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Electroweak Tests at SLAC/SLD*

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Abstract

The SLD experiment at SLAC has performed several precise tests of the electroweak Standard Model. This paper summarizes the measurements of Z couplings to leptons and quarks. Most of these measurements are preliminary and many incorporate the full SLD dataset of 550,000 polarized Z decays. A future experiment with the SLAC polarized beam, E158, is also described. It will measure the lepton coupling asymmetry in a new kinematic region.

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1 Introduction

In the Standard Model, the coupling of a Z to a fermion-antifermion pair is described by a vertex factor:

$$\frac{-ig}{2\cos\theta_W}\gamma^\mu(c_V - c_A\gamma^5) \tag{1}$$

where g is the electroweak coupling constant, θ_W is the electroweak mixing angle, c_V is the vector coupling, and c_A is the axial-vector coupling. The couplings can also be expressed in terms of left- and right-handed couplings and are predicted by the Standard Model:

$$c_V = c_L + c_R = I_3 - 2Q\sin^2\theta_W \tag{2}$$

$$c_A = c_L - c_R = I_3 \tag{3}$$

here Q is the fermion charge and I_3 is the third component of the fermion weak isospin.

The Z-pole observables R_f and A_f can be written in terms of these couplings. R_f is defined as the rate of production of quark flavor f as a fraction of the total hadronic width.

$$R_f = \frac{\Gamma(Z \to f\bar{f})}{\Gamma(Z \to \text{hadrons})} \sim (c_L^f)^2 + (c_R^f)^2 \tag{4}$$

A_f represents the amount of parity violation at the $Zf\bar{f}$ vertex.

$$A_f = \frac{2c_A^f c_V^f}{(c_A^f)^2 + (c_V^f)^2} = \frac{(c_L^f)^2 - (c_R^f)^2}{(c_L^f)^2 + (c_R^f)^2} \tag{5}$$

The Standard Model predictions for A_f for the fermion families are given in Table 1. The lepton asymmetries are seen to be sensitive probes of the electroweak mixing angle $\sin^2\theta_W$. For the quarks, the b system is particularly interesting. Since $(c_L)^2 \sim 30(c_R)^2$, measurements of R_b and A_b correspond to nearly independent determinations of c_L and c_R. Precise measurements of A_f for the different fermions test the universality of the theory between the generations within each family.

The Born-level differential cross section for $e^+e^- \to Z \to f\bar{f}$, for longitudially polarized electrons and unpolarized positrons is:

$$\frac{d\sigma}{d\cos\theta_f} \sim (1 - A_e P_e)(1 + \cos^2\theta_f) + 2A_f(A_e - P_e)\cos\theta_f \tag{6}$$

where θ_f is the polar angle of the outgoing fermion with respect to the direction of the incoming electron beam, and P_e is the electron beam polarization. It is possible to isolate the various parameters in Eq. 6 by forming asymmetries in $\cos\theta_f$ and P_e.

The left-right asymmetry A_{LR} is defined as:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = |P_e| A_e \tag{7}$$

which isolates the initial-state coupling asymmetry A_e. Because no final-state identification or angular fitting are involved a measurement of A_{LR} reduces to a simple counting experiment.

The forward-backward asymmetry (for unpolarized beams) is defined as:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A_e A_f \frac{2\cos\theta}{1+\cos^2\theta} \tag{8}$$

where F refers to $\cos\theta > 0$. This isolates a combination of the inital- and final-state asymmetries. With a polarized beam it's possible to isolate A_f alone by forming the left-right-forward-backward double asymmetry:

$$\tilde{A}_{FB} = \frac{\sigma_{LF} - \sigma_{LB} - \sigma_{RF} + \sigma_{RB}}{\sigma_{LF} + \sigma_{LB} + \sigma_{RF} + \sigma_{RB}} = |P_e| A_f \frac{2\cos\theta}{1+\cos^2\theta} \tag{9}$$

Measuring $\tilde{A}_{FB}$ permits a direct measurement of the final-state coupling asymmetry A_f, independent of A_e. This method also has a statistical advantage of $(P_e/A_e)^2 \sim 25$ compared to A_{FB}.

2 The SLD experiment at SLC

The SLAC Linear Collider (SLC) delivered excellent performance in the 1997-98 run, reaching peak luminosities of $3 \times 10^{30} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. Approximately 350,000 Z decays were collected, more than doubling the SLD data set to a total of around 550,000 for 1993-98.

Two features of the SLC make it a good laboratory for electroweak measurements. The first is the highly polarized electron beam. During the 1997-98 run the average longitudinal beam polarization was 73%. The other is the small and stable beam spot ($1.5 \times 0.8 \times 700$ μm), essential for identifying weakly-decaying heavy mesons.

The SLD detector is described in detail in [1]. One unique feature of the SLD is its 3D CCD-based pixel vertex detector (VXD) [2]. In combination with the small SLC beams it allows determination of the interaction point to $4 \times 4 \times 14$ μm, and provides impact parameter resolution of 8×10 μm ($r\phi \times rz$) for high-momentum tracks. Another important component is the Cherenkov Ring Imaging Detector (CRID) [3], which provides good particle identification (particulary $\pi - K$ separation) over a wide momentum range.

3 Lepton Couplings

3.1 A_e from A_{LR}

A measurement of A_{LR} [4] provides a direct measurement of A_e as discussed above. Because no final-state identification is required, high statistical precision can be obtained. A raw asymmetry is formed by counting the numbers of triggers recorded for left- and right-polarized incident electron beam, filtered through a simple event selection which selects hadronic Z decays. This raw asymmetry is converted to a measured A_{LR} by dividing by the average beam polarization, therefore $|P_e|$ must be known precisely. Two complementary polarimeters have confirmed the standard Compton polarimeter calibration to $\pm 0.5\%$, and a dedicated measurement has excluded polarization of the positron beam to $< 0.1\%$. The total systematic error due to P_e is $\pm 0.5\%$. Finally, the measured A_{LR} must be corrected by $\sim$2% back to the Z-pole value A^0_{LR}. A peak scan around the Z was performed in 1998 to check the energy spectrometer calibrations, needed for the correction. This measurement is now final, for 1992-98 data we measure $A^0_{LR} = 0.15138 \pm 0.00218$, or equivalently $\sin^2\theta^{eff}_W = 0.23097 \pm 0.00027$. This is currently the most precise determination of $\sin^2\theta^{eff}_W$.

3.2 A_{lepton} from $\tilde{A}_{FB}$

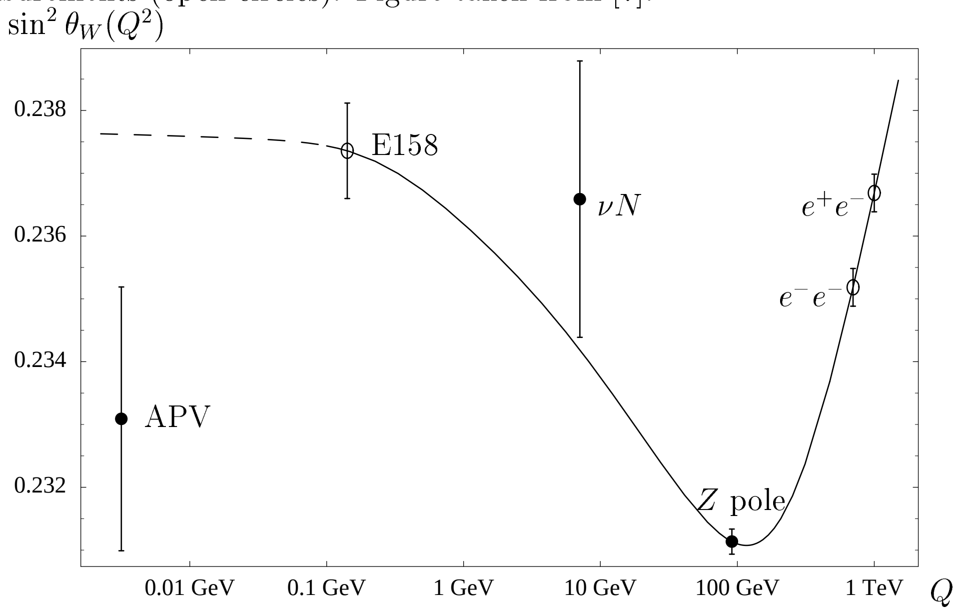
The lepton coupling asymmetries are measured [5] from dilepton decays of the Z^0. A maximum likelihood fit is used to extract A_e and A_f simultaneously from $\tilde{A}_{FB}$ for each of the three lepton species. The preliminary results for the 1993-98 data are $A_e = 0.1548 \pm 0.0059$, $A_\mu = 0.142 \pm 0.015$, and $A_\tau = 0.140 \pm 0.016$. These results are consistent with lepton universality, and can be combined to yield $A_{e\mu\tau} = 0.1519 \pm 0.0053$ and $\sin^2\theta_W^{eff} = 0.23090 \pm 0.00067$.

Combining A_{LR} and $A_{e\mu\tau}$ yields the preliminary results $A_{e\mu\tau} = 0.1514 \pm 0.0021$ and $\sin^2\theta_W^{eff} = 0.23096 \pm 0.00026$.

3.3 A_{LR} away from the Z - E158

A future experiment planned for the SLAC polarized electron beam, E158, will measure $\sin^2\theta_W$ away from the Z^0 pole [6]. A high-intensity beam of electrons will be scattered off a liquid-hydrogen target, and the left-right asymmetry measured. This will be the first observation of parity-violation in Møller scattering. The goal is to reach $\delta A_{LR} = \pm 7\% \pm 3\%$, or $\delta \sin^2\theta_W = \pm 0.0007 \pm 0.0003$. This result, at $Q^2 \sim 0.02$ GeV^2, will provide a check of the running of $\sin^2\theta_W$ [7] into a region similar to that measured by atomic

Figure 1: Predicted running of $\sin^2\theta_W(Q^2)$, and evidence from existing experiments (dark circles) along with expectations for future Møller and NLC measurements (open circles). Figure taken from [7].



parity violation, as seen in Figure 1. Beam tests and apparatus construction is currently underway, with the first physics run scheduled for 2001.

4 Quark Couplings

Measurements of the quark couplings require selection of individual species from the sample of hadronic Z decays. For bottom and charm events, this is done by searching for displaced secondary vertices resulting from weak decays. The event is split into two hemispheres using the thrust axis, and a topological vertex algorithm [8] is applied to each. The tracks found to originate from displaced vertices, along with any others consistent with the decay chain, are used to calculate a momentum and invariant mass for the hemisphere. The invariant mass is corrected for missing transverse momentum, estimated from the difference between the vertex momentum and flight direction from the IP. These quantities are shown in Figure 2. A typical bottom tag is $M > 2$ GeV, with 98% purity and 50% efficiency. Charm tagging is done by requiring $0.5 < M < 2$ GeV, $P > 5$ GeV, and $P - 15M > -10$ GeV, for 70% purity and 16% efficiency.

4.1 R_b and R_c

These quantities are measured using the respective tag rates, but the efficiency must be known. To reduce systematic errors these analyses calibrate it from the data, by measuring the hemisphere tag rate and also the fraction of events which are double-tagged. These can be expressed as:

$$\begin{aligned} F_{hemi} &= \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_c - R_b) \\ F_{double} &= \epsilon_b^2 R_b + \epsilon_c^2 R_c + \epsilon_{uds}^2(1 - R_c - R_b) \end{aligned} \tag{10}$$

In the R_b analysis [9], these equations are solved for ϵ_b and R_b. The charm and light-flavor efficiencies are taken from Monte Carlo, and the SM value of R_c is used. A correction for the tag inter-hemisphere correlation is also applied. The preliminary result for the 1993-98 data is $R_b = 0.2159 \pm 0.0014 \pm 0.0014$. Approximately 150,000 Z's from the 1998 data have not yet been included.

The R_c analysis [10] is done in a similar way. In addition to the hemisphere and double-tag rates, the rate to tag one hemisphere of an event with the bottom tag and the other with the charm tag is used, which allows calibration of the b background efficiency. The preliminary result for the 1993-98 data is $R_c = 0.1685 \pm 0.0047 \pm 0.0043$.

4.2 A_{quark} from $\tilde{A}_{FB}$

The heavy-quark asymmetry measurements use the same tags described above to select events. In addition, they must determine which of the hemispheres contains the quark and which the antiquark. The direction of the quark is estimated using the thrust axis, and A_f is extracted from a maximum-likelihood fit to $\tilde{A}_{FB}$. Several different techniques are used.

4.2.1 A_b with vertex charge

This measurement uses the total charge of the tracks in the secondary vertex of tagged hemispheres. Correct track assignment is critical, so this analysis attaches tracks using a neural-net algorithm for greater efficiency. Because not all particles are reconstructed in the drift chamber, this analysis also examines $\geq$ 3-hit vectors in the vertex detector to see if any are consistent with the decay chain. The charge of these can be determined by fitting to the VXD hits and the vertex position, and is correct $\sim$85% of the time. The analyzing power for bottom events is calibrated from the data, using double-tagged events. Figure 4.2.1 shows the polar angle distributions of the signed thrust axis for left- and right-handed electron beams. The preliminary result for 1997-98 data is $A_b = 0.926 \pm 0.019 \pm 0.027$.

4.2.2 A_b with jet charge

This measurement [11] uses the sum of the track charges in each hemisphere, with each track weighted by the square root of its momentum. Because both hemispheres are always used this analysis benefits from high statistics. The analyzing power for bottom events is calibrated from the data. The preliminary result for 1993-98 data is $A_b = 0.882 \pm 0.020 \pm 0.029$.

4.2.3 A_b with kaons

This measurement [12] uses charged kaons from the $b \to c \to s$ cascade to tag the b quark. The kaons are identified using the CRID, and only tracks which are attached to a secondary vertex are considered. The analyzing power for bottom events is calibrated from the data using double-tagged events. The preliminary result for 1993-98 data is $A_b = 0.960 \pm 0.040 \pm 0.069$.

4.2.4 A_b and A_c with leptons

These measurements [13] use semileptonic decays of bottom and charm hadrons to tag the quark hemisphere. The electron and muon identification is done using the SLD calorimeters and information from the CRID. Discrimination between b-prompt, b-cascade, and c-prompt decays uses the total and transverse momentum of the lepton. Geometrical information from the vertex detector is also used to improve assignment of the lepton track to the proper position in the decay chain. The asymmetry parameters are extracted simultaneously from a likelihood fit. The preliminary results for 1993-98 data are $A_b = 0.918 \pm 0.030 \pm 0.024$ and $A_c = 0.567 \pm 0.051 \pm 0.064$.

4.2.5 A_c with exclusive D mesons

This measurement [14] exclusively reconstructs six modes: $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, and $D^{*+} \to D^0\pi^+_{soft}$ with D^0 decaying into $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, and $K^-l^+\nu_l$ $(l = e, \mu)$. The efficiency is $\sim$4%, with high purity and analyzing power. The standard bottom tag is used as a veto on the opposite hemisphere to reject b background. The preliminary result for 1993-98 data is $A_c = 0.690 \pm 0.042 \pm 0.022$.

4.2.6 A_c with inclusive soft pions

This measurement [14] uses the soft pion produced in D^* decays to tag the charm quark. These pions have very low transverse momentum with respect to the D^* jet axis. A signal-to-background ratio of 1:2 is obtained by requiring $p_T^2 < 0.01$ GeV^2. The bottom tag is used to reject b background. The preliminary result for 1993-98 data is $A_c = 0.683 \pm 0.052 \pm 0.050$.

4.2.7 A_c with vertex charge and kaons

This measurement [15] uses the same charm tag as R_c. At least one hemisphere must be charm-tagged, and neither may be bottom-tagged. Both vertex charge and identified kaons are used for increased efficiency. The charm analyzing power is high (> 0.8) and is calibrated from the data using double-tagged events. The b background analyzing power is also calibrated from the data using the mixed charm-bottom-tagged events. The preliminary result for 1993-98 data is $A_c = 0.608 \pm 0.028 \pm 0.023$.

4.2.8 A_s with kaons

This measurement [16] identifies strange events using fast kaons. Charged kaons identified with the CRID and reconstructed neutral kaons are used. Both hemispheres must contain at least one K, with at least one signed. Information from the vertex detector is used to suppress the heavy-flavor backgrounds. The preliminary result for 1993-98 data is $A_s = 0.895 \pm 0.066 \pm$

0.063.

5 Conclusions

SLD has performed several precise tests of the electroweak Standard Model. The results are summarized in Table 4.2.8. The SLD A_{lepton} measurements support lepton universality and provide the most precise determination of $\sin^2\theta_W^{eff}$. The R_b and R_c results are in agreement with Standard Model predictions, with the SLD R_c measurement representing the single most precise determination. The combined SLD A_b, A_c, and A_s measurements are also in agreement with Standard Model predictions. The A_b and A_s measurements support down-type quark universality. Many of the SLD measurements are still in active development. In particular, work is proceeding to reduce the systematic errors on the A_b measurements.

In the future at SLAC, the E158 experiment will make the most precise measurement of $\sin^2\theta_W$ away from the Z-pole. This will provide a strict test of the Standard Model, with high sensitivity to new physics.

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Table 1: Coupling parameters and asymmetries for the fermion families.

fermion	I_3	Q	c_L	c_R	A_f	$\frac{dA_f}{d\sin^2\theta_W}$
ν_e, ν_μ, ν_τ	1/2	0	0.50	0.00	1	0
e, μ, τ	-1/2	-1	-0.27	0.23	0.155	-7.9
u, c, t	1/2	2/3	0.35	-0.15	0.667	-3.5
d, s, b	-1/2	-1/3	-0.42	0.08	0.935	-0.6

Table 2: Summary of SLD electroweak measurements.

A_{lepton}	0.1514 ± 0.0021
$\sin^2\theta_W^{eff}$	0.23096 ± 0.00026
R_b	0.2159 ± 0.0020
R_c	0.1685 ± 0.0064
A_b	0.913 ± 0.024
A_c	0.634 ± 0.027
A_s	0.895 ± 0.091

Figure 2: Distributions of (top) M, where the points are the data, and (bottom) P vs. M for uds (left), c (center), and b (right).

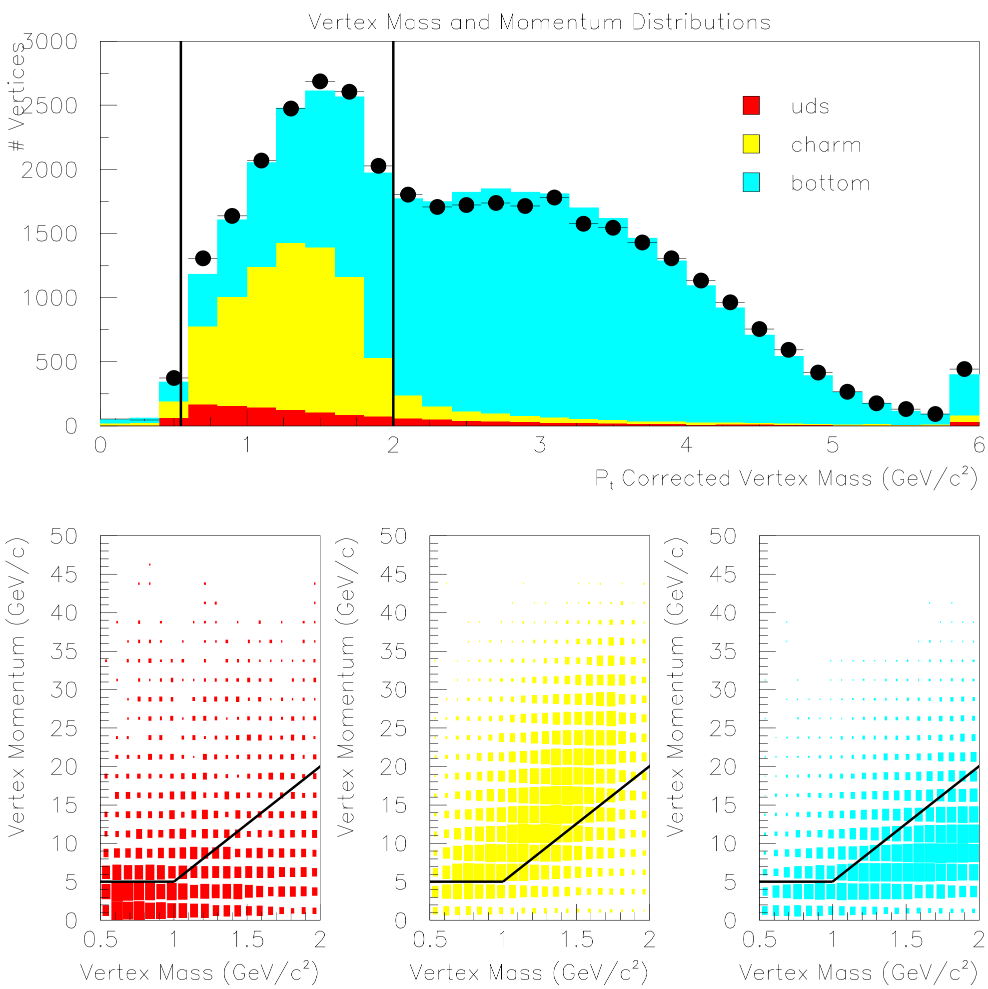

Figure 3: Polar angle distributions of the signed thrust axis for left- and right-handed electron beams. The data are represented by the points, the open histogram is the Monte Carlo reweighted to the same asymmetry, and the solid histogram is the estimated background.