BUDGET PROJECTIONS
1991 through 1996
for
Research in High Energy Physics
by
A Faculty Group in
THE DEPARTMENT OF PHYSICS
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MASTER

HARVARD UNIVERSITY HIGH ENERGY PHYSICS

Contract DE-AC02-76ER03064

1. Introduction

This research program in high energy physics is carried out under the general supervision of a committee which is composed of G.W. Brandenburg, G.J. Feldman, M.E. Franklin, R.J. Glauber, K. Kinoshita, F.M. Pipkin, K. Strauch, R. Wilson, and H. Yamamoto. Professor G.J. Feldman currently serves as chair of this committee. Dr. Brandenburg is the Director of the High Energy Physics Laboratory and administers the DOE high energy physics contract. In the fall of 1991 S. Mishra will join this committee. Harvard is planning to make one or two additional senior faculty appointments in experimental high energy physics over the next two years.

The principal goals of the work described here are to carry out forefront programs in high energy physics research and to provide first rate educational opportunities for students. The experimental program supported through HEPL is carried out at the major accelerator centers in the world and addresses some of the most important questions in high energy physics. Our educational efforts are concentrated in graduate education, where we are currently supporting thirteen research students. In addition, undergraduate students work in projects at HEPL during the academic year and over summers.

These budget projections cover all of the Harvard based high energy physics experimental activities. The "umbrella" nature of this contract greatly simplifies support of our essential central technical and computer services and helps us to take advantage of new physics opportunities and to respond to unexpected needs. The funding for the operation of the HEPL facility is shared proportionally by the experimental groups.

Harvard financially supports our high energy physics research program in many ways. The University pays the full salary of tenured faculty for the academic year from non-contract funds. It has also provided startup funds and support for special projects, for example the University contributed about one third of the funds for the purchase of our VAX computing facility. Pending final approval by the Dean of the Faculty of Arts and Sciences, the University has agreed to pay the full academic salary for new junior faculty appointments as of

July 1991. The University provides a tuition scholarship for first and second year graduate students. Finally, the salary of the HEPL Director is partially supported by Harvard.

Our activities greatly benefit from the existence at Harvard of several very strong theory groups, which are supported by the NSF and the University, in addition to Professor Glauber's group, which is supported under this contract. Our theoretical colleagues give exceptional stimulation and guidance for our experimental activities. The Physics Department also invites several Loeb Lecturers each year who provide the Cambridge community with fresh points-of-view in all areas of physics. In the 1990-91 academic year a visiting professor, R. Cousins from UCLA, has joined in the activities at HEPL. H. Kagan from Ohio State will spend his sabbatical with us during the 1991-92 academic year.

HEPL physicists are involved in numerous committees and activities which benefit the entire HEP community a few examples of which are given here. Professor Strauch recently served as chairman of the IUPAP Commission on Particles and Fields for three years. Professors Pipkin and Feldman have recently been serving on the Fermilab and Cornell PAC's respectively. Professor Feldman is the vice-chairman of the Division of Particles and Fields of the American Physical Society and is a Divisional Associate Editor of Physical Review Letters. Dr Brandenburg was a member of the DOE Energy Sciences Network Steering Committee until last year and has now been appointed to the National Research Network Advisory Committee. Finally, Professor Wilson and Dr. Brandenburg sponsored the annual U.S. Particle Accelerator School at Harvard in June of 1990.

2. Facilities

A. High Energy Physics Laboratory

The High Energy Physics Laboratory is the focus of the high energy experimental physics activities at Harvard University. The building, originally part of the Cambridge Electron Accelerator (CEA), has offices for faculty, postdocs, students, engineers and administrators. It houses a machine shop, an electronics shop, a high-bay equipment assembly area, test laboratory space and the VAX computer facility. The test laboratories are equipped with appropriate test electronics and several microcomputers with CAMAC interfaces. We have three engineering workstations which are used for circuit analysis and layout and for mechanical design by our engineering staff.

Even though data are taken at the accelerator centers (FNAL, CERN and Cornell), detectors are built at Harvard and much of the data are analyzed in-house. The ability to make major hardware contributions to our experiments permits us to be effective partners in collaborations; this ability constitutes a very important part of our program. Our excellent shop and assembly facilities were inherited from the CEA, but have been greatly improved in the years since.

The engineering staff consists of an electronics engineer, a mechanical engineer, a machine shop foreman, and a computer system manager. The technical staff consists of three electronics technicians, two machinists, and two mechanical technicians. The administrative staff consists of the Director, a secretary and a bookkeeper. No engineer or technician is assigned to a given group; instead the staff works on different group initiated projects according to priorities set by the high energy committee.

The size of the HEPL staff has decreased in recent years because of tight budgets. If our facility is to remain functional and effective it is essential that the erosion of technical personnel be stopped. In fact because of the increased demand for prototype development as planning for the SSC begins, we are adding a second mechanical engineer this year. This position will be funded by a grant from the TNRLC.

The HEPL shop facilities have been used to build equipment for numerous experiments. The major effort during 1978 and half of 1979 was devoted to the CLEO experiment at Cornell. The equipment built included the TOF system, two high-pressure Cerenkov counters, and the end-cap shower counter system. During the same period a proportional tube muon

detector was built for the Crystal Ball experiment at SLAC. The period 1980 through 1983 saw the design and completion of the major components for a proton lifetime experiment at the Park City mine. A luminosity monitor for the Crystal Ball detector in its new home at DESY was also designed and built in the spring of 1982. The machine shop completed large electromagnetic calorimeters for both the Collider Detector at Fermilab (CDF) and the Tevatron Muon experiment (E665) during the period 1984-1986. Following that in 1987-89 the machine shop constructed the upgraded CLEO TOF system and built hardware for both L3 and UA1 at CERN. More recently a new trigger hodoscope has been completed for E665. Our current project is the fabrication of an array of drift tubes to extend the muon coverage of CDF. Over the last three years the electronics shop has been designing and building readout electronics for CDF, CLEO, E665, and UA1 and is prototyping electronics for future experiments. The figures on the following pages illustrate the allocation of the HEPL resources to the different groups for the last three years. More details on schedules and on future plans can be found in the sections of this report for the individual groups.

We have always had an active program of detector R&D at HEPL involving several of our physicists. This work has resulted in new calorimeter designs and in advanced readout systems in recent years. This effort has recently been funded as a part of the SSC R&D program. Two members of our engineering staff, J. Oliver (electronics) and E. Sadowski (mechanical design), spend at least half of their time on this work. This program is described in a later section.

A new teleconferencing facility is being installed at HEPL in 1991. A conference room will be equipped with cameras, monitors, and microphones and the system will be connected to similar systems at Fermilab, SSCL and LBL. The equipment has been purchased with matching funds from the SSCL and the University (startup funds for Prof. Feldman). The telephone connection will be partially supported by HEPL, but the primary link from Boston to Chicago is being provided by DOE Energy Sciences Network as a part of their commitment to teleconferencing. This facility will make it possible to attend meetings and conferences without traveling will be especially valuable for both faculty and graduate students who have other commitments in Cambridge. It will also be made available whenever possible to other HEP groups in the Boston area who are participating in SSC and Fermilab experiments.

In an adjoining building is the Harvard Cyclotron laboratory with an external beam of 160 MeV protons. It is available at cost for testing counters and for detector development. Over the years several of our groups have taken advantage of this convenient facility.

HEPL MACHINE SHOP USAGE
FROM DEC-1987 TO DEC-1990

UA1 ◇-----◇
LEP3
CLEO - - - - -
E665 - . - . -
CDF _____
HEPL +-----+

HEPL ELECTRONICS SHOP USAGE
FROM DEC-1987 TO DEC-1990

UA1 ◇ — ◇
LEP3 ·····
CLEO - - -
E665 - · -
CDF ———
HEPL + — +

HEPL SHOPS-TOTAL USAGE
FROM DEC-1987 TO DEC-1990

UA1	◇
LEP3	
CLEO	----
E665	-.-.-.-
CDF	=====
HEPL	+

B. Computer Facility

We feel very strongly that it is essential for our physicists to have access to substantial computing resources at HEPL if they are to play leading roles in exploiting the physics potential of the major detectors they have helped to build. Indeed, for the vitality of high energy physics, it is extremely important that graduate students and post-doctoral researchers be able to participate fully in data analysis while resident at their home universities so that they may exchange ideas with their theoretical colleagues and scientists in other disciplines.

All HEPL experimental groups are participating in a variety of forefront high energy experiments that will require large data analysis efforts at Harvard. The CDF group has been involved in a major data analysis effort aimed at looking into the completely new mass scale made available at the Tevatron proton-antiproton collider. Fermilab E665, a muon scattering experiment at the Fermilab Tevatron, has a major data-taking run underway. The upgraded CLEO detector at Cornell's electron-positron facility, CESR, is carrying out extensive studies of hadrons composed of bottom-type quarks. Finally the L3 Collaboration is logging massive amounts of data on the Z^0 at LEP.

There is also a continuing need for computing by theorists and other researchers in the Harvard Physics Department that is currently being served by the HEPL computer facility. In return the Physics Department has contributed to the purchase of the system, and the non-HEP users contribute to the operating costs of the facility in proportion to their usage.

The heart of the HEPL computer system is a VAX 8650 which was purchased in 1985. It was acquired with funds from both the Department of Energy and the Harvard Physics Department. In 1987 the VAX CPU was upgraded and memory was added for a total of 56 megabytes. The system currently has 3500 Mb of disk storage, numerous tape and cassette drives and several dozen terminals. Our users in the Physics Dept. and elsewhere on campus can reach the system via the campus-wide ethernet. The HEPL VAX is linked via HEPnet to the major labs and most other U.S. high energy groups, and is also connected to LEP3net, NSFnet and BITnet. We serve as a routing node on the network for the HEP groups at both Brandeis and Tufts. A diagram of the current configuration of the VAX system is shown at the end of this section.

Two VAXstations are transparently "clustered" with the system via ethernet. The first is a color 3200 system which is intended for interactive analysis and which is directly connected to the program library and data disks. The second is a black and white 3100 system which is also

used for analysis, but which doubles as a network router for the 8650. The latter system was purchased with Physics Department funds. (Three additional VAXstations are in use by the CDF group at Fermilab).

The VAX system has performed admirably. Many analysis programs have been written, installed, and used including those for the following experiments: the CCM Muon Spectrometer, CLEO, Mark II, Crystal Ball, the Park City Proton Lifetime Experiment, and CERN UA1. Currently there is extensive DST analysis and Monte Carlo production underway for CDF and CLEO, and software development is proceeding for E665 and L3.

In future years we will need to increase our total CPU power even further as CDF and CLEO accumulate ever higher integrated luminosities. It is now clear that the best way to do this is not to invest in "mainframe" style of computing, but to link multiple microprocessors together. This can be done with specialized processors such as the Fermilab ACP, or it can be done with modern workstations, such as VAXstations or RISC processors, all connected by ethernet. This "distributed computing" scenario is the best for a university environment because of its flexibility and generality, and because it can be completely assembled from commercially available products. All of our experiments are heading in the direction of UNIX systems, making the more powerful RISC workstations the obvious choice for the future. The VAX 8650 can continue to be useful as the file server and network interface for such a distributed system of workstations, but must eventually be replaced by a smaller, faster machine.

We are requesting \$50K in equipment funds in both 1992 and 1993 to continue to build our computing power. With the \$50K we have received for 1991 we will purchase several new RISC workstations and associated peripherals. A possible choice is the DECstation 5000/200 which has the computing power of 25 MIPs and can be purchased through the University for well under \$10K. Other possibilities are the Apollo DN10,000 used extensively by L3 and the Silicon Graphics devices being used in computing farms at Fermilab. With the funds requested in future years our goal will be to increase the number of workstations until we have a total CPU power of several hundred VAX 780's. Along with the purchase of workstations it will be necessary to increase our data storage capacity, i.e. acquire at least one additional disk drive per workstation. In another year it will be necessary to replace the venerable 8650 with a smaller faster server that is more suited to the UNIX environment. At that time we will also investigate the possibility of a video cassette jukebox to allow our large data sets to be on-line for all the workstations.

HEPL COMPUTER FACILITY

April 1991

3. Proton-Antiproton Colliding Beam Program at Fermilab – CDF

(Professors Feldman, Franklin, and Mishra; Drs. Brandenburg, Konigsberg and Schlabach; Mr. Baumann, Mr. Daw, Mr. Dignan, Mr. Jessop, Mr. Ng, and Mr. Ptohos)

Since 1980 the primary physics activity of this group has been focused on the CDF program at the Fermilab Tevatron Collider. Our students and postdocs have been in an excellent position to exploit the tremendous physics opportunities provided by 1.8 TeV proton-antiproton collisions at the Tevatron. We are producing and studying the properties of the weak vector bosons, searching for new kinds of heavy quarks and leptons, and making systematic studies to test the theory of strong interactions, QCD. We are in a position to look for entirely new phenomena such as Higgs boson production, super-symmetric particles, and all manner of other exotic possibilities. Some of us are also participating in the planning of the SDC experiment which has initial approval from the SSC Laboratory, which is discussed in a separate section.

Prof. Gary Feldman, who joined the Harvard faculty in 1990, now heads the CDF group together with Dr. George Brandenburg and Prof. Melissa Franklin. Prof. Feldman is on sabbatical leave to work on CDF during the 1991-92 academic year. In the fall of 1991 Prof. Sanjib Mishra will also be joining the group. Prof. Steve Geer left Harvard for a Fermilab staff position at the end of 1990. Other faculty members who have worked with this group in previous years are Prof. Roy Schwitters, Prof. Craig Blocker and Prof. Marjorie Shapiro who are now at the SSC Laboratory, Brandeis University, and U.C. Berkeley respectively.

Our group also includes two talented postdoctoral research associates, Dr. Jacobo Konigsberg, who is working with Prof. Franklin on calorimetry improvements, and Dr. Phil Schlabach, who is working with Dr. Brandenburg on muon upgrades. We also would like to add an additional postdoc position during 1991 to work part time on CDF and also to participate in the development of muon systems for the SSC/SDC collaboration. There are currently five graduate students associated with the group, and six have already finished their theses.

The CDF collaboration consists of almost twenty U.S. university groups including Harvard, two national laboratory groups outside of Fermilab, and several Japanese and Italian high energy physics groups. The entire enterprise is being managed through the Fermilab CDF department, but all of the collaborating institutions are expected to contribute substantial

effort to the construction and running of this apparatus. Equipment funds for this purpose have been assigned to Fermilab and divided among the participating institutions according to a formal agreement procedure with Fermilab.

The design philosophy of CDF was to build an apparatus capable of detecting the production of quarks and leptons in proton-antiproton collisions provided by the Tevatron. Quarks are manifested as jets of hadrons. Therefore the apparatus must be capable of detecting dense clusters of hadrons, isolated leptons, and missing energy due to neutrinos. It is also highly desirable to measure the energies of all hadrons through calorimetry and momenta of charged particles by magnetic analysis over as much of the solid angle as is feasible.

The final design for CDF has a central magnetic spectrometer built around a solenoid magnet with charged particle tracking, shower counters, and hadron calorimetry. The central detector is augmented with forward-backward arms capable of measuring hadron energies and electromagnetic energies through calorimetry. Many of the components of this apparatus were built with a high degree of modularity for ease in assembly and to provide the granularity that is desirable for detecting jets of hadrons and leptons. This modularity also allowed for construction by several different groups. The Harvard group constructed (together with Brandeis) and is responsible for the electromagnetic shower calorimeter for the forward angle regions ($2^\circ - 10^\circ$) at both ends of the detector. We are also currently producing drift tubes to extend the muon coverage of the central region of the detector.

CDF had a short test run in the fall of 1985 and the first engineering run in the spring of 1987. A long physics run, which began in June 1988 and ended in May 1989, yielded a total integrated luminosity of 4.5 pb^{-1} logged to tape. In our next run, which will take place in 1992-93, we should gain a factor of approximately 5 in total integrated luminosity.

The commitments of the Harvard group to CDF include: A) the maintenance and support of the Forward/Backward Electromagnetic Calorimeter (FEM), B) the fabrication, testing and installation of drift tubes for the Central Muon Extension (CMEX), C) the coordination of the "gas" calorimeter systems of CDF including their calibration and the development of new electronics, D) developing software for data reduction of the CDF calorimetry and for general purpose use by online and offline analysis programs, and E) participation in the physics analysis and coordination of the Electroweak Physics group. These commitments are described below.

A. Forward/Backward Electromagnetic Calorimeters

Our group in collaboration with the Brandeis University group designed, constructed, tested, and installed a large electromagnetic shower counter system for use in the small angle region ($2^\circ - 10^\circ$) of the CDF colliding beam detector at Fermilab. The system uses proportional tube calorimetry with lead sheets as the radiator. The proportional tube planes are constructed using a novel technique which combines aluminum tubes and cathode pad readout. The total system (both forward and backward regions) has approximately 3000 independent pad towers which are read out in two depth segmentations.

The proportional tube planes and cathode pads were fabricated as individual sealed chambers for each layer of each quadrant. The quadrants were tested in a high energy electron beam at Fermilab. The response of the calorimeter as a function of energy was linear up to 100 GeV and the measured energy resolution was approximately 3% at 100 GeV. This calibration has been repeated during the 1990 test beam run and agrees with previous calibrations. It is being recalibrated with a shorter gate width during the 1991 test beam run.

During the 1987 engineering run and the 1988-89 long run, the calorimeter performed well. It is a standard part of the CDF readout and is included in the electromagnetic energy and jet triggers. Data from the forward calorimeters are being used in the measurement of the jet scattering angles and missing E_T and in the analysis of multijet events. Electromagnetic clusters in the forward calorimeters are also being used in the study of the Z^0 vector boson.

B. Central Muon Extension

It has been clear that good lepton identification capability has been extremely important for many important CDF physics topics, in particular the search for the top quark and the study of B decays. Although there is the potential for electron identification at all angles currently, muons can only be directly identified in the central region, $\theta > 55^\circ$, and in the forward region, $2^\circ < \theta < 10^\circ$. Therefore we are participating in the upgrade of this system.

In particular our group has designed and are building an extension of the central muon detector (CMEX). This utilizes the steel in the yoke and hadron calorimeters to extend the existing coverage from $\theta \approx 55^\circ$ down to within 40° of the beam. It is being accomplished by adding a ring of drift tubes covering the region $40^\circ < \theta < 55^\circ$. The ring will have "spokes" consisting of individual drift chamber cells approximately six feet long and six inches across. The ring will have four layers at both ends of the detector, and each ring will contain

approximately 1200 drift tubes. The layout is designed so that these tubes appear as a logical extension to the current central muon detector.

The CMEX drift tube design was developed at Harvard by Dr. Brandenburg and Mr. Sadowski. It consists of an aluminum extrusion with a 1" by 6" cross section. Circuit boards with longitudinal cathode strips are laminated to the top and bottom inner surfaces of the tubes. A resistor chain steps the voltage of these strips, and they shape the field so that a uniform drift field is maintained throughout the tube volume. We are building these drift tubes in the HEPL shops with funding provided through the CDF management. We plan to have the necessary tubes for rings at both ends of the detector ready for the 1992 CDF run. They will be tested at HEPL and laminated into 15° azimuthal "wedges" before shipment to Fermilab for installation on the CDF detector. At Fermilab Dr. Schlabach is in charge of the installation of the CMEX system and is overseeing the checkout of the readout electronics.

Prof. Feldman, Dr. Brandenburg, and Dr. Schlabach have been involved in discussions with our CDF colleagues at Wisconsin and the SSCL about participation in the next level muon upgrade. This is being planned for the 1995 run and would involve the relocation and reinstrumentation of the forward muon toroids. The idea is to move this system to the location currently occupied by the forward calorimetry, assuming it has been replaced by an upgraded plug calorimeter. This would allow muon coverage from the limit of the CMEX system down to about 6°. We are particularly interested in the part of this system that geometrically connects to CMEX. It may be possible to utilize a modified version of the CMEX design for this region, so we can make use of our previous experience for the drift chambers and the trigger and readout electronics.

C. Gas Calorimetry and Electronics Development

Prof. Franklin is the coordinator of all work on CDF gas calorimetry. This includes four calorimeters covering the plug and forward regions ($30^\circ > \theta > 2^\circ$). These systems are currently being recalibrated with a shorter integration time and outfitted with new electronics to enable the calorimeters to run successfully through the 1991-1994 period - or up to a luminosity of 5×10^{31} with 6 bunches. With the help of Dr. Konigsberg and others the performance of the calorimeters in the conditions of high luminosity were investigated last summer in the Fermilab testbeam. In particular we tested new front end electronics and low input impedance buffers with gain. The latter were developed to enable lowering the voltage of the chambers at high luminosity to avoid glow mode, and to increase the speed of charge

collection such that 90% of the charge is collected in less than 400 nanoseconds. New front-end charge integrators were designed by the Fermilab CDF electronics group, PIG, in order to make triggering possible with the 6 bunch running. These cards have been specified and were also checked out in the testbeam by the gas calorimeter group last summer.

It was also demonstrated that the gas gain of the calorimeters could be kept constant by changing the voltage on the chambers as the density of gas in the chambers changes with temperature and atmospheric pressure. This will make the absolute scale of the calorimeters more accurate and reliable and will be utilized in the upcoming run. The Harvard group is also working on a new neural network trigger for electrons in the plug region to enable decreasing the trigger threshold from 23 GeV to 12 GeV for the next run. Tests of this trigger will be made this summer in the Fermilab testbeam.

In addition to designing the new input buffers, the Harvard group had originally developed the front-end electronics for all the gas-tube calorimetry in CDF. These boards contained 24 preamplifier and charge-sensitive integrator channels, and were designed to interface with the RABBIT System designed at Fermilab. The other related electronics projects we have pursued are the following: A board has been designed for electrical checkout of the gas calorimeters by pulsing the anode wires. An upgrade of the Analog-to-Digital Conversion (ADC) board in the RABBIT system has been prototyped. A FASTBUS interface for the master clock generator, which provides timing information to the RABBIT system, was developed. A system for fanning the precision timing signals from the CDF master clock system in the counting room to the front-end electronics was designed and produced.

D. Software Development

The Harvard CDF group has played a very significant role in the ongoing development and management of the enormous body of code used in analyzing CDF data. The group made significant contributions to the definition of the data structures used for offline analysis. A macro expander used to maintain site dependent code within a single source file was entirely designed and implemented at Harvard. The main analysis driver, used for online calibration and offline reconstruction and physics analysis, was also written at Harvard.

Several members of the Harvard group have been involved in CDF efforts to define the standard CDF reconstruction package. A large portion of the calorimetry reconstruction code has been written by our group. This includes the code to perform offline calibration corrections and to clean-up the data sample (remove noise and remove energy deposits

associated with neutrons). The jet cluster algorithm currently used by CDF was developed at Harvard and we have also made significant contributions to the electron detection algorithms. A study of whether tracking information can be used to enhance jet cluster energy resolution at low energies has just been completed. Members of our group have also been involved writing and maintaining the code used online to monitor the quality of the data being written to tape and in the development of a fast detector simulation package used extensively in CDF analysis.

Finally, we have developed and now maintain the version of the CDF event display program which runs on workstations. This package is now being converted to run in an X-Windows environment, which will make it possible to run the program on the powerful UNIX-based workstations which are now being acquired by most groups in our collaboration.

E. Physics Analysis

Prof. Franklin is currently co-convener of the CDF electroweak physics analysis group. The Harvard group has been involved in various electroweak studies and is finishing a set of three measurements of the Z boson: the total cross-section, the forward backward asymmetry and the transverse momentum distribution. All three are tests of the Standard Model. The students who have completed or are completing theses on these topics are Ed Kearns, Peter Hurst and Johnny Ng. William Trischuk completed his thesis on the W mass in the $e\nu$ channel last summer. (Our postdoc Phil Schlabach did his thesis on the $\mu\nu$ channel at Univ. of Illinois.) Another student, Tom Baumann, is now preparing to do work on the W mass from the 1992 run. This involves studies of the missing transverse energy resolution, which is intricately linked to the gas calorimeters and their reconstruction code. The mass plots for the Z and W as obtained by CDF are shown on the next page.

One area we have been investigating for the upcoming run are alternative top quark analyses. Our student Colin Jessop is beginning his thesis on the topic of non-standard top quark decays. Also our other postdoc, Jacobo Konigsberg, has been reviewing the possibilities for observing a hadronic top signal. This year we have had a visitor from UCLA, Bob Cousins, who has been working with us on studies of jet resolution and ways to improve it with the idea of top quark analyses in mind.

Prior to the last run the Harvard group contributed primarily to the study of QCD via the production of high transverse momentum jets. Three students, David Brown, Robert Carey, and Richard St. Denis have already completed their theses on the following topics. The distribution of the scattering angle of jets with respect to the beamline was studied for both two

and three jet systems. This can be predicted by QCD and is sensitive to the evolution of the proton structure functions with momentum transfer. Second the angular distribution of jets in multi-jet events was utilized to place a limit on the cross section for multi-parton interactions.

Mass distributions for the W and the Z⁰ bosons in the muon and electron channels from CDF.

Finally a search for a light Higgs boson was completed by Steve Geer and others. If the Higgs boson is very light ($\leq$ few GeV) it will be produced in about 1% of all W and Z events, and will decay with a large branching ratio to a positive and negative track pair. A search has enabled the Higgs boson with a mass less than a few GeV to be excluded.

The majority of the analysis described above has been performed at Harvard using the HEPL VAX system. We use the VAX 8650 both for reconstruction and for final physics analysis. We do Monte Carlo simulation at Harvard on both the 8650 and on our MicroVAX workstations. Finally the workstations have also been used for interactive analysis of data samples and for display of interesting events. Our ability to perform CPU-intensive analysis at our home institution has meant that our graduate students can reside in the Boston area while they are working on their thesis analysis. This fact has allowed us to profitably interact with other members of the Harvard Physics department (both theorists and other experimentalists).

F. Timetable

1991 Analysis of the 1988-89 run is being completed. The production of the central muon extension (CMEX) is underway and three-quarters of the system will be installed for the 1992 run. The gas calorimeters are being recalibrated in the FNAL test beam and the capabilities of the entire gas calorimetry system for the higher luminosity 1991 collider run has been investigated. We will acquire our first UNIX workstations and port the newly converted CDF analysis package to them.

1992 The next Tevatron collider run is scheduled to begin in early 1992 and finish before the end of the year. We will have commissioned both the CMEX system and the gas calorimetry prior to the start of the run. The CDF detector will also include the new silicon vertex detector to aid in top and B identification. We will take part in the data-taking aspects of the run and in the initial checking of the data. When the run is completed we will install the final quarter of the CMEX system. We will also be developing the next phase of the muon upgrade, which will extend to the forward region.

1993 The second half of the next collider run will get underway in early 1992 after the linac is upgraded. The CMEX system will now be complete. By the time this run is completed in late 1993 we will have accumulated as much as 50 pb^{-1} , which will make it possible to find the top quark or push the lower limit on its mass as high as 150 GeV. It will also be possible to make substantial improvements in other measurements such as the W mass. During this year we will also begin production of part of the forward muon upgrade this year.

1994 This year the collaboration will concentrate on analysis of the new 1992-93 data. We will continue work on the forward muon upgrade, which is to be installed for the 1995 run.

1995 Sometime this year CDF will begin a new run with a substantially upgraded detector. In addition to the forward muon upgrade there will be a new plug calorimeter replacing the gas systems, an upgraded vertex detector, and extensive electronics improvements. The Tevatron will be operating in multi-bunch mode and will deliver luminosities approaching $2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. This run will probably be the last CDF run until after the completion of the Fermilab Main Injector, which will make even higher luminosities possible.

4. Electron-positron colliding beam program at CESR

(Professors Kinoshita, Pipkin, Wilson and Yamamoto, Dr. Henderson, Mr. Wolinski, Mr. Liu, Mr. Saulnier and Mr. Hsu)

With the number of generations (with light neutrinos) limited to three by LEP experiments, the study of third generation quarks has assumed greater prominence in particle physics. The bottom quark is so far the heaviest quark as well as the only third-generation quark accessible to us. Although it is of utmost importance to discover the top quark, it is the study of bottom quarks that is expected to provide rigorous tests of the Standard Model. Since the bottom quark cannot decay to the top quark, it must cross the generation boundary to decay; thus, primary decay rates are "Cabbibo-suppressed". This brings within experimental reach some important effects which would be otherwise too small to observe:

- 1) Long lifetimes of B mesons (about 1ps).
- 2) $\bar{B}B$ mixing which can take place because of the slow decay rate
- 3) $b \rightarrow u$ transition.
- 4 Other rare decays such as $b \rightarrow s\gamma$ through the "penguin" diagram.
- 5) CP violation.

Items 1) through 3) have been measured while 4) and 5) have not. The most important is the observation of CP violation. At present, the neutral kaon system is the only place where CP violation has been observed, and all the effects so far can be described by a single complex constant ϵ ; consistent with the standard model but not a strong constraint. A rigorous check of the standard model explanation can be made only by studying CP violation in the bottom sector. Such a study requires a dedicated machine (a B-factory) with a luminosity in excess of a few times $10^{33} \text{ sec}^{-1} \text{cm}^{-2}$ (about 20 times the present maximum at CESR). We are currently building up our knowledge and experience toward a B-factory while generating riches of physics along the way. This endeavor will stringently test the standard model, and such tests may lead to an unexpected breakthrough.

The Harvard group has been a major collaborator of the program at CESR since its beginning, and even though the size of the group has shrunk in the recent years, we expect to strengthen the group to at least the previous level by the fall of 1991. While Mr. Wolinski is about to complete his Ph.D. degree and leave our group, Mr. Liu and Mr. Saulnier joined as graduate students last summer. Prof. Yamamoto and Dr. Henderson have just arrived, and another postdoc and a graduate student (not listed above) are expected to join this fall. Our

current hardware responsibility is focused on the time of flight system, the BLT online tracking system (Binary Link Tracker), and the continued exploration of the design for a silicon vertex detector. These projects are going to be expanded toward the B factory while intense physics analysis efforts will be continued in parallel.

A. Performance of the CESR Storage Ring and CLEO II Detector

In Oct 1990, CESR was upgraded to run with a single interaction point (CESR+) this, increased the luminosity by raising the beam-beam instability limit on beam current. The plan to use fourteen or more bunches, however, was abandoned since the learning curve would delay the break-even point to the late 1990's. With seven bunches each of e^+ and e^- the luminosity has steadily improved and to date reached a peak luminosity of $1.7 \times 10^{32} \text{ sec}^{-1} \text{cm}^{-2}$, 8.6 pb^{-1} in one day, and 38.9 pb^{-1} in one week. The bunch length is now near the optimum point: for $\beta_v^* = 1.5 \text{ cm}$, the bunch length σ_z is 1.7 cm, and further shortening of bunches would not significantly increase the luminosity (the rule of thumb is $\beta_v^* = \sigma_z$). Since the conversion to the single interaction point configuration, the machine has been running on the Y(4S) and CLEO II has collected about 300 pb^{-1} of data. Overall the machine performance has been excellent.

One of the recurring problems has been vacuum leaks in RF cavities. New cavities fabricated by a different method (MKIII cavities) have been undergoing tests and are found to hold about 10 times better vacuum than the old cavities. The first of these will be installed in mid-1991. The new cavities are also designed to stand more current. With the reduced down time, it is anticipated that it will be possible to collect 1 fb^{-1} of data per year in the near future.

The assembly of the CLEO II detector was completed in the summer of 1989. Major upgraded components were magnet, time of flight system, crystal shower calorimeter, muon system and data acquisition-trigger system. Much has been accomplished in understanding the new detector: the effect of raising the magnetic field to 1.5 tesla (was 1.0 tesla) has been carefully analyzed, the alignment of tracking chambers and the understanding of electron drift in them is now good enough to produce physics results, the energy resolution of the calorimeter is 1.5% at 5 GeV and 4.1% at 100 MeV, and the time of flight system has achieved 139ps resolution for Bhabha events. A new data acquisition system (DAQ-90), which will make it possible to record events at a faster rate, has been in preparation for more than a year and will be installed this summer. Although there remains a great deal of work to be done to understand the detector completely, we are poised to generate a large array of physics results.

B. Time of Flight System

(Prof. Yamamoto, Dr. Henderson, Mr. Saulnier)

In the CLEO detector, the time of flight system (TOF) performs two roles: to provide particle identification and to be an important part of the lowest level trigger which requires reliable trigger information shortly after the beam crossing. The TOF system consists of two parts: the barrel TOF covers 80% of 4π , and the endcap TOF covers 18%. The Harvard group designed and built the barrel TOF counters. The endcap TOF counters were designed and built by the SUNY Albany group. The power supplies for the phototubes and the data acquisition cards for all the TOF counters were designed and built at Harvard. In the following discussions, we will focus on the barrel TOF system which is a primary responsibility of the Harvard group.

For a given momentum P , the difference of time of flight Δt between particles of mass m_1 and m_2 is given by $2\Delta t = t_0(m_1^2 - m_2^2)/P^2$, where t_0 is the time of flight for $\beta=1$. Thus, a 20% improvement in timing resolution would result in a 10% increase in the momentum at which particles are separated by a given number of sigmas. For kaons, two sigma separation from the massless case is at 1.25 GeV for 160 ps resolution. Since this momentum range is highly populated in typical hadronic events, a small improvement in time resolution results in a large gain in reconstruction efficiency.

The TOF system for CLEO II was designed to give good timing resolution by making it thick (48 mm) and to provide good granularity (95 mm wide, 64 counters total). The phototube was carefully selected (XP2020) and the design of the base was optimized for fast timing by using a large voltage between cathode and first dynode (about 600 V). Bench tests using cosmic rays gave timing resolutions of better than 130 ps, which should also be obtainable in the real setting with proper calibration. The TOF system was installed in the CLEO II detector in January of 1989 .

The high voltages for phototubes were adjusted so that the gains were equal within 25% (except two tubes which were slightly outside of this range). Each counter was calibrated for the effective speed of light, pulse height-dependent time-walk and offset. Each counter is viewed by two phototubes, one attached on each end, and the constants including the effective speed of light were fit independently for the two phototubes. The calibration made use primarily of Bhabha events because of their high statistics. The calibration data sets were produced using the computing facility at Harvard.

It was crucial to use different effective speeds of light for the two directions in scintillator. This improved the overall timing resolution by 40 ps and by more than 150 ps for some counters. The reason for the direction dependence is not clearly understood but it is not as strange as it may seem at first: since the photons that determine the timing have incident angles at the end of counter of about 40 degrees which is close to the critical angle, the quality of joint between scintillator and light pipe could significantly affect the angular acceptance of photons which will determine the actual path length to the phototube.

The standard way to correct for pulse height dependence is to use the form $K \times q^{-0.5}$, where q is the integrated charge and K is a constant. In our case it turned out that the best fit was obtained by using the functional form $q^{-0.15}$. It was important to weight correctly the timing information from both ends when combining them. When one makes an error of ϵ in estimating the relative resolutions of the two ends, the resulting timing resolution after the two ends are combined becomes worse by ϵ^2 . Namely, 20% misevaluation of relative timing resolutions results in 4% degradation of final timing resolution. In practice, a proper weighting improved the resolution by 12 ps compared to the simple averaging of two ends. The final time resolution after the above treatment as of April 1991 was 139 ps (see below).

Timing resolution of Bhabha events. The resolution of 139ps was obtained by using an effective speed of light that is direction dependent, a time-walk correction of form $q^{-0.15}$ and taking the weighted average of two ends.

For pions in hadronic events, a time resolution of 161 ps was obtained for tracks below 700 MeV for which pions are well separated. So far little work has been done to optimize the calibration for hadrons and to handle complicated cases such as multiple tracks per counter or multiple counters per track. In the next year we will continue to try to improve the timing resolutions for Bhabha's to the level of the bench test value – 130ps or better – while studying methods to analyze hadronic events effectively.

As a future R&D project, Prof. Yamamoto has proposed to develop a new generation of time-of-flight system with timing resolution of better than 80 ps and good multiple-hit resolution. It is intended for a B factory, and based on either highly segmented scintillator blocks or scintillation fibers.

C. Charged Particle Trigger

(Prof. Kinoshita)

In CLEO I it was possible to use a relatively loose trigger in order to accommodate the inefficiencies resulting from incomplete angular coverage and cracks without incurring an intolerable final trigger rate (more than a few Hz). At CLEO II the rates using similar triggers were expected to be considerably higher due to higher efficiencies and luminosity. Concurrently, the anticipated precision of measurements reached a point where a better understanding of triggering was crucial to the further improvement in systematic uncertainties. We were thus in the position of needing to control the trigger rate while maintaining or even increasing its efficiency. The Harvard group has designed and built a trigger which addresses this issue and has used it in studies to determine further approaches.

The most direct way to decrease systematic effects associated with the trigger is to increase the efficiency; in CLEO I the acceptance was around 70% for two-jet events, allowing for substantial room for improvement (such an upgrade would also benefit events which typically have low multiplicity, such as $e^+e^- \rightarrow \tau^+\tau^-$, two-photon events and the cascade decays $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)$, $\Upsilon(2S) \rightarrow \mu^+\mu^-$ or nothing detectable). Most desirable in this context would be a trigger on tracks in the inner tracking chambers with minimal requirements on time-of-flight or calorimetry. Tracking detectors are central and monolithic, so that the acceptance is high and can be readily modeled, and there is little loss of particles by interaction or absorption. In addition, the availability of a large number of sense wire cylinders in the CLEO II drift chamber compared to the original CLEO I chamber provides for a significant increase in the

number of well-measured tracks not entering the fiducial volume of the outer barrel detector, even given the increased coverage of CLEO II.

The Binary Link Tracker (BLT), designed and built at Harvard, uses a new algorithm for finding tracks which is more general than that of the conventional memory-based tracker. Track-finding efficiencies are based on transverse momentum rather than on the detailed geometry of drift cell configurations. This trigger is able to identify tracks with transverse momentum as low as 90 MeV/c, which corresponds to a radius of curvature of 19 cm, compared to ~200 MeV/c for the conventional trigger. It is also designed to be used at a low level, without requiring hits in other parts of the CLEO detector.

All software associated with BLT has been developed and is maintained by the Harvard group. The BLT hardware is located in its own electronics crate and trigger information is read out to the data bus by the crate controller. The crate software is used to test the trigger logic and to generate a higher level trigger output, as well as for readout. Logic tests, diagnostics for online analysis and a Monte Carlo simulator have also been developed.

BLT has been included in the CLEO II trigger since May 1990. At the lowest level of drift chamber tracking (Level 1) the BLT information has been merged with information from the conventional tracker (TSP) to provide expanded tracking options. Following studies of triggering using BLT, higher level tracking (Level 2) was developed using output from the BLT trigger and calculations via software within the BLT crate controller. This level is able to flag tracks with higher transverse momentum, determine the sign of a track's charge within a limited momentum window and give an improved estimate of the true number of tracks in an event. Using BLT at both Levels 1 and 2, we are now able to trigger requiring only one TOF counter, one low threshold calorimeter hit and three tracks with a minimum of 90 MeV transverse momentum.

With the prospect of higher luminosities at CESR, accompanied by inevitable increases in rates, it is appropriate to reconsider the entire CLEO trigger to try and improve the efficiency and reduce unwanted background events. An improvement in background rejection is particularly desirable, as the trigger rate, which is approaching 10 Hz, now exceeds the capacity of the first pass of offline analysis which runs in parallel with data taking.

Findings from a study of triggering by the Harvard group has suggested several approaches to increase effectiveness which will form a basis for future developments. The objective of the trigger is to maximize the acceptance for true e^+e^- collisions while minimizing the total trigger rate. Background at CESR consists mainly of beam-gas or beam-wall interactions and cosmic rays. The present (hardware) trigger seeks to discriminate against such events by looking at charged particle multiplicity, energy, and back-to-back correlations of tracks and calorimeter hits. The thresholds both for track momenta and calorimeter energy must be low, since the criteria are primarily based on multiplicity. It has been possible to lower the momentum threshold for tracking using the BLT through discrimination against events containing no negatively charged particles; beam-nucleus interactions often consist exclusively of nuclear fragments. A "precision tracker" which requires that tracks appear to originate at the event vertex in the vertex chamber has also been useful.

Other effective criteria which are not utilized in the present trigger include z-tracking and isotropy of particles. More sophisticated criteria suitable for higher levels or software triggers involve quantitative estimates of track and calorimeter energies and missing momentum and energy.

The installation later this year of a data acquisition system which is capable of accommodating rates up to 100 Hz allows for higher triggering efficiencies; it is found that using BLT, the trigger can be operated in a mode in which 10-20% more hadronic event candidates and 50% more $\tau\tau$ events are found than with the former trigger, due to a higher acceptance for events with low transverse energy or low dip angle. The rate for such a trigger is found to be 10-20 Hz with current luminosities and depends greatly on beam conditions. To allow it to be implemented, the CLEO system will include a higher level "software trigger" to reduce the final rate to a tractable level.

A digital track finder/fitter using the BLT algorithm and drift chamber hits has been written by the Harvard group and has excellent speed, efficiency and accuracy (its speed is limited by the overhead of retrieving drift chamber hits from the data banks). The application of this algorithm to a software trigger and the possibility of increasing its speed using vertex detector hits are being investigated.

D. Silicon Drift Detector

(Prof. Wilson, Dr. Henderson, Mr. Liu, Mr. Hsu)

Good resolution in tracking at the innermost parts of the detector is important for the isolation of secondary from primary interaction vertices and, for the reduction of background in identification of long-lived particles. An upgrade to this capability would enhance CLEO's ability to reconstruct B mesons and to measure precisely the lifetimes of charmed hadrons and τ leptons. In particular, the measurement of the decay vertices is crucial in detecting CP violation in an asymmetric B factory.

In 1989, a 6-layer "straw" inner vertex chamber constructed from carbon filament drift tubes by OSU was inserted just outside the beam pipe (inside the 10-layer vertex detector, which was installed in 1984 and remains unchanged). The possibility of further improving the vertex detector at CLEO by utilizing solid state devices is being considered by the collaboration. An ideal candidate is the silicon drift detector because of the high spatial resolution (20 μm) and true two-dimensional measurement capability, achieved with only a small number of readout channels (30/cm²). To investigate this possibility, a prototype silicon drift detector has been designed and ordered from SI, Inc. in Oslo, Norway. The prototype readout system has been designed at Harvard, and consists of a commercial low noise preamplifier, a wired pulse shaper unit, the Kleinfelder waveform analyzer chip and a pulse height digitizer. Four sets of readout systems have been built for testing; they can be used either together (as a detector telescope array) or separately. Testing will involve position resolution measurements and detector stability studies with infrared laser radiation as well as charged particle beams. Charged track reconstruction performance will be studied with the detector telescope array and a proton beam at Harvard. Finally, radiation damage will be investigated with the aim of characterizing the detector deterioration due to controlled damage to the interface due to charge buildup (with gamma irradiation) and to the bulk material (with neutron irradiation). The results of the prototype silicon drift detector testing are applicable not only to CLEO and the proposed B-factory, but bear upon the possibility of using such devices for charged particle tracking at the SSC as well (see Section 9C).

A VLSI system is being considered for the final detector design. This will utilize a preamplifier mounted on a high resistivity silicon substrate designed by P. Rehak at BNL, either matched to the drift detector, or made on the same silicon sheet. JFET technology will be utilized in order to enhance the radiation resistance of the system. The preamplifier will then

feed a VLSI shaper and the Kleinfelder waveform analyzer chip.

The prototype silicon drift detector has been delivered recently (April 1991). The tests described above are scheduled to be completed by September 1991. The completion of the tests will enable a decision to be made on the choice of the silicon vertex detection system for CLEO II.

E. Physics Program

CLEO has made, and continues to make, significant contributions not only to B meson and τ lepton-related physics but also in the areas of τ leptons and charm. The highest luminosity in the world combined with high cross sections gives rise to large samples of charmed particles and taus. The CESR energy is well suited to the study of these particles with masses in the 2 GeV region, for the following reasons: while kinematic constraints available on resonances (e.g. $\Psi'' \rightarrow \bar{D}D$) do not apply, charm jets are well separated and fragmentation processes of the charm quark can be studied. Energies are sufficiently high that τ pairs are easily distinguished from hadronic events by their topologies yet not so high that decay products tend to overlap in the detector.

A measurement relevant to B physics which has recently held much interest is the production of $\bar{B}B^*$ in the region just above the $\Upsilon(4S)$ resonance. A $\bar{B}B$ pair produced with a $L=\text{even}$ component (as in $e^+e^- \rightarrow \bar{B}B^*$) displays CP violating branching ratio asymmetries in decays to CP eigenstates such as $B \rightarrow \Psi K_S$. When a $\bar{B}B$ pair is produced in an $L=\text{odd}$ state [as on $\Upsilon(4S)$], the CP violating effect cancels when integrated over decay times and can be observed only through decay length distributions. Experimentally such measurements are feasible only with a high-luminosity e^+e^- collider with asymmetric energies, a type of machine which has never been built. A measurement of the, $\bar{B}B^*$ cross section was necessary to make a comparative evaluation of the two methods for detecting CP violation in the B system. This cross section was measured by looking for the photons in the decay $B^* \rightarrow B\gamma$, utilizing the excellent photon detection capability of CLEO II. The measured $\bar{B}B^*$ production cross section of about 0.2 nb was substantially less than expected, and as a result we have opted for an asymmetric B factory.

Recent highlights of published physics results are listed below (limited to the ones published in 1990 and after [with *] or to be submitted soon):

B meson physics

- (1)* $b \rightarrow u$ transition in semileptonic decays
- (2)* B meson decays to D_s
- (3)* exclusive and inclusive semileptonic decays $B \rightarrow D$
- (4) semileptonic branching ratios of B mesons
- (5) baryon production in B decay
- (6) exclusive reconstruction and inclusive properties of B mesons

Upsilon physics

- (1)* radiative $\Upsilon(1S)$ decays
- (2)* $\Upsilon(4S)$ decays to ΨX
- (3)* two photon widths of charmonium states
- (4)* $\pi^+\pi^-$ transitions of $\Upsilon(3S)$ and search for h_b ($PC=+-$)
- (5) non $B \bar{B}$ decay of $\Upsilon(4S)$

Charm physics

- (1)* observation of D^{**} meson
- (2)* $D^0 \rightarrow KK, \pi\pi$
- (3)* $B(D_s \rightarrow \phi\pi)$ by observation of $D_s \rightarrow \phi l \nu$
- (4)* Λ_c decay asymmetry
- (5) $D^0 \rightarrow \pi^0, \eta^0 + X$
- (6) D^* polarization
- (7) Λ_c inclusive production
- (8) D^0 rare decays

τ lepton physics

- (1)* search for neutrinoless decays of τ lepton
- (2)* K^* production in τ decay

Miscellaneous

- (1) $B \bar{B}^*$ production above $\Upsilon(4S)$

The list below shows some of the ongoing and future physics topics of CLEO II. Because of higher statistics and significantly upgraded detection capabilities (particularly photon detection), we are able to study a wide range of new topics as well as to improve previous measurements significantly:

B meson physics

- (1) exclusive $b \rightarrow ul\nu$
- (2) $B \rightarrow D^* l\nu$ form factors
- (3) B_s production on $\Upsilon(5S)$
- (4) B_s $\bar{B}_s$ mixing
- (5) B $\bar{B}$ mixing by partial reconstruction of D^* together with lepton tagging
- (6) full reconstruction of B decays (for tagging)
- (7) search for $B \rightarrow K^* \gamma$ ($b \rightarrow s\gamma$ transition)

Upsilon physics

- (1) radiative and $\pi^+\pi^-$, $\pi^0\pi^0$ transitions of upsilons, search for new states
- (2) gluon fragmentation

Charm physics

- (1) charmed baryon searches (Σ_c , etc)
- (2) $D^{*+} \rightarrow D^+ \gamma$
- (3) decays of D, D_s with $\pi^0(s)$
- (4) charm quark fragmentation

 τ lepton physics

- (1) precision measurement of $\tau \rightarrow l\nu\nu$ branching ratio
- (2) determination of Michel parameter for τ
- (3) τ lifetime (current experimental value is 2σ away from expectation)
- (4) $\tau \rightarrow$ hadron branching ratio, measurement of α_s
- (5) $\tau \rightarrow$ 1 prong + $n\pi^0$ branching ratios (1 prong deficit is still unresolved)
- (6) ν_τ mass

Miscellaneous

- (1) study of baryon production mechanisms
- (2) strange and charmed baryon spectroscopy

A major objective of the CLEO II experiment is to assemble a large sample of fully reconstructed B mesons. These may be used to tag one B in the $\Upsilon(4S) \rightarrow \bar{B}B$ decay and allow an unbiased analysis of the other B, with very little background for which there is a reliable flavor tag. It is estimated that with 1 fb^{-1} one can obtain 10,000 tagged events. With a sample this large, one can measure the absolute branching ratios of B decays, study the relative importance of meson decay mechanisms such as spectator, color mixed, annihilation, exchange, etc., check the validity of various approximation schemes for handling QCD effects, and measure the form factors in semileptonic decays such as $B \rightarrow D^* l\nu$.

The increased data sample will also make possible improved measurements of $B-\bar{B}$ mixing and a better determination of the associated parameters in the KM matrix. An extended run above the $\Upsilon(4S)$ would make feasible a measurement of $B_s-\bar{B}_s$ mixing, which will give information on $t\rightarrow s$ transitions.

The Harvard group has initiated and been instrumental to the development of some of the major analyses at CLEO. The development of the analysis to search for exclusive $b\rightarrow u\ell\nu$ decays is one such example which became the topic of a PhD thesis (D. Xiao, 1990). For the study of $b\rightarrow u$ transitions, it is important to identify individual exclusive channels for $b\rightarrow u$ decay which establish unequivocally the existence of such a transition. Due to uncertainties caused by long distance effects and the other (spectator) quark in the decaying B meson, it is necessary to observe more than one channel to provide a measure of the systematic errors in extracting the $b\rightarrow u$ transition amplitude. Using our methods, we hope to observe exclusive $B\rightarrow u\ell\nu$ decays in the next data set.

The Harvard group has recently established that a large sample of tagged neutral B's can be "partially reconstructed" in the decay $\bar{B}^0\rightarrow D^{*+}\ell^-\bar{\nu}$, via detection only of a lepton and the pion produced in the decay $D^{*+}\rightarrow D^0\pi^+$. This sample is being used to make a number of useful measurements with CLEO I data including two new methods for $\bar{B}B$ mixing and branching fractions of neutral B's to leptons and D^{*+} . More measurements will be possible with CLEO II data. This method and the measurements arising from it are likely to have an impact on the long-term program of CLEO II leading up to the B-factory.

Other analyses with the Harvard group's initiative or active involvement are: $b\rightarrow u$ transitions in semileptonic decays measured by carefully studying the end point of lepton energy distribution (see figure on next page), full B reconstruction, and study of baryon production mechanisms.

As can be inferred from the lists above, physics output in the near future is limited only by one's imagination. With the increased manpower, the Harvard group is currently in the process of strengthening its analysis efforts and looking forward to a productive future.

End point energy distribution of leptons in semileptonic B meson decay. The excess of events beyond the maximum for $b \rightarrow c$ transition signals a non-vanishing $b \rightarrow u$ transition. The data (solid circles) is compared to the sum of continuum (open circles) and $b \rightarrow c l \nu$ yield (dashed line). An expanded version is shown in (b).

F. B-Factory Working Group

(Profs. H. Yamamoto and K. Kinoshita, Dr. S. Henderson)

A subgroup of the CLEO II collaboration is now working toward the realization of a B factory at Cornell. This group has produced a detailed study of physics and detector issues which has been submitted to the NSF as part of a proposal to build a B factory. The Harvard group is taking an active role in this effort, coordinating the effort on Monte Carlo software for particle identification and writing detector simulation for time-of-flight and Cerenkov detectors. Flavor tagging via particle identification is a critical issue for the feasibility of the B factory, and the Harvard group will be participating in the development of detectors to be used there, in particular leading efforts for time-of-flight and silicon vertex detector devices. A proposal has been made to the DOE OJI program for this work.

G. Summary of Future Effort of the Harvard Group

The CLEO II detector is now fully operational and a long run on the $\Upsilon(4S)$ is underway with the objective of collecting $1 \text{ fb}^{-1}/\text{year}$. This data sample will not only contain many more events than the previous runs, but detector improvements such as the crystal calorimeter and the new time-of-flight system will make it possible to study the B meson and the associated b quark in much greater detail.

For the immediate future, the major activities of the Harvard group will be:

1. Analysis of the data from CLEO II as outlined above
2. Enhancement and maintenance of the time-of-flight system
3. Development of the next generation of time-of-flight systems
4. Maintenance of BLT and development of software tracker
5. Development of silicon drift detectors
6. Active participation in studies for a B factory

The Harvard group has recently seen many changes. The graduate students and research associates who have been active in CLEO I analysis and in the commissioning of CLEO II are moving on to new positions at other universities. The time of flight system and the BLT trigger, which were major hardware contributions of the Harvard group to the CLEO II detector, are becoming well understood tools for doing physics and will shortly only require routine maintenance. The emphasis will now shift to analysis of CLEO II data and R&D toward detectors which will apply to a B factory. Past and new analysis enterprises of the Harvard group are being studied by new members and will certainly lead to extensions made possible by CLEO II. A new faculty member and research associate are rapidly moving into the task to improve further the time-of-flight so that it may reach its maximum potential and lead to the development of a new generation of TOF detectors. The development of silicon drift detectors may lead to significant increases in the capability of CLEO II. New ideas for triggering are being investigated. In spite of major changes in personnel in the last year, the group is maintaining a vital role in the CLEO collaboration and anticipates further growth in the near future.

5. Muon Scattering at FNAL

(Professors Pipkin and Wilson, Dr. Fang, Ms. Conrad, Mr. Schmitt, Mr. Ashutosh and Mr. Lancaster)

The Harvard group constructed in collaboration with a group from the University of Maryland, an electromagnetic calorimeter for use in the forward spectrometer of the Tevatron muon experiment. The calorimeter is built using twenty planes of proportional tubes of the design first developed by Iarocci at Frascati for use in the Mont Blanc proton decay experiment. The Harvard group refurbished the frames for the E98 spark chambers for use as drift chambers. The Harvard group took over from UCSD a major responsibility for planning, design, and construction of the second level trigger electronics. More recently, the Harvard group constructed a scintillation counter wall using the time of flight counters previously employed in the CLEO I detector at Cornell. The Harvard group also constructed a veto counter and electronics for a constrained logic veto which are essential for the operation of the experiment. The Harvard group, in addition, also built the electronics for the new vertex detector.

In the summer of CY1983 the Maryland group supervised at Frascati and CERN the construction and stringing of the 400 modules required to build the electromagnetic calorimeter. The modules were shipped to Harvard in September 1983. The mechanical design of the calorimeter was completed in early CY1984 and the construction of the aluminum boxes required to house the chambers was started. At Harvard half of the chambers were modified so that they could be operated vertically. All the chambers were sealed to eliminate residual leaks due to compromises in the design. Each chamber was then tested at six positions with a source and the calibration data recorded. A specially constructed test set up was used to measure the resistance of the graphite coating in the profiles so that the individual modules could be located advantageously in the detector.

The cathode pads for the readout were manufactured by a firm near Boston and shipped to Maryland for attachment of the cable harnesses. They were then shipped back to Harvard where the pads were fastened to the chambers. The electronic amplifiers attached to the chambers were designed and constructed at Harvard.

In January 1985 the aluminum boxes for containment of the chambers and the support structure were completed. The aluminum boxes and the chambers were shipped to FNAL at

the end of January. The edge connectors for the chambers were shipped to FNAL in February. The installation of the iron absorber at FNAL was completed in April and shortly thereafter, the structure for the support of the calorimeter modules was erected. The Harvard group then started the insertion of the Iarocci tubes and the electronics in the aluminum boxes. Each of the planes was carefully tested prior to hanging.

In March of CY1985 the construction of the lead radiator modules was started at Harvard. Each module consists of a sheet of aluminum to which is bonded a lead sheet. The modules were completed in June 85 and shipped to FNAL in July 85.

The assembly of the 16 planes with summed anode readout was completed in July 85 and some test data were obtained when the muon beam was completed and operated in a test mode. The tests were terminated at the end of August when one of the magnets in the accelerator failed and the running period for fixed target experiments was prematurely terminated.

Near the end of the run an attempt was made to hang the lead modules. While the third module was being hung the hanger for the module twisted unexpectedly and collapsed. This brought to our attention a serious deficiency in the design. The hangers were shipped back to Harvard and rebuilt with a new design so as to eliminate the transverse instability.

The rebuilt hangers for the lead modules were shipped to FNAL in April 1986 and the lead properly hung. The assembly of the four planes of individually read-out anode wires was completed and the chambers were hung in the summer of 1986. During the latter part of 1986, the electronics were completed, the installation of the cabling was started, and work began on the software to read out the FASTBUS data acquisition system. A system was set up to supply gas to the chamber, and to monitor the gain for the gas mixture.

Also during 1986 code for the Monte Carlo simulation of showers was written and installed in the E665 offline environment. An event display for viewing individual events in the calorimeter was written, and work on pattern recognition software was begun. In addition extensive hardware and software development for the calorimeter FASTBUS system was performed by the Harvard group.

The first quarter of 1987 was devoted to bringing the calorimeter into operation. The cabling was completed and all wires, pads and associated electronics were tested.

As a result of unanticipated delays, the Harvard group agreed to help the group from UCSD in an attempt to finish the Level-II trigger processor in time for the run. Despite this effort the intended trigger processor was not ready and data taking during the 1987 run was triggered by a system based on beam-veto similar to that previously employed in E98. Harvard played a major role in bringing this system into operation.

The beam was commissioned by early July and proved to have properties closely matching those predicted by Monte-Carlo calculations. During beam tuning and up until mid-August the apparatus was brought into operation and the trigger improved. Data taking then commenced and continued until mid-January 1988.

Three different targets and two beam energies were used. Alignment, empty target and various test data were also recorded. The number of muons and the luminosity in the different runs were as follows:

<u>Target</u>	<u>Energy</u> (GeV)	<u>Muons</u> ($\times 10^{11}$)	<u>Luminosity</u> (pb^{-1})
D ₂	500	2.5	2.4
H ₂	500	1.5	0.6
Xe	500	1.5	1.1
D ₂	100	0.26	0.25
Xe	100	0.35	0.47

For about half the data, the large RICH counter for forward hadron identification was not operational; all the other detector systems performed reasonably well.

In addition to the muon data taking there was a short (1 week) period in January when the beam was converted to an electron test beam. This enabled us to collect calibration data for the calorimeter, for the wide-angle Cherenkov counters, and for the time of flight counters.

A total of 600K streamer chamber pictures were taken of which approximately 170K have good deep inelastic scattering (DIS) events. 3400 tapes of electronic data were recorded; a total of 2×10^7 triggers of which 1.4×10^6 are DIS events.

1988

CY1988 was devoted to careful analysis of the muon and calibration data taken during the 1987 run. There were a number of problems with the electromagnetic calorimeter which had to

be understood in order to analyze the data. Other collaborators in the experiment worked on the analysis of the data for the components of the hardware for which they were responsible. Groups at FNAL, Munich, and Cracow began the analysis of the streamer chamber pictures. The focus of the initial analysis of the electronic data was the production of a scan list for selection of the "interesting" streamer chamber pictures.

The Harvard group divided its effort between the analysis of the calorimeter data, the completion of the level two trigger system and a study of the deficiencies in the apparatus which should be corrected for the next run. Detailed studies of the data taken with the beam-veto trigger showed that the rates were too high for the scattered muon trigger to work the way it was originally designed. The rejection rate of the level I trigger was not sufficient for the level II trigger to function properly. The Harvard group studied this problem and proposed the construction of a new scintillator wall immediately in front of the calorimeter. It was proposed to use the time-of-flight counters from the CLEO I detector for the construction of the scintillator wall. This proposal was accepted by the Muon collaboration and the CLEO I octants were transported to Harvard for removal of the scintillation counters.

A table for lifting and repair of the calorimeter modules with problems was constructed at Harvard, transported to FNAL and assembled at FNAL. It was subsequently used to repair the three chambers that had developed serious problems.

1989

The effort of the Harvard group in 1989 was devoted to the construction and installation of the new scintillation counter wall, the completion and testing of the level two trigger, the design and construction of a beam veto counter, and the design and construction of electronic modules for use in the muon experiment. A considerable effort was devoted to the constrained logic veto. The Harvard group was also responsible for design and construction of the electronics for the new vertex chamber.

The scintillator counter wall was shipped to FNAL in October and assembled in November. The completion of the level-2 trigger was more time consuming than anticipated and not completed during this calendar year.

The design and development of the beam veto counter was a major effort. The veto counter used in the 1987 run was inefficient and did not provide as large a rejection of beam muons as desired. This is a complicated problem and a great deal of effort was devoted to understanding

the shortcomings of the early beam veto and to designing a better beam veto counter. This took into account the experience of the Harvard group in the earlier muon experiments E98 and E398. Once the design was complete the construction was relatively straight forward.

After a considerable debate taking into account the time and cost, the muon group decided in December 1988 to propose the construction of a series of drift chambers as a replacement for the streamer chamber in the vertex magnet. This would provide electronic readout of vertex information and increase the data rate for the forward spectrometer. The proposal for construction of the chambers was presented to the FNAL Policy Advisory Committee in January 1989; the PAC felt this was a good proposal and the Director subsequently gave the project his blessing.

These chambers were a joint project of several institutions in the muon collaboration. Frames were made at the University of Washington; the chambers were strung at FNAL; the University of Wuppertal (F.R.G.) provided funds for construction. Harvard made a major contribution by designing and construction of the electronics for the chambers. Harvard, in particular, designed the preamplifier chip by modifying a previously used FNAL design and built the "mother Boards" and the shaping circuits. This electronics performed admirably and has been adapted by other groups.

1990

The muon experiment received first beam in February and ran until the August shutdown. The vertex chambers was installed in the vertex magnet and brought into operation; the trigger was understood; data were taken. The beam veto counter was installed in March and performed as expected. In early April the veto counter was used successfully to provide a trigger for deep inelastic scattering and it was shown that the level-2 trigger could be used to enhance the rate for hadronic events at high W . The constrained logic veto, which provides a less restrictive veto trigger, was also brought into operation and used to provide a check on the other triggers.

The data taking with a good trigger started in June. The focus of the run was the study of inelastic muon scattering from complex nuclei. Data were taken with hydrogen, deuterium, carbon, calcium, copper and lead targets.

On the basis of the analysis of the 1989 data, the group decided to devote the rest of the allotted time to the study of hadrons produced from hydrogen and deuterium targets. The

experiment was originally scheduled to run two months after the August shutdown. The E665 group requested additional running time and the run scheduled to start after the August shutdown was extended from two months to five months.

This period also yielded the first results from the 1987-88 run. Results were presented at the meeting of the Division of Particles and Fields of the American Physical Society, at a Moriond Conference, at the Washington Meeting of the American Physical Society and at the Singapore Conference. Several of the students completed their theses. Some of the highlights are the following:

- 1) Extension of measurements of shadowing to very low Bjorken x .
- 2) Studies of Bose-Einstein correlation in muon-produced pions.
- 3) Study of energy flow in jets at high W .
- 4) Measurements of the ratio of the neutron and proton form factors at low Bjorken x .
- 5) Study of inclusive hadron production.
- 6) Measurements of rho production at low x and high W .
- 7) Study of multiplicity and two-particle correlations in rapidity.

Two Harvard students, Douglas Michael, and Michael Schmitt undertook, respectively, the analysis of the jets and the muon-production of rhos. The calorimeter makes it possible to include neutral particles such as π^0 's in the analysis of the jets. The preliminary studies indicate that a dominate source of jets for the muon experiment is gluon fusion and study of the jets may provide a better measure of the gluon structure function. The rho data is in the interesting region where shadowing turns in and where the cross section for longitudinal production of rhos become important. This experiment should resolve the inconsistencies in the data reported by the EMC group.

1991

It was initially planned to start the next fixed target run at Fermilab in December 1990. It was discovered, however, that there were serious radiation problems which needed to be eliminated before the accelerator could run for experiments. As of early April there is no published schedule, but it is anticipated that the experimental program will not start until this summer. This delay is unfortunate for the muon experiment. The remaining vertex chambers have been installed and the experiment has been ready to run since early December. The group is now being weakened by the departure of the students to take positions elsewhere and the obligations of the physicists to other projects.

The muon group is using this period to reduce the data taken in the 1990 run and to convert the analysis software to UNIX. The analysis of the 87-88 data is limited by the available computing power and the most accessible source of additional computing is the UNIX farm now being assembled at FNAL.

The 1991 run will be devoted totally to measurements with hydrogen and deuterium targets and will focus on production of hadrons. The addition of the vertex chambers in front of the vertex magnet provides coverage to negative x and should make feasible high statistical studies of both the forward hadrons produced by the struck quark and the target hadrons coming from the diquark left behind.

Future Plans

It is clear that in addition to the A dependence studies and the study of hadron production at high W, there are well defined physics problems that should be studied further in muon experiments. The group considered this situation and decided that a new group should be formed for further experiments; the majority of the collaborators in the present group were not interested in continuing with the muon experiments. A subgroup of the present group, which included Harvard, submitted in March 1990 a letter of intent for an experiment to make precise measurements the structure functions. The number of individuals signing the letter is too small for another experiment. One possibility is combining with one of the European groups planning new experiments.

Structure functions are important both for what can be learned about the nucleon and as ingredients for a detailed understanding of some of the data from other experiments, such as $\bar{p}p$ colliders. Recently a large discrepancy between the EMC and BCDMS F_2 measurements has come to light. At low x, BCDMS finds a value of F_2 which is 12% larger than that found by EMC, and curiously, close to that found earlier by E98 and E398 at Fermilab. The parameter identifying the scaling violation becomes very different; the quoted value of the scaling parameter, Λ , is ~60-90 MeV for EMC and ~220 for BCDMS, again close to the E398 value. This is a difference of two to three standard deviations. The gluon distributions extracted from the EMC data are strongly correlated with the value of Λ and are extensively quoted in the literature. The final D_2 data from EMC is now published and suffers from large systematic errors. It was not possible to take advantage of the pure non-singlet distribution $FP_2 - F^{\eta}_2$ in extracting Λ .

There is a clear need to remeasure the proton and neutron structure functions with high statistical accuracy and small systematic errors. In order to have adequate statistical accuracy, we would need a much longer target than is being used in the current measurements. We can double the Q^2 range covered by existing data and cover the entire Q^2 , x range of all previous experiments, including those at SLAC, in a single experiment. We should be able to obtain D_2 data with the same quality as the H_2 data. With a long liquid target run we expect a large number of exclusive ρ^0 and ϕ , especially with our very low Q^2 trigger ($<0.5 \text{ GeV}^2$). This would allow careful study of the transition between vector dominance and parton scattering. ψ/J production would be copious enough to allow photon gluon fusion studies, and some fraction of the target could be used for a continued study of final state hadrons. We anticipate that after the 1991 run we will understand how to improve the apparatus well enough to be able to control systematic uncertainties to the requisite 1% level.

The principal improvement needed is to make a set of detectors and an analysis system that has close to 100% efficiency. The multichannel vertex detector built for the 1990 run will help to increase the trackfinding efficiency. Further improvement can be made by removing the particle identifying RICH counter, which adds multiple scattering and confusion. In its place can be a bank of proportional counters, close together, at the back of the apparatus where all particles are well separated. This was the plan for E98 in 1973 when nearly 100% efficiency was achieved. One possibility is to build a layer version of the vertex chamber.

6. The L3 Experiment

(Professor Strauch, Drs. McBride, Kumar, Kunin, Ms. Wang and Mr. Scott)

The annihilation of high energy electrons and positrons has proven to be one of the most powerful probes into the nature of fundamental properties of matter. The first observations of large hadron production at high energies were made at the Cambridge Electron Accelerator; the subsequent discovery of the ψ/J at BNL and SLAC opened a whole new world of particle physics. Our group was part of the original CEA team. From 1976 to 1987 we were members of the Crystal Ball collaboration using SPEAR at SLAC and then DORIS at DESY to investigate a wide variety of phenomena involving the properties and decays of charmonium ($c\bar{c}$) and bottomium ($b\bar{b}$) states. At DESY, our group was particularly active in the analysis of the inclusive reaction $\Upsilon(2S) \rightarrow \gamma X$ and two photon reactions $e^+e^- \rightarrow e^+e^- X$ where $X = \pi^0, \eta, \eta'$. Two photon production of π^0 and η was observed and studied for the first time. Except for paper preparation using existing Crystal Ball data, our group has worked only on the L3 program since the start of 1987.

When CERN decided to build LEP, our group joined in 1980 in the planning of a LEP experiment with MIT colleagues (Professor Ting's group) with whom we had previously collaborated on the ISR experiment I-209. Out of these discussions evolved the "Magnetic Hall" concept of the L3 experiment which was formally approved as one of four LEP experiments in September 1982. By the end of 1990, the collaboration included groups from Bulgaria, China, France, Germany, Hungary, India, Italy, The Netherlands, Spain, Sweden, Switzerland, Taiwan, USA, USSR. The U.S. participants came from Alabama, CIT, Carnegie-Mellon, Harvard, Johns Hopkins, Lawrence Livermore, Los Alamos, MIT, Michigan, Northeastern, Oak Ridge, Princeton, Purdue, UC-San Diego, Union College.

The L3 detector is a general purpose detector with emphasis on accurate identification and energy measurement of photons, electrons and muons. It is installed at the interaction point #2. LEP started operation in the summer of 1989 and has already reached peak luminosities of about 50% of the design value at the Z^0 peak energy. In its phase I, LEP will operate at a maximum center-of-mass energy $\sqrt{s} \approx 100$ GeV. In its phase II (1993-4), the maximum value of $\sqrt{s}$ will be increased to ~ 190 GeV well above the W pair production threshold. When $\sqrt{s}$ is set to the Z^0 peak energy and with an average luminosity of $L=10^{31} \text{cm}^{-2}\text{sec}^{-1}$, one Z^0 is produced every 3 seconds!

During our previous collaboration with the MIT group, we jointly developed a new type of drift chambers to measure the momentum of high energy muons. For reasons of effectiveness

and efficiency, we again worked with our MIT colleagues (and others) on developing the precision muon detection system of L3.

Dr. Antreasyan (then with our group), Dr. McBride and Ms. Wang spent full time with MIT and Northeastern colleagues building five full size muon chambers, assembling them into an octant at Harvard High Energy Physics Laboratory, and testing them successfully with cosmic rays. Dr. Antreasyan moved to CERN in April of 1986. Dr. McBride moved there in September of 1986. Their major responsibility was to form and lead the two groups charged with setting up, instrumenting and using test stations for (1) drift chambers after they are produced and (2) octants after they are assembled. This involved both hardware and software tasks. Dr. Schmitt joined the group on October 1, 1986, at CERN with special responsibility for the muon detector's VME monitoring system.

Close coordination with the chamber builders led to a successful construction and testing schedule which produced eighty satisfactory drift chambers installed in 16 octants. The chambers were tested with the standard gas mixture and high voltages, and the wire alignment in each octant was verified to better than 30 μm using both UV laser tracks and cosmic rays. The software developed for the octant tests is being used in the detector calibration and the track reconstruction in the experiment. All 16 octants were tested and readied for moving into pit #2 by November 1988. The move and installation of the octants on the support tube took place in December 1988 - January 1989 as scheduled several years earlier.

The HEPL machine shop produced a variety of chambers and octant parts such as cable trays, piping for chamber gas, mountings for printed circuits, stands, etc. J. Oliver and the HEPL Electronics Shop built 16 VME based ADC modules (972 channels in total) for muon chamber monitoring. They also designed and built a multiplexed pulse height monitoring system for muon detector calibration.

Ms. Wang moved to CERN in January 1988 after completing her work on the wire bridges in Cambridge. She joined the Octant Testing group. Meeting the L3 installation schedule required a great effort by all concerned. Some additional technical help was required: we supported one technician at CERN during most of 1988-89.

Having received an offer which he could not refuse, Dr. Schmitt left our group and CERN on April 30, 1989. He had contributed greatly to the assembly of the muon detector and to its preparation for data taking. Dr. Schutte joined the group in June 1989 and soon took on major responsibilities in maintenance and improvements in the muon chambers. With the approval of DOE we searched for an additional group member in order to be able to participate

significantly in analysis while keeping our responsibilities for operation of the L3 muon detection system. Dr. Kumar was appointed in December 1989 and joined the group at CERN in February 1990. Mr. Scott worked with us during the summer of 1989, returned to Harvard to finish his course program and pass his oral examination, and moved to CERN in March 1990.

The first half of 1989 was a mad scramble to finish installation of all L3 detector components, wiring them up, connecting their electronics, testing with and without magnetic field. The first LEP beam was stored on July 14 and usable luminosities with colliding e^+e^- beams were obtained within a few weeks. By the end of September the L3 detector had been brought into operation and serious data taking began. By the end of the 1989 run L3 had recorded $\sim 1\text{pb}^{-1}$ of data at and around the Z^0 peak yielding $\sim 20,000$ Z^0 events! This data formed the basis for six publications listed in the "Publications".

The Harvard group was deeply involved in bringing the L3 muon detection systems into operation, and in taking and analyzing data. Dr. McBride implemented and maintained TOOCAL, the Hard and Software Investigation Tool for checking and calibrating the muon chamber electronics. She is co-leader in the analysis of $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$ events. The first LEP measurements of $\Gamma_{b\bar{b}}$ and A_{FB}^b were reported in 1989. Dr. Schutte implemented and maintained part of the Data Acquisition Software and maintained and studied the read-out electronics. Ms Wang concentrated on the analysis of $e^+e^- \rightarrow \mu^+\mu^-$ events collected in 1989.

1990 This was a most exciting year because of very substantial data taking and effective analysis of this data. LEP started operation in the Z^0 region in April 1990 and ran until the beginning of October 1990. Data was collected with an integrated luminosity of 5.5 pb^{-1} in the energy range $88.2 \leq \sqrt{s} \leq 94.2\text{ GeV}$ yielding a sample of 115 k hadronic and 10k leptonic Z^0 decay events. During the run average and peak luminosity increased steadily. Beam focusing tests by the LEP staff at the L3 location explain why the L3 luminosity has been $\sim 25\%$ lower than the Aleph luminosity and suggest how to eliminate this loss in the future.

The October 1990 - April 1991 shut-down was used to complete the BGO barrel detector with the installation of the forward and backward parts. The μ detection system underwent routine maintenance and repairs. Drs. Schutte and Kumar participated in careful studies of various factors affecting the muon energy resolution. This resulted in the design and implementation of improvements in the electronics used in the drift time determination.

Data analysis became the major activity of the LEP collaborations in 1990. The L3 collaboration submitted for publication 24 papers based on the 1989-90 data, with more to

come. The papers are listed under "Publications." Here we give a very brief summary of the major physics results.

(1) Measurement of major Z^0 parameters:

$$M_{Z^0} = 91.18 \pm 0.010 \pm .02(\text{LEP})\text{GeV}; \Gamma_{Z^0} = 2501 \pm 17 \text{ MeV};$$

$$\Gamma_{\text{hadron}} = 1742 \pm \text{MeV}; \Gamma_e = 83.3 \pm 1.1 \text{ MeV}; \Gamma_\mu = 84.5 \pm 2.0 \text{ MeV}; \Gamma_\tau = 84.0 \pm 2.7 \text{ MeV}$$

(2) The number of light neutrino species $N_\nu = 3.05 \pm 0.10$.

(3) Measurement of the forward-backward asymmetry A in the leptonic decays

$$Z^0 \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^- \text{ as a function of } \sqrt{s}.$$

(4) Calculation of electroweak parameters from the above results:

$$\bar{g}_V = -0.046^{+0.015}_{-0.012}; \bar{g}_A = 0.500 \pm .003; \sin^2\theta_w = 0.2315 \pm 0.0025.$$

$$\text{An estimate of the top mass is also obtained: } m_t = 193^{+52}_{-69} \text{ GeV}.$$

(5) Measurement of $Z^0 \rightarrow b\bar{b}$ events:

$$B^0 - \bar{B}^0 \text{ mixing is observed with } \chi_b = 0.178^{+0.049}_{-0.040}$$

We also obtain values of $\Gamma_{b\bar{b}}$ and $A_{b\bar{b}}$ and an average b lifetime.

(6) Inclusive Production of π^0 and charged particles:

agrees with QCD prediction.

(7) Test of QCD based on 4 jet-events from Z^0 decays:

agrees with QCD prediction.

(8) Determination of α_s at $\sqrt{s} = 91 \text{ GeV}$ using hadronic Z^0 decays:

$$(a) \text{ from Jet Multiplicities: } \alpha_s = 0.115 \pm 0.005(\text{exp.})^{+0.012}_{-0.010}(\text{theory});$$

$$(b) \text{ from energy-energy correlations: } \alpha_s = 0.121 \pm (\text{exp}) \pm 0.006 (\text{theory});$$

$$(c) \text{ from } \Gamma_{\text{had}}: \alpha_s = 0.125 \pm .041.$$

(9) Search for Minimal Standard Model Neutral Higgs Boson:

$$M_{H^0} > 41.8 \text{ GeV at } 95\% \text{ c.l.}$$

(10) Search for Charged Higgs Boson: $M_{H^\pm} > 36.5 \text{ GeV at } 95\% \text{ c.l.}$

(11) Search for Neutral Scalar Higgs h^0 and Pseudo Scalar Higgs A^0 of Minimal SSSM:

$$M_{h^0} > 41.5 \text{ GeV}, M_{A^0} > 41.5 \text{ GeV at } 95\% \text{ c.l.}$$

(12) Search for Scalar Muons, Scalar Electrons and Winos:

$$M_{\tilde{\mu}} > 41 \text{ GeV}; M_{\tilde{e}} > 41 \text{ GeV}; M_{\tilde{w}} > 44 \text{ GeV at } 95\% \text{ c.l.}$$

(13) Search for Excited Electrons, Muons, Taus and Neutrinos:

$$M_{e^*} > 45.0 \text{ GeV}; M_{\mu^*} > 45.3 \text{ GeV}; M_{\tau^*} > 45.5 \text{ GeV}; M_{\nu^*} > 91 \text{ GeV at } 95\% \text{ c.l.}$$

(14) Search for Heavy Charged and Neutral Leptons

$$\text{for most models } M_L > 42.8 \text{ GeV at } 95\% \text{ c.l.}$$

Members of the Harvard group were especially active in the Physics of $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow \tau\bar{\tau}$. We purchased an Apollo DN 10,000 and an HP Apollo 9000 for use by our group at CERN. Mr. Scott analyzed test beam data taken by the muon chamber group in 1989. The goal was to improve the time to distance relation used in track reconstruction in the L3 muon chambers. This is an important factor in the muon momentum resolution. The results of this analysis have been made available to the collaboration in an internal publication, and will be used in the reconstruction of L3 data starting in 1991. Dr. Kumar concentrated his analysis efforts on $\tau^+\tau^-$ physics. He studied the identification of electrons and muons in low multiplicity events and the efficiency of their identification. The aim is to measure the τ polarization in addition to measuring Γ_τ and A_τ . Dr. Strauch spent February-August 1990 at CERN while on sabbatical leave. Having received a very tempting offer, Dr. Schutte left the collaboration on December 31, 1990. He is being replaced by Dr. Kunin (from the Russian L3 group) who started on April 1, 1991.

1991 A substantial LEP run is scheduled this year starting in May 1991. The aim is to considerably increase the number of Z^0 events collected by each detector collaboration. L3 will operate for the first time with the completed BGO detector.

The Harvard group has been engaged in the preparation of this run, particularly in the improvement of the timing electronics of the muon chambers. We will of course contribute to the substantial data taking effort. Our major effort will be in data analysis. Dr. McBride will continue to co-lead the $b\bar{b}$ physics study. The expected substantial increase in number of events will lead to a more accurate measurement of the mixing parameter, the semi-leptonic branching ratios and the forward-backward asymmetry. This will result in a more accurate determination of $\sin^2 \theta_W$. Dr. Kumar will concentrate on $\tau\tau$ physics. The presently available data yields the τ lifetime and angular distribution; it is hoped that with the new data to be acquired this year it will be possible to measure the τ polarization. Dr. Kunin, co-leader of the Higgs search group will, in addition to continuing this search, join the τ polarization effort. Mr. Scott, in addition to his μ chamber calibration activities has also joined the $\tau\tau$ physics effort.

1992 This will be the third full year of operation of LEP and L3. Results obtained by the end of 1991 will determine the run energies and the physics to be studied most extensively.

1993 L3 will continue to take data and the beam energy will probably start to increase toward the 94-95 goal of passing the W^+W^- threshold. Prof. Strauch is scheduled to retire in the summer of this year. The continued long-term participation of a Harvard group in the L3 effort will depend on the interests of the Harvard High Energy Physics faculty at that time.

7. A Next Generation High Energy Neutrino Experiment at FNAL

(Prof. S. Mishra)

Physics goals of a next generation high energy neutrino experiment are: a) precision measurements of the nucleon structure functions and tests of QCD predictions with $\delta\Lambda_{\text{QCD}} \leq 10\text{-}15\text{ MeV}$; b) determination of the electroweak parameters, $\sin^2\theta_W$ and ρ approaching an accuracy of 0.65% and 0.25% respectively, and c) exploring rare processes and new phenomena that include exclusive $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations, typically with an order of magnitude higher sensitivity. These neutrino measurements will be unique, and would complement the collider studies towards uncovering new physics.

Neutrino interactions convey a composite view of the Standard Model which is complementary to other endeavours in elementary particle physics. The success of two high statistics, high energy neutrino experiments by the CCFR collaboration at the Fermilab Tevatron inspired us to consider "A Next Generation Neutrino Experiment" --- with a cumulative 20×10^6 neutrino charged current statistics in the energy range $10 \leq E_\nu \leq 600\text{ GeV}$, after fiducial and kinematic cuts, and a detector with commensurate systematic precision. At Snowmass (1990) a group of physicists further explored the physics implications and feasibility of such an undertaking. Following is a summary of some of these investigations.

The accelerator upgrades at the Fermilab Tevatron, following the new Linac and the Main Injector, would permit the delivering of more than $\geq 3 \times 10^{13}$ protons per cycle to the neutrino experiment. It should thus be easily feasible to collect more than an order of magnitude more neutrino events, in a CCFR type neutrino detector (690 ton Fe target), than those accumulated in the earlier experiments.

Neutrinos uniquely elucidate nucleon structure. In $\nu_\mu(\bar{\nu}_\mu)\text{-N}$ scattering, quark and antiquark currents have distinct "y" dependence, and hence flavour selection is an inherent feature of neutrino experiments. The content and shape of the strange sea of the nucleon can only be explored in neutrino-induced opposite sign dimuons. Furthermore, the parity violating amplitude of $\nu\text{-N}$ scattering yields the non-singlet structure function F_3 , whose evolution with respect to Q^2 can be unambiguously predicted by perturbative QCD, and thus provides one of the cleanest tests of this theory. Another equally amenable test of perturbative QCD is comparing the measured $R(x, Q^2)$ with absolute prediction of the theory. Finally, the simultaneous availability of the non-singlet (F_3) and the singlet (F_2) structure functions provide

a strong handle on the gluon structure functions ($G(x, Q^2)$). We point out the enormous improvement upon these past measurements in a future neutrino experiment with an order of magnitude more statistics and a corresponding alleviation of systematic errors.

A better understanding of the nucleon substructure implies and impels a better measurement of the electroweak parameters, $\sin^2\theta_W$ and ρ in ν -induced neutral current (NC) interactions: a channel with unique sensitivity to the electroweak radiative correction. We explored techniques and systematic improvements which might permit an accuracy of ± 0.0015 in $\sin^2\theta_W$, and of ± 0.0025 in ρ in ν -experiment. These measurements, if realised, would complement and vastly strengthen the ultimate collider measurements ($p\bar{p}$ and e^+e^-) towards the testing of the electroweak unification.

Finally, a variety of rare processes, such as the inverse muon decay, neutrino tridents and W-Z interference, neutral current induced J/ψ production, and trimuon could be measured with much higher accuracy and test the Standard Model prediction. New phenomena, such as exclusive $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations, isosinglet type neutral heavy leptons, right handed currents, and wrong-sign single muons could be explored with unprecedented sensitivity in a new experiment.

For the immediate future, at Harvard we wish to investigate two aspects of the future neutrino experiment:

Detector Development: For the future neutrino experiment, the research clearly lies in improving upon the target calorimeter and the spectrometer. The specific questions are:

1. Scintillation Counters: What should the transverse segmentation be? What improvements do we expect to achieve in the hadronic and electromagnetic showers? What is the effect of making longitudinal sampling finer/coarser (at present the Lab-E detector has 4" Fe longitudinal sampling and no transverse segmentation)? What are the expected non-linearities? What is the P_T -resolution of hadronic showers assuming a 12" transverse segmentation, a 6" transverse segmentation? Some of these can be answered in a test setup using a cosmic ray telescope. A related question is, what improvement do we expect in the time resolution? What are the map and slewing corrections? We hope to achieve an event-by-event time resolution of 100 psec for a charge current event. Such a precision will be invaluable in looking for new physics (long lived neutral heavy lepton search), and to eliminate cosmic ray backgrounds in slow spill.

2. Gas Calorimetry: A reliable measurement of the P_T of the neutrino-induced hadron shower provides a very powerful handle to look for $\nu_\mu \rightarrow \nu_\tau$ oscillation. The crucial experimental variable is the precision with which one can determine the direction of the hadron shower. The Harvard CDF group has considerable expertise in the gas calorimetry. We wish to explore the feasibility of measuring the angle of a 100 GeV shower to better than 10mrad precision. What should the longitudinal segmentation of the drift chambers be? Is it possible to devise algorithms, assuming a Flash ADC readout, to tag very "short" hadron events that vitiate good angular resolution? What are the factors that change the gain of such a system? How could it be monitored? What beam-tests should be planned?

3. Spectrometer: For precision measurements of the scaling violation in neutrino scattering, the most important variable is the energy of the muon. The use of an iron toroidal magnet poses an insuperable barrier in terms of the multiple Coulomb scattering --- the resolution of the muon momentum can be no better than 9-10%. We wish to have a spectrometer with a resolution of about 1% and a systematic precision of 0.05%. At present, the only feasible means appears to be an air core superconducting toroidal magnet. The cost of such a device gives one a long pause indeed. The question emerges: is there any alternative system that could furnish the desired resolution? If not, how best to go about designing an air core toroid?

Understanding the Projected Systematics: Many of the proposed measurements, at present, suffer from systematic limitations. Some of these can be eliminated or reduced by detector improvements (see above). There are, however, theoretical uncertainties that need to be understood via detailed calculations, by identifying kinematic regions that would yield "clean" measurements, and by exploring alternative techniques to achieve redundant measurement. Specific topics include:

1. Higher Twist Effects: How do they affect the QCD tests? How can they be parametrized using the SLAC data, or even our own data that could extend down to $Q^2=0.5 \text{ GeV}^2$? What is the effect on the weak mixing angle measurement? How does the Mean Square Charge Test, F_2^ν to F_2^μ comparison, help bracket the error incurred due to higher twist effects?

2. $x_{BJ} > 1$ events: What the sources that cause smearing the dominant effect in this region? What are the target mass and higher twist effects in this region? How to characterize "QCD-inspired" (e.g. parton recombination scenario) events in this region?

3. m_c error in the weak mixing angle: The dominant theoretical error in $\sin^2\theta_W$ measurement comes from the lack of knowledge pertaining the charm threshold in charge current scattering.

How can one use the 150,000 opposite sign dimuon events to eliminate this uncertainty? Are there alternative checks? Could one concentrate upon a kinematic region so that m_c uncertainty does not matter?

4. Non-isoscalar target correction: The iron target has a small non-isoscalarity of about 5-6%. There are some concern pertaining the validity of Llewellyn-Smith formula due to this effect. We have to understand if it would pose a fundamental problem in achieving a precision of 0.65% in $\sin^2\theta_W$ measurement. What alternative measurement would eliminate this uncertainty?

5. ν_e measurement: An insitu measurement of ν_e not only diminishes the ν_e -induced contamination to the neutral currents, but also offers a novel means to search for $\nu_\mu \rightarrow \nu_e$ oscillation. What are the systematic limitation of the " ϵ_3 " method?

6. Quasi-elastic Like Processes: In neutrino-nucleon interactions these appear as low hadron energy events. To meet the projected precision for the structure functions and inverse muon decay measurements,

Commencing with the discovery of scaling and scaling violation, to the discovery of neutral current, to the discovery of "open" charm, to the precision measurement of perturbative QCD and of $\sin^2\theta_W$, deep-inelastic experiments have been a fertile ground for extending the horizons of our understanding. For a substantial improvement over our present understanding, a next generation of deep inelastic experiments is extremely important both in the breadth of topics pertaining to the Standard Model and regarding precision measurements of the parameters. Finally, questions pertaining neutrino masses, neutral heavy leptons, and other mysteries in the lepton sector can be uniquely explored in the proposed endeavour.

In order to carry out this program it will be necessary to hire a postdoctoral research associate starting in mid-1992 as well as one or two graduate students. Prof. Mishra will submit a OJI proposal to fund these activities in the fall of 1991.

8. The Solenoidal Detector Collaboration at the SSC

(Professor Feldman, Dr. Brandenburg, Dr. Oliver, Dr. Schlabach, Mr. Sadowski, Mr. Carnivale)

The Superconducting Super Collider will allow us to address crucial questions that can be addressed in no other way. Among them are:

1. What is the origin of mass? Or equivalently, by what mechanism is the electroweak symmetry broken? Is it by a simple Higgs mechanism? Or is the Higgs linked to other particles through a larger symmetry, such as supersymmetry? Or is the Higgs a composite, formed from a new set of strong interactions, such as in technicolor?
2. Are there additional heavy bosons in nature, indicating new, as yet undiscovered, forces?
3. Are quarks and leptons elementary, or are they composites of even more fundamental particles?
4. What are the properties of the top quark? Does its high mass give it a role in symmetry breaking?

The Solenoidal Detector Collaboration is proposing to construct an SSC detector aimed at answering these questions, as well as addressing a broad range of other physics issues. Based on a solenoidal magnetic field, the detector will have powerful tracking, calorimetry, and muon detection.

The detection and precision measurement of leptons, both electrons and muons is central to answering these questions. For this reason, the Harvard SDC group has decided to focus on the problem of muon detection in the SDC detector. (The muon system lends itself to being constructed by university groups, while the calorimetry system, needed for electron identification and measurement, will probably be largely built at national laboratories.)

We have formed a close collaboration with groups from Brandeis University and Tufts University to work particularly on the design and production of drift chambers that can be produced economically and that can meet the necessary requirements for precision. Mr. Sadowski is leading the engineering effort and will be joined by Mr. Carnivale in May. We are actively consulting with engineers from Draper Laboratory on this project.

We are also involved with the general design of the system and the electronics coordination. Professor Feldman is one of the co-chairman of the SDC muon group and Dr.

Oliver is acting as the electronics coordinator. Our collaborator, Professor Bensinger of Brandies University, is acting as the project manager.

We are presently investigating a "wine-rack" design in which nine-meter long drift tubes are inserted into a "wine rack," whose bulkheads provide intermediate support and are alignable to high precision. One of the problems with the SDC central muon detectors is that the long length of the barrel, which requires tracks to cross the plane of the detectors are large angles, up to 60° from the normal. This design allows us to orient the tubes so that all valid trajectories pass within 12° of the normal. It also allows us to overlap the tubes so that there are no cracks between them.

We plan to have working prototypes by the end of the summer. At that point the SDC muon group will begin the process of reviewing design and prototyping efforts taking place in the U.S. and Japan, leading to a design decision in February 1992.

We expect that Harvard will be one of the locations in which SDC muon chamber production will occur. This construction is scheduled to begin in October 1993. Design and fabrication of tooling and assembly lines will take place in the previous year.

The SDC muon system will contain more than 50,000 square meters of drift chambers (15 U.S. football fields), which must be aligned to an accuracy of between $100\ \mu\text{m}$ and $250\ \mu\text{m}$, depending on function and location. One of our goals is to learn how to build, support, and align chambers to this level of precision over the large distances involved. As part of this investigation, we plan to build a test stand which will allow ten meter by ten meter supermodules of chambers to be supported in all of the configurations in which they will have to be supported on the detector. We expect to start the design of this test stand this year, and perform tests with it during 1992.

Dr. Oliver will provide overall coordination of electronics for the SDC muon system and will probably take direct responsibility for the front end pre-amplifier, discriminator and shaper circuits. The division of responsibility for the electronics and trigger is now being discussed within the collaboration.

Funds for the engineering and prototyping work being described above are being supplied from a grant from the Texas National Research Laboratory Commission (\$348K in 1991) and from funds from the SSCL funnelled through the SDC collaboration. However, funds for scientific personnel are not provided from either of these sources. We are thus requesting funds for the support of a research associate and two students to work part time on this effort.

9. Detector R&D

A. Warm Liquid Calorimetry

(Dr. Brandenburg, Prof. Geer, Dr. Oliver, Mr. Sadowski, Mr. Daw, Mr. Ptohos)

To be sensitive to new physics signals SSC detectors must have a wide and general detection capability. This implies a 4π detector geometry with good electron, muon, and jet detection; good calorimetry will be crucial for any such detector. The main issues will be 1) good energy resolution with uniform response to electromagnetic and hadronic interactions, 2) good segmentation, 3) good hermeticity (few cracks and holes), 4) fast response times, and 5) radiation resistance. We believe that an attractive readout medium for an SSC calorimeter would be warm liquids along the lines of those tested for the UA1 calorimeter upgrade. Such liquids as TMP and TMS have good electron mobility. They have also been shown to be extremely resistant to radiation. The radiator material could be uranium, lead or tungsten, and the radiator thickness should be chosen so as to equalize the electromagnetic and hadronic response.

The first area we have investigated is the electron mobility of different liquids. This was done in collaboration with a group from Brookhaven. Several candidate liquids other than TMS and TMP have emerged from these studies. A graduate student from Harvard worked at Brookhaven carrying out this work under the supervision of Prof. Geer and with the assistance of Dr. Holyrod of Brookhaven.

The major goal of our project has been the construction and testing of a prototype "swimming pool" calorimeter. We hope to provide a "proof of principle" for a warm liquid calorimeter design where the readout and radiator plates are totally immersed in the liquid as in liquid argon devices. Dr. Brandenburg has coordinated this effort and Mr. Sadowski has spent a major fraction of his time on the engineering aspects. In addition to the other Harvard participants, Dr. Theriot of Fermilab has helped with the design of this prototype. We are currently members of the WALIC collaboration, and will be assisted by them in the filling and testing of the prototype.

We decided that a small electromagnetic calorimeter would be the most appropriate device to build as a first prototype. Therefore we designed and built a sealed box which contains 25 layers of radiator plates and ionization gaps. It is subdivided into 16 towers each with two

depth segmentations. The radiator is one radiation length of tungsten and the liquid gap width is 1.5mm.. The box has been constructed using stainless steel and ceramics so that it can be cleaned by baking. We have investigated the use of depleted uranium which is clad with stainless steel as the radiator. However, because of the difficulties cleaning and baking out the clad uranium, for the first prototype we have used tungsten, which is simpler to clean and can be directly immersed in the liquid. This device has been completed, is now being filled with TMP at LBL, and will be tested in a beam at Fermilab this summer in collaboration with the WALIC group.

Finally, our group joined with the SSC Subsystem Group (Moishe Pripstein, spokesman) to study the design of a complete warm-liquid calorimetry system for the SDC detector. We have been assisted in this effort by an engineering team from EG&G Corporation. Our starting point was a conceptual design that emerged from the Tuscaloosa SSC Calorimetry Workshop earlier this year. This study has not only been concerned with the internal details of the calorimetry, but the structural issues of constructing a huge detector has been investigated along with related topics such as placement of electronics, routing of cables, access for maintenance. The design will be optimized for hermeticity, i.e. inter-module cracks will be minimized, and front-end electronics will be located as close to the active elements as is possible. The goal is to build a full-scale warm-liquid calorimeter test beam module (TBM). The Harvard and Penn groups are responsible for the readout system of the TBM. It should be ready for testing in 1992.

This project was initially funded under the generic R&D program, and in 1990 and 1991 has received SSC subsystem funding. In 1991 we are receiving \$35K in operations funds and \$35K in equipment funds. We do not anticipate requesting further funding.

B. Front End Electronics

(Drs. Brandenburg and Oliver, Prof. Feldman)

The second project is a study of the possibilities for fast readout of calorimetry towers. The capacitance of a stack of plates and the inductance of the signal cabling are the limiting factors in obtaining short readout times. Thus proper segmentation of a calorimeter and proximity of front end electronics are the crucial design issues. Dr. Oliver has been studying the optimization of these factors at Harvard. He also has an informal collaboration with Dr. Radeka and his group at Brookhaven. He and Dr. Brandenburg are currently members of the

SSC Front End Electronics Subsystem Group. (Brig Williams, spokesman) investigating the issues. The project is receiving \$50K of SSC subsystem equipment funds in 1991.

Our major effort in front end electronics has been in analog signal processing circuits for calorimetry. In particular we have been investigating several methods of implementing externally programmable shapers, in an integrated circuit process. Such circuits are required in order to optimally filter calorimeter signals in the presence of front end electronic noise as well as detector pile-up. Furthermore, the time structure of the filtered signals must be of sufficient accuracy to associate the event with the appropriate 16ns rf bucket of the SSC. This must be done in the face of variations in calorimeter capacitance and front end amplifier risetime as well as process variations in the shaper integrated circuits. Programmable shaping time is required to fulfil these goals.

This work has led to two different design approaches. One approach utilizes "translinear" circuit techniques and could be implemented in a bipolar transistor process. The other approach utilizes biCMOS technology and has the advantages of wider dynamic range, more functionality per chip, and lower power. We plan to implement the latter approach in a custom IC. Prof. C. Blocker of Brandeis has collaborated on this project and we have been in close consultation with V. Radeka, S. Rescia, P. O'Connor, and others at BNL on the formulation of device specifications and implementations.

Finally as a part of our CDF/SDC group's work on muon systems, Dr. Oliver and Prof. Feldman are coordinating the development of the front-end electronics for the SDC muon system. They are working closely with the Penn and Michigan groups on this project and may be requesting further SSC subsystem funding for this work in 1992.

C. Silicon Drift Detectors

(Profs. Wilson and Clark, Drs. Henderson and Oliver)

A third collaboration is with the SSC Subsystem Group headed by Dr. Pavel Rehak of Brookhaven National Laboratory to study the applicability of silicon drift detectors to the SSC program. A silicon drift detector is, in principle, an elegant solution to the problem of vertex detection. Each particle traversing the detector gives an x, y readout independently of all other particles. In addition the low capacitance (0-3pf) of the readout pads allows a good signal to noise ratio, and permits the design of JFET preamplifiers with high radiation resistance. It is even possible to include the preamp on the high resistivity silicon wafer of the detector itself,

avoiding the connection problems. This project is receiving \$20K of operations funds and \$5K of equipment funds from the SSC subsystem program in 1991.

In collaboration with Brookhaven National Laboratory we plan to study radiation damage in these detectors. For testing with minimum ionizing particles we will use a Co^{60} source; probably at BNL using their radiation facility. We also have available the Co^{60} radiotherapy facilities at Massachusetts General Hospital. For heavily ionizing particles, we will probably use the Harvard Cyclotron, with 150 MeV protons, but the Lowell University neutron generator is also available. We expect this to be done in summer 1991 together with a graduate student.

The silicon devices to be tested will hopefully include the circular drift detector developed by Munich-BNL-Milan for the NA39 experiment at CERN. We will also test the detectors made by SI of Oslo for the CLEO detector. (See Section 40). We will measure the time and position resolution both before and after the irradiation. We expect to use up to 10^6 rads of gamma rays and 2×10^5 rads of neutrons and protons.

We also plan, on a slow and measured time scale, to work on the integrated electronic circuits for read out of these devices. The preamplifier is likely to be the preamp made of high resistivity silicon of Rehak; the waveform analyzer, the chip by Kleinfelder; although since this is CMOS and subject to radiation damage, we hope to change this at a later date. The primary development task will be the pulse shaping chip.

We do not at the present time anticipate Monte Carlo studies ourselves during this year. However, we will follow the work of others in the group (from Princeton and University of Pittsburg) and get set up to perform these calculations ourselves.

D. Diamond Radiation Detectors

(Prof. Franklin and Dr. Konigsberg)

Melissa Franklin and Jacobo Konigsberg are members of a collaboration studying the possibility of using chemical vapour deposited (CVD) diamond as radiation hard charged particle detectors for the high rate environment of the SSC. We have demonstrated that signals can be seen at the KEK 5 GeV testbeam. Future work involves maximising the signal/noise for single particles and building and testing a prototype EM calorimeter. This work is being funded at Harvard in 1991 by a grant of \$15K from the TRNLC.

E. General HEPL R&D Support

The funds for detector R&D at HEPL have come from the SSC generic detector and subsystem programs in recent years. For 1992 and beyond we will continue to support some of these activities with funds from the SSC program, probably in connection with the SDC collaboration, but we are also requesting a small sum (\$20K) of generic R&D funds to support new developments.

10. Theory

(Professor R. Glauber and Dr. Z. Ryzak)

The program of phenomenological analysis of high energy $\bar{p}p$ cross sections begun in collaboration with members of the old UA4 group at CERN continues. The fits that have been found to the differential cross sections measured at the SPS--Collider suggest that further experimental attention must be paid to the small--momentum--transfer region of the differential cross section and to the the extrapolations made to its forward values.

Our analysis has in fact spurred a remeasurement of the small--momentum--transfer cross sections that is to be carried out in the Fall of 1991. We expect to be closely involved in the analyses of these data, since it is now clear they cannot be carried out in a wholly model--independent way. The models we have been using should also be of value in dealing with the momentum transfer distributions for the process of diffractive dissociation.

In many high--energy collision experiments in which pions and kaons are multiply produced, it has been found that there is a distinct tendency for the particles of like charge to emerge with closely correlated momenta. This effect, which was predicted and searched for on the basis of a quantum optical analogy, has sometimes been called the "Bose-Einstein Effect", but more recently by the name of its optical analogue, the Hanbury-Brown-Twiss effect. That effect is a photon--photon correlation that is due, as we have shown many years ago, to the highly random (and incoherent) nature of the field excitations from ordinary light sources. (It tends to be completely absent in coherent sources.) The analysis of pion relative momentum distributions that has been carried out by analogy with the Hanbury-Brown-Twiss analysis makes implicit assumptions of incoherence that are likely to prove quite extreme in the elementary particle context --- for example, the assumption that the coherence length of the field excitations is infinitesimal compared to the dimensions of the collision volume. We propose to test these assumptions by means of simple field theoretical models, in order to see what the correlation effects may be telling us in more realistic terms about the collision processes.

Recently developed techniques for trapping ions and charged particles in time--varying electromagnetic fields are making new classes of experimental measurements possible, at unprecedentedly high levels of accuracy. While the inspiration for the trapping schemes has usually come from classical calculations, their mechanisms may be significantly influenced by quantum fluctuation effects. It will be necessary to understand the fluctuation effects in general, in order to deal with the cooling of the trapped particles, and for the precise analysis of

experiments performed on them. We have been able to develop for this purpose a complete theory of the quantum mechanical behavior of particles trapped in an arbitrarily time-varying quadrupole field. The analysis shows that for suitable ranges of the parameters the trapping is absolute; *i.e.*, there is no quantum mechanical leakage. The non-stationary wave functions form a discrete sequence in one-to-one correspondence with the stationary states of a static harmonic oscillator. Coherent states can also be formed from the pseudostationary trapped states, and externally applied fields lead simply to transitions between these coherent states.

Several years ago we developed (in collaboration with P.Osland and M.Bleszynski) an asymptotic form of diffractive collision theory that applies to particle and nuclear collisions in the high energy limit. We have performed many calculations applying the scheme in various contexts and are preparing a lengthy review of the work.

Quantum Chromodynamics (Dr. Z. Ryzak): In collaboration with T. Mannel and W. Roberts we have studied QCD systems containing heavy quarks. We have analyzed the theoretical foundations and phenomenological applications of the Heavy Quark Effective Theory (HQET). In particular, we have shown that HQET can be derived from QCD by using the path integral formalism. The idea is to "integrate out" the degrees of freedom which correspond to highly virtual quantum excitations. The dynamics of the resulting effective theory is then given in terms of a lagrangian that is build out of an infinite series of operators of increasing dimensions, suppressed by powers of $1/m_Q$. The usefulness of HQET becomes apparent when one realizes that the QCD Green's functions describing transitions between heavy quarks contain a natural small parameter $\epsilon = \Lambda_{\text{QCD}}/m_Q$. It follows that the most efficient way of doing QCD calculations corresponds to construction of an asymptotic expansion of QCD. In particular we show that in the limit $\epsilon = 0$ new symmetries arise: a spin symmetry and a flavor symmetry. Those symmetries are not apparent from the QCD lagrangian, but they have powerful phenomenological applications.

The spin symmetry is a consequence of the $1/m_Q$ suppression of the chromomagnetic interactions, and it corresponds to the decoupling of the heavy quark's spin degrees of freedom. It follows that the number of independent QCD form-factors which describe a given matrix element, is much smaller than general considerations of Lorentz invariance would allow. We have used the spin symmetry to show that various transitions between heavy hadrons are related to each other. For example, a semileptonic decay $B \rightarrow D$ is related to $B \rightarrow D^*$, and $\Lambda_b \rightarrow \Sigma_c$ is related to $\Lambda_b \rightarrow \Sigma_c^*$, or the e^+e^- production of the pairs $\bar{B}B$ ($\bar{\Sigma}_c \Sigma_c$) is related to the production of the pairs $\bar{B}B^*$ ($\bar{\Sigma}_c \Sigma_c^*$) or the pairs $\bar{B}^*B^*$ ($\bar{\Sigma}_c^* \Sigma_c^*$). Similarly, angular distributions or spin correlations can be predicted for certain processes, for example,

the angular distribution of the meson and baryon pairs in the e^+e^- experiments, and the asymmetry parameters for the decays of Λ_b or Λ_c . In particular, in one of the first tests of HQET the asymmetry parameter α for the decay $\Lambda_c \rightarrow \Lambda \pi$ was shown to be -1, and this agrees with a very recent measurement from CLEO $\alpha = -1 (+0.4 / -0.0)$ published in *Phys. Rev. Lett.* **65**, 2842 (1990).

The flavor symmetry arises because the light quanta in a heavy hadron cannot probe the identity of the heavy quark, *i.e.*, all quarks of mass $m_Q \gg \Lambda_{\text{QCD}}$ act in the same way as a static source of color. This effective symmetry allows one to normalize the QCD form-factors of the heavy hadron weak currents, and it means that in certain exclusive weak decays, (*e.g.*, semileptonic $B \rightarrow D$ or $\Lambda_b \rightarrow \Lambda_c$) one can directly measure the value of the appropriate KM matrix element (V_{bc}). Such a measurement will eventually give the most accurate determination of V_{bc} , in the same way that the superallowed transitions between the O^+ nuclei give the best measurement of the Cabbibo angle.

In our most recent preprint (in preparation) we show that the $1/m_Q$ corrections in general violate the flavor and spin symmetries. Therefore, in order to assess the real significance of the effective symmetries, one must understand the structure and the size of the symmetry-violating terms. We discuss their general form, and present a detailed analysis of the $1/m_Q$ effects in the decays of Λ_b .

Another area of our work on QCD involves studies of deep inelastic scattering. We have addressed some theoretical issues associated with the parton-model description of polarized processes. In particular, we have become interested in the questions of the proper theoretical definition and the possible experimental measurements of the polarized gluon densities. This problem arises in the context of the theoretical interpretation of the SLAC-EMC measurements of the polarized structure function $g_1(x)$, as well as in discussions of future polarized experiments. In some of our work (done in collaboration with L. Mankiewicz) we have shown that the proper definition of the gluon density requires an implementation of constraints imposed by the anomaly equation and gauge invariance. Also, we have used PCAC analysis to obtain a prediction for the size of the first moment of the polarized gluon density.

In related research we have studied the parton model interpretation of the polarized structure function $g_2(x)$. We have shown that the piece of $g_2(x)$ which corresponds to the twist-3 operators (it is not kinematically suppressed compared with the contribution from the twist-2 operators), cannot be interpreted in terms of the one-particle parton densities. In general we point out that $g_2(x)$ is the best place to measure partonic coherence effects, *i.e.*, the effects of the higher twists.

11. Publications, Conference Reports and Theses

CDF

- "Lepton Asymmetry in W Decays from $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be submitted to *Phys. Rev. Lett.*
- "Inclusive Jet Cross Section in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be submitted to *Phys. Rev. D.*
- "Measurement of the Drell-Yan Invariant Mass Distribution in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be submitted to *Phys. Rev. Lett.*
- "Study of Three Jet Topology in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be submitted to *Phys. Rev. D.*
- "Measurement of the Z p_T Distribution in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be submitted to *Phys. Rev. Lett.*
- "Measurement of the W P_T Distribution in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, submitted to *Phys. Rev. Lett.*, Fermilab-PUB-91/33-E.
- "A Measurement of $\sigma(W \rightarrow e\nu)$ and $\sigma(Z^0 \rightarrow e^+e^-)$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1800$ GeV," F. Abe *et al.*, submitted to *Phys. Rev. D.*, Fermilab-PUB-90/229-E.
- "A Determination of $\sin^2 \theta_W$ from the Forward-Backward Asymmetry in $\bar{p}p \rightarrow ee$ Interactions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, to be published in *Phys. Rev. Lett.*
- "Measurement of QCD Jet Broadening in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, submitted to *Phys. Rev. D.*, January 23, 1991.
- "The CDF Level 3 Trigger," J. T. Carroll *et al.*, *Nucl. Instrum. Methods*, **A300**, 552-567 (1991).
- "Top Quark Search in the Electron + Jets Channel in Proton-Antiproton Collisions at $\sqrt{s} = 1.8$ TeV," F. Abe *et al.*, *Phys. Rev. D.* **43**, 664 (1991).
- "A Measurement of the W Boson Mass," F. Abe *et al.*, *Phys. Rev. Lett.* **65**, 2243 (1990).

- "A Measurement of the W Boson Mass in 1.8 TeV $\bar{p}p$ Collisions," F. Abe *et al.*, *Phys. Rev. D* 43, 2070 (1991).
- "A Measurement of D* Production in Jets from $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV", F. Abe *et al.*, *Phys. Rev. Lett.* 64, 348 (1990).
- "Two Jet Differential Cross Section in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV", F. Abe *et al.*, *Phys. Rev. Lett.* 64, 157 (1990).
- F. Abe *et al.*, "Measurement of the Ratio $\sigma(W \rightarrow e \nu)/\sigma(Z \rightarrow ee)$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV", F. Abe *et al.*, *Phys. Rev. Lett.* 64, 152 (1990).
- "A Search for New Heavy Quarks in Electron-Muon Events at the Fermilab Tevatron Collider", F. Abe *et al.*, *Phys. Rev. Lett.* 64, 147 (1990).
- "A Search for the Top Quark in the Reaction $\bar{p}p \rightarrow \text{Electron} + \text{Jets}$ at $\sqrt{s} = 1.8$ TeV", F. Abe *et al.*, *Phys. Rev. Lett.* 64, 142 (1990).
- "Pseudorapidity Distributions of Charged Particles Produced in $\bar{p}p$ Interactions at $\sqrt{s} = 630$ and 1800 GeV", F. Abe *et al.*, *Phys. Rev. D, Rapid Communication*, 41, 2230 (1990).
- "The Two Jet Invariant Mass Distribution at $\sqrt{s} = 1.8$ TeV", F. Abe *et al.*, *Phys. Rev. D, Rapid Communication*, 41, 1722 (1990).
- "Search for a Light Higgs Boson at the Tevatron Proton-Antiproton Collider", F. Abe *et al.*, *Phys. Rev. D, Rapid Communication*, 41, 1717 (1990).
- G. Brandenburg *et al.*, "An Electromagnetic Calorimeter for the Small Angle Regions of the Collider Detector at Fermilab", *NIM A* 267, 257 (1988).
- "Recent Results on W,Z Production at $\sqrt{s} = 1.8$ TeV", J. Ng, published Proceedings XXVIth Rencontres de Moriond, Hadronic Session, France, March, 1991.
- "High Energy Antiproton-Proton Collisions - The Collider Detector at Fermilab, The CDF Collaboration, G. Brandenburg, published Proceedings Yukawa Memorial Symposium, Nishinomiya, Japan, October 1990.
- "The Standard Model and Beyond - Physics at the Proton-Antiproton Colliders", M. Franklin, Proc. of V Lake Louise Winter Institute, World Scientific, February 1990.

CLEO

- "Observation of B-Meson Semileptonic Decays to Noncharmed Final States," R. Fulton *et al.*, *Phys. Rev. Lett.* 64, 16 (1990)
- "P-wave Charmed Mesons in e^+e^- Annihilation," P. Avery *et al.*, *Phys. Rev. D* 41, 774 (1990).
- "Search for Neutrinoless Decays of the τ lepton," T. Bowcock *et al.*, *Phys. Rev. D* 41, 805 (1990).
- "Radiative $\Upsilon(1S)$ Decays," R. Fulton *et al.*, *Phys. Rev. D* 41, 1401 (1990).
- "Exclusive and Inclusive Decays of B Mesons into D_S Mesons," D. Bortoletto *et al.*, *Phys. Rev. Lett.* 64, 2117 (1990).
- "Observation of $\Upsilon(4S)$ Decays into non- $B\bar{B}$ Final States Containing Ψ Mesons," J. Alexander *et al.*, *Phys. Rev. Lett.* 64, 2226 (1990).
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- "Study of $D^0 \rightarrow KK$, $D^0 \rightarrow \pi\pi$," J. Alexander *et al.*, *Phys. Rev. Lett.* 65, 1250 (1990).
- "Determination of $B(D_S \rightarrow \phi\pi)$ via observation of $D_S \rightarrow \phi l^+ \nu_l$," J. Alexander *et al.*, *Phys. Rev. Lett.* 65, 1531 (1990).
- "Study of K^* Production in τ Decay," M. Goldberg *et al.*, *Phys. Lett. B* 251, 223 (1990).
- "Measurement of the Λ_c Decay Asymmetry Parameter," P. Avery *et al.*, *Phys. Rev. Lett.* 65, 2842 (1990).
- "Exclusive and Inclusive Semileptonic Decays of B Mesons to D Mesons," R. Fulton *et al.*, CLNS-90-989, accepted by *PRL*.
- "Study of $\pi^+\pi^-$ from the $\Upsilon(3S)$ and a Search for the h_b ," I. Brock *et al.*, accepted by *PRD*.
- "Inclusive Production of the Charmed Baryon Λ_c from e^+e^- annihilations at $\sqrt{s} = 10.55$ GeV," P. Avery *et al.*, CLNS 90-992, submitted to *PRD*.
- " D^0 Decays into Final States Containing a π^0 or η^0 ," P. Avery *et al.*, CLEO 90/12, submitted to *PRD*.

"Spin Alignment of D^* Mesons Produced in e^+e^- Annihilations," in preparation, to be submitted to *PRD*.

"Semileptonic Branching Ratio of B-mesons," in preparation, to be submitted to *PRD*.

"Rare Decays of D^0 Mesons," in preparation, to be submitted to *PRD*.

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Crystal Ball

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"Search for D^0 and B^0 decays into $\pi^0 \pi^0$ " D. Antreasyan *et al.*, submitted to *Z. Phys. C*.

"Measurement of Direct Photon Spectrum from $\Upsilon(1S)$ Decays. A. Bizzeti *et al.*, to be published.

"Measurement of the Decay of the $\Upsilon(1S)$ and $\Upsilon(2S)$ Resonances to Muon pairs" Michael Kobel *et al.*, to be published.

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- W. Trischuk, "A Measurement of the W Boson Mass in 1.8 TeV Proton-Antiproton Collisions", April 1990.
- D. Xiao, "Charmless Semileptonic Decays of the B Mesons", May 1990.

12. Budget Tables

Our budget projections for the next five years are contained in the tables on the following pages. The CY1991 figures represent actual funding. The columns for CY1992 and beyond present the operations budgets that are required for the effective functioning of each group and the HEPL facility in future years. The first two pages give summary budget projections for each task for the years 1991-93 and 1994-96. Following the operations summaries are detailed budgets for each task for the period 1991-93.

An indirect cost rate of 35.5% is used for 1991. This is a special reduced rate which has been negotiated with the University for HEPL and is still awaiting final approval from the Dean of the Faculty of Arts and Sciences. This rate applies to all operations costs and is assumed to increase to 37% for 1992 and beyond. The fringe benefit rate on salaries rises from 21% to 23% on 7/1/91, so an effective rate of 22% has been used for 1991.

For each group the PhD level physicists are identified and the fractional f.t.e. cost to the contract is given. We note that starting in mid-1991 the University has also tentatively agreed to cover the full academic salaries of new junior faculty appointments in high energy physics, except for those terms when they are excused from teaching.

We have included budgets for several new initiatives in the coming years; we will also be seeking funding from other sources such as the OJI program for these projects. A new experimental group is budgeted to start in CY1993 pending the successful outcome of a faculty search. In addition we are assuming that the budget of the L3 Group will continue adiabatically with a new principal investigator after Prof. Strauch retires in mid 1993.

The 1991 operations budget for the HEPL facility assumes that approximately \$425K of additional income will be available to cover costs. This income is expected both from HEP equipment fabrication projects and from work done for other non-HEP groups at Harvard. Most of the facility costs continue to be covered by this contract via the "HEPL Facility Tax" received from the experimental groups. We are requesting increased coverage of the facility costs from the contract in future years so that it will be available full-time for HEP projects.

Our equipment fund requests are summarized in the final table. Descriptions of the various items may be found in the text. The VAX Facility Upgrade and General Detector R&D items are intended to benefit all the experimental groups at Harvard, while the remaining items are attached to specific projects.

*Budget pages removed
VK*

HEPL Equipment Funds

	CY1991	CY1992	CY1993
CLEO Detector Upgrades	20,000	30,000	
E665 Detector Upgrades	20,000		
B-Factory TOF R&D		20,000	50,000
L3 Apollo System Upgrade		20,000	
Computing Facilities	50,000	50,000	50,000
General Detector R&D		20,000	20,000
SSC Detector R&D			
Warm Liquid Calorimetry	35,000		
Front End Electronics	50,000		
Silicon Drift Detectors	5,000		
Total Equipment Funds	180,000	140,000	120,000
Other Equipment Funds			
CDF Muon System Upgrade (a)	200,000	50,000	200,000
SDC Muon System Design (b)	100,000	100,000	100,000

(a) Funds to be transferred from CDF Management

(b) Funds provided by TNRLC (50K) and SDC Management (50K)

HEPL Facility - Operations Summary

Item	CY1991	CY1992	CY1993
Regular Employees *	635,496	690,480	731,909
(f.t.e.)	(14.2)	(14.5)	(14.5)
Casuals	0	0	0
Benefits	139,809	158,810	168,339
Total Salaries	775,305	849,290	900,248
Supplies	6,000	6,600	7,260
Travel-Tickets	2,000	2,200	2,420
Travel-Other	2,000	2,200	2,420
Telephone	6,000	6,600	7,260
Shipping	2,000	2,200	2,420
Subcontract**	8,000	8,800	9,680
Services Purch.	4,000	4,400	4,840
Miscellaneous	0	0	0
Total M&S	30,000	33,000	36,300
Total Operations	805,305	882,290	936,548
Overhead	285,695	326,710	346,452
Total inc. Ovhd.	1,091,000	1,209,000	1,283,000

* Mach. Shop (5), Elect. Shop (4), Design Eng. (1.7 in 91, 2 in 92,93),
 Computer Syst. Mgr. (1), Admin. (2.5)
 Of the above f.t.e., 0.1 are paid by the University

** Leased line to ESnet for computing and teleconferencing