Electron Neutral Current Couplings*^{*}

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ABSTRACT

The cross section for Bhabha scattering $(e^+e^- \rightarrow e^+e^-)$ with polarized electrons at the center of mass energy of the Z^0 resonance has been measured with the SLD experiment at the SLAC Linear Collider (SLC) during the 1992 and 1993 runs. The first measurement of the left-right asymmetry in Bhabha scattering $(A_{LR}^{e^+e^-}(|cos\theta|))$ is presented. From $A_{LR}^{e^+e^-}(|cos\theta|)$ the effective weak mixing angle is measured to be $sin^2\theta_W^{\text{eff}} = 0.2245 \pm 0.0049 \pm 0.0010$. The effective electron vector and axial vector couplings to the Z^0 are extracted from a combined analysis of the polarized Bhabha scattering data and and the left-right asymmetry (A_{LR}) previously published by this collaboration. From the combined 1992 and 1993 data the effective electron couplings are measured to be $v_e = -0.0414 \pm 0.0020$ and $a_e = -0.4977 \pm 0.0045$.

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The Standard Model of electroweak interactions is a gauge theory based on the $SU(2)_L \times U(1)$ group, which unifies the electromagnetic and weak interactions. Four gauge bosons constitute the electroweak theory: the massless photon (γ) and three massive bosons, the W^+ , W^- , and Z^0 . The massive bosons acquire mass and the neutral bosons (γ and Z^0) are mixed through spontaneous symmetry breaking. The photon and the Z^0 mixing is described by a single parameter, $sin^2\theta_W$. While the electromagnetic interaction (the fermion-photon coupling) conserves parity, the fermion couplings to the Z^0 , having both vector and axial vector components, do not. These components are specified as a function of $sin^2\theta_W$ within the Standard Model. Precision measurements of the fermion vector and axial vector couplings to the Z^0 are a stringent test of the electroweak model. Deviations from the electroweak theory may result from physics beyond the Standard Model.

The SLD Collaboration has recently performed the most precise single measurement of the effective electroweak mixing angle, $sin^2\theta_W^{\text{eff}}$, by measuring the left-right cross section asymmetry (A_{LR}) in Z boson production at the Z^0 resonance [1]. The left-right cross section asymmetry is a measure of the initial state electron coupling to the Z^0 , which allows all visible fermion final states to be included in the measurement. For simplicity, the e^+e^- final state (Bhabha scattering) is omitted in the A_{LR} measurement due to the dilution of the asymmetry from the large QED contribution of the t-channel photon exchange. In this Letter, we present two new results: the first measurement of the left-right cross section asymmetry in polarized Bhabha scattering $(A_{LR}^{e^+e^-}(|cos\theta|))$, and measurements of the effective electron coupling parameters based on a combined analysis of the A_{LR} measurement [1] and the Bhabha cross section and angular distributions. The vector coupling measurement is the most precise yet presented. In the Standard Model, measuring the left-right asymmetry yields a value for the quantity A_e , a measure of the degree of parity violation in the neutral current, since:

$$A_{LR} = A_e = \frac{2v_e a_e}{v_e^2 + a_e^2} = \frac{2[1 - 4sin^2 \theta_W^{\text{eff}}]}{1 + [1 - 4sin^2 \theta_W^{\text{eff}}]^2},\tag{1}$$

where the effective electroweak mixing parameter is defined [2] as $sin^2\theta_W^{\text{eff}} = \frac{1}{4}(1 - v_e/a_e)$, and v_e and a_e are the effective vector and axial vector electroweak coupling parameters of the electron. The partial width for Z^0 decaying into e^+e^- is dependent on the coupling parameters :

$$\Gamma_{ee} = \frac{G_F M_Z^3}{6\sqrt{2}\pi} (v_e^2 + a_e^2)(1 + \delta_e), \qquad (2)$$

where $\delta_e = \frac{3\alpha}{4\pi}$ is the correction for final state radiation. G_F is the Fermi coupling constant and M_Z is the Z^0 boson mass. By measuring A_e and Γ_{ee} , the above equations can be utilized to extract v_e and a_e .

The data presented in this letter were collected during the 1992 and 1993 runs of the SLAC Linear Collider (SLC), which collides unpolarized positrons with longitudinally polarized electrons at a center of mass energy near the Z^0 resonance [3]. The luminosity-weighted center of mass energy was measured to be 91.55 \pm 0.02 GeV for the 1992 run and 91.26 \pm 0.02 GeV for the 1993 run [4]. The luminosityweighted electron beam polarization ($\langle \mathcal{P}_e \rangle$) was measured to be (22.4 \pm 0.7)% for the 1992 run and (63.0 \pm 1.1)% for the 1993 run [1] [5].

The analysis presented here utilizes the calorimetry systems of the SLD detector [6]. Small angle coverage (28-65 mrad from the beamline) is provided by the finely-segmented silicon-diode/tungsten-radiator luminosity calorimeters (LUM) [7]. The LUM measures small angle Bhabha scattering, thereby providing both the absolute luminosity and a check that the left-right luminosity asymmetry is small. Events at larger angles from the beamline (> 200 mrad) are measured with the liquid argon calorimeter (LAC) [8]. The LAC is comprised of a fine sampling electromagnetic section followed by a coarse sampling hadronic section. The electromagnetic section is 21 radiation lengths in depth for normal incident particles and contains ~99% of a 50 GeV electron shower. The LAC covers 98% of the solid angle with projective tower segmentation.

The LUM detectors surround the beampipe on both sides of the interaction point. Event selection criteria are designed to discriminate high energy electromagnetic showers from background. Selected events are narrow and deposit energy throughout the depth of the calorimeter while the low energy beam backgrounds from the SLC are diffuse. Electron position is inferred from the energy sharing between adjacent silicon pads.

To minimize systematic uncertainties in the LUM due to detector misalignment and the location of the interaction point, we employ a "gross-precise" method [9] in the small angle measurement, which uses a larger fiducial region on one end of the detector than the other. The gross-precise method employs the two luminosity monitors as single-arm spectrometers. Bhabha events are identified in both detectors, but the events are counted based on the location of each shower in the respective detector. In each detector, a tight fiducial region and a loose fiducial region are defined. The tight fiducial region is defined by silicon pad boundaries, where the position resolution is optimal [10]. Events in which both the electron and positron showers are within the tight fiducial region are labeled as "precise" Bhabhas and counted with weight 1. Events in which one of the two showers is inside the tight fiducial region and the other shower is outside the tight fiducial region are labeled as "gross" events and given weight 1/2. With the gross-precise method applied to these data, the misalignment error on the effective number of calculated events is negligible [11]. The effective cross section is calculated by using the Monte Carlo programs BABAMC [12] and BHLUMI [13]. Detector simulation is performed with GEANT [14] and the electromagnetic showers are parameterized using the GFLASH algorithm [15].

The overall errors for the physics measurements to be presented are limited by small statistics. For this reason, our systematic error analysis of the luminosity measurement is conservative. A detailed description of the systematic error analysis for the luminosity measurement is given elsewhere [11]. The total systematic uncertainty is 0.93%, which is composed of 0.88% experimental and 0.3% theoretical uncertainty. The experimental systematic error is limited by the size of the data set. The integrated luminosity is $\mathcal{L} = 385.4 \pm 2.5$ (stat) ± 3.6 (sys) nb⁻¹ for the 1992 polarized SLC run and $\mathcal{L} = 1781.1 \pm 5.1$ (stat) ± 16.6 (sys) nb⁻¹ for the 1993 SLC run.

The wide angle Bhabha selection algorithm makes use of the distinct topology of the e^+e^- final state. Selected events are required to possess two clusters which contain at least 70% of the center of mass energy and manifest a normalized energy imbalance of less than 0.6 [16]. The two largest energy clusters are also required to have less than 3.8 GeV of energy in the hadronic calorimeter. The total number of reconstructed clusters found in the event must be less than 9. Collinearity in the final state is controlled by requiring the absolute value of the rapidity sum of the two main clusters to be less than 0.30.

The efficiency and contamination for the wide angle events are calculated from Monte Carlo simulations. Corrections are applied as a function of scattering angle to account for angle-dependent changes in response. The $e^+e^- \rightarrow e^+e^-$ process at large angles is simulated with BHAGEN [17]. The efficiency for accepting wide angle $e^+e^- \rightarrow e^+e^-$ events is found to be 86.7% overall and 93% in the central region of the detector, with the largest inefficiency arising from events which enter the gaps between adjacent liquid argon modules. The efficiency falls off in the forward regions due to materials in front of the calorimeter from the interior detector systems.

Two small sources of contamination are $e^+e^- \rightarrow \gamma\gamma$ (1.25%) and $e^+e^- \rightarrow \tau^+\tau^-$ (0.28%). The Monte Carlo programs RADCOR and KORALZ are used to calculate these contributions [18,19]. Other sources of contamination such as hadronic decays of the Z^0 , two-photon, cosmic rays and beam background were all found to give negligible contributions.

Tables I and II show the number of events accepted, by beam helicity, for the 1992 and 1993 SLC runs. The raw asymmetry is defined as:

$$\widetilde{A}_{LR}^{e^+e^-}(|\cos\theta|) = \langle \mathcal{P}_{\mathbf{e}} \rangle A_{LR}^{e^+e^-}(|\cos\theta|) = (N_L - N_R)/(N_L + N_R),$$

where $N_L(N_R)$ is the number of events tagged with a left-(right-) handed electron beam as a function of the $|cos\theta|$, where θ is the center-of-mass scattering angle for the e^+e^- system after initial state radiation. Aside from the charge ambiguity which is unresolved by the calorimeter measurement, the center-of-mass scattering angle is derived trivially from the measured electron and positron laboratory scattering angles. The angular regions in the table are chosen to emphasize the different regimes of the $e^+e^- \rightarrow e^+e^-$ distribution: for $|cos\theta| < 0.7$ the s-channel Z^0 decay dominates; from 0.7 to 0.94 the s-channel Z^0 decay, the tchannel photon exchange and the interference between those two interactions all contribute; for $|cos\theta| > 0.94$, the t-channel photon exchange dominates. The region of $0.998 < |\cos\theta| < 0.9996$ is that which is covered by the LUM. The expected asymmetry $(A_{LR}^{e^+e^-}(|\cos\theta|))$ is largest at $\cos\theta = 0$, and may be approximately written as $A_{LR}^{e^+e^-}(|\cos\theta|) = A_e(1 - f_t(|\cos\theta|))$, where $f_t(|\cos\theta|)$ represents the t-channel contribution. For the region $|\cos\theta| < 0.7$, $< f_t > \simeq 0.12$. The expected asymmetry falls to very small values ($\sim 10^{-4}$) in the small angle region where the t-channel photon exchange dominates.

To extract Γ_{ee} and A_e , the data are fit to the differential e^+e^- cross section using the maximum likelihood method. Two programs are used to calculate the differential e^+e^- cross section: EXPOSTAR [20] and, as a cross check, DMIBA [21]. The EXPOSTAR program calculates the differential cross sections within the framework of the Standard Model. The DMIBA program calculates the differential e^+e^- cross section in a model independent manner. To extract the maximal amount of information from the differential polarized Bhabha scattering distribution, the fit is performed over the entire angular region accepted by the LAC ($|cos\theta| < 0.98$). No t-channel subtraction is performed. All ten lowest order terms in the cross section are included in the fit: the four pure s-channel and t-channel terms for photon and Z^0 exchange, and the six interference terms [22]. The fit also includes initial state radiation. Since the measurement is calorimetric it is insensitive to final state radiation.

The partial width Γ_{ee} is extracted from the data in two ways: (1) using the full fit to the differential cross section for $|\cos \theta| \leq 0.98$, and (2) measuring the cross section in the central region ($|\cos \theta| < 0.6$) where the systematic errors are smaller, yielding a more precise measurement. For the fits we use $M_Z = 91.187 \text{ GeV/c}^2$ and $\Gamma_Z = 2.489 \text{ GeV/c}^2$ [23]. Figure 1 shows the fit to the full $e^+e^- \rightarrow e^+e^$ distribution. This fit has a $\chi^2 = 51.6$ for 39 degrees of freedom, yielding $\Gamma_{ee} =$ $83.14 \pm 1.03 \text{ (stat)} \pm 1.95 \text{ (sys)}$ MeV. The 2.4% systematic error is dominated (2.1%) by the uncertainty in the efficiency correction factors in the angular region $0.6 < |\cos\theta| < 0.98$, where the LAC response is difficult to model due to materials from interior detector elements[11].

A more precise determination of Γ_{ee} was performed using only the central region of the LAC ($|cos\theta| < 0.6$) and the small angle region in the LUM [24]. The program MIBA [25] is then used to calculate Γ_{ee} based on the total measured cross section within the defined fiducial region. From this method, we find:

$$\Gamma_{ee} = 82.89 \pm 1.20 \text{ (stat)} \pm 0.89 \text{ (sys) MeV}.$$

The loss in statistical precision of the limited fiducial region is more than compensated by the improvement in the systematic error. The 1.1% systematic error is dominated by the accuracy of the detector simulation (0.74%) and the uncertainty in the absolute luminosity (0.52%). Other contributions are the uncertainty in the contamination (0.3%), the uncertainty in M_Z and Γ_Z (0.3%), the accuracy of the cross section calculation (0.3%), and the center of mass energy uncertainty (0.2%),

To extract A_e from the Bhabha events, the right- and left-handed differential $e^+e^- \rightarrow e^+e^-$ cross sections are fit directly for v_e and a_e using EXPOSTAR. This yields

$$A_e = 0.202 \pm 0.038 \text{ (stat)} \pm 0.008 \text{ (sys)}.$$

Figure 2 shows the measured left-right cross section asymmetry for $e^+e^- \rightarrow e^+e^ (A_{LR}^{e^+e^-}(|\cos\theta|))$ compared to the fit. The fit shown in Figure 2 has a χ^2 of 4.36 for 5 degrees of freedom. The measurement of A_e is limited by the statistical uncertainty. The 3.8% systematic is dominated by a 3.2% uncertainty in the angle-dependent response correction factors. The polarization uncertainty contributes 1.7% and asymmetry factors from the SLC contribute 0.06% as discussed in Refs. [1] and [11]. Other systematic error contributions to A_e are the beam energy spread and center of mass energy uncertainty (0.25%), the accuracy of the EXPOSTAR program (0.7%) and the uncertainty on the Z^0 mass and width (0.7%).

The results for Γ_{ee} and A_e from above may now be used in equations (1) and (2) to extract the effective vector and axial vector couplings to the Z^0 : $v_e = -0.0507 \pm 0.0096$ (stat) ± 0.0020 (sys), $a_e = -0.4968 \pm 0.0039$ (stat) ± 0.0027 (sys), where lower energy e^+e^- annihilation data have been utilized to assign $|v_e| < |a_e|$, and $\nu_e e$ scattering data have been utilized to establish $v_e < 0$ and $a_e < 0$ [26]. Figure 3 shows the one standard deviation (68%) contour for these electron vector and axial vector coupling measurements. Most of the sensitivity to the electron vector coupling and, hence, $sin^2 \theta_W^{\text{eff}}$ arises from the measurement of A_e , while the sensitivity to the axial vector coupling arises from Γ_{ee} . Also shown are standard model calculations using the program ZFITTER [27].

The effective electroweak mixing angle represented by these vector and axial vector couplings is:

$$\sin^2 \theta_W^{\text{eff}} = 0.2245 \pm 0.0049 \text{ (stat)} \pm 0.0010 \text{ (sys)}.$$

We reiterate that this measurement derives strictly from the Bhabha events.

The SLD Collaboration has published a more precise measurement of A_e from the left-right cross section asymmetry (A_{LR}) measurement[1]. Combining the Bhabha results with the SLD measurement of A_{LR} gives:

$$v_e = -0.0414 \pm 0.0020$$
 $a_e = -0.4977 \pm 0.0045$

the most precise measurement of the electron vector coupling to the Z^0 published to date. The v_e , a_e contour including the A_{LR} measurement is also shown in Figure 3, demonstrating the increased sensitivity in v_e from A_{LR} . The LEP average for the electron coupling parameters to the Z^0 are $v_e = -0.0370 \pm 0.0021$ and $a_e = -0.50093 \pm 0.00064$ [28].

In summary, the effective electron coupling parameters have been determined with a new method which combines the left-right cross section asymmetry (A_{LR}) with the polarized Bhabha scattering differential cross section. The effective electron vector coupling to the Z^0 is determined with the best precision to date.

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$ cos \theta $	left-handed	right-handed	$\widetilde{A}_{LR}^{e^+e^-}(\cos\theta) = <\mathcal{P}_{e} > A_{LR}^{e^+e^-}(\cos\theta)$
< 0.70	157	137	0.068 ± 0.058
0.70 - 0.94	208	205	0.0073 ± 0.049
0.94 - 0.98	305	318	-0.021 ± 0.040
0.998 - 0.9994	12,395	12,353	0.0017 ± 0.0064

Table I. Number of accepted Bhabha events and their raw asymmetry for the1992 run. The average electron beam polarization was 22.4%.

Table II. Number of accepted Bhabha events and their raw asymmetry for the1993 run. The average electron beam polarization was 63.0%.

$ cos \theta $	left-handed	right-handed	$\widetilde{A}_{LR}^{e^+e^-}(\cos\theta) = <\mathcal{P}_{e} > A_{LR}^{e^+e^-}(\cos\theta)$
< 0.70	864	702	0.103 ± 0.0253
0.70 - 0.94	1,039	946	0.047 ± 0.022
0.94 - 0.98	1,566	$1,\!479$	0.029 ± 0.018
0.998 - 0.9996	93,727	94,319	-0.0032 ± 0.0023

Figure 1. Differential angular distribution for $e^+e^- \rightarrow e^+e^-$. The points are the corrected data, the dashed line is the fit.

Figure 2. Left-right asymmetry, $A_{LR}^{e^+e^-}(|\cos\theta|)$, for polarized $e^+e^- \rightarrow e^+e^-$. The points are the corrected data, the dashed curve is the fit.

Figure 3. One-sigma (68%) contour in the a_e, v_e plane. The large ellipse is for $e^+e^- \rightarrow e^+e^-$, the smaller ellipse includes the measurement of A_{LR} . The shaded region represents the Standard Model calculation for 130 GeV $< m_{top} < 250$ GeV and 50 GeV $< M_{Higgs} < 1000$ GeV.



Figure 1



Figure 2



Figure 3