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FIRST MEASUREMENT OF THE LEFT-RIGHT ASYMMETRY IN Z-BOSON PRODUCTION

THE SLD COLLABORATION*

represented by

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We review the first measurement of the left-right cross section asymmetry (A_{LR}) in Z-boson production observed at the SLAC Linear Collider. In 1992 the SLD detector recorded 10,224 Z events produced by the collision of longitudinally polarized electrons with an unpolarized positron beam at a center-of-mass energy of 91.55 GeV. The average electron beam polarization during the run was $(22.4 \pm 0.6)\%$. We measure A_{LR} to be 0.100 ± 0.044 (stat.) ± 0.004 (syst.), which determines the effective weak mixing angle to be $\sin^2\theta_W^{\rm eff} = 0.2378 \pm 0.0056$ (stat.) ± 0.0005 (syst.).

1. Introduction

In this article we review the first measurement[1] of the left-right cross section asymmetry (A_{LR}) in Z-boson production by e^+e^- collisions. The left-right asymmetry is defined as[2]

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\,, \tag{1}$$

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. The tree-level Standard Model calculation of this quantity yields

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

where v_e and a_e are the vector and axial-vector couplings of the electron current to the Z and $\sin^2\theta_W^{\rm eff} \equiv (1 - v_e/a_e)/4$ is the effective electroweak mixing parameter.[3]

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The left-right asymmetry has several advantages, both theoretical and experimental, over competing Z-pole asymmetries such as the forward-backward asymmetry with leptons or b-quarks and the tau-polarization asymmetry. These advantages include:[4]

- A_{LR} is very sensitive to $\sin^2\theta_W^{\rm eff}$;
- A_{LR} depends only on the electron's couplings to the Z, so all visible final states can be used (except electron pairs, which in the t channel manifest no asymmetry);
- A_{LR} is expected to be large (0.10-0.15);
- A_{LR} is independent of detector acceptance/efficiency asymmetries;[5]
- The measurement of A_{LR} has negligible systematic error (as compared with statistical error) until very high polarizations and large samples are achieved.

In addition, A_{LR} shares with the other asymmetries two important properties:

- The asymmetries require no knowledge of the absolute luminosity;
- The asymmetries become sensitive to the top quark and Higgs masses in a high-precision measurement.

These characteristics allow A_{LR} to provide a precise, low-systematics Standard Model test with a modest event sample.

The measurement of A_{LR} requires a longitudinally polarized electron beam of reversible helicity. In practice, we use a partially polarized beam; the relationship of A_{LR} to the measured asymmetry in Z production (A_m) is then given by the expression

$$A_{LR} = \frac{A_m}{\mathcal{P}_e} \equiv \frac{1}{\mathcal{P}_e}\left(\frac{N_L - N_R}{N_L + N_R}\right), \tag{3}$$

where $\mathcal{P}_e$ is the longitudinal beam polarization and N_L and N_R are the numbers of Z bosons produced with left-handed and right-handed electron beams. The extraction of A_{LR} from the measured Z asymmetry thus depends on accurate knowledge of $\mathcal{P}_e$.

2. The Polarized SLC

In 1989 the SLAC Linear Collider (SLC) began producing Z bosons with unpolarized beams. Polarization of the electrons was incorporated in 1992.[6,7] The layout of the SLC is shown in Fig. 1.

2.1. *The polarized electron source*

The phenomenon of polarized electron emission from a gallium arsenide crystal was discovered in 1976[8] and has since been exploited for use in accelerator experiments. The SLC bunches are produced by illuminating a GaAs photocathode with circularly polarized laser light at 715 nm.[9,10] A cesium and NF_3 surface treatment gives the GaAs a negative work function and allows emission of the longitudinally polarized electrons. The maximum polarization theoretically obtainable from such

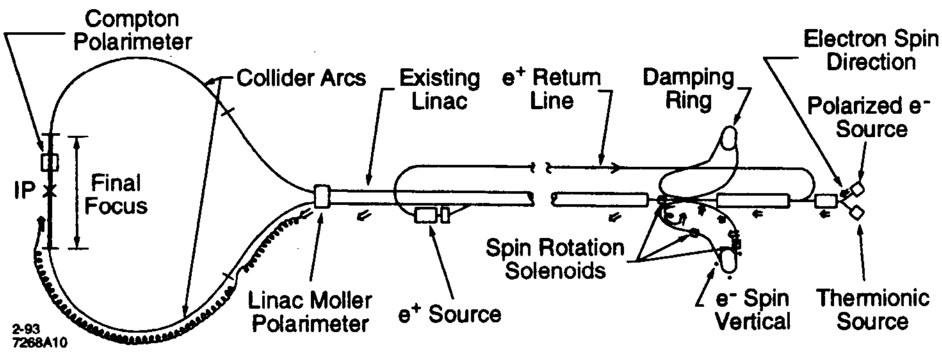

Fig. 1. The polarized SLC. The electron spin direction is indicated by the double arrow.

a source is 50%;[a] however, laser wavelength constraints and depolarization inside the cathode limited the electron polarization to ~28% during the run. The electron helicity is chosen randomly pulse-by-pulse at the SLC frequency of 120 Hz by changing the laser light helicity.

2.2. *Spin transport*

The electron bunches must now be delivered to the interaction point (IP) with longitudinal polarization, a task that is confounded by spin precession in the magnetic bend fields of the SLC. To prevent the loss of a horizontal component of polarization in the damping ring, a spin rotation solenoid orients the electron spins in the vertical direction before entering the ring. Upon exit from the ring, the electrons pass through two more solenoids which can provide an arbitrary spin direction down the accelerator. This flexibility is necessary due to the horizontal and vertical bends in the SLC arcs. There is a fractional polarization loss ($\frac{\delta\mathcal{P}}{\mathcal{P}}$) of ~5% in the damping ring (it was not possible to run at the proper damping ring energy to orient the spins exactly vertical) and another ~5-10% in the arc due to energy spread in the beam causing incoherent spin precession.

2.3. *Polarimetry*

Two independent devices are used to measure the electron beam polarization. At the end of the linear accelerator, a polarimeter based on Møller scattering can be inserted into the beam diagnostically to monitor transverse and longitudinal polarization before the electrons enter the north arc. After the beams collide at the IP, the electrons continue to the Compton polarimeter where a measurement of the longitudinal beam polarization is made. The polarization at the IP was typically 22% during the run. Before the electron and positron beams are dumped, they pass through precision energy spectrometers.[12] The mean center-of-mass energy (E_{cm}) was 91.55 ± 0.04 GeV.

[a] A "strained lattice" cathode can achieve 100% polarization theoretically; such a cathode is now in use at the SLC.[11]

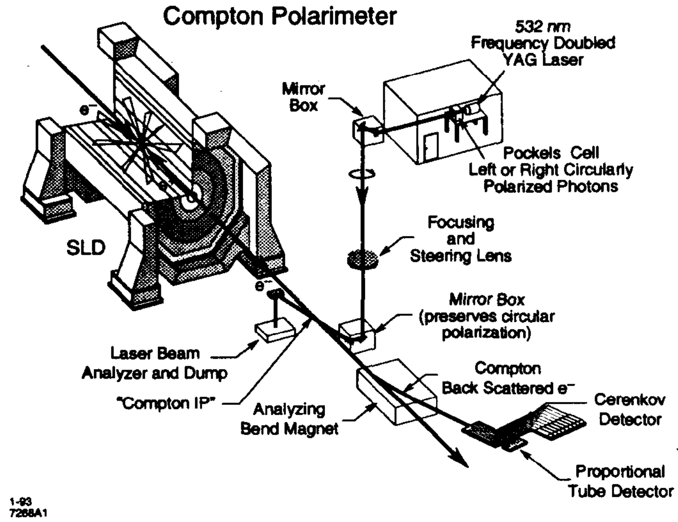

Fig. 2. A schematic diagram of the Compton Polarimeter.

3. The Polarization Measurement

The Compton polarimeter (Fig. 2) provides a continual measurement of the longitudinal electron polarization near the IP. At the Compton IP, 33 m past the SLC IP and before any dipole magnets, the spent electron beam collides with a beam of circularly polarized photons from a 532 nm frequency-doubled Nd:YAG laser. The Compton-scattered electrons, which lose up to 28 GeV of energy but remain essentially undeflected, pass through a bend magnet and are dispersed horizontally according to their momentum, and then enter two redundant Compton detectors: a nine-channel Čerenkov device and a 16-channel proportional tube detector. These detectors accept electrons in a momentum range of 17–30 GeV/c.

The differential cross section for Compton scattering of longitudinally polarized electrons by circularly polarized photons is given by[13]

$$\frac{d\sigma_p}{dE_s} = \frac{d\sigma_u}{dE_s}[1 + \mathcal{P}_\gamma \mathcal{P}_e A(E_s)] , \tag{4}$$

where σ_p is the polarized cross section, E_s is the energy of the scattered electron, σ_u is the unpolarized Compton-scattering cross section, $\mathcal{P}_\gamma$ is the circular polarization of the photon, $\mathcal{P}_e$ is the longitudinal polarization of the electron, and $A(E_s)$ is the Compton asymmetry function. The largest asymmetry occurs at the Compton endpoint at 17.4 GeV, and the asymmetry changes sign at 25.2 GeV; thus these two features of the asymmetry spectrum fall within the detector acceptance and are used for calibration. The laser light circular polarization has been measured directly at the Compton IP to be (93±2)% and was monitored continually during the run.

We measure the Compton flux in each detector channel for parallel and antiparallel combinations of photon and electron helicities. The measured Compton

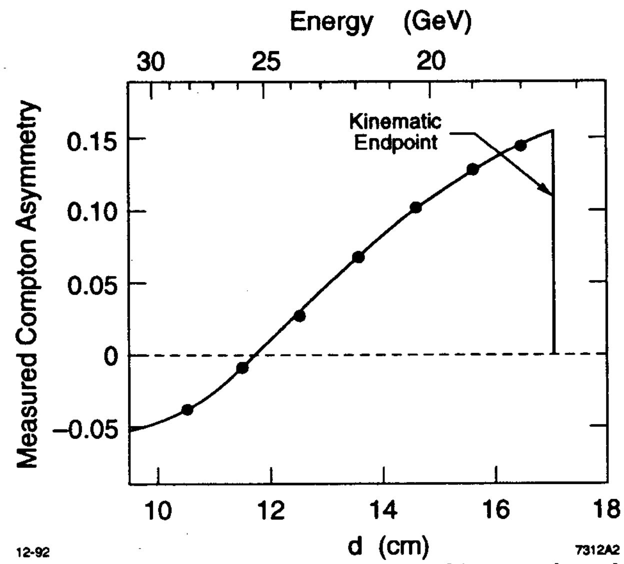

Fig. 3. The polarized Compton-scattering asymmetry measured in seven channels of the Čerenkov detector, plotted versus the transverse channel distance from the undeflected beam. The Compton asymmetry function, normalized by the product of photon and electron polarizations, is fit to the data.

asymmetry (A_C^m) in channel i formed with these rates follows from Eq. (4):

$$(A_C^m)_i = \mathcal{P}_\gamma \mathcal{P}_e \langle A_i \rangle \ , \tag{5}$$

where $\langle A_i \rangle$, the analyzing power for channel i, is the average Compton asymmetry over the channel weighted by the unpolarized Compton cross section and a simulated detector response function. The channel-by-channel measured asymmetry for the Čerenkov detector, averaged over the data sample, is shown in Fig. 3. The Compton asymmetry function has been fit to the data using the normalization factor $\mathcal{P}_\gamma \mathcal{P}_e$, and the horizontal distance scale is calibrated at the Compton endpoint and the zero-asymmetry point.[14]

We have investigated other polarimeter systematic effects, including detector phototube/electronics linearity, time dependence of the calibration, and electronic noise pickup and cross-talk. In addition, we have checked that the average longitudinal beam polarization measured at the Compton IP does not differ from the luminosity-weighted average beam polarization at the e^+e^- interaction point. This difference could occur through spin precession after the SLC IP, beam-beam interaction depolarization,[15] or a systematic deviation of the luminosity-weighted average beam energy from the average beam energy.[16] The total systematic error in the polarization measurement is estimated to be $\delta\mathcal{P}_e/\mathcal{P}_e = 2.7\%$. The composition of this error is listed in Table 1.

Table 1. Systematic uncertainties in the polarization measurement.

Systematic Uncertainty	$\delta\mathcal{P}_e/\mathcal{P}_e$
Laser Polarization	2.0%
Detector Linearity	1.5%
Interchannel Consistency	0.9%
Spectrometer Calibration	0.4%
Electronic Noise Correction	0.4%
Total Polarization Uncertainty	2.7%

The polarimeter operates continually in runs of about three minutes. For each run, $\mathcal{P}_e$ is determined from the measured asymmetry using Eq. (5). The absolute statistical error in a single measurement is $\delta\mathcal{P}_e \sim 0.8\%$.

4. Event Selection

We collect our Z sample using the SLD detector.[17] For this measurement, the event selection was made using only calorimetry. The liquid argon calorimeter (LAC)[18] covers 98% of the full solid angle and is composed of 17,000 projective towers, each segmented in depth into two electromagnetic sections and two hadronic sections for a total thickness of 2.8 interaction lengths.

We exploit this fine granularity and projective geometry to select against two kinds of beam backgrounds: low-energy electrons and photons that scatter from beamline elements, and high-energy muons created far upstream that traverse the detector parallel to the beam axis at large radius. Thus, a set of cuts has been designed to eliminate events with small amounts of energy deposited in many towers parallel to the beamline. Each Z candidate must contain fewer than 3000 accepted towers; the total energy deposited in the endcap region of the warm iron calorimeter[19] must be less than 12 GeV. In addition, a Z candidate must have at least 20 GeV in the LAC and must be energy-balanced. In order to estimate the effectiveness of these criteria, we compare this selection procedure with a tracking-based analysis, and also apply these cuts to Monte Carlo events: we conclude that the beam-related background in our event sample is 0.7%. Monte Carlo simulation predicts that the two-photon background is less than 0.1% of our sample. We estimate that the combined trigger and selection efficiency is (90±2)% for hadronic Z decays and about 30% for tau pairs. Muon pairs escape the LAC and are not included in our sample.

In addition to beam-related backgrounds, e^+e^- events must be removed from the sample, as the photon-exchange process in the t channel has no asymmetry. The e^+e^- identification criteria require large energy deposition in a small number of LAC towers. We estimate the e^+e^- background in the Z sample to be 0.7%.

The final Z sample comprises 10,224 events. Each Z is associated with the helicity of the electron bunch that created it. We find that 5,226 (N_L) Z events were made with left-handed electron beam and 4,998 (N_R) events were made with right-handed beam.[20] The measured Z cross section asymmetry (A_m) is then

$$A_m \equiv \frac{N_L - N_R}{N_L + N_R} = (2.23 \pm 0.99) \times 10^{-2} \,. \tag{6}$$

5. Secondary Systematics

The primary systematic error in the A_{LR} measurement is in the electron polarization determination. There are a number of secondary effects whose magnitude must be evaluated. The dependence of A_{LR} on these effects is given by

$$A_{LR} = \frac{A_m}{\mathcal{P}_e} + \frac{1}{\mathcal{P}_e}[A_m f_b + A_m^2 A_{\mathcal{P}} - E_{cm}\frac{\sigma'(E_{cm})}{\sigma(E_{cm})}A_E - A_\varepsilon - A_{\mathcal{L}}] \,, \tag{7}$$

where A_m is the measured Z asymmetry, $\mathcal{P}_e$ is the luminosity-weighted average beam polarization, f_b is the Z 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 $A_{\mathcal{P}}$, A_E, A_ε, and $A_{\mathcal{L}}$ are the left-right asymmetries of the beam polarization, center-of-mass energy, product of detector acceptance and efficiency, and integrated luminosity. These corrections to A_{LR} have been assessed[1] and only the background fraction and luminosity asymmetry terms contribute non-negligible uncertainties. The resulting relative errors in A_{LR} are 1.4% and 1.9%, respectively. Table 2 lists all of the systematic errors in the A_{LR} measurement.

Table 2. Systematic uncertainties in the A_{LR} measurement.

Systematic Uncertainty	$\delta A_{LR}/A_{LR}$
Total Polarization Uncertainty	2.7%
Luminosity Asymmetry	1.9%
Background Fraction	1.4%
Total Systematic Uncertainty	3.6%

6. Results

Since all of the corrections in Eq. (7) are much smaller than the statistical error in the A_{LR} measurement, we do not apply these corrections to A_{LR}, but we include their uncertainties in the total systematic error. We calculate the luminosity-weighted average electron polarization with the expression

$$\mathcal{P}_e = \frac{1}{N_Z}\sum_{i=1}^{N_Z}\mathcal{P}_i = (22.4 \pm 0.6)\% \,, \tag{8}$$

where N_Z is the total number of Z events and $\mathcal{P}_i$ is the polarization measurement associated in time with the i^{th} event. The uncertainty is dominated by systematics.

Using Eqs. (3), (6), and (8), we find the left-right asymmetry to be

$$A_{LR} = 0.100 \pm 0.044(\text{stat.}) \pm 0.004(\text{syst.}) \,, \tag{9}$$

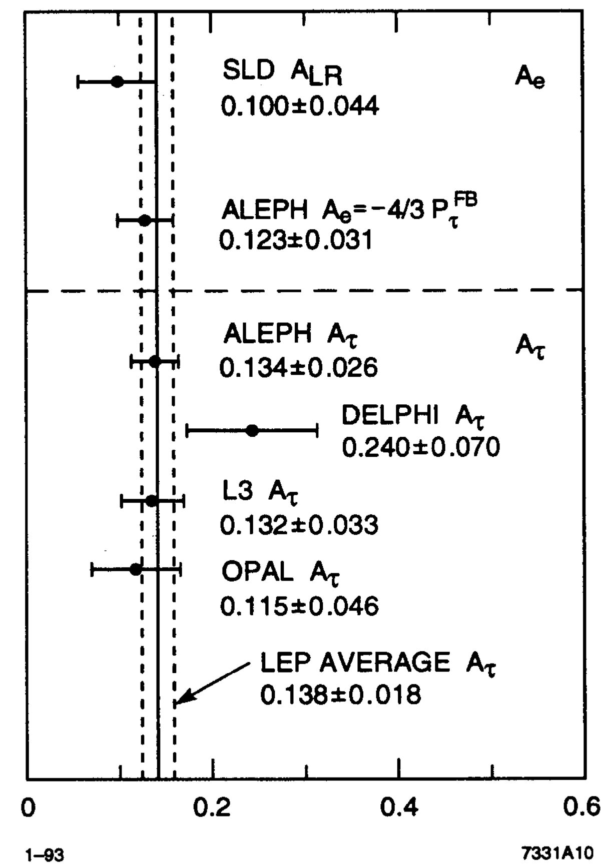

Fig. 4. A comparison of the SLD A_{LR} measurement with recent LEP results.

where the systematic error contributions are listed in Table 2. Fig. 4 shows a comparison with recent LEP measurements[21] of the tau polarization asymmetry, which equals A_{LR} in size assuming lepton universality, and the forward-backward asymmetry of the tau polarization, which measures the same couplings as A_{LR}.

From Eq. (2) the effective weak mixing angle has the value

$$\sin^2\theta_W^{\text{eff}} = 0.2378 \pm 0.0056(\text{stat.}) \pm 0.0005(\text{stat.}) \; , \tag{10}$$

where we have corrected the result to account for the difference between the SLC center-of-mass energy and the Z-pole energy, and for initial-state radiation.[22]

7. Conclusions

The first measurement of the left-right asymmetry at SLD demonstrates the power of Z physics with a polarized beam. By preparing the initial spin state of the electrons, it is possible to make a precise test of the Standard Model with a limited event sample.

The 1993 SLD run, now well underway, promises to improve dramatically the precision in the A_{LR} measurement. A new "strained lattice" cathode design[11] is regularly achieving >60% polarization at the IP; this performance, coupled with the 50,000 Z events expected this run, will allow a precision of $\delta \sin^2\theta_W^{\rm eff} = 0.001$.

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