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Electroweak Coupling Measurements from Polarized Bhabha Scattering at SLD

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Abstract

The cross section for Bhabha scattering ($e^+e^- \to e^+e^-$) 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 ($A_{LR}^{e^+e^-}(\theta)$) is presented. From $A_{LR}^{e^+e^-}(\theta)$ the effective weak mixing angle is measured to be $sin^2\theta_W^{\rm eff} = 0.2245 \pm 0.0049 \pm 0.0010$. When combined with the measurement of A_{LR}, 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 SLD Collaboration has recently performed the most precise single measurement of the effective electroweak mixing angle, $sin^2\theta_W^{\rm eff}$, 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. Here, two new results are presented: 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 [2].

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:

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

where the effective electroweak mixing parameter is defined as $sin^2\theta_W^{\rm eff} = \frac{1}{4}(1 - v_e/a_e)$, 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:

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

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.

Event selection is calorimetry-based and makes use of the distinct topology of the e^+e^- final state. 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.

Table 1: Number of accepted events for the 1992 run. ($<\mathcal{P}_e>= 22.4\%$)

region	left-handed	right-handed	$A_{LR}^{e^+e^-}(raw)$
$0.0 < cos\theta_{CM} < 0.70$	157	137	0.068 ± 0.058
$0.70 < cos\theta_{CM} < 0.94$	208	205	0.0073 ± 0.049
$0.94 < cos\theta_{CM} < 0.98$	305	318	-0.021 ± 0.040
$0.998 < cos\theta_{CM} < 0.9994$	12,395	12,353	0.0017 ± 0.0064

Table 2: Number of accepted events for the 1993 run. ($<\mathcal{P}_e>= 63.0\%$)

region	left-handed	right-handed	$A_{LR}^{e^+e^-}(raw)$
$0.0 < cos\theta_{CM} < 0.70$	864	702	0.103 ± 0.0253
$0.70 < cos\theta_{CM} < 0.94$	1,039	946	0.047 ± 0.022
$0.94 < cos\theta_{CM} < 0.98$	1,566	1,479	0.029 ± 0.018
$0.998 < cos\theta_{CM} < 0.9996$	93,727	94,319	-0.0032 ± 0.0023

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:

$$\tilde{A}_{LR}^{e^+e^-}(\theta) =<\mathcal{P}_e> \mathrm{A}_{\mathrm{LR}}^{e^+e^-}(\theta) = (\mathrm{N_L} - \mathrm{N_R})/(\mathrm{N_L} + \mathrm{N_R}),$$

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 t-channel 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 small angle silicon/tungsten luminosity mon-

itor (LUM). The expected asymmetry ($A_{LR}^{e^+e^-}(\theta)$) is largest at $cos\theta = 0$, and may be approximately written as $A_{LR}^{e^+e^-}(\theta) = A_e(1 - f_t(|cos\theta|))$, 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.

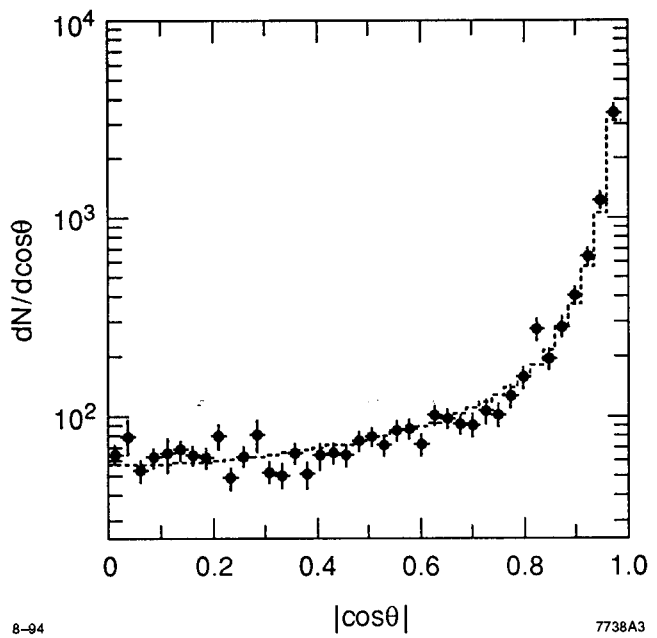

Figure 1: Differential angular distribution for $e^+e^- \rightarrow e^+e^-$. The points are the corrected data, the dashed line is the fit.

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 [4] and, as a cross check, DMIBA [5]. 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 liquid argon calorimeter (LAC), where $|cos\theta| < 0.98$. 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 [6]. 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 $M_Z = 91.187$ GeV/c^2 and $\Gamma_Z = 2.489$ GeV/c^2 [7]. Figure 1 shows the fit to the full $e^+e^- \rightarrow e^+e^-$ distribution, which yields $\Gamma_{ee} = 83.14 \pm 1.03$ (stat) ± 1.95 (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 [3].

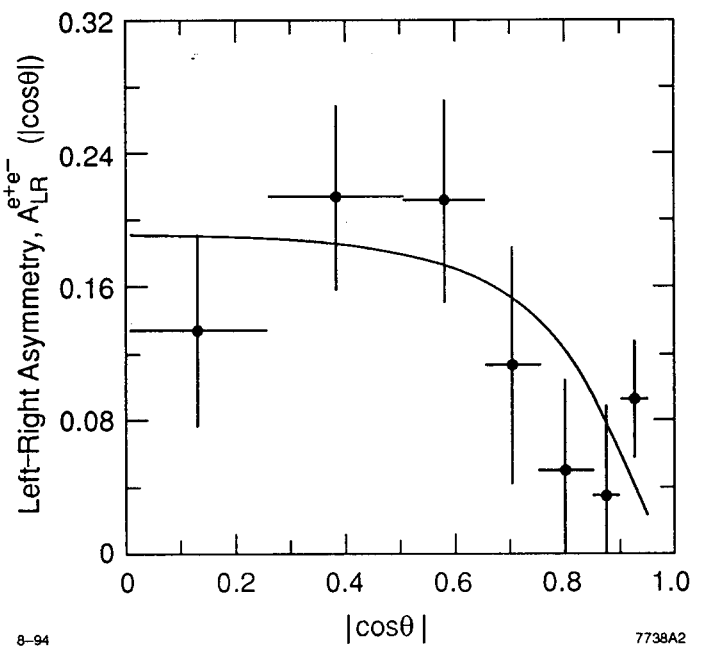

Figure 2: Left-right asymmetry, $\tilde{A}_{LR}^{e^+e^-}(|cos\theta|)$ for polarized $e^+e^- \rightarrow e^+e^-$. The points are the correctd data, the solid curve is the fit.

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 [8]. The program MIBA [9] 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%).

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 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 [3].

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) $\pm$ 0.0020 (sys), $a_e = -0.4968 \pm 0.0039$ (stat) $\pm$ 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 $a_e < 0$ [10]. 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 [11].

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.

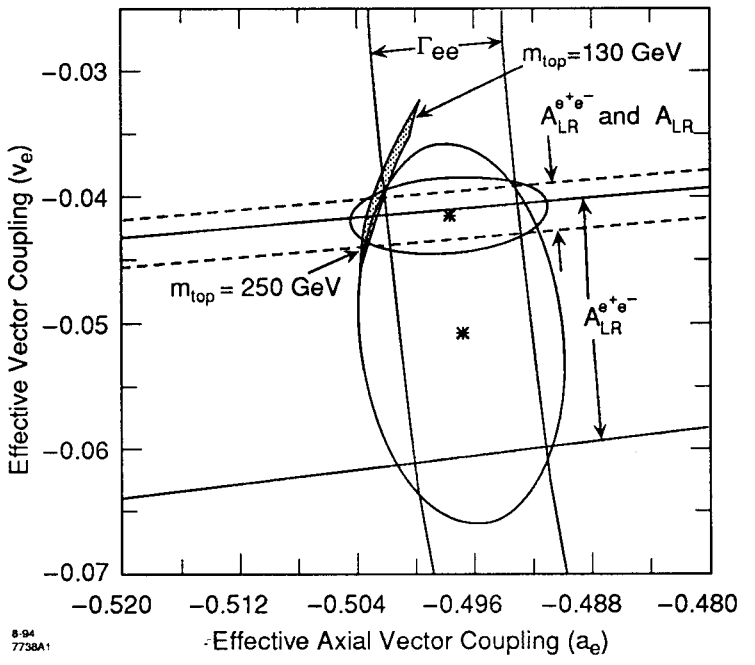

Figure 3: One standard deviation (68%) contour in the a_e, v_e plane. The large ellipse is for $e^+e^- \to e^+e^-$, the smaller ellipse includes the measurement of A_{LR}. The hatched region shows the Standard Model calculation as a function of the mass of the top quark. The width of the hatched region is the variation due to the uncertainty in the Higgs mass.

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:

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

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}.

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