Measurement of the Left-Right Cross Section Asymmetry in Z Boson Production in e⁺e⁻ Collisions*

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ABSTRACT

A precise measurement of the left-right cross section asymmetry (A_{LR}) for Z boson production by e^+e^- collisions has been performed at the SLAC Linear Collider with the SLD detector. Data for the 1993 run, with its significant improvements in luminosity and electron beam polarization, are presented. When combined with the (less precise) 1992 result, the preliminary result for the effective weak mixing angle is $\sin^2\theta_W^{\text{eff}} = 0.2290 \pm 0.0010$.

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1 Introduction

The SLC luminosity improved by a factor of two due mostly to the use of flat beams; the polarization improved by slightly less than a factor of three, due to the use of strained lattice photocathodes. Overall, SLD accumulated five times the number of Z's in 1993 (Ref. 1) compared to 1992 (Ref. 2); coupled with the polarization increase, the overall error in $\sin^2\theta_W^{\rm eff}$ decreased by a factor of ten.

The left-right asymmetry is defined as

$$A_{LR} \equiv (\sigma_L - \sigma_R) \,/\, (\sigma_L + \sigma_R)\,, \tag{1}$$

where σ_L and σ_R are the e^+e^- production cross sections for Z bosons (at the Z pole) with left-handed and right-handed electrons, respectively.

The properties of A_{LR} are discussed in detail elsewhere.[3,4] To leading order, the Standard Model predicts that this quantity depends upon the vector (v_e) and axial-vector (a_e) couplings of the Z boson to the electron current,

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

where the effective electroweak mixing parameter is defined by $\sin^2\theta_W^{\rm eff} \equiv (1 - v_e/a_e)/4$.

A_{LR} is a sensitive function of $\sin^2\theta_W^{\rm eff}$, with $\delta\sin^2\theta_W^{\rm eff} \approx \delta A_{LR}/7.8$. It is large ($> 0.1$) and relatively insensitive to energy. Finally, A_{LR} does not depend upon the couplings of the Z to its final states. Hence, all visible Z decay modes can in principle be used in the measurement. In practice, the e^+e^- final state is discarded by SLD due to its large zero-asymmetry contribution from photon exchange.

There is no need to identify specific final states, except to discard e^+e^- events. In practice, conditions for left- and right-handed running are identical. Then the measured asymmetry becomes

$$A_m = \frac{N_L - N_R}{N_L + N_R}. \tag{3}$$

The systematic error in A_{LR} is dominated by that of the electron beam polarization, $\mathcal{P}_e$. For a partially polarized beam $A_{LR} = A_m/\mathcal{P}_e$, the A_{LR} measurement error is

$$\delta A_{LR} = \Big[\frac{1}{N_Z\mathcal{P}_e^2} + A_{LR}^2\Big(\frac{\delta\mathcal{P}_e}{\mathcal{P}_e}\Big)^2\Big]^{1/2}, \tag{4}$$

where $N_Z = N_L + N_R$ is the total number of events, and $\delta\mathcal{P}_e$ is the error in the polarization measurement.

2 Polarized Beam Delivery

The main features of the operation of the SLC are well described[4] elsewhere. New to the 1993 run are the use of strained-lattice cathodes at the SLC source, which gave a large increase in electron beam polarization (from 22% to 63%), and the advent of flat beam operation, which gave higher luminosity.

A Ti-Sapphire laser[5] operating at 865 nm illuminated a strained-lattice Ga-As (Ref. 6) photocathode. The electron helicity was randomly flipped for each pulse.

Elliptical beams,[7] with a 3:1 transverse aspect ratio, were found to increase the luminosity by a factor of about two over round beams. This coupling of the horizontal and vertical precluded the ability to use solenoids to set the electron spin orientation. It was found that a pair of large betatron oscillations[8] in the SLC arc could be used to maximize the longitudinal polarization at the interaction point (IP). About 4–5% of the polarization was lost in the arcs.

Precision energy spectrometers were used to measure the center-of-mass energy, which was found to be 91.26 ± 0.02 GeV.

2.1 Chromatic Correction

The typical energy spread of the SLC beam is $\Delta E/E \approx 0.2\%$. Since the net spin precession in the North Arc is proportional to energy, one expects each beam energy component to have a slightly different degree of longitudinal polarization at the IP. For the Gaussian core of the beam, the net reduction in polarization at the IP due to this "spin diffusion" is small ($< 1\%$) and is in itself of little consequence.

Now, in principle, the focusing of the beams at the IP can map each beam-energy component to a different effective point of focus, resulting in a correlation between transverse position at the IP and energy, or equivalently between position and polarization. Even though the present SLC Final Focus optics includes chromatic correction, the extremely small vertical emittance in 1993 allowed this position-energy correlation to become more significant, a result of third-order chromatic aberrations in the optics. Models have indicated that the vertical spot size at the IP indeed may have been limited by these higher order aberrations in 1993. Still, this would not be an experimental issue except that the polarization of those electrons which weight Z production at the IP can be different from the polarization of the entire electron beam, averaged over its full spatial extent.

In the former case, the electron beam is sampled by its interaction probability to make Z's via positrons; this is referred to as the luminosity-weighted polarization, $\mathcal{P}_e$. The latter case is relevant for the polarization measurement using Compton scattering, $\mathcal{P}_e^C$, as the spatial extent of the Compton laser beam is much larger than the electron beam, hence sampling all electrons with equal weight.

If the electron beam had only Gaussian energy tails, the difference between $\mathcal{P}_e$ and $\mathcal{P}_e^C$ would be small ($< 0.2\%$) and readily modeled. However, the beam was observed to have a long low-energy tail extending to $\Delta E/E$ of about -1%. The correction for this effect has been addressed in the following way. First, the beam tail and optics were modeled, and it was found that the measured $\mathcal{P}_e^C$ agreed well with the amount of beam tail allowed to propagate to the IP, as determined by the position of a collimator at a low-dispersion point of the North Arc. The model can be confidently used to estimate the minimum possible difference between $\mathcal{P}_e$ and $\mathcal{P}_e^C$ by the constraint that it not predict a luminosity in excess of that observed. The maximum effect is conservatively given by the difference between the measured polarization at the end of the Linac and that at the IP. Assigning no *a priori* preference within this allowed range, the correction[9] becomes

$$\mathcal{P}_e = (1.024 \pm 0.016)\mathcal{P}_e^C. \tag{5}$$

The model alone, without further input, gives a similar correction of 1.019 ± 0.005.

3 Polarization Measurement

The measurement of the longitudinal electron beam polarization is accomplished via Compton scattering of polarized light with the polarized electrons, as shown in Fig. 1.

Longitudinally polarized photons, produced by 532 nm circularly polarized laser pulses from a frequency-doubled Nd:YAG laser, collide with the outgoing electron beam 33 m past the IP. The backscattered Compton electrons, ranging in energy from about 17 to 30 GeV, are detected by a multichannel Cherenkov detector after being separated from the main electron beam by two dipole magnets which are the final bend magnets of the SLC Final Focus.

Counting rates in the Cherenkov detector are measured for parallel and anti-parallel orientations of the photon and electron helicities. The resulting asym-

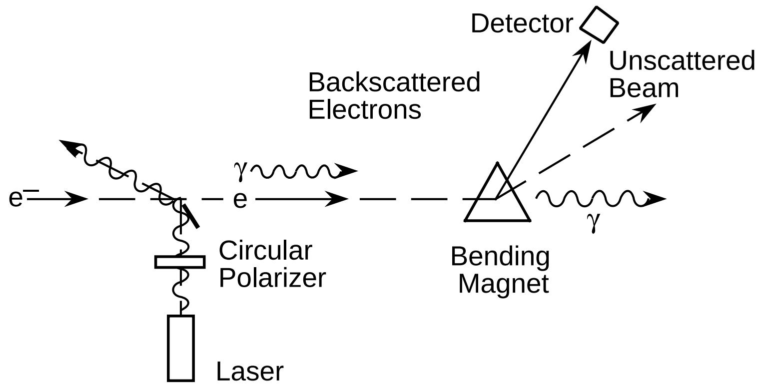

Figure 1: Schematic of Compton scattering process detection.

metry is given by $\mathcal{P}_e\mathcal{P}_\gamma A(E)$, where $\mathcal{P}_e$ is the electron polarization; $\mathcal{P}_\gamma$ is the circular polarization of the photon beam, and $A(E)$ is the theoretical asymmetry, a function of the scattered electron energy.[10]

Table 1

Systematic uncertainties that affect the A_{LR} measurement.

Systematic Uncertainty	$\delta\mathcal{P}_e^C/\mathcal{P}_e^C$ (%)	$\delta A_{LR}/A_{LR}$ (%)
Laser Polarization	1.0	
Detector Calibration	0.4	
Detector Linearity	0.6	
Interchannel Consistency	0.5	
Electronic Noise Correction	0.2	
Total Polarimeter Uncertainty	1.3	1.3
Chromaticity Correction		1.1
Background Fraction (see text)		0.1
Total Systematic Uncertainty		1.7

The polarimeter data are acquired asynchronously with the detection of Z events in the SLD detector. Runs of approximately three minutes result in statistical precision of about 1% on $\mathcal{P}_e$. Systematic effects are listed in Table 1; the largest error is from the laser polarization. In fact, this error was dominated by the period at the beginning of the run when diagnostics were in a more rudimentary state. The error contribution from subsequent data was at the 0.6% level. The total systematic error on $\mathcal{P}_e$ for 1994 was estimated to be 1.3%.

4 Selection of Z Events

Unlike other precision electroweak measurements involving e^+e^- at the Z resonance, A_{LR} does not rely on the detailed reconstruction of the final state. The primary requirements for SLD (shown in Fig. 2) are a good efficiency for detection of hadronic final states which is symmetric in scattering angle, and a good separation of these events from e^+e^- final states and accelerator-related backgrounds. The measured "raw" asymmetry, A_m, defined in Eq. (3), can then be formed.

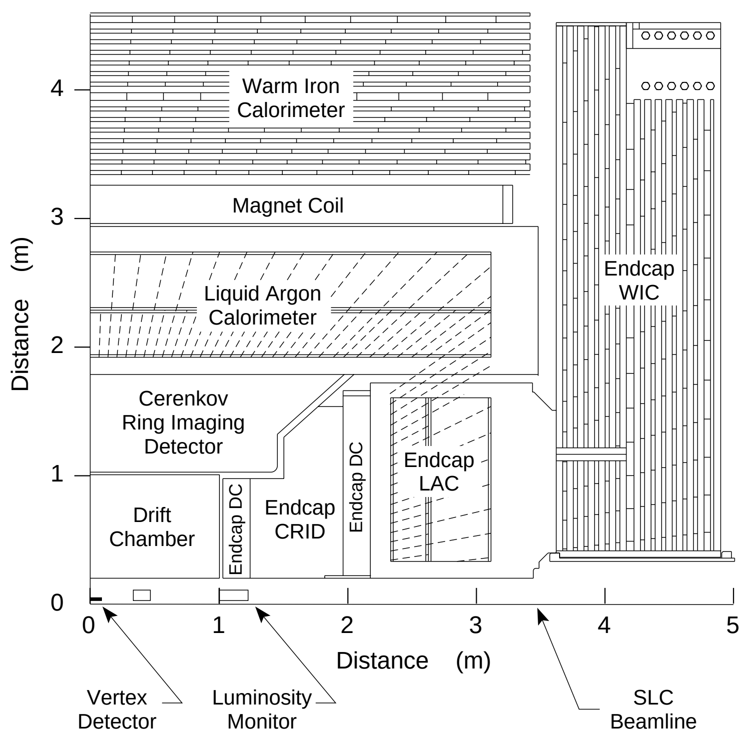

Figure 2: Quadrant view of the SLD detector.

Triggers used in this measurement use calorimetric[11] information only. Liquid argon calorimeter towers with at least twice the expected minimum ionizing signal were summed. Events with at least ten such towers adding to at least 22 GeV were retained. This reduced about three million triggers to about 6.4×10^4 events, which were then subjected to a full cluster reconstruction analysis. Events were required to have at least eight clusters summing to at least 40% of the center-of-mass energy. The requirement on cluster number was primarily responsible for removing e^+e^- final states. (The predominantly t-channel e^+e^- events at small angle ($\theta \sim 50$ mrad) were separately triggered and analyzed to provide the luminosity measurement.) Accelerator-related backgrounds were largely removed by requiring that the selected events be reasonably well-balanced in energy.

This procedure yielded $49,392$ events. The efficiency for triggering and selecting hadronic events is $(93 \pm 1\%)$, while it is 30% for $\tau^+\tau^-$ events. Muon-pair events are excluded by this procedure. The residual background fraction due to e^+e^- events and accelerator backgrounds is estimated to be $0.23 \pm 0.10\%$. Other backgrounds, due to cosmic rays or $\gamma\gamma$ events, are negligible.

5 Results

The measured asymmetry A_m is related to A_{LR} by the following expression, an extension of that given in Sec. 1, which incorporates a number of small correction terms in square brackets,

$$A_{LR} = \frac{A_m}{\langle \mathcal{P}_e \rangle} + \frac{1}{\langle \mathcal{P}_e \rangle} \left[A_m f_b - A_{\mathcal{L}} + A_m^2 A_{\mathcal{P}} - E_{cm} \frac{\sigma'(E_{cm})}{\sigma(E_{cm})} A_E - A_\varepsilon \right], \qquad (6)$$

where $\langle \mathcal{P}_e \rangle$ is the mean luminosity-weighted polarization for the 1993 run; f_b is the background fraction; $\sigma(E)$ is the unpolarized Z cross section at energy E; $\sigma'(E)$ is the derivative of the cross section with respect to E; and $A_{\mathcal{L}}$, $A_{\mathcal{P}}$, A_E, and A_ε are the left-right asymmetries of the integrated luminosity, the beam polarization, the center-of-mass energy, and the product of detector acceptance and efficiency.

Of the $49,392$ events recorded by SLD in the 1993 run, $27,225$ were produced with a left-hand polarized electron beam and $22,167$ with a right-handed beam. This gives, by Eq. (3),

$$A_m = 0.1024 \pm 0.0045. \qquad (7)$$

The mean beam polarization for the run is calculated by averaging over the Compton polarimeter measurements associated with each Z event, giving the mean $\mathcal{P}_e^C$ for the run. The correction factor for the beam chromaticity, Eq. (5), is applied to give a preliminary result for the mean luminosity-weighted IP polarization for the run:

$$\langle \mathcal{P}_e \rangle = \frac{1}{N_Z} \sum_{i=1}^{N_Z} \mathcal{P}_i = (63.0 \pm 1.1)\%. \tag{8}$$

The contributions to the error were given in Table 1. The dominant error is due to the polarization measurement. The error on the chromaticity correction, Eq. (5), also contributes to the error for this run.

The contributions of the various correction factors given in Eq. (6) are small and essentially negligible. The largest contribution is due to the dilution of the asymmetry from background contamination, f_b, giving a $0.17 \pm 0.07\%$ correction. The remainder of the contributions are negligible, none exceeding 0.04% correction to A_{LR}, with the total correction summing to $0.10 \pm 0.08\%$.

Finally, we obtain by Eq. (6) at $\sqrt{s} = 91.26$ GeV the 1993 result

$$A_{LR} = 0.1628 \pm 0.0071 \pm 0.0028\,, \tag{9}$$

where the first error is statistical and the second systematic. The corresponding 1993 weak mixing parameter is

$$\sin^2 \theta_W^{\mathrm{eff}} = 0.2292 \pm 0.0009 \pm 0.0004. \tag{10}$$

This result has been corrected for the off Z-pole average center-of-mass energy and for initial state radiation. Combining this with our previous result from the 1992 run gives the preliminary value

$$\sin^2 \theta_W^{\mathrm{eff}} = 0.2294 \pm 0.0010. \tag{11}$$

This result is presently the most precise single measurement of this quantity. The result is 2.5 σ below the combined LEP average[12] 0.2322 ± 0.0004.

Within the framework of the Minimal Standard Model, this result predicts the top quark mass to be $m_t = 240^{+30+18}_{-45-30}$ GeV, where the second set of errors reflect the range of Higgs masses from 60–1000 GeV.

6 The 1994 Run

At the time of this writing, the 1994 run at the SLC is nearing completion. Figure 3 shows the improvement in polarization over the 1993 value (80% vs. 60%) due to

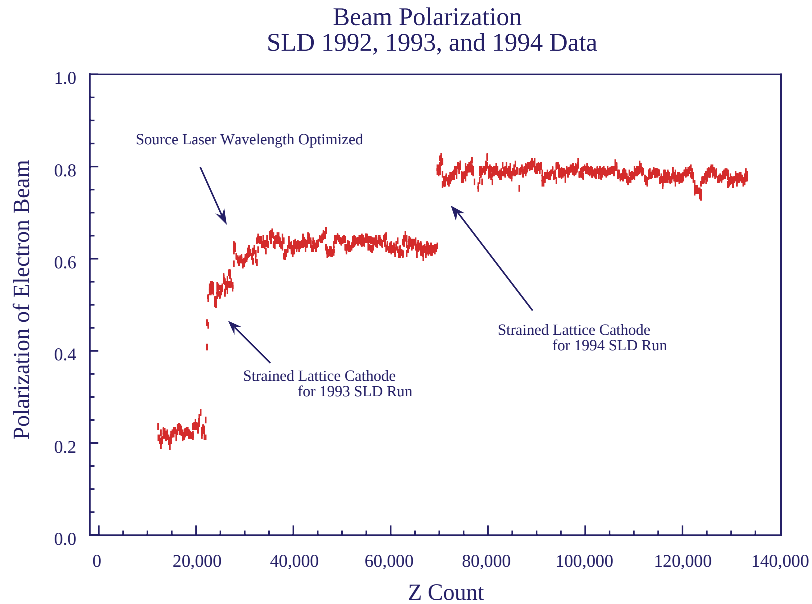

Figure 3: History of polarization from 1992-1994.

the use of a thinner strained cathode. With improvements in the beam delivery reducing the chromatic correction and with 100K Z's, we expect the error in $\sin^2\theta_W^{\rm eff}$ to reach 0.0005.

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