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PHYSICS WITH POLARIZATION AT THE SLD*

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ABSTRACT

The SLD detector is nearing completion and will start physics-quality data-taking at the SLC in 1991 with a longitudinally polarized electron beam and unpolarized positron beam. The current status of the detector is reviewed and the rich program of physics measurements possible with polarization and the SLD detector is briefly presented. In particular, the left-right polarization asymmetry, A_{LR}, will be a unique measurement for the next few years and will allow tight bounds to be set upon the mass of the top quark.

1. STATUS OF THE SLD DETECTOR

The SLAC Large Detector (SLD) has been described in detail elsewhere.[1)] At the time of writing, the detector is in the final stages of assembly and commissioning. Starting in August, it is planned to take cosmic ray data with most of the subsystems of the detector running in a unified mode and exercising the FASTBUS data acquisition system and the associated online and offline software. This will allow an extensive shakedown and commissioning of the detector in advance of its installation in the SLC beamline, so that the first physics-quality data can be obtained in 1991 with polarized Z^0's delivered by the SLC.[2)]

The important features of the SLD detector which give it a potential advantage over other detectors are:

1. Excellent hadron calorimetry with an expected resolution of $55\%/\sqrt{E}$ in the Liquid Argon Calorimeter; only the L3 detector compares.
2. Excellent particle identification capability over a large momentum range with the Čerenkov Ring Imaging Detector;[3)] only the DELPHI detector compares.
3. The ability to reconstruct decay vertices with high resolution and very close to the e^+e^- interaction point using the charge-coupled device vertex detector, which has an inner radius of 25 mm; no other detector sits so close to the interaction point and has such good resolution.

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Combined with the ability of the SLC to produce polarized Z^0 decays, these characteristics suggest that the SLD can perform a competitive and complementary program of high-precision physics measurements to test the Standard Model.[4] Of particular interest are the areas of polarized asymmetry measurements and heavy flavor physics, though clearly *any* measurements relying on 1–3 above will benefit, such as the study of production of different baryon and meson species in QCD. In this article I shall concentrate on the polarized asymmetry measurements; most of the results are based upon the work of my SLD colleagues[5,6] and the excellent CERN review[7] of polarization physics. SLD strengths in heavy flavor physics are discussed elsewhere.[8,9]

2. ELECTROWEAK ASYMMETRY MEASUREMENTS WITH POLARIZATION

Considering the reaction $e^+e^- \rightarrow f\bar{f}$ in the case of an electron beam of longitudinal polarization $\mathbf{p}$ and an unpolarized positron beam, one can write the Born-level cross section formula for the production of massless fermions f at the Z^0 pole, $\sqrt{s} = M_Z$, as:

$$\frac{\mathrm{d}\sigma(\mathbf{p})}{\mathrm{d}\cos\theta} = 2\,\sigma_0\,(v_e^2 + a_e^2)\,(v_f^2 + a_f^2)\{\,(1 + \mathbf{p}\,A_e)\,(1 + \cos^2\theta) + 2\,A_f\,(\mathbf{p} + A_e)\cos\theta\}$$

where:

$$\sigma_0 = \frac{\pi\,\alpha^2}{4\,\Gamma_Z^2\,\sin^4(2\,\theta_w)} \qquad A_{f,e} = \frac{-2\,v_{f,e}\,a_{f,e}}{v_{f,e}^2 + a_{f,e}^2}$$

The differential cross section depends on $\mathbf{p}$, where $\mathbf{p} = +\,(-)\,1$ for a purely right (left)-handed beam. One expects the SLC to deliver an electron beam with $|\mathbf{p}| \sim 40\%$ for physics running in 1991.[2]

The Standard Model asymmetries which can be considered when longitudinally polarized Z^0's are produced are the forward-backward asymmetry, A_{FB}, the forward-backward polarization asymmetry, $\tilde{A}_{FB}$, and the left-right polarization asymmetry A_{LR}. These are defined as follows:

$$A_{FB}(p) = \frac{\int_0^x \frac{\mathrm{d}\sigma(p)}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta - \int_{-x}^0 \frac{\mathrm{d}\sigma(p)}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta}{\int_0^x \frac{\mathrm{d}\sigma(p)}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta + \int_{-x}^0 \frac{\mathrm{d}\sigma(p)}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta}$$

$$= \frac{\sigma_F(p) - \sigma_B(p)}{\sigma_F(p) + \sigma_B(p)}$$

$$\tilde{A}_{FB}(p) = \frac{\int_0^x \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta - \int_0^x \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta - \left(\int_{-x}^0 \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta - \int_{-x}^0 \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta\right)}{\int_0^x \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta + \int_0^x \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta + \left(\int_{-x}^0 \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta + \int_{-x}^0 \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta\right)}$$

$$= \frac{\sigma_F^L(p) - \sigma_F^R(p) - (\sigma_B^L(p) - \sigma_B^R(p))}{\sigma_F^L(p) + \sigma_F^R(p) + (\sigma_B^L(p) + \sigma_B^R(p))}$$

$$A_{LR}(p) = \frac{\int_{-x}^x \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta - \int_{-x}^x \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta}{\int_{-x}^x \frac{d\sigma^L(p)}{d\cos\theta} d\cos\theta + \int_{-x}^x \frac{d\sigma^R(p)}{d\cos\theta} d\cos\theta}$$

$$= \frac{\sigma^L(p) - \sigma^R(p)}{\sigma^L(p) + \sigma^R(p)}$$

where the subscript F (B) denotes the forward (backward) hemisphere, $\cos\theta > (<) 0$ with respect to the incoming positron beam, and the superscript L (R) denotes a left (right)-handed electron beam with polarization of magnitude p. The value x represents the limit of the integration over $\cos\theta$, which for all experiments is less than unity because the acceptance falls to zero at low angles, near the beam pipe.

These asymmetries are evaluated, using the Born cross section, in Table 1, where the dependence upon $\mathbf{p}$ and the initial and final state Z^0 vertex couplings, A_e, A_f respectively, is shown. In the general case, A_{FB} and $\tilde{A}_{FB}$ depend upon x, whereas A_{LR} is independent of x— *i.e.* does not depend on the detector acceptance. One can see also that A_{FB} depends upon both A_e and A_f, whereas $\tilde{A}_{FB}$ depends upon A_f only and A_{LR} upon A_e only. Without longitudinal polarization, *i.e.* $\mathbf{p} = 0$, only A_{FB} is properly defined and hence available to be determined experimentally. With polarization, all three asymmetries are available for measurement and the couplings A_e, A_f can be measured *separately* via $\tilde{A}_{FB}$ and A_{LR} respectively.

Table 1. Comparison of electroweak asymmetries

	$\int^x$	$\int^1$	$\int^1, \mathbf{p} = 0$
$A_{FB}(\mathbf{p})$	$\frac{x}{1+x^2/3} A_f \frac{(\mathbf{p}+A_e)}{1+\mathbf{p}A_e}$	$\frac{3}{4} A_f \frac{(\mathbf{p}+A_e)}{1+\mathbf{p}A_e}$	$\frac{3}{4} A_e A_f$
$\tilde{A}_{FB}(\mathbf{p})$	$\frac{-x}{1+x^2/3} \mathbf{p} A_f$	$-\frac{3}{4} \mathbf{p} A_f$	0
$A_{LR}(\mathbf{p})$	$-\mathbf{p} A_e$	$-\mathbf{p} A_e$	0

From now on, I shall define $A_{LR} \equiv A_{LR}(\mathbf{p} = -1) = A_e$ and concentrate on the measurement of the quantity A_{LR}, which has many desirable properties:

1. Its numerical value is 'large': *e.g.*, for $M_Z = 91.17$ GeV, $A_{LR} \sim 13$–15%, compared with say $A^{\mu}_{FB} \sim 1\%$, which makes it less susceptible to possible systematic bias in an experimental determination.
2. It is independent of the detector acceptance.
3. It is independent of final state mass effects.
4. One can use *all* visible final states except electron pairs in its determination: *i.e.* 96% of visible Z^0 decays as opposed to only 4% for A_{FB} using muon pair events.
5. It is *very* sensitive to the electroweak mixing parameter $\sin^2\theta_W$, for one may write:

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

   which gives:

$$\delta A_{LR} \simeq -8\,\delta\sin^2\theta_W$$

   which also makes A_{LR} intrinsically more sensitive to $\sin^2\theta_W$ than A^{μ}_{FB}:

$$\delta A^{\mu}_{FB} \simeq -1.6\,\delta\sin^2\theta_W$$

6. It is very *in*sensitive to initial-state QED radiation, in contrast to A_{FB}, which varies rapidly in the c.m. energy region around the Z^0 pole.[10] The QED correction at the pole is $\Delta A_{LR} \sim 0.002$.[10,11]
7. QCD corrections vanish at $O(\alpha_s)$.[12]
8. By contrast, A_{LR} is very sensitive to virtual electroweak radiative corrections which depend on the masses of the top and Higgs particles. For example, varying the Higgs mass in the range 10–1000 GeV produces a corresponding change in A_{LR} of ± 0.009.[13] This can be compared with the ultimate theoretical precision on A_{LR} of ± 0.003[5] which comes mainly from the uncertainty in running the fine-structure constant α up to the Z^0 mass.

3. EXPERIMENTAL ERRORS IN THE DETERMINATION OF A_{LR}

In the previous section, A_{LR} was defined for the case of a 100% polarized electron beam. In practice, the polarization at the SLC is expected to be around 34% at startup in 1990, rising to between 40 and 45% for physics running with the SLD detector in 1991.[2] The *measured* left-right asymmetry, A^{exp}_{LR} is therefore related to A_{LR} by:

$$A^{exp}_{LR} = p\,A_{LR} \qquad (0 \le p \le 1)$$

Assuming equal luminosities for the left- and right-polarized beams, and no systematic biases in the detector acceptance:

$$A_{LR}^{exp} \quad = \quad \frac{N_L(p) \; - \; N_R(p)}{N_L(p) \; + \; N_R(p)}$$

So that one may write the statistical error as:

$$\delta^2 A_{LR} \quad = \quad \frac{1}{p^2\, N_Z}\,(1 \; - \; A_{LR}^2)$$

Making the reasonable assumption that the dominant systematic error is the error δp on the measurement of the magnitude of the polarization itself, the total experimental error is:

$$\delta A_{LR} \quad = \quad \sqrt{\frac{1 \; - \; (pA_{LR})^2}{p^2\, N_Z} \; + \; \left(\frac{\delta p}{p}\right)^2 \; A_{LR}^2}$$

Taking $p = 0.40$ and $\delta p/p = 5\%$, which are reasonable estimates of what may be achieved in the first year of physics running of the SLD, one sees that the systematic error dominates for $N_Z > 100$ k events, *i.e.* the precision on the asymmetry measurement is not limited by the expected precision on the measurement of the polarization until more than 100 k events have been collected.

Table 2 shows the precision achievable on $\sin^2\theta_W$, determined from a measurement of A_{LR}, as a function of the number of Z^0 events collected. The values $A_{LR} = 0.135$ and $p = 0.40$ were assumed.

Table 2. Precision on determination of $\sin^2\theta_W$ from measurement of A_{LR}

N_Z	$\delta p/p$	δA_{LR}	$\delta\sin^2\theta_W$
10^5	5%	0.010	0.0013
3×10^5	5%	0.008	0.0010
10^6	1%	0.003	0.00035

One can compare the precision of this measurement with that of measurements by methods using unpolarized Z^0 events, such as A_{FB} or the τ polarization.[5] Considering just the statistical errors, we know:

$$\delta A_{LR}^2 = \frac{1}{p^2 N_Z} \quad \Rightarrow \quad \delta \sin^2\theta_W = \frac{1}{8\sqrt{N_Z}\,p}$$

$$\delta {A_{FB}^{\mu}}^2 = \frac{1}{N_\mu} \quad \Rightarrow \quad \delta \sin^2\theta_W = \frac{1}{1.6\sqrt{N_\mu}}$$

$$\delta {A_{FB}^{b}}^2 = \frac{1}{N_b} \quad \Rightarrow \quad \delta \sin^2\theta_W = \frac{1}{5.6\sqrt{N_b}}$$

$$\delta {A_{pol}^{\tau}}^2 = \frac{1}{N_\tau} \quad \Rightarrow \quad \delta \sin^2\theta_W = \frac{1}{8\sqrt{N_\tau}}$$

For the same precision on $\sin^2\theta_W$ in each case, one can equate these expressions to obtain the relative numbers of events needed. For A_{FB}^{μ} one obtains $N_\mu/N_Z = 4$; but the branching ratio for $Z^0 \to \mu^+\mu^-$ is 4% of all visible Z^0 decays, which gives:

$$\frac{N_Z(A_{FB}^{\mu})}{N_Z(A_{LR})} \sim 100$$

In other words, roughly 100 times more Z^0 events are needed to obtain the same precision on $\sin^2\theta_W$ via A_{FB}^{μ} than via A_{LR}.

Similarly for A_{FB}^{b}, $N_b/N_Z = 0.32$, but the branching ratio for $Z^0 \to b\bar{b}$ is 22% of all visible Z^0 decays, and assuming a b-tagging efficiency of 10% one finds:

$$\frac{N_Z(A_{FB}^{b})}{N_Z(A_{LR})} \sim 17$$

For A_{pol}^{τ}, $N_\tau/N_Z = 0.16$, but the branching ratio for $Z^0 \to \tau^+\tau^-$ is 4% of all visible Z^0 decays, and the decay mode $\tau \to \pi\nu$, which contributes most of the information on the polarization, has a branching ratio of about 11%, so one finds:

$$\frac{N_Z(A_{pol}^{\tau})}{N_Z(A_{LR})} \sim 36$$

These numbers do not take into account systematic errors; when these are included, it is estimated[14] that for a measurement with precision $\delta \sin^2\theta_W = 0.001$, between five and ten million unpolarized Z^0 events are needed for A_{FB}^{μ}, A_{FB}^{b} and A_{pol}^{τ}, compared with around 100 k Z^0 events with a 40% polarized electron beam via A_{LR}. For this measurement, the polarization at SLC effectively makes up for an advantage of 50–100 in luminosity at LEP.

The Standard Model prediction for the dependence of A_{LR} on the top quark and Higgs masses is shown in Fig. 1.[2] $M_Z = 91.17$ was used in the calculation, and the width of the bands represents the variation in the prediction when M_Z is varied by ± 20 MeV around this value; this error is an estimate of the ultimate systematic uncertainty which can be obtained from LEP. The theoretical error on A_{LR} (Section 2) is shown as a point with dashed error bars. Two points with solid error bars are shown to represent the precision expected from a measurement of A_{LR} with the SLD detector at the SLC; both points assume a 40% polarized electron beam. The error bars indicated correspond to the sum of the statistical and systematic errors in the cases where the measurement is made using 100 k Z^0 events with a relative polarization determination of 5% and one million events with a relative polarization determination of 1%. Also shown is a point representing the error on a measurement of the τ polarization using six million unpolarized Z^0 events; this error is somewhat larger than that from the 100 k polarized Z^0 measurement.

The 100 k event A_{LR} measurement allows the top quark mass to be constrained to within ± 30 GeV at best (at $\pm$ one standard deviation); this is comparable in precision with a determination of M_t via measurement of the W mass to within 100 MeV[8]. The 1 M event A_{LR} measurement allows a constraint on M_t to within ± 10 GeV at best. Even the latter measurement could only constrain the Higgs mass to within several hundred GeV.

4. SUMMARY

Measurement of the left-right polarization asymmetry, A_{LR}, allows a very precise determination of $\sin^2\theta_W$. For a measurement by the SLD detector at the SLC using 100 k events with a 40% polarized electron beam, the precision on $\sin^2\theta_W$ is expected to be about 0.001, which would constrain the mass of the top quark to within about ± 30 GeV. Assuming the polarization can be measured with a relative error of 5%, the measurement is systematics-limited with statistics beyond a few hundred thousand events. If the polarization can be measured with a relative error of 1%, the systematics start to dominate only after several million events have been obtained. In this case, the top quark mass could be constrained to within ± 10 GeV. A comparable precision of 0.001 on $\sin^2\theta_W$ measured using unpolarized beams, via the forward-backward asymmetry for muons or b quarks, or via the τ polarization, requires a sample of between five and ten million events.

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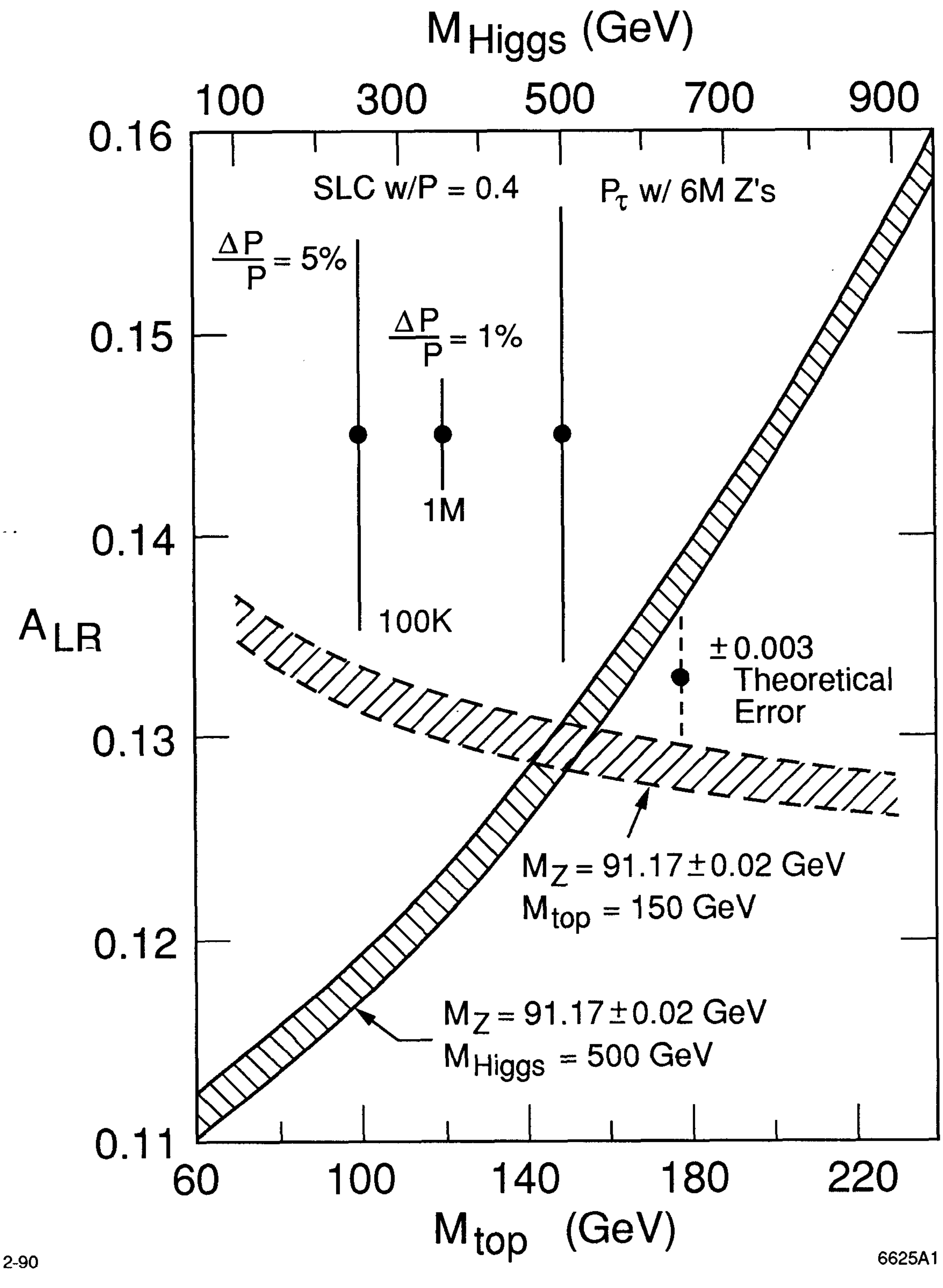
M Higgs (GeV)
100
300
500
700
900
0.16
0.15
0.14
0.13
0.12
0.11
SLC w/P = 0.4
Pτ w/ 6M Z's
ΔP/P = 5%
ΔP/P = 1%
1M
100K
A LR
± 0.003
Theoretical
Error
MZ = 91.17 ± 0.02 GeV
Mtop = 150 GeV
MZ = 91.17 ± 0.02 GeV
MHiggs = 500 GeV
60
100
140
180
220
Mtop (GeV)
2-90
6625A1

Fig. 1