# Measurements of $A_{LR}$, $A_{lepton}$ and $A_b$ from SLD

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We present the measurements of the leptonic asymmetries in $Z^0$ decays measured by the SLD experiment at SLAC. A data sample of approximately 550,000 $Z^0$ bosons are used for the preliminary measurement of $A_{LR}(A_e)$ and the leptonic final state measurements of $A_e$, $A_\mu$ and $A_\tau$, representing the entire set of 1992-1998 SLD runs. When combining all results, a preliminary value for the effective weak mixing angle is obtained: $\sin^2\theta_W^{eff} = 0.23109 \pm 0.00029$. We also present the direct measurements of $A_b$ from left-right forward-backward asymmetries, using partial data samples from 1993-1998 SLD runs. The preliminary value combines jet charge, cascade kaon and semileptonic decay analyses to obtain $A_b = 0.866 \pm 0.036$.

## I. INTRODUCTION

The SLC linear electron-positron collider [1] has long been a powerful facility for testing the Standard Model via measurements of electroweak couplings at the $Z^0$ pole. Its unique attributes of a highly longitudinally polarized electron beam ($P_e \approx 75\%$) and small spot size (1.5 x 0.8 x 700) $\mu$m$^3$ in (x,y,z) have recently been augmented by improved luminosity for the 1997-1998 SLD run and these have proved advantageous for precision electroweak measurements. The SLD detector [2] is designed to take advantage of these special attributes of the SLC.

### A. Asymmetries

The polarized differential cross section at Born level for the process, $e^+e^- \to Z^0 \to f\bar{f}$ is given by:

$$\frac{\mathrm{d}\sigma^f}{\mathrm{d}z} \propto (1 - P_e A_e)\left(1 + z^2\right) + 2A_f\left(A_e - P_e\right)z \tag{1}$$

where $A_f = 2v_f a_f/(v_f^2 + a_f^2)$ is the final state coupling, $P_e$ is the electron beam polarization ($\equiv +1$ for right-handed beams), $z = \cos\theta$ where $\theta$ is the angle of the final state fermion with respect to the electron beam axis, and $v_f$ and $a_f$ are the vector and axial vector couplings which specify the Z-f coupling.

One can define the left right asymmetry which equals the initial state coupling asymmetry $A_e$,

$$A_{LR}^0 \equiv \frac{1}{|P_e|}\frac{\sigma\left(e^+e^-_L \to Z^0\right) - \sigma\left(e^+e^-_R \to Z^0\right)}{\sigma\left(e^+e^-_L \to Z^0\right) + \sigma\left(e^+e^-_R \to Z^0\right)} = \frac{1}{P_e}\left[P_e\frac{2v_e a_e}{v_e^2 + a_e^2}\right] = A_e \tag{2}$$

Although one can use all final states to build the asymmetry, in practice, our cuts select hadronic final states: leptonic final states are treated separately (see section IV). If $P_e$ can be measured precisely, then $A_{LR}$ provides us with an effective way to measure $\sin^2\theta_W$:

$$A_{LR}^0 = \frac{2\left(1 - 4\sin^2\theta_W^{eff}\right)}{1 + \left(1 - 4\sin^2\theta_W^{eff}\right)^2} \tag{3}$$

where the evolution of $\sin^2\theta_W \to \sin^2\theta_W^{eff}$ signifies the convention of making Eqn. 3 the *definition* of the weak mixing angle. Thus higher order effects must be explicitly accounted for when comparing this value to non-$Z^0$-pole measurements.

Additionally, one can construct a forward-backward left-right asymmetry and extract the final state coupling $A_f$ ,

$$\begin{aligned}\tilde{A}_{FB}^f(z) &= \frac{[\sigma_L^f(z) - \sigma_L^f(-z)] - [\sigma_R^f(z) - \sigma_R^f(-z)]}{\sigma_L^f(z) + \sigma_L^f(-z) + \sigma_R^f(z) + \sigma_R^f(-z)} \\ &= |P_e|A_f\frac{2z}{1+z^2}.\end{aligned} \tag{4}$$

For b-quark final state fermions and assuming full detector acceptance, Eqn. 4 yields $\tilde{A}^b_{FB} = (3/4)|P_e|A_b$. It is interesting to note that while $A_{LR}$ is very sensitive to the weak mixing angle, $A_b$ in insensitive to $\sin^2\theta_W^{eff}$, and instead is sensitive to vertex effects which in the Standard Model are expected to be negligible at the $Z^0e^+e^-$ vertex.

## II. POLARIZATION MEASUREMENTS

Precision polarimetry of the SLC electron beam is accomplished with the Compton Polarimeter [3], which employs Compton scattering between the high-energy electron beam and a polarized Nd:YAG laser beam ($\lambda = 532$nm) to probe the electron beam polarization. The Compton scattered electrons, which lose energy in the scattering process but emerge essentially undeflected, are momentum analyzed by the Compton spectrometer downstream of the SLD interaction point, beyond which they exit the beam-line vacuum through a thin window, and enter a threshold Čerenkov detector segmented transverse to the beam-line.

A history of polarization performance is given elsewhere [4]. The preliminary measurement for 1998 is $P_e = 73.1 \pm 1.01(\text{syst})\%$ where the relative systematic uncertainty can be expected to improve substantially (to below the 0.7% level) when the analysis is complete.

## III. MEASURING $A_{LR}$

$A_{LR}$ is essentially measured with hadronic final states only, as the selection efficiency for leptonic final states is intentionally kept low. For the last three measurements (1996, 1997 and 1998), a 99.9% pure hadronic sample was selected by requiring that the absolute value of the energy imbalance (ratio of vector to scalar energy sum in the calorimeter) be less than 0.6, that there be at least 22 GeV of visible calorimetric energy, and that at least 4 charged tracks be reconstructed in the central tracker; this selection was 92% efficient. After counting the number of hadronic decays for left- and right-handed electron beams and forming a Left-Right Asymmetry, a small experimental correction for backgrounds (and negligible corrections for false asymmetries) was applied; for the 1998 dataset this correction was 0.06%. This then yielded a value for the measured Left-Right Asymmetry (1998) of

$$A_{LR}^{meas} = \frac{1}{P_e}\frac{N_L - N_R}{N_L + N_R} \tag{5}$$
$$= 0.1450 \pm 0.0030 \pm 0.0015 \tag{6}$$

where the systematic uncertainty is dominated by the uncertainty in the polarization scale. The translation of this result to the $Z^0$-pole asymmetry $A^0_{LR}$ was a $1.8 \pm 0.4\%$ effect, where the uncertainty arises from the precision of the center-of-mass energy determination. This small error due to beam energy uncertainty is slightly larger than seen previously (it has been quoted as $\pm 0.3\%$), and reflects the results of a scan of the Z peak used to calibrate the energy spectrometers to LEP data, which was performed for the first time during the 1998 run. This correction yields the 1998 preliminary result of

$$A^0_{LR} = 0.1487 \pm 0.0031 \pm 0.0017 \tag{7}$$
$$\sin^2\theta_W^{\text{eff}} = 0.23130 \pm 0.00039 \pm 0.00022. \tag{8}$$

The six measurements $A^0_{LR}$ performed by SLD are shown in Table I, along with their translations to $\sin^2\theta_W$. The values are consistent with each other yielding a $\chi^2/dof = 6.95/5$ for a straight line fit to the (preliminary) average. The (preliminary) averaged results for 1992-98 are

$$A^0_{LR} = 0.1510 \pm 0.0025 \tag{9}$$
$$\sin^2\theta_W^{\text{eff}} = 0.23101 \pm 0.00031 \tag{10}$$

## IV. MEASURING $A_e$, $A_\mu$ AND $A_\tau$ USING FINAL STATE LEPTONS

Parity violation in the $Z^0$-lepton couplings is measured by a maximum likelihood fit to the differential cross section (Eqn. 1) separately for the three leptonic final states, including the effects of t-channel exchange for the $Z^0 \to e^+e^-$ final state. For the 1996-98 data sample, leptonic final states in the range $|\cos\theta| < 0.8$ are selected by requiring that events have between two and eight charged tracks in the CDC, at least one track with $p \geq 1$ GeV/c. One of the two event hemispheres was required to have a net charge of -1, while the other one had to have a net charge of +1. Events are identified as bhabha candidates if the total calorimetric energy associated with the two most energetic tracks is greater than 45 GeV. On the other hand, if there is less than 10 GeV of associated energy for each track, and there is a two-track combination with an invariant mass of greater than 70 GeV/c$^2$, the event is classified as a muon candidate. The selection criteria for tau candidates is somewhat more complex. First, the $\tau^+\tau^-$ pair invariant mass is required to be less than 70 GeV/c$^2$, with a separation angle between the two tau momentum vectors of at least 160°. At least one track in the event must have a momentum greater than 3 GeV/c. Each $\tau$ hemisphere must have an invariant mass less that 1.8 GeV/$c^2$ (to suppress $Z^0$ hadronic decays), and the associated energy in the LAC from each track must be less than 27.5(20.0) GeV for tracks with polar angles less than (greater than) $|\cos\theta| = 0.7$. For the electron final state, t-channel effects are incorporated into the angular distribution, while for the tau final state, a $\cos\theta$-dependent efficiency correction has been applied to account for the correlation between visible energy and net tau polarization. Note that all channels provide information about $A_e$, which comes in through the left-right cross section asymmetry.

The preliminary combined result for the 1993-1998 datasets are $A_e$=0.1504 ± 0.0072, $A_\mu$=0.120 ± 0.019 and $A_\tau$=0.142 ± 0.019. The result for $A_\mu$ (which is the only direct measurement) reflects the best single measurement, and is competitive with the overall LEP value $A_\mu^{LEP} = 0.145 \pm 0.013$ [5]. A combination of these values, assuming lepton universality, yields the value

$$A_{lepton} = 0.1459 \pm 0.0063 \tag{11}$$

$$\sin^2\theta_W^{\text{eff}} = 0.2317 \pm 0.0008. \tag{12}$$

## V. MEASURING $A_b$

The determination of $A_b$ requires three ingredients: a measurement of the polarization, tag the $b$-quark (i.e., discriminate from *udsc* flavored events) and tag the $b$-quark charge (i.e., was the underlying quark a $b$ or $\bar{b}$?). The SLD has three separate analyses for obtaining these quantities and measuring $A_b$: 1) jet charge, 2) cascade kaon tag and 3) lepton tag. Although $A_b$ can be extracted from Eqn. 4, most of these analyses use a maximum likelihood treatment based on Eqn. 1.

$$L = \big(1+\cos^2\theta\big)(1-A_eP_e) + 2\cos\theta(1-A_eP_e) \times \big[A_bf_b(1-2\bar{\chi})\big(1-\Delta^b_{QCD}\big) + A_bf_b\big(1-\Delta^c_{QCD}\big) + A_{bkg}f_{bkg}\big] \tag{13}$$

Here, $f_q$ is the fraction of tagged events of quark flavor $q$, $(1-2\bar{\chi})$ is a correction factor to account for asymmetry dilution due to $B^0\bar{B}^0$ mixing and $\Delta^q_{QCD}$ is a $\cos\theta$ dependent QCD correction for quark flavor $q$.

**Momentum-Weighted Jet-Charge:** This analysis uses an inclusive vertex mass tag to select a sample of $Z^0 \to b\bar{b}$, and the net momentum-weighted jet-charge to identify the sign of the underlying quark. The track charge sum and difference between the two hemispheres are used to extract the analyzing power from data, thereby reducing MC dependencies and lowering many systematic effects.

**Cascade Kaon:** The decay channel $\bar{B} \to D \to K^-$ is exploited to tag the b charge in this analysis. The gas-radiator data of the Čerenkov Ring imaging Detector (CRID) is used to identify charged kaons with high-impact parameter tracks. The charges of the kaon candidates are summed in each hemisphere and the difference between the two hemisphere charges is used to determine the polarity of the thrust axis for the b-quark direction.

**Leptonic Tag:** Electrons and muons are identified in hadronic decays to enrich the $b\bar{b}$ event samples. The lepton charge provides the quark-antiquark discrimination while the jet nearest in direction to the lepton approximates the quark direction. The lepton total and transverse momentum (with respect to the jet axis) are used to classify each event by deriving probabilities for the decays $b \to l^-$, $\bar{b} \to \bar{c} \to l^-$, $b \to \bar{c} \to l^-$, $\bar{c} \to l^-$ and misidentified electrons.

### A. Preliminary Combined $A_b$

The preliminary results for the three analyses are given in Table II, along with the corresponding statistical and systematic errors. The jet-charge analysis uses the most amount of available data covering 1993-1998 partial data sample of approximately 400,000 $Z^0$ decays (from a total of 550K events available). The lepton tag analysis uses data from 1993-1996, or approximately 200,000 events. Finally, the kaon tag uses the 1993-1995 runs, or approximately 150k events. The SLD average is also given in the table along with the LEP average for comparison.

## VI. SUMMARY OF (PRELIMINARY) SLD RESULTS

Combining $A_{LR}$ and $A_{leptons}$ obtains the preliminary SLD result for the effective weak mixing angle,

$$\sin^2\theta_W^{\text{eff}} = 0.23109 \pm 0.00029. \tag{14}$$

Combining this result with LEP gives the SLD-LEP world average,

$$\sin^2\theta_W^{\text{eff}} = 0.23155 \pm 0.00018. \tag{15}$$

These results are shown in Figure 1. It is interesting to note that the world values for $\sin^2\theta_W^{\text{eff}}$ from lepton measurements (the results presented here, the LEP leptonic averages $A_{FB}^l$ and $A_e$ , and the LEP results of $A_\tau$ from $\tau$-polarization) are in excellent agreement with each other, and differ by $\sim 2.3\sigma$ from those obtained from "hadron-only" measurements ($A_{FB}^b$, $A_{FB}^c$, and $Q_{FB}$).

The combined preliminary SLD result for $A_b$ is,

$$A_b = 0.866 \pm 0.036. \tag{16}$$

These results for $A_b$ and $A_{LR}$ have been transformed and displayed in Figure 2, following the scheme of a full $Z^0b\bar{b}$ coupling analysis proposed by Takeuchi et al. [6] Here, $\zeta_b$ is a variable which isolates deviations in the right-handed $b$-quark neutral current couplings. This is plotted versus $\delta\sin^2\theta_W^{\text{eff}}$. Since LEP's $A_{FB}^b$ is a mixture of $A_b$ and $A_e$, it comes in at 45°. The standard model is the horizontal line below the 68% and 90% CL contours.


[1] The SLAC Linear Collider Design Handbook (1984););
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[2] The SLD Design Report, SLAC Report 273 (1984).
[3] M. Woods, in *Spin-96 Conference Proceedings*, 843 (1997);
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[4] P.L. Reinertsen, SLAC-PUB-8029 (1998);
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[5] LEP Electroweak Working Group.
[6] R. Takeuchi, in *Proc. of the 8th Meeting of DPF*, 1231-1240 (1994).

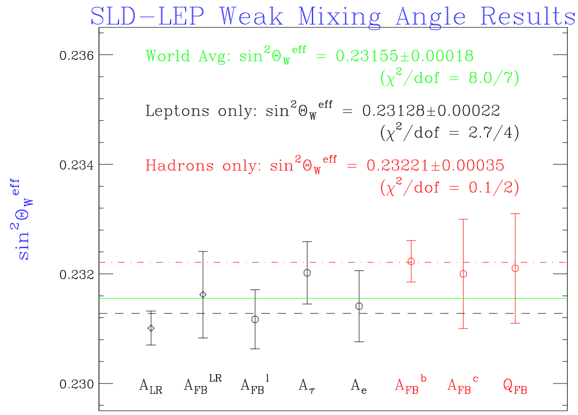


Fig. 1. Status of SLD and LEP $\sin^2\theta_W^{eff}$ measurement. Notice that the leptonic results are consistent with each other and different from the LEP hadronic results.

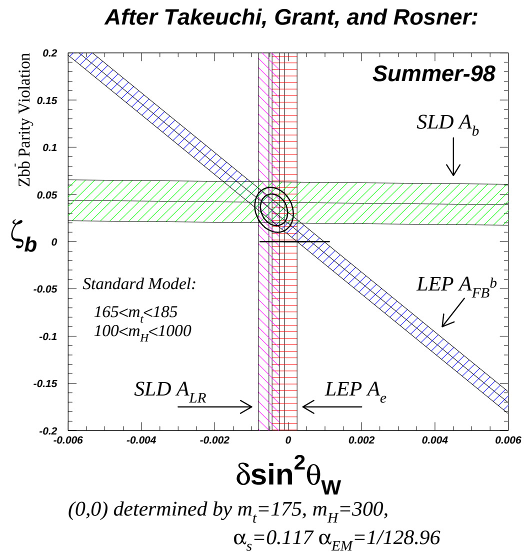


Fig. 2. Transformation of $Z^0 b\bar{b}$ coupling parity violation versus $\sin^2\theta_W^{eff}$.

TABLE I. The six measurements of $A^0_{LR}$ and $\sin^2\theta^{\rm eff}_W$ performed by the SLD experiment. The *'s indicate preliminary results.

| Run | $A^0_{LR}$ | $\delta A^0_{LR}$ | $\sin^2\theta^{\rm eff}_w$ | $\delta\sin^2\theta^{\rm eff}_w$ |
|---|---|---|---|---|
| 1992 | 0.100 | $\pm 0.044 \pm 0.004$ | 0.2378 | $\pm 0.0056 \pm 0.0005$ |
| 1993 | 0.1656 | $\pm 0.0071 \pm 0.0028$ | 0.2292 | $\pm 0.0009 \pm 0.0004$ |
| 1994-95 | 0.1512 | $\pm 0.0042 \pm 0.0011$ | 0.23100 | $\pm 0.00054 \pm 0.00014$ |
| 1996 | $0.1570^*$ | $\pm 0.0057 \pm 0.0011^*$ | $0.23025^*$ | $\pm 0.00073 \pm 0.00014^*$ |
| 1997 | $0.1475^*$ | $\pm 0.0042 \pm 0.0016^*$ | $0.23146^*$ | $\pm 0.00054 \pm 0.00020^*$ |
| 1998 | $0.1487^*$ | $\pm 0.0031 \pm 0.0017^*$ | $0.23130^*$ | $\pm 0.00039 \pm 0.00022^*$ |
| Combined | $0.1510^*$ | $\pm 0.0025^*$ | $0.23101^*$ | $\pm 0.00031^*$ |

TABLE II. Combined results of $A_b$ from the 1993-98 data(partial sample). The SLD results are preliminary and are thru Summer 1998. The LEP results are included for comparison. Note that the LEP measurement are derived from $A_b = 4A^{0,b}_{FB}/(3A_e)$, where $A_e = 0.1491 \pm 0.0018$ (the combined SLD $A_{LR}$ and LEP $A_{lepton}$.

| Analysis | $A_b \pm (stat) \pm (syst)$ | Combined |
|---|---|---|
| SLD Jet-Charge | $0.849 \pm 0.026 \pm 0.031$ | |
| SLD Lepton | $0.932 \pm 0.058 \pm 0.038$ | |
| SLD Kaon | $0.854 \pm 0.088 \pm 0.106$ | |
| SLD Average | | $0.866 \pm 0.036$ |
| ALEPH Lept | $0.908 \pm 0.041 \pm 0.020$ | |
| DELPHI Lept | $0.904 \pm 0.057 \pm 0.026$ | |
| L3 Lept | $0.869 \pm 0.055 \pm 0.030$ | |
| OPAL Lept | $0.851 \pm 0.038 \pm 0.020$ | |
| ALEPH Jet-Charge | $0.953 \pm 0.037 \pm 0.029$ | |
| DELPHI Jet-Charge | $0.898 \pm 0.042 \pm 0.021$ | |
| L3 Jet-Charge | $0.806 \pm 0.106 \pm 0.051$ | |
| OPAL Jet-Charge | $0.898 \pm 0.047 \pm 0.037$ | |
| LEP Average | | $0.885 \pm 0.022$ |
| Standard Model | | 0.935 |