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Direct Measurement of Leptonic Coupling Asymmetries with Polarized Z's *

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Abstract

We present direct measurements of the Z^0-lepton coupling asymmetry parameters, A_e, A_μ, and A_τ, based on a data sample of 12,063 leptonic Z^0 decays collected by the SLD detector. The Z bosons are produced in collisions of beams of polarized e^- with unpolarized e^+ at the SLAC Linear Collider. The couplings are extracted from the measurement of the left-right and forward-backward asymmetries for each lepton species. The results are: $A_e = 0.152 \pm 0.012(\text{stat}) \pm 0.001(\text{syst})$, $A_\mu = 0.102 \pm 0.034 \pm 0.002$, and $A_\tau = 0.195 \pm 0.034 \pm 0.003$.

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The structure of the parity violation in the electroweak interaction can be probed directly in the production and decay of polarized Z^0 bosons. All three leptonic states can be studied in e^+e^- annihilations at the Z^0 resonance, providing an important test of lepton universality and the Standard Model [1].

We report measurements of production and decay asymmetries of $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ made by the SLD experiment at the SLAC Linear Collider (SLC). SLC produces Z bosons in e^+e^- collisions using a polarized electron beam. The polarization allows us to form the left-right cross section asymmetry to extract the initial-state coupling A_e. It also enables us to extract the final-state coupling for lepton l, A_l, directly using the polarized forward-backward asymmetry. The parity-violating parameter $A_l = \frac{2v_l a_l}{v_l^2+a_l^2}$ depends only on the ratio of the vector and axial vector couplings of the lepton l to the Z^0, v_l and a_l respectively. Previous experiments at the Z^0 resonance [2] have measured the product of initial and final-state coupling, $A_e \cdot A_l$. The polarization enables us to present the first direct measurement of A_μ. The polarized asymmetries enhance the statistical precision on the final-state parameter by a factor of about 25 compared to the simple forward-backward asymmetry. The data were collected during 1993 ($\sqrt{s} = 91.26$ GeV center-of-mass energy, 63% e^- beam polarization, $5 \cdot 10^4 Z$'s analyzed) and 1994-5 ($\sqrt{s} = 91.28$ GeV, 77% polarization, $10^5 Z$'s analyzed). The SLD detector [3] and the SLC accelerator [4] have been described elsewhere.

Production of the vector Z boson in electron-positron collisions requires the longitudinal spin projections of the electron and positron to be parallel. The helicity of the electron controls the direction of the spin projection of the Z^0. There are two spin configurations of the e^+e^- system that have a non-zero Z^0 production cross section: The cross section with the spin of the Z^0 pointing in the direction opposite to the electron's momentum is referred to as the 'Left-handed' cross section since it contains a left-handed electron. Because the couplings of the Z boson to the fermions are parity violating, the left-handed cross section is not equal to the right-handed cross section, where the spin of the Z^0 points in the same direction as the electron's momentum vector. In addition to this Left-Right Asymmetry in the Z production cross section, A_{LR}, Z couplings to fermions also produce asymmetries in the angular distributions of the Z decay products with respect to the beam axis.

The dominant term in the cross section for polarized production of a pair of leptons at the Z resonance is due to Z exchange:

$$Z(s, A_e, A_l, x) = \left(\frac{d\sigma}{dx}\right)_{Z(s)} = f_{Z(s)} \Big((1 - PA_e)(1 + x^2) + (A_e - P)A_l 2x\Big), \tag{1}$$

where P is the electron beam polarization [5]. $P < 0$ means mostly left-handed beam electrons and $P > 0$ mostly right-handed beam electrons. $x = \cos\ \theta$, where θ is the angle of the l^- direction with respect to the electron beam direction. Photon exchange terms and, if the final-state leptons are electrons, t-channel contributions [6], have to be taken into account. Events with $\cos\ \theta < 0$ will be called 'backward' events; 'forward' events have $\cos\ \theta > 0$. The sign of the polarization was switched randomly on each beam pulse; this minimizes asymmetries arising from SLC/SLD operation [7]. Half of the luminosity has a positive polarization, half a negative polarization. We measure the polarization with the Compton polarimeter [8] and obtained for the 1994-5 run $|P| = 77.23 \pm 0.52\%$(uncertainty dominated by systematics). [7] The polarization for the 1993 run was $|P| = 63.0 \pm 1.1\%$. [7]

Simple asymmetries can be used to extract A_e and A_l from the data. The left-right asymmetry measures the difference in Z production for the left and right polarized electron beams. The left-right forward-backward asymmetry is a double asymmetry which is formed by taking the difference in the number of forward (F) and backward (B) events for left (L) and right (R) beam polarization data samples. These asymmetries can be derived from equation (1), using obvious subscripts, (and assuming acceptance over the full solid angle)

$$A_{LR} = \frac{1}{|P|}\frac{N_L - N_R}{N_L + N_R} = A_e \tag{2}$$

$$\tilde{A}^l_{FB} = \frac{4}{3|P|}\frac{(N_{LF} - N_{LB}) - (N_{RF} - N_{RB})}{(N_{LF} + N_{LB}) + (N_{RF} + N_{RB})} = A_l. \tag{3}$$

Events are reconstructed and accepted in this analysis only within $|\cos\,\theta| < 0.7$ where SLD trigger and reconstruction efficiencies are high and uniform. Then the geometric factor 4/3 in equation (3) is replaced by 1.66.

The essence of the measurement is contained in equations (2) and (3), but instead of simply counting events we perform a maximum likelihood fit, event by event, using the likelihood function

$$\mathcal{L}(A_e, A_l, x) = \int ds' H(s,s')\,(Z(s', A_e, A_l, x) + Z\gamma(s', A_e, A_l, x) + \gamma(s', x)) \tag{4}$$

to determine simultaneously A_e and A_μ with the mu-pair events (or A_e and A_τ with the tau-pair events). The integration over s' is done with the program DMIBA [9] to take into account the initial-state radiation from two times the beam energy $\sqrt{s}$ to the invariant mass of the propagator $\sqrt{s'}$ described by the radiator function $H(s,s')$. The spread in the beam energy has a negligible effect. The maximum likelihood fit is less sensitive to detector acceptance as a function of polar angle than the counting method, and has more statistical power. $Z(...), \gamma(...)$ and $Z\gamma(...)$ are the tree-level differential cross sections for Z exchange, photon exchange, and their interference. The integration is performed before the fit to obtain the coefficients $f_Z, f_{Z\gamma}$ and f_γ, and the likelihood function becomes

$$\mathcal{L}(A_e, A_l, x) = f_Z \cdot Z(A_e, A_l, x) + f_{Z\gamma} \cdot Z\gamma(A_e, A_l, x) + f_\gamma \cdot \gamma(x). \tag{5}$$

These coefficients give the relative sizes of the three terms at the SLC center-of-mass energy. For the electron final-state we include the t-channel contributions in the likelihood function to determine A_e.

Leptonic decays of the Z are characterized by low charged multiplicity and two back-to-back leptons (or in the case of the tau-pair events, the tau decay products). This analysis relies on the charged track reconstruction in the central drift chamber (CDC) and the measurement of the energies associated with the tracks in the liquid argon calorimeter (LAC).

A pre-selection requires lepton-pair events to have between 2 and 8 charged tracks, each of which must pass within 1 cm of the nominal e^+e^- interaction point. This excludes most hadronic Z decays, which have an average charged multiplicity of approximately 20. Since the leptons have about 45 GeV in energy, there is little problem assigning reconstructed tracks to one of two event hemispheres, corresponding to the two leptons. One hemisphere must have a net charge 1 and the other a net charge -1 to ensure unambiguous assignment of the scattering angle. Each event is assigned a polar production angle based on the thrust axis defined by the charged tracks. Additional requirements are imposed to select e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ final-states and further reduce backgrounds. Table 1 summarizes the electron, muon, and tau event selections.

A single additional cut is required to select the e^+e^- final state. We require the sum of the energy deposited in the LAC by the highest momentum track in each hemisphere to be more than 45 GeV. The electron sample has a small contamination (0.7%) from tau events.

Events of the type $Z \to \mu^+\mu^-$ must have the invariant mass of the measured charged tracks above 70 GeV/c^2. This removes most $Z \to \tau^+\tau^-$ events and virtually all two-photon events and any remaining hadronic Z decays. The majority of events remaining are $Z \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$. We remove the e^+e^- final-state by requiring the energy deposited in the LAC by the highest momentum track in each hemisphere to be less than 10 GeV (but more than 0 GeV to eliminate events with both tracks entering spaces between calorimeter modules). The muon sample has no backgrounds except for 0.4% tau events.

The tau selection takes the complement of the muon sample and requires the event mass to be less than 70 GeV/c^2. Requiring the maximum of the two energies in the LAC associated to the highest momentum track in each hemisphere to be non-zero but below 27.5 GeV removes $e^+e^- \to e^+e^-$ events. Two-photon events are suppressed by requiring the angle between the momenta of the two hemispheres, as measured by the sum of the charged track momenta in each hemisphere, to be greater than 160^0. Requiring one charged track to have momentum greater than 3 GeV/c also reduces two-photon background. The remaining background from hadronic Z decays is suppressed by requiring each hemisphere invariant mass, measured using charged tracks, to be less than 1.8 GeV/c^2. The tau sample is contaminated with muons (2%), electrons (1.5%), two-photon (1%), and hadronic events (0.5%).

There are several systematic effects which can bias the result. (1) The uncertainty on the beam polarization is correlated among all the measurements and corresponds to an uncertainty on A_e and A_l of ± 0.001. (2) Uncertainties in the amount of background and its effect on the fitted parameters must also be taken into account. For the e^+e^- and $\mu^+\mu^-$ final-states we rely on Monte Carlo simulation to estimate the effect of backgrounds. For these samples, background has a negligible effect (< 0.0005). The tau sample contains significant background, which we have studied using samples of background-rich events selected from the data itself. These events were used to estimate the polar-angle distribution of the background events that eventually populate the tau sample. The results are listed in table 2. (3) The dominant systematic error in the tau analysis comes about because we measure not the taus themselves, but their decay products. The helicities of the two taus from Z decay are

100% anti-correlated: one will be left-handed and the other right-handed. So, given the V-A structure of tau decay [10], the decay products from the τ^+ and the τ^- from a particular Z 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 and asymmetric tau polarization as a function of polar production angle. In addition, the sign of the polarization is approximately opposite for left- and right-handed e^- beam events at a given polar angle. Thus selecting events based on event mass, for example, may cause polar angle dependence in selection efficiency for taus which has 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 $+0.0080 \pm 0.0019$ on A_τ due to this effect (the value extracted from the fit must be reduced by this amount). The value of A_e extracted from $\tau^+\tau^-$ final-states is not affected since the overall relative efficiencies for left-beam and right-beam events are not changed significantly (only the polar angle dependence of the efficiencies are changed). (4) The calculation of the maximum likelihood function depends on the average beam energy $\sqrt{s}$. The uncertainty due to a $\pm 1\sigma$ variation of this energy is of the order 10^{-3} (see table 2).

We have also studied the effect of the uncertainty in the thrust axis determination and found that this contribution is negligible. The selection efficiency as a function of polar angle is another possible source of bias in A_l. If this efficiency is symmetric about $\cos\,\theta = 0$ then A_l (and A_e) will be unaffected for muons and taus (see equations (2) and (3)). However, the maximum likelihood fit for the e^+e^- final state will be affected even for a symmetric efficiency, if it is not uniform. We did not find a significant deviation from a uniform efficiency within $|\cos\,\theta| < 0.7$ and estimate conservatively the upper limit of $\Delta A_e < 10^{-4}$. A small detector-induced forward-backward asymmetry would also introduce a bias in A_l, but A_e would still be unaffected. Using the data, we have studied the effect of the selection cuts as a function of polar angle. No systematic effect is observed and we assign a conservative systematic uncertainty of $\Delta A_l = 5 \cdot 10^{-4}$. The systematic uncertainties are summarized in table 2, they are negligible compared to the statistical uncertainties.

Figure (1) shows the $\cos\,\theta$ distributions for electron, muon and tau final-states for the 1994-5 data. The solid line represents the fit, while the points with error bars show the data in bins of 0.1 in $\cos\,\theta$.

We have presented direct measurements of the Z-lepton coupling asymmetries A_e, A_μ, and A_τ using $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ events produced with a polarized e^- beam. The results are

$$\begin{aligned} A_e &= 0.152 \pm 0.012 \\ A_\mu &= 0.102 \pm 0.034 \\ A_\tau &= 0.195 \pm 0.034. \end{aligned} \tag{6}$$

Our results are consistent with lepton universality. Assuming universality, we can combine them into $A_{e-\mu-\tau}$ which in the context of the standard model is simply related to the electroweak mixing angle [1]

$$A_{e-\mu-\tau} = 0.151 \pm 0.011,$$

$$\sin^2\theta_W^{eff,\ lept} \equiv \frac{1}{4}\left(1-\frac{v_l}{a_l}\right) = 0.2310 \pm 0.0014. \tag{7}$$

This measurement is independent of the SLD result from A_{LR} [7] using Z decays to hadrons. The combined results from the four LEP experiments [2] can be written as $A_e = 0.1461 \pm 0.0059$, $A_\mu = 0.1476 \pm 0.0132$, $A_\tau = 0.1463 \pm 0.0062$.

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[5] We define the polarization as $P = \frac{R-L}{R+L}$ where L (R) is the number of left-handed (right-handed) electrons.

[6] The photon s-channel cross section terms are $\left(\frac{d\sigma}{dx}\right)_{\gamma(s)} \propto (1+x^2)$ and $\left(\frac{d\sigma}{dx}\right)_{\gamma(s)Z(s)} \propto \frac{v_e}{a_e}\frac{v_l}{a_l} \times \left(\left(1 - P\frac{a_e}{v_e}\right)(1+x^2) + \left(\frac{a_e}{v_e} - P\right)\frac{a_l}{v_l}2x\right)$, the dominant t-channel cross section for electrons is $\left(\frac{d\sigma}{dx}\right)_{\gamma(t)} \propto \frac{4+(x+1)^2}{(x-1)^2}$

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Table 1: Summary of event selections for $Z \to l^+l^-$

event sample	backgr. as % of sel. events	effic. in $\lvert\cos\theta\rvert < 0.7$	# of selected events
$e^+e^- \to e^+e^-$	0.7% $\tau^+\tau^-$		1993 run: 1434
		92%	1994-5 run: 3093
$Z \to \mu^+\mu^-$	0.4% $\tau^+\tau^-$		1993 run: 1185
		96%	1994-5 run: 2603
$Z \to \tau^+\tau^-$	1.5% e^+e^-		
	2% $\mu^+\mu^-$		1993 run: 1211
	1% two-photon	90%	1994-5 run: 2537
	0.5% hadrons		

Table 2: Uncertainties on A_e, A_μ and A_τ in the polarized asymmetry analysis of leptonic Z decays. The total systematic error is the quadratic sum of the systematic contributions.

	total	stat.	total syst.	Systematic contributions			
				e^- pol.	backgr.	effic. bias	$\sqrt{s}$
A_e	0.012	0.012	0.001	0.001	negl.	negl.	0.001
A_μ	0.034	0.034	0.002	0.001	negl.	n.a.	0.002
A_τ	0.034	0.034	0.003	0.001	0.001	0.002	0.001

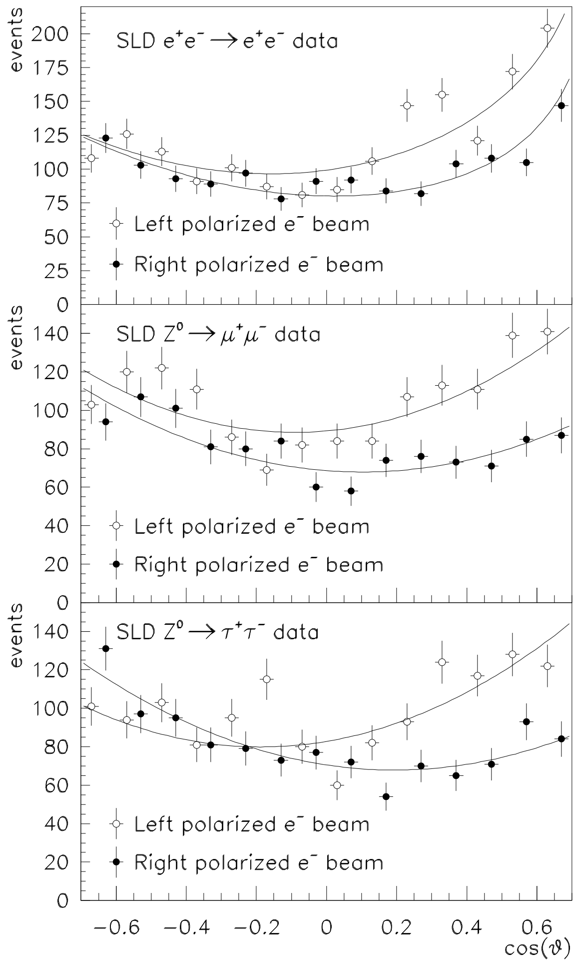

Figure 1: Polar angle distribution for Z decays to e, μ and τ pairs for the 1994-5 SLD run. The asymmetries in the 1993 data look similar but are less pronounced due to the lower polarization.

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