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# HIGHLIGHTS OF SLD PHYSICS

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ABSTRACT

The SLAC polarized electron beam allows the SLD experiment a high-precision measurement of $\sin^2\theta_W^{\rm eff}$ using the parity violating cross section asymmetry $A_{LR}$ at the $e^+e^-\to Z^0$ vertex. The SLD also uses the small luminous $e^+e^-$ collision region and CCD vertex detector to tag heavy quark final states for probing the $Z^0\to q\bar{q}$ vertex. Results are presented on the following selected topics: $A_{LR}$, the $Z^0\to b\bar{b}$ branching fraction $R_b$, and the parity violating cross section asymmetries $A_b$ and $A_c$ for the $Z^0\to b\bar{b}$ and $Z^0\to c\bar{c}$ final states.

# 1 Introduction

The SLD/SLC experiment accumulated 50 K hadronic $Z^0$ events at an average electron beam polarization of 63% during the 1993 run, and 100 K events at a polarization of 77% during the 1994–95 run. The SLD detector is described in detail elsewhere.[1] We emphasize here the importance of the small $e^+e^-$ collision region and three-dimensional tracking of the CCD pixel vertex detector for tagging heavy quark decays. The SLD $e^+e^-$ interaction point (IP) is known to a precision of 7 $\mu$m in the $x, y$ plane and to 35 $\mu$m in the $z$ (beam) direction. The vertex detector has an impact parameter resolution in the $x, y$ plane of $\sigma_{xy} = 11\,\mu\text{m} \oplus 70\,\mu\text{m}/p\,(\text{GeV/c})\sin^{3/2}\theta$ and an $r, z$ resolution of $\sigma_{rz} = 38\,\mu\text{m} \oplus 70\,\mu\text{m}/p\,(\text{GeV/c})\ \sin^{3/2}\theta$.

The polarized electron beam provides the SLD with enhanced sensitivity to parity violation at the $Z^0$ pole. Most measurements discussed in subsequent sections rely on the polarization. The next section outlines the generation and detection of the electron polarization at the SLC. The following sections present some selected measurements for the combined 1993 and 1994–95 data sets.

# 2 Polarization

Longitudinally polarized electron beam pulses are generated at 120 Hz by GaAs electron photoemission using circularly polarized laser light. The sign of the electron polarization $P_e$ is chosen at random by reversing the laser helicity. High values of $P_e$ are achieved by using GaAs photocathodes grown epitaxially on GaAsP so that the crystal lattice is strained.

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The electron polarization is analyzed ten meters downstream of the $e^+e^-$ IP by Compton scattering the electon beam with 532 nm circularly polarized laser light. A dipole magnet deflects the lower energy scattered electrons away from the main beam into a Čerenkov detector. The Compton scattering cross section asymmetry is measured for electrons polarized parallel ($\sigma_{m_j=3/2}$) and antiparallel ($\sigma_{m_j=1/2}$) to the photon polarization $P_\gamma$. The Compton asymmetry $A(E)$ is a function of the scattered electron energy E in the lab. Calibration of the energy scale relies on two features of this asymmetry: a zero asymmetry point at a $E = 25.2$ GeV (corresponding to 90° scattering in the center of momentum frame) and the Compton edge at $E = 17.4$ GeV (180° scattering in the center of momentum frame). The electron polarization is extracted from the cross section asymmetry:

$$\frac{\sigma_{3/2} - \sigma_{1/2}}{\sigma_{3/2} + \sigma_{1/2}} = A(E) P_\gamma P_e \ . \tag{1}$$

For the remainder of this note, we adopt the notation $R$ for electrons polarized parallel to the electron beam direction and $L$ for electrons polarized antiparallel.

## 3 Measurement of $\sin^2\theta_W^{\rm eff}$ Using $A_{LR}$

We define $A_{LR}$ to be the parity-violating cross section asymmetry for $Z^0$ production at the $Z^0$ pole:

$$A_{LR} \equiv \frac{\sigma(e^+e^-_L \to Z^0) - \sigma(e^+e^-_R \to Z^0)}{\sigma(e^+e^-_L \to Z^0) + \sigma(e^+e^-_R \to Z^0)} \ . \tag{2}$$

$A_{LR}$ depends on the left-handed and right-handed couplings ($R_e$ and $L_e$) at the $e^+e^- \to Z^0$ vertex; it is a sensitive function of $\sin^2\theta_W^{\rm eff}$:

$$A_{LR} = \frac{L_e^2 - R_e^2}{L_e^2 + R_e^2} = \frac{2(1 - 4\sin^2\theta_W^{\rm eff})}{1 + (1 - 4\sin^2\theta_W^{\rm eff})^2}, \tag{3}$$

where $\delta A_{LR} \approx -7.9\delta\sin^2\theta_W^{\rm eff}$. The superscript "eff" indicates that electroweak radiative corrections at the $Z^0$ pole are incorporated in $\sin^2\theta_W$ when it is used in the tree level expression for $A_{LR}$ given by Eq. (3). These corrections are dominated by corrections to the $Z^0$ propagator that depend quadratically on the top quark mass and logarithmically on the Higgs mass.

The measurement of $A_{LR}$ uses all $Z^0$ final states, with the exception of $Z^0 \to e^+e^-$. $Z^0$ events are detected by energy deposited in the liquid argon calorimeter with an efficiency of 90% and a background of 0.3%. The product $P_e A_{LR}$ is the asymmetry between the number of detected $Z^0$ events produced by left- and right-polarized beam pulses. This asymmetry is independent of the $Z^0$ final state and the detector acceptance. The systematic error for $A_{LR}$ is dominated by the error in the polarization. This error has two contributions: (1) the Compton measurement of the polarization, and (2) the uncertainty in the difference ($0.1 \pm 0.2\%$) between the average polarization at the Compton IP and the luminosity weighted polarization at the $e^+e^-$ collision point. Additional systematic uncertainties due to asymmetries in the backgrounds, luminosity, beam energy, and polarization amount to $0.3 \pm 0.1\%$. The combined systematic error is $\delta A_{LR}/A_{LR} = 0.8\%$ for the 1994 data.

The 1994 run accumulated 92,261 $Z^0$ events, yielding the result $A_{LR} = 0.1524 \pm 0.0042(\text{stat.}) \pm 0.0012(\text{syst.})$. This measurement may be combined with earlier data (mostly from 1993) to yield $A_{LR} = 0.1551 \pm 0.0040$, or $\sin^2\theta_W^{\text{eff}} = 0.23049 \pm 0.00050$.

$A_{LR}$ is plotted in Figure 1 with measurements of the $W$ and $Z^0$ masses $M_W$ and $M_Z$, the $Z^0$ width $\Gamma_Z$, the combined LEP results for $\sin^2\theta_W^{\text{eff}}$, and the ratio $R_\nu$ of the neutral to charged currents for deep-inelastic neutrino scattering. These measurements appear as one sigma confidence bands on the S-T plane following the analysis of Peskin and Takeuchi.[2]

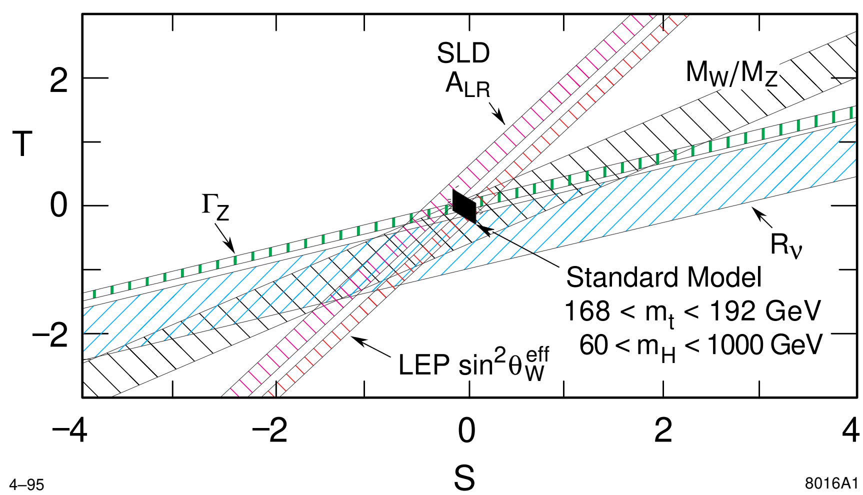


Fig. 1. Electroweak data in the S,T plane.

The parameters S and T express electroweak corrections to the $Z^0$ propagator, where the point S=0, T=0 is chosen arbitrarily at a standard model Higgs mass $m_H$ of 300 GeV and a top quark mass $m_t$ of 180 GeV. The parameter S is weak global isospin conserving and is sensitive to the masses of the heavy fermions in the loop; it has a logarithmic dependence on both $m_H$ and $m_t$. The parameter T is weak global isospin breaking and quadratic in the fermion doublet mass splitting; T also depends logarithmically on the $m_H$. The standard model variations of S and T are also shown for a range of values of $m_H$ and $m_t$; the electroweak data plotted in Figure 1—including the SLD measurement of $A_{LR}$—appear consistent with the standard model.

## 4 The $Z^0 \to b\bar{b}$ Branching Fraction $R_b$

Unlike $A_{LR}$, the dominant electroweak corrections to $R_b$ involve the $Z^0 \to b\bar{b}$ vertex rather than the propagator. The standard model predicts $R_b = 0.2157 \pm 0.0004$ at $m_t = 174$ GeV.[3] Extensions beyond the standard model are expected to change $R_b$ by $\sim 1\%$.[4]

To measure $R_b$, $Z^0 \to b\bar{b}$ events are tagged using tracks from combined hits in the CCD vertex detector and the surrounding drift chamber. The event is divided into two hemispheres using the highest momentum jet direction, and each hemisphere is independently analyzed for a tag. To tag a hemisphere, each track is refit with the IP added as a track hit. A small increase in $\chi^2$ for the refitted track indicates that the track is more likely to originate directly from the IP than from a secondary quark vertex. All the refitted tracks in the hemisphere are combined to form a joint probability that the hemisphere tracks originate from a light (uds) quark event. A low uds probability comprises a $b$ tag. The uds probability cut chosen for the $R_b$ analysis yields a $b$ hemisphere tag purity of 87% and an efficiency of 42%. The fractions of single and double hemisphere tags for the data set are used to solve simultaneously for $R_b$ and the hemisphere tagging efficiency $\epsilon_b$. This measurement yields $R_b = 0.2171 \pm 0.0040$ (stat.) $\pm 0.0045$ (syst.), where the uncertainty in the $Z^0 \to c\bar{c}$ branching fraction contributes the largest single systematic error.

## 5 The Parity Violating Asymmetries $A_b$ and $A_c$

The angular distribution of the final state heavy quark $f = b, c$ with respect to the electron beam direction in the decay $Z^0 \to f\bar{f}$ has a forward-backward asymmetry due to the difference between the left-handed and right-handed couplings ($L_f$ and $R_f$) at the $Z^0 \to f\bar{f}$ vertex:

$$\frac{d\sigma_f}{d\cos\theta} \propto (1 - A_{LR}P_e)(1+\cos^2\theta) + 2A_f(A_{LR} - P_e)\cos\theta \ ,$$

$$A_f = \frac{L_f^2 - R_f^2}{L_f^2 + R_f^2} \ . \tag{4}$$

The ability to reverse the electron beam polarization allows a direct measurement of $A_f$ by forming a double asymmetry in polarization and $\cos\theta$:

$$|P_e|A_f \frac{2\cos\theta}{1+\cos^2\theta} = \frac{d\sigma_L(\cos\theta) - d\sigma_L(-\cos\theta) - d\sigma_R(\cos\theta) + d\sigma_R(-\cos\theta)}{d\sigma_L(\cos\theta) + d\sigma_L(-\cos\theta) + d\sigma_R(\cos\theta) + d\sigma_R(-\cos\theta)} \ . \tag{5}$$

An experiment with $P_e = 0$ must rely upon $A_{LR} \approx 15\%$ to provide the analyzing power to extract the product $A_{LR}A_f$. The polarized electron beam provides an advantage in analyzing power of $P_e/A_{LR} \sim 5$, and $A_f$ is measured directly. These measurements require both a tag for the $Z^0 \rightarrow f\bar{f}$ events and a charge separation technique to isolate $f$ from $\bar{f}$.

Several analyses to measure $A_b$ are being pursued by SLD; the technique described here determines the $b$ quark direction by summing the momentum-weighted track charge. $Z^0 \rightarrow b\bar{b}$ events are tagged by requiring at least three tracks in the event to have a normalized impact parameter in the $x, y$ plane $> 3$. This tag isolates $Z^0 \rightarrow b\bar{b}$ events with an efficiency of 61% and a purity of 89%; most of the background is due to $Z^0 \rightarrow c\bar{c}$. The direction of the $b$ quark is taken to be the thrust axis direction $\hat{T}$ signed by requiring that the momentum-weighted track charge sum $Q$ be positive:

$$Q = -\sum_{\text{tracks}} q_i(\vec{p}_i \cdot \hat{T})|(\vec{p}_i \cdot \hat{T})|^{\kappa-1} > 0 \;, \tag{6}$$

where $q_i$ and $\vec{p}_i$ are the charge and momentum for track $i$, and $\kappa$ is chosen to be 0.5 to optimize the sensitivity of $Q$ to the $b$ quark direction. Figure 2 is a histogram of $\cos\theta_T$ for $Z^0$ events produced by left-handed and right-handed electron beam polarizations, where $\theta_T$ is the angle between $\hat{T}$ and the electron beam. The forward-backward asymmetry of the $b$ quark direction is evident for both the 1993 and 1994–95 data sets.

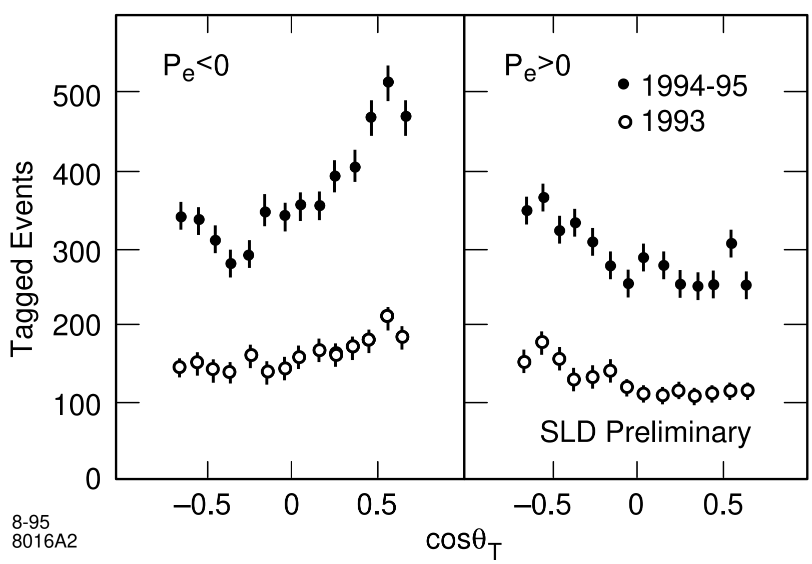


Fig. 2. Forward-backward asymmetry for tagged b events.

The analyzing power to correctly assign the $b$ quark direction is evaluated using Monte Carlo; it is checked in the data by forming $Q$ for each hemisphere in the event and comparing the sign of $Q$ for each hemisphere. The preliminary result for $A_b$ using the 1993–95 data is $A_b = 0.843 \pm 0.046$ (stat.) $\pm 0.051$ (syst.), where most of the systematic error is assigned from the uncertainty in the analyzing power. This may be compared with the standard model prediction[3] of $A_b = 0.93$.

A measurement of $A_c$ requires isolating $Z^0 \to c\bar{c}$ decays. This is accomplished by reconstructing $D^+$ and $D^{*+}$ decays using the channels $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ and $D^0 \to K^-(\pi^0)\pi^+$; the $\pi^0$ is not identified in the detector. To reject $B \to D^{(*)}$ decays from $Z^0 \to b\bar{b}$ background, the reconstructed $D^{(*)}$ is required to either point back to the IP (taking advantage of the small $e^+e^-$ collision region) or to have a high fraction of the available center-of-mass energy. The direction of the $c$ quark is taken to be the reconstructed $D^{(*)}$ direction. The preliminary result for $A_c$ from the 1993–95 data is $A_c = 0.64 \pm 0.11$ (stat.) $\pm 0.06$ (syst.); the largest systematic error is from the uncertainty in the magnitude and asymmetry of the combinatoric background under the reconstructed $D^+$ and $D^{*+}$ invariant mass peaks. The standard model predicts[3] $A_c = 0.67$.

# 6 Conclusions

The SLD measurement of $A_{LR}$ is presently the most precise single measurement of $\sin^2\theta_W^{\rm eff}$; the systematic error is entirely dominated by the uncertainty in the electron beam polarization. Analysis of all the SLD data to date shows no inconsistency with the standard model.

SLD remains competitive in several heavy quark electroweak measurements because of the high beam polarization and the CCD vertex detector. These measurements are presently consistent with standard model predictions.

Analyses are beginning to use the particle identification provided by the ring imaging Čerenkov detector, and a new CCD vertex detector will be be installed before the 1996 run with a factor two improvement in impact parameter resolution and significantly greater solid angle coverage than the present device ($|\cos\theta| < 0.90$ instead of $|\cos\theta| < 0.75$). The SLD experiment plans to accumulate an additional 500 K hadronic $Z^0$ decays with the new vertex detector and to search for $B_s^0$ mixing in addition to improving the precision of its present measurements.

# 7 Acknowledgements

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# 8 References

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