

FINAL REPORT DOE/ER/40689--T2

CLOSEOUT REPORT

This is the closeout report for D.O.E. supported research in high energy physics for the period 1992-1996, under grant number DE-FG03-92ER40689 at the Santa Cruz Institute for Particle Physics (SCIPP) at U.C. Santa Cruz. The research during this period consisted primarily of:

1. Data taking with the SLD detector at the SLC at SLAC. This effort built on substantial work on commissioning of the SLC accelerator and has resulted in the single most accurate measurement of the Weinberg angle.
2. Participation in the ALEPH physics program at LEP and LEP-2 at CERN in Geneva, with a technical emphasis on its silicon vertex detector and physics emphasis on events containing b quarks.
3. Electronics development for the leading proton spectrometer for the ZEUS experiment at DESY in Hamburg, data taking with ZEUS, and studies of both diffractive and rare events.
4. Participation in the SMC experiment at CERN, with a particular interest in searches for lepton flavor violation.
5. Participation in design and construction activities for the BaBar detector for CP-violation studies at SLAC.
6. Design, testing and development for a silicon tracker for the ATLAS experiment at the LHC, building on our earlier work for the SSC.
7. Theoretical physics program emphasizing phenomenology, electroweak radiative corrections, Higgs physics, unification, supersymmetry, and some issues in cosmology.

We summarize below the accomplishments in each of the areas listed above.

1 The SLD Experiment

1.1 Introduction

During the 1994-5 run of the SLC, the SLD experiment accumulated a total of 100,000 hadronic Z^0 decays with a mean longitudinal electron beam polarization of $77.3 \pm 0.6\%$. Analysis of this data, combined with a somewhat less statistically

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significant sample of 50,000 Z^0 decays with a mean electron beam polarization of $63.0 \pm 1.1\%$, has yielded numerous important results in the areas of precision tests of the Standard Model, heavy flavor physics, and QCD.

Currently, SCIPP responsibilities within the SLD include maintenance and upgrade of the electron beam polarimetry, maintenance and commissioning of the Cerenkov Ring Imaging Detector, analysis of electroweak asymmetry data, and leadership of the SLD Heavy Flavor Analysis Group and Heavy Quark Asymmetries Subgroup. In addition, SCIPP professor Terry Schalk is the SLC liaison for the SLD, overseeing a wide range of issues pertaining to the interface between the SLC accelerator and SLD detector. Current SCIPP personnel associated with the SLD project include professors Terry Schalk and Bruce Schumm, and graduate students Jorge Fernandez and Per Reinertsen.

1.2 The Left-Right Asymmetry A_{LR}

The left-right asymmetry

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{\langle P_e \rangle} \frac{N_L^Z - N_R^Z}{N_L^Z + N_R^Z}$$

where L (R) refers to production with an electron beam with $P_e < 0$ ($P_e > 0$), and N^Z refers to the number of Z^0 decays observed with the given sign of polarization, provides an exacting test of the Standard Model via the relation

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

The combined 1993-5 SLD measurement

$$A_{LR} = 0.1551 \pm 0.0040$$

yields a value

$$\sin^2 \theta_W = 0.23049 \pm 0.00050,$$

currently the single most precise measurement of this critical quantity in the Standard Model. This measurement is statistically limited, the dominant systematic contribution being ± 0.00016 from the $\delta P_e / P_e = \pm 0.8\%$ error on the measurement of polarization scale provided by the SLD Compton Polarimeter, currently the most precise electron polarimeter in the world.

SCIPP personnel have played a central role in the operation and calibration of the Compton Polarimeter, and are a very important component of the ongoing analysis of the 1994-5 A_{LR} data. In 1995, the SCIPP group designed and fabricated a temperature control system which will stabilize the calibration of the Compton

Polarimeter. In addition, a laser/light-fiber phototube calibration system, currently under development at SCIPP facilities on campus at UCSC, is expected to lead to better understanding and control of non-linearities in the Compton Polarimeter Electron Detector. Both of these upgrades are necessary if the error on the polarization scale is to be reduced below $\delta P_e/P_e = \pm 0.5\%$.

2 The ALEPH Experiment at LEP

The ALEPH group in SCIPP has devoted its efforts to the ALEPH experiment at LEP-1 ($\sqrt{s} = M(Z)$), LEP-1.5 ($\sqrt{s} = 130, 136$ GeV), and LEP-2 ($\sqrt{s} \geq M(W^+W^-)$)

In our LEP-1 work, we have developed tools and done measurements of interest for future experiments on CP violation in the b-quark sector. Our work on B^{**} , B flavor tagging, and $B \rightarrow \pi^+\pi^-$ falls in this category. We have also made measurements of the B_s and Λ_b masses, searched for the B_c (with an interesting candidate found), and made a precise measurement of the τ lifetime. In the area of QCD, we have measured the inclusive production of hyperons, and have underway a study of Υ production.

At LEP-1.5, we have been involved in the work on four-jet production. A tantalizing peak in the di-jet mass sum is found at 105 GeV/c². Moreover, the events in the peak have characteristics that are not consistent with the expectation from the QCD background. These events indicate either a new-physics signal or a statistical fluctuation. Fortunately, there will be additional data which will, in all likelihood, settle this issue. Also at LEP-1.5, we have studied single and multi-photon production, and compared with the expectations of QED.

At LEP-2, we will continue our work on four-jet production, and expand this to encompass a more general search for the Higgs boson. We will also continue our study of events containing only photons. Our activities overall mesh well with our long-term plans to work on BaBar (Johnson) and ATLAS (Litke).

2.1 Notes on Personnel

- Litke's article on "The Silicon Microstrip Detector" (co-authored with Andreas Schwarz, one of our former postdocs) has been published in *Scientific American* magazine. It has appeared in at least eight languages: English, Japanese, French, German, Italian, Spanish, Chinese, and Polish. Litke is on the International Scientific Program Committee for the VERTEX 96 International Workshop, and has been invited to give a "short-course" on the impact of semiconductor detectors on high energy physics at the IEEE Nuclear Science Symposium in November, 1996. Also, he is the convener of the weak and rare B decays physics group in ALEPH.

- Graduate student McNeil was chosen by ALEPH to report on our results on Υ and B_c production at the "Quarkonium Physics Workshop" in Chicago.
- Taylor was chosen by ALEPH to give one of the first public presentations of the tantalizing results on four-jet production mentioned above.

2.2 Hardware-related Activities

The radiation monitoring system has been the specific hardware responsibility of the Santa Cruz group. It is based on a set of silicon PIN diodes. It is designed to detect rapid beam losses, and then to trigger a safe beam dump using fast kicker magnets.

3 ZEUS Project

ZEUS is an ambitious, 4π coverage detector designed to study physics at the HERA electron-proton collider at DESY. Besides completing the important foreseen tasks such as measuring the proton structure function and placing limits on new physics such as lepto-quarks, the ZEUS collaboration has also made several major discoveries, including the rise of the proton structure function at very low x -Bjorken and the abundance of diffractive events in deep inelastic scattering (DIS) characterized by large rapidity gaps. The latter has started a modern revival of diffractive physics.

SCIPP plans to continue its active role at ZEUS. Besides contributing to the task of maintaining the hardware and developing the reconstruction code for the Leading Proton Spectrometer (LPS), we are also leading the advance in the important subjects of diffractive physics and exotic physics at high momentum transfer.

3.1 Deep Inelastic Scattering (DIS)

With the advent of the HERA collider a new kinematical regime was opened up for exploring the proton structure at previously inaccessible values of large (negative) four-momentum transfer Q^2 and small x where x denotes the momentum fraction carried by the interacting quark in the proton. The HERA data have shown a striking rise of the proton structure function $F_2(x, Q^2)$ with decreasing x . This regime of high parton densities is of particular interest as predictions from perturbative QCD have to break down at some point and the transition to the photoproduction region with $Q^2 \approx 0$ can be investigated.

3.2 Diffractive Physics at HERA

Diffractive hadronic physics, first pioneered by proton-proton colliders in the late 1970s, has enjoyed a recent revival at HERA. Physics at an electron-proton

collider is not hidden by the fragmentation of two protons, as it is at proton-proton colliders such as the Tevatron allowing the study of diffraction in a simpler context. This has permitted diffractive physics to expose itself at HERA in the dramatic form of events with large rapidity gaps, first discovered by ZEUS. In addition, the large Q^2 scale introduced by the photon allows reliable theoretical calculations in perturbative QCD. The mechanism behind diffractive physics remains a matter of strong debate among theorists. Frequently, diffraction is described as the result of exchange of a colorless object called the Pomeron.

3.3 Diffractive Physics and the Leading Proton Spectrometer

In the initial published measurements of diffractive DIS at HERA, the proton remained unobserved and the variable t unmeasured. The LPS, which measures the momentum of the deflected proton, promises to change this, and thus open up an entirely new field of exploration of diffractive physics at HERA. In particular, each of the theoretical models listed above has specific predictions for the t dependence of the DIS cross section that can only be measured by the LPS. In addition, the traditional methods of identifying diffractive DIS events using rapidity gaps or calorimeter mass suffer from uncertainties in background from ordinary DIS events. These backgrounds are substantially reduced by the LPS. The correlation between the rapidity gap variable η_{max} and the LPS variable x_L , the fractional longitudinal momentum of the outgoing proton shows that the LPS variable allows a much sharper definition of diffraction: before the LPS, a cut at $\eta_{max} < 1.5$ was needed which still included events from diffraction dissociation of the proton, while the LPS cut of $x_L > 0.95$ has high purity without a mass bias. The LPS consists of six stations placed from 24 to 90 meters from the ZEUS interaction point along the proton beam line.

Some of the technical aspects of LPS reconstruction being handled by SCIPP include alignment of the detectors, calibration of the beam optics, acceptance corrections, track fitting, and Monte Carlo simulation.

3.4 The High Q^2 Neutral Current DIS Cross Section and Compositeness

The extended family of chemical elements was unified by the discovery of protons. The family of hadrons was unified by the discovery of quarks. Extending this paradigm, theorists have proposed models of *compositeness* that unify the quarks and leptons by giving them a common substructure. Using the classic technique developed at SLAC in the 1970s for the discovery of the quark, the study of DIS at the high momentum transfer Q^2 made available by HERA is an ideal approach in the search for quark compositeness.

The study of neutral current DIS at high Q^2 at ZEUS and subsequent limits on compositeness has been pioneered by SCIPP. Preliminary results, using data from

the 1993, 1994, and 1995 runs, have placed limits on compositeness at the order of 1-2 TeV.

4 Deeply Inelastic Muon Scattering (NMC,SMC) at CERN

The CERN-based muon scattering program (CERN experiments NA-37, NA-47) has accumulated a large data sample during the past few years. During this period, Santa Cruz took full responsibility for the large electromagnetic and hadronic calorimeter, H2, as well for the "lepton structure trigger" T6, pioneered by our group. On the analysis end, we were solely responsible for all calorimetry calibration and reconstruction, and did the special set of analysis steps that are needed for an evaluation of the lepton flavor changing reactions $\mu + \text{nucleon} \rightarrow \text{electron} + \text{hadrons}$, $\mu + \text{nucleon} \rightarrow \tau + \text{hadrons}$. We stress that a parallel effort is being conducted by our group, with comparable sensitivity, at the electron-proton collider HERA, in the framework of the ZEUS Collaboration. The group working at CERN was C. Heusch, W. Kroeger, and G. Perez

In 1995, we ran with a highly stable polarized-deuteron target, and the combined results of our proton and deuteron runs over the past several years therefore now permit us the most meaningful evaluation of the (fundamentally important) Bjorken Sum Rule, which had been challenged by a competing SLAC-based collaboration: $\Gamma_1^p - \Gamma_1^n$, evaluated at $Q^2 = 10 \text{ GeV}^2$, has the values 0.195 ± 0.033 , whereas theory predicts a value of 0.180 ± 0.004 - certainly a very compatible set of numbers.

The main preoccupation of our group has continued to be the lepton flavor conservation aspect of our data: Trigger 6, the only trigger that does not demand a scattered muon in the final state. The analysis was carried on both at CERN and the Universities of California in Santa Cruz and of Honduras in Tegucigalpa. We expect to soon produce a publishable account of our findings, never before attempted, on (space-like) high- Q^2 flavor-changing neutral currents, hopefully in conjunction with the analogous results of our ZEUS investigations.

Our successful operation was made possible by assistance from the Alexander von Humboldt Foundation and from the European Communities, who entirely fund the participation, as a Santa Cruz guest member, of Prof. Gustavo Perez in our program, including both the running of shifts at the experiment and the active participation in our analysis effort.

The Collaboration has published a number of papers, several of which were explicitly dependent on our detailed input, particularly, the semi-inclusive hadron production data depend critically on our calorimetry's precision, and are quite novel in their interpretation. In addition, we were invited to present summary talks

and conference contributions in various places. In particular, the critical review interpretation "Is There A Nucleon Spin Problem?" by C. Heusch was solicited repeatedly.

5 BaBar

5.1 Silicon Vertex Tracker

The major motivation for building BABAR is to find and precisely measure CP violation in the decays of neutral B mesons. To this end, the time interval between the two B -meson decays must be measured for each event by reconstructing the two primary decay vertices. This is the primary task of the vertex detector. The track angles and impact parameters are chiefly determined by measurements from the vertex detector. The vertex detector is also designed to provide complete standalone tracking. This is particularly important for the reconstruction of the many particles with low transverse momenta ($p_t < 100$ MeV/c) which cannot be reconstructed in the drift chamber. The BABAR vertex detector is therefore known as the silicon vertex tracker (SVT). To achieve these goals, the SVT has five layers of double-sided silicon microstrip detectors, with the strips oriented orthogonally to provide five measurements in the r - ϕ and r - z planes, respectively.

5.2 SVT software development

After the completion of the BABAR technical design report (TDR) in March, 1995, the emphasis in BABAR software shifted from detector design studies to a more systematic development of the simulation and reconstruction software needed for a running experiment. A formal hierarchy of software managers was established in 1995. Dr. William Lockman (SCIPP) was appointed manager of the silicon vertex tracker (SVT) simulation group. Dr. Giuseppe Triggiani (INFN-Pisa) and Dr. Gerald Lynch (LBNL) were named SVT reconstruction and tracking managers, respectively. In addition to heading the simulation group, Dr. Lockman is also coordinating the development of a Kalman filter track fitting package.

5.3 SVT Readout Chip

R. Johnson has continued to lead the UCSC effort to develop a VLSI CMOS front-end readout chip for the BaBar Silicon Vertex Tracker. The specifications for that chip were largely worked out by a UCSC/LBNL group led by Johnson. The design of the full-scale rad-soft prototype, done by the UCSC, LBNL, Pavia collaboration and is now complete. The design is for a 128-channel chip with both analog and digital functionality.

The analog section, designed by the LBNL and Pavia groups, has a preamp, shaping amp, and a comparator for each channel. Following that is a large digital block designed by J. DeWitt of UCSC that has for *each channel* a test input, a 193-bit long buffer to cover the BaBar trigger latency, a 5-bit latch for the hit time stamp, a 4-bit counter for the time-over-threshold measurement, and the associated control logic for handling triggers and moving the data. The command decoding, global control, and the back end, which includes 3 levels of buffering and a sparse readout, was designed at LBNL. In addition, all of the receivers for external clock and control signals, the drivers for the data output, and the drivers and receivers for chip-to-neighbor-chip communication were designed at UCSC by N. Spencer, P. Poplevin, and E. Kashigin. All of the various sections have been designed, verified, prototyped, and combined into a single layout.

5.4 Data Transmission and Power Distribution for BaBar SVT

UCSC is responsible for designing and constructing the Data Transmission and Power Distribution Systems for the BaBar Silicon Vertex Detector. The reason for combining these two components of the SVT is that the severe space constraints inside the detector volume require that the cabling for both be integrated. Also, the biasing constraints of the silicon detectors require that the incoming and outgoing signals be referenced to the independent bias supplies of each detector module. Therefore, there is an obvious dependence of the Data Transmission System on the power being distributed to the detector. The transmission and distribution system interfaces between the detector modules (defined electrically by the High Density Interconnect (HDI) hybrid circuits and the Kapton Tails inside the detector) and the Data Acquisition System (DAQ) and Power Supplies outside the detector. These other components, HDI, Kapton Tail, DAQ and Power Supplies, are being furnished by other collaborators.

The basic strategy of the SVT Data Transmission System is to transport information within the detector volume as electrical signals and to convert to high speed optical signals immediately outside the detector. These optical signals can then interconnect to the DAQ outside of the interaction hall. The electrical signals will be full differential to minimize noise disturbance to the front-end electronics. Furthermore, the electrical signals will be referenced to the digital common potential of the Readout Section to which they connect. One goal of this strategy is to minimize the number of active components inside the detector volume to improve reliability.

5.5 Drift Chamber PreAmplifier Chip

The Central Drift Chamber of the BaBar detector plays a central role in triggering and tracking of charged particles. Its main features are small cells and a

gas with low multiple scattering (He). Both the drift time (for tracking) and the pulse height (for particle ID by dE/dx) have to be measured in a gas which has low ionization and relatively low drift velocity because of the low electric field. Thus both ion statistics and the dispersion of electron arrival times reduce the effective pulse height useful for timing. In order for the electronics to be able to trigger on one electron the noise has to be reduced to 1/3 of that. The relatively resistive sense wire adds to the noise and reduces the signal for pulses originating at the far end.

The amplifier chip was designed by David Dorfman and Edwin Spencer at UC Santa Cruz. Four identical channels are combined on a chip of the MAXIM semi-custom bipolar process. In addition to individual channels, there are many global sections which generate signals and bias levels and currents to all channels, ensuring good matching between the four channels.

6 ATLAS

6.1 R&D for the ATLAS Silicon Tracking Detector

Our R&D program on silicon strip detectors for high luminosity hadron colliders started in 1987 for the SSC. With our joining ATLAS we have been able to continue this work. Due to limitations in funding and manpower, we decided early on to focus on the development of front-end electronics chips, while starting a close cooperation with Japanese institutions who have the know-how and industrial base to develop silicon strip detectors. This program emphasized testing on the bench and in particle beams to gain operational experience with front-end electronics chips and detectors. We tried to simulate actual running conditions and put emphasis on testing irradiated samples at realistic shaping times and read out speed. At the same time, we gained experience with a whole system by assembling, installing and operating the LPS system at HERA. In March 1996, our efforts reached a major milestone when ATLAS decided to select our technical solutions as the baseline.

The early discussions in the ATLAS silicon strip community centered around the type of detectors developed for LEP. They were either p-side or double-sided detectors on n-bulk, AC coupled with analog readout and floating strips to improve the resolution. They are fairly straight forward to produce. Based on radiation studies, we were able to convince ATLAS that for the high radiation dose of the LHC, a new approach was necessary. Our measurements, taken first in our laboratory by an undergraduate student working on his Senior Thesis using a Ruthenium source and then confirmed in the beam tests at KEK showed that the inversion of the bulk from n- to p-type changes the detector properties so much that the collection of electrons on the n-side becomes a major advantage. The n-side will

afford much more "head room" in operation, allowing us to survive unexpected increases in radiation dose and/or more conservative biasing to save power.

Consequently, ATLAS choose single-sided, AC coupled n-strips-on-n-bulk detectors read out directly, *i.e.*, without intermediate floating strips. Related to this choice, ATLAS selected so-called binary readout, *i.e.*, readout with one single threshold where a bit is set in channels in which the pulse height is above the threshold, in contrast to the option to record the pulse height. The performance of this combination of detector-frontend electronics has been studied in great detail in several beam tests. The noise occupancy is well controlled at a threshold setting above about 0.9 fC and the efficiency is above 98% for thresholds below 1.5 fC. The performance of the system will be maintained even if the threshold is changed by more than 50% from the nominal value of 1 fC.

One of the main reasons we could convince the collaboration to adopt the cheaper and simpler binary solution for the frontend electronics was our experience with the LPS silicon system at HERA. We operate 55,000 channels with one threshold as close as 2mm from the outgoing proton beam of 820 GeV, and maintain noise occupancy numbers of about 10^{-4} .

The large scale silicon strip tracking device in ATLAS is based on the concept that they will be assembled from a large number of self-contained building blocks called "modules". Although the collaboration adopted our solution to have so-called $r - \phi$ modules, where the detector strips are directly coupled to the frontend electronics (we even mount the chips across the detector), there is much work to be done in solving the problem of bringing power into the module and removing the heat from frontend electronics and detector leakage current as well as maintaining the modules at a stable temperature.

6.2 ATLAS SCT Readout Electronics

Since joining the ATLAS collaboration, UCSC has continued its development of readout electronics for silicon detectors, building on the work started for ZEUS and SDC detectors. Prior to UCSC joining ATLAS, the European groups had been pursuing the development of two readout architectures which differed in at least two respects from the UCSC one which has now been named "Binary Readout". The European designs made use of a CMOS front-end amplifier instead of the bipolar technology used by UCSC. Also, the European schemes aimed at acquiring a measure of the charge deposited in the silicon strip rather than simply discriminating hit channels from noise as in the binary scheme.

The Binary Readout Architecture consists of two chips. The first is a bipolar IC with the functional blocks of amplifier, shaper, and discriminator. The second chip is a CMOS pipeline IC which stores the "hits" in the form of binary 1's until a decision can be made by the off-detector trigger logic as to whether the data is interesting to be read out. The amplifier/discriminator is alive at all times and

the pipeline IC stores the data as one bit per channel and one column of bits per beam crossing of the collider. When a trigger decision is made, the data from the interesting beam crossing is formatted, data compressed and transmitted to off-detector data acquisition hardware.

For the past two years, UCSC with its collaborator LBNL has worked with the proponents of the other schemes so that all three options could be evaluated and the best one chosen. One of the first accomplishments was the acknowledgment by ATLAS that the bipolar technology is the best suited to meet the low noise, low power, fast shaping time requirements of the front-end amplifier. Binary readout electronics were used in the detector tests conducted at CERN and at KEK. A detailed review of the three options was conducted at CERN which included comparisons of test results against requirements, status of system development and analysis of estimated costs. The Binary option was found to meet the ATLAS requirements, to be the furthest developed and also to be the least costly. At the March-96 ATLAS Week collaboration meeting, the Binary option was chosen as the ATLAS baseline. This decision was not only a welcome recognition of the work UCSC and LBNL had done but it also now focuses all the ATLAS SCT groups on completing the needed engineering of the one selected option.

6.3 LHC RD-47

The LHC RD-47 group was approved by CERN to study the impact of commodity computing on the High Energy environment. The current Intel cpus are very fast and have a powerful I/O system. It appears that the current commodity market hardware and software is well over threshold for being an excellent

- desktop environment
- network machine
- engineering platform
- program development environment
- analysis platform (for example, to run PAW)
- Monte Carlo engine
- reconstruction platform, and
- batch environment.

Today, these machines are costing roughly \$100/CU (CERN computing unit) as opposed to comparable UNIX machines which cost 3-5 times as much. There is every reason to believe these costs will drop to the \$10/CU in the 1999-2000 time period and hopefully to the \$1/CU by 2003. The RD-47 proposal was to do a feasibility study in the context of current and future experiments of compilers, CERNLIB compatibility, GEANT, batch facilities and to run a test service to see how robustly these worked on the high end PC/NT machines. We have already benchmarked the current Pentium Pro ("P6") processors with the same ATLAS

Monte Carlo program that has been running on the UNIX farms. We have run the standard CERN benchmark suite on P6's with the following results (the CU is defined to be 1 on a DEC VaX 8600):

Machine	CU
P6 (Hp 6/200)	41.5
DEC 8200 (300Mhz)	87.7
IBM RS/6000 (43P)	42.8
HP PA 7150	35.4
SGI challenge (R4400)	29.9

As with all of the "UNIX" companies there new generation hardware in the pipe have both higher processing speed and 64 bit architecture. The tested Windows NT machines have C/C++ and Fortran compilers from a number of vendors, have the current version of CERNLIB up and running, have run long production batch jobs (8 day duration), have complete access to the UNIX file servers (via the SAMBA package) and even have a UNIX emulation layer. We believe that the "PC" and UNIX is clearly a good choice for today's HEP processing. One of us at SCIPP (T. Schalk) is part of the RD-47 project and is looking into Disk and network I/O, starting with farm system maintenance via removable 1 Gb disks.

7 Theoretical Particle Physics

UCSC faculty presently doing DOE supported research in particle theory are Michael Dine and Howard Haber. The DOE grant has supported several post-docs during this period: Robert Leigh (now on the faculty of the University of Illinois), Carl Schmidt (now on the faculty of Michigan State University), and Jens Erler (who is the current DOE-supported post-doctoral research associate). Other post-docs at Santa Cruz during this period include Scott Thomas (supported by an SSC fellowship, now on the faculty of Stanford University), Alex Pomarol (supported by a Spanish Fellowship, now on the faculty at the Universidad Autónoma de Barcelona), and Patrick Huet, who is presently supported for one year by Dine's joint NSF-KOSEF grant with Soo Jong Ray (Seoul).

During the period 1992-96, the SCIPP Theory Group has had several long term and short term visitors. Alberto Casas of the Consejo Superior de Investigaciones Científicas (CSIC) in Madrid spent his sabbatical year at UCSC during 1995-96, with the support of a Spanish fellowship. Yosef Nir (Weizmann Institute, four visits during this period, supported by a joint U.S.-Israel Binational Science Foundation grant), and Thomas Banks (Rutgers University) have each made several visits. Soo Jong Ray has made several visits in conjunction with visits to SLAC

(supported in part by a joint NSF-KOSEF grant held with Dine). Mariano Quiros (CSIC, Madrid) visited in May, 1996 for three weeks, supported by funds from the DOE grant. Piotr Chankowski, Michal Spalinski, and Zygmunt Lalak (from the theoretical physics group at Warsaw University) have each made one visit (ranging from two to four weeks), supported by the Polish-USA Maria Sklodowska-Curie Joint Fund.

Several students have received their Ph.D's during this period: John Bagnasco (now working on experimental projects at SLAC), Jaipal Tuttle (declined a post-doc offer from Stanford, now working in the financial industry); John Hiser (now working in the computer industry in southern California), and Yuri Shirman (Ph.D. expected in June, 1997; has accepted a post-doctoral position at Princeton).

7.1 Professor Howard Haber

Haber's work from 1992-96 centered primarily on electroweak symmetry breaking and physics beyond the Standard Model at future colliders. Many models of new physics invoke (softly-broken) supersymmetry to explain the origin of the large hierarchy of scales between the scale of electroweak symmetry breaking and the Planck scale. Haber's work has also focused on the consequences of low-energy supersymmetry for the search for new physics at future colliders.

At hadron colliders, the largest supersymmetric particle cross-sections involve the strongly interacting gluinos and squarks. Much has been written about search strategies for these particles with primary emphasis on events with multiple hadronic jets plus missing energy. However, the gluino and squark signatures can be much more complex, particularly if the supersymmetric decay chains involve a number of intermediate steps. In such cases, the missing energy is less pronounced, and the events are harder to separate from background. Barnett, Gunion, and Haber pointed out that like-sign di-lepton events in which the leptons are emitted at large transverse momentum and isolated from hadronic jets can provide a powerful technique for discovering gluinos and exploring their properties. This signature can extend the gluino search at the LHC out to about 2 GeV, and provides a way of determining the gluino mass which is accurate to about 10%.

At future high energy e^+e^- colliders, the $\gamma\gamma$ collider option provides some unique opportunities for discovering and exploring the properties of the Higgs bosons. Gunion and Haber explored in detail the capabilities of the $\gamma\gamma$ collider for studying the Higgs sector (with particular attention to the Higgs bosons of the minimal supersymmetric model [MSSM]). The $\gamma\gamma$ collider can extend the Higgs mass reach of the e^+e^- collider, since $\gamma\gamma$ collisions can singly produce the neutral CP-even or CP-odd Higgs scalar. In addition, one can measure the partial width of the Higgs boson to two photons, which is sensitive (in principle) to all charged particles that gain mass via the Higgs mechanism (via the loop diagram that mediates the decay).

Haber was co-convener of the the Electroweak Symmetry Breaking and New Physics at the TeV Scale Working Group for the Division of Particles and Fields Committee on Long Term Planning. This group studied the requirements for future high energy facilities needed to make further progress on the development of the theory of TeV scale particle physics. Haber and collaborators have also focused their attention on the expected difficulties in probing the details of a non-minimal Higgs sector at future colliders. For example, Haber and Thomas showed that the non-minimal Higgs sector parameters are likely to lie in the so-called “decoupling limit”, in which the lightest CP-even Higgs scalar is indistinguishable from the Standard Model Higgs boson. The results of this working group provided significant input into the 1996 Snowmass Summer Study on New Directions for High-Energy Physics co-organized by the Division of Particles and Fields. Haber served as a co-convener for the working group on precision electroweak interactions and weakly-coupled Higgs physics. A major focus of this effort was an assessment of the capabilities of future collider facilities to conduct precision measurements of Higgs properties. It was emphasized that the non-minimal Higgs states encode the dynamics of electroweak symmetry breaking. As a result, precision measurements are crucial for distinguishing between the Standard Model Higgs boson and the Higgs scalars of an extended Higgs sector.

Haber has also contributed to extended workshops in Europe focusing on the physics of Higgs bosons and low-energy supersymmetry at LEP-2 and a future e^+e^- linear collider. With Hempfling and Hoang, Haber developed a simple analytical algorithm for computing the radiatively-corrected Higgs masses of the MSSM that is accurate to within about 2 GeV. Such computations played an important role in the LEP-2 workshop, since the Higgs reach of the LEP-2 collider depends critically on the size of these radiative corrections. With Djouadi and Zerwas, Haber studied the possibility of measuring the size of Higgs self-couplings at a high energy e^+e^- collider. This can only be done by observing double Higgs production. Small cross-sections and large Standard Model backgrounds pose a significant challenge to this program.

Other works include a study of the implications of precision electroweak data for models of low-energy supersymmetry. With Carena and Wagner, Haber studied a four generation supersymmetric model that could provide for an enhanced rate for Z decays to $b\bar{b}$ seen at LEP. Such a model can be quickly confirmed or ruled out by the new high energy data from LEP-2. Grossman, Haber, and Nir showed that the decay $b \rightarrow c\tau\nu$ (which has been observed experimentally) provides a unique upper bound for the important parameter $\tan\beta$ (the ratio of vacuum expectation values in the two-Higgs-doublet model) as a function of the charged Higgs mass. Although this bound can still allow for rather high values of $\tan\beta$ (unless the charged Higgs mass is of order the W mass), it was stringent enough to place significant restrictions on certain supersymmetric models that attempted to explain

the enhanced rate of $Z \rightarrow b\bar{b}$ in terms of the virtual exchange of a light CP-odd Higgs boson with enhanced couplings to the b -quark.

7.2 Professor Michael Dine

Dine has worked in several areas during this period, including construction of supersymmetric models and analysis of their phenomenology, the problem of baryogenesis at the electroweak phase transition, and questions in string theory.

Principally in collaboration with Ann Nelson and graduate student Yuri Shirman, Dine has constructed the first viable models of particle physics in which supersymmetry is broken dynamically at low energies. These models have many theoretical advantages over pre-existing models of supersymmetry breaking, and have spawned an enormous amount of activity. With Scott Thomas, Savas Dimopoulos (Stanford) and Stuart Raby (Ohio State), Dine has explored the phenomenology of these models, noting in particular that they often predict a signature consisting not only of missing energy but also of γ -ray pairs. This is compatible with an event observed at the Femilab collider, and such events are being searched for by Alan Litke and students at LEP-2.

Dine's work on string theory has focused on aspects of string theory in four dimensions, both in order to understand how string theory might be brought into contact with experiment, and in order to gain further insight into the nature of the theory itself. With post-doc Robert Leigh and graduate student Douglas MacIntire, he showed that in string theory CP is a discrete gauge symmetry. As a result, it should not be broken by unknown quantum gravity effects. This has also motivated a reexamination of the problem of spontaneous CP violation as an explanation of the smallness of θ ; this work is currently in progress with Leigh and Alex Kagan (SLAC). With Tom Banks, Dine has explored extensively the question of one of string theory's most serious problems: the stabilization of the "moduli" and the selection of the true vacuum. They have offered, so far, the only plausible scenario for how these problems might be resolved, and have explained how one can make predictions in such a picture.

Dine also maintained his interest in cosmology. With Thomas and L. Randall (MIT), Dine has reexamined the "Affleck-Dine" mechanism of baryogenesis, and resolved a set of outstanding theoretical questions. These authors also pointed out a variety of general issues in inflation, particularly relevant to theories with moduli. Dine also continued his researches into the electroweak phase transition and the problem of electroweak baryogenesis, particularly in collaboration with Thomas.

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