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Measuring The Left-Right Cross Section Asymmetry in Z Boson Production by e^+e^- Collisions at the SLC

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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 $\sin^2\theta_W^{\rm eff} = 0.2292 \pm 0.0009({\rm stat}) \pm 0.0004({\rm syst})$.

1. Introduction

In 1992, the SLD Collaboration performed the first measurement of the left-right cross section asymmetry (A_{LR}) in the production of Z bosons by e^+e^- collisions [1]. In this talk, we present a substantially more precise result based upon data recorded during the 1993 run of the SLAC Linear Collider (SLC).

The left-right asymmetry is defined as $A_{LR} \equiv (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$, where σ_L and σ_R are the e^+e^- production cross sections for Z bosons (at the Z pole) with left-handed and right-handed electrons, respectively. 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,

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

where the effective electroweak mixing parameter is defined as $\sin^2\theta_W^{\rm eff} \equiv (1 - v_e/a_e)/4$. Note that A_{LR} a sensitive function of $\sin^2\theta_W^{\rm eff}$, and therefore depends upon electroweak radiative corrections—including those which involve the top quark and Higgs boson, and those arising from new phenomena.

We measure A_{LR} by counting hadronic (and $\tau^+\tau^-$) decays of the Z boson for each of the two longitudinal polarization states of the electron beam. These measurements require knowledge of the absolute beam polarization, but do not require knowledge of the absolute luminosity, detector acceptance, or efficiency.

2. Polarized SLC

The 1993 run of the SLC featured enhanced beam polarization and luminosity. The beam polarization at the SLC source was increased by the use of a strained-lattice GaAs photocathode [2] illuminated by a Ti-Sapphire laser operating at 865 nm [3]. As in 1992, the circular polarization of each laser pulse (and hence, the helicity of each electron pulse) was chosen randomly.

The maximum luminosity of the collider was increased to 5×10^{29} cm^2/sec by the use of flat (elliptical) beams which had transverse aspect ratios of 3/1 [4]. The flat-beam mode of operation precluded the use of the two solenoidal spin rotator magnets (located downstream of the electron damping ring) that had previously been used to orient the electron spin direction prior to acceleration in the linac. To maintain the vertical spin orientation of the beam in the north damping ring during acceleration and launch into the SLC North Arc, a pair of large amplitude betatron oscillations in the arc was used to adjust the spin direction [5] to achieve longituinal polarization at the SLC interaction point (IP). Due to energy-spread-induced spin diffusion and imperfect spin orientation, the longitudinal polarization of the electron beam at the IP was typically 95-96% of the polarization in the linac. The luminosity-weighted mean e^+e^- center-of-mass energy ($E_{c.m.}$) was measured with precision energy spectrometers [6] to be 91.26±0.02 GeV.

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Systematic Uncertainty	$\frac{\delta\mathcal{P}_e}{\mathcal{P}_e}$ (%)	$\frac{\delta A_{LR}}{A_{LR}}$ (%)
Laser polarization	1.0	
Detector calibration	0.4	
Detector linearity	0.6	
Interchannel consistency	0.5	
Electronic moise	0.2	
Total polarization uncertainty	1.3	1.3
Chromaticity correction (ξ)		1.1
Total small corrections		0.1
Total systematic uncertainty		1.7

Table 1. Systematic uncertainties on the A_{LR} measurement

2.1. Beam Polarization Measurements

The longitudinal beam polarization ($\mathcal{P}_e$) was measured by a Compton scattering polarimeter [7] located 33 m downstream of the IP. After passing through the IP and before it is deflected by dipole magnets, the electron beam collides with a circularly polarized photon beam produced by a frequency-doubled Nd:YAG laser of wavelength 532 nm. The scattered and unscattered electron beams remain unseparated until they pass through a pair of dipole magnets. The scattered electrons are dispersed horizontally and exit the vacuum system through a thin window. Multichannel Cherenkov and proportional tube detectors measure the momentum spectrum of the electrons in the interval from 17 to 30 GeV/c.

The counting rates in each detector channel are measured for parallel and antiparallel combinations of the photon and electron beam helicities. The asymmetry formed from these rates is equal to the product $\mathcal{P}_e\mathcal{P}_\gamma A(E)$ where $\mathcal{P}_\gamma$ is the circular polarization of the of the laser beam at the electron-photon crossing point and $A(E)$ is the theoretical asymmetry function at the accepted energy E of the scattered electrons [8].

Polarimeter data are acquired continually during the operation of the SLC. We obtain $\mathcal{P}_e$ from the observed asymmetry using the measured value of $\mathcal{P}_\gamma$ and the theoretical asymmetry function (including $\sim 1\%$ corrections for detector effects). The absolute statistical precision obtained in a three-minute interval is typically $\delta\mathcal{P}_e = 1\%$. The systematic uncertainties that affect the polarization measurement are summarized in Table 1. After the uncertainty on the laser polarization, the largest contributions are due to the linearity of the Cherenkov detector and the analyzing power calibration, which includes energy scale and response function uncertainties. The total relative systematic uncertainty is estimated to be $\delta\mathcal{P}_e/\mathcal{P}_e = 1.3\%$.

2.2. The Chromatic Effect

The Compton polarimeter measures $\mathcal{P}_e^C$, which can differ slightly from the polarization of the beam that actually annihillates on the positrons to produce Z bosons. Effects due to beam disruption of the electron bunch by the positron bunch, or spin rotation due to quadrupoles between the SLC interaction point and the Compton interaction point, have been shown to be negligible. However, a chromatic effect at the SLC interaction point is not. Because of the electron energy-dependent rate of spin precession in the SLC Arc, the off-nominal energy tails of the beam have a different net longitudinal polarization at the SLC interaction point than does the core of the beam. In the chromatic effect, off-energy electrons are not well focused at the SLC interaction point and thus cannot contribute to luminosity. Thus, the polarization of the beam that produces luminosity is different than the total beam polarization. This implies that the instantaneous polarization at the SLC interaction point will be a weighted average over number density, luminosity, and polarization as functions of energy,

$$\mathcal{P}_e = \int n(E)\mathcal{P}(E)\mathcal{L}(E)\,dE \Big/ \int n(E)\mathcal{L}(E)\,dE \ . \quad (2)$$

The Compton polarimeter, with its interaction point at a place of low-dispersion downstream of the SLC interaction point, measures the total beam polarization, which is the same as the SLC interaction point polarization in the case where the luminosity is constant with energy,

$$\mathcal{P}_e^C = \int n(E)\mathcal{P}(E)\,dE \Big/ \int n(E)\,dE \ . \quad (3)$$

we characterize the difference between the SLC interaction point and Compton interaction point polarizations with a single parameter ξ, refered to as the *chromaticity correction*,

$$\mathcal{P}_e = (1+\xi)\ \mathcal{P}_e^C \ . \quad (4)$$

The size of the chromaticity effect can be estimated from a simple chromaticity model. With the luminosity given by,

$$\mathcal{L}(E) = N^+(E)N^-(E)\,/4\pi\sigma_x(E)\sigma_y(E) \ , \quad (5)$$

we see that calculation of the size of the effect requires some knowlege of the spot-size dependence on energy. This is taken from a simple model of the chromatic effects in the SLC final focus [9]. The other required inputs are the intensity versus energy profile $n(E)$ (found by measuring scattered radiation as a thin wire is scanned across the SLC electron beam at a high dispersion point) and the polarization $\mathcal{P}(E)$ versus energy profile (measured directly by varying the beam energy and monitoring polarization). For the Gaussian core of the beam $\Delta E/E = 0.2\%$, the model predicts a small effect $\xi < 0.002$. However, $n(E)$ has a low-energy tail extending to $\Delta E/E = 1\%$, with correspondingly low polarization and large beam size. With this effect, the size of the chromaticity correction is estimated to be $\xi = 0.019 \pm 0.005$.

A more rigorous bound on the size of the chromaticity effect can be made using a conservative, essentially model-independent estimate based on experimental

Parameter	Assumed Limit
θ_y^{rms}	$< 200\ \mu$rad
θ_x^{rms}	$< 300\ \mu$rad
ϵ_y	$> 650\ \mu$m-rad
ϵ_x	$> 100\ \mu$m-rad
σ_E	$> 0.15\%$
$\mathcal{P}_e/\mathcal{P}_e(\Delta E/E=0)$	< 0.986

Table 2. Beam parameters used in chromatic effect estimate.

observations. The chromaticity correction is rigorously limited by the following relation:

$$(1-\xi) \leq \left[\frac{\mathcal{P}_e^C\left(\frac{\Delta E}{E}=0\right)}{\mathcal{P}_e^C}\right]_{\max}\left[\frac{\mathcal{P}_e}{\mathcal{P}_e^C\left(\frac{\Delta E}{E}=0\right)}\right]_{\max} \quad (6)$$

where the upper limit on ξ is determined by finding the upper limit on the two polarization ratios defined in this equation. Comparision of the polarization of a monochromatic beam, $\mathcal{P}_e^C(\Delta E/E=0)$, versus a normal energy spread beam, $\mathcal{P}_e^C$, comes from direct measurement. In special tests, the core width of the electron beam energy distribution was reduced to less than 0.1%, and the low-energy tail was removed by over-compressing the beam in the damping ring. In this configuration, the spin diffusion due to the SLC North Arc has been made negligible, since the energy spread of the beam has been made negligible. When compared to the measured polarization during normal beam running the upper limit on the first of the two ratios is,

$$\left[\mathcal{P}_e^C(\Delta E/E=0)/\,\mathcal{P}_e^C\right] < 1.0628(95\%\text{C.L.})\ . \quad (7)$$

A bound on the second ratio is found by noting that $\mathcal{P}_e$ must be less than $\mathcal{P}_e(\Delta E/E=0)$, and the ratio is at most unity. We make a conservative estimate, assuming that the energy tail of the beam does not contribute to the luminosity weighted polarization, and that all of the polarization comes from the core of the beam. The upper bound on this ratio is determined by a TURTLE transport simulation of the arc and final focus region, with the conservative (that is, tending to maximize the ratio) beam parameters listed in Table 2. This gives the upper limit,

$$\left[\mathcal{P}_e\,/\mathcal{P}_e^C(\Delta E/E=0)\right] < 0.986(95\%\text{C.L.}) \quad (8)$$

for the ratio of normal polarization to that which would be seen with a monocromatic beam. The limit on the chromaticity correction is thus $0 \leq \xi \leq 0.048$. The central value is taken as the correction, and the width as the error, $\xi = 0.024 \pm 0.016$ [7].

3. Event Selection

The e^+e^- collisions are measured by the SLD detector with a trigger that relies on a combination of calorimeter and tracking information. In order to maximize the number of events availible for the A_{LR} measurement in the sometimes harsh background environment of the SLC the event selection is entirely based on the liquid argon calorimeter [1]. The combined efficiency of the trigger and selection criteria is (93±1)% for hadronic Z decays. Less than 1% of the sample consists of tau pairs. Muon pair events deposit only small energy in the calorimeter; they are not included in the sample. The residual background in the sample is due primarily to beam-related backgrounds and e^+e^- final state events. From the data, we estimate the background fraction due to these sources to be $(0.23 \pm 0.10)\%$. The background fraction due to cosmic rays and two-photon processes is (0.02±0.01)%.

Using the detector, the number (N_L, N_R) of hadronic and $\tau^+\tau^-$ decays of the Z boson for each of the two longitudinal polarization states (L,R) of the electron beam is counted. The electron beam polarization is precisely measured with the polarimeter.

Applying the selection criteria, we count 27,225 (N_L) events produced with the left-polarized electron beam and 22,167 (N_R) produced with the right-polarized beam. The measured left-right cross section asymmetry for Z production is

$$A_m \equiv (N_L - N_R)/(N_L + N_R) = 0.1024 \pm 0.0045\ . \quad (9)$$

The measured asymmetry A_m does not vary significantly as more restrictive criteria (calorimetric and tracking based) are applied to the sample, and A_m is uniform when binned by the azimuth and polar angle of the thrust axis.

The measured asymmetry A_m is related to A_{LR} by the following expression, which incorporates a number of small correction terms in lowest-order approximation,

$$A_{LR} = \frac{A_m}{\langle\mathcal{P}_e\rangle} + \frac{1}{\langle\mathcal{P}_e\rangle}\Big\{f_b(A_m - A_b) - A_{\mathcal{L}} + A_m^2 A_{\mathcal{P}}$$

$$-E_{c.m.}\left[\sigma'(E_{c.m.})/\sigma(E_{c.m.})\right]A_E - A_\varepsilon + \langle\mathcal{P}_e\rangle\mathcal{P}_{e^+}\Big\}\,, \quad (10)$$

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; $\mathcal{P}_{e^+}$ is any longitudinal positron polarization assumed to have constant helicity [11]; and A_b, $A_{\mathcal{L}}$, $A_{\mathcal{P}}$, A_E, and A_ε are the left-right asymmetries of the residual background, the integrated luminosity, the beam polarization, the center-of-mass energy, and the product of detector acceptance and efficiency, respectively.

The luminosity-weighted average polarization $\langle\mathcal{P}_e\rangle$ is estimated from measurements of $\mathcal{P}_e$ made when Z events were recorded,

$$\langle\mathcal{P}_e\rangle = (1+\xi)\,\frac{1}{N_Z}\,\sum_{i=1}^{N_Z}\,\mathcal{P}_i = (0.630 \pm 0.011)\ , \quad (11)$$

Correction	Value (10^{-4})	$\Delta A_{LR}/A_{LR}$ (%)
f_b	23 ± 10	0.17 ± 0.07
A_b	310 ± 100	
A_ϵ	≈ 0	≈ 0
$A_{\mathcal{L}}$	0.38 ± 0.50	-0.037 ± 0.049
$A_{\mathcal{P}}$	-33 ± 1	-0.034 ± 0.001
A_E	0.0044	0.00085 ± 0.00002
$\mathcal{P}_{e^+}$	< 0.15	< 0.0009
Total correction		0.10 ± 0.08

Table 3. A list of possible sources of error on the A_{LR} measurement. None are significant.

where N_Z is the total number of Z events and $\mathcal{P}_i$ is the polarization measurement associated in time with the ith event. The error on $\langle \mathcal{P}_e \rangle$ is dominated by the systematic uncertainties on the polarization measurement and the chromaticity correction, ξ.

The corrections defined in square brackets in Eq. 10 are very small but for completeness they are shown in Table 3. Of these corrections, the most significant one is that due to background contamination. The correction for this is moderated by a nonzero left-right background asymmetry ($A_b = 0.031 \pm 0.010$) arising from e^+e^- final states which remain in the sample. Backgrounds give a net fractional correction to A_{LR} of $(+0.17 \pm 0.07)\%$.

The corrections in Eq. 10 give a net correction to A_{LR} of only $(+0.10 \pm 0.08)\%$ of the uncorrected value. The contributions to the systematic error are summarized in Table 1.

4. Results

Using Eq. 10, we find the left-right asymmetry to be

$$A_{LR}(91.26\ \mathrm{GeV}) = 0.1628 \pm 0.0071(\mathrm{stat}) \pm 0.0028(\mathrm{syst})\ . \quad (12)$$

This result is corrected 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). The result for pole asymmetry A^0_{LR} and the effective weak mixing angle is

$$A^0_{LR} = 0.1656 \pm 0.0071(\mathrm{stat}) \pm 0.0028(\mathrm{syst})\ ,$$

$$\sin^2\theta^{\mathrm{eff}}_W = 0.2292 \pm 0.0009(\mathrm{stat}) \pm 0.0004(\mathrm{syst})\ . \quad (13)$$

We also cite the measurement combined with our previous measurement [1] with 10,000 Z bosons at 20% polarization (statistically weak by comparison) for a value of $\sin^2\theta^{\mathrm{eff}}_W = 0.2294 \pm 0.0010$, which corresponds to the pole asymmetry, $A^0_{LR} = 0.1637 \pm 0.0075$.

5. Conclusions

We note that with this measurement we have made the most precise single determination of $\sin^2\theta^{\mathrm{eff}}_W$ to date. When considered within the Minimal Standard Model framework, this result predicts the top mass to be $m_t = 240^{+30+18}_{-45-20}$ GeV where the first errors are experimental and the second reflect a range of possible Higgs mass values from 60 to 1000 GeV. This $\sin^2\theta^{\mathrm{eff}}_W$ determination is smaller by 2.5 standard deviations than a recent LEP average value 0.2322 ± 0.0004 extracted from measurements of the forward-backward asymmetries of leptonic, hadronic, b-quark, and c-quark final states, and those of the polarization of tau lepton final states (assuming universality of the weak neutral current couplings) [10]. With the SLC now providing 80% polarized electron beam, and with on the order of 100,000 Z bosons next year, we should be able to reduce the error on $\sin^2\theta^{\mathrm{eff}}_W$ as determined by the A_{LR} measurement by a factor of two.

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