SLAC-PUB-6667
September 1994
(E)

PRECISE MEASUREMENT OF THE LEFT-RIGHT CROSS SECTION ASYMMETRY IN Z BOSON PRODUCTION BY e^+e^- COLLISIONS

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ABSTRACT

We present a precise measurement of the left-right cross section asymmetry (A_{LR}) for Z boson production by e^+e^- collisions. The measurement was performed at a center-of-mass energy of 91.26 GeV with the SLD detector at the SLAC Linear Collider (SLC). The luminosity-weighted average polarization of the SLC electron beam was (63.0±1.1)%. Using a sample of 49,392 Z decays, we measure A_{LR} to be 0.1628±0.0071(stat.)±0.0028(syst.) which determines the effective weak mixing angle to be $\sin^2\theta_W^{\rm eff} = 0.2292 \pm 0.0009(\rm stat.) \pm 0.0004(\rm syst.)$. We combine this result with our result obtained in 1992 and obtain $\sin^2\theta_W^{\rm eff} = 0.2294 \pm 0.0010$, which constitutes the best measurement of $\sin^2\theta_W^{\rm eff}$ in a single experiment presently available.

Presented at the 8^{th} Meeting of the American Physical Society,
Division of Particles and Fields (DPF94),
Albuquerque, NM, August 2-6, 1994.

*Work supported by Department of Energy contract DE-AC03-76SF00515.

1. Introduction

The left-right asymmetry at the Z-pole is defined as $A^{\circ}_{LR} \equiv (\sigma_L - \sigma_R) / (\sigma_L + \sigma_R)$ where σ_L and σ_R are the e^+e^- production cross sections for Z bosons at the Z pole energy with left-handed and right-handed electrons, respectively. The standard model predicts that this quantity depends strongly on the effective weak mixing angle, $\sin^2\theta_W^{\rm eff}$.[1] The measurement[2] was performed using the SLD detector, where we counted the number (N_L, N_R) of hadronic decays of the Z boson for each of the two longitudinal polarization states (L,R) of the electron beam. The electron beam polarization was measured precisely with a Compton polarimeter. From these measurements we determined the left-right asymmetry[†],

$$A_{LR}(E_{cm}) = \frac{1}{\mathcal{P}_e^{lum}} \cdot \frac{N_L - N_R}{N_L + N_R}, \tag{1}$$

where E_{cm} is the mean luminosity-weighted collision energy, and $\mathcal{P}_e^{lum}$ is the mean luminosity-weighted polarization.

A_{LR} has several desirable properties. The asymmetry is large in magnitude relative to other asymmetries at the Z pole, and is a sensitive function of $\sin^2\theta_W^{\rm eff}$, with $\delta\sin^2\theta_W^{\rm eff} \approx \delta A_{LR}/7.9$. It does not depend on the couplings of the Z to final-state fermions, so all final states (except the e^+e^- final state) can be used in the measurement. The measurement does not require knowledge of absolute luminosity, detector acceptance, or detector efficiency. The principal source of systematic uncertainty is in the determination of $\mathcal{P}_e^{lum}$.

2. Production and Transport of Polarized Electrons

The polarized electrons were produced by a strained-lattice photocathode. Such cathodes are capable of delivering electron beams with higher polarizations than conventional GaAs cathodes. Conventional cathodes are limited to a maximum 50% polarization due to the degeneracy of two competing photo-ionization transitions. In strained-lattice cathodes, an epitaxial layer of GaAs is deposited over a GaAsP substrate, which has a smaller lattice spacing than GaAs, and thus creates a mechanical strain which removes the degeneracy.[3] With this technique, polarizations significantly larger than 50% are possible.

After extraction from the cathode, the electrons were injected into the accelerator. The electron spin orientation was longitudinal at the source and remained longitudinal until the transport to the Damping Ring (DR). The Linac-to-Ring transport rotated the electron spin to be vertical in the DR to preserve the polarization during the 8ms storage time. The spin orientation was vertical upon extraction from the DR and remained vertical during injection into the linac and subsequent acceleration to 46 GeV.

[†] A_{LR}, unlike A°_{LR}, is not corrected for the effects of $\gamma - Z$ interference and initial-state radiation.

The SLC North Arc (NARC) transported the electron beam from the linac to the SLC Interaction Point (IP). The betatron phase advance and the spin-precession in each section of the NARC were close to the same value. The NARC was therefore operating near a spin-tune resonance. We took advantage of this resonance and introduced a pair of vertical betatron oscillations, called *spin bumps*, to adjust the spin direction.[4] The amplitudes of these spin bumps were empirically adjusted to achieve longitudinal polarization at the IP.

3. The Compton Polarimeter

The longitudinal polarization of the electron beam ($\mathcal{P}_e$) was measured by the Compton polarimeter.[5] This polarimeter detected Compton-scattered electrons from the collision of the longitudinally polarized electron beam with a circularly polarized photon beam; the photon beam was produced from a pulsed Nd:YAG laser operating at 532 nm. The Compton Interaction Point (CIP) was situated 33m past the IP. After the CIP, the electrons passed through a dipole spectrometer; a nine-channel Čerenkov detector (CKV) then measured scattered electrons in the 17 to 30 GeV range.

The counting rates in each channel of the CKV were measured for parallel and anti-parallel combinations of the photon and electron beam helicities. The Compton asymmetry, the difference over the sum of the two combinations, was used to determine the beam polarization. The Compton asymmetry depends on polarization as $A(E) = \mathcal{P}_e \mathcal{P}_\gamma a_i$, where $A(E)$ is the measured Compton asymmetry, $\mathcal{P}_\gamma$ is the laser polarization, and a_i is the analyzing power for a given channel.

Measurements of $\mathcal{P}_\gamma$ were made before and after the CIP. By monitoring and correcting for small phase shifts in the laser transport line, we were able to achieve $\mathcal{P}_\gamma = (99.2 \pm 0.6)\%$ for the latter three-quarters of the 1993 data. For the intial quarter of the 1993 data, measurements yielded $\mathcal{P}_\gamma = (97 \pm 2)\%$.

The analyzing power for a given channel was determined by integrating the calculated Compton asymmetry function over the acceptance of the channel, modified by small corrections ($\approx 1\%$) due to electromagnetic shower effects as modeled by the EGS Monte Carlo. Figure 1 shows the good agreement achieved between the measured and expected Compton asymmetry spectrum.

Once the detector was calibrated, we used channel 7 to measure $\mathcal{P}_e$ precisely. The asymmetry spectrum observed in channels 1-6 then served as a cross-check; deviations of the measured asymmetry spectrum from the modeled one are reflected in the inter-channel consistency systematic error.

Polarimeter data were acquired continually during the operation of the SLC. The absolute statistical precision attained in a 3 minute interval was typically $\delta\mathcal{P}_e = 1.0\%$. Averaged over the 1993 run the mean beam polarization was $\mathcal{P}_e = (61.9 \pm 0.8)\%$. The systematic uncertainties that affect the polarization measurement are summarized in Table 1.

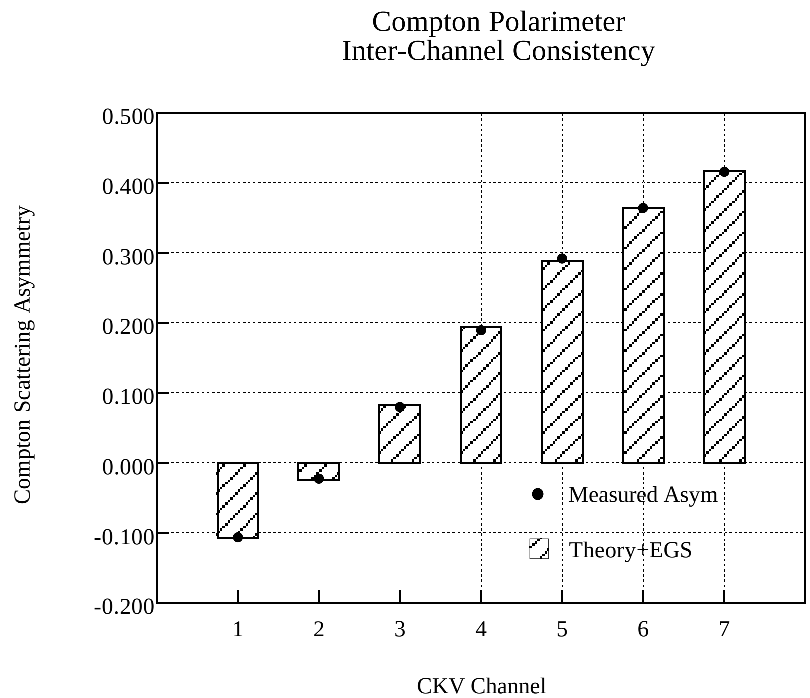

Figure 1: Measured and expected Compton asymmetry.

4. The Chromatic Correction

The Compton polarimeter measured $\mathcal{P}_e$ (the beam polarization weighted by the beam number density), but the quantity of interest in the A_{LR} measurement is the luminosity-weighted beam polarization, $\mathcal{P}_e^{lum}$ (the beam polarization weighted by the beam number density and luminosity).

Off-energy electrons had reduced longitudinal polarization at the IP due to spin precession in the NARC. They also contributed less to the luminosity than on-energy electrons because they did not focus to a small spot at the IP; however they contributed the same as on-energy electrons to the Compton measurement of the beam polarization. Thus, $\mathcal{P}_e^{lum}$ could be greater than $\mathcal{P}_e$. Using dedicated polarization transport studies, the relative difference between $\mathcal{P}_e$ and $\mathcal{P}_e^{lum}$, labelled the chromatic correction, was conservatively estimated to be $(1.7{\pm}1.1)\%$.

We find the luminosity-weighted polarization for the 1993 run, after the chromatic correction is applied, to be $\mathcal{P}_e^{lum} = (63.0 \pm 1.1)\%$.

5. Event Selection

The e^+e^- collisions were measured by the SLD detector, which has been described elsewhere.[6] The triggering of the SLD relied on a combination of calorimeter and tracking information, while the event selection was based entirely on the liquid argon calorimeter (LAC).[2]

For each event candidate that passed minimal selection criteria, energy clusters were reconstructed in the LAC. Selected events were required to contain at least 22 GeV of energy in the clusters, and have a normalized energy imbalance, $\sum \vec{E} / \sum E$, of less than 0.6.

Since the left-right asymmetry associated with final state e^+e^- events is diluted by the t-channel photon exchange, we excluded e^+e^- final states by requiring at least nine calorimeter clusters if the event was contained in the central region, ($|\cos\theta| < 0.8$, where θ is the angle the thrust axis makes with the beamline) and at least twelve clusters if the event was in the forward region ($|\cos\theta| \geq 0.8$).

6. Measurement of A_{LR}

Applying the selection criteria, we find 27,225 (N_L) of the events were produced with the left-polarized electron beam and 22,167 (N_R) were produced with the right-polarized beam. To determine A_{LR}, we use Eq. 1 corrected by some small terms, including terms for backgrounds, luminosity asymmetry, polarization asymmetry, energy asymmetry, efficiency asymmetry and possible positron polarization. These corrections were found to be small, affecting the A_{LR} measurement by $(0.1 \pm 0.08)\%$.

After corrections, we find the left-right asymmetry to be

$$A_{LR}(91.26 \text{ GeV}) = 0.1628 \pm 0.0071(\text{stat.}) \pm 0.0028(\text{syst.}). \tag{2}$$

Correcting this result to account for photon exchange and for electroweak interference which arises from the deviation of the effective e^+e^- center-of-mass energy from the Z-pole energy (including the effect of initial-state radiation), we find the effective weak mixing angle and the Z-pole asymmetry to be

$$\begin{aligned} \sin^2\theta_W^{\text{eff}} &= 0.2292 \pm 0.0009(\text{stat.}) \pm 0.0004(\text{syst.}) \\ A_{LR}^{\circ} &= 0.1656 \pm 0.0071(\text{stat.}) \pm 0.0028(\text{sys.}). \end{aligned} \tag{3}$$

Table 1: Systematic Uncertainties

Systematic Uncertainty	$\delta\mathcal{P}_e/\mathcal{P}_e$ (%)	$\delta A_{LR}/A_{LR}$ (%)
Laser Polarization ($\mathcal{P}_\gamma$)	1.0	
Detector Calibration	0.4	
Detector Linearity	0.6	
Inter-channel Consistency	0.5	
Electronic Noise	0.2	
Total Polarimeter Uncertainty	1.3	1.3
Chromatic Correction		1.1
Backgrounds and Other Asymmetries		0.1
Total Systematic Uncertainty		1.7

7. Conclusions

We note that this is the most precise single determination of $\sin^2\theta_W^{\mathrm{eff}}$ yet performed. Combining this value of $\sin^2\theta_W^{\mathrm{eff}}$ with our 1992 measurement[7] at $E_{CM} =$ 91.55 GeV, we obtain $\sin^2\theta_W^{\mathrm{eff}} = 0.2294 \pm 0.0010$. The LEP collaborations combine roughly 30 individual measurements of quark and lepton forward-backward asymmetries, final state τ-polarization, and the forward-backward asymmetry of τ-polarization to give a LEP global average of $\sin^2\theta_W^{\mathrm{eff}} = 0.2322 \pm 0.0005$.[8]

The 1994 running period for SLD began June 1, 1994 and beam polarizations of over 80% have been achieved. The luminosity goals for the 1994 run call for over 100,000 Z events. By the end of this run, the SLD expects to achieve a statistical precision approaching 0.0004 for $\sin^2\theta_W^{\mathrm{eff}}$.

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