Electroweak Precision Measurements with Leptons

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Abstract
The precision measurements of lepton electroweak parameters at SLD and LEP are reviewed and discussed. The updated SLD weak mixing angle measurement from A_{LR} and the lepton left-right forward-backward asymmetries is $\sin^2\theta_W^{eff} = 0.23099 \pm 0.00026$, and the combined SLD/LEP lepton-based value is 0.23119 ± 0.00020. This value differs by over 3σ from the comparable quark-based value.

1. Introduction

The 90's era of precision electroweak measurements at the Z has come to an end with the last run of SLD. SLD has completed the analysis of all of its data. The left-right asymmetry measurement, the SLD left-right forward-backward asymmetry for leptons, and the LEP tau polarization measurements have all recently been updated. Here we summarize these recent results.

2. SLD Left-right Asymmetry

The SLD left-right asymmetry measurement is unique among all electroweak precision measurements in that no efficiency or acceptance corrections are needed. Furthermore, the final state identification is relatively unsophisticated. These features allow a careful measurement with a small systematic error (now $\sim 0.65\%$), much smaller than the statistical error ($\sim 1.3\%$).

The polarized differential cross section at the Z pole is given by :

$$\frac{d\sigma}{dcos\theta} \sim (1-\mathcal{P}_e A_e)(1+\cos^2\theta) + 2A_f(A_e - \mathcal{P}_e)cos\theta,$$

where the parity violating asymmetries in terms of the vector and axial vector NC couplings for fermion flavor f are $A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}$. The polarized e^- beam at the SLC allows for the isolation of the initial state (A_e) and final state (A_f) asymmetries. The initial state couplings are determined most precisely via the left-right Z production asymmetry

$$A_{LR}^0 = \frac{1}{\mathcal{P}_e}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e.$$

Table 1. Summary of SLD Runs

	'92	'93	'94-5	'96	'97-8
Total Z^0's	10k	50k	100k	50k	350k
<Pol>	22%	63%	78%	78%	73%

The precision of the SLD left-right asymmetry measurement has improved substantial during the 90's as an increasing luminosity has reduced the statistical error, and improved controls and understanding of the experiment has led to smaller systematic errors. The unique precision of the left-right asymmetry demands extensive cross-checks to confirm the measurement, and three of the significant recent checks have been the secondary, independent measurements of the electron polarization, the verification of the center-of-mass collision energy, and the measurement of the positron polarization (confirming its non-existence).

Table 1 presents the history of SLD luminosity and polarization. The experiment was capped with its most productive run in 1997-98, when approximately 350 thousand Z bosons were detected. The peak luminosities achieved were about $3 \times 10^{30} cm^{-2}s^{-1}$.

2.1. Evolution of SLD systematic errors

Table 2 presents the evolution of the SLD systematic errors. The final achieved systematic error of 0.65% represents several years of instrumental work and cross-checks, supplemented by extensive accelerator based tests. This effort has established a high degree of confidence in the measurement of the left-right asymmetry. Three of the recent checks are described below.

2.2. Recent SLD checks

Electron polarization. Two additional independent measurements have been made to confirm the electron polarization measurement. The primary polarimeter for SLD is the Cerenkov detector which detects the Compton scattered electrons in a Compton scattering polarimeter system just downstream of the e^+e^- interaction point. It measures the asymmetry in the Compton cross section at the kinematic edge, with a 70% analyzing power.

Now, two additional detectors measure the Compton scattered gammas. The Polarized Gamma Counter (PGC) consists of a Cerenkov detector behind a variable thickness of lead radiator. It has an analyzing power of 16 to 22 %, depending on the amount of lead. The Quartz Fiber Calorimeter (QFC) absorbs the Compton gammas, with an analyzing power of 18%. These polarimeters have confirmed the Cerenkov measurements.

Center-of-mass collision energy. A scan of the Z^0 resonance confirms the SLC beam energy measurements. Two off energy points were taken and the center of mass energy was found to be off the true Z peak by $-46 \pm 25 MeV$.

Positron Polarization. A measurement of the positron polarization was made with the End Station A fixed target polarimeter. The result was $P_{e^+} = -0.02\% \pm 0.07\%$, consistent with zero.

2.3. The final SLD result on A_{LR}

Table 3 shows the time history of the SLD results for A^0_{LR}. The measurement has a consistent history, with improving precision, to the current value of

$$A^0_{LR} = 0.15108 \pm 0.00218$$

which translates into a value for $\sin^2\theta_W^{eff}$ of

$$\sin^2\theta_W^{eff} = 0.23101 \pm 0.00028$$

3. SLD Left-right Forward-backward Asymmetry for electron, muons, and taus

SLD has updated its left-right forward-backward asymmetry measurement for the leptons. This measures the final state coupling of the Z to leptons. The asymmetry is defined as

Table 3. History of the SLD measurement of A_{LR}

Year	A^0_{LR}
1992	$0.100 \pm 0.044 \pm 0.004$
1993	$0.1656 \pm 0.0071 \pm 0.0028$
1995	$0.1512 \pm 0.0042 \pm 0.0011$
1996	$0.1570 \pm 0.0057 \pm 0.0011$
1997-98	$0.1490 \pm 0.0024 \pm 0.0010$

$$\tilde{A}^f_{FB} = \frac{(N_{LF} - N_{LB}) - (N_{RF} - N_{RB})}{(N_{LF} + N_{LB}) + (N_{RF} + N_{RB})} = \frac{3}{4}\mathcal{P}_e A_f,$$

for final state lepton flavor $f = e, \mu, \tau$

Each lepton asymmetry, A_f is determined by fitting the angular distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}cos\theta} \sim (1-P_eA_e)(1+cos^2\theta)+2A_{\mu,\tau}(A_e-P_e)cos\theta,$$

as shown in Figure 1.

The combined preliminary results for the 1993-98 data are consistent with lepton universality:

$$\left.\begin{array}{r} A_e = 0.1558 \pm 0.0064 \\ A_\mu = 0.137 \pm 0.016 \\ A_\tau = 0.142 \pm 0.016 \end{array}\right\} A_{e\mu\tau} = 0.1523 \pm 0.0057$$

$$\sin^2\theta_W^{eff} = 0.23085 \pm 0.00073$$

There is analysis remaining to be done on this data. Presently the angular coverage is $|\cos\theta| < 0.8$, but will be extended to $|\cos\theta| < 0.9$. With this coverage, and with improved efficiencies, the error on $\sin^2\theta_W^{eff}$ is expected to reach ± 0.0006.

When SLD combines this left-right forward-backward asymmetry result with the A_{LR} result above, the SLD measurement for the electroweak mixing angle for leptons is:

$$\sin^2\theta_W^{eff} = 0.23099 \pm 0.00026$$

4. τ Polarization from LEP

There is a new measurement of τ polarization presented by DELPHI at this meeting. The τ polarization measurements from LEP now are as presented in Table 4.

Table 2. Evolution of the SLD systematic errors

	1992	1993	1995	Now
Polarimetry	2.7%	1.7%	0.67%	0.5%
E_{cm}	$\lesssim$0.3%	$\lesssim$0.3%	0.3%	0.4%
Background (frac.)	1.4%	0.25%	0.11%	0.044%
SLC asymmetry (10^{-4})	1.8 ± 4.2	0.4 ± 0.5	-1.9 ± 0.3	-1.3 ± 0.7
Total fractional error	3.6%	1.7%	0.75%	0.65%

Table 4. τ polarization results

	A_τ	A_e
ALEPH	$.1452 \pm .0061$	$.1505 \pm .0069$
DELPHI	$.1359 \pm .0096$	$.1382 \pm .0116$
L3	$.1476 \pm .0108$	$.1678 \pm .0130$
OPAL	$.1340 \pm .0134$	$.1290 \pm .0149$

5. Consistency of Electroweak Lepton Measurements

The combined SLD measurement of $\sin^2\theta_W^{eff}$ from leptons is 0.23099±0.00026. The LEP measurement of lepton forward-backward asymmetries, and tau polarization have been combined into a LEP lepton-based $\sin^2\theta_W^{eff}$ measurement of 0.23151 ± 0.00033. Combining these two purely lepton measurements yields:

$$\sin^2\theta_W(world - leptons) = 0.23119 \pm 0.00020.$$

These results are fully consistent.

When the quark-based measurements are compared to these lepton-based results (see Figure 2), some indication of inconsistency is suggested. The hadrons only measurement of $\sin^2\theta_W^{eff}$ is 0.23236 ± 0.00031, more than 3σ from the lepton-based measurement

6. Conclusion

SLD has completed the analysis of the data from its final run. The SLD and LEP measurements of lepton couplings to the Z are fully consistent, while a significant difference from the quark sector has been observed.

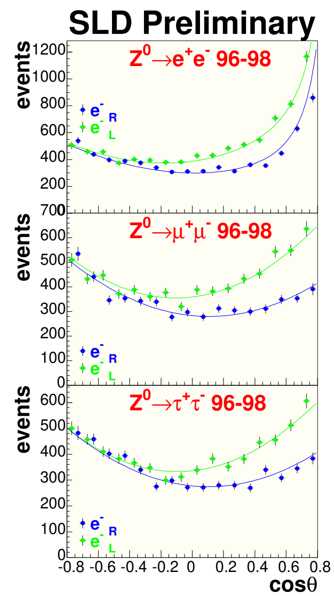

Figure 1. SLD di-lepton angular distributions.

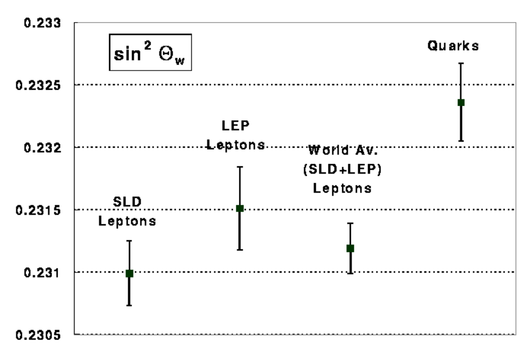

Figure 2. Comparison of the lepton- and quark-based measurements of the electroweak mixing angle