The final SLD results for A_{LR} and A_{lepton}[*]

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Representing the SLD Collaboration

Abstract

We present the final measurements of the left-right cross-section asymmetry A_{LR} for Z boson production by e^+e^- collisions and Z boson-lepton coupling asymmetry parameters A_e, A_μ, and A_τ in leptonic Z decays with the SLD detector at the SLAC Linear Collider. Using the complete sample of polarized Z bosons collected at SLD, we get $A_{LR} = 0.15056 \pm 0.00239$, $A_e = 0.1544 \pm 0.0060$, $A_\mu = 0.142 \pm 0.015$, and $A_\tau = 0.136 \pm 0.015$. The $A_{LR}(\equiv A_e)$ and A_e results are combined and we find $A_e = 0.1516 \pm 0.0021$. Assuming lepton universality, we obtain a combined effective weak mixing angle of $\sin^2 \theta_W^{eff} = 0.23098 \pm 0.00026$. Within the context of the SM, our result prefers a light Higgs mass.

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1   Introduction

The SLD collaboration has reported a series of A_{LR} measurements [1] and A_e, A_μ, and A_τ measurements [2] in the production and decay of Z bosons by e^+e^- collisions. A_{LR} is the single best measurement of the effective weak mixing angle ($\sin^2\theta_W^{eff}$) and has remarkably small systematic error. The measurements of A_e, A_μ, and A_τ improve precision for the effective weak mixing angle measurement. These measurements also provide a test of lepton universality and SLD makes the only direct measurement of A_μ. In the context of the Standard Model (SM), these measurements provide the best sensitivity to the Higgs mass and favor a light Higgs. In this letter, we will present the final results of these measurements at SLD.

2   Asymmetry measurements at SLD

Polarization-dependent differential cross section for $e_{L,R}^- + e^+ \to Z^0 \to f\bar{f}$ is expressed as follows

$$\frac{d\sigma}{dx} \propto (1 - P_e A_e)(1 + x^2) + 2A_f(A_e - P_e)x$$

where $x = \cos\theta$ is the direction of the outgoing fermion with respect to the electron beam direction. The signed longitudinal polarization of the electron beam is shown as P_e with the convention that left-handed bunches have negative sign. The asymmetry parameter is defined as

$$A_f = 2v_f a_f / (v_f^2 + a_f^2)$$

where v_f and a_f are the effective vector and axial-vector couplings of the Z boson to the fermion (flavor "f") current, respectively. The SM assumes lepton universality and lepton asymmetry parameters are directly related to the effective weak mixing angle

$$A_l \equiv \frac{2\left[1 - 4\sin^2\theta_W^{eff}\right]}{1 + \left[1 - 4\sin^2\theta_W^{eff}\right]^2}.$$

The polarized electron beam at SLD allows for measurements of the lepton asymmetry parameters with two different techniques. One is a left-right asymmetry. The left-right asymmetry is the cross-section asymmetry for the production of Z-bosons by left-handed and right-handed electron beams. This is sensitive to the initial state coupling ($e^+e^- \to Z$). The other is a polarized forward-backward asymmetry. This asymmetry is a double asymmetry which is formed by taking the difference in the number of forward and backward events for left-handed and right-handed beam polarization. This is sensitive to the final state coupling ($Z \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$).

From hadronic final states, we measure A_e using the left-right asymmetry, which is known as the A_{LR} measurement. Leptonic final states provide A_e from the left-right asymmetry and A_e, A_μ, and A_τ from the polarized forward-backward asymmetry. We compare these asymmetry measurements to test lepton universality. Assuming universality, we combine A_{LR} with A_e, A_μ, and A_τ to derive our grand average effective weak mixing angle.

SLD has collected polarized Z data from 1992 to 1998. We collected about 530K polarized Z events with about 75% electron beam polarization.

3 The A_{LR} measurement

The event selection for the A_{LR} measurement requires a hadronic signature and discriminates against beam background, two photon, and e^+e^- final states events. The selection efficiency is about 91% for hadronic final states. There is a small amount of $\tau^+\tau^-$ final state (0.3%) which is not background. The background fraction is only 0.04%. Using selected events, we extract the measured cross-section asymmetry A_m as follows

$$A_m = \frac{N_L - N_R}{N_L + N_R}$$

where N_L (N_R) is a number of selected events for left-handed (right-handed) electron beam. We need two more steps to evaluate the result. First, we correct background and small machine/beam related asymmetries, which are small, and divide by the measured polarization as follows,

$$A_{LR} = \frac{A_m}{P_e} + \frac{1}{P_e}\delta A_m = \frac{A_m}{P_e} + O(10^{-4}).$$

Next, A_{LR} is converted to the Z-pole result by applying γZ interference and initial state radiation corrections

$$A_{LR}^0 = A_{LR} + \delta A_{EW}.$$

This calculation requires knowledge of our luminosity weighted mean center-of-mass energy. The relative size of the correction is about 2%.

The electron polarization plays an important role in the measurement. There are three detectors to measure the electron polarization. Our primary polarimeter is the Cherenov detector (CKV), which detects Compton-scattered electrons. Polarized Gamma Counter (PGC) and Quartz Fiber Calorimeter (QFC) are used to assist in the calibration of CKV and detect Compton-scattered photons. Fig. 1 shows a comparison of measured polarizations with these detectors. The mea-
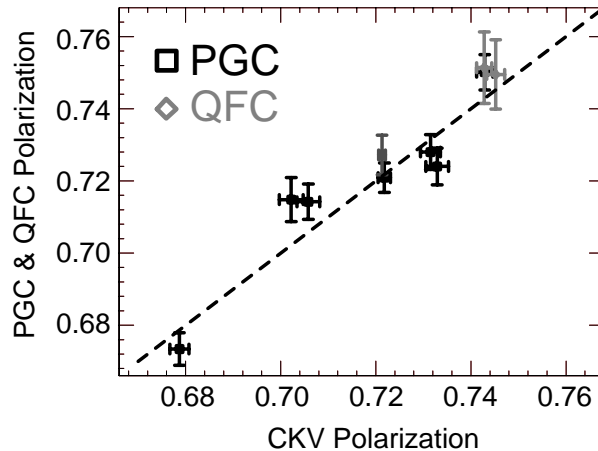

Figure 1: Comparison of PGC and QFC polarizations measurements to the one from the primary polarimeter CKV.

surements of electron polarization by these detectors are consistent and the systematic error from

the calibration uncertainty is 0.40%. The obtained total systematic uncertainty from polarization measurement is 0.50%, which is the biggest systematic error source for the A_{LR} measurement.

We performed two additional systematic error checks in the 1997-98 run, of the energy scale and positron polarization. For precise understanding of the average center-of-mass energy, we did a Z-pole scan. We measured two off-peak data points and obtained the average center-of-mass energy of $\sqrt{s} = 91.237 \pm 0.029$ GeV. The uncertainty of the center-of-mass energy leads to systematic error of 0.39% on A_{LR}^0 due to energy dependence of the γZ interference and initial state radiation corrections. This is the second biggest systematic error source of the A_{LR} measurement. In the past, we had assumed positron polarization is zero. We now have directly measured the positron polarization with a Møller polarimeter in End Station A and obtained a result of (-0.02 ± 0.07)% which is consistent with zero.

The final result of the A_{LR} measurement is

$$
\begin{aligned}
A_{LR}^0 &= 0.15138 \pm 0.00216, \\
\sin^2 \theta_W^{eff} &= 0.23097 \pm 0.00027.
\end{aligned}
$$

The systematic error in the effective weak mixing angle measurement is about 0.0001. Our error is still dominated by the statistical error.

4 $A_e, A_\mu,$ and A_τ measurements

Leptonic Z decay candidates are required to have low charged multiplicity and two back-to-back leptons (or in the case of the tau-pair events, the tau decay products). The selection efficiencies for each lepton species are $70 \sim 75\%$ and their purities are about 99% except tau (about 95%). Fig. 2 shows angular distributions of selected leptonic final states for left- and right-handed electrons (Selection efficiency is corrected in the figure).

Using these events, A_e and A_μ or A_τ are simultaneously determined from an unbinned maximum liklihood functions include Z, γZ, and γ cross-section terms, and initial state radiation effects. We find the results for $A_e, A_\mu,$ and A_τ from leptonic Z decay events are

$$
\begin{aligned}
A_e &= 0.1544 \pm 0.0060 \quad, \\
A_\mu &= 0.142 \pm 0.015 \quad, \text{and} \\
A_\tau &= 0.136 \pm 0.015.
\end{aligned}
$$

5 The SLD grand average result

The A_{LR} measurement measures the initial state coupling ($A_{LR}^0 \equiv A_e$). Hence we combine the A_{LR}^0 result and A_e from purely leptonic final states taking care of small effects due to correlations in systematic uncertainties, and obtain

$$
A_{LR}^0 + A_e = 0.1516 \pm 0.0021.
$$

Our results are consistent with lepton universality. Therefore we can assume universality and the obtained our grand average result of the lepton asymmetry parameter and the effective weak mixing
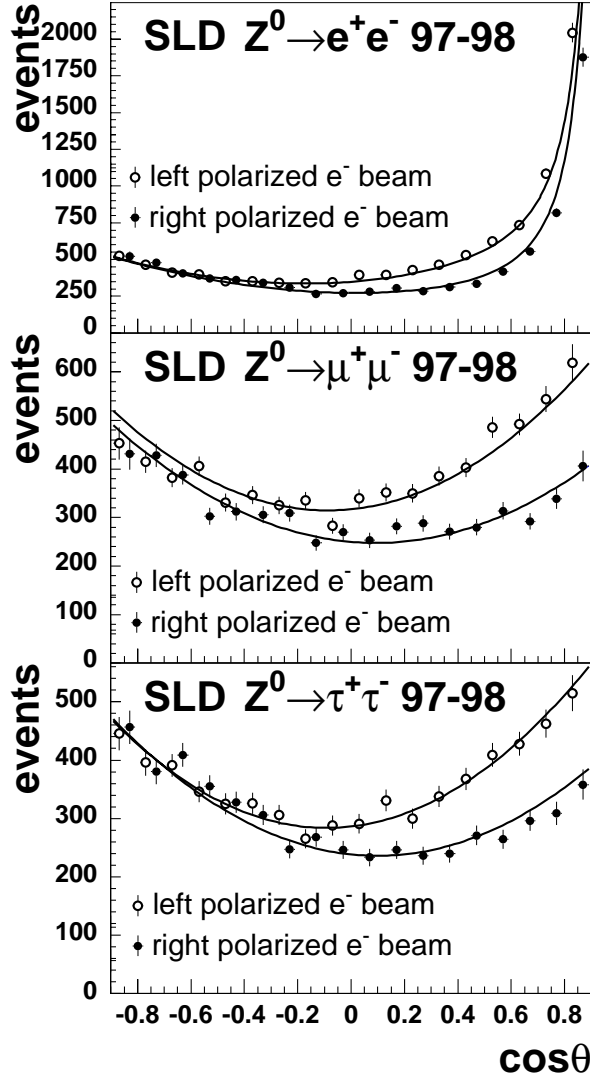
Figure 2: Polar-angle distributions for Z decays to e, μ, and τ pairs.

angle are

$$
\begin{aligned}
A_l &= 0.15130 \pm 0.00207, \\
\sin^2\theta_W^{eff} &= 0.23098 \pm 0.00026.
\end{aligned}
$$

6 World effective weak mixing angle measurements

Now we compare our result with other measurements [3]. Fig. 3 shows the world effective weak mixing angle measurements. The world average value is $\sin^2\theta_W^{eff} = 0.23147 \pm 0.00017$. Results with leptonic asymmetry are consistent each other ($\chi^2/NDF = 2.6/4$) and the average value is $\sin^2\theta_W^{eff} = 0.23113 \pm 0.00020$. Results with hadronic technique ($\sin^2\theta_W^{eff} = 0.23231 \pm 0.00031$) are self-consistent ($\chi^2/NDF = 0.2/2$). However there is 3$\sigma$ difference between leptons only and
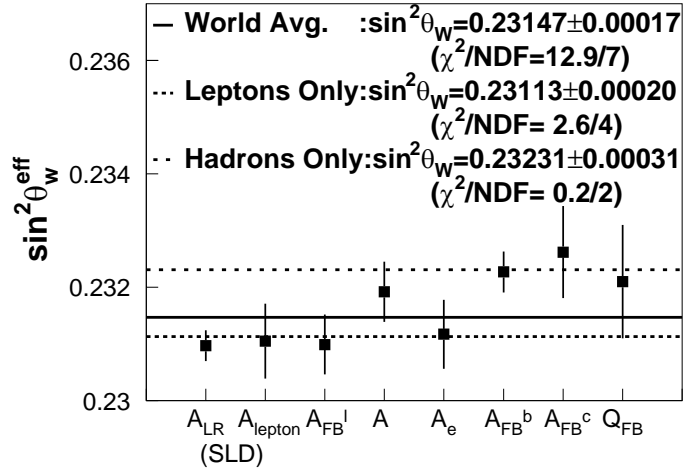
Figure 3: The world effective weak mixing angle measurements.

hadrons only results.

Since the effective weak mixing angle is very sensitive to the Higgs mass, it is interesting to derive the allowed Higgs mass region. We use the measured Z boson [3] and top quark [4] masses, a determination of $\alpha(M_Z^2)$ [5], and the ZFITTER 6.23 program [6] to obtain the results. Fig. 4 shows the allowed Higgs mass regions given by the individual measurements. The SLD result prefers a light Higgs mass [7]. On the other hand, the result by the hadron technique expects a heavy Higgs mass. There are several measurements sensitive to the Higgs mass, W mass (m_W) and Z width (Γ_Z) measurements. The allowed Higgs mass regions by the measurements are also shown in Fig. 4. The most sensitive measurement to Higgs mass is given by the effective weak mixing
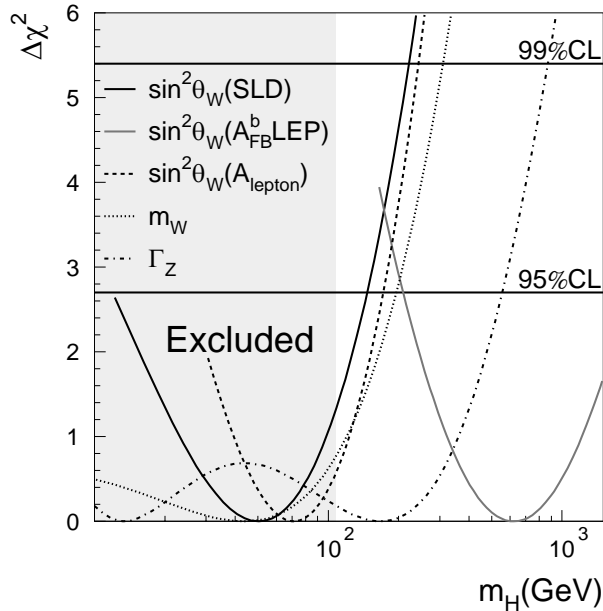

Figure 4: Higgs mass plot by technique.

angle by the lepton technique. The curve given by W mass measurement and the result is in good agreement with the one by the lepton technique. These results prefer a light Higgs mass.

7 Conclusions

The SLD collaboration has finalized its very precise measurement of the weak mixing angle and the result is $\sin^2\theta_W^{eff} = 0.23098 \pm 0.00026$. The SLD error is equivalent to an W mass measurement uncertainty of 38MeV assuming the SM, which is equal to the error of global direct m_W measurements from FERMILAB and LEP II. The SLD/LEP lepton asymmetry measurements are self-consistent. In the context of the SM, our data prefers a light Higgs mass.

References

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[7] There is a nice summary about the effective weak mixing angle measurement and Higgs mass issue. See http://www-sldnt.slac.stanford.edu/alr/ .