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DOE Progress Report

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1. Introduction

The Oregon experimental high energy physics group came into existence in 1988 when Jim Brau came to Oregon. Ray Frey joined him and the Oregon faculty in 1989, and David Strom came in 1991. During these seven years the research focus of the group has been electroweak symmetry breaking and related measurements. Jim Brau and Ray Frey have devoted most of their effort to the SLD experiment at SLAC and David Strom has worked on the OPAL experiment at CERN. During the SSC era the group was very active in the R&D and planning for the SSC experiments, first on EMPACT, and eventually on GEM.

The University of Oregon has supported this effort very generously, beginning with the \$175,000 of start-up funds for the creation of the group, additional start-up contributions for Frey and Strom, machine and electronics shop credits equaling about \$3000 annually, and support for staff and matching support for grants. This extra direct support, which is in addition to faculty salaries, exceeds \$40,000 yearly. The university has always recognized the large off-campus component of the group in the indirect charges. Beginning with the next grant year (1996-97) the university has agreed to charge the entire project at the off-campus overhead rate of 26%. The university supported Institute of Theoretical Science provides clerical and administrative support.

During the first seven years, the group has included five postdoctoral research associates. Two of them have 'graduated' from the group: Cary Zeitlin (who left the group in 1991 to take a staff position at LBL, where he still works) and Koichiro Furuno (who left in 1993 to return to Japan). Three are still working with the group: Jennifer Huber (working on heavy quark physics at SLD), Robert Drucker (working on the NuTeV experiment at Fermilab), and Nikolai Sinev (working on the vertex detector upgrade for SLD).

Seven graduate students have worked in the group. Three graduated: Hwan-bae Park wrote a thesis on the left-right asymmetry measurement and is now a postdoctoral research associate at the University of Colorado working on CLEO and BaBar; Kevin Pitts wrote a thesis on the left-right asymmetry in Bhabha scattering and is now a postdoctoral research associate at Fermilab; and Hyun Hwang wrote a thesis on QCD tests in three jet events. The remaining students have been working on SLD (Matt Langston, Xiaoqing Yang, and Jingchen Zhou), OPAL (Wen-Ping Lai) and NuTeV (David Mason).

During the past year, the group pursued a vigorous program of research on SLD at SLAC (Brau and Frey), OPAL at CERN (Strom), and Experiment E-815 (NuTeV) at Fermilab (Brau and Frey). The group also completed a beam test for the GEM tracker project.

The SLD effort continues to span much of the collaboration's activities, from maintaining and operating the SLD luminosity monitor which was built at Oregon, to significant responsibility in physics analysis, such as event selection and background analysis for the left-right asymmetry measurement, studies of QCD in the polarized Z^0 decays, and polarized Bhabha scattering. In addition, Jim Brau serves as project manager for the new vertex detector upgrade (VXD3), and Ray Frey is the SLD Commissioner, requiring his presence at SLAC on a daily basis. Oregon currently maintains five people in residence at SLAC, including Frey.

The OPAL work focuses on the new silicon-tungsten luminosity monitor and the associated physics analyses. Oregon contributed in several important ways to the construction of this calorimeter, the commissioning of the detector and the writing of the reconstruction software, and has now made significant contributions putting forth the resulting precision luminosity measurements. Oregon currently maintains one student in residence at CERN, while Strom travels to CERN regularly.

The sign-selected neutrino experiment (NuTeV at Fermilab) has made good progress this past year in preparation for a physics run set to begin in 1996.

Overall, the Oregon group has made very significant progress on all the research projects it has undertaken, as the following report will affirm.

2. SLD

2.1 1994-95 Run

During the 1994-95 run, the SLAC Linear Collider produced over 100,000 Z^0 events at an average polarization of $(77.3 \pm 0.6)\%$. This allowed SLD to contribute world-class electroweak measurements, particularly with the new A_{LR} result.

The 1994-95 run began in earnest for physics in early July and continued through March, 1995. Further improvement in the strained GaAs photocathode technique provided the increased polarization of $\approx 80\%$.

2.2 SLD Physics Results

With the continued improvement in luminosity and polarization, the SLD physics program has expanded in the past year to cover a broad range of significant topics. There are many papers now published, and many others are in final preparation for submission for publication.

Table 2.1 lists many of the physics topics under investigation by the SLD Collaboration.

The Oregon group participates directly in the analysis of many of these topics. Most of the group is involved in one way or another in the measurement of the Left-right cross section asymmetry, A_{LR} .

The study of polarized $e^+e^- \rightarrow e^+e^-$ was essentially an Oregon project. Kevin Pitts wrote his Ph.D. thesis on this topic. (Pitts is now a research associate at Fermilab working on CDF). The Oregon group developed this into a paper which was published by the SLD Collaboration in Physical Review Letters this past year.

A paper based on the Ph.D. thesis of H. Hwang on three jet events and a test of QCD is in preparation. Likewise, the QCD analysis of J. Zhou on multiplicity distributions and factorial moments is being prepared for publication. J. Huber has worked on the b lifetime analysis and other heavy flavor topics, and is now working on the measurement of A_c . Xiaoqing Yang is doing her thesis on b-quark mixing. Group members have been active in a variety of other pieces of these efforts.

Table 2.1 Summary of Latest SLD Results

Measurement	Result	Publication
A_{LR}	0.1551 ± 0.0040 (preliminary 92-95)	PRL 73, 25 (1994)
Polarized $e^+e^- \rightarrow e^+e^-$	$v_e = -0.0414 \pm 0.0020$ $a_e = -0.4977 \pm 0.0045$	PRL 74, 2880 (1995)
A_b (tagged K^{+-}) A_b (jet charge) A_b (ℓ 's max likelihood)	$0.91 \pm 0.09 \pm 0.09$ $0.843 \pm 0.046 \pm 0.051$ $0.87 \pm 0.07 \pm 0.08$	PRL 74, 2890 (1995) PRL 74, 2895 (1995)
A_c (ℓ 's max likelihood) A_c (D^* tag)	$0.43 \pm 0.11 \pm 0.13$ $0.64 \pm 0.11 \pm 0.06$	PRL 74, 2895 (1995) w/ A_b PRL to be published
R_b (Double tag) τ_b (δ) τ_b ($\Sigma\delta$) τ_b (topol. vtx) τ_{B^0} (semilep.) τ_{B^+} (semilep.) τ_{B^+}/τ_{B^0} (semilep.) τ_{B^0} (topol.) τ_{B^+} (topol.) τ_{B^+}/τ_{B^0} (topol.)	$0.2171 \pm 0.004 \pm 0.0037$ $1.617 \pm 0.048 \pm 0.086$ ps $1.627 \pm 0.054 \pm 0.132$ ps $1.564 \pm 0.030 \pm 0.036$ ps $1.60^{+0.15}_{-0.14} \pm 0.10$ ps $1.49^{+0.11}_{-0.10} \pm 0.05$ ps $0.94^{+0.14}_{-0.12} \pm 0.07$ ps $1.55 \pm 0.07 \pm 0.12$ ps $1.67 \pm 0.06 \pm 0.09$ ps $1.08^{+0.09}_{-0.08} \pm 0.10$ ps	Submitted to PRD Submitted to PRL
τ_τ h_ν ξ $\xi\delta$	$297 \pm 9 \pm 5$ fsec $-0.89 \pm 0.21 \pm 0.07$ $1.17 \pm 0.35 \pm 0.21$ $0.49 \pm 0.24 \pm 0.13$	to be published in PRD, Nov. 1995
α_s (jet rates) α_s (EEC) α_s (combined methods) Δn_b Jet Handedness Flavor dependence of α_s : $\frac{\alpha_s(uds)}{\alpha_s(all)}$ $\frac{\alpha_s(c)}{\alpha_s(all)}$ $\frac{\alpha_s(b)}{\alpha_s(all)}$	$0.118 \pm .002 \pm .003 \pm .010$ $0.124^{+.003}_{-.004} \pm .009$ $0.1200 \pm .0025 \pm .0078$ $3.31 \pm 0.41 \pm 0.79$ $< 6.3\%, 9.9\%$ $0.987 \pm .027 \pm .022 \pm .022$ $1.012 \pm .104 \pm .102 \pm .096$ $1.026 \pm .041 \pm .041 \pm .030$	PRL 71, 2528(1993) PRD 50, 5580 (1994) PRD 51, 962 (1995) PRL 72, 3145(1994) PRL 74, 1512 (1995)] submitted to PRL]

In the following we describe some of the more significant results of the SLD experiment during the past year.

2.2.1 The Left-right Cross Section Asymmetry

The most notable physics result from SLC/SLD to date is the measurement of the left-right cross section asymmetry, A_{LR} . It represents the single most precise measurement of the electroweak mixing angle, hence providing a substantial test of the Standard Model. Figure 2.2.1.1 summarizes the electroweak mixing angle measurements from SLC and LEP as reported in Summer 1995. The SLD $\sin^2 \theta_W^{\text{eff}}$ measurement is the left-most point. (Note that the SLD A_{LR} measures the parity-violating parameter for electrons only, which strictly speaking, is only directly comparable to the LEP electron asymmetries A_{FB}^e and $\mathcal{P}_\tau^{FB}$.) In the discussion below, we give an introduction and brief history of the A_{LR} measurement in terms of SLC performance, followed by a discussion of the most recent result from the 1994-95 run. We emphasize the areas which involve substantial involvement by the Oregon group, in particular the event selection and background determination. In addition, the group is leading a substantial upgrade to the Compton beam polarization measurement, the most critical systematic input to A_{LR} . This is described in Section 2.5 and mentioned again in Section 2.4 of the Proposal.

Table 2.2.1.1 summarizes the history of the SLD A_{LR} measurement. Figures 2.2.1.2 and 2.2.1.3 graphically illustrate the improvement of the SLC luminosity and electron-beam polarization, respectively. The first run with longitudinally polarized electron beam at the SLAC Linear Collider (SLC) took place during 1992. By a combination of improved luminosity and much greater polarization, the precision of the result for the 1993 run improved by a factor 10. Roughly speaking, the SLC luminosity improved by a factor 2 in 1993 due to many factors, most notably the advent of flat beams; the polarization improved by slightly less than a factor of 3, due to the use of strained lattice photocathodes. The error on A_{LR} improved by a factor 2 for the 1994-95 run, with a factor $\sqrt{2}$ due to integrated luminosity and a factor $\sqrt{2}$ due to further improvement in beam polarization. (The A_{LR} error goes roughly as $1/\sqrt{N_Z \mathcal{P}_e^2}$, as discussed below, where $\mathcal{P}_e$ is the electron beam polarization.) Thinner GaAs photocathodes, which reduce the number of de-polarizing scatters of the photo-electrons in the GaAs, were responsible for the polarization improvement.

Table 2.2.1.1. History of A_{LR} measurement. The first A_{LR} error is statistical, the second systematic.

Run	Z Events	Polarization	A_{LR}	Reference
1992	10.2×10^3	$22.4 \pm 0.7\%$	$0.100 \pm 0.044 \pm 0.004$	PRL 70, 2515 (1993)
1993	49.4×10^3	$63.0 \pm 1.1\%$	$0.1628 \pm 0.0071 \pm 0.0028$	PRL 73, 25 (1994)
1994-95	92.3×10^3	$77.34 \pm 0.62\%$	$0.1495 \pm 0.0042 \pm 0.0012$	prelim.
Combined			0.1551 ± 0.0040	prelim.

The left-right asymmetry is defined as

$$A_{LR} \equiv (\sigma_L - \sigma_R) / (\sigma_L + \sigma_R),$$

where σ_L and σ_R are the e^+e^- production cross sections for Z bosons (at the Z pole) with left-handed and right-handed electrons, respectively. To leading order, the Standard Model predicts that this quantity depends upon the vector (v_e) and axial-vector (a_e) couplings of the Z boson to the electron current,

$$A_{LR} = A_e = \frac{2v_e a_e}{v_e^2 + a_e^2} = \frac{2 [1 - 4 \sin^2 \theta_W^{\text{eff}}]}{1 + [1 - 4 \sin^2 \theta_W^{\text{eff}}]^2}$$

We retain the tree-level relations between the couplings and the electroweak mixing parameter to compare with the experimental measurement of A_{LR} , effectively including higher-order corrections in $\sin^2 \theta_W^{\text{eff}}$ (as well as a_e and v_e). This effective electroweak mixing parameter is then defined by $\sin^2 \theta_W^{\text{eff}} \equiv (1 - v_e/a_e)/4$. This convention is particularly useful for the measurement of the electroweak asymmetries at the Z resonance. The quantity A_e is the neutral-current parity violating parameter for electrons.

A_{LR} has a number of nice properties. First, it is a sensitive function of $\sin^2 \theta_W^{\text{eff}}$, with $\delta \sin^2 \theta_W^{\text{eff}} \approx \delta A_{LR}/7.5$. It is a large asymmetry with well known radiative corrections. It is relatively insensitive to energy. Finally, A_{LR} does not depend upon the couplings of the Z to its final states. Hence, all visible Z decay modes can in principle be used in the measurement. In practice, the e^+e^- final state is discarded by SLD due to its large zero-asymmetry contribution from photon exchange. Also, for the calorimetric event selection used in the A_{LR} analysis, SLD does not select $\mu^+\mu^-$ final states, and is not very efficient in selecting $\tau^+\tau^-$ events. However, this still leaves about 3/4 of the total Z cross section which can be used for A_{LR} . This represents a tremendous statistical advantage over Z asymmetry measurements which rely on a single final state.

The experimental aspects of the A_{LR} measurement are also rather unique. The SLD detector is not required to identify specific final states, except to discard e^+e^- events. The switching between left and right-hand polarization states is done randomly at 120 Hz, which, in principle, makes the integrated luminosity for left and right-handed running identical. In this case, the definition above becomes

$$A_m = \frac{N_L - N_R}{N_L + N_R}$$

The experimental difficulty is dominated by the measurement of the electron beam polarization, $\mathcal{P}_e$. For a partially polarized beam the experimental determination of A_{LR} is essentially $A_{LR} = A_m/\mathcal{P}_e$. Small corrections to this formulation are discussed below. In this approximation, the A_{LR} measurement error is

$$\delta A_{LR} = \left[\frac{1}{N_Z \mathcal{P}_e^2} + A_{LR}^2 \left(\frac{\delta \mathcal{P}_e}{\mathcal{P}_e} \right)^2 \right]^{1/2},$$

where $N_Z = N_L + N_R$ is the total number of events and $\delta \mathcal{P}_e$ is the error of the polarization measurement. We see immediately from this that a large polarization is critical, and that the relative error on the polarization measurement needs to be a few percent or less.

A convenient expression for the luminosity of a linear e^+e^- collider is

$$\mathcal{L} = \frac{N^+ N^- f H_D}{4\pi (\beta_x^* \beta_y^* \epsilon_x \epsilon_y)^{1/2}}$$

Here N^+ and N^- are the colliding e^+ and e^- bunch populations, and f is the frequency of collision (120 Hz for the SLC). β^* is essentially the focal length at the e^+e^- interaction point (IP), and ϵ is the beam emittance. H_D is an enhancement factor ("pinch") due to the additional contraction of one bunch as it passes through the intense collective electromagnetic field of the other bunch. This factor is one for small fields. It was estimated to be as large as 1.1–1.2 during the best 1993–95 running, but has yet to be directly measured.

The most dramatic changes for the 1993 run included the use of strained-lattice cathodes at the SLC source, which gave a large increase in electron beam polarization (from 22% to 63%), and the advent of flat beam operation, which gave higher luminosity (by a factor ≈ 2). During the initial run with polarized beam in 1992, the polarization was mostly limited by the "thick" GaAs photocathode at the electron source, resulting in an average polarization at the e^+e^- IP of 22.4%. Meanwhile, an interesting program of R&D on strained-lattice photocathodes indicated

[2.2.1.1] that much higher polarization was possible. These results are summarized in Fig. 2.2.1.4. In unstrained GaAs, the theoretical maximum polarization of the emitted electrons is 50%, owing to the degeneracy of two competing transitions. The 1993 strained lattice consisted of a $\text{GaAs}_{1-x}\text{P}_x$ ($x = 0.24$) substrate of thickness $2.5\text{ }\mu\text{m}$ with an epitaxial layer of GaAs of thickness $0.1\text{--}0.3\text{ }\mu\text{m}$. This alters the lattice spacing over a significant depth in the photocathode, hence removing the transition degeneracy. As with previous photocathodes, approximately one atomic layer of cesium and fluorine applied to the cathode surface substantially increases the quantum efficiency (5–15%), thereby making the devices practical for SLC operation. With the GaAs degeneracy removed, a Ti-sapphire laser operating at 865 nm excites the lower-energy transition. The variation of the measurements over time, as can be seen in Fig. 2.2.1.3, represents correlations with changes in SLC operation, generally either due to re-coating of the source photocathode or to a re-tuning of the arc orbit.

In the absence of chromatic effects, the beam spot size at focus is proportional to the square root of the product of the beam emittances, ϵ_x and ϵ_y . It had long been known that the IP spot size could possibly be reduced by producing “flat” (i.e. elliptical) beam. Damping rings will naturally tend to give a lower emittance product, $\epsilon_x\epsilon_y$, when ϵ_y is allowed to be made smaller than ϵ_x . However, prior to 1992 it was thought that polarized beam transport was incompatible with flat beams. A solenoidal field will introduce x - y coupling of the beam phase space due to the beam betatron motion. Therefore, the SLC RTL solenoid, necessary to produce longitudinal polarization, would ruin the flat beams. Flat-beam running with polarized beam was made possible by “spin bumps”, a phenomenon of the SLC arcs discovered [2.2.1.2] during the 1992 run. It was found that the polarization at the IP was strongly affected by the position of the electron beam launch into the arc. Longitudinally polarized electrons launched into the North Arc undergo $g - 2$ precession in the arc bending fields. Normally, the resulting IP polarization would be very insensitive to the arc launch details. However, as it turns out, the spin precession frequency in the arc is almost exactly equal to the arc betatron oscillation frequency. (Each of the 23 arc achromats produces 1085° of spin precession and 1080° of betatron oscillation.) This means that spin precession in a non-bend plane can accumulate during the focussing-defocussing process by an amount which depends on arc launch position. In practice, a vertically polarized beam at the end of the Linac can be made longitudinal at the IP by a pair of large betatron oscillations in the North Arc. This was standard practice for the 1993-95 runs.

In principle, the focussing of the beams at the IP can map each beam-energy component to a different effective point of focus, resulting in a correlation between transverse position at the IP and energy, or equivalently between position and

polarization. This would not be an experimental issue except that the polarization of those electrons which weight Z production at the IP can be different from the polarization of the entire electron beam, averaged over its full spatial extent. In the former case, the electron beam is sampled by its interaction probability to make Z 's via positrons; this is referred to as the luminosity-weighted polarization, $\mathcal{P}_e$. The latter case is relevant for the polarization measurement using Compton scattering, $\mathcal{P}_e^C$, as the spatial extent of the Compton laser beam is much larger than the electron beam, hence sampling all electrons with equal weight. If the electron beam had only gaussian energy tails, the difference between $\mathcal{P}_e$ and $\mathcal{P}_e^C$ would be small ($< 0.2\%$) and readily modelled. However, in 1993 the beam was observed to have a long low-energy tail extending to $\Delta E/E$ of about -1% . This gave rise to the largest systematic error for the 1993 run (although still negligible compared to the statistical error): $\mathcal{P}_e = (1.017 \pm 0.012)\mathcal{P}_e^C$. This was dispensed with for the 1994-95 run by eliminating the low-energy tail at the front-end of the SLC. In addition, the energy spread was measured throughout the run, and several scans of $\mathcal{P}_e$ with beam energy allowed a complete verification of the size of the effect and its error.

The overall layout of the Compton scattering measurement of the electron beam polarization is shown in Fig. 2.2.1.5. Longitudinally polarized photons of energy 2.33 eV, provided by 532 nm circularly polarized laser pulses from a frequency-doubled Nd:YAG laser, are brought into collision with the outgoing electron beam 33 m past the IP. The back-scattered Compton electrons, ranging in energy from 17.4 GeV to about 30 GeV, are detected by a multi-channel Cherenkov detector after being separated from the main electron beam by two dipole magnets which are the final bend magnets of the SLC Final Focus. At the face of the Cherenkov detector, the Compton electrons shower in a retractable 8 mm lead radiator. The Compton cross section can be written

$$\frac{d\sigma}{dE_s} = \frac{d\sigma_0}{dE_s} [1 + \mathcal{P}_\gamma \mathcal{P}_e^C A(E_s)],$$

where E_s is the Compton-scattered electron energy, $\mathcal{P}_\gamma$ is the polarization of the laser photon beam, $\mathcal{P}_e^C$ is the electron beam polarization, and $A(E_s)$ is the Compton polarization asymmetry function. $A(E_s)$ is the asymmetry in the theoretical Compton cross section for the $J_z = \frac{3}{2}$ versus $\frac{1}{2}$ combinations of $e\gamma$. It also includes corrections of about 2% to account for the response of the Cherenkov detector. The maximum asymmetry occurs at the kinematic endpoint, $E_s = 17.4$ GeV, which corresponds to 180° electron scattering in the $e\gamma$ center-of-momentum frame. The Compton process itself gives fiducials which can be used to calibrate the Cherenkov detector. The kinematic endpoint can be precisely determined in the detector.

The detector can, in special runs, be translated across the endpoint on its moveable table to verify the position of the endpoint, thus providing a calibration of the position-momentum relationship. The measured asymmetry in each detector channel is equal to the combination $\mathcal{P}_\gamma \mathcal{P}_e^C A(E_s)$, where E_s corresponds to the mean energy for that channel.

Unlike other precision electroweak measurements involving e^+e^- at the Z resonance, A_{LR} does not rely on the detailed reconstruction of the final state. The primary requirements for SLD are a good efficiency for detection of hadronic final states which is symmetric in scattering angle, and a good separation of these events from e^+e^- final states and accelerator-related backgrounds. The measured "raw" asymmetry, A_m can then be formed. Of primary importance for the A_{LR} analysis is the SLD liquid argon calorimetry (LAC). The LAC consists of projective towers, longitudinally segmented into two electromagnetic (EM) sections of 21 radiation lengths total depth, and two hadronic sections, which combine with the EM sections to give 2.8 interaction lengths. This is the case for both barrel and endcap sections. The LAC covers 98% of the total solid angle, with about 80% of this in the barrel section. The small scattering angle region uses silicon-tungsten calorimetry, built at Oregon, to measure luminosity with Bhabha scattering.

The offline calorimetric event selection for A_{LR} occurs in two stages. The Pass1 process provides a loose selection of physics events by means of a few cuts on energy deposition in the LAC. All triggered events are subject to Pass1 analysis, which requires only calibrated raw data as input. About 90% of background events are removed at this stage, with a corresponding reduction of the event count by a factor ~ 50 , depending upon running conditions.

At the Pass2 stage, calorimeter reconstruction is performed, and a more refined selection of events is performed, the end product being the final event sample. The Pass2 reconstruction forms clusters from the LAC tower data. An algorithm is employed to discard energy depositions resulting from background muons. The following quantities are defined in terms of the LAC clusters which exceed an energy threshold, E_{min} :

- N_{cl} : total number of clusters exceeding E_{min} ;
- $E_{tot} = \sum E_i$;
- $I = |\sum E_i \hat{r}_i| / E_{tot}$;

where the sums are over clusters above E_{min} , which is typically 100 MeV. E_i is the energy of a LAC cluster and $\hat{r}_i$ is a unit displacement vector from the nominal SLD origin to the i th LAC cluster. The quantity I , known as the energy imbalance, is the magnitude of the 3-dimensional energy imbalance vector, relative to the total energy.

The distributions in the quantities E_{tot} , I , and N_{cl} are shown in 2.2.1.6 for the 1993 data for the events selected by Pass1. The N_{cl} distribution is separated into central and forward regions. In this analysis we refer to $\cos \theta_{th} < 0.8$ as the central region and $\cos \theta_{th} > 0.8$ as the forward region, where $\cos \theta_{th}$ is the absolute value of the cosine of the thrust axis in the LAC. This division corresponds roughly to regions of different LAC response.

The Pass2 event selection consisted of the following:

1. $E_{tot} > 15$ GeV
2. $I < 0.6$
3. $N_{cl} \geq \begin{cases} 9, & \cos \theta_{th} < 0.8 ; \\ 12, & \cos \theta_{th} \geq 0.8. \end{cases}$

The first cut broadly accepts hadronic events. The second cut is designed to eliminate beam-related backgrounds. The third cut is designed to eliminate wide-angle Bhabha events. All three cuts reduce the efficiency for selection of tau-pair final states relative to hadronic final states. Figure 2.2.1.7 is a scatter plot of I versus N_{cl} for the endcap region, $\cos \theta_{th} \geq 0.8$. The backgrounds from both sources are negligible in the barrel region relative to the endcap. WAB events accumulate in the lower-left corner of this plot and beam background events, being typically not momentum balanced, accumulate in the upper portion. The rectangular cuts listed above are shown on the plot, leaving mostly hadronic events in the lower right rectangle.

The primary backgrounds to this selection are due to beam-related backgrounds and wide-angle Bhabha (WAB) events. The beam backgrounds are primarily interactions of off-axis beam electrons or positrons with accelerator structures (masks, collimators, beam pipe) producing electromagnetic showering, for interactions near SLD, or muons for distant interactions. Beam gas interactions are also present, although these represent a small contribution to backgrounds in the case of the calorimetric selection. The beam background is extracted from the shape of the distribution in I based on the data only, as depicted in Fig. 2.2.1.7. For the WAB background monte carlo simulation is used to aid the estimation of the number of events crossing the N_{cl} cut. For the 1994-95 preliminary result, this procedure yielded a beam background fraction of $(0.12 \pm 0.03)\%$ and a WAB background of $(0.17 \pm 0.10)\%$. The total background fraction for the preliminary result is therefore $f_b = (0.31 \pm 0.10)\%$. Since the WAB events include s-channel and s—t channel interference contributions, this background itself has a small left-right asymmetry, A_b , which is taken into account in the A_{LR} correction factor ($A_m - A_b$) given below. Other backgrounds, due to cosmic rays or $\gamma\gamma$ events, are negligible.

The final analysis of the 1994-95 data is in progress and includes some refine-

ments commensurate with the increased statistical precision. This includes some improvements in the event selection and background determination. Since A_{LR} is statistics limited, the fact that in previous runs the central drift chamber (CDC) was occasionally off led to the use of the purely calorimetric analysis. However, in the 1994-95 run the drift chamber missed only a small fraction of the data, and the increased systematic control available with the inclusion of the tracking data has led to a global analysis which will likely be used for the final published results. Figure 2.2.1.8 is a scatter plot of the calorimetric quantity N_{cl} discussed above versus the CDC track multiplicity in the barrel region. The hadronic events are clearly separated from backgrounds. Two-prong WAB events are tightly clustered, and one prong versus three prong τ pair events are clearly visible. The tracking information also allows virtual elimination of beam backgrounds.

The measured asymmetry A_m is related to A_{LR} by the following expression, an extension of that given earlier, which incorporates a number of small correction terms in square brackets,

$$A_{LR} = \frac{A_m}{\langle \mathcal{P}_e \rangle} + \frac{1}{\langle \mathcal{P}_e \rangle} [f_b(A_m - A_b) - A_{\mathcal{L}} + A_m^2 A_{\mathcal{P}} - E \frac{\sigma'(E)}{\sigma(E)} A_E - A_{\epsilon} + A_m(1 - \langle \mathcal{P}_e \rangle^2) \mathcal{P}_p]$$

where $\langle \mathcal{P}_e \rangle$ is the mean luminosity-weighted polarization for the 1993 run; f_b is the background fraction; $\sigma(E)$ is the unpolarized Z cross section at center of mass energy E ; $\sigma'(E)$ is the derivative of the cross section with respect to E ; and A_b , $A_{\mathcal{L}}$, $A_{\mathcal{P}}$, A_E , and A_{ϵ} are the left-right asymmetries of the background, the integrated luminosity, the beam polarization, the center-of-mass energy, and the product of detector acceptance and efficiency, respectively. $\mathcal{P}_p$ is any longitudinal positron polarization.

Table 2.2.1.2 below summarizes the systematic errors and corrections for the preliminary 1994-95 A_{LR} result. All of the small correction terms in the square brackets in the equation above are included in the "asymmetry corrections" in the Table. The analyses are still in progress, and it is expected that a total systematic error of about 0.5% can be achieved.

Table 2.2.1.2. Systematic uncertainties and corrections for A_{LR}
(preliminary 1994-95.)

Systematic Uncertainty	$\delta \mathcal{P}_e^C / \mathcal{P}_e^C$ (%)	$\delta A_{LR} / A_{LR}$ (%)
Laser Polarization	0.2	
Detector Linearity	<0.5	
Analyzing Power calib	0.29	
Cross Checks	<0.4	
Electronic Noise Correction	0.2	
Total Polarimeter Uncertainty	0.8	0.8
Chromaticity Correction		0.2
Asymmetry Corrections		0.1
Total Systematic Uncertainty		0.8

As recorded in Table 2.2.1.1, the preliminary result for the 1994-95 run is

$$A_{LR} = 0.1495 \pm 0.0042 \pm 0.0012$$

The mean center-of-mass energy for this data was 91.270 GeV, which is slightly off the Z pole. Including this effect, plus very small corrections for Z-photon interference and e^+e^- annihilation to photons, gives the equivalent pole value

$$A_{LR}^0 = 0.1524 \pm 0.0042 \pm 0.0012$$

This gives a preliminary electroweak mixing angle result for 1994-95 of

$$\sin^2 \theta_W^{\text{eff}} = 0.23084 \pm 0.00054 \pm 0.00015$$

which when combined with the previous SLD results gives

$$\sin^2 \theta_W^{\text{eff}} = 0.23049 \pm 0.00050$$

This is the value plotted in Fig. 2.2.1.1. The LEP average given in this figure is 0.2318 ± 0.0004 , which is 2.0 standard deviations from the SLD result.

The group plans to report the final results by the end of 1995 in two publications: Physical Review Letters and Physical Review D. R. Frey is writing up the event selection and background determination sections.

One way of evaluating the impact of the A_{LR} result is given in Fig. 2.2.1.9, which shows the $S - T$ parameterization of electroweak symmetry breaking of Peskin and Takeuchi for various measureables as of Summer 1995. The black region in the center represents the Standard Model prediction within the errors of the Tevatron top mass measurement and within a broad Higgs mass range.

As discussed in the Proposal, the fact that the A_{LR} measurement is statistics limited implies that an extended high-statistics run would provide an “archival” measurement of $\sin^2 \theta_W^{\text{eff}}$. Figure 2.2.1.10 indicates how the error on $\sin^2 \theta_W^{\text{eff}}$ varies with accumulated data. The upper curve assumes a polarization of 75% and a total systematic error of 1.0%, while the lower curve is for 90% and 0.5%, respectively.

2.2.2 The Left-right Cross Section Asymmetry in $e^+e^- \rightarrow e^+e^-$

The left-right cross section asymmetry described above is a measure of the initial state electron coupling to the Z^0 . For simplicity, the e^+e^- final state (Bhabha scattering) was omitted in the A_{LR} measurement due to the dilution of the asymmetry from the large QED contribution of the t-channel photon exchange. In a separate analysis we made two additional measurements: the first measurement of the left-right cross section asymmetry in polarized Bhabha scattering ($A_{LR}^{e^+e^-}(|\cos \theta|)$), and measurements of the effective electron coupling parameters based on a combined analysis of the A_{LR} measurement [2.2.2.1] and the Bhabha cross section and angular distributions. The vector coupling measurement is the most precise yet presented by any one experiment. This analysis was solely the work of the Oregon group, being led by Kevin Pitts for his Ph.D. thesis research and carried forward to publication by Jim Brau after Pitts left Oregon. During the past year the analysis was published by the SLD Collaboration in Physical Review Letters. [2.2.2.2] An analysis based on the most recent SLD data (1994-95) is being prepared by Matt Langston of Oregon.

In the Standard Model, measuring the left-right asymmetry yields a value for the quantity A_e , a measure of the degree of parity violation in the neutral current, since:

$$A_{LR} = A_e = \frac{2v_e a_e}{v_e^2 + a_e^2} = \frac{2[1 - 4\sin^2 \theta_W^{\text{eff}}]}{1 + [1 - 4\sin^2 \theta_W^{\text{eff}}]^2}, \quad (1)$$

where the effective electroweak mixing parameter is defined as $\sin^2 \theta_W^{\text{eff}} = \frac{1}{4}(1 - v_e/a_e)$, and v_e and a_e are the effective vector and axial vector electroweak coupling parameters of the electron. The partial width for Z^0 decaying into e^+e^- is dependent on the coupling parameters :

$$\Gamma_{ee} = \frac{G_F M_Z^3}{6\sqrt{2}\pi} (v_e^2 + a_e^2) (1 + \delta_e), \quad (2)$$

where $\delta_e = \frac{3\alpha}{4\pi}$ is the correction for final state radiation. G_F is the Fermi coupling constant and M_Z is the Z^0 boson mass. By measuring A_e and Γ_{ee} , the above equations can be utilized to extract v_e and a_e .

The analysis was based on data collected during the 1992 and 1993 runs; it utilizes the calorimetry systems of the SLD detector. Small angle coverage (28-65 mrad from the beamline) is provided by the finely-segmented silicon-diode/tungsten-radiator luminosity calorimeters (LUM) [2.2.2.3], originally designed and built by the Oregon group, and now operated in SLD by the Oregon group. The LUM measures small angle Bhabha scattering, thereby providing both the absolute luminosity and a check that the left-right luminosity asymmetry is small. Events at larger angles from the beamline (> 200 mrad) are measured with the liquid argon calorimeter (LAC) [2.2.2.4].

To minimize systematic uncertainties in the LUM due to detector misalignment and the location of the interaction point, we employ a "gross-precise" method [2.2.2.5] which uses a larger fiducial region on one end of the detector than the other. The systematic error analysis of the luminosity measurement is conservative [2.2.2.6]. The total systematic uncertainty is 0.93%, which is composed of 0.88% experimental and 0.3% theoretical uncertainty. The integrated luminosity is $\mathcal{L} = 385 \pm 3$ (stat) ± 4 (sys) nb^{-1} for the 1992 polarized SLC run and $\mathcal{L} = 1781 \pm 5$ (stat) ± 17 (sys) nb^{-1} for the 1993 SLC run.

The efficiency for accepting wide angle $e^+e^- \rightarrow e^+e^-$ events is found to be 86.7% overall and 93% in the central region of the detector. Two small sources of contamination are $e^+e^- \rightarrow \gamma\gamma$ (1.25%) and $e^+e^- \rightarrow \tau^+\tau^-$ (0.28%). Other sources of contamination are all negligible.

This analysis is based on 7926 accepted events in the wide-angle region and 212,794 accepted events in the small-angle region. The asymmetry is defined as:

$$A_{LR}^{e^+e^-}(|\cos\theta|) = \frac{1}{\langle \mathcal{P}_e \rangle} (N_L - N_R) / (N_L + N_R),$$

where $N_L(N_R)$ is the number of events tagged with a left-(right-) handed electron beam as a function of the $|\cos\theta|$, where θ is the center-of-mass scattering angle for the e^+e^- system after initial state radiation. The expected asymmetry ($A_{LR}^{e^+e^-}(|\cos\theta|)$) is largest at $\cos\theta = 0$, and may be approximately written as $A_{LR}^{e^+e^-}(|\cos\theta|) = A_e(1 - f_t(|\cos\theta|))$, where $f_t(|\cos\theta|)$ represents the t-channel contribution. For the region $|\cos\theta| < 0.7$, $\langle f_t \rangle \simeq 0.12$. The expected asymmetry is very small ($\sim 10^{-4}$) in the small angle region.

To extract Γ_{ee} and A_e , the data are fit to the differential e^+e^- cross section using the maximum likelihood method. Two programs are used to calculate the

differential e^+e^- cross section: EXPOSTAR [2.2.2.7] and, as a cross check, DMIBA [2.2.2.8]. To extract the maximal amount of information from the differential polarized Bhabha scattering distribution, the fit is performed over the entire angular region accepted by the LAC ($|\cos \theta| < 0.98$). No t-channel subtraction is performed. All ten lowest order terms in the cross section are included in the fit: the four pure s-channel and t-channel terms for photon and Z^0 exchange, and the six interference terms [2.2.2.9]. The fit also includes initial state radiation. Since the measurement is calorimetric it is insensitive to final state radiation.

The partial width Γ_{ee} is extracted from the data in two ways: (1) using the full fit to the differential cross section for $|\cos \theta| \leq 0.98$, and (2) measuring the cross section in the central region ($|\cos \theta| < 0.6$) where the systematic errors are smaller, yielding a more precise measurement. For the fits we use $M_Z = 91.187 \text{ GeV}/c^2$ and $\Gamma_Z = 2.489 \text{ GeV}/c^2$ [2.2.2.10]. Figure 2.2.2.1 shows the fit to the full $e^+e^- \rightarrow e^+e^-$ distribution. This fit has a $\chi^2 = 51.6$ for 39 degrees of freedom, yielding $\Gamma_{ee} = 83.14 \pm 1.03 \text{ (stat)} \pm 1.95 \text{ (sys)} \text{ MeV}$.

A more precise determination of Γ_{ee} was performed using only the central region of the LAC ($|\cos \theta| < 0.6$) and the small angle region in the LUM [2.2.2.11]. The program MIBA [2.2.2.12] is then used to calculate Γ_{ee} based on the total measured cross section within the defined fiducial region. From this method, we find:

$$\Gamma_{ee} = 82.89 \pm 1.20 \text{ (stat)} \pm 0.89 \text{ (sys)} \text{ MeV}.$$

To extract A_e from the Bhabha events, the right- and left-handed differential $e^+e^- \rightarrow e^+e^-$ cross sections are fit directly for v_e and a_e using EXPOSTAR. This yields

$$A_e = 0.202 \pm 0.038 \text{ (stat)} \pm 0.008 \text{ (sys)}.$$

Figure 2.2.2.2 shows the measured left-right cross section asymmetry for $e^+e^- \rightarrow e^+e^-$ ($A_{LR}^{e^+e^-}(|\cos \theta|)$) compared to the fit. The fit shown in Figure 2.2.2.2 has a χ^2 of 4.36 for 5 degrees of freedom.

The results for Γ_{ee} and A_e from above may now be used in equations (1) and (2) to extract the effective vector and axial vector couplings to the Z^0 : $v_e = -0.0507 \pm 0.0096 \text{ (stat)} \pm 0.0020 \text{ (sys)}$, $a_e = -0.4968 \pm 0.0039 \text{ (stat)} \pm 0.0027 \text{ (sys)}$, where lower energy e^+e^- annihilation data have been utilized to assign $|v_e| < |a_e|$, and $\nu_e e$ scattering data have been utilized to establish $v_e < 0$ and $a_e < 0$ [2.2.2.13]. Figure 2.2.2.3 shows the one standard deviation (68%) contour for these electron vector and axial vector coupling measurements. Most of the sensitivity to the electron vector coupling and, hence, $\sin^2 \theta_W^{\text{eff}}$ arises from the measurement of A_e , while the sensitivity to the axial vector coupling arises from Γ_{ee} . Also shown are

standard model calculations using the program ZFITTER[2.2.2.14]. The effective electroweak mixing angle represented by these vector and axial vector couplings is:

$$\sin^2 \theta_W^{\text{eff}} = 0.2245 \pm 0.0049 \text{ (stat)} \pm 0.0010 \text{ (sys)}.$$

We reiterate that this measurement derives strictly from the Bhabha events.

The SLD Collaboration obtains a more precise measurement of A_e from the left-right cross section asymmetry (A_{LR}) measurement as described above[2.2.2.1]. Combining the Bhabha results with the 1993 SLD measurement of A_{LR} gives:

$$v_e = -0.0414 \pm 0.0020 \quad a_e = -0.4977 \pm 0.0045,$$

the most precise measurement of the electron vector coupling to the Z^0 published by a single experiment to date. The v_e, a_e contour including the A_{LR} measurement is also shown in Figure 2.2.2.3, demonstrating the increased sensitivity in v_e from A_{LR} . Matt Langston is working on the update of this measurement with the 1994-95 data.

2.2.3 Heavy Quark Coupling Measurements

The measurements of the Z^0 couplings to the fundamental fermions are an important part of the precision tests of the Standard Model (SM) of electroweak interactions. Possible new physics beyond the Standard Model may manifest themselves through the radiative corrections to these couplings. The measurements of Z^0 couplings to heavy quarks are of especial interest due to the expected larger radiative corrections to the Z - $q\bar{q}$ vertex with q being a heavy quark, both within the Standard Model and from models beyond.

The search for new physics can benefit from an unique set of precision measurements with enhanced sensitivity through the utilization of longitudinally polarized electron beams at the SLC. In addition the small beam size at the SLC IP, $(\sigma_x, \sigma_y, \sigma_z) \approx (2.5, 0.8, 700) \mu\text{m}$, and the stability of the spot in time allows excellent identification and resolution of secondary decay vertices. These factors combined with the long time between beam crossings (8.3 msec) make the use of a high-precision CCD vertex detector possible. The CCD vertex detector (VXD) consists of 60 CCD ladders, 1.2×10^8 pixels altogether, with an inner radius of 2.95 cm, and extending to a radius of 4.15 cm. (The local resolutions in r - ϕ and z are $7 \mu\text{m}$ and $8 \mu\text{m}$, respectively.) The coverage is to $|\cos \theta| < 0.76$. The efficiency of linking to central drift chamber tracks is $> 95\%$. Using $Z \rightarrow \mu^+ \mu^-$ events, the impact parameter resolution of the system is found to be $11 \mu\text{m}$ in the x - y plane and $37 \mu\text{m}$ for r - z .

The most precise SLD measurements of the $Z-q\bar{q}$ vertex are from the left-right forward-backward asymmetries for b and c quarks,

$$\tilde{A}_{FB}^q = \frac{(\sigma_{LF}^q - \sigma_{LB}^q) - (\sigma_{RF}^q - \sigma_{RB}^q)}{(\sigma_{LF}^q + \sigma_{LB}^q) + (\sigma_{RF}^q + \sigma_{RB}^q)},$$

and from the b quark partial width, $R_b = \Gamma_{bb}/\Gamma_{had}$.

SLD has measured the left-right forward-backward asymmetries $\tilde{A}_{FB}^q$ for b and c quarks with several techniques. The parity violating parameters (A_b and A_c) can be isolated from

$$\tilde{A}_{FB}^q(\cos \theta) = \mathcal{P}_e A_q \frac{2 \cos \theta}{1 + \cos^2 \theta}.$$

The current analyses extract A_b and A_c using maximum likelihood techniques based on the Born-level differential cross section. The first technique is an improved self-calibrated analysis based on jet charge to distinguish b quark jets from anti-b quark jets. This method yields $A_b = 0.843 \pm 0.046 \pm 0.051$. A new analysis uses K^{+-} identified by the Cerenkov Ring Imaging Detector for $B/\bar{B}$ discrimination, measuring a value of $A_b = 0.91 \pm 0.09 \pm 0.09$. A third method identifies leptons in hadronic decays and uses the lepton momentum and transverse momentum to classify the event, distinguishing between the quark and anti-quark from the lepton charge. This method yields $A_b = 0.87 \pm 0.07 \pm 0.08$ and $A_c = 0.43 \pm 0.11 \pm 0.13$. Finally A_c is measured from exclusive D^*, D^+ reconstruction through a combination of kinematic and decay length analysis. This technique results in $A_c = 0.64 \pm 0.11 \pm 0.06$. These values are all in good agreement with the Standard Model expectation of $A_b = 0.94$ and $A_c = 0.67$. The long term goal of SLD, with the vertex detector upgrade, is to measure A_b to a few percent in order to be sensitive to possible deviations from the Standard Model.

R_b has been measured by SLD using several techniques. The most precise method uses a lifetime double tag that b-tags hemispheres with a 3D impact probability tag. The preliminary result of this new analysis is:

$$R_b = 0.2171 \pm 0.004 \pm 0.0037.$$

With future data and the SLD vertex detector upgrade, the double tag method promises to yield a measurement of R_b accurate to about $\frac{1}{2}\%$.

2.2.4 B Lifetimes

Two techniques have been employed to extract the B lifetime, averaged over B^+ , B^- , and B^0 . One is the standard impact parameter analysis, either based on the impact parameter distribution (τ_b^δ) or using the distribution of the sum of

impact parameters in each event ($\tau_b^{\Sigma\delta}$). The other is to use reconstructed vertices in three dimensions. The results from these methods are:

$$\tau_b^\delta = 1.617 \pm 0.048 \pm 0.086 \text{ ps}$$

$$\tau_b^{\Sigma\delta} = 1.627 \pm 0.054 \pm 0.132 \text{ ps}$$

$$\tau_b^\delta = 1.564 \pm 0.030 \pm 0.036 \text{ ps.}$$

The lifetimes of B^0 and B^+ mesons have been measured using two new techniques. The first analysis identifies semileptonic decays of B mesons and reconstructs the B meson decay length and charge by vertexing the lepton with a partially reconstructed D meson. The second analysis uses a 2D impact parameter tag with topological vertex reconstruction. The maximum likelihood fits give:

Measurement	Semileptonic	Topological
τ_{B^0}	$1.60^{+0.15}_{-0.14} \pm 0.10 \text{ ps}$	$1.55 \pm 0.07 \pm 0.12 \text{ ps}$
τ_{B^+}	$1.49^{+0.11}_{-0.10} \pm 0.05 \text{ ps}$	$1.67 \pm 0.06 \pm 0.09 \text{ ps}$
τ_{B^+}/τ_{B^0}	$0.94^{+0.14}_{-0.12} \pm 0.07$	$1.08^{+0.09}_{-0.08} \pm 0.10$

2.2.5 QCD Physics

2.2.5.1. Multiplicity Distributions and Moments

Oregon graduate student Jingchen Zhou has been studying charged-particle multiplicity distributions in SLD. Various moments of the multiplicity distribution have received much theoretical attention in recent years. The factorial moments have been linked to the degree to which QCD parton cascades have self-similar evolution. More recently, the ratio of cumulant to factorial moments (H_q) have been calculated within the framework of higher-order perturbative QCD. This allows, for the first time, the possibility to compare experimental multiplicity distributions to the dynamics of perturbative QCD.

Jingchen presented a preliminary version of this work for the 1994 Albuquerque DPF meeting. Since then, the work has been refined. In particular, experimental corrections and systematic errors have been properly evaluated. The complete result was presented at the EPS meeting in Belgium in Summer 1995 as part of the SLD QCD presentation, and a journal submission, probably to PRL, is currently under review by SLD. These results are summarized below. In addition to this work, Jingchen plans to include in his dissertation the first complete SLD study of the absolute tracking efficiency. (The work below depends primarily on the multiplicity-dependence of the efficiency.)

Recent theoretical work [2.2.5.1– 2.2.5.4] in perturbative QCD gluodynamics has led to introduction of the quantity H_q , the ratio of factorial to cumulant moments of rank q . The factorial moment of rank q is defined as

$$F_q \equiv \frac{\langle n(n-1)\dots(n-q+1) \rangle}{\langle n \rangle^q},$$

where n is the number of particles in a hadronic event, and $\langle n \rangle$ is the average multiplicity in the event sample. The cumulant moments K_q are related to the F_q by

$$F_q = \sum_{m=0}^{q-1} C_{q-1}^m K_{q-m} F_m,$$

where $C_{q-1}^m = \frac{(q-1)!}{m!(q-m-1)!}$ are the binomial coefficients, and $F_0 = F_1 = K_1 = 1$.

The use of H_q to compare with the SLD charged-particle data is dictated by two points: It is calculable to higher orders in pQCD, and because it is quite sensitive to the shape of the multiplicity distribution. Figure 2.2.5.1 indicates the behavior of H_q for pQCD partons as higher orders in the calculation are included, beginning with the leading double logarithmic approximation (DLA), with next-to-leading corrections (NLA) included, and finally with next-to-next-to-leading corrections (NNLA) included. With the inclusion of higher orders, pQCD predicts the qualitative features of a negative minimum followed by quasi-oscillatory behavior. The location of the minimum at $q_{min} \approx 5$ is a simple function of α_s .

Figure 2.2.5.2 gives the corrected charged-particle multiplicity distribution as measured by SLD. The curves marked NBD and LND are phenomenological distributions (negative binomial and log-normal, respectively) which have often been used to model multiplicity data. Figure 2.2.5.3 shows the SLD data (points with error bars) for H_q . The important point is that the data closely resembles the expectation from higher-order pQCD given in Fig. 2.2.5.1, with $q_{min} \approx 5$ followed by quasi-oscillations. It is remarkable that a prediction for parton-level gluodynamics would be able to predict the behavior of multiplicity fluctuations of measured hadrons. This indicates that H_q is a measure of the underlying dynamics of QCD. The phenomenological distributions (NBD and LND) are also given in the figure for comparison.

2.2.5.2. Calorimetric Measurement of Jet Distributions in $e^+e^- \rightarrow \text{three-jets}$

Hyun Hwang (of Oregon) developed a calorimetric measurement of the jet distributions of three jet events in the SLD data for his Ph.D. thesis. The distributions of jet energy and the three orientation angles of the jet plane were found to agree well with expectations from perturbative QCD (see Figure 2.2.5.4). The data has also been compared with models of scalar and tensor gluon production, and the limits on the relative contributions of these to three-jet production has been determined. (The calculation of distributions expected for tensor gluons were provided by T. Rizzo.) This study is the first comparison with a tensor gluon calculation. A publication based on this work is in progress.

2.3 CCD Vertex Detector Upgrade for SLD

The SLD experiment was approved by the SLAC Director for an upgraded CCD vertex detector (VXD3) on March 30, 1994, following the EPAC final review of the SLD proposal for the upgrade and a multi-year extended run. The VXD3 is illustrated and compared geometrically with the original SLD vertex detector (VXD2) in Figure 2.3.1. Jim Brau of the Oregon group serves as project manager for this upgrade and was in residence at SLAC for the 1994-95 academic year. SLD has been approved so far to run into 1998, when the the B factory is expected to be ready for physics. This approval is based on the exceptional physics reach of SLD in two particular areas:

1. measurement of the left-right asymmetry, A_{LR} , and
2. B-physics with a polarized beam and a pixel vertex detector.

The excellent vertex detection provided by the SLD pixel vertex detector, close in, with small SLD beam spots, gives SLD an outstanding ability to tag quark flavor. The upgrade vertex detector (VXD3) has exceptional performance provided by very thin ladders ($\sim 0.4\%/layer$) and good distances from inner layer to outer layer ($\sim 2cm$), resulting in impact parameter resolutions that can be parametrized as:

$$\sigma_{XY}(\mu m) = 9 \oplus \frac{29}{p \sin^{\frac{3}{2}} \theta}$$

$$\sigma_{RZ}(\mu m) = 14 \oplus \frac{29}{p \sin^{\frac{3}{2}} \theta}$$

These resolutions are compared to the resolution of the original SLD vertex detector (VXD2) measured with data in Figure 2.3.2. They represent an unprecedented

precision for low momentum tracks and will have a significant impact on the ability to separate charm vertices. The anomalous value of R_b observed at LEP may suffer from the difficulty of the charm measurement, which VXD3 should help to resolve. Perhaps most significantly, SLD will be able to look at $B - \bar{B}$ mixing with enough data. Polarized Z's yield a measurement of the time development of B_d with $\sim 10^5$ Z's, which SLD now has. This analysis is in progress. With a few hundred thousand Z's SLD will get a first look at B_s mixing, and can do accurate measurements to a few percent of B_s mixing with half a million Z's. The very good vertex resolution of SLD gives sensitivity to $x_s = \frac{\Delta M}{\Gamma}$ up to $\sim 15-20$. This is something SLD can do particularly well since the resolution in proper time depends on the decay length measurement (which SLD gets to $\pm 5\%$) and the measurement of the B^0 momentum ($\pm 10\%$ for SLD). The b-track tagging, which VXD3 does exceptionally well, is critical in achieving a good B^0 momentum measurement.

The successful operation of VXD2 in SLD for the past three years is a solid validation of our choice of a CCD-based pixel vertex detector as best suited to the special SLC beam environment. The experience with VXD2 has answered the fundamental questions about the mechanical stability, hit efficiency, and resolution capabilities associated with a CCD-based pixel vertex detector. VXD2 has the world's best capability in many performance criteria. Nevertheless, due to the limitations of technology at the time of designing VXD2, limited resources, stringent time schedule, and some conservatism necessarily attached to a pioneering design, some aspects of the performance are compromised. The upgrade to VXD3 will significantly improve performance and open new, exciting possibilities for physics at SLD.

In addition to its other contributions, the Oregon group has had a very significant role in the new VXD3 electronics, where Nikolai Sinev has devoted a large fraction of his effort.

VXD2 has 4 barrels of loosely spaced ladders with barrel-2 ladders covering the ϕ gaps of barrel-1, and barrel-4 ladders covering the ϕ gaps of barrel-3 (see Figure 2.3.3). Thus the detector provides only 2-hit coverage for most of the azimuthal region, with about 30% of the tracks having 3 or more hits. In our standard analysis, tracks are extrapolated from the central drift chamber (CDC) into the VXD to search for associated hits and form linked tracks. A fairly high linking efficiency of $\approx 95\%$ is achieved and the Monte Carlo represents the data reasonably well. However, the probability of finding a pair of background hits on different layers faking a good hit vector for the nominal 2 hit layer geometry of VXD2 is not negligible and this accounts for most of the mislinking. Mislinked tracks typically introduce very long tails that generally spoil the stability of measurement results thus worsening the systematics. It is therefore highly desirable to have a full 3-

layer hit coverage to clean up the pattern recognition. Figure 2.3.3. illustrates the resulting advantage for VXD3. A 3-layer detector of course also gives a fairly comfortable fall back position in case of any CCD/ladder failure. The availability of large area CCDs at present allows a simplified ladder design using only two CCDs covering the entire length of the ladder. Each barrel provides complete azimuthal coverage, as a result of the 'shingled' structure between ladders.

The present VXD2 ladders have a half active length of 46 mm. The outermost layer is at a radius of 41 mm, thus providing a $\cos \theta$ coverage for 2 hits only up to 0.75. With the VXD tracking coverage extended to a $\cos \theta$ of 0.85 with a longer VXD3 ladder active length 20% more events can be used for all vertex detector related analyses. In some important physics cases, the extra solid angle has much more significance than the simple 20% gain in event rate. The highly polarized SLC electron beam produces Z^0 events with final state fermions having large forward-backward asymmetries correlated to the beam polarization handedness. One sensitive application of the polarized forward-backward asymmetry is its use as a tag to distinguish the initial production of quark or anti-quark for the $B - \bar{B}$ mixing measurements.

The choice of $\cos \theta_{max} = 0.85$ was made to provide the best matching to CDC coverage, which is necessary for VXD linking, thus providing uniform tracking over the whole sensitive $\cos \theta$ region up to 0.85. The practicality of this has only been realized by advances in technology during the last 6 years, with the emergence of large area custom design CCDs at high yield and lower cost, and improvements in ceramic manufacturing technology. The VXD3 design employs two 8-cm-long CCDs per ladder, one on each side, for a full active length of 159 mm. Spatial resolution deterioration at the ends of the ladder is not an issue thanks to the very thin active EPI silicon layer of 20 μm on the CCDs.

Besides solid angle coverage, the track impact parameter resolution near the IP is the other driving consideration behind the detector geometry layout. The best way to improve the impact parameter resolution and coverage is to reduce the beampipe radius. However, VXD2 already has an inner beampipe radius of 25 mm. By moving the upgrade beampipe inner radius to 23.5 mm, a layer-1 radius of 28.40 mm is possible. Then the outer radius is chosen as a compromise between maximizing the lever arm of the tracking for improved impact parameter resolution, and maximizing the solid angle coverage with the 8-cm-long CCDs. We therefore selected a layer-3 radius of 48.26 mm to achieve the desired solid angle coverage, to $\cos \theta = 0.85$. Another major contribution to the impact parameter resolution is multiple scattering at low and intermediate track momentum. By using a beryllium-flex circuit laminate as the motherboard, and thinning the CCDs to less than 200 μm , the material radiation length for a VXD3 ladder is reduced

to $\sim 0.4\%$. As the VXD2 beam background hit pulse height distribution does not show a dominant contribution from very soft photons that the $100\ \mu\text{m}$ titanium liner on the existing beampipe inner surface is designed to absorb, the thickness of the Ti liner can be halved. A similarly motivated reduction of the beryllium beampipe thickness from 1 mm to 0.75 mm is felt to be mechanically acceptable.

The major improvements in impact parameter resolution expected from VXD3 compared to VXD2 can be summarized as follows:

1. the lengthening of the lever-arm and the reduction of detector material improve both x - y and r - z impact parameter resolution by $\approx 75\%$ compared to VXD2 at low momentum.
2. the lengthening of lever-arm improves the r - z impact parameter resolution by a factor of 2 at high momentum. The dependence on CDC ϕ -angle measurement has also been reduced for the high momentum x - y impact parameter resolution, making VXD3 closer to a standalone detector for impact parameter resolution with the global alignment between CDC and VXD becoming less critical.
3. The shingled VXD3 barrel layout gives a more efficient and uniform ϕ coverage such that the average inner hit radii are reduced compared to VXD2 and also avoids the problem of large hit pattern lever-arm variation around ϕ as in VXD2.
4. The VXD3 layout is such that in case one hit is lost the resulting lever arm is still better than that achievable with a fully efficient two-layer VXD2.

The VXD3 project involved the parallel development and procurement of the 80 millimeter CCDs, the development and fabrication of the 21 centimeter ladders, the development and procurement of new electronics, the fabrication of a new beryllium support structure, a new cryostat, and significant modification of the R20 structure and its associated shielding, as well as the fabrication of a new beryllium beampipe. Excellent progress has been achieved on all aspects of the project.

The vertex detector upgrade budget and schedule were set after a careful analysis of the SLD experience with the development of the first SLD CCD vertex detector, VXD2, and the original development of the R20 module (which contains the vertex detector and inner masks and supports), as well as its installation, and commissioning. While recognizing that the project was extremely aggressive, a very strong team of collaborators was assembled and the experience from VXD2 was applied through the new participants.

The collaborators on the VXD3 project are:

Brunel University

S. Watts, A. McKemey, N. Allen, P. Dervan,

Colorado State University

J. Harton, M. Smy

Univ. of Massachusetts

S. Hertzbach, R. Kofler, M. Strauss, A. Trandafir

Massachusetts Institute of Technology

P. Burrows, D. Dong, H. Kendall, V. Lia, L. Osborne, F. Taylor, R. Verdier

Moscow State University

G. Bashindzhagyan, D. Karmanov, M. Merkin

Univ. of Oregon

A. Arodzero, J. Brau (project manager), R. Frey, J. Huber, N. Sinev

Rutherford-Appleton Laboratory

C. Damerell, A. Gillman, D. Jackson, G. Tappern, L. Lintern, R. English

SLAC

M. Breidenbach, G. Crawford, J. Jaros, Su Dong, G. Haller, J. Hoefflich, K. Skarpaas VIII

Univ. of Wisconsin

G. Zapalac, V. Serbo

Yale University

C. Baltay, G. Grigoryev, S. Manly, J. Snyder, W. Emmet, J. Sinnott, A. Wandersee

Tohoku University

H. Yuta, K. Abe, F. Suekane, T. Nagamine, K. Hasuko

The institutional assignments of responsibility are:

CCD specification, design, manufacture	RAL, SLAC
Electronics	SLAC, Oregon
Ladder motherboards	SLAC, Oregon
Ladder and Annulus Block Assembly	Yale
Final Assembly	Yale
Inner and Outer Striplines	SLAC
Ladder and Detector Survey	MIT
Beamline elements and modifications	SLAC, Oregon
Inner Cart Fabrication	SLAC, Oregon
Cryostat	RAL
Inner Cryostat Pipes	RAL
Capacitive Position Monitor	MIT
Inner Electronics Support and Cooling	Oregon
R20 Assembly	SLAC, UMass, VXD3 Collaboration
Online Software	Collaboration
Offline Software	Collaboration

The CCD's themselves are clearly the most critical element of the project. A prototype order (phase I) was placed on April 14, 1994, and the prototypes were delivered beginning in February, 1995. The Production CCDs were ordered in April, 1995, and delivery of production devices began in September, 1995. The CCDs are n-buried channel devices fabricated on p-type epitaxial layer and having a p^+ substrate. They are operated in a full-frame readout mode. The substrate resistivity is specified to be less than $20 \times 10^{-3} \Omega\text{-cm}$ to maintain short carrier lifetimes. The epitaxial layer is 18 – 22 microns thick with a resistivity of $\sim 20 \Omega\text{-cm}$ for adequate diffusion length, optimal diffusion/drift ratio, and clean high rate clocking. The pixel sizes are $20 \mu\text{m} \times 20 \mu\text{m}$. The readout registers operate on two-phase clocking and the imaging area on three-phase. There are 4 readout nodes, one on each corner of the device. As this is written (October, 1995), 40 production ladders (each supporting two CCDs) of the 48 required for VXD3 have been shipped to SLAC. Acceptance testing of these ladders is being done at 190K in the SLAC test fixture, with the VXD3 electronics. Nikolai Sinev of the Oregon group was the principal person responsible for setting up the CCD test facility at SLAC. This facility is now used by a team of SLD physicists to test incoming ladders, but Nikolai remains the primary expert on the system and on CCD performance.

The other critical components, including the beryllium support structure and the beryllium beampipe, have been received. The SLD Collaboration is on track

to install the vertex detector into SLD in time for the next SLD run, scheduled to being in January, 1996.

2.4 SLD Luminosity Monitor Operation and Analysis

The SLD Collaboration pioneered the use of silicon-tungston calorimetry in luminosity monitors for collider experiments. The SLD luminosity monitor, built at Oregon, was installed into SLD in 1991. It has operated very successfully since that time, being maintained by University of Oregon group members in residence at SLAC (Cary Zeitlin, Kevin Pitts, Jennifer Huber, and Matt Langston). Based on its early success, OPAL and ALEPH at LEP have also now installed systems employing silicon-tungston calorimeters.

The LUM operated successfully during the recent 1994-95 SLD run. The overall performance of the LUM was excellent, with no major hardware problems. There were, however, a few minor electronics problems which must be accounted for in calculating the absolute normalizing luminosity. These different parts of the run are characterized below.

The luminosity calculation uses a technique known as the "gross/precise" method to help reduce the systematic error on the luminosity measurement. This technique defines and uses an "effective cross section" which is defined by the LUM's acceptance region. Since different hardware configurations have unique acceptance regions, one must make a separate luminosity calculation for each configuration of the hardware. For the purpose of calculating the absolute normalizing luminosity for the 1994-95 run it is necessary to divide the run into two "epochs", where each "epoch" is characterized by a particular configuration of the hardware.

The first epoch represents approximately the first 20% of the luminosity logged by SLD during the 1994-95 run. The North LUM module performed exceptionally well with no problems whatsoever. The South LUM module operated with 3 disconnected and 1 dead preamp channels (out of a total of 320 preamp channels). Additionally, a small region of the South silicon detectors (about 1/10th) were operated without bias voltage due to a loose bias voltage board. These effects are well modeled by the monte carlo, which predicts an "effective cross section" of 60.42 nb for Bhabha scattering into the LUM. Using the gross/precise method, the luminosity logged by SLD during this epoch is measured to be $0.7556 \pm 0.0035(\text{stat.}) \pm 0.0057(\text{sys.}) \text{ pb}^{-1}$.

The second epoch represents the remainder of the run (80% of the luminosity logged by SLD for the 1994-95 run). The North LUM module again performed

exceptionally well with no major problems, with the exception of a few days (about 1.5% of the luminosity) of "noisy" running which is discussed separately below. The South LUM module operated with only 1 dead preamp channel. The original problem of the unbiased silicon in the south module was fixed for this period of the run, but a faulty cable (which was masked by the earlier problem with the loose bias voltage board) prevented an even smaller region of the South silicon detectors (about 1/20th) from operating with bias voltage. Again these effects are successfully modeled with the Monte Carlo, which predicts an effective cross section of 66.75 nb for Bhabha scattering into the LUM. Using the gross/precise method, the luminosity logged by SLD during this epoch (not including the aforementioned noise period) is measured to be $2.8811 \pm 0.0064(\text{stat.}) \pm 0.0219(\text{sys.}) \text{ pb}^{-1}$.

The 1.5% of the luminosity logged by SLD during the LUM noise period represented such a small fraction of the total luminosity that for convenience the same effective cross section was used as for the second epoch (since the hardware configurations are the same for the two periods), but a larger systematic error is assigned to the noise period. The effect the noise had on the LUM which affects the luminosity calculation was due to channels being taken out of the data acquisition system due to some channels failing to calibrate properly. For convenience, and to be conservative, the worst calibration taken during this period is used to represent the entire noise period. This calibration effectively reduced the LUM's overall effective cross section to about the cross section of the first epoch. Since the cross section for the first epoch is 9% lower than the cross section for the second epoch, we conservatively estimate a 10% systematic error for the luminosity measurement of the noise period. Using the gross/precise method, an effective cross section of 66.75 nb and a 10% systematic error, the luminosity logged by SLD during the noise period is measured to be $0.0619 \pm 0.0009(\text{stat.}) \pm 0.0062(\text{sys.}) \text{ pb}^{-1}$.

Combining these three separate luminosity measurements, the absolute normalizing luminosity logged by SLD during the 1994-95 run is measured to be $3.6987 \pm 0.0074(\text{stat.}) \pm 0.0283(\text{sys.}) \text{ pb}^{-1}$.

In concert with the SLD vertex detector upgrade, we have undertaken some improvements of the luminosity monitor. The luminosity monitor was removed from SLD in March, 1995, in preparation for the installation of the new vertex detector. The electronics boards were refurbished and cleaned up. A new set of cables, employing kapton flex circuits, have been fabricated and will be installed for the 1996 run. Since the medium angle silicon calorimeter is being removed in the future runs of SLD, and since it has shared electronics with the luminosity monitor, the available readout channels to the luminosity monitor nearly doubled. The new kapton flex circuits have been configured to increase the longitudinal segmentation

in the luminosity monitor readout to four (for the previous two), which is expected to improve background rejection for the Bhabhas at the smallest angles of the luminosity monitor. These Bhabhas have been rejected in the past, but the plan is to try to use the new segmentation to clean them up and significantly improve the on-line counting rate for Bhabhas (by a factor of 2). This will also protect the performance of the luminosity monitor from the occasional dead channel.

2.5 Compton Polarimetry Upgrades

During 1995 the Oregon group has been involved in an effort to upgrade the SLC electron beam polarization measurement for the 1996 run and beyond. Oregon is building a new gas Cherenkov counter to be placed in the SLC south Final Focus. It will analyze the Compton-scattered photons produced by the same laser-electron interactions which are presently used to measure beam polarization via the Compton-scattered electrons. This upgrade was put before SLD by R. Frey and approved in July 1995. It involves a relatively modest monetary commitment and a moderate amount of additional effort. This new Cherenkov Polarization Gamma Counter (PGC) will measure the longitudinal component of beam polarization (as is the case with the existing polarimeter) but with quite different systematics. The PGC will be joined by a new quartz-fiber detector being built by Tennessee and Mississippi, which will be able to measure the transverse polarization, which nominally is zero. The PGC effort is largely being carried out by Frey and R.C. Field of SLAC. The implementation of the detector requires a prior calibration in a test beam, scheduled for January 1996. The detector itself is being fabricated by the Oregon mechanical shop. Below we discuss the motivation for the PGC, the physics of the measurement, and the plans for its implementation.

Beginning in 1996 SLD begins the first phase of its extended running with polarized beam at the SLC, with the goal of recording 5×10^5 Z events. The A_{LR} measurement, discussed in Section 2.2.1, already provides the single best measurement of the electroweak mixing angle. Recently LEP has discontinued running at the Z^0 resonance. During the next few years SLD will have the opportunity to make the "archival" measurement of $\sin^2 \theta_W^{\text{eff}}$ and should provide a degree of experimental control commensurate with this. As shown in Section 2.2.1, the A_{LR} error is statistics limited, with the dominant systematic being due to the polarization measurement. To good approximation this is

$$\delta A_{LR} = \left[\frac{1}{N_Z \mathcal{P}_e^2} + A_{LR}^2 \left(\frac{\delta \mathcal{P}_e}{\mathcal{P}_e} \right)^2 \right]^{1/2},$$

where the polarization error in the second term is presently approaching 0.5%. This level of systematic error should be acceptable for the duration of SLD run-

ning. However, the measurement is provided by a single detector, for which the physical polarization scale has never been checked at a level of accuracy approaching 1%. During 1992 and 1993, Moller polarimetry was employed to spot-check the polarization. However, this technique has relatively poor systematics ($\approx 3\%$) due to intrinsic uncertainties associated with Moller targets, as discussed in Ref. 2.5.1. Of course, these systematics are avoided with Compton scattering of the electron beam with a well-measured and readily controlled laser system. The present measurement with the Compton electrons is depicted in Fig. 2.2.1.5 and is discussed in that section. It makes use of a strong dipole magnet, actually an element of the SLC Final Focus lattice, to momentum analyze the Compton-scattered electrons. The electrons shower in lead radiator in front of the segmented counter, and the signal is recorded by channel position. Hence, this detector measures the energy dependence of the Compton cross section, actually the polarization asymmetry of the cross section, but the measurement must provide the distance-energy relationship.

On the other hand, for the measurement of the Compton-scattered photons, such separation by energy is not possible, as each Compton event consists of a few thousand photons over a broad energy spectrum (see below). In this case one measures the total energy asymmetry, and the calibration is provided by an external determination (test beam) of the detector energy response. Hence, the systematics are quite different in this case. The common systematic results from the knowledge of the laser polarization. However, this is a very well measured and well understood system, providing a steady photon polarization in excess of 99%.

Figure 2.5.1 shows the Compton cross section as a function of the ratio of the scattered photon energy to its maximum value: $\rho = E_\gamma/E_{\max}$. $E_{\max} = 28$ GeV is determined by the beam energy and photon energy (2.3 eV). The cross section is plotted separately for the two $e\gamma$ spin combinations, $j = 1/2$ and $j = 3/2$. Note that the spin aligned-anti-aligned cross section asymmetry,

$$A_n = \frac{\sigma(3/2) - \sigma(1/2)}{\sigma(3/2) + \sigma(1/2)},$$

increases rapidly near $\rho = 1$. Hence, measurement of the higher-energy photons will be most important.

The PGC will measure the energy asymmetry of Compton photons. The Compton cross section can be written

$$\sigma_c(\rho) = \sigma_0(\rho) \pm \sigma_1(\rho)$$

where the upper (lower) sign corresponds to $j = 3/2$ ($j = 1/2$). The cross section asymmetry at fixed ρ is then σ_1/σ_0 . For fully polarized electron and photon beams,

the energy asymmetry is equal to the analyzing power, a , where

$$a = \frac{\int_0^1 \rho \sigma_1(\rho) R(\rho) d\rho}{\int_0^1 \rho \sigma_0(\rho) R(\rho) d\rho}$$

where $R(\rho)$ is the detector response function. If the detector measures an energy asymmetry A_m with electron and photon beam polarizations $\mathcal{P}_e$ and $\mathcal{P}_\gamma$, respectively, then this is related to the analyzing power by

$$A_m = \mathcal{P}_e \mathcal{P}_\gamma a$$

The Compton cross section is accurately known, and the laser polarization is well measured. Hence, once the response function $R(\rho)$ is determined, then the electron beam polarization can be extracted. For $R = 1$, the analyzing power is $a = 0.17$. For the PGC, the Compton photons will be converted by a lead radiator, and the showered pairs will be measured by the Cherenkov detector. (A rough assembly drawing of the PGC is shown in Fig. 2.5.2.) Hence, the detector response increases with photon energy, making an analyzing power in excess of 17% possible.

The principle of the PGC has been demonstrated with data taken during the latter part of the 1994-95 SLC run with an existing detector, the beamstrahlung monitor [2.5.2] (BSM), which sits physically in the same location as will the PGC. The BSM is also a gas Cherenkov device, but is designed to measure beamstrahlung [2.5.3] from the colliding electron and positron beams, and has a different optimization than does the PGC. (The BSM itself will be replaced for the 1996 run by a new, more compact Cherenkov detector.) The primary reason for the extensive use of Cherenkov counters for the various detectors in this location in the Final Focus is due to the huge low-energy backgrounds, mostly due to synchrotron radiation or Compton scatters initiated by synchrotron photons. The bend magnet depicted in Fig. 2.2.1.5 produces a synchrotron spectrum for the outgoing electron beam with critical energy ≈ 1 MeV. The total number of photons per bunch is $\mathcal{O}(10^{12})$. On the other hand, ethylene gas has a Cherenkov threshold of

$$\frac{13.8 \text{ MeV}/c}{\sqrt{P(\text{Atm})}}$$

which even at a pressure of 1 Atm reduces the synchrotron background to negligible levels. (Ethylene is chosen because it is non-scintillating and has an acceptable refractive index.)

For the test with in 1995, the gain of the BSM photomultiplier tube (PMT) was increased substantially, lead was inserted in front of its acceptance to convert

the Compton photons, and the SLC was run with only electron beam. The table below summarizes some of this data taken for various values of lead thickness and gas pressure. The pulse height distributions for one of these runs is given in Fig. 2.5.3. The upper distribution is with laser off, hence this is the background (plus pedestal). It is gaussian, very stable, and was found not to change with Cherenkov pressure. Therefore it was almost certainly due to scattered synchrotron radiation interacting near the PMT. This background was later virtually eliminated by beam re-steering. The middle plot is for laser on and beam polarization predominantly $j = 3/2$, while the bottom plot is for $j = 1/2$. A clear asymmetry is visible.

Table 2.5.1. Summary of some Compton/BSM test runs.

Run	Pb (")	P (°Hg)	Laser On (ADC)	Laser Off (ADC)	Asym
180167	1.0	-25	191	172	0.121(7)
180171	0.5	-25	279	267	0.092(12)
180173	0.5	-25	277	262	0.082(17)
180174	0.5	-20	290	266	0.085(7)
180175	0.5	-15	303	265	0.082(5)
180178	0	-15	617	617	0

A detailed monte carlo program was written by R. Frey to simulate the Compton data in this test with the BSM. Figure 2.5.4 summarizes the analyzing power derived from the test data with that expected in the simulation as a function of lead radiator thickness. The agreement is good. This gives a "first-order" indication that it may indeed be possible to understand the PGC analyzing power, actually a simpler detector than the BSM, at the required level. We also see in Fig. 2.5.4 the hardening of the response function with increasing lead thickness, as discussed above, with clear evidence for analyzing powers in excess of 17%.

The PGC beam test is scheduled for January 1996, which is when the Final Focus Test Beam (FFTB) facility at SLAC is first available as a user test beam. The momentum and particle flux ranges available at FFTB are a good match for what is required to determine the PGC response function. Other members of the Oregon group will help prepare and man the test beam run. The SLC/SLD run will also be in progress at this time. After completion of the beam test, the PGC will be installed in the SLC at the first access opportunity.

The PGC is mechanically quite simple to make and the electronics and readout is simple, inexpensive, and compatible with that employed by the existing electron

Compton polarimeter. The table below was prepared for SLD management as part of the PGC approval process.

Table 2.5.2. PGC cost estimates.

Item	est. cost (k\$)	cost to SLD (k\$)	Comment
counter fabrication	2.5	0	provided by Oregon
counter assembly	1.5	0	provided by Field tech.
ADC	0	0	see Note 1 below
PMT	0.5	0.5	base made by Field tech.
cables (not instl.)	0.1	0.1	1 RG214, 1 HV
HV supply	0.5	0.5	remote control/readout
in situ calibration	0.5	0.5	see Note 2 below
gas system	0.5	0.5	see Note 3 below
Pb movers	1.0	1.0	two required
optical attenuator	0.7	0.7	mover included
TOTAL	7.8	3.8	

Note 1. One channel required. We plan to use a currently unused channel of LRS 2249W from the LBL detector.

Note 2. We plan to extend by one channel the laser plus fiber system to be implemented for the LBL detector for the 1996 run. We may also use a small scintillator, excited by radioactive source, placed directly on the PMT face.

Note 3. The ethylene gas system for the present south BSM counter can be modified to service both this detector and the new counter which will replace the BSM. Gas supply, flow valves, and tubing exists. Cost is for conversion from sub-atmospheric to atmospheric regulation, output bubbler, gas fittings, etc.

The fabrication costs at Oregon are to come entirely from University shop credits.

3. OPAL

Since joining the OPAL collaboration four years ago, the University of Oregon group has concentrated on the construction of a new silicon-tungsten luminosity monitor and the subsequent luminosity determination. This new luminosity monitor was designed to measure the LEP luminosity to better than 1/1000. The 1/1000 goal was chosen to be commensurate with the expected statistical and systematic errors on the measured number of Z^0 leptonic and hadronic decays. By reducing systematic error on the luminosity it is possible to make improved measurements of the Z^0 line shape parameters.

The OPAL silicon-tungsten luminosity monitor upgrade was approved by the LEPC [3.0.1] in the fall of 1991. A prototype silicon-tungsten calorimeter was tested using the CERN SPS in the following summer. In spring of 1993 the new monitor, which consists of two highly segmented silicon-tungsten calorimeters, was installed. The new detector was commissioned fully by the start of the 1993 LEP energy scan and was used to determine the relative and absolute luminosity. By exploiting the new precision detector the experimental error on the absolute luminosity was reduced to below 1/1000. The OPAL luminosity determination is currently the most precise one at LEP.

The OPAL effort at Oregon consists of faculty member David Strom and graduate student Wen-Ping Lai, who has been resident at CERN since the summer of 1994.

In the following we first discuss the performance of the LEP machine in the 1993, 1994, and 1995 runs. Next, the OPAL results from measurements of the Z^0 line shape, with emphasis on the determination of the invisible width of the Z^0 , are presented. This is followed by some discussion of the OPAL luminosity determination. Finally, we briefly discuss an analysis of the energy spread of the LEP machine.

3.1 LEP Performance

From the start of Z^0 physics at LEP in 1989, various improvements to the LEP machine and reliability have allowed the experiments to record large samples of Z^0 decays. In 1993, the first year in which the new OPAL luminometer was installed, stable running with the 8 bunches in the Pretzel scheme was achieved. This allowed significant data to be collected off-peak. Although no major physical improvements to the LEP machine were made for the 1994 run, improvements in the reliability and the understanding of the machine optics led to record luminosities. In 1995,

the LEP machine began operating in "bunch train" mode in preparation for LEP-II operation. This mode of operation is thought to be essential for high luminosity run at energies higher than the Z^0 . Much of the 1995 running has been devoted to understanding how to efficiently run LEP with bunch trains. The goal of the 1995 LEP I run was to at least match the off-peak luminosity of the 1993 run so that the errors on the mass and total width of the Z^0 can be reduced. The integrated luminosity and number of Z^0 decays recorded by the OPAL experiment at LEP is shown in the following table.

Table 3.1 Summary of OPAL integrated luminosity. (*Includes taken up to the end of the 1995 LEP I run.)

Year	Hadronic Z^0 decays	Integrated luminosity (pb^{-1})
1989	29k	1.3
1990	147k	6.8
1991	345k	14.0
1992	766k	25.1
1993	703k	33.3
1994	1711k	58.0
1995*	729K	34.5

The emphasis of the 1993 and 1995 run were to make definitive measurements of the Z^0 mass and width. As a result the number of Z^0 decays recorded in 1993 and 1995 was reduced somewhat because of the large amount of data recorded off peak and because some time has been devoted to the machine physics needed for establishing the energy scale of the machine. By frequently measuring the energy of the machine with polarization runs and by carefully logging the information about the operation of the machine the systematic errors on the Z^0 mass and width due to energy scale of the LEP machine have been improved from our previous results. For individual calibration runs, the energy of the LEP machine was determined to approximately 1 MeV [3.1.1]. Extrapolation of these energy calibrations to other times results in systematic errors of 1.5 MeV on the Z^0 mass and 1.7 MeV on the Z^0 width for the 1993 data. Similar or better energy calibration results are expected for the 1995 data.

The 1994 running was on the Z^0 peak. The additional statistics gathered here help us to improve our measurement of the leptonic forward-backward asymme-

tries, the ratio of hadronic to leptonic decays, R_Z , and the ratio of invisible (neutrino) to leptonic decays, $\Gamma_{\text{inv}}/\Gamma_{l+l-}$. Other important OPAL analyses, such as the determination of $\Gamma_{b\bar{b}}/\Gamma_Z$, also benefit from the increased statistics.

3.2 Electroweak Results

The most recent electroweak results from OPAL are briefly summarized here. The analysis is described in detail in reference [3.2.1]. Additional details of the luminosity analysis are given below in section 3.3. The most recent electroweak results from the four LEP experiments can be found in reference [3.2.2].

Figure 3.2.1 shows the measured cross sections as function of energy for $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$, and $e^+e^- \rightarrow \text{hadrons}$. Figure 3.2.2 shows the forward backward asymmetries for the three leptonic decay modes of the Z^0 . These data can be used to determine, M_Z , $\sigma_{\text{had}}^{\text{pole}}$, R_{ll} and $A_{\text{FB}}^{\text{pole}}$ where $R_{ll} = \frac{\Gamma_{\text{had}}}{\Gamma_{l+l-}}$. This parameter set is shown in Table 3.2.

Table 3.2 OPAL lineshape results. The Standard Model predictions are obtained using $M_t = 150$ GeV, $M_H = 300$ GeV and $\alpha_s = 0.12$. The error on the Standard Model predictions allow for variations in value of M_t and M_H of $50 < M_t(\text{GeV}) < 230$ and $60 < M_H(\text{GeV}) < 1000$.

	Without Lepton Universality	With Lepton Universality	SM Prediction
R_e	20.90 ± 0.10		
R_μ	20.796 ± 0.073		
R_τ	21.00 ± 0.11		
R_{ll}		20.851 ± 0.059	$20.75^{+0.03}_{-0.04}$
$A_{\text{FB}}^{\text{pole}}(e^+e^-)$	0.0081 ± 0.0051		
$A_{\text{FB}}^{\text{pole}}(\mu^+\mu^-)$	0.0137 ± 0.0027		
$A_{\text{FB}}^{\text{pole}}(\tau^+\tau^-)$	0.0183 ± 0.0035		
$A_{\text{FB}}^{\text{pole}}$		0.0142 ± 0.0020	$0.014^{+0.006}_{-0.003}$
M_Z [GeV]	91.1852 ± 0.0036	91.1846 ± 0.0035	input
Γ_Z [GeV]	2.4960 ± 0.0052	2.4959 ± 0.0052	$2.489^{+0.027}_{-0.020}$
$\sigma_{\text{had}}^{\text{pole}}$ [nb]	41.47 ± 0.10	41.47 ± 0.10	$41.46^{+0.07}_{-0.04}$

The OPAL value obtained for M_Z is consistent with the combined LEP value of $M_Z = 91.187 \pm 0.007$ GeV which was determined from the 1991 LEP energy scan. The four-fold increase in off-peak luminosity in 1993 has improved the error on Γ_Z by almost a factor of 2. An additional improvement by as much as 1.5 can be expected from the 1995 data.

In the context of the Standard Model the data from the Z^0 line shape and asymmetries can be used to find M_Z , M_t and α_s . The results are:

$$M_Z = 91.1846 \pm 0.0035 \text{ GeV}$$

$$M_t = 158_{-22}^{+19}_{-17} \text{ GeV}$$

$$\alpha_s(M_Z^2) = 0.132 \pm 0.006 \pm 0.002$$

The central values of M_t and $\alpha_s(M_Z^2)$ are for $M_H = 300$ GeV. The second error gives the uncertainty due to a Higgs Mass variation from 60 to 1000 GeV. The error on the top mass has been significantly reduced from our previous analysis. These results are consistent with the combined top mass reported by the CDF and D0 collaboration of 180 ± 12 GeV [3.2.3].

A more precise prediction for the top mass can be obtained by using all the quantities measured at LEP sensitive to radiative corrections, e.g. τ polarization and heavy quark asymmetries. Combining the OPAL results with those of the three other LEP experiments, the SLD measurements discussed earlier, and M_W as determined in hadron colliders and ν scattering,

$$M_t = 178 \pm 8_{-20}^{+17} \text{ GeV}$$

and

$$\alpha_s(M_Z^2) = 0.123 \pm 0.004 \pm 0.002.$$

is obtained [3.2.2]. The sensitivity of the LEP/SLC electroweak results combined with the D0/CDF top measurement to the Higgs mass is illustrated by the χ^2 curve shown in figure 3.2.3.

Another interesting quantity which can be obtained from these data is the ratio $\Gamma_{\text{inv}}/\Gamma_{l+l-}$. Assuming lepton universality

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{l+l-}} = \frac{\Gamma_Z}{\Gamma_{l+l-}} - \frac{\Gamma_{\text{had}}}{\Gamma_{l+l-}} - 3.$$

Since the radiative corrections for both quantities are similar, this ratio primarily tests the structure of the electroweak theory and has little dependence on the top

quark and Higgs boson masses. Any deviation of this ratio from the Standard Model prediction is evidence for the breakdown of the Standard Model or new physics. The dependence of this ratio on the luminosity measurement can be seen by using the relation

$$\sigma_{ll}^{\text{pole}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{l+l-}^2}{\Gamma_Z^2}$$

to calculate $\frac{\Gamma_Z}{\Gamma_{l+l-}}$. Including the 1994 run, $\Gamma_{\text{inv}}/\Gamma_{l+l-}$ was determined by OPAL to be 5.944 ± 0.047 which can be compared to the Standard Model value of 5.976 ± 0.009 . The new value is dominated by the 1993 and 1994 data where the experimental systematic error on the luminosity has been reduced from 0.41% (old detector) to approximately 0.08% (new detector) [3.2.4]. The error on $\Gamma_{\text{inv}}/\Gamma_{l+l-}$ is dominated by the theoretical error on the Monte Carlo Bhabha calculation used to extract the luminosity of 0.15%. There has been considerable theoretical activity aimed at reducing this uncertainty and it is hoped that in the future the theoretical uncertainty will be commensurate with the experimental uncertainty [3.2.5]. Because the result is dominated by the theoretical systematic error, the combine LEP value of $\Gamma_{\text{inv}}/\Gamma_{l+l-} = 5.9596 \pm 0.031$ is not significantly better than the OPAL result.

The ratios $R_c = \Gamma_{c\bar{c}}/\Gamma_{\text{had}}$ and $R_b = \Gamma_{b\bar{b}}/\Gamma_{\text{had}}$ have also been precisely measured by OPAL. In the context of the Standard Model, these ratios are also largely free of unknown radiative corrections. The ratio R_b does contain non-universal corrections from vertex corrections involving the top quark mass. However, as M_t has been directly measured, the uncertainties in the Standard Model prediction are smaller than the experimental uncertainties. R_b and R_c are both sensitive to physics beyond the Standard Model, with theoretical prejudice indicating that new physics might first make itself visible in R_b .

The preliminary OPAL measurement of $R_b = 0.222 \pm 0.0029$, based on lepton and lifetime tags, is the most precise at LEP and SLC. The OPAL measurement benefits from earlier work done at the University of Oregon on electron identification. The preliminary OPAL measurement of $R_c = 0.1517 \pm 0.0114$, determined primarily from D^* tags, is also competitive with the other LEP experiments. Both of these values disagree with the Standard Model values of $R_b = 0.2156$ and $R_c = 0.1724$. The disagreement becomes significant when the results of the four LEP experiments and SLD are combined, with the largest effect apparent in the R_b as can be seen in figure 3.2.4.

Additional constraints on R_b and R_c can come from the line shape measurements of Γ_Z , R_Z , $\sigma_{\text{had}}^{\text{pole}}$ and an external value of α_s . It has been noted by several authors [3.2.6] that the relatively high value of α_s obtained from the line shape fit

might be due to anomalous contribution to $\Gamma_{b\bar{b}}$. This can be quantified by allowing an non-Standard Model contribution to $\Gamma_{b\bar{b}}$, i.e, by taking $\Gamma_{b\bar{b}} = \Gamma_{b\bar{b}SM} + \Delta_b$. A global fit yields:

$$\Delta_b = 11.7 \pm 3.8 \pm 1.4 \text{ MeV}$$

$$M_t = 181 \pm 8^{+17}_{-19} \text{ GeV}$$

$$\alpha_s = 0.102 \pm 0.008$$

(The second error is due to the unknown Higgs Mass). The value of α_s obtained in this fit is significantly smaller than that obtained from the Standard Model fit and is somewhat lower than the world average (adjusted by removing the input from the LEP line shape measurement) of $\alpha_s(M_Z) = 0.117 \pm 0.006$ [3.2.7]. Allowing for a similar non-Standard Model contribution to $\Gamma_{c\bar{c}}$, a value of $\alpha_s = 0.18 \pm 0.04$ is obtained. This value is inconsistent with the work average of $\alpha_s(M_Z)$ indicating that if new physics is present in $\Gamma_{c\bar{c}}$ and $\Gamma_{b\bar{b}}$ it is likely to affect the other hadronic partial widths as well.

3.3 Luminosity Analysis

The luminosity measurement with the new silicon-tungsten luminosity monitored, was designed so that the largest systematic errors could be transparently related to measured quantities. The largest systematic error, from position reconstruction, is based on test beam measurements and careful metrology. The other dominant contribution to the systematic error is from uncertainties in the energy response of the detector. In this case, we are able to use the data itself to establish the size of the uncertainty.

The Oregon group has played a leading role in establishing the analysis framework and in setting limits on the size of many of the systematic effects discussed here. We are especially active in understanding the energy response of the detector and in understanding the observed Bhabha energy spectrum which has contributions from both detector effects (resolution) and physics (final and initial state radiation). We are also taking a leading role in the analysis of the 1994 test beam data.

In what follows we briefly describe the construction of the detector, the selection procedure used for Bhabha events, and then focus on the issues of position reconstruction and energy resolution. Additional information about the analysis can be found in reference [3.2.4].

3.3.1 Detector Construction

The new luminosity monitor consists of two identical annular position sensitive silicon-tungsten calorimeters located approximately ± 2.5 meters from the OPAL interaction region. These devices register electromagnetic showers from small angle Bhabha scattering in a fiducial range of 28 to 55 mrad in polar angle and 2π in azimuth. The electromagnetic showers are sampled with 19 layers of silicon detectors interleaved between 14 tungsten absorbers of $1 X_0$ and 4 tungsten absorbers of $2 X_0$. The silicon detectors are finely segmented as shown in figure 3.3.1, with a radial pitch of 2.5 mm and an azimuthal pitch of 11.25° . Adjacent detectors overlap each other, so that there is not a dead region between detectors. Each layer of both calorimeters is individually readout, giving a total of 38,912 channels. Details of some aspects of the construction of the new luminosity monitor can be found in the OPAL proposal given to the LEPC[3.0.1].

The University of Oregon team has made significant contributions to the detector construction and commissioning. Our contributions included providing prototype silicon detectors and the precision tungsten absorber used in both the test module and in the entire detector. We were active in the design of the silicon detectors. We also designed and implemented much of the online readout system.

3.3.2 Analysis Strategy

The analysis strategy is apparent from the selection criteria list in Table 3.3. The cuts are divided into definition and isolation cuts. The definition cuts depend entirely on the radial position reconstruction. The isolation cuts are designed to cut only a small amount from the Bhabha sample while removing all of the background from coincidences of off-momentum particles. To determine the luminosity we take the average of events passing tight cuts on the right (N_R) and events passing tight cuts on the left (N_L). Most effects of longitudinal and transverse beam offsets and alignments cancel in the average of N_R and N_L .

The experimental systematic errors of the analysis are tabulated in Table 3.4. The most important effects are from radial metrology, possible bias in the coordinate reconstruction and from the energy response of the detector. The Monte Carlo used to calculate the acceptance of isolation cuts, as the acceptance of the definition cuts can be determined using test beam data and detector metrology. The error on the detector response is almost entirely due to uncertainties in the measured energy response of the detector.

Table 3.3 Definition and isolation cuts used in the Bhabha selection. The energy is calculated from clusters falling with the fiducial radial acceptance of the detector, 67 mm to 137 mm, and the acoplanarity and acollinearity are constructed from the most energetic cluster within this fiducial region.

<i>Definition cuts:</i>	
$N_R(N_L)$	$77 \text{ mm} < R_R(R_L) < 127 \text{ mm}$
<i>Isolation cuts:</i>	
Minimum Energy Cut, Right (Left)	$E_R (E_L) > 0.5 \cdot E_{\text{Beam}}$
Average Energy Cut	$\frac{(E_R + E_L)}{2} > 0.75 \cdot E_{\text{Beam}}$
Acoplanarity Cut	$ \phi_R - \phi_L - \pi < 200 \text{ mrad}$
Acollinearity Cut	$ R_R - R_L < 25 \text{ mm}$

Table 3.4 Summary of the corrections applied and the corresponding experimental systematic uncertainties on the absolute luminosity measurement for the 1994 running. The 1993 results are similar. These results are preliminary and may be reduced in the final publication.

Effect	Correction $\times 10^{-4}$	Systematic $\times 10^{-4}$
SiW radial dimensions ($\pm 9\mu\text{m}$)	—	4.1
Radial coordinate bias	—	3.4
Monte Carlo, detector response	-7.3	3.8
Monte Carlo, cross section calculation (stat.)	—	3.7
Detector instability (mechanical + response)	—	0.5
Trigger inefficiency	0	< 0.01
LEP Beam parameters (average)	+3.1	2.0
Fluctuations in LEP beam parameters	—	0.5
Accidental coincidence background	+1.0	1.0
$\gamma\gamma$ background	+2.0	0.1
Total	-1.2	7.9

3.3.3 Radial Metrology and Reconstruction

The small angle Bhabha cross section is proportional to $1/\theta^3$, where θ is the polar angle. Thus the luminosity measurement has a large sensitivity to the position of the inner cut on θ . A simple calculation shows that a bias on this angle of 10 microradians ($25\text{ }\mu\text{m}$ at 2.5 m) corresponds to a systematic error of 1/1000 in the luminosity. As a result great care was taken in the construction of the detector and extensive measurements of the calorimeters were made to establish the position of the average inner radius of the two detectors.

The average radius of each of the layers was measured during the construction of the detector. The R.M.S. of the average radius distribution was less than $3\text{ }\mu\text{m}$. For the forward layers, the comparison of the average radius as measured before and after the 1993 is shown in figure 3.3.2. The uncertainty on these measurements of the inner radius of the detector is dominated by the uncertainty in the absolute calibration of our metrology instrument against a reference laser interferometer ($4\text{ }\mu\text{m}$), with additional contribution from the alignment of the masks used in processing the silicon detectors ($3\text{ }\mu\text{m}$) and temperature variations during the metrology measurements ($2\text{ }\mu\text{m}$). A difference in the overall metrology scale of $5\text{ }\mu\text{m}$ between the 1993 and 1994 surveys is currently under investigation. We have added an uncertainty of $\pm 5\text{ }\mu\text{m}$ to account for this difference. Additional uncertainties in the inner radius are due to measured changes in its position as the detector is moved from the horizontal to vertical position ($-3 \pm 6\text{ }\mu\text{m}$) and when the electronics and cooling are switched on ($-6 \pm 3\text{ }\mu\text{m}$). The effects of the heat load generated by the electronics have been minimized by careful integration of the cooling with the detector structure. Combining these uncertainties, the overall systematic error on the position of the average inner radii of the two detectors is $10\text{ }\mu\text{m}$, corresponding to a systematic error on the luminosity of 4.1×10^{-4} .

The distance between the two calorimeters, the other crucial parameter in the determination of θ , was measured to be $2460.220 \pm 0.075\text{ mm}$, which implies a 6×10^{-5} uncertainty in the luminosity.

Test beam measurements were used in order to reference the radial coordinate used in the analysis, which combines measurements in the silicon layers between 2 and 10 X_0 , to the detector geometry. This reference procedure has three steps. First muons are used in the test beam to establish the position of the pad boundaries relative to an external tracker. Next the image of the pad boundary in a given layer is reconstructed using the pad in that layer with the maximum energy deposition (pad-max). The small bias in this image from the curved pad boundaries and the finite shower size was measured to be $8 \pm 6\text{ }\mu\text{m}$. Finally the radial coordinate, is referenced to the image of the pad boundary in a particular layer. Using this

procedure it is possible to reference the radial coordinate used in the analysis to the detector geometry with a precision of $6\text{ }\mu\text{m}$ which implies a 2.5×10^{-4} uncertainty in the luminosity.

Figure 3.3.3 shows the radial coordinate on the right and left side of the detector, after the isolation cuts (see Table 3.4) have been applied. Because of the non-projective geometry of the detector, we can compare the residual bias of the coordinate, as measured at different depths in the calorimeter, with the change in acceptance as the radial cut is varied in data and Monte Carlo. The agreement between the expected and observed shifts as the cut is varied is shown in Fig. 3.3.4. The largest discrepancy seen in this figure is 2.4×10^{-4} . This effect, while compatible with expected uncertainty from the reference procedure, is currently under investigation. Pending the outcome of our additional work, we have provisionally assigned an additional error of 2.4×10^{-4} to cover any uncertainty in the reference procedure. The total systematic error on the radial coordinate reconstruction is then 3.4×10^{-4} .

3.3.4 Energy Response

In reconstructing the energy of each shower we have taken full advantage of the longitudinal segmentation of our detector. Although the luminosity monitor has been designed to have minimal material at the inner and outer edges of the acceptance, significant material in the middle of the acceptance could distort the energy response of the detector. We correct for showering in the upstream material as a function of the ratio of energy deposited in the first four layers of the calorimeter to the total energy deposited in the calorimeter and as a function of the azimuthal angle.

The largest potential source of uncertainty on the isolation cuts comes from the energy cuts. Because of relatively unfavorable background conditions in 1993, a rather high total energy cut of $0.75 \cdot E_{\text{Beam}}$ was imposed. In order to determine the acceptance of the energy cuts, the measured energy response of the detector has been used. The shape of the energy response for beam energy electrons (positrons) is measured by selecting collinear events with a tight energy cut on the opposite positron (electron). The extrapolation of the energy response to lower energy has been checked by using acollinear events where a single initial state photon has been radiated in the direction of the beam. Based on a comparison of event kinematics and the measured cluster energies, the nonlinearity of the energy response of our detector was measured to be $1 \pm 2\%$. Figure 3.3.5 shows the energy spectra for collinear events which are expected to have the beam energy. The low energy tail is caused, in part, by events which shower late and are not fully contained in the calorimeter.

To calculate the acceptance of the selection the four vectors from a Monte Carlo of Bhabha scattered are convoluted with the measured energy response of the detector. The change in acceptance from the four vector level to the detector level is $(7.1 \pm 3.8(\text{sys})) \times 10^{-4}$, where the systematic error is due to the uncertainties in the measured detector response. As a check on this result, we scale the energy cuts and compare the background subtracted data with Monte Carlo. As can be seen in figure 3.3.6, the measured luminosity changes by less than 10^{-4} as the average energy cut is varied from 0.7 to 0.8 of the beam energy.

3.4 Beam Test

To further reduce the uncertainties in the experimental error on the luminosity, additional test beam data was taken in August 1994. The University of Oregon group played an important role in this test providing much of the data acquisition system as well as much of the man-power needed to take the data.

In contrast to our previous test beam data in 1992, the 1994 test employed a fully instrumented calorimeter so that issues of shower reconstruction and position resolution could be better studied. The silicon microstrip telescope which was used in the test was also significantly improved from the one employed in the 1992 test. The Oregon group has taken over the responsibility for the analysis of this data and is presently using it to improve the systematic error associated with the radial coordinate reconstruction.

3.5 Determination of the LEP Energy Spread

The Oregon OPAL group has also determined the energy spread in the LEP machine. An accurate determination of the RMS energy spread of the LEP center-of-mass energy is needed for the determination of Γ_Z and the total hadronic cross sections. In the case of Γ_Z a center-of-mass energy spread of 55 ± 5 MeV leads to a 4 ± 1 MeV correction. The effect of the center-of-mass energy spread on the measurement of the peak cross section is also important. Just above the peak a 55 MeV energy spread lowers the cross section by more than 0.1%.

The beam energy spread can be determined from the longitudinal size of beam using the relation:

$$\sigma_z = \frac{\sigma_{E_{\text{beam}}}}{E_{\text{beam}}} \frac{\alpha_c R_{\text{LEP}}}{Q_s}$$

where σ_z is the longitudinal beam size, E is the beam energy, α_c is the momentum compaction factor for LEP, R_{LEP} is the bending radius of LEP and Q_s is the synchrotron tune. The longitudinal beam size has been measured as a function of

emittance wiggler current as shown in figure 3.5.1. Using this method the energy spread in LEP center-of-mass energy for the 1993 energy scan was determined to be 55 ± 5 MeV.

In anticipation of the more precise determination of Γ_Z expected from the 1995 data, we have initiated work to reduce the systematic error on the energy uncertainty. The main error comes from the difference between the coherent Q_s which is a function of the beam current and the incoherent Q_s which drives the energy spread and is not a function of beam current. Examination of the 1993 and 1994 data sets are consistent with a 6% change in the value of the coherent Q_s for the maximum values of beam current. Figure 3.5.2 shows the ratio of the longitudinal beam size to its calculated size using the coherent value of Q_s as function of the current in the LEP beams. The observed 6% slope is consistent with expected ratio of coherent to incoherent Q_s . In the 1993 analysis, an uncertainty of 10% was allowed for this effect. By correcting for the effect of beam current we can reduce the error on the beam energy spread so that it has a negligible contribution to the error on Γ_Z .

4. NuTeV (E815)

The NuTeV collaboration has made good progress during the past year. The work required to take neutrino data is on track to be ready well before June 1996, which the Fermilab schedule gives as the fixed target startup. The preparations and upgrades to the Lab E/CCFR detector are mostly complete, and the group has been taking cosmic ray data for several months with the whole system operational. The new sign-selected beam line is being installed. Oregon postdoc Bob Drucker joined NuTeV in Spring 1994 and has made significant contributions to many aspects of NuTeV. In the key area of beam measurement, which is the primary responsibility of the Oregon group, Bob has become the NuTeV leader. A major component of the beam instrumentation system, the BPMs, are being built at Oregon. First-year Oregon graduate student David Mason spent Summer 1995 at Fermilab, and brought the beam toroid system to a nearly beam-ready state. Oregon has purchased many X-terminals as well as four 9 GByte hard drives for use with the Lab E SGI Unix system. In September 1995, Oregon hosted the NuTeV collaboration meeting.

We discuss the collaboration's progress below, highlighting some of the specific Oregon contributions. There has also been a number of interesting new physics results which have come out of the analysis of CCFR data, which are briefly discussed below. Every NuTeV physicist has free access to analyze CCFR data, and during the last year the CCFR meetings have been scheduled for the day before the NuTeV meetings. From the NuTeV perspective this has the practical benefit of promoting analysis readiness, in addition to the clear cultural and educational benefits. In Chapter 4 of the proposal we discuss the physics prospects for NuTeV and the direction of the Oregon group's efforts over the next year.

4.1 Detector Readiness

NuTeV will use the CCFR detector in Lab E as the neutrino "target"/detector. A few years ago, the E815 collaboration began the effort of revitalizing and upgrading the detector to meet the physics requirements of NuTeV. The revitalization effort has been perhaps the greatest single effort undertaken by the collaboration to date. The repair/upgrade of the liquid scintillation counters has been completed with excellent results. The toroids have been powered and used for the cosmic ray running. The new veto wall is complete. The tracking chambers have to be repaired, put under high voltage, have broken wires replaced and tested, etc., which is work still in progress. All of the electronics has had to be recovered, put into place, and tested. The trigger electronics has been systematically restored and recabled. The new data acquisition system works and the whole system has been successfully used to record cosmic ray events, which in turn is being used

for detector debugging and alignment. The cosmic ray event displays are gradually revealing a nearly complete detector. The data acquisition is now in the process of incorporating the slow detector monitoring information (high voltages, temperatures, etc.) and the beamline instrumentation information. Much progress has been made in developing a new online software system which has a good user interface and which is consistent with the offline software, which itself has been streamlined and modernized relative to CCFR.

In addition to the new neutrino beam, a new test beam is also being prepared. NuTeV receives neutrino beam only during the fast spills, which occupy only a few seconds of the each beam cycle. During the remaining time, the detector can acquire a good sample of test beam events, consisting of momentum analyzed electron, meson, and muon secondaries, produced in a separate beam line and transported to Lab E. These beams will give essential calibration and detector mapping information, which past CCFR runs have shown to be invaluable for making precision measurements. This is a major new effort, and has required much of the group's attention.

4.2 The New Beam

The essential new element of NuTeV is the sign-selected beam, which will allow NuTeV to run in either neutrino or anti-neutrino mode. This is an important feature for making electroweak measurements, and is what makes a combined measurement of $\sin^2 \theta_W$ and ρ possible. The other essential feature of the sign-selected beam is that neutral secondaries are de-selected. Hence, backgrounds due to production of K_L^0 and its subsequent decay to $e\nu_e$ will be essentially eliminated. This was the dominant systematic error for the recent measurement of $\sin^2 \theta_W$ based on previous CCFR running, recently published in Physical Review Letters. The new beam will allow NuTeV to produce the most precise measurements of $\sin^2 \theta_W$ and ρ in neutrino interactions, and to do so in such a way that the measurements will be statistics limited for the foreseeable future. The projected NuTeV measurement errors are shown in the corresponding section of the proposal.

The Oregon group is responsible for the beam monitoring, including all instrumentation and software. This consists of the measurement of the position and angle of the primary proton beam on target, the profile of this beam, and its intensity. It also requires having some modest knowledge of these same quantities for the beam of charged secondaries in the decay tube. Monte Carlo calculations were made which gave specific requirements for the precision of the measurements, and an appropriate monitoring system was designed. The instrumentation employed will consist of beam position monitors (BPMs) for continual measurement of the proton beam position, angle, and intensity; a toroid will provide a more precise

intensity measurement as well as a timing signal for the Lab E trigger; secondary emission wire detectors (SEEDs) will measure primary beam profile, position, and relative intensity; segmented wire ion chambers (SWICs) in the secondary beam will measure its intensity, position, and profile. The SWICs will also be used to measure the position of a target-out proton beam of energy 250 GeV at the very beginning of the run. This will provide a precise check of the alignment of the new sign-selected magnet elements, an important piece of the systematic error budget.

The proposed program for carrying out the beam instrumentation effort during the next year is presented in the proposal. Below, we briefly describe some of the work carried out by the Oregon group during the past year.

Figure 4.2.1 is a plan view of the beam elements just upstream of the proton target, which is indicated at the bottom of the figure. The distances in z are in feet. The locations of the pre-target BPMs and SEEDs are indicated. In addition, a toroid will be present (discussed below) which is not shown.

The BPMs are presently being built at Oregon. They are replicas of the "short" BPMs used previously in the beam switchyard. They consist of vacuum chambers within which are a pair of precision pick-off plates, separated by 180° , which are connected outside the vacuum to a LC circuit tuned to the accelerator RF frequency. A BPM schematic is given in Fig. 4.2.2. The beam passes between the BPM pickoff plates. The fields of the passing beams induce a current on the pickoff plates which, after the resonant filter, are passed to custom electronics. The fields due to the beam, at the location of the pickoffs, depends sensitively on the charge center of the beam. Figure 4.2.3 shows a calculation performed by Bob Drucker of the electric field due to the beam, the magnitude and direction of the field is indicated by the arrows. The BPM vacuum pipe is the dark full circle at radius ≈ 5 cm, while the pick-off plates are the arcs at radius ≈ 3.5 cm. The pick-off signals measured by the two plates, call them A and B , can be combined to measure the total beam charge ($A + B$) and the beam position in one dimension. The expected beam to signal relationship is expected to be given by

$$x = \alpha \left[\frac{A - B}{A + B} \right],$$

where α is a constant to be determined. Bob Drucker has extended his field calculation to verify the equation above, known as the "transfer function". The result, shown in Fig. 4.2.4 shows that the transfer behaves as expected. He checked the ansatz of factorization of x and y . We see that even a huge offset of the beam in y of 5 mm has a very small effect on the x measurement. The position resolution of the BPMs is primarily limited by signal to noise in the electronic readout. We

expect to be able to achieve an accuracy of $\sim 100 \mu\text{m}$ with our BPMs, whereas the required accuracy is closer to 1 mm. Four BPMs are required, one x - y pair at two z locations. The electronics is being built by the FNAL Research Division. The data will be distributed via a FNAL software package called Epicure to both Lab E and accelerator operations.

A pair of devices known as SEEDs are being built to the specifications given by the Oregon group. Each SEED consists of an x - y pair of wire planes. The wire plane aperture and wire spacing set by the beam size. The device will work using secondary emission due to beam scattering in the wires. The SEEDs have two main functions. The wires sample beam density, hence mapping the transverse beam profile. The BPMs measure charge center only, giving essentially no information on the shape of the charge distribution. This profile must be known at the $\approx 10\%$ level in order to keep neutrino beam systematics low. Secondly, the SEEDs will provide a physical, in-situ calibration of the BPM transfer function. The wire plans will normally be in a position retracted from the beam, and will be moved into the beamline on demand. Bob Drucker has done a calculation of the effect of the passing beam on the SEED wire tension due to heating. This is shown in Fig. 4.2.5. Since these wires are short and robust, this is not expected to be a problem. The SEED data will also go into the Epicure system by way of new FNAL SWIC scanner readout modules.

A beam toroid will also be placed around the primary proton beam. This serves two functions: A precise measurement of the total beam current, and a well-defined beam gate which sets the neutrino detector beam gate timing. David Mason worked on this system during Summer 1995. A schematic of the toroid system is given in Fig. 4.2.6. The toroids themselves were recovered from previous fixed target use. There was no electronics, however. David and Bob were able to modify toroid electronics used for the Tevatron to be compatible to the fixed target timing structure and beam current. David tested the linearity of the system by using a calibration pulse line, which passes through the toroid. The results are shown in Fig. 4.2.7. The two data sets correspond to two different toroids with different values of self-inductance.

Monitoring of the secondary beam has called for a new SWIC detector, designed from the ground up by Bob Drucker, to be installed in the NW2 enclosure of the secondary beam decay line. Figure 4.2.8 shows the layout of the SWIC in the NW2 enclosure. The aperture of the SWIC is very large, about 3 feet in diameter. In this way the SWIC does not provide a significant rescattering source for the secondary beam particles, which could be an important source of backgrounds, especially from K_L^0 and wrong-sign charged pion production. Bob Drucker did a complete Turtle plus GEANT calculation which showed that a SWIC done in this

way was a small perturbation on the (small) backgrounds. The NW2 SWIC will have a plane each of x and y as well as a foil plane to measure intensity. The transverse view of one wire plane is shown in Fig. 4.2.9, while the structure of the various planes in depth is shown in Fig. 4.2.10. Bob did detailed calculations which showed that to eliminate space-charge non-linearities, the SWIC should use helium gas with an electric field giving no gas multiplication. The SWIC is being fabricated by the FNAL Research Division.

4.3 Analyses of CCFR Data

The CCFR/NuTeV collaboration on physics analyses of CCFR data from previous run, mentioned in the introduction to this chapter, is very active. Three new results were presented by NuTeV collaborators at the EPS meeting in Brussels in Summer 1995. One paper represents an extension of the previous CCFR measurement of the electroweak mixing angle to report the "model-independent" quantity R^ν (see NuTeV chapter in proposal for definitions). The reported result is

$$R^\nu = 0.3149 \pm 0.0010(\text{stat}) \pm 0.0019(\text{syst}) \pm (\text{theory})$$

There is a completely new measurement α_s by means of the Gross-Llewellyn Smith (GLS) sum rule, which constrains the integral of the valence quark, non-valence quark momentum distributions to be 3 for nucleons to leading order. Higher-order QCD corrections to this are a function of α_s , thus allowing its measurement. The measurement is quite low in Q^2 with the result

$$\alpha_s(3\text{GeV}^2) = 0.26 \pm_{0.03}^{0.02} \pm 0.02 \pm 0.03,$$

where the errors are statistical, systematic, and theoretical ("higher twist"), respectively. When run up to the scale of M_Z this becomes

$$\alpha_s(M_Z^2) = 0.108 \pm_{0.005}^{0.003} \pm 0.004 \pm_{0.006}^{0.004},$$

with the errors ordered as above. This is one of many results for α_s at low Q^2 which are somewhat lower than the average α_s from measurements at the Z^0 . This measurement will improve with NuTeV, so may well remain quite topical.

Finally, there has been a new analysis of neutrino mixing from CCFR data. The analysis technique is new and is based on the principle that the ratio of observed neutral-current to charged-current neutrino events, as a function of depth in the CCFR calorimeter, is quite sensitive to oscillation of neutrino species. The ν_μ beam will produce a larger than expected fraction of apparent neutral current events with increasing depth in the calorimeter because ν_e and ν_τ interactions will tend to be

identified as neutral current events, due to the lack of final-state muon in the final state. There is no evidence for mixing. And the result gives the most stringent mixing limit yet for

$$\nu_\mu \rightarrow \nu_\tau \text{ for } 25 < \Delta m^2 < 90 \text{ eV}^2, \text{ and}$$

$$\nu_\mu \rightarrow \nu_e \text{ for } 250 < \Delta m^2 < 400 \text{ eV}^2.$$

Bob Drucker has presented preliminary results at CCFR meetings of an analysis for neutrino mixing, where he uses a unique analysis technique employing a neural network algorithm to aid in the identification of τ , e , and μ final states. Figure 4.3.1 gives the neural network output tuned to identify ν_τ interactions in the detector in the Monte Carlo. There is a good separation from ν_μ interactions. He has thrown 100 random experiments with realistic event statistics to determine what kind of error might be determined with this technique. The distribution of oscillation probability limits for these 100 possible outcomes is shown in Fig. 4.3.2. The technique seems quite promising.

5. R & D for Future Colliders

5.1 Beam Test of 18 cm Silicon Tracker

A prototype silicon microstrip detector which was assembled for the GEM general purpose detector proposed for the Super Collider was tested in a high energy beam at SLAC in November, 1994. The system was designed for performance in the GEM environment: 60 MHz bunch crossing at 10^{33} luminosity with inner barrel occupancies of 0.16%. Signals from the strips were amplified by high-speed, low-power, low-noise, low-mass, integrated microelectronics, custom designed for operation at a hadron collider. The mechanical design of the GEM tracker motivated the selection of long (18 cm) strip lengths (achieved by wire-bonding three 6 cm long detectors). The longer detectors considerably reduced the number of electronics channels and simplified the mechanical and thermal design of the tracker. Results have been evaluated to demonstrate the feasibility of this approach.

The Oregon GEM group made measurements of the efficiency and time resolution of a prototype ladder as a function of the azimuthal and polar angle of tracks which hit the ladders and as a function of position. By using a high energy test beam (25 GeV electrons) it was possible to accurately reconstruct the position of the tracks as they crossed the detectors under test. The particles in the test beam were extrapolated with a precision of $20\text{ }\mu\text{m}$ or better, making some measurements of the charge sharing between strip possible. The amount of charge sharing as a function of azimuthal and polar angle was also measured.

The inefficiency as a function of threshold is shown in figure 5.1.1 for tracks with normal incidence. The detector becomes almost fully efficient at thresholds of 1.5 fC. At this value, the noise occupancy in a 15 ns interval is well below 10^{-3} .

Examples of two other measurements needed for evaluation of the 18 cm ladder concept are shown in figure 5.1.2. The minimum time resolution is obtained for thresholds of 1.2 fC counts. Below this threshold the resolution is dominated by the noise of the amplifier. At larger thresholds the resolution is dominated by variations in the pulse size and shape from the incident particles. Also shown in figure 5.1.2 is the dependence on mean time on threshold and longitudinal position of the ladder. For values close to 1.5 fC the measured time difference between tracks 1 cm and 17 cm from the electronics agrees well with laboratory measurements based on a pulsed infrared laser.

Our results have been summarized in a final report to the SSC Lab. We presented these results at the IEEE Nuclear Science Symposium in October, 1995, in San Francisco, and are submitting a paper for journal publication.

5.2 NLC Studies of the Top

In preparation for Snowmass 1996 and as part of the normal progress toward developing a NLC "Zero-th order Design Report", or ZDR, a number of working groups have been organized for the accelerator and the physics. Much progress has already been made, on the physics front this has been reported in the proceedings of the previous LCWS workshops, for example in Finland and Hawaii (1993). The R&D for the future linear colliders has been very impressive, has been international in character, and has resulted in a growing confidence in the technical soundness of a linear e^+e^- collider at center-of-mass energy 0.5 to 1.0 TeV.

R. Frey, J. Jaros (SLAC), and R. Raja (FNAL) are leaders of the top physics working group. R. Frey gave the top plenary talk at the first U.S. NLC physics workshop in preparation for Snowmass which was held at Estes Park, Colorado in July 1995. The second meeting in this series will take place at FNAL in November 1995, and R. Frey will give a similar talk there.

Frey has worked on a number of analysis efforts in top physics. He contributed a parallel session talk at the LCWS95 in Japan in September 1995 on the subject of the measurement of top anomalous couplings. This is described briefly below. In addition, he gave the top plenary talk at LCWS95.

Top pair production in e^+e^- offers the possibility to study the event final states in exquisite detail. Studies have shown that the $t\bar{t}$ final states can be easily separated from backgrounds and that the final states can be fully reconstructed in most cases. The Standard Model predicts that $t \rightarrow bW$ with a branching ratio of nearly one. The W 's will be about 70% longitudinally polarized and will decay in the usual way. The most interesting feature in the open top region is that due to the fact that the $\Gamma(t \rightarrow bW) \propto m_t^3$, the top will decay before it hadronizes. Thus, the bW final states completely reflect the helicity structure of the initial $t\bar{t}$. For example, one can look for events where one W decays to jets and the other to $e\nu$ or $\mu\nu$ (branching fraction 30%). The lepton charge determines t versus $\bar{t}$, and the reconstruction of the W and top masses allows the unknown neutrino longitudinal momentum be determined.

There are now four helicity angles which can be reconstructed. The $t\bar{t}$ production angle, the angle of the W 's with respect to top spin in the top proper frame, and the angle of the e or μ with respect to W spin in the W proper frame. Polarization of course is a powerful tool in such studies. A parton-level Monte Carlo due to Carl Schmidt and Michael Peskin has been used to study the sensitivity to neutral-current and charged-current couplings to top in the reconstruction and analysis outlined above. Since the helicity angles and beam polarization are all correlated, all of the reconstructed information can be combined to form a likelihood function. As an example, Fig. 5.2.1 shows the log-likelihood function variation with respect to a non-zero right-handed W charged-current coupling to the top for an "NLC year" luminosity of 10 fb^{-1} , an energy of 0.5 TeV, a top mass of 180 GeV, and no beam

polarization. Fig. 5.2.2 is the same as above with a beam polarization of -0.80 , clearly showing the significant improvement offered by polarization. The corresponding limits are about 10% of the standard model left-handed coupling.

In addition, Frey has been working with the interaction region working group, which has some significant overlap with top physics. Figure 5.2.3 shows a calculation of the $t\bar{t}$ threshold cross section (normalized to the point cross section), for a top mass of 150 GeV in this case, after convoluted with the significant effects due to initial state radiation loss.

6. References

SLD

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Opal

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7. Figures

Figure 2.2.1.1. Comparison of SLD and LEP measurements of $\sin^2 \theta_W^{\text{eff}}$. The SLD point is the left-most point, and is based on the preliminary 1992-95 A_{LR} determination.

Figure 2.2.1.2. Evolution of SLC luminosity in terms of recorded Z events.

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Figure 2.2.1.9. Trajectories in the S - T plane of Peskin-Takeuchi of various electroweak measurements, including the SLD A_{LR} . The black region is the SM prediction within the indicated ranges of top and Higgs masses.

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Figure 2.2.2.1. Differential angular distribution for $e^+e^- \rightarrow e^+e^-$. The points are the corrected data, the dashed line is the fit.

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Figure 2.3.1. Comparison of VXD2 and VXD3 RZ profiles showing the beam pipe, beryllium support structure, ladders, and CCDs.

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Figure 4.2.8. Beam's eye view (figure top) and plan view (bottom) of SWIC detector showing its placement in secondary beam enclosure NW2.

Figure 4.2.9. One of the NW2 SWIC wire planes.

Figure 4.2.10. Structure of the NW2 SWIC in depth, showing the function of the planes, including the x and y wire planes and the intensity foil plane ("I-Sig").

Figure 4.3.1. Output of neural network for ν_τ event identification from a Monte Carlo sample of mixed ν_τ and ν_μ events.

Figure 4.3.2. Distribution of possible limits for the probability that a muon neutrino oscillated to a tau neutrino. At high Δm^2 , the limit on $\sin^2(2\theta)$ is 2 times this oscillation probability.

Figure 5.1.1. Hit efficiency for tracks of normal incidence.

Figure 5.1.2. The width from a Gaussian fit to the time distribution as a function of threshold for tracks at normal incidence.

Figure 5.2.1. Logarithm of the likelihood function as a function of the value of a non-standard right-handed top- W coupling for 10 fb^{-1} of NLC data at $\sqrt{s} = 500 \text{ GeV}$ with $m_t = 180 \text{ GeV}/c^2$ and zero beam polarization.

Figure 5.2.2. Same as previous figure, but for a predominantly left-handed electron beam of polarization 80%.

Figure 5.2.3. Cross section (in units of R) for $e^+e^- \rightarrow t\bar{t}$ near threshold ($m_t = 150 \text{ GeV}/c^2$) with the effects of initial state bremsstrahlung included.

SLD-LEP Comparison

LEP Average (Moriond '95): $\sin^2 \theta_W^{\text{eff}} = 0.2318 \pm 0.0004$

SLD A_{LR} ('92 - '95): $\sin^2 \theta_W^{\text{eff}} = 0.23049 \pm 0.00050$

- SLD
- ◆ ALEPH
- ▲ DELPHI
- L3
- OPAL
- LEP Data from Moriond '95

Figure 2.2.1.1. Comparison of SLD and LEP measurements of $\sin^2 \theta_W^{\text{eff}}$. The SLD point is the left-most point, and is based on the preliminary 1992-95 A_{LR} determination.

1991 - 1994 SLD Luminosity

Figure 2.2.1.2: Evolution of SLD luminosity in terms of recorded Z events.

Beam Polarization SLD 1992 – 1995 Data

Figure 2.2.1.3. Measured electron-beam polarization, indicating the improvements in strained-lattice cathodes, as a function of recorded Z events.

Figure 2.2.1.4. Results from strained-lattice photocathode measurements of measured polarization as a function of laser wavelength.

Compton Polarimeter

9-92
7268A1

Figure 2.2.1.5. Schematic of Compton polarization measurement configuration.

Fig 1a, E_{tot} , Pass1 data

Fig 1b, l , Pass1 data

Fig 1c, N_{cl} , central region, Pass1 data

Fig 1d, N_{cl} , forward region, Pass1 data

Figure 2.2.1.6. Distributions relevant to calorimeter-based event selection for A_{LR} after the first offline filtering stage of data processing. The upper-left plot is E_{tot} , upper-right is energy imbalance, and lower plots are numbers of clusters for barrel (bottom-left) and endcap (bottom-right) regions.

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Energy in R bins for Collinear Events in 93 and 94

Figure 3.3.5 Energy spectrum for collinear events in the right and left calorimeters, in regions with and without significant upstream material. The solid curves show the parameterization used in the detector simulation. This is composed of two Gaussians, indicated by the dotted curves, and an extreme value distribution. The dashed curves show the amount by which the extreme value component of the parameterization is varied to determine the systematic error. The solid bullets are the 1994 data, the histogram the 1993 data.

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Figure 3.5.2 The ratio of the measured size of the longitudinal beam size to the calculated size as a function of LEP beam current. The calculation uses the measured (coherent) value of Q_s . The slope of the fitted line is due to the dependence of the coherent Q_s on beam current.

Experiment 815 Pre-target Configuration

27 June 1994

Figure 4.2.1. Plan view of the pre-target elements of the new NuTeV beam line. The locations of BPM and SEED instrumentation is indicated. The unit of z is inches.

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BPM Transfer Function

Figure 4.2.4. Calculation of the uncorrected beam position for an x -sensitive BPM versus the true beam position in x . The two sets of points correspond to $y = 0$ and $y = 5$ mm, as indicated.

Figure 4.2.5. Tension loss in SEED wires due to beam heating during a spill.

Vin (into toroid) vs Vout (after ADC)

Figure 4.2.7. Test of the linearity of the NuTeV beam toroid system. The two sets of points and fitted curves correspond to two toroid modules of different construction.

NW2 SWIC

Enclosure layout comes from
drawing 8-2-66, PS-1, 5/1/80

Figure 4.2.8. Beam's eye view (figure top) and plan view (bottom) of SWIC detector showing its placement in secondary beam enclosure NW2.

Scale: $4/25 = 1$

Wire spacing: 0.4 inches

Grounded guard ring

CAD: $1'' = 1/0.0055$ pixels

Figure 4.2.9. One of the NW2 SWIC wire planes.

Figure 4.2.10. Structure of the NW2 SWIC in depth, showing the function of the planes, including the x and y wire planes and the intensity foil plane ("I-Sig").

Figure 4.3.1. Output of neural network for ν_τ event identification from a Monte Carlo sample of mixed ν_τ and ν_μ events.

Figure 4.3.2. Distribution of possible limits for the probability that a muon neutrino oscillated to a tau neutrino. At high Δm^2 , the limit on $\sin^2(2\theta)$ is 2 times this oscillation probability.

Figure 5.1.1. Hit inefficiency for tracks of normal incidence.

Figure 5.1.2. The width from a Gaussian fit to the time distribution as a function of threshold for tracks at normal incidence.

Figure 5.2.1. Logarithm of the likelihood function as a function of the value of a non-standard right-handed top- W coupling for 10 fb^{-1} of NLC data at $\sqrt{s} = 500 \text{ GeV}$ with $m_t = 180 \text{ GeV}/c^2$ and zero beam polarization.

Figure 5.2.2. Same as previous figure, but for a predominantly left-handed electron beam of polarization 80%.

Figure 5.2.3. Cross section (in units of R) for $e^+e^- \rightarrow t\bar{t}$ near threshold ($m_t = 150 \text{ GeV}/c^2$) with the effects of initial state bremsstrahlung included.

8. Personnel

The participants of this research in 1995-96 were:

Faculty

James E. Brau

Raymond E. Frey

David M. Strom

Research Associates

Robert Drucker**

Jennifer Huber*

Nikolai Sinev*

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Matt Langston*

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9. Foreign Trips

David Strom - December 11 to December 28, 1994, CERN, Switzerland, OPAL, continued work on line shape and luminosity analysis, attended OPAL collaboration meetings.

David Strom* - March 18 to March 26, 1995, CERN, Switzerland, OPAL, continued work on line shape luminosity analysis, attended OPAL collaboration meetings.

David Strom* - June 13 to July 5, 1995, CERN, Switzerland, OPAL, continued work on line shape and luminosity analysis.

David Strom* - July 26 to August 2, 1995, Brussels, attended EPS conference.

David Strom - September 6 to September 22, 1995, CERN, Switzerland, OPAL, continued work on line shape and luminosity analysis.

Ray Frey - September 6 to September 13, 1995, Morioka-Appi, Japan, contributed to the "Workshop on Physics and Experiments with Linear Colliders"

Jennifer Huber* - July 26 to August 2, 1995, Brussels, presented SLD heavy flavor results at the EPS conference.

Nikolai Sinev* - June 11 to June 16, 1995, Ein Gedi, Dead Sea, Israel, presented work on the SLD vertex detector upgrade at the 4th International Workshop on Vertex Detectors (Vertex 95)

* indicates that the travel costs were partially or fully covered by the University funds.

10. Recent Publications and Reports

SLD Papers

1. Berridge, S.C., *et al.*, "First Results from the SLD Silicon Calorimeters", Conference Record of the 1991 IEEE Nuclear Science Symposium and Medical Imaging Conference, volume 1, 236 (1992).
2. Berridge, S.C., *et al.*, "First Results from the SLD Silicon Calorimeters", IEEE Trans. Nucl. Sci **39**, 1242, (1992).
3. K. Abe, *et al.*, SLD Collaboration, "First Results from SLD with Polarized Electron Beam at SLC", SLAC-PUB-6027, Dec. 1992, SLAC Summer Inst.1992:341-358 (QCD161:S76:1992), Presented at SLAC Summer Inst. on Particle Physics, Stanford, CA, July 13-24, 1992.
4. K. Abe, *et al.*, SLD Collaboration, "QCD Studies of Hadronic Decays of Z^0 Bosons By SLD", SLAC-PUB-5973, Nov. 1992, Dallas HEP 1992:892-898 (QCD161:I41:1992), Presented at the XXVI International Conference on High Energy Physics, Dallas, TX, Aug. 6-12, 1992.
5. K. Abe, *et al.*, SLD Collaboration, "Measurements of Spin-Sensitive Quantities in Hadronic Decays of Z^0 Bosons Produced in e^+e^- Annihilations", SLAC-PUB-6004, Nov. 1992. Presented at the 10th International Symposium on High Energy Spin Physics, Nagoya, Japan, Nov. 9-14, 1992.
6. K. Abe, *et al.*, SLD Collaboration, "A Preliminary Measurement of $R_b = \frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow \text{hadrons})}$ at SLD", SLAC-PUB-5972, Nov. 1992, Presented at Particles & Fields 92: Meeting of Division of Particles & Fields of the APS (DPF92), Batavia, IL, Nov. 10-17, 1992.
7. R.D. Elia, *et al.*, SLD Collaboration, "First Measurement of the Left-Right Cross-Section Asymmetry in Z Boson Production by e^+e^- Collisions", SLAC-PUB-6030, Jan.1993, Phys. Rev. Lett. **70**, 2515 (1993).
8. K. Abe, *et al.*, SLD Collaboration, "Studies of QCD B-Physics and Jet Handedness at SLD", SLAC-PUB-6225, June 1993. Presented at Rencontre de Moriond, QCD and High-Energy Hadronic Interactions, Les Arcs, France, Mar. 20-27, 1993.
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10. K. Abe, *et al.*, SLD Collaboration, "A Measurement of α_s From Jet Rates at the Z^0 Resonance", SLAC-PUB-6133, July 1993, Phys. Rev. Lett. **71**, 2528 (1993).

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12. K. Abe, *et al.*, SLD Collaboration, "A Measurement of $R_b = \frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow \text{hadrons})}$ at SLD", SLAC-PUB-6292, Sept. 1993, International Symposium on Lepton-Photon Interactions, Cornell University, Ithaca, NY, Aug. 10-15, 1993.
13. K. Abe, *et al.*, SLD Collaboration, "A Study of Jet Handedness at the Z^0 Resonance", SLAC-PUB-6362, Oct. 1993. Presented at Int. Europhysics Conf. on High Energy Physics, Marseille, France, Jul. 22-28, 1993.
14. K. Abe, *et al.*, SLD Collaboration, "SLD Results from the Study of Polarized Z^0 Produced at the SLC", SLAC-PUB-6285, Jul. 1993, Presented at Rencontres de la Valle d'Aoste, La Thuile, Italy, Mar. 7-10, 1993.
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16. Axen, D., *et al.*, "The Lead Liquid Argon Sampling Calorimeter of the SLD Detector", Nucl. Inst. and Methods **A328**, 472 (1993).
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21. K. Abe, *et al.*, SLD Collaboration, "Polarized Bhabha Scattering a Precision Measurement of the Electron Neutral Current Couplings", OREXP-94-07, SLAC-PUB-6605, Sept. 1994, Phys. Rev. Lett. **74**, 2880 (1995).
22. K.G. Baird, *et al.*, SLD Collaboration, "A Study of K_s^0 , Λ and $\bar{\Lambda}$ Production in Hadronic Z^0 Decays", SLAC-PUB-6601, Presented at the DPF Meeting, Albuquerque, N. Mex., Aug. 1994.

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24. K. Pitts, "Electroweak Coupling Measurements from Polarized Bhabha Scattering at the Z^0 Resonance", OREXP-94-06, Presented at Int Symp. on High Energy Sping Physics, Bloomington, IN, Sept. 1994.
25. M.E. King, *et al.*, SLD Collaboration, "A Measurement of the Left-Right, Forward-Backward Asymmetry for Charm Quarks Using D^{*+} AND D^+ Mesons", SLAC-PUB-6653, Presented at the DPF Meeting, Albuquerque, N. Mex., Aug. 1994.
26. Michael J. Fero, *et al.*, SLD Collaboration, "Precision Standard Model Tests with Polarized e^+e^- Beams", SLAC-PUB-6678, Presented at the Int. Conf. on Physics in Collision, Tallahassee, FL, Jun. 1994.
27. E. Vella, *et al.*, SLD Collaboration, "Heavy Quark Physics at SLD (Preliminary Results)", SLAC-PUB-6711, Presented at the SLAC Summer Inst., Stanford, CA, Aug. 1994.
28. K. Abe, *et al.*, SLD Collaboration, "A Test of the Flavor Independence of Strong Interactions" By SLD Collaboration), SLAC-PUB-6687, Dec. 1994. Submitted to Phys.Rev.Lett.
29. M. Swartz, *et al.*, "Observation of Target Electron Momentum Effects in Single Arm Moller Polarimetry", Nucl. Instrum. Meth. **A363** 526 (1995).
30. K. Abe, *et al.*, SLD Collaboration, "Measurement of $\alpha_s(M(z)^2)$ from Hadronic Event Observables at the Z^0 Resonance", Phys. Rev. **D51**, 962 (1995).
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33. K. Abe, *et al.*, SLD Collaboration, "Measurement of A_b and A_c from the Left-Right Forward-Backward Asymmetry of Leptons in Hadronic Events at the Z^0 Resonance", Phys. Rev. Lett. **74**, 2895 (1995).
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41. K. Abe, *et al.*, SLD Collaboration, "Measurement of the Average B Hadron Lifetime in Z^0 Decays Using Reconstructed Vertices", Submitted to Phys. Rev. Lett.
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OPAL Papers

43. OPAL Collaboration, P.D. Acton, *et al.*, "Evidence for b-flavoured Baryon Production in Z^0 Decays at LEP", Phys. Lett. **B 281** (1992) 394-404.
44. OPAL Collaboration, P.D. Acton, *et al.*, "A Measurement of Electron Production in Hadronic Z^0 Decays and a Determination of $\Gamma(Z^0 \rightarrow b\bar{b})$ ", Z. Phys. C **55** (1992) 191-208.
45. OPAL Collaboration, P.D. Acton, *et al.*, "A Test of Higher Order Electroweak Theory in Z^0 Decays to Two Leptons with an Associated Pair of Charged Particles", Phys. Lett. **B 287** (1992) 389-400.
46. OPAL Collaboration, P.D. Acton, *et al.*, "A Study of Two-particle Momentum Correlations in Hadronic Z^0 Decays", Phys. Lett. **B 287** (1992) 401-412.
47. OPAL Collaboration, P.D. Acton, *et al.*, "Measurement of the τ Topological Branching Ratios at LEP", Phys. Lett. **B 288** (1992) 373-385.
48. OPAL Collaboration, P.D. Acton, *et al.*, "Inclusive Neutral Vector Meson Production in Hadronic Z^0 Decays", Z. Phys. C **56** (1992) 521-536.

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50. OPAL Collaboration, P.D. Acton, *et al.*, "A Measurement of the Forward-Backward Charge Asymmetry in Hadronic Decays of the Z^0 ", *Phys. Lett. B* **294** (1992) 436-450.
51. OPAL Collaboration, P.D. Acton, *et al.*, "A Search for Doubly-Charged Higgs Production in Z^0 Decays", *Phys. Lett. B* **295** (1992) 347-356.
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53. OPAL Collaboration, P.D. Acton, *et al.*, "A Study of $K_S^0 \bar{K}_S^0$ Bose-Einstein Correlations in Hadronic Z^0 Decays", *Phys. Lett. B* **298** (1993) 456-468.
54. OPAL Collaboration, P.D. Acton, *et al.*, "Search for Anomalous Production of High Mass Photon Pairs in e^+e^- Collisions at LEP", *Physics Lett. B* **301** (1993) 391-407.
55. OPAL Collaboration, P.D. Acton, *et al.*, "A Study of the Electric Charge Distributions of Quark and Gluon Jets in Hadronic Z^0 Decays", *Phys. Lett. B* **302** (1993) 523-532.
56. OPAL Collaboration, P.D. Acton, *et al.*, "A Measurement of $K^*(892)^\pm$ Production in Hadronic Z^0 Decays", *Phys. Lett. B* **305** (1993) 407-414.
57. J.D. Hobbs *et al.*, "A Modular Electronic Readout System for the OPAL Electromagnetic Presampler", *Nucl. Instr. Meth., A* **325** (1993) 494-508.
58. OPAL Collaboration, P.D. Acton, *et al.*, "QCD Coherence Studies Using Two Particle Azimuthal Correlations", *Z. Phys. C* **58** (1993) 207-218.
59. OPAL Collaboration, P.D. Acton, *et al.*, "Precision Measurements of the Neutral Current from Hadron and Lepton Production at LEP", *Z. Phys. C* **58** (1993) 219-238.
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71. OPAL Collaboration, P.D. Acton, *et al.*, "Measurement of the B_S^0 Lifetime", *Phys. Lett. B* **312** (1993) 501-510.
72. OPAL Collaboration, R. Akers, *et al.*, "Measurements of $B^0\bar{B}^0$ Mixing $\frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow \text{hadrons})}$ and Semileptonic Branching Ratios for b-flavoured Hadrons in Hadronic Z^0 Decays", *Z. Phys. C* **60** (1993) 199-216.
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