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Measurements of A_{LR} and A_{lepton} from SLD

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Abstract

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1 Introduction

The first-of-its-kind SLC linear electron positron collider [1] has proven to be a powerful facility for tests of the Standard Model via the measurement of Electroweak couplings at the Z^0 pole. Its highly longitudinally-polarized electron beam ($P_e \sim 75\%$) and small luminous region of $(1.5 \times 0.8 \times 700)$ μm in (x,y,z) are particularly advantageous for the measurement of electroweak quantities. The SLD detector, described in more detail elsewhere [2] is tailored to take maximum advantage of these attributes of the SLC.

1.1 Asymmetries

At Born level, for an electron beam polarization P_e, the differential cross section for the process
$e^+e^- \to Z^0 \to f\overline{f}$ is given by

$$\begin{aligned}\sigma^f(z) \propto\ & [(v_e^2 + a_e^2 - 2a_e v_e P_e)(v_f^2 + a_f^2)](1+z^2) \\ & + [2a_e v_e - (v_e^2 + a_e^2)P_e]4v_f a_f z \end{aligned} \quad (1)$$

where $z = \cos\theta$ is the angle of the final state fermion with respect to the beam axis, and $\sigma^f(z) = d\sigma_f/dz$. Here, it is assumed that $P_e = +1$ for a right-handed (positive helicity) electron beam. Thus, the vector (v) and axial-vector (a) couplings are the free parameters which specify the $Z - f$ coupling. In the Standard Model,

$$v = I_3^{Weak} - 2Q\sin^2\theta_W \quad (2)$$

$$a = I_3^{Weak}. \quad (3)$$

With the use of a *polarized* electron beam, these coupling parameters can be extracted independently of the initial state couplings v_e and a_e, via the two following observables. The first of these, the ratio of partial widths

$$R_q \equiv \frac{\int_{-1}^{1}\sigma_q(z)dz}{\sum\limits_{q'}\int_{-1}^{1}\sigma_{q'}(z)dz} = \frac{v_q^2 + a_q^2}{\sum\limits_{q'}(v_{q'}^2 + a_{q'}^2)} = \frac{\Gamma_q}{\Gamma_{had}}, \quad (4)$$

does not require the use of polarized beams; the restriction of the denominator to quark species only (no leptons) leads to the cancellation of QCD radiative effects. The second of these, the polarized forward-backward asymmetry, does require the use of polarized beams:

$$\begin{aligned}\tilde{A}^f_{FB}(z) &= \frac{[\sigma_L^f(z) - \sigma_L^f(-z)] - [\sigma_R^f(z) - \sigma_R^f(-z)]}{\sigma_L^f(z) + \sigma_L^f(-z) + \sigma_R^f(z) + \sigma_R^f(-z)} \\ &= |P_e| A_f \frac{2z}{1+z^2}, \end{aligned} \quad (5)$$

where the subscript L (R) refers to left-handed (right-handed) electron beam, and

$$A_f \equiv \frac{2v_f a_f}{v_f^2 + a_f^2} \quad (6)$$

is the quantitative extent of parity violation in the $Z^0 f\bar{f}$ coupling. These two measurements specify the $Z^0 f\bar{f}$ coupling in generality.

Finally, one can define the left-right asymmetry

$$\begin{aligned}A_{LR} &= \frac{1}{P_e}\frac{\sum\limits_{f\neq e}\int_{-1}^{1}\sigma_L^f(z)dz - \sum\limits_{f\neq e}\int_{-1}^{1}\sigma_R^f(z)dz}{\sum\limits_{f\neq e}\int_{-1}^{1}\sigma_L^f(z)dz + \sum\limits_{f\neq e}\int_{-1}^{1}\sigma_R^f(z)dz} \\ &= \frac{1}{P_e}[P_e\frac{2v_e a_e}{v_e^2 + a_e^2}] = A_e \end{aligned} \quad (7)$$

where the sum is restricted to all final states except e^+e^- in order to avoid having to unravel t-channel effects. This is a particularly potent way to measure $\sin^2\theta_W$ provided P_e can be measured precisely:

$$A_{LR} = \frac{2(1 - 4\sin^2\theta_W)}{1 + (1 - 4\sin^2\theta_W)^2} \quad (8)$$

making A_{LR} very sensitive to the weak mixing angle:

$$\frac{dA_{LR}}{d\sin^2\theta_W} \simeq -7.8. \quad (9)$$

It should be pointed out that these relations have been derived for the case of the Born-level interaction. However, since the Z^0-pole measurements now provide the most accurate constraints on Standard Model consistency, the convention that has arisen is to incorporate higher order effects by making Eqn. 8 the *definition* of the weak mixing angle. This is denoted by the notation $\sin^2\theta_W^{eff}$; higher order effects must then be explicitly accounted for when comparing this value with that of non-Z^0-pole measurements.

In this paper, we discuss the most recent measurements of A_{LR} and $A_{e-\mu-\tau}$ (or A_{lepton}) performed by the SLD Collaboration. Both analyses utilize the approximately 350K Z^0 decays which were obtained in the 1997-98 physics run, and combine these new results with those from the earlier dataset of approximately 200K Z^0 decays (see Fig. 1). After first discussing polarimetry, which is crucial for both analyses, we discuss the measurement of A_{LR} and the corrections need to express it in terms of the Z^0-pole asymmetry shown in Eqn. 8. We then present measurements of A_{lepton} using final-state leptons. We conclude by combining our results for $\sin^2\theta_W^{eff}$, and comparing our results with leptonic and hadronic measurements from LEP.

2 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 analyzed by the first beam-line dipole downstream of the SLD interaction point (the "Analyzing Bend Magnet" shown in Fig. 2), beyond which they exit the beam-line vacuum through a thin window, and enter a threshold Cerenkov detector segmented transverse to the beam-line.

The laser beam polarization, typically 99.9%, is continuously monitored. The average polarization of each bunch is measured, but the relevant quantity for analysis is the luminosity-weighted polarization at the IP. This leads to a very small correction ($< 0.1\%$), whose uncertainty is shown in in Table 1. Also shown is this table is the luminosity-weighted average polarization for each run, as well as the relative systematic uncertainties in the Compton polarization measurement. In 1996 a relative polarization scale uncertainty of $\pm 0.64\%$ was obtained; the preliminary 1997/98 values of $\pm 1.03\%$ will improve substantially once the analysis is complete.

In addition to the Compton Polarimeter, two additional detectors are in place to measure the electron beam polarization by examining the Compton backscattered photons. These two devices [4], the Polarized Gamma Counter (PGC) and the Quartz Fiber Calorimeter (QFC), both require dedicated electron-only conditions due to beamstrahlung backgrounds. Both devices provide sub-1% cross-checks of the Compton polarimeter.

3 The Measurement of A_{LR}

In practice, A_{LR} is measured with hadronic final states only, as the selection efficiency for $\tau^+\tau^-$ and $\mu^+\mu^-$ pairs is very low (the leptonic final states are considered separately). 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 3 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

$$A_{LR}^{meas} = \frac{1}{P_e}\frac{N_L - N_R}{N_L + N_R} \tag{10}$$
$$= 0.1450 \pm 0.0030 \pm 0.0015 \tag{11}$$

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_{LR}^0 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 that 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

$$A_{LR}^0 = 0.1487 \pm 0.0031 \pm 0.0017 \tag{12}$$
$$\sin^2\theta_W^{eff} = 0.23130 \pm 0.00039 \pm 0.00022. \tag{13}$$

As an additional crosscheck, in 1998 a dedicated experiment was performed in order to directly test the expectation that any accidental polarization of the positron beam is negligible. The Moller Polarimeter [5] in SLAC End Station A was used to analyse the bhabha process for the e^+ beam; the (preliminary) results of this measurement indicated that the e^+ polarization was consistent with zero: $P_{e^+} = -0.02 \pm 0.07\%$.

The six measurements A_{LR}^0 performed by SLD are shown in Table 2, along with their translations to $\sin^2\theta_W$. In Figure 3 the six $\sin^2\theta_W$ results are plotted as a function of measurement year; clearly the measurement fluctuations are statistical in nature. The (preliminary) averaged results for 1992-98 are

$$A_{LR}^0 = 0.1510 \pm 0.0025 \tag{14}$$
$$\sin^2\theta_W^{eff} = 0.23101 \pm 0.00031 \tag{15}$$

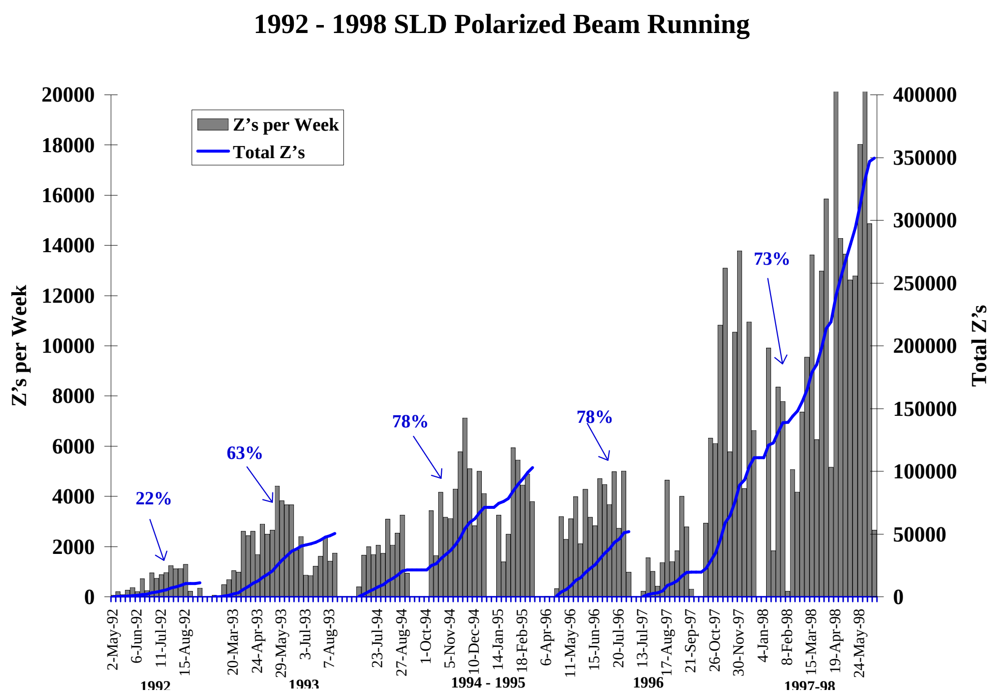

Figure 1: Luminosity history of the SLD experiment, along with average beam polarizations for each run.

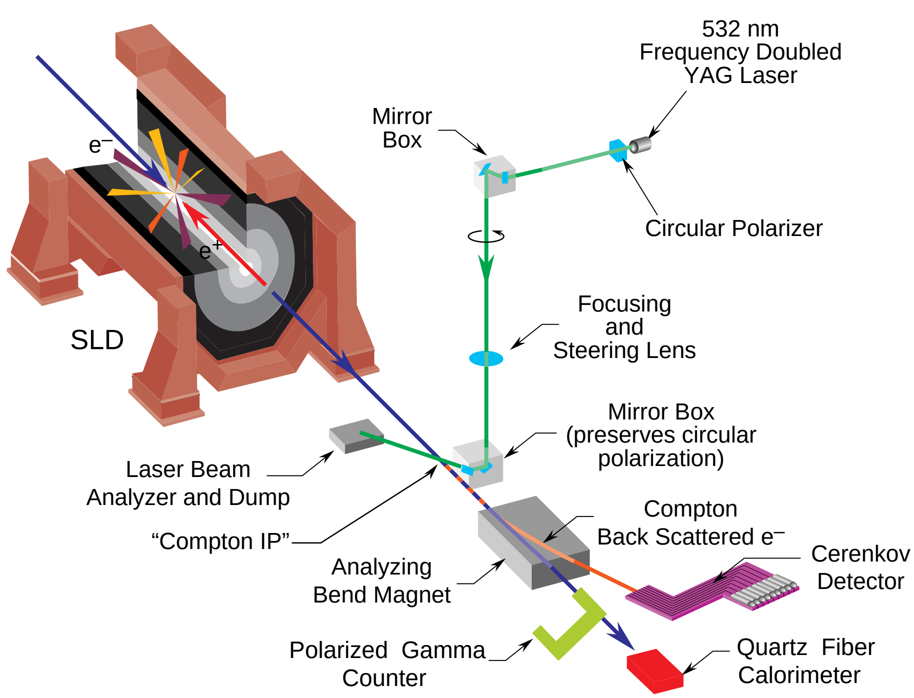

Figure 2: A view of the SLD Polarimeters used to determine electron-beam polarization. The two new devices, the Polarized Gamma Counter and the Quartz Fiber Calorimeter, examine the Compton backscattered photons.

Table 1: The year-by-year luminosity-weighted average polarization for each run (with statistical error), along with the systematic uncertainty on the electron beam polarization scale, as measured by the Compton Polarimeter. The 1996-98 results are preliminary, and the systematic uncertainties are expected to be reduced after the full analysis is completed.

Ave. Polarization	1992 0.224 ± 0.006	1993 0.626 ± 0.012	1994/5 0.772 ± 0.005	1996* 0.765 ± 0.005	1997* 0.733 ± 0.008	1998* 0.731 ± 0.008
Sys. Uncertainties						
Laser Polarization	2.0	1.0	0.20	0.20	0.20	0.10
Detector Linearity	1.5	1.0	0.50	0.50	0.50	0.50
Detector Calibration	0.4	0.5	0.29	0.30	0.30	0.30
Electronic Noise	0.4	0.2	0.20	0.20	0.20	0.20
Interchannel Consist.	0.9	0.5	—	—	0.80	0.80
Sum of Pol. Unc.	2.7	1.6	0.64	0.64	1.03	1.01
Compton/SLD IP	—	1.1	0.17	0.18	0.07	0.08
Total P_e Unc.	**2.7%**	**1.9%**	**0.67%**	**0.67%**	**1.03%**	**1.01%**

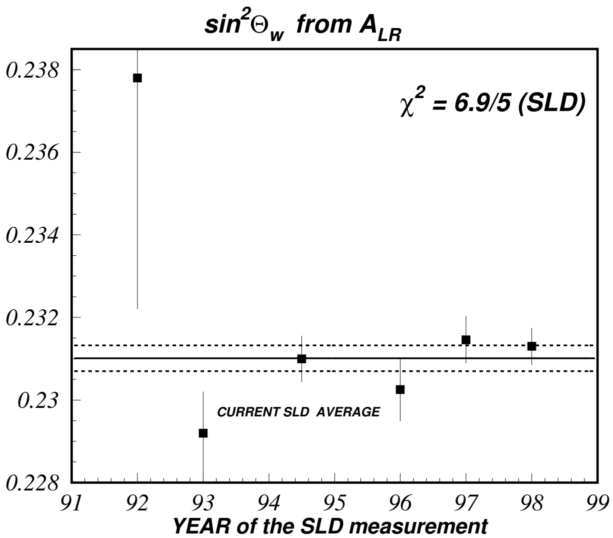

Figure 3: The six measurements of A_{LR}^0 performed by the SLD experiment. Here, the results have been translated into $\sin^2\theta_W^{eff}$ using Eqn. 8 in the text.

4 The Measurements of A_e, A_μ,A_τ using final-state leptons

Parity violation in the Z^0-lepton couplings is measured by fits 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 τ 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) $|\cos\theta| = 0.7$. The resulting efficiencies and purities are shown in Table 4.

An example of the resulting polar angle distributions for the 1996-98 dataset is shown in Fig. 4. The results of fits to the angular distributions, after correcting for the small background contamination, are summarized in Table 4. 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 final-state lepton couplings are constrained by the angular distributions.

A summary of the (preliminary) combined results for the 1993-98 datasets is shown in Table 5. The SLD result for A_μ reflects the best single measurement, and is competitive with the overall LEP value $A_\mu^{LEP} = 0.145 \pm$

Table 2: The six measurements of A^0_{LR} and $\sin^2\theta^{eff}_W$ performed by the SLD experiment.

Run	A^0_{LR}	δA^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* (preliminary)	0.1570	$\pm 0.0057 \pm 0.0011$	0.23025	$\pm 0.00073 \pm 0.00014$
1997* (preliminary)	0.1475	$\pm 0.0042 \pm 0.0016$	0.23146	$\pm 0.00054 \pm 0.00020$
1998* (preliminary)	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 3: The lepton sample statistics for the 1996-98 dataset.

Channel	Sample Size	Efficiency ($\lvert\cos\theta\rvert < 0.8$)	Purity	Dominant Background(s)
e^+e^-	9419	87.3%	98.6%	$\tau^+\tau^-$ (1.2%)
$\mu^+\mu^-$	7564	85.5%	99.8%	$\tau^+\tau^-$ (0.2%)
$\tau^+\tau^-$	7088	78.1%	94.6%	$\mu^+\mu^-$ (2.0%), 2γ (1.7%)

Table 4: Results of the lepton asymmetry analysis for 1996-98 data

Channel	A_{lepton}
$\mu^+\mu^-$	A_μ=0.128 ± 0.022
$\tau^+\tau^-$	A_τ=0.117 ± 0.023
e^+e^-,$\mu^+\mu^-$,$\tau^+\tau^-$	A_e=0.1497 ± 0.0088

Table 5: Combined results of the lepton asymmetry analysis for 1993-98 data

Channel	A_{lepton}	$\sin^2\theta^{eff}_W$
e^+e^-	A_e=0.1504 ± 0.0072	
$\mu^+\mu^-$	A_μ=0.120 ± 0.019	
$\tau^+\tau^-$	A_τ=0.142 ± 0.019	
	$A_{e\mu\tau}$=0.1459 ± 0.0063	0.2315 ± 0.008

0.013[6]. A combination of the values in Table 5, assuming lepton universality, yields the value

$$A_{lepton} = 0.1459 \pm 0.0063 \quad (16)$$

$$\sin^2\theta_W^{eff} = 0.2317 \pm 0.0008. \quad (17)$$

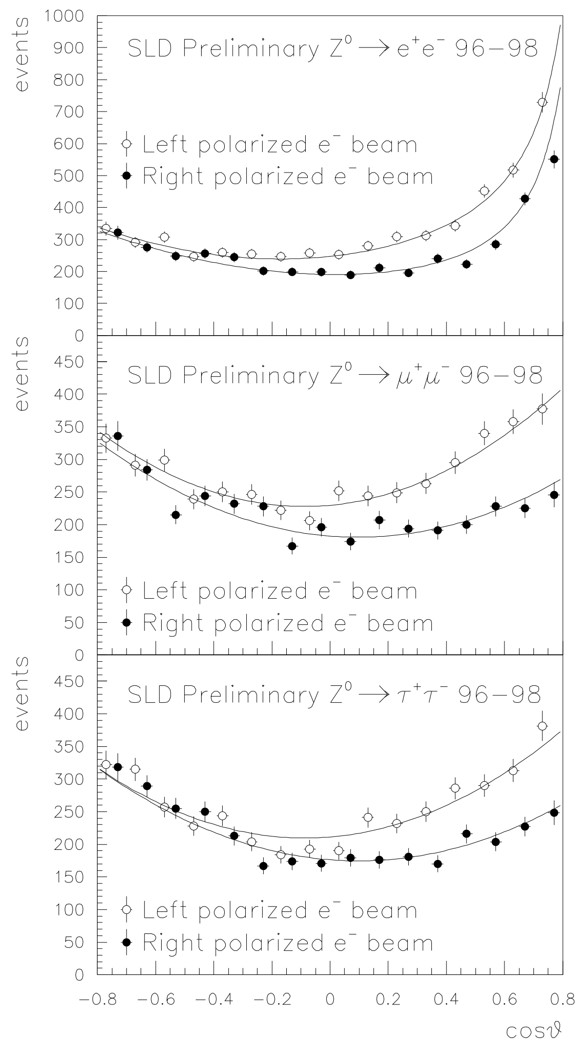

Figure 4: Angular distributions for SLD lepton-pairs in the 1996-98 data sample, separately for left- and right-handed electron beams.

5 Summary of Results

Combining these results with previous results yields the preliminary SLD combined value of

$$\sin^2\theta_W^{eff} = 0.23110 \pm 0.00029. \quad (18)$$

Combining this with other recent results, we compute the SLD-LEP world average to be

$$\sin^2\theta_W^{eff} = 0.23155 \pm 0.00028. \quad (19)$$

These results are shown in Figure 5. It is interesting to note that the world values for $\sin^2\theta_W^{eff}$ from lepton measurements (the results presented here, the LEP leptonic averages A^l_{FB} and A_e , and the LEP results of A_τ from τ-polarization) are in excellent agreement with each other, and differ by $\sim 2.3\sigma$ from those obtained from "hadron-only" measurements (A^b_{FB}, A^c_{FB}, and Q_{FB}).

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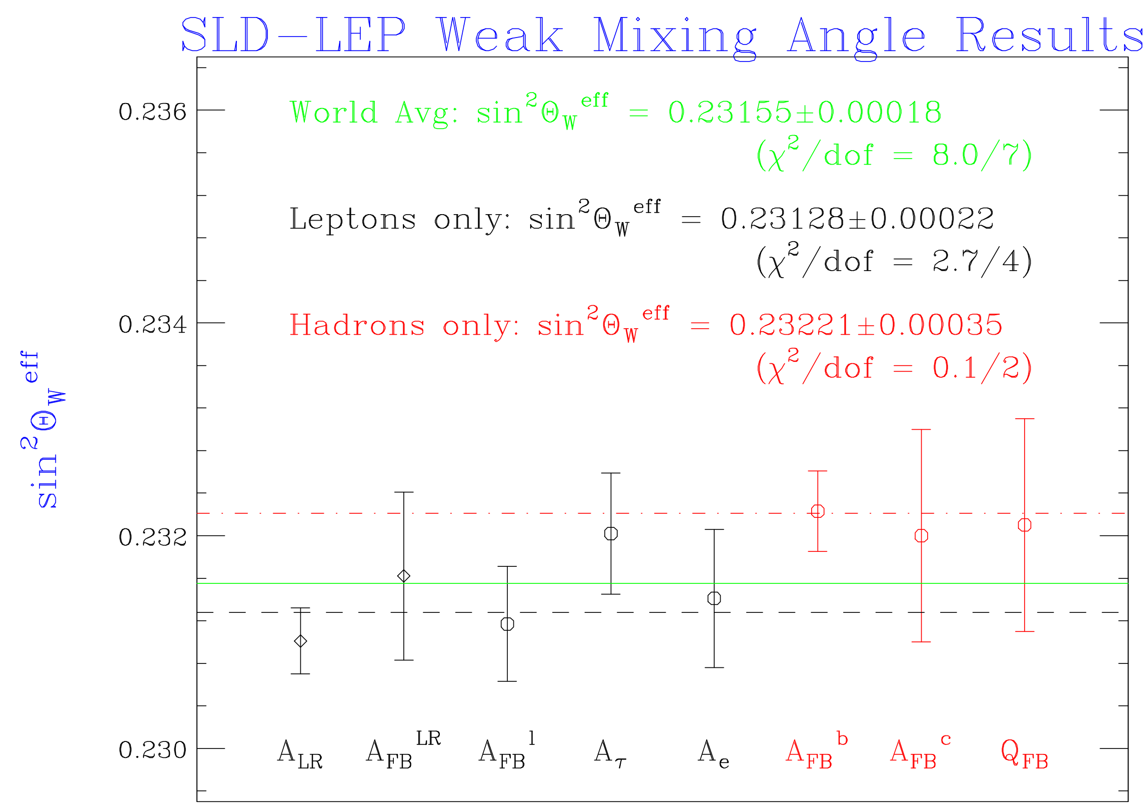

Figure 5: Status of the SLD and LEP $\sin^2\theta_W^{eff}$ measurements as of the XXIXth ICHEP conference.