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Neutral Current Couplings of Leptons to Polarized Z^0's in the SLD Experiment*

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We study neutral current couplings of leptons to polarized Z^0's in the SLD experiment in terms of the leptonic asymmetry parameters A_e, A_μ and A_τ. We discuss in detail $e^-_{L,R} + e^+ \to Z^0 \to \mu^-\mu^+$ and $\tau^-\tau^+$, with left(L)- or right(R)-handed polarized electron beams. SLD's most precise measurement of A_e is shown to result from the left-right cross section asymmetry, A_{LR}, where the dependence on initial state electronic couplings enable use of essentially all of the data. Comparing A_μ and A_τ with A_e tests the universality of leptonic couplings. $A_\mu = 0.102 \pm 0.033 \pm 0.001$, $A_\tau = 0.190 \pm 0.034 \pm 0.001$, and $A_e = 0.148 \pm 0.016 \pm 0.002$ from these two leptonic channels. If lepton universality is assumed, a combined asymmetry parameter $A_{e\mu\tau} = 0.147 \pm 0.013$ results, which directly corresponds to an effective value of the weak mixing angle $\sin^2\theta_W^{eff} = 0.2315 \pm 0.0017$.

1. INTRODUCTION

The standard model of electroweak interactions assumes all leptons couple with the same strength. Hence, evidence for a breakdown of lepton universality with respect to the neutral current couplings would be of major importance. We study the couplings of leptons to polarized Z^0's in the SLD experiment. These data have been collected with the SLAC Large Detector (SLD) at the SLAC Linear Collider (SLC).

Parity violation in Z^0 production from electron-positron collisions gives rise to asymmetrical polarization-dependent cross sections and final state angular distributions. The measured asymmetries relate directly to the asymmetry parameters which, in turn, are functions of the neutral current couplings. Within the framework of the electroweak standard model, the asymmetry parameters are all a function of the weak mixing angle, $\sin^2\theta_W^{eff}$. [1]

We concentrate on the reactions $e^-_{L,R} + e^+ \to Z^0 \to \mu^+\mu^-$ and $\tau^+\tau^-$, where L (R) refers to the left (right)-handed electron beam polarization. With these final states as an example, we discuss SLD's asymmetry measurements more generally. *SLD*'s single most sensitive measurement, the left-right polarization-dependent cross section asymmetry, A_{LR}, gives the best accuracy for A_e because it relies only on initial state couplings and, therefore, uses essentially all hadronic as well as leptonic events. The polarization-dependent forward-backward asymmetry of leptonic Z^0 decays yields the asymmetry parameters A_μ and A_τ with a precision equivalent to that obtained from unpolarized beam experiments at the Z^0 with about 25 times as much data.

We report results based on SLD's measurements of leptonic asymmetry parameters with data taken through the beginning of 1995. We also project the improved accuracy expected with the remainder of SLD's data through 1998

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and from a possible 3 million Z^0 run from an "SLD2000." The comparable measurements from the LEP experiments have been summarized at this conference. [2]

2. THE SLC AND THE SLD

Details about the SLC, the polarized electron source, the measurements of the electron-beam polarization with the Compton polarimeter, and the SLD detector are described elsewhere. [4] This analysis relies on tracking by the central drift chamber and by the Liquid Argon Calorimeter (LAC). High energy muons are cleanly separated from high energy electrons by noting the strong showering of electrons contrasted with the nearly undeflected passage of muons. Tau pairs selected for this study rely on tracking provided by the central drift chamber and on energy measurements with the LAC.

3. THEORY

3.1. A_{LR} and $\widetilde{A}^l_{FB}$

Polarization-dependent asymmetries are easily computed from the tree-level differential cross section, equation (1), for the process $e^-_{L,R} + e^+ \to Z^0 \to l^- + l^+$, where l represents either a μ- or a τ-lepton. The results apply as well to hadronic final states via quark-pair production.

$$\frac{d\sigma}{d\cos\theta} \propto \quad (1 + PA_e\delta_{LR})(1+\cos^2\theta) \\ +2(P\delta_{LR} + A_e)A_l\cos\theta. \qquad (1)$$

The direction between the electron beam and the outgoing lepton is given by $\cos\theta$. The leptonic asymmetry parameters A_μ and A_τ, appear in this expression as A_l. Note that the first term, symmetric in $\cos\theta$, exhibits initial state coupling to the electron by its dependence on A_e. The second term, asymmetric in $\cos\theta$, is mostly influenced by A_l. P is the magnitude of the effective longitudinal polarization of the electron beam and δ_{LR} is +1 for a left-handed and -1 for right-handed electron beams.

The asymmetry parameters are defined in terms of the vector- and axial-vector couplings, or, alternately, left- and right-handed couplings. They are related by the following expressions: $g^l_L = g^l_A + g^l_V$ and $g^l_R = g^l_A - g^l_V$.

$$A_l = \frac{2g^l_V g^l_A}{{g^l_V}^2 + {g^l_A}^2} = \frac{{g^l_L}^2 - {g^l_R}^2}{{g^l_L}^2 + {g^l_R}^2}. \qquad (2)$$

The Standard Model relates the Weak Mixing angle to the couplings by the expressions $g^l_A = -\frac{1}{2}$ and $g^l_V = -\frac{1}{2} + 2\sin^2\theta^{eff}_W$.

Integrating equation (1) over all $\cos\theta$ gives σ^l_L or σ^l_R for left- and right-handed beams, respectively. (For convenience, we drop the superscript in the following discussions since the meaning of the expressions will be clear enough in context.) Parity violation causes σ_L and σ_R to be different. Hence, we define the left-right cross section asymmetry, A_{LR}.

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}. \qquad (3)$$

Four cross sections are obtained by integrating forward (F) and backward (B) hemispheres separately, along with left- and right-handed polarization. Based on these four possibilities, we define the polarized forward backward asymmetry, $\widetilde{A}^l_{FB}$.

$$\widetilde{A}^l_{FB} = \frac{(\sigma_{LF} - \sigma_{LB}) - (\sigma_{RF} - \sigma_{RB})}{(\sigma_{LF} + \sigma_{LB}) + (\sigma_{RF} + \sigma_{RB})} \qquad (4)$$

3.2. Leptonic Asymmetry Parameters: A_e, A_μ and A_τ

With equal luminosities for left- and right-handed electron beams, the cross sections (σ) in equation (3) may be replaced with the numbers of events: N_L and N_R. After integrating equation (1) over all angles to get expressions for N_L and N_R in terms of P, δ_{LR}, A_e and A_l, and after substituting in equation (3) for both signs of polarization (δ_{LR}), what remains is given by

$$A_e = A_{LR}/P. \qquad (5)$$

In a similar fashion, integrating over foward or backward hemispheres, and substituting both signs of polarization in equation (4), gives the expression

$$A_l = (\widetilde{A}_{FB}^l/P)(1 + \frac{x_{max}^2}{3})/x_{max}, \quad (6)$$

where $x_{max} = \cos\theta_{max}$ is the maximum value of the magnitude of the polar angle accepted by the lepton event trigger.

3.3. γ-exchange and $Z\gamma$-interference

The expressions giving A_e and A_l, equations (5) and (6), are based on the tree level formula, equation (1), where only Z^0 exchange in the direct channel is considered. This is the major contribution, but non-negligible contributions from direct channel γ-exchange, as well as from $Z^0\gamma$ interference, must be considered too. Matters are further complicated by the fact that the three terms have different energy dependences. While the Z^0- and γ-exchange terms change slowly with energy, the interference term has a strong energy dependence away from the Z^0 pole. The energy-dependence must be considered because initial state photon emission smears the center-of-mass (cm) energy. While most events occur with a cm energy near twice the beam energies, initial state radiation creates a long low energy tail in the energy distribution. To correct for γ-exchange, A_e obtained via A_{LR} and A_l from $\widetilde{A}_{FB}^l$ must each be increased by about 0.001. The correction for the $Z^0\gamma$ interference term is approximately 0.002. The net effect is that the values obtained from equations (5) and (6) must be increased by 0.003 to account for γ-exchange and $Z\gamma$-interference.

3.4. The Maximum Likelihood Approach

The need to correct A_e and A_l for the effects discussed in the previous section are avoided by using a maximum likelihood fitting procedure which incorporates all three direct channel terms and accounts as well for the energy dependence. Further details are provided below in the section on fitting procedure. Determining A_e and A_l from the left-right and polarized forward-backward asymmetries, as defined above, has the advantage of simplicity. However, the maximum likelihood method offers the most rigorous means by which to estimate the parameters, as it effectively incorporates both kinds of asymmetry.

3.5. Impact of Large Beam Polarization

The advantage of polarized over non-polarized Z^0 production is seen by comparing the resultant asymmetries and the relative numbers of events required to gain the same precision. For example, the polarized forward-backward asymmetry, $\widetilde{A}_{FB}^l$, is proportional to PA_l, as indicated in equation (6). However, the unpolarized forward-backward asymmetry, A_{FB}, is proportional to the product, A_lA_e. Hence, the ratio, $\widetilde{A}_{FB}^l/A_{FB} = P/A_e$, or approximately a factor of five if $P = 0.8$ and $A_e = 0.15$. Likewise, it is straightforward to show that for the same precision, i.e., $\delta A_l/A_l$, the number of unpolarized Z^0's needed compared with polarized Z^0's varies as $(P/A_e)^2$, or a factor of 25. There is no direct comparison to be made with SLD's unique A_{LR} except to note that the error on A_e is approximately given by $\frac{1}{P\sqrt{N}}$, and N is essentially the total number of Z^0's irrespective of the final state.

4. ANALYSIS

4.1. Data Sample

The data samples used for this study are based on the 1993 SLD run and the 1994-95 run. The 1993 data sample consists of approximately 50,000 Z^0's with an electron beam polarization of 63% while the 1994-95 data set consists of about 100,000 Z^0 events with the beam polarization increased to 77%. The data were recorded at a mean center-of-mass energy of 91.28 ± 0.02 GeV.

4.2. Fitting Procedure

The probability density functions used for the maximum likelihood fits are based on the differential cross section formulas. This includes the three s-channel cross section terms: the dominant Z^0-exchange contribution given by equation (1), as well as the γ-exchange and $Z^0\gamma$-interference terms. The detector efficiency, $\epsilon(\cos\theta)$, need not be known, except that it must be symmetric in $\cos\theta$, i.e., $\epsilon(\cos\theta) = \epsilon(-\cos\theta)$. With this requirement, the $\cos\theta$-dependence of the efficiency does not need to be included in the probability density function for the maximum likelihood fit.

Ideally, the experiment could be done at the pole energy and the formulas used in the fit would be the expressions obtained at that singular energy. However, because of initial state QED radiation and the intrinsic beam energy spread, the effective center-of-mass energy is a distribution that peaks near twice the average beam energy with a rapidly decreasing tail that extends to lower energies. The dominant Z^0 s-channel resonance varies slowly with energy near the pole energy but the $Z\gamma$ interference term has a strong energy dependence away from the pole. To incorporate the energy-dependence of the data in the maximum likelihood fit, an effective probability density function is formed by convoluting the energy-dependent cross section formulas with a spectral function that includes the known energy variation (the QED initial state radiation and the intrinsic beam spread) and the effect of event selection cuts which are weakly correlated with the effective center of mass energy. The resultant expression used for the probability density function is a function of the scattering angle, the magnitude of the effective beam polarization (with the correct sign for left- or right-hanedness), and the parameters to be estimated, A_e and A_μ or A_τ.

4.3. Event Selection

Leptonic Z^0 decays are characterized by their low multiplicity and high momentum charged tracks. Muons and electrons are particularly distinctive as they emerge back-to-back with little curvature from the primary interaction vertex, and tau pairs form two tightly collimated cones directed in well-defined opposite hemispheres. Lepton pair candidates are chosen on the basis of the momentum of the charged tracks as well as from energy deposited in the calorimeter. The criteria used for the event selection give a high efficiency for finding the signal events while the backgrounds remain sufficiently low as to be almost entirely negligible.

Lepton-pair candidates are initially selected by restricting the charged multiplicity to lie between two and eight charged tracks to reduce background from hadronic Z^0 decays. The product of the sums of the charges of the tracks in each hemisphere must be -1. This insures a correct determination of the sign of the scattering angle. Requiring that at least one track have at least 1 GeV momentum reduces two-photon background while capturing candidate events with a high efficiency.

After the preselection, additional conditions are applied. All lepton pairs are restricted to the polar angle range with $|\cos\theta| < 0.7$ as a result of the event triggers implemented through the 1995 run. This angle is computed from the the momentum sums of the tracks in the two hemispheres with respect to the beamline; it is equivalent to the thrust axis.

A single cut effectively selects e^+e^- final states: the sum of the energies associated with the most energetic track from each hemisphere must be greater than 45 GeV as measured in the electromagnetic calorimeter.

Muon final state selection starts by demanding that the invariant mass of the event, based on charged tracks, be greater than 70 GeV. Tau final states usually fail this selection. Since muons deposit little energy as they traverse the calorimeters, we require also that the energy recorded in the calorimeter by the highest momentum track in each hemisphere be greater than zero and less than 10 GeV. Electron pairs are removed by this requirement.

Tau selection requires that the calorimeter energy associated with the most energetic track in each hemisphere is less than 27.5 GeV to distinguish them from e^+e^- pairs. We take the compliment of the muon event mass cut and require the event mass to be less than 70 GeV. At least one track must have momentum above 3 GeV to reduce backgrounds from two-photon events. We define the event acollinearity from the vector sums of the momenta of the tracks in the seperate hemispheres and angle between the resultant momentum vectors must be greater than 160 degrees; this also removes two-photon events. Finally, the invariant mass of charged tracks in each hemisphere is restricted to less than 1.8 GeV to further restrict hadronic backgrounds.

The results from the event selections are summarized in Table 1. Note that the efficiency is given for the restricted range $|\cos\theta| < 0.7$ within

Table 1
Summary of Event Selection.

Sample	% Background	Efficiency for $\lvert\cos\theta\rvert < 0.7$	# Events
Muons	0.4% $\tau^+\tau^-$	95%	1993: 1185 1994-95: 2603
Taus	1% e^+e^- 2% $\mu^+\mu^-$ 0.5% 2γ 0.5% hadrons	89%	1993: 1211 1994-95: 2537

which leptonic events are triggered.

4.4. Backgrounds

Muon-pair samples are relatively background-free but tau-pair candidates are contaminated by electron-pairs, or from two-photon and hadronic events. Beam-gas and cosmic ray backgrounds have been estimated and found negligible. Estimates of non-negligible backgrounds in tau-pair events from other lepton-pairs, from two-photon events and from hadronic events are given below in Table 2. These estimates have been derived from detailed Monte Carlo simulations as well as from studying the effect of cuts in background-rich samples of real data.

The background estimates are used as input for studies of corrections to the asymmetry parameters A_e, A_μ and A_τ. This is the subject of the next section.

4.5. Corrections to Asymmetry Parameters

The maximum likelihood procedure with the effective probability density functions functions described above incorporates all that is needed to estimate the asymmetry parameters except for two added non-negligible corrections that must be applied after the fits are made. These include non-negligible corrections (i.e., greater than 10^{-3}) to the fitted asymmetery parameters due to backgrounds in the tau sample, and a correction (the "V-A effect") which applies only to A_τ.

Effect of Backgrounds:

We estimate how the backgrounds discussed above effect each asymmetry parameter by fitting an ensemble of "toy Monte Carlo experiments." Each individual "experiment" consists of 4,000 events (the approximate size of a leptonic data set), with each event consisting of a $\cos\theta$ value for either a left- or a right-handed beam polarization. The distribution is generated from the same formula for the cross-section used to fit the real data. Trial backgrounds are then superimposed on each toy data set, where the shape of the background has been obtained from the shape of the data that forms the particular background. Each background is normalized relative to the signal according to detailed Monte Carlo estimates. The effect of each background on each asymmetry parameter is determined from the differences between the averages of the fitted parameter values before and after inclusion of the backgrounds in the set of toy experiments. The only net corrections that must be made due to backgrounds according to this procedure is to increase the fitted values of A_e and A_τ each by 0.002 ± 0.001 for the tau-pair final state.

V-A structure in tau decays:

Another large systematic effect for the tau analysis comes about because we measure not the taus themselves, but their decay products. The longitudinal spin projections of the two taus from Z^0 decay are 100% anti-correlated: one will be left-handed and the other right-handed. So, given the V-A structure of tau decay, the decay products from the τ^+ and the τ^- from a particular Z^0 decay will take their energies from the same set of spectra. For example, if both taus decay to $\pi\nu$, then both pions will generally be low in energy (in the case of a left handed τ^- and right handed τ^+) or both will be generally higher in energy. The effect is strong at SLD because the high beam polarization induces very high tau polarization as a function of polar production angle. And, most importantly, the sign of the polarization is basically opposite for left and right beam events. So a cut on event mass, say, may cause polar angle dependence in selection efficiency for taus which has the opposite effect for taus from events produced with the left and right polarized electron beam. Taking all tau decay modes into account, using Monte Carlo simulation, we find an overall shift of $+0.008 \pm 0.0002$ on A_τ, (the value extracted from the fit must be reduced by this amount). A_e is not affected since the overall relative efficiencies for left-beam and right-beam events are not changed much (only the polar angle dependence of the efficiencies are changed).

4.6. Other Corrections

The above-mentioned corrections are non-negligible, although small compared with current statistical errors. Other potential corrections are discussed below. Their effect on the asymmetry parameters is deemed negligible for the current measurements.

Effect of polarization asymmetries:

SLD's asymmetry measurements rely critically on the time-dependent polarization values and the polarization is measured during the run at least once an hour. Details on the polarization measurements are discussed in connection with SLD's latest report on A_{LR} that includes the 1994-95 data. The current estimate of the error on the polarization is given by $\delta P/P = 0.67\%$. [4]

Effect of detector asymmetries:

Electron and muon pairs are characterized by two back-to-back tracks with little curvature in the drift chamber. Since there will generally be no bias in the fit as long the the efficiency is symmetric in $\cos\theta$, there will be a problem only if the efficiency for detecting positive tracks is different from that of negative tracks. Tau pairs are mostly one-pronged, and similar to electrons and muons in this respect. Those tau decays which result in three or more prongs can be more complex, but unless there is an inherent bias that favors one sign of charge over the other, the symmetry in $\cos\theta$ will be preserved. We estimate this effect by examining the relative numbers of opposite sign back-to-back tracks with positive-positive and negative negative pairs. The latter will occur whenever one of the two back-to-back tracks in a two-pronged event has a wrong sign of measured charge. Double charge mismeasurement is less likely. The correction for biases due to charge mismeasurement is found to be negligible.

Final state thrust angle resolution:

We have studied the effect of imprecise measurements of the thrust axis by smearing the directions of outgoing tracks. The results depend on the final state with muons measured best of all and taus least well measured. Final state QED radiation can affect the determination of the track angle particularly for for electrons, although we find the angle to be well-determined in that case as well. The result depends somewhat on how final pairs are selected but this source of correction is also deemed negligible from our studies.

5. RESULTS

Results from fits to the data are summarized in Tables 2. The numbers in this table have been corrected for the effect of backgrounds and the "V-A effect" for taus. The estimates for A_e, A_μ and A_τ were obtained by fitting each lepton sample separately, for both signs of polarization, by the maximum likelihood procedure. A comprehensive value of A_e is obtained from all lepton species combined. A slighlty more precise value is obtained by assuming lepton universality and combining all of the lepton data. This global asymmetry parameter is referred to as $A_{e\mu\tau}$. The values of A_μ and A_τ and are consistent with A_e. An upper limit to the overall systematic error estimated at 0.003 when taken in quadrature with the current statistical error is ignorable.

Binned angular distributions for muon- and tau-pair final states from the 1993 data and from the 1994-95 data are shown in Figures 1 and 2, respectively. The data are well fit by these curves.

Table 2
Summary of A_e, A_μ, A_τ and $\sin^2\theta_W^{eff}$ from SLD's $Z^0 \rightarrow \mu^+\mu^-, \tau^+\tau^-$, and hadrons.

Final States	Asymmetry Parameter	$\sin^2\theta_W^{eff}$
$\mu^+\mu^-$	$A_\mu = 0.102 \pm 0.033 \pm 0.001$	
$\tau^+\tau^-$	$A_\tau = 0.190 \pm 0.034 \pm 0.001$	
$\mu^+\mu^-$ and $\tau^+\tau^-$	$A_e = 0.148 \pm 0.016 \pm 0.002$	
	$A_{e\mu\tau} = 0.147 \pm 0.013$	0.2315 ± 0.0017
hadrons	$A_e = 0.1543 \pm 0.0039$	0.23060 ± 0.00050

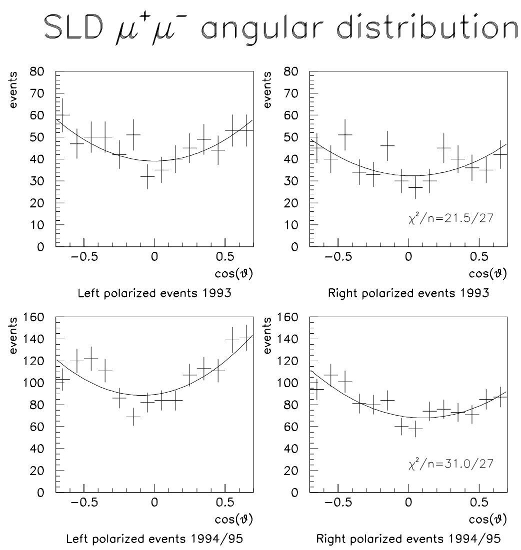

Figure 1. Muon-pair angular distributions with left- and right-handed polarization (left and right plots) and for 1993 (top) and 1994-95 (bottom) data sets. Curves are based on fitted parameters.

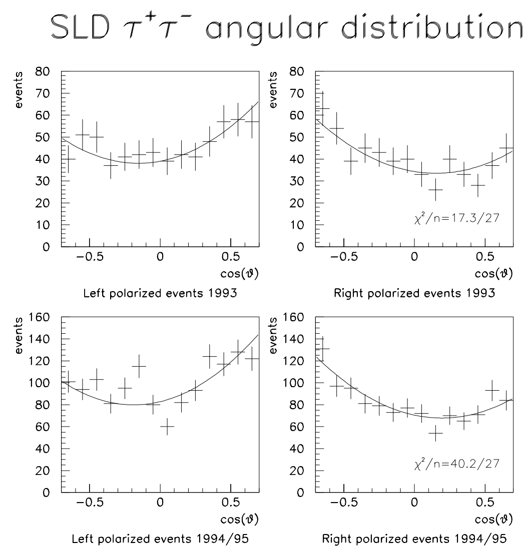

Figure 2. Tau-pair angular distributions with same set of conditions described in the Figure 1 caption.

6. SUMMARY AND OUTLOOK

We report measurements of the leptonic asymmetry parameters, A_e, A_μ and A_τ from SLD data collected from 1993 through 1995. Maximum likelihood fits to the reactions $e^-_{L,R} + e^+ \rightarrow Z^0 \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$ were used to estimate the parameters. The probability density function used in the fit incorporates all three s-channel terms required from the tree-level calculations. This function results from convoluting the energy dependent cross section formulas with a spectral function that incorporates initial state QED radiation, the intrinsic beam energy spread, and the effect of energy-dependent selection criteria. The parameters estimated from these fits require no corrections except in the case of tau-pair final states where backgrounds and the V-A structure of tau decays bias the results. Hence the fitted value of A_τ is corrected for the biases. Results are summarized in Table 2.

SLD's current data measures $\delta A_\mu/A_\mu$ and

$\delta A_\tau/A_\tau$ to a precision of about 20% while $\delta A_e/A_e$ is measured with an accuracy of about 2.5%. The much greater precision in determining A_e results from the fact that it is sensitive to the intial state electronic couplings and all final states can be used. A_e can be shown to relate directly to the left-right cross section asymmetry, i.e., $A_e = A_{LR}/P$, where P is the magnitude of the effective longitudinal beam polarization. LEP currently determines A_μ to about 10% based on forward-backward asymmetry measurements. A_τ from LEP is determined with a precision of about 5% because the polarization of final state tau decays adds a powerful measure of both A_e and A_τ. [3] All of the data to date is consistent with lepton universality. LEP's analysis of data at the Z^0 is nearly complete and the precision of their measurements will not improve significantly. However, SLD's ultimate data based on runs through 1998 will likely improve the accuracy on both A_μ and A_τ to about 10%. An "SLD2000" with about three million Z^0's and the current polarization of about 80% would improve the precision on A_μ and on A_τ to nearly 3%, an accuracy that could reveal potential differences in the leptonic neutral current couplings.

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