Annual Report
for the
High Energy Physics Program at Texas A&M University

DOE Contract DE-AS05-81ER40039

For the period
April 1, 1990 to March 31, 1991

Department of Physics
Texas A&M University
College Station, Texas 77843

October, 1990

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

Abstract.....	i
I. The Fermilab CDF Program.....	1
II. The MACRO Experiment.....	39
III. SSC Detector R&D Program.....	47
IV. SSC Experimental Program.....	30
V. Theoretical Physics Program.....	94
Appendix A Publications and Reports for 1990.....	106

ABSTRACT

The Texas A&M high energy physics program has achieved significant milestones in each of its research initiatives. We are participating in two major operating experiments, CDF and MACRO; the development of two new detector technologies, liquid scintillating fiber calorimetry and knife-edge chambers; and two SSC detector proposals, SDC and TEXAS/EMPACT.

In CDF, the Texas A&M group has spearheaded the analysis of jet cross-sections to produce the most sensitive test of quark structure. In preparation for the 1991 physics run, we are conducting extensive test beam studies of the energy response of the forward calorimeter systems. We are beginning an analysis of b-quark jets as a component of the top search which will be a prime feature of the next physics run.

In MACRO, we have developed and built the wave form digitizing system for the scintillator system. The first super module of the experiment logged its first year of data, observing nearly 10^6 single-muon events and several thousand multi-muon events in coincidence with an extensive-air-shower array.

We have developed prototypes of a liquid-scintillator fiber calorimeter system, in which internally reflecting channels are imbedded in a lead matrix and filled with liquid scintillator. This approach combines the performance features of fiber calorimetry and the radiation hardness of liquid scintillator, and is being developed for forward calorimetry in TEXAS/EMPACT.

The microstrip chamber is a new technology for precision track chambers that offer the performance required for future hadron colliders: 20 μm precision, 20 nsec live time, $\sim 10^{-3}$ occupancy, and modest cost. The Texas A&M group is leading a collaborative effort to develop knife-edge chambers for use in CDF and SDC.

A new element in this program is the inclusion of a theoretical high energy physics research program being carried out by D. Nanopoulos and C. Pope. D. Nanopoulos has succeeded in building a string-derived model that unifies all known interactions: flipped SU(5), which is the leading candidate for a TOE. The impact of this work on string phenomenology certainly has far reaching consequences. C. Pope is currently working on some generalisations of the symmetries of string theory, known as W algebras. These are expected to have applications in two-dimensional conformal field theory, two-dimensional extensions of gravity and topological gravity, and W-string theory.

The following report presents details of the accomplishments of the Texas A&M program over the past year and the proposed plan of research for the coming year.

I. The Fermilab CDF Program

Following the last Collider run, our group has now focussed its attention on several important areas of the CDF program. First of all, we have begun to contribute to the high level of activity in the analysis of this new data. The areas to which we have made important contributions have been in the study of the electron data sample and the study of high E_t jets. In addition to these analysis activities, we have participated heavily in the setup and running of the test beam program in the M-Test beamline at Fermilab. This test beam work is critical for the preparation of the gas calorimeter systems for the 1991 Collider run.

In the sections which follow, we will outline the impact of these latest results on the CDF program, describe the status of the current CDF analysis activities and present our CDF plans for the coming funding cycle.

A. Current Physics Analyses in Progress

Following the very successful CDF data taking run which concluded in 1989, our team has been heavily involved in several key analysis projects being carried out by the collaboration. One of graduate students, Timothy Hessing has been working on the measurement of the inclusive jet cross section and a search for quark compositeness and Teruki Kamon has been contributing to the work on the measurement of the W and Z cross sections. In addition, Themis Bowcock, a new addition to our CDF group over the past year, has been working on several aspects of the QCD analysis and doing b physics with Collider data. In the sections which follow we will briefly outline the progress being made in each of these areas.

Report on the QCD Analysis

In the 1988–1989 CDF data run, approximately 4.5 pb^{-1} of data were collected at $\sqrt{s} = 1.8 \text{ TeV}$. The jets in this sample range from 30 GeV to 400 GeV and span 7 orders of magnitude in cross section. Compared to the previously published CDF result[1], QCD can be examined over a much larger range of E_t and the point-like scattering of partons can be probed at distance scales smaller than $5 \times 10^{-17} \text{ cm}$. In addition, order α_s^3 QCD calculations are now available[2,3], which feature a variation of cross section with jet cluster cone size.

Data Selection

The CDF detector has been described in detail elsewhere[4]. Jets in the central pseudorapidity region ($0.1 \leq |\eta| \leq 0.7$), with an event vertex within 60 cm of the center of the detector, were used in this measurement. The data were collected using a single-jet trigger, which formed jets from clusters of energy deposited in the calorimeter. Events were required to contain at least one jet having an E_t above a threshold of 20, 40 or 60 GeV where the 20 and 40 GeV triggers were pre-scaled.

For events passing the trigger requirements, jets were reconstructed using a fixed cone algorithm[1]. The cone size (R) is defined by $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where η and ϕ represent the pseudorapidity and azimuthal angle. The trigger efficiency for each cone size (0.4, 0.7 and 1.0) was determined by comparisons of the data from the different triggers in the regions where they overlapped. To eliminate trigger threshold effects, cuts were imposed on jet E_t , to insure $\sim 100\%$ efficiency.

Cosmic rays, which can deposit significant amounts of energy by bremsstrahlung, were removed from this sample in two ways. Cosmic rays, not in coincidence with the beam-beam crossing, were removed using timing information in the hadron calorimeter. The remaining events, containing at least one jet with $E_t \geq 150$ GeV, were scanned. From this scanning, events were then rejected on the basis of: the average electromagnetic fraction of the jets in the event, the average Charge/Total energy for central jets, the missing E_t of the event. The estimated contamination after these cuts is $\leq 1\%$ for jets with $E_t \geq 150$ GeV.

Jet Energy Response

The effects of resolution smearing and energy degradation due to calorimeter non-linearities, uninstrumented regions of detector, etc. can distort the measured E_t distribution. In order to correct the cross section for these effects, a detector simulation was used. It was tuned to reproduce the single pion response observed in the test beam and the jet fragmentation observed in the data.

The response of the detector to jets was extracted from the simulation. This response function was used in the unsmearing procedure to correct the data. Corrections for energy loss outside the cone of the jet were not applied in order to be able to compare the next-to-leading order (α_s^3) QCD calculations. When comparing to leading order (α_s^2) QCD calculations, for which an out-of-cone energy correction would be appropriate, this may have some effect.

The unsmearing procedure combines the effects of a falling E_t spectrum and the response function obtained from the tuned simulation. The procedure starts with a parameterized curve and smears this with the response function. The resulting smeared curve is then binned in the same way the data is binned and the result is compared to the data. Using the χ^2 formed between the smeared

curve and the data, the parameters in the initial curve are tuned until the χ^2 is minimized. The information from the resulting smeared curve and the input curve are then used to unsmear and correct the data.

Systematic Uncertainties

The major sources of systematic uncertainty on the jet energy scale results from uncertainty on calorimeter response, the fragmentation tuning, and energy from the underlying event (within the cone). The dominant uncertainty in the response for jets containing pions with energies less than 25 GeV comes from the uncertainty in the low energy response. For jets containing pions with energies greater than 25 GeV, the dominant uncertainty comes from the modeling of the response in the azimuthal boundary regions between calorimeter cells. The overall tuning of the fragmentation is in good agreement with the data. The uncertainty in the fragmentation tuning is correlated with the tracking efficiency. The uncertainty in the tracking efficiency for tracks in the cone of the jet was found to be $\pm 7\%$. This uncertainty was varied, within these limits, in the simulation to give a corresponding uncertainty on the energy scale. Finally, due to differences in the definition of the underlying event, there is a ~ 540 MeV uncertainty in the underlying event contribution to a cone of 0.7. Adding all these uncertainties in quadrature, the overall systematic uncertainty on the jet energy scale varies from $\sim 4\%$ at 20 GeV to $\sim 3\%$ for energies in excess of 100 GeV. The uncertainty in the RMS width of the response was obtained by comparing the results of balancing the E_t in two-jet events for the data and simulation. From this comparison a conservative 8% uncertainty on the jet resolution was assigned. Finally, an overall 15% systematic uncertainty is assigned to the measurement of the luminosity.

Results

The resulting cross section for cone sizes of 0.4, 0.7 and 1.0 can found in Tables 1a-c. Figure 1 shows the cross section for a cone size of 0.7 compared to a leading order QCD calculation. The QCD calculation was normalized to the data by minimizing the χ^2 between the data and the QCD calculation in a limited range of E_t (in Figure 1 we choose to use the range from 80 to 160 GeV). The reason for normalizing in a limited region of E_t , is due to the fact that QCD and compositeness will agree in shape over some range of E_t and disagree elsewhere. Therefore in order to search for compositeness, the predictions are normalized in a region where they agree and the data is then compared to the predictions in the region where the predictions disagree. A slight excess of events at the high E_t end can be seen in Figure 1. The statistical level of this excess, however, is only 2.5 to 3.5 standard deviations.

Figure 2 shows the same cross section now compared to next-to-leading order QCD, where the QCD normalization is absolute. A comparison is also made to

next-to-leading order QCD in Figure 3, which shows the cross section as a function of cone size for 100 GeV E_t jets. The data, in these figures, appears to be consistent with both leading and next-to-leading order QCD.

Also shown in Figure 3 is the ratio of the cross sections, for different cone sizes, to the cross section for jets with a cone size of 0.7. This shows the data appears to have a steeper variation as a function of cone size, than α^3 calculations would predict. The data and associated statistical errors for Figure 3 can be found in Tables 2a-b. Bin to bin correlations of the systematic uncertainties are under study, therefore the systematic uncertainties have not been listed in the tables or shown in the figures.

Summary

The inclusive jet cross section at $\sqrt{s} = 1.8 \text{ TeV}$ has been measured in the E_t range from 30 to 420 GeV, spanning 7 orders of magnitude. Investigations of the dependence of jet cross section with cone size are in progress. The data appears to be consistent with both leading and next-to-leading order QCD for the structure functions examined, with a small excess of events observed, at high E_t , over leading order QCD predictions. Correlations in the systematic uncertainties are under study. Based on previous studies, we can set a lower limit of 950 GeV (95% C.L.) for the quark compositeness scale parameter Λ^* [5], associated with an effective contact interaction. Work is in progress to extract a final cross section and composite limit.

Report on the Z^0 Analysis

In the naive parton model, Z^0 bosons produced in $\bar{p}p$ collisions have little or no transverse momentum (p_t) with respect to the direction of the colliding beam. QCD, however, predicts associated jet production that gives rise to Z^0 s with large p_t . Furthermore, the differential cross-section as a function of $p_t^{Z^0}$ can be predicted from QCD calculations [6,7]. A measurement of $\frac{d\sigma}{dp_t^{Z^0}}$ thus provides a test of QCD predictions of dynamical properties of hadron interactions. An excess of Z^0 s produced with high $p_t^{Z^0}$ would indicate new physics such as a strong electroweak sector[8].

In this section we describe a measurement of $\frac{d\sigma}{dp_t^{Z^0}}$ using the electron sample from data collected during the 1988-89 run.

QCD Predictions of $\frac{d\sigma}{dp_t^{Z^0}}$

There are two approaches to the prediction of differential cross-section for vector boson production in QCD. One approach is to study exclusive processes

of boson + n jet(s)[9]. The matrix elements for vector boson plus partons are obtained. Structure function convolution and phase-space integration are done numerically to obtain the cross-section. These predictions become invalid when final state partons are not well separated in phase-space due to collinear singularities. Another approach is to study inclusive boson production, with any number of jets[6,7]. Perturbation theory is used where it is valid in the high p_t region. At low p_t , soft gluon resummation is necessary to handle large logarithmic terms. Because the perturbation series is truncated to finite order, all these QCD predictions depend on the choice of a renormalization scale. There is also theoretical uncertainty due to uncertainty in the value of Λ_{QCD} and the parametrization of structure functions.

We compare our measurement with predictions of absolute inclusive Z^0 boson production differential cross-section as a function of $p_t^{Z^0}$.

Perturbative QCD Calculation

A complete second order QCD calculation of inclusive $\frac{d\sigma}{dp_t^{Z^0}}$ is available for $p_t^{Z^0} > 20$ GeV[7]. Including $\mathcal{O}(\alpha_s^2)$ terms reduces the uncertainty in theoretical predictions. The interference of first order and one-loop corrections diagrams contributes to the second order calculation. We have also included two-jet production in these calculations. In this case, phase-space integral is performed analytically so that the divergence associated with the two jets being collinear is canceled by a similar divergence in the one-loop corrections to single-jet production. Diagrams for quark-gluon, and gluon-gluon scattering are obtained by crossing.

Parametrizations of the structure function evolved to $\mathcal{O}(\alpha_s^2)$ are used to obtain the differential cross-section[10]. The factorization scale appearing in the structure function is chosen to be the same as the renormalization scale Q^2 appearing in α_s . Theoretical uncertainty is estimated by varying the renormalization scale from $p_t^{Z^0}$ to M_{Z^0} , and varying the value of Λ_{QCD} from 160 MeV to 360 MeV. When Λ_{QCD} is varied, the particular form of the parametrization is also varied because the value of Λ_{QCD} used in evolving the structure function is fixed for each parametrization. The resulting error is $\pm 15\%$ from the nominal value obtained choosing $Q^2 = M_{Z^0}^2$ and Λ_{QCD} (4 flavors) = 0.260 GeV.

Gluon Resummation Calculation

Because of soft gluon radiation, terms of the form $\log^2(\frac{Q^2}{p_t^2})$, where Q is the vector boson mass, are present in the summation of the perturbation series. In the region $\Lambda_{QCD} \ll p_t^{Z^0} \ll Q$, these terms are large and must be resummed to all orders to obtain a meaningful result. These double logarithmic terms are

typical of a gauge theory with massless vector field quanta. In QED, for example, similar terms arise from soft photon radiation. In the soft region, the production cross-section of n photons factorizes into independent distributions. Ordering in photon emission no longer holds in the soft limit where the matrix element for n photon emission factorizes into a product of independent matrix elements. The resummation of double logarithmic terms to all orders results in an exponential factor $\exp[-\frac{\alpha}{2\pi} \log^2(\frac{Q^2}{p_t^2})]$, the square of the Sudakov form factor. The appearance of such a factor in the photon emission cross-section implies that the probability for no soft photon radiation in high momentum transfer process is exponentially small. In QCD, resummation follows the same procedure as in QED, assuming independent soft gluon radiation, and taking into account color factors and running coupling. The QCD analog of the square of the Sudakov form factor is again obtained[6,11].

Another approach is to exponentiate the whole lowest order differential cross-section[12]. It is equivalent to exponentiating only terms from soft gluon emission at the leading double logarithm approximation, with the advantage of being able to calculate the hadronic energy radiated with the gluons.

In both approaches, perturbative distributions are recovered at large $p_t^{Z^0}$. The integral of $\frac{d\sigma}{dp_t^{Z^0}}$ obtained with gluon resummation reproduces the known results for the total cross-section. Resummation only affects the shape of the distribution but not the normalization[11].

Data Sample

In this measurement, Z^0 s are observed in their decay to e^+e^- pairs. The $\vec{p}_t$ of the Z^0 is reconstructed from the vector sum of the measured transverse momentum, with respect to the beam axis, of the electrons:

$$\vec{p}_t^{Z^0} = \vec{p}_t^{e1} + \vec{p}_t^{e2}$$

The data sample used in this measurement is based on the Electroweak output stream of the Spin Cycle (EWS03) [13]. as in $\sigma \cdot B(Z^0 \rightarrow e^+e^-)$ measurements [14,15,16].

Starting with raw data from the 1988-89 run, pedestal shifts, dead electronic channels, cable noise, as well as fake energy clusters resulting from slow neutrons interacting with detector material ("Texas Towers") are removed. Tracks and physics objects such as electrons are reconstructed using standard algorithms. Events of interest to electroweak physics, such as those with a high E_t electron, are then selected. Only a subset of these events with two or more electromagnetic clusters are kept, resulting in about 20K events. Data banks of these events are

compressed into micro-DSTs (ESU) and are saved on 4 magnetic tapes. No specific hardware trigger is required at this stage.

Luminosity

The integrated luminosity is calculated using collision rate and live time information recorded for each event by the beam-beam counters (BBC) and an estimate of the component of the total $\bar{p}p$ cross-section seen by the BBC [17]. A total luminosity for each run, as well as each tape, is accumulated, using the BBC information from the event with smallest event number and the event with the largest event number. This is not exact since events were written to tape out of order by Level 3. The total for each run is exact except for events that were rejected in Level 3 after the event with highest event number was written, and for cases where one or more of the tapes later found unusable and individual tape luminosity had to be subtracted [18].

The inelastic cross-section used to estimate the BBC cross-section is based on theoretical prediction of the total cross-section and an extrapolation of the ratio of elastic and total cross-section measured at $\sqrt{s} = 0.546$ TeV. The components of the inelastic cross-section measured at $\sqrt{s} = 0.546$ TeV is also extrapolated to $\sqrt{s} = 1.8$ TeV to obtain the hard core component of the inelastic cross-section. A Monte Carlo is used to obtain the BBC acceptance. The BBC cross-section has a 15% uncertainty. The hard core component of the inelastic cross-section measured using the small angle spectrometer has a much smaller uncertainty [19]. The BBC cross-section at $\sqrt{s} = 1.8$ TeV obtained by measuring the BBC coincidence rate and Tevatron instantaneous luminosity at two Tevatron beam energies, $\sqrt{s} = 1.8$ and 0.546 TeV also has a smaller uncertainty [20]. Work to obtain a BBC cross-section with smaller uncertainty is not completed yet. We use the BBC cross-section with 15% uncertainty in this measurement.

Some runs with abnormally high trigger rates, and some runs with a large number of dead PEM channels are removed from our final sample. There's also an approximately 7% loss in events written to tape due to inefficiency in the data acquisition system (Event Builder) for some runs, resulting in a corresponding correction in the luminosity. Multiple interactions per event are also accounted for. The total integrated luminosity is $\mathcal{L} = 4.31 \text{ pb}^{-1}$, with a 15% uncertainty associated with the BBC cross-section estimate.

Electron Identification Cuts and Efficiency

In offline data analysis, an electromagnetic (EM) cluster is formed from a list of towers bordering a seed tower in $\eta - \phi$ space. Isolated EM clusters matching a charge track and having shower shape and hadronic leakage consistent with test-beam electrons are identified as electrons. We impose these electron identification requirements by making cuts on a set of electron quality variables. The efficiencies of these cuts are obtained from a sample of isolated Z^0 electrons by requiring one

of the electrons to pass all cuts and testing cuts on the second electron. Efficiency of the isolation cut is obtained separately, by assuming azimuthal symmetry in Z^0 decay and recalculating isolation as if the electron were in a different ϕ position [11,21]. The cuts and efficiencies used in this measurement are the same as those used in our $\sigma \cdot B(Z^0 \rightarrow e^+e^-)$ and Z^0 decay asymmetry measurements [14,22].

Electrons are also required to have an event z -vertex within 60 cm of the center of the CDF detector, and be well contained by the calorimeter. Geometric acceptance as a function of $p_t^{Z^0}$ is obtained from Monte Carlo simulation and is discussed in later section.

Electron Trigger Efficiency

We require that each event in our final data sample passes the Level 2 12 GeV Central Electron triggers. The threshold response of the Level 2 trigger as a function of cluster E_t is determined by selecting events passing the 7 GeV Central Electron trigger and requiring that a 12 GeV trigger bit be set [23]. The efficiency for the $E_t > 20$ GeV threshold is approximately 100%. Selecting on Missing E_t triggers or Photon triggers gives the same result. Similarly, the Level 3 12 GeV Central Electron trigger efficiency for $E_t > 20$ GeV is determined to be $99.2\% \pm 0.3\%$. The slight inefficiency is attributed to the Level 3 (DF) tracking algorithm. We do not require a Level 3 trigger since it is not available for all the runs.

Although the cuts in the central electron triggers are fully efficient, there is an additional inefficiency due to the trigger hardware itself. For our $\frac{d\sigma}{dp_t^{Z^0}}$ measurement, we need the trigger efficiency for events with electrons passing cuts discussed in the section on electron identification. This is measured using W events that pass $E_t > 20$, $\cancel{E}_t > 20$, $M_t > 50$ GeV, and $\sigma_{\cancel{E}_t} > 2.5$. We also reject events with a jet cluster with $E_t > 10$ GeV within 30° back-to-back in ϕ of the electron candidate to reduce di-jet background. The fraction of events with a CEM electron passing both our identification cuts and the central electron triggers is $(97.2 \pm 0.4)\%$. This is the trigger efficiency for C-P and C-F events. C-C events have two chances of satisfying the central electron triggers. The trigger efficiency for C-C events is $(99.9 \pm 0.1)\%$.

Electron Energy Corrections

We correct the measured energy of each electron. For each CEM calorimeter tower, scintillator light collection efficiency and shower leakage depend on the electron impact point on the face of the tower, leading to a response correction [24]. Tower dependent corrections and absolute energy scale calibration obtained from E/P studies using the W electron sample are also applied [25]. For PEM, tower dependent corrections obtained from test beam scans are applied. Dead layer

corrections, as well as non-linearity corrections are also applied [26]. Quadrant gain variations are obtained from W transverse mass and Z^0 mass distributions. For the FEM, quadrant gain variations and non-linearity corrections are applied. FEM quadrant gain variations are obtained from the azimuthal energy flow of "Texas Towers" [27]. Non-linearity corrections and absolute energy scale calibration are obtained from the Z^0 mass peak [28]. (There are no dead layers in the FEM for the 1988-89 run.)

Direction of the momentum vector is given by the beam-constrained fitted track for central electrons. For plug electrons in regions covered by strips, the strip positions are used. For PEM electrons in regions not covered by strips, the EM cluster centroid is used. For FEM electrons, the EM cluster centroid is used.

EM calorimeter energy resolution measured at the test beam is parametrized in terms of the electron energy. Correction for energy resolution smearing in the p_t spectrum is discussed in a later section.

Z^0 Selection

Our Z^0 sample is selected by requiring:

- a) at least one well identified central electron, and a second electron in the central, plug, or forward regions, and
- b) $E_t^1 > 20$ GeV, $E_t^2 > 10$ GeV, and
- c) $75 \text{ GeV} < M_{e^+e^-} < 105 \text{ GeV}$, and
- d) the event passes 12 GeV Central Electron triggers.

The E_t kinematic cuts differ from those used in [14,22], but are more efficient for high p_t Z^0 s and uniform as a function of $p_t^{Z^0}$. The selection efficiency as a function of $p_t^{Z^0}$ is obtained from Monte Carlo simulation as discussed in a later section.

The mass distribution of the Z^0 sample is shown in Figure 4, where we included events outside Z^0 mass window cut. It shows a clear peak at the Z^0 mass peak. The number of events outside the Z^0 mass peak is consistent with Drell-Yan continuum contribution predicted by Monte Carlo simulation discussed later.

Background Estimate

As shown in Figure 4, non-dielectron contamination in our Z^0 sample is very small. Fake electron background from jet fluctuation estimated using isolation of the electrons to extrapolate a flat background beneath the Z^0 peak is very small [14,15]. We estimate approximately 2 ± 2 events, or 1 % of our sample. We ignore this background. We also ignore background from $Z^0 \rightarrow \tau^+\tau^-$, as in $\sigma \cdot B(Z^0 \rightarrow e^+e^-)$ measurements [14,15,16].

Acceptance and Resolution Corrections

Because the Z^0 's are not produced at rest in the laboratory, the fiducial and kinematic acceptances depend on Z^0 production properties, such as $p_t^{Z^0}$. Also, because the $p_t^{Z^0}$ spectrum is not flat, smearing in $p_t^{Z^0}$ due to finite detector resolution leads to distortion in the observed $p_t^{Z^0}$ spectrum. Therefore, corrections for acceptance and resolution effects are necessary before obtaining a measurement of $\frac{d\sigma}{dp_t^{Z^0}}$ that can be directly compared with theoretical predictions.

Monte Carlo Simulation

Event Generation

$p\bar{p} \rightarrow Z^0 \rightarrow e^+e^-$ events are generated using ISAJET V6.22 [29]. Event generation starts with the hard scattering cross-section. Annihilation and Compton scattering diagrams and the full matrix element for Z^0 decay are included. A cutoff to remove the $\frac{1}{p_t^2}$ singularity is chosen to reproduce approximately the $p_t^{Z^0}$ spectrum calculated by gluon-resummation. QCD radiative corrections are added to get the correct event structure. Final state radiation is approximated by a cascade process, determined by the probability for a parton with finite mass to radiate. For initial state radiation, the shower is evolved backwards starting at hard scattering, and the probability of radiation is derived from the Altarelli-Parisi equations for the structure functions. Quarks and gluons are hadronized using the independent fragmentation ansatz of Field and Feynman. Finally, beam jets are added based on a model tuned to hard scattering data.

Detector Model

For the purpose of obtaining acceptance and resolution corrections, only the four-vectors of the Monte Carlo electrons are used, along with a simple model of the detector with the following features:

- 1) Event z -vertex smearing by a Gaussian, $\sigma_z = 30$ cm.
- 2) Fiducial volume: electron impact position at the calorimeter is determined by extrapolating its momentum vector to the detector.
- 3) Electron energy smearing according to nominal calorimeter energy resolution:

Monte Carlo Simulation vs. Raw Data

Before proceeding further, we check that our Monte Carlo simulation reproduces the raw data. We check that the Z^0 production, as well as decay properties

are well reproduced. The comparison is shown in Figures 5-8. The shape of the p_t spectrum agrees well over the full range of observed data. Agreement in the Z^0 rapidity distribution, Figure 6, shows that the longitudinal production property is also well modeled. The Z^0 decay properties are well reproduced, as shown in distributions of electron E_t , Figure 8, and electron η , Figure 7. The fraction of events with a decay electron in a given detector region is also properly reproduced. The cracks between the two halves of the CEM at 90° , the CEM and PEM at 30° , and the PEM and FEM at 10° polar angles are correctly modeled, as can be seen in the electron η distribution. The agreement in the mass distribution, shown in Figure 4, shows that energy smearing is properly modeled. Our Monte Carlo simulation is thus adequate and can be used to obtain acceptance and resolution corrections.

Resolution Correction

We now use the sample of Monte Carlo events that passed the fiducial cuts to obtain correction for resolution smearing. The basic idea is that the p_t spectrum observed in the raw data is a convolution of the true spectrum with the resolution of the detector. We unfold the smearing in the raw p_t spectrum to obtain the true spectrum. This is accomplished by a deconvolution matrix A , where each element A_{ij} gives the fraction of events in the j^{th} smeared p_t bin that originated in the i^{th} generated p_t bin. The matrix maps the spectrum observed in smeared p_t space, raw data, to the spectrum in true p_t space:

$$U_i = \sum_j A_{ij} \cdot D_j,$$

where D_j is the p_t spectrum given by the raw data and U_i is the p_t spectrum after resolution smearing has been unfolded.

Procedure in Obtaining the Result

Let's first recall how we obtain the raw $p_t^{Z^0}$ spectrum from data:

- 1) Apply fiducial cut to $Z^0 \rightarrow e^+e^-$ candidate.
- 2) Measure electron four-vectors. Finite calorimeter energy resolution means that electron energy is smeared.
- 3) Apply Z^0 selection cuts.

We apply acceptance and resolution corrections as follows:

- 1) Correct for selection efficiency for each smeared p_t bin.
- 2) Unfold resolution smearing using deconvolution matrix.
- 3) Correct for fiducial acceptance for each unsmeared p_t bin.

- 1) Statistical uncertainty in N_j^{raw} ,
- 2) systematic uncertainty in ϵ_j , and
- 3) systematic uncertainty in A_{ij} .

We compare p_t spectrum with and without resolution correction in Figure 9. The effect is approximately 40% for $p_t^{Z^0}$ around 3 GeV.

The corrected number of events in a given bin is:

$$N_i^{corr} = \frac{1}{a_i} \cdot \sum_j A_{ij} \cdot \frac{1}{\epsilon_j} \cdot N_j^{raw},$$

where

The differential cross-section as a function of $p_t^{Z^0}$ is obtained:

$$\frac{d\sigma}{dp_t^{Z^0}} = \frac{\Delta N_{Z^0}^{corr} \cdot f_{DY}}{\Delta p_t^{Z^0} \cdot \mathcal{L} \cdot B(Z^0 \rightarrow e^+e^-) \cdot \epsilon_{zv}},$$

where

We also measure the average $p_t^{Z^0}$:

$$\langle p_t^{Z^0} \rangle = \frac{\int p_t^{Z^0} \cdot \frac{d\sigma}{dp_t^{Z^0}} \cdot dp_t^{Z^0}}{\int \frac{d\sigma}{dp_t^{Z^0}} \cdot dp_t^{Z^0}}.$$

Before comparing our results with theoretical predictions, we discuss uncertainties in the measurement.

Uncertainty in the Result

Sources of uncertainties in our measurement include statistical fluctuations in the number of events observed in a raw p_t bin, uncertainties due to assumptions made in the Monte Carlo, and uncertainties in the luminosity. Because the area under the p_t spectrum must be conserved, any procedure for correcting resolution smearing effects leads to correlation between neighboring bins in the unsmeared p_t spectrum. As can be seen in the equation for N_i^{corr} above, uncertainties in our result from the following sources are correlated:

Uncertainties in our result due to other sources such as the luminosity are not correlated.

Comparison with QCD Predictions

Result of $\langle p_t^{Z^0} \rangle$, along with those reported by UA2, is plotted in Figure 10 and compared with QCD $\mathcal{O}(\alpha_s)$ calculations. The increase in $\langle p_t^{Z^0} \rangle$ is as predicted, although the prediction is above data by about 1σ . The uncertainty on $\langle p_t^{Z^0} \rangle$ is statistical only, and the calculation is only leading order and has large uncertainty.

The result of $\frac{d\sigma}{dp_t^{Z^0}}$ measurement is plotted in Figure 11. The error bars are given by the diagonal elements of the covariance matrix and are correlated, as discussed previously. Also plotted is prediction from QCD $\mathcal{O}(\alpha_s^2)$ calculations mentioned earlier. The calculation uses $Q^2 = M_{Z^0}^2$, Λ_{QCD} (4 flavors) = .260 GeV, and the DFLM parametrization of structure functions [7]. Note that there is a $\pm 15\%$ uncertainty in this prediction due to uncertainties in the choice of Q^2 and the value of Λ_{QCD} . We also compare $\frac{d\sigma}{dp_t^{Z^0}}$ for low $p_t^{Z^0}$ in Figure 12 with gluon-resummation calculations[6]. Again, errors bars plotted are correlated. Predictions are obtained with three choices of Λ_{QCD} , $Q^2 = M_{Z^0}^2$, and using the DFLM structure functions. Predictions by gluon-resummation calculations, when extended to the high $p_t^{Z^0}$ region, are higher than the $\mathcal{O}(\alpha_s^2)$ predictions. The gluon-resummation calculation included only leading order diagrams and used 1-loop evolution of α_s . These plots show good agreement between our results and QCD predictions. To make the comparison quantitative, and include the correlations in the errors, we calculate a χ^2 between data and theoretical predictions:

$$\chi^2 = \sum_{i,j} (U_i - Q_i) \cdot H_{ij}^{-1} \cdot (U_j - Q_j),$$

where U_i is data and Q_i is QCD prediction for i^{th} bin. H_{ij}^{-1} is the inverse of the covariance matrix. The number of degree of freedom in the χ^2 calculation, n_D , is the number of data points used. Results of the χ^2/n_D are summarized in Table 3.

As can be seen in Table 3, best agreement is obtained with $\Lambda_{QCD} = .260$ GeV for $0 < p_t^{Z^0} < 25$ GeV. However, this must not be taken as a measurement of Λ_{QCD} because of the large theoretical uncertainty involved in the $\mathcal{O}(\alpha_s)$ gluon-resummation calculation. For $p_t^{Z^0} > 20$ GeV, predictions with various assumptions all agree well with our measurement. Improved theoretical calculations in the low

$p_t^{Z^0}$ region, along with more statistics are needed before we can make a more quantitative test of QCD.

Conclusions and Outlook

The QCD predictions of the absolute inclusive differential cross-section for Z^0 production, obtained at high $p_t^{Z^0}$ with perturbation calculations and at low $p_t^{Z^0}$ with gluon resummation calculations, agree well with our measurement. The change in average $p_t^{Z^0}$ as a function of $\sqrt{s}$ predicted by $\mathcal{O}(\alpha_s)$ calculations also agrees well our measurement.

The good agreement at high $p_t^{Z^0}$ implies that we can put limits on exotic models [2]. These models predict the existence of a triplet of heavy vector bosons that couple strongly to the electroweak bosons. The decay of these heavy vector bosons gives rise to an excess of high p_t W 's and Z^0 's over the QCD prediction. Putting limits on exotic models is the subject of a forthcoming CDF note.

In the future, we hope to enlarge our data sample by including the muon channel. We also hope to study associated jet production properties.

B. CDF 1990 Test Beam Run

The 1990 test beam run served two purposes for the CDF gas calorimeters. First, to provide an energy calibration for the data taken in 1988/1989 and second, to prepare for the upgrades to the Tevatron in the 1991 collider run.

The higher luminosity and shorter bunch separation expected for the next run require that modifications be made to the gas calorimeter operation. Without these changes the increased particle flux could cause ageing and a continuous discharge within the calorimeters (*glow mode*). In order to overcome the problem of glow mode and ageing it is necessary to decrease the gas gain within the chambers; this is achieved by reducing the HV operating point. However smaller signals from the calorimeters worsen the intrinsic energy resolution and require the use of higher gain amplifiers. Both the new voltage and the new electronics were tested in the 1990 test beam.

The goals of this test beam run may be summarized as follows:

- to recalibrate the calorimeters
- determine the operating voltage, amplifier gain and input impedance of the new amplifiers
- study the onset of glow mode
- investigate and reduce electronic noise
- map the response of the calorimeters to low momentum pions
- and determine the response of the calorimeters to pions at many different incident points.

The Texas A&M group was involved in preparing the Forward Hadron Calorimeter (FHA) for this test beam run, collecting and analysing the calibration data. The final corrections to the data are still being made, but whilst our conclusions are preliminary we do not expect them to change substantially.

Recalibration of FHA

Our objective was to recalibrate the chambers for comparison to previous data and test beam runs. This was done with the original electronics (CARROT) and at an operating point of 2.1kV. The test beam area (MT6) delivered beams of pions, muons and electrons with well measured momenta. Data were collected with pion momenta of 25, 50, 100, 150 and 227 GeV/c with FHA high voltage set at 50 volt intervals between 1.65 and 2.10kV. This enabled an accurate study of the voltage/resolution and gain characteristics to be made. A summary of this information is given in Table 4.

Glow Mode and Ageing

In addition the chambers were exposed to intense beams of pions in order to study glow mode. For the FHA operating at 2.1kV there was no evidence of the onset of glow mode using beams of 5×10^5 charged pions per spill. This corresponded to a current density of 30 nAcm^{-2} . In Table 5 we list the observed current density (at 2.1kV) for the 1988/1989 run together with the expected current densities in the FHA chambers for the 1991 and 1993 collider runs. We do not expect the FHA chambers will "glow" in either of these runs.

The decision to lower the operating voltage for 1991 to 2.0kV was taken on the basis of previous studies on the ageing of the FHA chambers and the twin requirements of maintaining good resolution and being able to identify a signal from minimum ionizing particles. Ageing is dependent on the net charge deposited on each wire. The total charge deposited is proportional to the chamber gain times the amount of ionization deposited; the ionization is in turn proportional to the luminosity of the Tevatron. If the luminosity is to be increased then to avoid ageing it is necessary to decrease the chamber gain.

New Electronics

Having chosen the HV operating point, data were taken with new electronics from Fermilab (General Purpose Amplifier) — the GPA cards. The response of the FHA detector to pions was studied. The resolution was compatible with that observed with the CARROT cards (see Table 4). The feedback capacitance, C_f of the amplifier was chosen to maintain high gain and stability; the input impedance of circuit, Z_i was adjusted so to minimize amplifier "ringing". The parameters of the GPA card for the next run were selected to be $C_f = 56\text{pF}$ and $Z_i = 30\Omega$.

Short Gate Study

Part of the upgrade to the Tevatron involves shortening the interbunch spacing. This requires the reducing of the ADC gate widths from 1650ns to 800ns. Table 4 summarizes the results of shortening the gate widths on the resolution. A loss in the measured integrated charge is observed consistent with the pulse profile from the chambers. The minimum ionizing signal from muons passing through the chambers is detectable with a 800ns gate.

Improvements to Chamber Performance

Prior to the test beam data taking the 400Hz power supplies for the FHA amplifier electronics were physically and electrically isolated from the the FHA chambers. This was achieved by removing the supplies from their previous mount on the absorber steel and placing them in a separate rack. The result was a factor 3 decrease in the observed pedestal widths. This indicates the similar modifications should be performed in B0.

C. Plans for Further Test Beam Running in 1990-91

Following the recent data taking run, the collaboration once more began to organize its efforts to set up once again in the test beam in M-West in the meson area. After the current run there were once again a long list of detector issues to be addressed in order to understand several anomalies in the performance of CDF during the past run and to prepare the detector for the next Collider run in 1991. Due to the importance of many of these questions to the collaboration, this test beam activity is a very high priority activity for CDF at this time. Hence our team is making a significant contribution to the preparations and staging of this test beam run.

Of the several important detector issues requiring immediate attention, the reestablishment of the gas calorimeter energy calibration is perhaps one of the highest priority activities for the test beam. Despite the efforts made in the test

beam in 1987 to understand the calibration of the gas calorimeters in detail, a number of questions arose during the recent run of the detector which indicate further testing is necessary to pin down the performance of these devices. Next on the list of items to investigate will be a study of the performance of the improved RABBIT electronics presently being fabricated for use on the gas calorimeter systems for the next run. To deploy these improved front-end cards on the detector requires that we carry out a complete re-calibration of the gas based calorimeters using this electronics. In addition to the plans for studying the calibration of the FHA using a variety of different electronics circuits, we are interested in studying ways of improving the overall performance of the FHA for the 1991 running and perhaps for runs beyond that. To that end we will also be investigating questions of noise pick up on the FHA chambers as well as trying out an interleaved readout scheme designed to improve our rejection capability for Texas Towers.

It appears that once again our team will be called on to play a major role in the test beam activities being carried out in the coming year. Dr. Bowcock, who has recently joined our CDF program, will be heading up this effort with the assistance of a post-doc and a graduate student.

D. Future Plans and CDF Upgrade Participation

CDF Physics Analysis

A central goal of the coming physics run of CDF is the search for the top quark. We now know that the top lies above the W mass, so that it will decay via $t \rightarrow W + b$. The key challenge then is to identify events of this kind among the total ensemble of W events. Profs. Bowcock and McIntyre will participate in this effort by applying the techniques used for partial reconstruction of B's. Partial reconstruction can yield a much larger B sample than full reconstruction, while still achieving good background rejection.

Figures 13 and 14 show two examples of some of the tools available for full reconstruction of B's. The $K\pi$ mass spectrum for oppositely charged track combinations near high- $p_{\perp}$ electron candidates shows a clear resonance at the D^0 mass. The $eK\pi$ mass for $K\pi$ pairs within 30 MeV of the $K\pi$ peak show a very clean B reconstruction.

The efficiency of such full reconstruction is however miniscule. The branching ratios for B meson decays and D^0 decays which accommodate full reconstruction are:

$$\begin{array}{ll} B^0 \rightarrow D\pi^+\pi^- & 0.04 \\ D^0 \rightarrow K\pi & 0.04 \end{array}$$

These processes must occur in sequence; the net probability is 1.6×10^{-3} . By contrast, the branching ratios for partial reconstructions are

$B \rightarrow D^* \rho$	0.08
$B \rightarrow D^* e \nu$	0.14
$B \rightarrow D^* + n \pi$	0.05

These processes permit an order of magnitude increase in reconstruction acceptance. In e^+e^- collisions, a partial reconstruction algorithm isolated this improved sample with modest background. It remains to be tested whether a similar approach can succeed in analyzing $\bar{p}p$ collisions in CDF. The additional constraint of reconstructing a decay vertex for charm and τ events using SVX will help considerably if we can produce clean vertices.

Professors Bowcock and McIntyre will be in residence at Fermilab during the period January–August 1991 to provide leadership in test beam studies of gas calorimetry and to conduct the above physics analysis program. Three postdoctoral associates, Drs. Kamon, Barasch, and Phillips, will also carry a substantial on-site role in both tasks.

Gas Calorimetry

The Texas A&M group continues to shoulder a major share of the tasks to maintain, calibrate, and improve the gas calorimetry system which is used in CDF for $\theta > 30^\circ$. The calibration of the calorimetry is being carefully refined in test beam studies at Fermilab during the past summer and again in early 1990. These calibrations are crucial to overall CDF performance in its coming physics run.

TAMU is modifying the cabling and electronics to improve the noise immunity of the forward hadron calorimeters. "Charge suckers" are being installed to test a method to reduce the settling time of the readout electronics. This latter improvement will be crucial to gas calorimetry performance with 400 nsec and 200 nsec bunch spacings as the Tevatron upgrade proceeds.

CDF proposes to replace the gas calorimetry systems in the plug and forward regions with a new plug assembly containing scintillating tile calorimetry. This replacement would make it possible to move the forward muon systems in to provide complete muon coverage over the entire rapidity range $y < 4$, increasing the acceptance for muons from top decays by 40 %.

CDF plans to maintain the gas calorimetry system in a state of readiness for use in the 1993 run in the event that the proposed upgrade cannot be funded or completed in time for the run. The TAMU group will provide for the maintenance of the gas calorimetry for this purpose.

CDF Tracking Upgrades

The tracking system in CDF will require substantial upgrades for each of the coming physics runs (1991, 1993, 1995). For the '91 run, the addition of the

SVX microvertex chamber should enable us to distinguish the decay vertex for charmed particles and τ leptons. For the '93 run, the anticipated reduction of bunch spacing to ≤ 100 nsec and increased radiation damage will likely require a significant upgrade or replacement of SVX. For the '95 run, the further reduction of bunch spacing and multi-event buffering will likely require replacement of most of the entire tracking system (SVX, VTX, CTC).

In addition, the proposed upgrade of the plug calorimetry for the '93 run currently does not include any provision for tracking and momentum analysis in the forward region. This will likely compromise our ability to clean by identify electrons and thereby make effective use of the improved calorimetry.

All of the above tracking applications require chamber performance beyond what is possible with existing technology. Section III of this proposal describes a completely new chamber technology which is being pioneered at Texas A&M - the microstrip chamber. We are developing this technology both for the above application in CDF upgrade and for the tracking system in SDC. This development could be a key factor in CDF performance for the '95 upgrade with the new injector.

REFERENCES

- [1] CDF Collaboration, F. Abe, *et al.*, Phys. Rev. Lett., **62** (1989) 613.
- [2] S.D. Ellis, Z. Kunszt and D.E. Soper, ETH-TH/90-3 (1990).
- [3] F. Aversa, *et al.*, LNF-90 (1990).
- [4] CDF Collaboration, Nucl. Instr. and Meth. **A267**, 249, 257, 272, 280, 301, 315, 330; **A268** 24, 33, 41, 46, 50, 75, 92 (1988).
- [5] CDF Collaboration, Presented by S. Bertolucci. Proceedings 8th Topical Workshop on $p\bar{p}$ Collider Physics, Castiglione, Italy, September 1, 1989.
- [6] G. Altarelli, R.K. Ellis, M. Greco, G. Martinelli: Nucl.Phys. **B246**, 12 (1984); G. Altarelli, R.K. Ellis, G. Martinelli: Z. Phys. **C27**, 617 (1985).
- [7] P.B. Arnold, M.H.Y. Peno: Nucl.Phys. **B319**, 37 (1989), Erratum, *ibid.* **B330**, 284 (1990); P.B. Arnold, R.K. Ellis, M.H. Reno: Phys. Rev. **D40**, 613 (1989).
- [8] R. Casalbuoni, P. Chiappetta, D. Dominici, F. Feruglio, R. Gatto: Phys. Lett. **B224**, 237 (1989).
- [9] A.C. Bawa, W.J. Stirling: Phys. Lett. **B203**, 172 (1988); F.A. Berends, W.T. Giele, H. Kuijf, R. Kleiss, and W.J. Stirling: Phys. Lett. **B224**, 237 (1989).
- [10] M. Diemoz, F. Ferroni, E. Longo, and G. Martinelli: Z. Phys. **C39**, 21 (1988).
- [11] G. Altarelli: Phys. Rep. **81**, 1 (1982); G. Parisi, R. Petronzio: Nucl. Phys. **B154**, 427 (1979).
- [12] R.S. Fletcher, F. Halzen, A. Grau, G. Pancheri, and Y.N. Srivastava: Phys. Lett. **237**, 113 (1990).
- [13] C. Campagnari, M. Campbell, H. Frisch, P. Tipton: CDF Note 794; C. Campagnari, P. Derwent, H. Frisch, E. Schmidt, J. Siegrist, P. Tipton, B. Winer: CDF Note 795;
- [14] E. Kearns, M. Franklin, P. Hurst, J. Ng: CDF Note 1125.
- [15] M. Gold, A. Yagil, A. Clark: CDF Note 1094.
- [16] C. Campagnari, P. Derwent, H. Frisch, C. Grosso-Pilcher, M. Miller: CDF Note 1107.
- [17] T. Liss: CDF Note 552.
- [18] A. Clark, S. Hahn, *et al.*: CDF Note in preparation.
- [19] P. Giromini: CDF Collaboration Meeting, Feb. 10, 1990.
- [20] S. White: CDF Collaboration Meeting, Feb. 10, 1990; S. White: CDF Note 1031; R. Johnson: CDF Note 876; H.B. Jensen: CDF Note 770.
- [21] E. Kearns, J. Ng, M. Franklin, P. Hurst: CDF Note in preparation.
- [22] P. Hurst, M. Franklin, E. Kearns, J. Ng: CDF Note 1126.
- [23] J. Proudfoot: CDF Note 1008, CDF Note 860.
- [24] T. Kamon: CDF Note 905; T.Kamon, D.Connor, S.Hahn: CDF Note 989.

- [25] S. Errede, W. Trischuk: CDF Note 1081; W. Trischuk, A.B. Wicklund, *et. al.*: CDF Note 883.
- [26] S. Kim, S. Ogawa: CDF Note 1021; S. Kim, *et. al.*: CDF Note 906.
- [27] J. Ng: CDF Note bf 968.
- [28] E. Kearns: CDF Note 1077.
- [29] F. Paige and S.D. Protopopescu: BNL38034 (1986).

Table 1a. (CDF PRELIMINARY)		
Inclusive Jet Cross Section at $\sqrt{s} = 1.8 \text{ TeV}$ for Cone Size = 0.4		
$E_t(\text{GeV})$	Cross Section (nb/GeV)	Statistical Error
36.2	$0.817 \times 10^{+2}$	$\pm 0.011 \times 10^{+2}$
41.9	$0.395 \times 10^{+2}$	$\pm 0.007 \times 10^{+2}$
47.5	$0.196 \times 10^{+2}$	$\pm 0.005 \times 10^{+2}$
53.3	$0.110 \times 10^{+2}$	$\pm 0.004 \times 10^{+2}$
59.0	$0.654 \times 10^{+1}$	$\pm 0.009 \times 10^{+1}$
64.5	$0.401 \times 10^{+1}$	$\pm 0.007 \times 10^{+1}$
69.9	$0.248 \times 10^{+1}$	$\pm 0.006 \times 10^{+1}$
75.3	$0.168 \times 10^{+1}$	$\pm 0.005 \times 10^{+1}$
80.6	$0.115 \times 10^{+1}$	$\pm 0.004 \times 10^{+1}$
85.8	$0.762 \times 10^{+0}$	$\pm 0.031 \times 10^{+0}$
91.1	$0.537 \times 10^{+0}$	$\pm 0.026 \times 10^{+0}$
96.3	$0.410 \times 10^{+0}$	$\pm 0.022 \times 10^{+0}$
101.6	$0.276 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
106.9	$0.204 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
112.1	$0.157 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
117.3	$0.110 \times 10^{+0}$	$\pm 0.002 \times 10^{+0}$
122.7	0.861×10^{-1}	$\pm 0.019 \times 10^{-1}$
127.9	0.650×10^{-1}	$\pm 0.017 \times 10^{-1}$
133.1	0.494×10^{-1}	$\pm 0.015 \times 10^{-1}$
138.3	0.395×10^{-1}	$\pm 0.013 \times 10^{-1}$
143.5	0.327×10^{-1}	$\pm 0.012 \times 10^{-1}$
148.8	0.268×10^{-1}	$\pm 0.011 \times 10^{-1}$
153.9	0.188×10^{-1}	$\pm 0.009 \times 10^{-1}$
159.1	0.152×10^{-1}	$\pm 0.008 \times 10^{-1}$
166.9	0.121×10^{-1}	$\pm 0.005 \times 10^{-1}$
177.0	0.755×10^{-2}	$\pm 0.041 \times 10^{-2}$
187.5	0.456×10^{-2}	$\pm 0.032 \times 10^{-2}$
198.2	0.260×10^{-2}	$\pm 0.024 \times 10^{-2}$
210.4	0.178×10^{-2}	$\pm 0.016 \times 10^{-2}$
227.2	0.107×10^{-2}	$\pm 0.013 \times 10^{-2}$
241.4	0.535×10^{-3}	$\pm 0.091 \times 10^{-3}$
259.3	0.429×10^{-3}	$\pm 0.081 \times 10^{-3}$
277.5	0.301×10^{-3}	$\pm 0.059 \times 10^{-3}$
299.2	0.926×10^{-4}	$+0.458 \times 10^{-4} - 0.321 \times 10^{-4}$
317.6	0.693×10^{-4}	$+0.416 \times 10^{-4} - 0.276 \times 10^{-4}$
338.9	0.346×10^{-4}	$+0.338 \times 10^{-4} - 0.188 \times 10^{-4}$
371.1	0.232×10^{-4}	$+0.227 \times 10^{-4} - 0.127 \times 10^{-4}$
409.2	0.104×10^{-4}	$+0.138 \times 10^{-4} - 0.067 \times 10^{-4}$

Table 1b. (CDF PRELIMINARY)		
Inclusive Jet Cross Section at $\sqrt{s} = 1.8 \text{ TeV}$ for Cone Size = 0.7		
$E_t(\text{GeV})$	Cross Section (nb/GeV)	Statistical Error
41.6	$0.728 \times 10^{+2}$	$\pm 0.010 \times 10^{+2}$
47.6	$0.349 \times 10^{+2}$	$\pm 0.007 \times 10^{+2}$
53.5	$0.189 \times 10^{+2}$	$\pm 0.005 \times 10^{+2}$
59.9	$0.986 \times 10^{+1}$	$\pm 0.035 \times 10^{+1}$
66.2	$0.589 \times 10^{+1}$	$\pm 0.027 \times 10^{+1}$
72.3	$0.354 \times 10^{+1}$	$\pm 0.006 \times 10^{+1}$
78.2	$0.234 \times 10^{+1}$	$\pm 0.005 \times 10^{+1}$
83.8	$0.168 \times 10^{+1}$	$\pm 0.004 \times 10^{+1}$
89.3	$0.110 \times 10^{+1}$	$\pm 0.004 \times 10^{+1}$
94.8	$0.769 \times 10^{+0}$	$\pm 0.030 \times 10^{+0}$
100.2	$0.540 \times 10^{+0}$	$\pm 0.025 \times 10^{+0}$
105.6	$0.402 \times 10^{+0}$	$\pm 0.022 \times 10^{+0}$
111.0	$0.302 \times 10^{+0}$	$\pm 0.019 \times 10^{+0}$
116.4	$0.206 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
121.8	$0.156 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
127.1	$0.115 \times 10^{+0}$	$\pm 0.002 \times 10^{+0}$
132.5	0.870×10^{-1}	$\pm 0.019 \times 10^{-1}$
137.8	0.669×10^{-1}	$\pm 0.017 \times 10^{-1}$
143.1	0.519×10^{-1}	$\pm 0.015 \times 10^{-1}$
148.5	0.414×10^{-1}	$\pm 0.013 \times 10^{-1}$
153.7	0.323×10^{-1}	$\pm 0.012 \times 10^{-1}$
158.9	0.266×10^{-1}	$\pm 0.011 \times 10^{-1}$
164.2	0.206×10^{-1}	$\pm 0.009 \times 10^{-1}$
171.9	0.155×10^{-1}	$\pm 0.006 \times 10^{-1}$
182.2	0.104×10^{-1}	$\pm 0.005 \times 10^{-1}$
193.0	0.617×10^{-2}	$\pm 0.037 \times 10^{-2}$
203.5	0.346×10^{-2}	$\pm 0.028 \times 10^{-2}$
215.7	0.241×10^{-2}	$\pm 0.019 \times 10^{-2}$
231.9	0.148×10^{-2}	$\pm 0.015 \times 10^{-2}$
246.9	0.849×10^{-3}	$\pm 0.113 \times 10^{-3}$
264.9	0.442×10^{-3}	$\pm 0.082 \times 10^{-3}$
282.0	0.358×10^{-3}	$\pm 0.064 \times 10^{-3}$
302.2	0.186×10^{-3}	$+0.059 \times 10^{-3} - 0.046 \times 10^{-3}$
322.9	0.816×10^{-4}	$+0.440 \times 10^{-4} - 0.302 \times 10^{-4}$
343.9	0.584×10^{-4}	$+0.397 \times 10^{-4} - 0.253 \times 10^{-4}$
380.7	0.237×10^{-4}	$+0.231 \times 10^{-4} - 0.129 \times 10^{-4}$
418.5	0.975×10^{-5}	$+1.292 \times 10^{-5} - 0.631 \times 10^{-5}$

Table 1c. (CDF PRELIMINARY)		
Inclusive Jet Cross Section at $\sqrt{s} = 1.8 \text{ TeV}$ for Cone Size = 1.0		
$E_t(\text{GeV})$	Cross Section (nb/GeV)	Statistical Error
45.8	$0.524 \times 10^{+2}$	$\pm 0.011 \times 10^{+2}$
53.8	$0.235 \times 10^{+2}$	$\pm 0.006 \times 10^{+2}$
61.3	$0.123 \times 10^{+2}$	$\pm 0.004 \times 10^{+2}$
68.1	$0.667 \times 10^{+1}$	$\pm 0.030 \times 10^{+1}$
74.6	$0.431 \times 10^{+1}$	$\pm 0.024 \times 10^{+1}$
80.4	$0.239 \times 10^{+1}$	$\pm 0.005 \times 10^{+1}$
86.5	$0.171 \times 10^{+1}$	$\pm 0.005 \times 10^{+1}$
92.8	$0.116 \times 10^{+1}$	$\pm 0.004 \times 10^{+1}$
98.7	$0.820 \times 10^{+0}$	$\pm 0.031 \times 10^{+0}$
104.3	$0.559 \times 10^{+0}$	$\pm 0.026 \times 10^{+0}$
109.9	$0.416 \times 10^{+0}$	$\pm 0.022 \times 10^{+0}$
115.5	$0.301 \times 10^{+0}$	$\pm 0.019 \times 10^{+0}$
120.9	$0.220 \times 10^{+0}$	$\pm 0.016 \times 10^{+0}$
126.2	$0.163 \times 10^{+0}$	$\pm 0.003 \times 10^{+0}$
131.6	$0.121 \times 10^{+0}$	$\pm 0.002 \times 10^{+0}$
137.0	0.935×10^{-1}	$\pm 0.020 \times 10^{-1}$
142.4	0.703×10^{-1}	$\pm 0.017 \times 10^{-1}$
147.8	0.542×10^{-1}	$\pm 0.015 \times 10^{-1}$
153.1	0.467×10^{-1}	$\pm 0.014 \times 10^{-1}$
158.5	0.351×10^{-1}	$\pm 0.012 \times 10^{-1}$
163.9	0.281×10^{-1}	$\pm 0.011 \times 10^{-1}$
171.7	0.205×10^{-1}	$\pm 0.007 \times 10^{-1}$
182.2	0.140×10^{-1}	$\pm 0.006 \times 10^{-1}$
193.1	0.835×10^{-2}	$\pm 0.043 \times 10^{-2}$
203.4	0.487×10^{-2}	$\pm 0.033 \times 10^{-2}$
216.4	0.318×10^{-2}	$\pm 0.022 \times 10^{-2}$
233.1	0.189×10^{-2}	$\pm 0.017 \times 10^{-2}$
247.5	0.108×10^{-2}	$\pm 0.015 \times 10^{-2}$
264.6	0.558×10^{-3}	$\pm 0.092 \times 10^{-3}$
282.0	0.467×10^{-3}	$\pm 0.073 \times 10^{-3}$
305.4	0.216×10^{-3}	$+0.062 \times 10^{-3} - 0.049 \times 10^{-3}$
326.5	0.102×10^{-3}	$+0.047 \times 10^{-3} - 0.033 \times 10^{-3}$
348.6	0.450×10^{-4}	$+0.358 \times 10^{-4} - 0.216 \times 10^{-4}$
377.4	0.451×10^{-4}	$+0.271 \times 10^{-4} - 0.179 \times 10^{-4}$
427.8	0.181×10^{-4}	$+0.144 \times 10^{-4} - 0.087 \times 10^{-4}$

Table 2a. (CDF PRELIMINARY) Cross Section vs Cone Size at 100 GeV		
Cone Size	Cross Section (nb/GeV)	Statistical Error
1.0	0.759	± 0.025
0.7	0.548	± 0.024
0.4	0.318	± 0.007

Table 2b. (CDF PRELIMINARY) Cross Section Ratio vs Cone Size at 100 GeV		
Cone Size	Cross Section (nb/GeV)	Statistical Error
1.0	1.386	± 0.076
0.7	1.000	± 0.063
0.4	0.580	± 0.029

Theoretical Predictions	χ^2/n_D		
	a	b	c
$\mathcal{O}(\alpha_s), 0 < p_t^{Z^0} < 25 \text{ GeV}, Q^2 = M_{Z^0}^2$ [6]			
$\Lambda_{QCD} = .160 \text{ GeV}, \text{DFLM1}$	1.86	2.19	3.00
$\Lambda_{QCD} = .260 \text{ GeV}, \text{DFLM2}$	0.85	1.10	1.40
$\Lambda_{QCD} = .360 \text{ GeV}, \text{DFLM3}$	1.49	1.75	2.12
$\mathcal{O}(\alpha_s^2), p_t^{Z^0} > 20 \text{ GeV}, Q^2 = M_{Z^0}^2$ [7]			
$\Lambda_{QCD} = .160 \text{ GeV}, \text{DFLM1}$	0.21	0.24	0.24
$\Lambda_{QCD} = .260 \text{ GeV}, \text{DFLM2}$	0.22	0.24	0.24
$\Lambda_{QCD} = .360 \text{ GeV}, \text{DFLM3}$	0.24	0.26	0.26
$\mathcal{O}(\alpha_s^2), p_t^{Z^0} > 20 \text{ GeV}, Q^2 = p_t^2$ [7]			
$\Lambda_{QCD} = .160 \text{ GeV}, \text{DFLM1}$	0.27	0.30	0.30
$\Lambda_{QCD} = .260 \text{ GeV}, \text{DFLM2}$	0.37	0.44	0.44
$\Lambda_{QCD} = .360 \text{ GeV}, \text{DFLM3}$	0.45	0.56	0.56

Table 3: Summary of χ^2 s between data and theory for $\frac{d\sigma}{dp_t^{Z^0}}$. a) Systematic and statistical uncertainties. b) Same as a), but not including uncertainty in luminosity. c) Statistical uncertainty only.

CARROT cards					
HV(volts)	gate width (ns)	cathode resolution		anode resolution	
		$\sigma/E = A/\sqrt{(E)} + B$		$\sigma/E = A/\sqrt{(E)} + B$	
		A(%)	B(%)	A(%)	B(%)
2100	1650	97	2	89	3
2000		99	3	98	3
1900		147	1	91	4
GPA cards, $C_f = 82\text{pF}$					
2000	1650	105	1	98	2
	800	131	0	107	2

Table 4: Resolution in the FHA calorimeter from 1990 test beam data.

Run	L	current/layer nA/cm ²	voltage kV
1988/1989	10 ³⁰	0.03	2.1
1991	10 ^{31*}	2.0	2.1
1991	10 ^{31*}	1.0	2.0
1993	10 ^{32*}	10.0	2.0
* estimated			

Table 5: Current/layer in the FHA calorimeter.

Inclusive Jet Cross Section (Cone Size 0.7)

Figure 1: The cross section is compared to a leading order QCD calculation, which uses EHLQ II structure functions and has been normalized to the data in the E_t range from 80 to 160 GeV.

Inclusive Jet Cross Section (Cone Size 0.7)

Figure 2: The cross section is compared to next-to-leading order QCD, which uses MRSB structure functions. The normalization is absolute.

Figure 3: The top plot is the jet cross section for jets with E_t of 100 GeV as a function of cone size compared to next-to-leading order QCD. The bottom plot is the ratio of the cross sections to the cross section for 100 GeV jets with a cone size of 0.7, again compared to next-to-leading order QCD.

Figure 4: Mass distribution of e^+e^- pairs, including low mass pairs. There are 214 events with $75 \text{ GeV} < M_{e^+e^-} < 105 \text{ GeV}$. The curve is Monte Carlo simulation, including Drell-Yan continuum contribution.

Figure 5: Normalized $p_t^{Z^0}$ distribution. Histogram is Monte Carlo.

Figure 6: Z^0 rapidity distribution. Histogram is Monte Carlo normalized to data.

Figure 7: Electron pseudo-rapidity distribution. Histogram is Monte Carlo normalized to data.

Figure 8: Electron distribution. Histogram is Monte Carlo normalized to data. Arrows indicate cuts on the two electrons.

Figure 9: p_t spectrum with and without resolution smearing correction.

Figure 11: Differential cross-section for Z^0 production. Errors bars are statistical and systematic and are correlated. Curve is $\mathcal{O}(\alpha_s^2)$ QCD prediction. The theoretical uncertainty is $\pm 15\%$.

Figure 10: Average values of $p_t^{Z^0}$. Statistical uncertainties only. Curve is $\mathcal{O}(\alpha_s)$ QCD prediction.

Figure 12: Differential cross-section for Z^0 production for low $p_t^{Z^0}$ region. Errors are statistical and systematic and are correlated. Curves are gluon-resummation calculation predictions with three choices of Λ_{QCD} .

Figure 13: Invariant Mass Spectrum K^+K^- combinations for hadron tracks near a high- $P_T e^- (e^+)$.

Figure 14: Invariant mass spectrum for $e^-K^-\pi^+(e^+K^+\pi^-)$ for combinations in the D^0 peak ($\pm 30 \text{ MeV}/c^2$) shown in Fig 13. Sidebands ($\pm 90 \text{ MeV}/c^2$) in the $K\pi$ spectrum have been subtracted to reveal the $e^-D^0(e^+\bar{D}^0)$ contribution. The spectrum peaks below the B-meson mass due to the missing ν and the additional pions in the B semileptonic decays.

II. The MACRO Experiment

The MACRO experiment being staged at the Gran Sasso Laboratory in L'Aquila, Italy is the next generation underground large surface area experiment designed to study magnetic monopoles, astrophysical neutrino sources and other cosmic ray phenomena. This detector will provide us with a view of particle physics phenomena well above the window of energy soon to be opened by projects like the SSC, and as such represents a very important aspect of future research in high energy physics. The details of the detector layout are shown in a schematic view of a single module presented in Figure 1, and the details of the physics program and the capabilities of this detector have been presented in previous renewal requests to the DOE as well as in the original scientific proposal^[1].

Over the course of the past year, this experiment has continued to take shape at the Gran Sasso Laboratory. Following the completion of the civil construction of the first module in early 1988, the collaboration has focussed its attentions on bringing this first detector module on-line to begin data taking. The plan was to run the first supermodule for approximately 3 months to get a glimpse of the physics and backgrounds that we will be dealing with when the entire detector is brought on line in the next year or so. This data taking run began in late February of 1989 and continued on into May of the same year. During this run we were able to collect approximately 10^5 single muon events for detector calibration, to record several hundred multi-muon events that were in coincidence with the air shower array on top of the mountain (EAS-TOP), and to study the backgrounds associated with searching for monopoles. Since this initial data taking run, the first module has been upgraded and brought back *on-line* to take data continuously while the remainder of the detector is commissioned. This second data taking run has been proceeding for nearly a year now, as the rest of the modules are outfitted.

In the sections that follow, we will discuss the progress made on this project over the past twelve months, as well as present our plans for the coming funding cycle.

A. Work on WFD for the Final Detector

Our group has been involved in the MACRO collaboration R&D effort to provide the necessary wave form digitizing system (WFD) for the MACRO detector's scintillator system over the last several years. Based on previous experience in this area of instrumentation on our previous cosmic ray search for GUT monopoles^[2], our team was uniquely qualified to carry out this work for the MACRO program.

The area of fast wave form digitization has been a very active area of device R&D over the past several years, and as a result, our work on this project to identify the "best" performing system for the needs of MACRO has continued over the past twelve months. The properties of the WFD electronics required for MACRO's needs are as follows:

- 1) 100 MHz sampling. This sampling frequency is the minimum needed to digitize single photoelectron signals from the scintillation counters. A higher sampling frequency could be used if an inexpensive FADC were available.
- 2) A minimum of 8 bit linear (10 bit nonlinear) dynamic range. This dynamic range is necessary to view the wide range of monopole velocities we hope to be sensitive to with MACRO.
- 3) Effective time sampling window of at least 500 μ sec. This corresponds to the maximum time-of-flight of a slow monopole through the detector that the streamer tube slow monopole trigger is sensitive to.
- 4) Zero suppressed data storage. In order to keep the amount of data transferred per event at a manageable level, the wave form information needs to be sparsified. A simple threshold requirement for zero suppression should be more than adequate for our application.
- 5) Double buffering of data to prevent dead time losses. Should the monopole triggering rate be high, this feature will be a necessity.
- 6) An input sensitivity of 3-30 millivolts for a single photoelectron. This system should be able to identify single photoelectron pulses to give us the lowest possible velocity cutoff for monopoles.
- 7) Pre and post pedestal of 4 samples for baseline measurements. This feature will allow us to monitor the zero suppression activity for the real data.
- 8) Channel density of 16 channels/card. This packaging density is recommended in order to take advantage of the system overheads associated with implementing this system.
- 9) Data Acquisition standard of either FASTBUS or VME. These DAQ standards give us enough space to contemplate getting 16 channels/card.
- 10) Total system size of 2000 channels plus spares.

Over the course of the past year we have been investigating the development of a custom designed system to achieve the above specifications based on a design put forward by the Caltech group. We have made some additions to this basic design to provide for pre and post pedestal monitoring, which we feel is important in tracking the performance of this electronics system. The block diagram of this

system is shown in Figure 2. The advantage of this particular solution to our WFD needs is that this FADC chip has TTL outputs which can offer a substantial savings of space when putting together a complete 16 channel board. Recently we have been working on debugging the prototype version of this circuit which we have assembled in a CAMAC module. This debugging is on going and we hope to have a working version of this prototype within the next month. In the meantime we have been working on the design of a higher density version of this same circuit on a 9U VME card. We anticipate that following the successful completion of the initial tests on the CAMAC prototype version of the circuit, we will then make a VME prototype for testing.

B. Plans for the Next Funding Cycle

During the coming 12 months we expect that the work on MACRO will continue to make significant progress toward the completion of the construction of the first 6 modules and the implementation of the final electronics and data acquisition systems for running the completed detector.

As mentioned above, our first priority for this funding cycle will be to conclude our design for the MACRO WFD system. We expect to begin construction of a final prototype VME circuit before the end of the current calendar year. After testing this design out extensively, we then anticipate that we will be ready to begin assembly of the first round of production WFD's providing equipment funding is available. By the end of the coming funding year, we should have enough WFD cards to begin instrumenting the scintillation tanks in modules 2 and 3, and by the end of the following funding cycle, we should have completed the construction of the complete system for 6 supermodules.

D. Time Schedules and Revised Milestones

The past year has seen significant progress toward the staging of the full MACRO experiment at the Gran Sasso Laboratory. In FY '87 the DOE provided MACRO with its first major funding for the construction of this detector. At the same time, the laboratory was finally given over to the experimental team and its contractors, to begin the construction of the detector. Over the course of the past year modules 2 and 3 were finished and the scintillation counters partially filled and the construction on the remaining 3 modules has been 85% completed. With a continuation of the flow of equipment monies from DOE during the coming FY, we will continue to see further progress toward our goal of completing the construction of the first 6 modules of this experiment within the next year.

According to the revised budget for the completion of the MACRO detector presented to DOE in 1988, the total cost to complete this experiment is \$6.8M. However due to the availability of funds for this project at DOE, we have indicated

that this funding will have to extend on into FY 1992 in order to complete this project at the present rate of funding. We have constructed the following list of milestones based on this funding scenario.

Milestones

Calendar Year 1985

- Completion of tests on prototypes.
- Engineering of detector components.
- Definition of final detector specifications.

Calendar Year 1986

- Place first orders and begin construction.
- Detector production begins.
- Tests measurements at the Gran Sasso site.

Calendar Year 1987

- Production of Scintillator for the first module completed (6/87.)
- Production of Streamer Tubes for the first module completed (5/87.)
- Experimental Hall completed (9/87.)
- Begin the assembly of the first module (9/87.)

Calendar Year 1988

- Construction of the next 2 modules begins (3/88.)
- Installation and filling of the first module (5/88.)
- First muon triggers recorded in first supermodule (10/88.)

Calendar Year 1989

- Begin "Muon" data taking run with the first module (2/89.)
- Complete construction of the first three modules (1/89.)
- Begin instrumenting modules 2 and 3 with PMT's and oil (3/89.)
- Begin "Monopole" data taking run with the first module (10/89.)
- Finalize the data acquisition and trigger hardware (9/89.)
- Finalize the design of the "Upper Deck" (11/89.)
- Begin construction of the next 3 modules (3/89.)

Calendar Year 1990

- Complete the construction of modules 4, 5 and 6 (3/90.)
- Begin data taking with 3 modules (9/90.)
- Begin construction of the upper deck of the detector (6/90.)
- Begin instrumenting modules 4, 5 and 6 (9/90.)

Calendar Year 1991

- Begin data taking with the first six modules (4/91.)
- Complete the construction of the hall filler (6/91.)

Calendar Year 1992

- Begin data taking with the completed detector (6/92.)

References

1. The MACRO Collaboration, "Proposal for a Large Area Detector Dedicated to Monopole Search, Astrophysics and Cosmic Ray Physics at the Gran Sasso Laboratory," November, 1984(unpublished).
2. C. Gagliardi, P. Green, T. Meyer, P. McIntyre, M. Shepko, R. Tribble and R. Webb, Phys. Rev. D,35, 2917(1987).

Figure 1: Ground level view of a single MACRO supermodule in Hall B of the Gran Sasso Laboratory, L'Aquila, Italy.

Figure 2: Logic diagram of the TAMU/Caltech waveform digitizer circuit.

III. SSC Detector R&D Program

During the last funding cycle our program has received funding to carry out two major thrusts in SSC detector development. The first of these efforts is a study of the efficacy of using liquid scintillation materials as the active medium in a radiation hard scintillating fiber calorimeter for SSC experiments, and the second area of investigation is the study of using microstrip tracking chambers to answer the stringent tracking needs of an SC detector. In the sections which follow we will outline briefly the progress being made on each of these two R&D projects and discuss our plans for the coming funding cycle.

A. Liquid Scintillator Based Fiber Calorimetry R&D

The use of scintillating liquids and radiation hard coatings has been suggested [1] as a possible alternative to the active medium in scintillating fiber calorimeters being proposed for the SSC. Over the course of the past year, our group has been investigating the design and performance of such a device which could be suitable for use in the highest radiation fields expected at the SSC. In addition to this independent research, our team has also been involved with the development and construction of several of the prototype scintillation calorimeters presently being staged at Fermilab as part of the SSCINTCAL subsystem R&D group. In the short report which follows, we will detail the progress we have made in the studies, outline our plans for further work in this area over the coming twelve month period.

Liquid Scintillator Fiber Calorimeter Progress Report

Our group has been working on several sets of measurements aimed at characterizing the expected performance of a liquid filled scintillating fiber calorimeter. The first set of measurements carried out by a Master Thesis student with our group, Shah Zaman, was a study of the absolute light output and light attenuation length of liquid filled Teflon tubes. This student investigated the light yield from a collection of 1mm. diameter Teflon lined channels filled with a standard liquid scintillating mixture BC517 from Bicron. The results of these first measurements shows the light output to range in value from 1-7 photoelectrons for a minimum ionizing particle passing through the diameter of one of these fibers. The attenuation length measured for the total integrated light output is approximately 30 cm for light produced close to the pmt and 80 cm for the light produced at distances greater than 30 cm. (See Figure 1)[2]. In addition to this study, another group of students investigated the properties of various combinations of coatings and scintillation liquids for use in spaghetti calorimeters. Parker Altice made measurements of the optical properties of Teflon-BC517 in a "lasagna configuration" as well as studying Glassclad-MACRO oil. In the "lasagna configuration", we have a long rectangular tank (1M) with a variable oil depth bounded by the test

coating on the bottom and an air interface on the top. We can then study the light produced by cosmic ray muons passing through the system.

From the studies described in Reference [3] we observed that the light output as a function of depth of liquid scintillator was non-linear when the depth of oil dropped below a couple of mm and that the light attenuation length measured in the shallow oil levels showed evidence of a two component attenuation length behavior similar to that seen in the Teflon tubes described earlier. (See Figure 2)

In addition to the work on testing the properties of various combinations of materials, we have also begun a study of the radiation hardness of the various calorimeter components being used. Thus far we have only studied the materials used for our test measurements, however we are in parallel investigating the use of new materials which may prove to be even more radiation resistant.

Lastly, over the course of the past year, we have been working to assemble a prototype electromagnetic calorimeter for testing at Fermilab. This prototype system is composed of seven hexagonal non-projective lead/Teflon tube modules. While we understand that Teflon has problems in the area of radiation hardness, we have chosen these materials more from the point of view of demonstrating that the principal is viable rather than from the point of view of finding the best materials in the first attempt. See attached Figures 3-4 for details of the design of these units.

Plans for Coming Year

For the coming twelve month period, we plan to conclude the assembly and beam tests of the seven unit electromagnetic calorimeter previously described. In addition, we will be undertaking the design of a projective tower prototype hadron calorimeter module using similar techniques to those employed in our electromagnetic prototype. Lastly, during this funding period, we will investigate further the radiation hardness of the various components of such a calorimeter in order to finalize the design of a suitable high density, forward, liquid/fiber calorimeter for use at the SSC.

B. MICROSTRIP CHAMBER DEVELOPMENTS

The performance required of track chambers in future hadron collider experiments cannot be met by any existing chamber technology. The entire CDF tracking system will likely need major upgrade for the 1995 physics run. The SDC tracking design is being reevaluated, and new technology development is a major focus of effort. We are developing a new chamber technology, the microstrip chamber, which is specifically designed to meet CDF and SDC requirements. We have formed an international collaboration (TAMU, KEK, CERN, Pisa) for its development and evaluation. Demonstrated performance exceeds that of any existing technology for track chambers: 20 μm resolution, 15 nsec live time, and Mrad radiation hardness. The calculated performance for spectrometry is likewise superior to present technologies and uniquely accommodates SSC spectrometry up to $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ luminosity.

Microstrip chambers have been developed over the past year using three different approaches: microstrip avalanche chambers (Bellazzini *et al.*, INFN Pisa), silicon knife-edge chambers (McIntyre *et al.*, Texas A&M), and polyimide knife-edge chambers (Maki *et al.*, KEK). In each case an array of electrodes are fabricated on a resistive dielectric substrate to produce a microscopic proportional chamber with $\sim 50 \mu\text{m}$ spacing between anodes. Prototypes of all three approaches have now been fabricated. Extensive test beam studies of the Bellazzini chambers have verified the above performance.

The microstrip chamber collaboration has the following goals:

- to further develop and evaluate prototype chambers of all three technologies, and select the best approach for CDF and SSC requirements;
- to analyze the mechanical, thermal, and electronics requirements for utilization of the technology in the central tracking chamber of CDF and the intermediate angle spectrometer of SDC;
- to design spectrometer systems which meet the above requirements;
- to simulate the performance of the above system for trigger, track reconstruction, and physics analysis of various physics processes at luminosities of 10^{33} and $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$.

The microstrip chamber technology is less than two years old. Its impressive performance has been proven in test beam studies of one design, while several improved designs have recently been successfully fabricated and will soon be ready for tests. This new technology may seem less mature than the current technologies being developed for SSC detectors: silicon microstrips, straw tubes, scintillating fibers, and radial wire chambers. Each of these current technologies has one or more strengths to commend it. However, no current technology has the combination of resolution, speed, occupancy, radiation hardness, and unit cost which will be required for spectrometer performance at 10^{33} luminosity. We therefore submit that this new tracking technology should be given a high priority for detector R&D funding. We have been funded by SSC Generic R&D (program now ending) and we have submitted a proposal for SSC Subsystem R&D. We request funding

in this contract for baseline funding not eligible for Subsystem support, and for development of microstrip chambers for possible use in CDF upgrade for the 1993 and 1995 run.

INTRODUCTION

The Superconducting Super Collider presents formidable challenges to the detector technology required to instrument its experiments. The challenges are particularly distressing in the central magnetic spectrometer [4] which is the heart of most collider detectors. Figure 5 shows simulations of two "typical" interesting events as they would be recorded in a conventional wire track chamber: a Higgs boson which decays into 2 Z bosons; and a 2-jet quark scattering with a momentum transfer of 1 TeV. Such events contain ≥ 200 charged particles, half of which curl partly or fully within the chamber volume. Superposed on the interesting event is a second, uninteresting event (on average there are 1.6 pp collisions in each bunch-bunch crossing at $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ luminosity). Also superposed are tracks recorded from interactions in several bunch-bunch crossings before and after the interesting event: the memory time of most track chamber technologies is many times the 16 nsec time between crossings. In total some 20,000 signals must be processed from each event, and the (few) interesting tracks must be extracted from the (many) irrelevant backgrounds.

Likewise in CDF, the 1995 physics run will have $\mathcal{L} \sim 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ thanks to the new injector upgrade. The tracking will require live times of ~ 20 nsec to use this luminosity for physics analysis.

The performance of the tracking spectrometer is determined by the spatial resolution with which the track chambers can distinguish and measure tracks to determine momenta. Wire chamber technologies [4] with $\sim 150 \mu\text{m}$ resolution and ≥ 4 mm pitch are problematic for momentum resolution and occupancy. Silicon microstrips [5] can achieve $\sim 20 \mu\text{m}$ spatial resolution, but have longer memory time (many bunch-bunch crossings) and smaller signal (noise/rate tradeoff). Scintillating fibers [6] are fast (~ 20 nsec), but have limited resolution ($> 200 \mu\text{m}$) and require expensive cryogenic readout. All three technologies are vulnerable to radiation damage at 1995 CDF and SSC particle fluxes.

A new technology for precision track chambers has been developed during the past two years: the microstrip chamber. The principle of operation is illustrated in Figure 6. An array of metallized electrodes are fabricated on a resistive substrate. Alternate electrodes are connected as anodes and as field-shaping electrodes. The chamber is equipped with a foil cathode, filled with Xe magic gas, and suitably biased (Figure 7) to produce $\sim 10^4$ gas multiplication. For an anode spacing of $50 \mu\text{m}$, a resolution of $20 \mu\text{m}$ can be obtained directly from the anode readouts without any requirement of time or pulse height digitizing. The anode pulse width is determined by the total drift time of electrons in the gas; for a gas thickness of 1 mm, the total live time is 15 nsec – one bunch-bunch crossing time in SSC.

Three fabrication approaches have been developed for microstrip chambers: a planar glass substrate (Bellazzini *et al.*), a knife-edge silicon substrate (McIntyre *et al.*), and a knife-edge polyimide substrate (Maki *et al.*). The three approaches are described below. The principle properties for tracking spectrometers are:

spatial resolution	20 μm
live time	15 nsec
channel occupancy	$\sim 10^{-4}$
pulse height	1 mV
chamber thickness	10^{-3} radiation length
radiation hardness	10 Mrad
projected cost	$\sim \$50,000/\text{m}^2$

These properties make the microstrip chamber an ideal choice for 1995 CDF and SSC tracking. We have developed a preliminary design for an Intermediate Angle Spectrometer (IAS) in SDC utilizing microstrip chambers. Figure 8 shows the location of IAS within SDC; Figure 9 shows the assembly of chambers for one octant of IAS. The spectrometer would complement the information from the inner silicon tracking to provide useful momentum resolution and triggering down to as little as 5° from the beam axis.

The microstrip chamber is particularly well suited for use in this angular region, where one wishes to configure chambers in an assembly of annular discs, with readout oriented to precisely measure azimuth. The knife-edge chambers may be used to tile a mosaic of any desired shape. Each layer can be arranged in two staggered layers to eliminate dead cracks at the location of the on-board CMOS electronics. This layering also facilitates routing of signal cables and gas manifolding throughout the spectrometer. We have developed a preliminary design for a modular tubular support structure which precisely positions all chambers. The total mass of 12 layers of chambers, including support structure, electronics, and cabling, is estimated at .05 radiation lengths.

The proposed multi-year program encompasses the construction and test beam evaluation of microstrip chambers using the above three technologies, the development of a full design for a central track chamber for CDF and an Intermediate Angle Spectrometer for SDC, and the simulation of its performance for triggering, track reconstruction, and physics analysis.

DESIGN AND PERFORMANCE OF MICROSTRIP CHAMBERS

A. Planar glass substrates (INFN Pisa)

The simplest geometry for a microstrip chamber is an array of metalized electrodes on a resistive glass substrate. Figure 10 shows the geometry of the chambers developed at INFN Pisa [7]. Thin anodic and cathodic parallel strips were laid down on a 500 μm thick glass substrate, with a 200 μm pitch. An upper cathode seals the chamber and defines the drift region for ionization charges.

The cathodic strips are biased to concentrate all electric lines of force on the anodes, and to contour the near-field potentials to preserve high gas gain as the MWPC geometry is miniaturized. Figure 11[8] shows the equipotential lines and drift lines for chamber operation.

The detection efficiency, energy resolution, spatial resolution, and two-track resolution have all been studied in test beam studies[9]. Figure 12 shows the pulse height spectrum of ^{55}Fe signals. The FWHM of the 6 keV peak is 18%, far better than any result ever before achieved with any wire chamber.

Figure 13 shows the pulse height spectrum of minimum-ionizing particles using a drift length of 5 mm and a Xe-DME gas mixture. The measured efficiency is 95%, limited by requirement of detection on both adjacent cathode strips.

The spatial resolution was measured by pulse height division on the signals induced on neighboring cathodic strips. Figure 14 shows the measured resolution using a Si microstrip telescope for reference position. A resolution of $33\text{ }\mu\text{m}$ is obtained. The two-track resolution is $250\text{ }\mu\text{m}$. By comparing the pulse height development on the adjacent cathode strips with that on the anode, it is found that at least 80% of the ions formed in gas multiplication are collected on the neighboring cathode strips. This local ion clearing, together with the short drift length, reduce the space charge effects of high particle fluxes by a factor of ~ 20 compared to straw tube chambers.

Four potential problems were encountered using the planar microstrip chamber. First, the gas gain is limited to $\sim 10^4$, corresponding to the limit to which the planar electrode configuration can be used to "stretch" the high-field region above each anode. Beyond this limit the chamber is subject to Geiger discharge.

Second, the fabrication procedure uses aluminum electrode strips. In previous chamber studies[10] aluminum has been observed to react with gas dissociation products to form insulating patches on the electrode surfaces. This effect could produce an aging of chamber performance under the radiation damage of the SSC.

Third, the readout scheme employed to achieve high spatial resolution requires measurement of the pulse height of the induced charge on the cathode strips flanking the anode strip. This approach requires demanding front-end and ADC electronics on every anode channel - a major complication for SSC spectrometers.

Fourth, the chamber tests revealed a bulk-charging process in the glass substrate which complicates the field geometry and introduces relaxation times of hours for stabilization of gas gain. In effect the bulk of the glass slowly charges after application of chamber voltages, so that the potential distribution slowly changes until an equilibrium is established.

The alternative approaches discussed below provide solutions to each of these problems.

B. Knife-edge array on silicon

If the anode and cathode strips are replaced by knife-edges as shown in Figure 6, the region of concentrated electric field in the gas multiplication region can be further extended (Figure 7) and the dielectric strength at the chamber surface

is greatly enhanced. This improved electric field geometry makes it possible to reduce the pitch of the array to 50 μm while retaining 10^4 gas gain. The desired spatial resolution can then be attained by straightforward operation as an MWPC. The position measurement is then a simple binary output of saturated signals (1,0), to be processed by synchronous CMOS registers on-board each chamber. No pulse height or time digitization is required. Triggering can be accommodated by fast bit manipulation, as discussed below.

The fabrication sequence used to produce a knife-edge chamber[11] is illustrated in Figure 15. A pattern of knife edges can be fabricated onto a thin silicon wafer using orientation-dependent etching (ODE). When a silicon surface is exposed to an appropriate alkaline wet-etch solution, the etch rate is about 50 times faster in the 100 and 110 crystal directions than in the 111 direction. By applying photoresist, lithographically defining a pattern of microscopic lines, and then etching using ODE, a series of parallel knife edges may be produced on the wafer. We are able to finely tune the shape of the knife edges to produce substrates of any desired shape, from a series of shallow steps to a full "saw-tooth" pattern. Figure 16 shows electron micrographs of several knife edge arrays following ODE fabrication. These knife edges may then be coated with an insulating dielectric and then gold to produce both signal and field-shaping electrodes. It should be emphasized that the silicon substrate is used only as a building material, upon which to produce knife-edges. Chamber performance does not require any semiconductor properties of the silicon.

Figure 17 shows the fabrication sequence employed to produce a knife-edge chamber. For prototype chambers we use 2"-diameter wafers, cleaved on the 100 direction, with a thickness of 250 μm . For chambers for CDF and SSC tracking we plan to use 4" square wafers, 75 μm thick (10^{-3} radiation length), available from Va. Semiconductor. We are now also fabricating chambers from this thin substrate.

The silicon is As-doped to a resistivity of .01 Ωcm - it is essentially metallic. Following the fabrication of the knife-edge array on the silicon surface, an oxide layer is diffused 2 μm into the silicon to provide a dielectric insulation layer. We then use ion implantation to produce a resistivity in this layer which we can control over the range $10^{11} - 10^{14} \Omega\text{m}$. In this way we provide a surface clearing current which eliminates surface charging phenomena for even the highest event rates ($10^5/\text{cm}^2/\text{sec}$).

Note that there is no bulk dielectric in the knife-edge chamber. The bulk substrate is metallic; the surface dielectric layer is μm thick and has a controlled resistance. The charging phenomena encountered in planar glass substrates are thereby eliminated.

The pattern of metallized electrodes are fabricated by sputtering a 1 μm gold layer on the array, and using co-registered lithography and etching to produce the appropriate pattern of electrodes, pads, and buses (Figure 17). The use of gold for the conductors has been shown[12] to eliminate the development of insulating

films which is observed on aluminum electrode surfaces.

The knife-edge chamber thus resolves the four limitations encountered with the planar glass substrate and appears to provide nearly ideal performance for SSC tracking.

C. Polyimide Knife-Edge Arrays

A disadvantage of the silicon knife-edge chamber is that it requires the use of a crystalline silicon substrate, which is currently available only up to sizes of ~ 10 cm in the $75\text{ }\mu\text{m}$ thickness required for SSC chambers. Tiling such chambers enables straightforward accommodation of most spectrometer geometries, in the present case the annular disc of Figure 9. However, it would be desirable to build chambers of considerably larger size, in order to reduce piecewise fabrication costs and simplify alignment.

A. Maki is developing such an alternative,[13] in which the desired knife-edge array is impressed on a polyimide sheet from a negative-image master. An ultraprecision diamond milling machine is used to make an array of V-grooves in a nickel-plated steel plate. A sheet of polyimide resin is then pressed by the master to mold the knife-edge pattern into the plastic surface. Electrodes are then printed onto the knife-edges, by vapor deposition or sputtering through a mask. Figure 18 shows the diamond milling machine, Figure 19 shows micrographs of V-groove patterns on a steel plate. KEK has recently succeeded in making $(5\times 5)\text{cm}^2$ arrays of knife edges on polyimide film. The next steps are to achieve an appropriate bulk resistivity in the polyimide, and to produce the pattern of metallized electrodes on the knife edges. We have succeeded in producing the required pattern of metalized lines and pads on planar polyimide film. We are now preparing a negative-image mask with which KEK can produce a pressed film pattern matching our mask. We will then produce co-registered metal lithography on their plastic film. This fabrication approach is readily extended to ~ 1 m chamber dimensions.

INTERMEDIATE ANGLE SPECTROMETER DESIGN

A. Mechanical Support and Segmentation

The Intermediate Angle Spectrometer in SDC provides track reconstruction, momentum analysis, and high $p_{\perp}$ triggering for charged tracks in the angle range 10° – 30° . We have developed a preliminary design employing microstrip chambers for this purpose. The configuration is shown in Figures 3,9. The desired geometry is achieved with a mosaic of $(10\times 10)\text{cm}^2$ chambers. If the polyimide substrate of Maki *et al.* proves feasible, the unit size could of course be much larger. Figure 20 shows a cross-section of one approach to modular chamber design. The two sides perpendicular to the microstrip axis are bonded to a thin ($25\text{ }\mu\text{m}$ wall) quartz tube whose diameter (~ 1 mm) is the desired anode/cathode gap. The ($25\text{ }\mu\text{m}$ thick) foil cathode is bonded to the opposite side of each tube to make a rigid assembly as shown. The other two sides are left fully open to accommodate unrestricted gas flow. The knife-edge arrays can be trimmed such that a gap of only $\sim 100\text{ }\mu\text{m}$

is inactive at each side border of a chamber. Adjacent chambers are stacked edge-to-edge along the side borders, so that acceptance is $\sim 99.8\%$ along each row of chambers.

The readout electronics is bonded to one end of each chamber, and successive rows of chambers are stagger-overlapped to provide continuous ϕ acceptance within each layer of chambers.

The internal alignment among chambers within the spectrometer is obviously most critical for the tower of chambers occupying a given solid angle segment, since that is the information base for momentum measurement of high- $p_{\perp}$ tracks. For this reason we envision segmenting the spectrometer into octants; precise alignment within an octant can be provided by a gossamer support structure to which all chambers are mounted. Figure 21 illustrates one approach under investigation, which is composed of thin Nynex paper tubes bonded to planar Kapton sheets to form an ultra-low-mass rigid assembly. This open structure permits ample space for cabling and gas manifolds to the chamber arrays.

The arrangement of chambers within the spectrometer is chosen to optimize the tasks of pattern recognition and triggering. In the design of Figure 9, three stations of chambers are equispaced through the 1.4 m depth of the spectrometer. Each station contains three layers of ϕ chambers (microstrip chambers oriented to measure the ϕ track coordinate) and one layer of r chambers. The three ϕ layers with a station are spaced a distance $\ell = 5$ cm apart. Pattern recognition for off-line analysis can thus begin by fitting ϕ vectors within a station. Since each chamber has a 10 cm size, the ϕ measurements are segmented in narrow bands of rapidity; the number of tracks within a single $(10 \times 10) \text{ cm}^2$ chamber is modest even within dense jet cones. Once (r, ϕ) vectors are formed within each station, the complete tracks are reconstructed by a connect-the-vectors algorithm among the three stations.

B. Readout Electronics

The anode signals from microstrip chambers will be converted directly into saturated logic states, so that position measurement is simply the binary pattern of knife-edges over threshold. This approach achieves excellent spatial resolution ($20 \mu\text{m}$) while eliminating the digitization of pulse height and/or time required by most chamber technologies.

Figure 22 shows a schematic of the readout electronics. Signals are amplified and then compared to a common threshold which is set by an external DAC. Following the comparator, all circuitry is thin-gate CMOS. The full sparse binary vector from each event is clocked synchronously through a pipeline register, whose time depth is the trigger decision time ($\sim 1 \mu\text{sec} = 64$ SSC clock cycles). Upon exiting the pipeline, the vector for triggered events only is compacted into a sequence of addresses and widths of hits using the same strategy as the PCOS electronics of MWPC vintage.

All of the above processing is provided on-board each chamber. The VLSI chip set is die-bonded to one end of the chamber wafer and the signal connections

are made either using wire-bonding (Figure 20) or indium bump bonding. The only data leaving a chamber are then the actual addresses of hits for triggered events – a very modest data volume that can be read on a single low-baud bus throughout an octant of the Intermediate Angle Spectrometer.

Exclusive of trigger requirements, the cabling of signals among microstrip chambers requires 24-bit data buses (16 data, 8 address lines). In a preliminary readout architecture, readout would be separately bussed to the five radial regions of the three stations, a total of 15 buses per octant of the spectrometer. All buswork would employ 25 μm thick gold-line Kapton flex PC. It should be noted that this volume of cabling is considerably less than that envisioned for most tracking technologies.

C. Trigger Electronics

A key provision for physics analysis is the ability to trigger on high $p_{\perp}$ charged tracks and correlate them with signals in the shower calorimetry to define electron candidates. Two alternative strategies are possible for achieving a high $p_{\perp}$ trigger using microstrip tracking. One strategy is to separate the trigger task to a completely different detector system: scintillating fibers. A five-layer telescope of scintillating fibers could produce a clean signature of high $p_{\perp}$ tracks. The typical fiber size ($\sim 500 \mu\text{m}$) is much too coarse to support precision $p_{\perp}$ measurement, but is just right for triggering. In this approach, the electronics requirements for the microstrip chamber readout as outlined above can all be accomplished on-board each chamber, with only low-baud buses needed for readout.

A second strategy is to generate fast $p_{\perp}$ triggers from the microstrip data within each station. The signals within each 3-layer station of the spectrometer would be routed to a local trigger processor, which would search for stiff track segments and provide for such segments an approximate measure of track $p_{\perp}$. The following discussion analyzes the implementation of this self-triggering for the IAS spectrometer.

The radius of curvature R for the transverse bending of a track in the solenoidal magnetic field B is

$$R = p_{\perp} / .3B.$$

The radius at which a track at polar angle r reaches a chamber layer a length $L = 3 \text{ m}$ from the intersect is

$$r = L \tan\theta.$$

The local azimuthal angle with which the track traverses the three chambers of a station is

$$\phi = r/R = \frac{.3BL}{P_{\perp}} \tan\theta$$

The information density from the microstrip chamber is over-rich for the requirements of $p_{\perp}$ triggering. For trigger analysis, wire-or signals from adjacent groups of channels are bussed within each station to a common fast trigger processor.

The three ϕ chamber layers within a station provide a measurement of the local azimuthal angle with a bin size

$$\delta = d/\ell$$

where d is the bin width of the wire-or signal vector to the trigger processor, and $\ell = 5$ cm is the spacing between ϕ chambers within a station.

The choice of the wire-or binning then determines the $p_{\perp}$ scale of measurement. In particular we can use a different bin width for chambers at different radius, so as to produce the same $p_{\perp}$ roads across the entire Intermediate Angle Spectrometer. The binning shown in Table I is a good match to the physics analysis requirements at trigger level.

The local track trigger processor would search for 3-fold coincidences within the four $p_{\perp}$ roads defined in TABLE I. One hardware approach for this purpose is the binary linking trigger (BLT) developed and tested by Kinoshita [14]. It uses a binary linking algorithm to seek a three-fold coincidence for each $p_{\perp}$ road. Using fast ECL logic components, it is capable of providing a track triggering 20 ns. Using synchronous CMOS gates, the track trigger would be pipeline processed, and emerge after ~ 80 nsec. This trigger would provide a high-speed level-one trigger with good noise immunity. It has proved to be highly efficient and simple.

The heart of the BLT algorithm is that any single track in a tracking chamber is strongly correlated in location to accompanying hits in nearby layers, so that a given cluster of hits can be associated with close neighbors in adjacent layers. By starting with hits in the innermost layer and establishing links to nearby hits in successive layers, one can construct a connected path between the innermost and outermost layers.

The track trigger data would emerge as a 12-bit dataway (4 bits $p_{\perp}$, 4 bits ϕ , 4 bits chamber location) bussed on each (constant- r) row of chambers. A total of 16 such dataways thus emerge from each station, 48 from an entire IAS octant. This data volume is again modest by comparison to other tracking technologies.

D. Cooling considerations

The heat load of the microstrip chamber spectrometer includes contributions from gas gain heat, substrate resistive dissipation, readout electronics, and trigger electronics. The gas gain heating P_g may be estimated from the charge per track ($q \sim 10^{-13}$ C), the rate of tracks through an octant ($f \sim 4 \times 10^8$ Hz at 10^{33} luminosity), the number of chamber layers in an octant ($N = 12$), and the chamber voltage ($V \sim 1500$ V)

$$P_g = NfqV = 0.6W$$

The readout electronics employs CMOS gates everywhere except the front-end amplifier and the fast-or trigger driver. Gate dissipation may be estimated from the capacitive switching requirements. Assuming that on average ~ 2 adjacent microstrip channels are "struck" by each track traversing a chamber, and a readout pipeline depth of $N_p = 64$ clock cycles, the dominant power dissipation is that

required to switch the (1,0) transitions in the gate array ($C_g \sim 1$ pF, $V_g \sim 10$ V) is

$$P_r = 2N N_p f C_g V_g^2 = 60W$$

Estimating the power requirements for the trigger processing requires a better definition of the trigger time requirements. If single-cycle track-trigger decisions are required, the processors will likely require ECL circuitry and the power budget will be larger. If a ~ 5 cycle pipelined trigger is sufficient, the BLT algorithm can be implemented in thin-gate CMOS, and the power budget is then comparable to that required for readout electronics.

The required cooling can be supplied by manifolded gas flow with a linear velocity of 3 cm/sec and a temperature rise of 10°C.

E. Simulation and Physics Analysis

We have recently succeeded in fully commissioning an SSC simulation activity at Texas A&M University. We have simulated the Intermediate Angle Spectrometer within the SDC detector, using GEANT 3.13; we have simulated SSC events for a variety of physics processes using ISAJET 6.28. Figure 23 shows one example of a Higgs leptonic event. We are now beginning to simulate the patterns of hits in the actual chambers, including resolution, diffusion, wraps, multiple scattering, and photon conversions. We will study the performance of several algorithms for pattern recognition and track reconstruction, and use them to guide the spectrometer design.

Dr. Barasch is a member of the Texas A&M group who is developing analysis shells for the entire SDC experiment and CDF tracking upgrades. These shells will support consistent simulation of detector design and performance by all collaborating institutions. He is furthermore integrating the data structures for our CAD analysis with that of GEANT, to provide a smooth transition from mechanical design to/from detector simulation.

A new element of the proposed budget is subcontract support for summer salary and travel funds for Prof. Rudolf Gaedke of Trinity University in San Antonio. His background is in experimental nuclear physics; he has made a career decision to refocus his research in high energy research, specifically the SSC program. He will spend a sabbatical semester at Texas A&M during Spring 1991, working with our microstrip chamber R&D effort. The subcontract funding would provide for summer salary and a modest travel budget with which to continue his involvement. Two college students from Trinity are working with him in his research.

REFERENCES

- [1] R. C. Webb, *et al*, "A Liquid Scintillating Alternative to Fiber Calorimetry for the SSC," a proposal submitted to the DOE SSC Generic R&D program, August 1989.
- [2] Shah M. Zaman, "Measurement of the Optical Performance of Liquid Scintillator Filled Teflon-Fiber Tubes," DOE-40039-43(unpublished).
- [3] P. P. Altice, "A Study of Liquid Scintillator and Fiber Materials for Use in a Fiber Calorimeter," DOE-40039-45 (unpublished).
- [4] G. G. Hanson, "Integrated SDC Tracking Configuration: Silicon and Wire Chambers," Proc. 1990 Workshop on Solenoidal Detectors, Tsukuba, April 1990.
- [5] A. Seiden, "Silicon Tracker for the SSC," *ibid*.
- [6] D. Koltick, "Scintillating Fiber Tracking for the SSC," *ibid*.
- [7] F. Angelini *et al.*, "The Microstrip Gas Avalanche Chamber: A New Detector for the Next Generation of High Luminosity Machines," Proc. ECFA Study of Instrumentation of High Luminosity Hadron Colliders, Barcelona, Sept. 1989.
- [8] F. Angelini *et al.*, Nucl. Inst. & Meth. A292, 199 (1990). F. Angelini *et al.*, Test Beam Study of the Microstrips Gas Avalanche Chamber, INFN preprint, 1990.
- [9] M. Atac, "Wire Chamber Aging and Wire Material," Vertex Detectors, F. Villa, ed., Plenum, New York (1988).
- [10] P. McIntyre *et al.*, "Knife-Edge Chamber," Proc. 1990 meeting, Div. of Part. & Fields, Am. Phys. Soc., Houston, January 1990.
- [11] A. Maki, "A Large-Size Knife-Edge Chamber," Proc. 1990 Workshop on Solenoidal Detectors, Tsukuba, April 1990.
- [12] K. Kinoshita, Nucl. Inst. & Meth. A276, 242 (1989).

TABLE I

p_⊥ Trigger Thresholds for Microstrip Trigger Processor

chamber location		road width	road bins				GeV
r(cm)	θ	d(μ m)	1	2-3	4-6	7-10	
20-50	4°-9°	50	∞ -160	160-80	80-40	40-20	
50-80	9°-15°	100	"	"	"	"	
80-110	15°-20°	150	"	"	"	"	
110-140	20°-25°	200	"	"	"	"	
140-170	25°-30°	250	"	"	"	"	

1mm Teflon Tubes (Translucent)

Figure 1: Light output versus distance for BC-517 scintillator in a 1 mm diameter TEFLON tube.

Figure 2: The plot to the right is the data taken using a Glassclad coating and MACRO oil. The plot to the left is data taken using a TEFLON coating and Bicron BC-517. Both of these measurements were taken in the "lasagna" configuration.

Figure 3: Detailed assembly drawing of the liquid scintillator TEFLON fiber electromagnetic calorimeter prototype under construction.

Figure 4: Photographs of various parts of the prototype electromagnetic calorimeter. (Top) LUCTE light mixer; (Center) Lead/TEFLON tube assemblies; (Bottom) Optical fiber light collector.

Figure 5. Simulations of two "interesting" events as they would be recorded in a magnetic spectrometer ($B = 2$ T):

a) Higgs boson: $pp \rightarrow H \rightarrow ZZ$

b) a 2-jet event corresponding to quarks scattering with a momentum transfer of 1 TeV. (from Ref. 1).

Figure 6. Knife-edge array on silicon. The signal electrode S collects the signal; the field-shaping electrodes I, C are used to shape the field for control of gas gain and ion clearing.

Figure 7. Calculated electric field distribution near the knife-edge array, with electrode potentials set for optimum gas gain.

Figure 8. Location of the Intermediate Angle Spectrometer in the SDC Detector (dimensions in meters).

Figure 9. Assembly drawing of one octant of IAS, showing placement of microstrip chambers.

Figure 10. Geometry of the microstrip chamber with planar glass substrate.

Figure 11.

a) Details of the equipotential lines in a region close to the anode strips.

b) The drift lines for electrons.

Figure 12. The pulse height spectrum of ^{55}Fe signals in Ar-CO_2 . The FWHM of the 6 KeV peak is 18%.

Figure 13. The pulse height distribution observed with a mixture of Xenon-DME.

Figure 14. Measured spatial resolution of microstrip chamber (MISGA) relative to silicon microstrip telescope.

Figure 15. Fabrication sequence used to fabricate the silicon knife-edge chamber.

Figure 16. Electron micrographs of knife-edge arrays.

a) HEPA air filtration system and entry air lock.

c) Ventilated wet-etch station:
temperature-controlled baths,
3-stage wash baths, N_2 drying

b) Fabrication equipment: metallurgical microscope, bake oven,
wire bonder, mesh aligner, plasma etcher, spin coater.

Texas A&M

Figure 17. Class 100 Clean Room Fabrication Facility

Figure 18. Diamond milling facility at KEK.

Figure 19. Micrograph of Vgroove milled on a nickel-steel plate.

Figure 20. Two Higgs events simulated in the SDC tracking volume with IAS.

Figure 21. Detail of microstrip chamber assembly, readout electronics, and trigger signal bus.

Figure 22. Detail of tubular support structure employing a Nynex tubes/ Kapton sheet construction. Also shown are cable paths for signal buses to trigger processor.

Figure 23. Functional schematic of readout electronics.

IV. SSC Experimental Program

Our group has been very active over the course of the past year in efforts aimed at defining a suitable detector configuration for use at the SSC. These efforts have been directed towards two of the major detector groups that have emerged as significant players in defining the SSC experimental program. Drs. Bowcock and McIntyre have been involved with the plans for the large solenoidal detector (SDC) and Drs. Karon and Webb have been working closely with the non-magnetic calorimeter based detector called TEXAS. These two groups prepared extensive documents outlining their group's interest in carrying out these experiments at the SSC laboratory. In the section which follows we outline the general concepts behind the TEXAS detector design.

Introduction to the TEXAS Experiment

We have proposed a simple and hermetic SSC detector that optimizes fast calorimetry for electrons and the measurement of jets and missing energy. Fig. 1 shows the overview of the detector conceptual design. A fiber calorimeter is complemented by a central scintillating fiber tracker pre-radiator and an outer muon spectrometer. The muon system uses TRD and dE/dx for fast triggering and momentum analysis. The three components and their few subsystems are assembled in a geometry that provides easy access and repair. The detector incorporates proven or prototype stage technology to assure on-time construction at a predictable and limited cost.

The signatures for anticipated new physics at the SSC have been well documented and provide a basis for optimizing the design of a focussed detector [1]. Higgs searches require lepton and jet reconstruction over the widest possible rapidity range. Signatures for supersymmetry demand excellent missing transverse energy sensitivity, and therefore truly hermetic calorimetry. Technicolor and substructure searches require fine calorimeter segmentation and compensation for good dijet invariant mass resolution. Some of the distinctive goals of the TEXAS detector, such as the search at high luminosity for an intermediate mass Higgs in the $\gamma\gamma$ and ZZ^* channels, or a heavy Higgs at the extreme of the SSC reach, pose specific challenges. We address them by letting the inner radius R of the calorimeter be large (2 meters). The $\gamma\gamma$ and jet-jet separation increase as R , while the radiation dose diminishes as R^{-2} . The calorimeter proper is preceded only by a beryllium beam pipe and a low- Z fiber tracker. At high luminosity and with a good jet-jet mass-resolution, we can search for rare but clean signatures of supersymmetry. We can also measure high p_T jets with the precision required to search at high mass for technicolor and substructure.

In optimizing calorimetry (and avoiding cracks, magnet support structures, etc.) we have eliminated a central magnetic field, thereby giving up the measurement of charge for $|\eta| < 1.5$. A narrow non-projective readout path at $\eta = 0$ remains. The entire detector is in two self-supporting mirror-image halves. The overall performance, simplicity and economy of the TEXAS detector, with only *three* basic components, provides an interesting alternative to the conventional general purpose solenoidal detector. Furthermore, our non-magnetic design preserves the narrow spatial structure of jets at the SSC, providing good jet triggering and reconstruction efficiency.

Detector Conceptual Design

The conceptual design of the TEXAS detector gives priority to the calorimeter, since optimal calorimeter performance is essential for our physics goals. The first fundamental design decision has been to eliminate magnetic fields. A second fundamental design decision has been to require that the detector and all its subsystems be operational and survivable at luminosity of $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$.

Scintillating Fiber Calorimeter

Since the precision of calorimetry increases with energy E as $1/\sqrt{E}$ + a constant, a calorimeter with no dead space for services or structural elements can yield high resolution in the TeV regime for electrons, missing E_T and jets, provided sources of systematic error are properly minimized. A very fast detector has obvious advantages in triggering and pile-up rejection, particularly at a luminosity $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

We propose to use cast lead eutectic and scintillating fiber for the calorimeter system. It is electronically fast, simple and easily manufactured. It has excellent energy resolution, can be arbitrarily segmented, and is naturally projective and hermetic. It is structurally designed to avoid inactive boundaries and supports. The specific optimization and tower structure we propose provides radiation hardness, homogeneity, hermeticity, electron/hadron compensation and easy *in-situ* access and calibration. The towers are monolithic, projective, self-supporting and modular. The imaging pre-radiator gives superior position resolution on e and γ and excellent e /hadron separation. Fig. 2 shows the detail of a single calorimeter tower. Spatial segmentation in η and ϕ is 0.025 in the electromagnetic and 0.05 in the hadronic compartment. Calorimetric coverage is continuous to $\eta = 5.5$. We use recirculable, radiation-hard liquid scintillator and tungsten absorber in the forward region for $\eta \geq 3$. Here, capillary tubes replace fibers allowing us to extend the fiber manufacturing technique to a liquid scintillator. The tungsten absorption length (one half that of lead) prevents shower size from dominating the segmentation. The energy resolutions ($6.5\%/\sqrt{E}$ and $30\%/\sqrt{E}$ for electromagnetic and

hadronic components) are saturated by energy-independent terms which reach 0.5% for electrons and 1% for hadrons at high energy. With the pre-radiator, the electron/hadron separation is expected to be better than 5×10^{-4} .

Separate electromagnetic and hadronic calorimeters can give important information for electron identification while decoupling the calorimeter design for each type of shower. This allows for different segmentation and mechanical support for the two sections, facilitates triggering, and provides for different transitions at tower boundaries as appropriate for the different shower sizes. For a scintillating fiber calorimeter, narrow electromagnetic showers sample many fewer fibers than do hadronic showers, with consequently greater demands upon uniformity of response between fibers and across module boundaries. The choice of fiber diameter and other properties involve trade-offs between calorimeter cost and performance which benefit from a separate optimization for the electromagnetic and hadronic sections. Radiation damage is also much greater near the electromagnetic shower maximum, while the effect of fiber attenuation length upon energy resolution (from longitudinal shower fluctuations) is much less.

Our current design calls for a scintillating fiber electromagnetic calorimeter with the fibers spliced at a mass-coupling connector to clear optical fibers for readout. In the prototype of this device being developed we couple 1 mm scintillating fibers with the EM calorimeter to bundles of clear fibers with less than the 1 mm diameter for readout through non-projective cracks in the hadronic calorimeter. The diameter mismatch decreases the fiber-to-fiber variation in coupling efficiency while minimizing the size of the gaps between hadronic calorimeter towers. The possibility of distributing readout fibers through the body of the downstream hadron calorimeter tower is also under study. Outside the hadron calorimeter, each EM fiber bundle will pass through an optical mixer (to minimize the effect of PMT efficiency variation across the photocathode) for readout by a single photomultiplier. Electromagnetic calorimeter modules will have their axes several degrees offset from pointing, in a pinwheel arrangement, to avoid "channelling" of electrons along individual fibers. The use of a thick pre-radiator to spread showers before entering the calorimeter may eliminate the need for such an angular offset, but this will require further study.

The calorimeter's potential for high energy resolution, scaling like $1/\sqrt{E}$, depends at low energy upon minimizing sampling fluctuations and at high energy upon minimizing systematic errors from nonuniformity or nonlinearity. The SPACAL collaboration has built and tested an electromagnetic calorimeter prototype with energy resolution of $13\%/\sqrt{E} + 0.5\%$ [2] with the first term determined by sampling fluctuations. The sampling fraction (20% fibers by volume) for this calorimeter was determined by the requirement of "compensation" or an equal response for electromagnetic and hadronic showers. The JETSET collaboration

has built and tested an electromagnetic calorimeter prototype which has been optimized for energy resolution (50% fibers by volume) and achieved $6.5\%/\sqrt{E^{[3]}}$

Tracker and Imaging Pre-Radiator

Preceding the calorimeter is a tracker and imaging pre-radiator. The pre-radiator consists of alternate superlayers (z, u, v) of scintillating fibers and lead sheets. The tracker includes three scintillating fiber superlayers. Fig. 3 shows the conceptual design of the tracker pre-radiator system. Fiber readout will be either by pixellated Silicon Intensified Target tubes or by avalanche photodiode arrays. Both are being investigated. The tracker/pre-radiator system occupies a cylindrical region between radii of 1 m and 2 m. The innermost cylindrical volume is not instrumented, leaving space for a high resolution vertex detector which could be added later if the physics so dictates.

The tracker is composed of 3 $zuvzuv$ plastic scintillating fiber (PSF) superlayers. At $\eta = 0$, the first superlayer is at a radius of 1.0m, the second at 1.4m and the third at 1.8m. At the outer radius of the tracker there are 9 zuv PSF layers separated by thin (≈ 2 mm) lead sheets so that the early part of the shower development can be measured and tracked accurately. The tracker therefore merges into the first part of the calorimeter to form an imaging pre-radiator.

Signals from the tracking system are extracted along a narrow non-projective readout path in the calorimeter at $\eta = 0$. The tracking detector, and per force the whole detector, will be constructed in two mirror sections. Signals are read out either optically, in which case scintillating fibers will be spliced to optical fibers and the electro-optical devices will be outside the calorimeter and in a relatively low radiation region, or electrically, in which case the electro-optical devices will be on the inside of the calorimeter.

It should be emphasized that the requirements placed on a tracking system inside a non-magnetic detector are much less stringent than those for a tracker in a magnetic field. In the case of a magnetic tracker, the need for an accurate determination of the sagitta of a curving track requires the best possible resolution. In a non-magnetic detector it is sufficient to identify straight tracks. We believe that 1mm diameter fibers are adequate for this system. With the above stated dimensions, the tracker section has $\approx 2 \times 150,000$ channels and the pre-radiator has $\approx 2 \times 300,000$ channels.

The imaging pre-radiator is approximately $2.5 L_{rad}$ thick and provides fine grained transverse and longitudinal electromagnetic shower sampling in 9 superlayers. The transverse resolution is determined by the size of the fibers used. Neighboring layers will be offset by half a fiber spacing. The longitudinal sampling must be sufficient to separate electrons from hadrons to better than 1% and deep

enough to allow, for approximately 95% of cases, both photons from a π^0 to have converted. The exact pre-radiator lead and fiber thicknesses have yet to be determined and will be chosen so as to preserve the compensation of the entire calorimeter.

Muon Spectrometer

For the measurement of muon energies we propose the use of transition radiation techniques sensitive to $\gamma \equiv E_\mu/m$ (an unsaturated observable at SSC energies). Transition radiation devices offer a unique alternative with broad η acceptance at a fraction of the cost of a magnetic device. There is indeed a compromise in resolution, but this is compensated by the superior resolution for electrons and the presumption of $e - \mu$ universality.

Muon detection and measurement are essential for confirming the universality of lepton decay channels of the Higgs, for a missing energy calculation in the fast trigger and for new physics signatures in general. Normally the electron channels observed with the exceptional calorimetric resolution will always have equivalent muon channels. Because muon identification has such a large confidence level, confirmation of electron modes in the muon channel is essential. The muon energy range of interest is from 60-600 GeV (gamma of $\approx 600 - 6,000$) for most heavy mass physics, a very modest dynamic range. Essentially 90% of all muons from the Higgs decay are found between 100 GeV and 600 GeV for M_H between 400-800 GeV.

At the SSC, practically all muons below 60 GeV are from c and b decay. Their rate ($\sim 10^4$ Hz for $p_T < 10$ GeV. Furthermore, charge discrimination is useful, but not overwhelmingly so. Above 400 GeV masses, only a factor of 2-3 reduction in the diboson mass background is achieved by knowing the sign of the charge of a particle (before any lepton discrimination cuts).

The TRD muon-momentum analysis borrows its detailed implementation from that of a large-area muon detector of similar size [4]. Liquid scintillator slabs would provide prompt signals with good timing resolution for associating streamer tube tracks in (ϕ, θ) and TRD hits with calorimeter hits in a $2\mu s$ trigger pipeline. The TRD spectrometer gives better than 10% resolution at 200 GeV (as seen in Fig. 4 which shows typical TRD yields as a function of gamma. The TRD spectrometer information can then be used in conjunction with the scintillating fiber calorimeter to give a high-level missing E_T trigger.

In contrast to the measurement of a particle's momentum by measuring its sagitta as it is deflected in a magnetic field which decreases with energy, the TRD yield increases with gamma. With sufficient radiator a TRD provides a natural way to measure momentum at high gamma. The TRD yield at saturation achieved in recent systems is about 25-30 X-rays above a 4 KeV threshold per meter

of detector thickness^[5]. The detector sets are typically ≈ 9 cm radiator, either polyethylene foam or embossed polypropylene films, to 1 cm of Xe-proportional gas detector (see Figure 5 for details). Recently foams with very uniform cell and wall sizes have been used, achieving 85% of the ideal TRD yield. The maximum quasi-linear response range for a TRD is 20:1, corresponding typically to γ 's of 500 to 10,000. This fortuitously corresponds to muon momenta from 50-1,000 GeV. Further, a dE/dx measurement in the relativistic rise region is sensitive over a muon energy range of ~ 10 –100 GeV. Figure 6 shows the muon momentum resolution achievable with this TRD system over the momentum range of 50 – 600 GeV/c.

Conclusion

We have presented here an SSC detector concept with precision calorimetry as the guiding aspect of the design. Its performance is not compromised by the constraints imposed by a magnetic spectrometer. TEXAS offers the possibility of operation at high luminosity and has precise calorimetry, both essential for full coverage of the natural range of Higgs masses. The features demanded by the physics: speed, energy resolution, segmentation, full rapidity coverage, uniformity, stability and hermeticity make this specialized detector concept attractive, and complementary to other designs. The conceptual simplicity of our three-basic-component detector facilitates construction, access and design. This specialized and cost-effective detector will be sensitive to most of the new physics anticipated at the SSC, and can be ready at start-up time.

TABLE 1

Anticipated Detector Performance and Physics Reach

In our discussion below we have characterized the TEXAS detector in the following manner:

Tracking System and Imaging Preradiator:

- Spatial Resolution = < 1 mm
- Speed = < 15 ns
- Coverage = $|\eta| < 3$
- e/π rejection = 30
- γ/e rejection = 100
- γ/π^0 rejection = 10
- Electron efficiency = 0.99

Electromagnetic Calorimeter:

- Resolution = $7\%/\sqrt{E} + 0.5\%$
- Speed = < 15 ns
- Coverage = $|\eta| < 3$
- Segmentation = $0.03\eta \times 0.03\phi$
- e/π rejection = 300
- Electron efficiency = 0.95

Hadronic Calorimeter:

- Resolution = $35\%/\sqrt{E} + 1\%$
- Speed = 20 ns
- Coverage = $|\eta| < 3$
- Segmentation = $0.05\eta \times 0.05\phi$
- $e/h = 1.0 \pm 0.05$

Forward Calorimeter:

- Resolution = $30\%/\sqrt{E} + 2\%$
- Speed = 20 ns
- Coverage = $|\eta| < 5.5$

Muon $S/A\alpha/A$ spectrometer:

- Resolution = 15% for $p > 0.1$ TeV/c, $\approx 0.15\%/p^2$ for $0.05 < p < 0.1$
- Speed = 100 ns
- Coverage = $|\eta| < 3$

References

1. See various Snowmass and LHC Workshops on this subject. E. Eichten et al., *Rev. Mod. Phys.* **56**, 579(1984),
Proceedings of the 1984 Snowmass Workshop on the Design and Utilization of the Superconducting Super Collider, edited by R. Donaldson and J.G. Morfin,
Proceedings of the 1986 Snowmass Workshop on "Physics of the Superconducting Super Collider", edited by R. Donaldson and J. Marx,
Proceedings of the 1987 Berkeley Workshop on "Experiments, Detectors and Experimental Areas for the Supercollider", edited by R. Donaldson and M. Gilchriese,
Proceedings of the 1988 Snowmass Workshop on "High Energy Physics in the 1990s",
Proceedings of the ECFA-CERN Workshop on the LHC, Lausanne, March 1984, CERN 84-10,
Proceedings of the Workshop on Physics at Future Colliders, CERN 87-07, La Thuile (1987),
Feasibility of Experiments at High Luminosity at the Large Hadron Collider, edited by J. Mulvey, CERN 88-2 (1988),
J. Gunion et al. *The Higgs-Hunters Guide*, UCD 89-4 (1989),
P. Jenni, *Aspects of Jets and Calorimetry at Future Hadron Colliders*, Barcelona, Sept. 1989, and CERN-EP/89-148, Nov. 1989.
2. H. Paar, "Status of Scintillating Fiber Calorimetry" in *Proceedings of Barcelona ECFA Meeting*, Sept. 1989.
3. D. Hertzog, "Scintillating Fiber Calorimetry" in *Proceedings of Tallahassee Workshop on Radiation Damage to Scintillator*, edited by K. Johnson (1990).
4. The MACRO Detector, Gran Sasso Laboratory.
5. A. Vorobyov, private communication and B. Dolgoshein et al. NIM 252, 137 (1986), B. Dolgoshein, private communication, P. Spinelli, private communication.

TEXAS SSC DETECTOR HALL Elevation View

Figure 1: Overview of the TEXAS experiment in a typical SSC experimental hall.

Figure 2: Detailed assembly of a single fiber calorimeter supertower. This figure shows the calorimeter as being composed of an electromagnetic and hadronic parts.

TEXAS SSC CALORIMETER 1/4 Central Tracker and Preradiator

1mm Scintillating Fibers
axial and 115°

Figure 3: Schematic design of the scintillating fiber tracker preradiator for the TEXAS experiment.

Figure 4: X-Ray output from a single TRD module stack. These Data are taken from Ref. 5.

Figure 5: Detail of a segment of the muon TRD spectrometer. This figure shows the area around the inner radius of the spectrometer, indicating the muon tracking chambers as well as the liquid scintillation counter used for fast triggering.

Muon Momentum Resolution in TEXAS Detector

Figure 6: A calculation of the muon momentum resolution achievable with the TRD system in conjunction with a dE/dx measurement in the TRD chambers.

V. Theoretical Physics Program

Since the beginning of the last funding cycle, a theoretical physics task has been added to our existing experimental high energy physics program. This theoretical work is being carried out by Professors Nanopoulos and Pope. In the section that follows we present a report of the activities that these two researchers have carried out under this program and their plans for the coming funding cycle.

Research carried out by D. V. Nanopoulos during 1989-90

My research line during the past academic year has gone through several points that can be described as follows: (1) Flipped Physics; (2) 4-D Superstring-related physics; (3) Phenomenology; (4) Cosmology, and finally (5) Quantum Mechanics. Let us analyze each of these in detail.

FLIPPED PHYSICS

A few years ago we suggested stringy flipped SU(5) as a candidate for the Theory of Everything (TOE) [1]. Our suggestion was based on a very simple observation that was shared by all known superstring theories: There is no adjoint Higgs particles in superstring theories [2], at least at level $K=1$ of the associated Kac-Moody Algebra, which basically encompasses all known string theories. Then there is only one available GUT that does not need adjoint Higgs to breakdown to the standard model: flipped SU(5), in the specific form suggested many years ago [3]. Then all our efforts concentrated on how to derive a satisfactory stringy flipped SU(5) model. After several tries [4], we succeeded to get a very satisfactory model: revamped flipped SU(5) [1]. The properties of this model are so extraordinary that it has become indeed the leading candidate for TOE. It is a three-generation model that contains a natural missing partner mechanism, natural see-saw mechanism, it provides natural large fermion masses for the third generation (m_t, m_b, m_τ) while it gives no masses for the other two generations at the classical level. Furthermore using a set of rules that we derived at Texas A&M with my group (S. Kalara and J. Lopez) [5], we have been able to calculate, for the first time, in string theories, explicitly the contribution of nonrenormalizable terms ((NRT) massive string modes exchange) on the above described tree-level structure. The results are rather fascinating. (i) The NRT not only do not upset our tree-level results but they do keep all F- and D-flat directions to any (possible) calculable level, i.e. stability. (ii) The NRT provides naturally small fermion masses for the first two generations [6,7], i.e. an hierarchical fermion mass spectrum emerges naturally.

(iii) We were able to calculate the effect of NRT to nuclear decay and despite naive expectations, we proved explicitly that our revamped flipped SU(5) model is free of any fast nucleon decay problem [8]. Furthermore, we found that the dominant decay modes are $p \rightarrow e^+ \pi^0, n \rightarrow e^+ \pi^-$, etc. with a lifetime in the $10^{33} - 10^{35}$ years, with specific B.R. and accesible to experimental scrutiny.

In a different front, we prove explicitly that in our model charge quantization is obeyed both at the massless and massive string modes [9]. This amazing result occurs because our “hidden sector” confines (a la QCD) and makes only 1 under all confining groups to be observable. This fact has some interesting consequences, like the existence of a new form of matter that we call cryptons, and may serve also as Dark Matter in the Universe. (More on these particles in the Cosmology section). All in all, this stringy revamped flipped SU(5) model has really gone far beyond our initially expectations and I hope I justified my initial assessment that has become the leading candidate for TOE.

4-D SUPERSTRING RELATED PHYSICS

As I mentioned above, (see [5]) we established the rules how to calculate the effects of nonrenormalizable terms (NRT) in the free-fermionic-formulation of 4-D heterotic superstring theories. This achievement opened the way for a real confrontation of string-derived low energy physics with experiment. We may soon know if the low-energy behavior of the string makes any physical sense or not. As I indicated above (1), the first results are rather encouraging.

Also we undertook a systematic analysis of $K > 1$ K-M algebras and their phenomenological consequences [10]. The results are rather disappointing: it looks like that $K > 1$ K-M algebras have a hard time to reconcile with established low-energy results, i.e. charge quantization and $\sin^2 \theta_w \approx 0.23$, etc. That is, in a different language, our analysis [10] reinforce the importance of $K=1$ K-M algebras and thus, as explained above (1), of revamped flipped SU(5) [5].

On a very different wavelength, I have tried with my students, A. Faraggi and K. Yuan, to get the standard model directly from the 4-D superstring without going through a GUT model [12]. We have succeeded in deriving a standard-like type of model, but more work needs to be done in order to claim that we have a successful model. Nevertheless it is interesting how powerful is the free-fermionic formulation of 4-D superstrings in getting physics out and to compare with our low energy experimentally accessible world.

We also looked at the problem of strong CP in string theories [13]. We found that many of the usual tricks do not work, while a virtually massless up quark may save the day. We have also tried to address the problem of SUSY breaking at the string level. Motivated by our flipped SU(5) model, we considered the generic possibility that there are “hidden group” states that carry U(1) charges that are also carried by the “observable sector” states. In such a case we found [11] that the SUSY breaking in the “hidden sector” can be communicated to

the “observable sector” by renormalizable, and thus calculable interactions. We found some interesting characteristics of this mechanism that reflects on the type of the SUSY spectrum that one gets at low energies and thus can be put under experimental scrutiny.

PHENOMENOLOGY

One of the “happenings” of the last year was the discovery of SLC and LEP that there are only three, left-handed, light neutrinos, confirming a prediction of GUTs we made more than ten years ago [14]. Naturally, I devoted some time working on further consequences [15] of these new experimental results. Furthermore, we tried to put limits on new possible particles like the Z' [16] or SUSY particles [15] or the Higgs sector [17] emerging from very rich LEP data. Actually very recently we discovered [18] that precise LEP measurements of $\sin^2\theta_w(M_Z)$ and $\alpha_3(M_Z)$, while are in contradiction with ordinary GUT theories, are consistent, in an amazing way, with SUSY GUTs. Furthermore, these values of $\sin^2\theta_w(M_Z)$ and $\alpha_3(M_Z)$ in a SUSY GUT theory predict the right value for $\frac{m_b}{m_s}$ for a rather heavy top quark in agreement with experiment. We suggested [18] that maybe we already have seen the first, indirect hints for the existence of supersymmetry.

On another front we put to rest [19] several claims that the electric dipole moment of the neutron d_n in SUSY theories is several orders larger than the experimental upper bound of $10^{-26} e \cdot cm$. We proved, [19] once more, that d_n in SUSY theories is sufficiently suppressed to satisfy all experimental limits, while it would be larger than the standard model thus making a clear distribution between SUSY and the standard model (see also [13]).

COSMOLOGY

Some part of my activity on this front was related with the cosmological consequences of the LEP results. For example, we used the fact that there are only 3 neutrinos together with primordial nucleosynthesis constraints to put interesting limits on the Z' mass and couplings [20]. We used the measured Z - decay width to exclude a lot of Dark Matter candidates (DM) including sneutrinos, or massive neutrinos and at the same time put stringent constraints on the SUSY candidates, e.g.: photinos, higgsinos, etc. [21]. Our analysis has far reaching consequences on the presently available or soon to be available DM detectors because our findings indicate that they have become already obsolete by the LEP data. Since the LEP data indicate rather “heavy” neutralinos, we decided to calculate in full detail the relic density of these photinos [22]. Since in most SUSY models there is a strong correlation between the neutralinos mass and other, experimentally accessible, SUSY particles masses, our findings have interesting consequences for the search of these particles at present colliders (CDF, UA2) or future ones (SSC, LHC,...). Also, as I mentioned above, (1), we found [9] a new class of particles in the revamped flipped SU(5), the cryptons that can be worth candidates of

dark matter. It is interesting that their existence is a direct consequence of the charge quantization, as realized in a class of string theories, and thus their possible discovery will be very strong circumstantial evidence for the string.

On a more theoretical front we have studied [23] in detail the possible phase transitions in the string, by using the language of effective field theories, which has been successfully applied in the QCD quark-hadron or other type of phase transitions. We believe we have clarified certain dark points and have discovered a useful way to penetrate into the difficult regions of string phase transition(s).

QUANTUM MECHANICS

Continuing our previous work [24] on the collapse of the wave function due to gravitational effects (e.g. wormholes) we suggested some experiments to test this hypothesis [25]. Indeed, we found that if wormholes cause loss of coherence then their effects in a SQUID could be observable [25]. Our calculations indicate that while for a microscopic system (e.g. the electron) QM remains valid, when we approach a macroscopic system with $N(\approx \frac{M_{Pl}}{m_e})$ constituents, worm-holes cause the collapse of the wavefunction. If we are right, not only we have, for the first time, a "derivation" of the Avogadro number $N_A \approx \frac{M_{Pl}}{m_e}$, but we have a natural understanding of the collapse of the wavefunction and thus a resolution of the measurement problem of Q.M. etc. The experiment we proposed [25] are feasible and may provide us with another way of dealing with physics at the Planck scale ($M_{Pl} \sim 10^{19} GeV$).

I have presented my activity in such a way that makes my future line of research apparent. I'll try with my group(s) to push flipped physics all the way to be confronted with experiment and get our predictions on fermion masses, CKM angles, CP-violation phases,... At the same time progress in SUSY breaking in strings, make us to believe that we will come with very "hard" numbers on the SUSY spectrum. I'll try also to understand more, and work further on the calculability of NRT, whose importance is tantalizing in every aspect of string physics. My untamed interest on hard core phenomenology will bring some calculations on SSC physics as well as further analyzing the consequences of fresh LEP data. My cosmological interests will concentrate on further constraints (and possible new candidates) on (of) DM, while we will continue our big programme of understanding string phase transitions. Our QM enterprise has taken us to rather uncharted waters and we plan to continue our program of understanding the collapse of the wavefunction in terms of gravitodynamics and suggest new experiments to test these ideas.

I would like to stress the fact that since I am involved in many projects with different groups in USA and Europe, it is essential for my research a strong travel support.

Research carried out by C.N. Pope during 1989-1990

My work during the last year has predominantly been concerned with various aspects of infinite-dimensional symmetries. Such symmetries have played a very important rôle in recent developments in many areas, including, for example, string theory, Chern-Simons higher-spin theories in $2 + 1$ dimensions and membrane theories.

The rôle of the Virasoro algebra in string theory is very well known and understood. It is the algebra generated by the energy-momentum tensor for a conformally-invariant two-dimensional matter system, such as the set of spacetime coordinates forming the target space for a string. This two-index tensor couples to the worldsheet metric tensor of the two-dimensional theory, and so one can think of the Virasoro algebra as being a “spin-2” algebra. It is natural then to think of extending the Virasoro algebra to include generators corresponding to spins greater than 2.

The first example of such an algebra was constructed by Zamolodchikov [26], who added a new field $W(z)$, with conformal spin 3, to the Virasoro system generated by $T(z)$. The algebra of these fields, known as W_3 , has the unusual feature of being non-linear; structurally, the form of the operator-product expansion $W(z)W(w)$ is $\Lambda + T$, where Λ is a “composite” spin-4 field that is built from an appropriately normal-ordered product of two T fields. The necessity for the non-linear terms is clear from the fact that the commutator of generators of conformal spins s and s' is itself of conformal spin $s + s' - 2$. Therefore as soon as one introduces fields of spins greater than 2, the commutators can always generate terms with spins higher than those of the commuted generators. Only by interpreting the higher-spin terms as composite fields can an algebra that terminates at a finite spin level be constructed. Higher-spin W_N algebras, with generators of spins $2, 3, \dots, N$, have also been built [27].

The non-linearities of the W_N algebras lead to severe complications when one tries to work with them. Indeed, it is only for a few small values of N that they have been explicitly constructed. This has motivated an interest in looking at W_N in the $N \rightarrow \infty$ limit. The argument given above for the necessity of non-linear terms in higher-spin algebras clearly allows a loophole if one is prepared to admit generators with arbitrarily-high spins. One can indeed find linear algebras by taking appropriate $N \rightarrow \infty$ limits of W_N . The first example [28], now known as w_∞ , has the very simple structure

$$[v_m^i, v_n^j] = ((j+1)m - (i+1)n) v_{m+n}^{i+j}, \quad (1)$$

where v_m^i denotes the m 'th Fourier mode of a spin- $(i+2)$ generator.

The process of taking the limit $N \rightarrow \infty$ of the W_N algebras is not a unique one. The w_∞ algebra described above is the simplest such limit, in which much of

the structure of the W_N algebras is lost. In particular, although the W_N algebras have central terms for generators of all spins ≥ 2 , the central charges in all sectors except the spin-2 sector get scaled to zero in the process of taking the limit.

In some research with L. Romans and X. Shen, during the last year we have been investigating alternative $N \rightarrow \infty$ limits of W_N that capture more of the essential features of the finite- N cases. We have found that there is indeed another linear algebra, which we call W_∞ , that can be viewed as a limit of W_N and which admits central terms for all spins. In view of our experience with string theory, we would certainly expect that if W_∞ is to be a symmetry algebra for some extended quantised system, it would be desirable, from the point of view of obtaining non-trivial representations for physical states, that the algebra should admit such extensions. The previously-mentioned algebra w_∞ arises as a contraction of W_∞ , and can be viewed as the classical limit of W_∞ .

Our original construction of W_∞ proceeded by writing down an *ansatz* for the algebra, whose form was motivated by the structure of the finite- N W_N algebras, and then demanding that the structure constants and central terms should be consistent with the Jacobi identities. This leads uniquely to the result

$$[V_m^i, V_n^j] = \sum_{r \geq 0} g_{2r}^{ij}(m, n) V_{m+n}^{i+j-2r} + c_i(m) \delta^{ij} \delta_{m+n, 0}, \quad (2)$$

where the structure constants $g_{2r}^{ij}(m, n)$ are given in terms of certain Saalschützian ${}_4F_3$ generalised hypergeometric functions, and the central terms $c_i(m)$ are polynomials in m of degree $2i + 3$, with i -dependent coefficients [29]. The sequence of terms on the right-hand-side of (2), with descending conformal spins, terminates at spin 2 or 3, owing to the occurrence of non-trivial zeros in the hypergeometric functions. Subsequently, we found that there exists another algebra, which we call $W_{1+\infty}$, that contains generators with all conformal spins ≥ 1 [29,30]. It has the same general form as (2), but with differences in the parameters of the generalised hypergeometric function which lead to a termination of the terms on the right-hand side with spin 1 or 2. We have also constructed a supersymmetric extension, known as super- W_∞ [31].

In [32], it was shown that the W_∞ algebra can be realised in terms of currents $V^i(z)$ constructed from appropriate combinations of $i + 2$ derivatives distributed over bilinears in a free complex scalar field φ : $V^i(z) \sim \partial^{i+2-n} \varphi^* \partial^n \varphi$. Similarly, the $W_{1+\infty}$ algebra can be realised in terms of bilinears in a free complex fermion. Putting the two together, and including also the mixed bilinears involving the scalar and the fermion, we constructed, in collaboration also with E. Bergshoeff and E. Sezgin, an $N = 2$ supersymmetric extension of these algebras, known as super W_∞ .

Very recently, Romans, Shen and I have looked at the BRST charge for these various algebras, and examined the conditions under which they are anomaly

free (i.e. when $Q^2 = 0$). Owing to the existence of infinite numbers of higher-spin fields in these algebras, the ghost contributions to the anomalies contain infinitely-many terms, giving rise to divergent expressions for the central charge. One can regularise these sums using the Riemann zeta function, to obtain finite answers. In the calculation of Q^2 , one finds that there are an infinite number of such anomaly terms, all of which must vanish for the same value of the central charge if the regularisation procedure is a consistent one. Some results for a few of these anomalies were obtained for W_∞ in [33], where it was found that anomaly-freeness seemed to imply that the central charge in the Virasoro sector should take the value $c = -2$. We extended these results [34] by formulating a general prescription for regularising all the anomaly terms, and showing by algebraic-computing techniques that our prescription seems consistently to give the same result, $c = -2$. Applying the same techniques to the other algebras, we find $c = 0$ for $W_{1+\infty}$, and $c = -2$ (corresponding to total spin-2 central charge -3) for super W_∞ . In all cases, the regularised value of the intercept α_0 (the ground-state energy) is zero.

The fact that there exists a consistent regularisation scheme for the BRST charge strongly suggests that there should be some underlying quantum field theory that provides an anomaly-free realisation of the W symmetry. This is reminiscent of Kaluza-Klein theory, where there are examples in which a divergent sum over one-loop ultraviolet divergences for a four-dimensional tower of fields can be regularised to zero, a result that can be understood from a higher-dimensional viewpoint where the finite number of fields have no one-loop ultraviolet divergences [35]. Thus it may be that the proper arena for interpreting the anomaly-free W algebras is in terms of some theories formulated in greater than two dimensions, where all the higher-spin fields are unified into a finite number of higher-dimensional fields. The necessity to regularise the central charges in the BRST calculations described above may then be seen as an artefact of viewing the theories from a two-dimensional standpoint.

One suggestion for a higher-dimensional theory that may be associated with the W algebras is self-dual gravity in four dimensions [36,37]. Self-duality of the Riemann tensor requires that the spacetime signature be either $(4,0)$ (Euclidean signature) or $(2,2)$. The former case was studied extensively some years ago in the context of Euclidean quantum gravity, but the latter has been largely neglected until recently. It has received recent attention both in the context of W gravity, and also as the target space for the $N = 2$ superstring theory [38]. It may, indeed, be the case that these two subjects are intimately related.

In work with Bergshoeff, Romans, Sezgin, Shen and Stelle, we have constructed two-dimensional gauge theories of the various $N = \infty$ w , W and super- W algebras [39,40]. These can be thought of as higher-spin generalisations of two-dimensional gravity, itself a topic that has seen great advances during the last year. In some of this work, we have obtained some supportive evidence for the

idea that there should exist a four-dimensional interpretation for these theories.

Other work that I have completed during the last year has been concerned with a study of the unitarity properties of certain gauged sigma models that can be derived from Chern-Simons theories in $2+1$ dimensions [41], an investigation of the area-preserving algebras associated with certain non-orientable two-dimensional surfaces, and some work on deriving the constraints for ten-dimensional supergravity from the requirement of light-like integrability in a loop superspace [42].

Intended research by C.N. Pope

The discovery of W_∞ and related algebras has opened up a wide field for research. Broadly speaking, there are two main areas of interest; one is concerned with the study of the representation theory of the algebras themselves, and the other is concerned with constructing field-theoretic realisations of the algebras.

The representation theory of the Virasoro algebra has proved a rich area for investigation. The work of Friedan, Qiu and Shenker [43], and others, led to a classification of all the unitary representations of the algebra, and to the construction and understanding of associated conformal-field-theoretic models. The W_N algebras and their large- N limits can be expected to be associated with extended higher-spin conformal field theories in two dimensions. I intend to investigate some of these issues further, with a view to gaining insights into the underlying representation theory. In particular, this will include an investigation of the structure of null states in the $N \rightarrow \infty$ limit.

So far, work on field-theoretic realisations of the W algebras has been centred around the so-called W -gravity theories described earlier, in which two-dimensional higher-spin gauge fields corresponding to all the generators of the algebra are introduced. The resulting theories can be viewed as extensions of two-dimensional gravity. One intriguing problem that arises is to try to formulate the theory in a "covariant" way. For gravity, we know what is meant by this: we should augment the two gauge-field components h_{++} and h_{--} that one originally introduces to gauge the left-handed and right-handed copies of the Virasoro algebra by additional gauge degrees of freedom, to make up the three components of a two-dimensional metric tensor, or the four components a two-dimensional vielbein. These extra components are associated with further gauge symmetries, namely Weyl and Lorentz symmetries, that may be used to gauge them away. The utility of introducing the extra "dummy" gauge fields is partly because the classical theory can then be formulated in a more manifestly-covariant way, and partly because on quantisation, the anomalies can conveniently be pushed into the "dummy" sector (the Weyl-symmetry sector).

In recent work with Bergshoeff and Stelle, I investigated the question of what one means by "covariance" for the higher-spin sectors of W gravity [44]. We were able to give a simple derivation of previous results [45] for a "covariant" gauging

of w_∞ , by introducing additional “dummy” degrees of freedom for the higher-spin gauge fields. The next step, which I intend to pursue in the next year, is to look at the quantisation of the theory, and study its anomalies. Hopefully, if the higher-spin “dummy” gauge fields have been correctly identified, we should find that the quantum anomalies can be relegated to the associated higher-spin analogues of the Weyl and Lorentz symmetries.

The work on the BRST anomaly-structure for the W algebras reported above [34], in which the values of the regularised central charges for anomaly-freeness of the algebras are derived, suggests some possible ideas for how to obtain anomaly-free field theoretic realisations. One idea, discussed in [34], is that there may exist an anomaly-free theory in which W_∞ is realised on a complex fermion. Since $W_{1+\infty}$ is anomaly free for a regularised central charge $c = 0$, it may be that this algebra would be associated with a purely geometrical or topological theory, with no matter fields at all. This may be a further piece of evidence in support of the idea that there is link with self-dual gravity in four dimensions [36,37]. One possible avenue for exploration is to see whether an interpretation of the BRST anomaly as the curvature of a ghost line bundle might lead to a link with a field theory of W_∞ or $W_{1+\infty}$. A further related project that I am developing is concerned with the construction of a theory of topological W gravity, along the lines of the W_N constructions given in [46].

Self-dual gravity is an interesting area of study in its own right. In particular, a new ingredient suggested both by W gravity, and by the $N = 2$ superstring [38], is that one should look at self-dual gravity in $(2, 2)$ spacetime signature. This is a fascinating, and little explored area. I am already involved in a project with G.W. Gibbons and M.J. Perry in which we are trying to apply some of the ideas previously developed in the study of gravitational instantons, and twistor theory, to this topic.

REFERENCES

1. D. Nanopoulos, I. Antoniadis, J. Ellis, and J. S. Hagelin, "The Flipped SU(5)XU(1) String Model Revamped", Phys. Lett. **231B**, 121 (1989).
2. D. Nanopoulos, H. Dreiner, J. L. Lopez and D. Reiss, "No Massless Scalar Adjoints for $N = 1$, $D = 4$ Heterotic Strings in the Free Fermionic Formulation", Phys. Lett. **216B**, 283 (1989).
3. D. Nanopoulos, J. P. Derendinger and J. E. Kim, "Anti-SU(5)", Phys. Lett. **139B**, 170 (1984).
4. D. Nanopoulos, I. Antoniadis, J. Ellis and J. S. Hagelin, "Supersymmetric Flipped SU(5) Revitalized", Phys. Lett. **194B**, 231 (1987); D. Nanopoulos, I. Antoniadis, J. Ellis and J. S. Hagelin, "GUT Model-Building with Fermionic Four-Dimensional Strings", Phys. Lett. **205B**, 459 (1988), and, D. Nanopoulos, I. Antoniadis, J. Ellis and J. S. Hagelin, "An Improved Flipped SU(5) x U(1) Model from Four-Dimensional String", Phys. Lett. **208B**, 209 (1988).
5. D. Nanopoulos and J. Lopez, "Nonrenormalizable Terms in the Free Fermionic Formulation of 3D Strings", Phys. Lett B **245**, 421 (1990); and, D. Nanopoulos, S. Kalara and J. Lopez, "Calculable Nonrenormalizable Terms in String Theory: A Guide to the Practitioner", Texas A&M University preprint CTP-TAMU-34/90 and ACT-5.
6. D. Nanopoulos and J. Lopez, "Hierarchical Fermion Masses and Mixing Angles from the Flipped String", Nucl. Phys. **B332**, 73 (1990).
7. D. Nanopoulos and J. Lopez, "Decisive Role of Nonrenormalizable Terms in the Flipped String", Texas A&M University preprint CTP-TAMU-59/90 and ACT-10, Phys. Lett. B, in press.
8. D. Nanopoulos, J. Ellis, and L. Lopez, "Baryon Decay: Flipped SU(5) Surmounts Another Challenge", Texas A&M University preprint CTP-TAMU-73/90, ACT-12 and CERN-TH 5852/90, Phys. Lett. B in press.
9. D. Nanopoulos, J. Ellis, and J. Lopez, "Confinement of Fractional Charges Yields Integer-Charged Relics in String Models", Texas A&M University preprint CTP-TAMU-52/90, ACT-8 and CERN-TH 5777/90, Phys. Lett. B in press.
10. D. Nanopoulos, J. Ellis and J. Lopez, "Constraints on Grand Unified Superstring Theories" Phys. Lett B **245**, 375 (1990).
11. D. Nanopoulos, I. Antoniadis, J. Ellis and A. B. Lahanas, "A New Approach to Supersymmetry Breaking in Superstring Models", Phys. Lett. **241B**, 24 (1990).
12. D. Nanopoulos, A. Faraggi and K. Yuan, "A Standard-Like Model in the 4D Free Fermionic String Formulation", Nucl. Phys. **B335**, 347 (1990).
13. D. Nanopoulos and J. Lopez, "Can an Anomalous U(1) Solve the Strong CP Problem?", Phys. Lett. B **245**, 111 (1990).

14. D. Nanopoulos, A. Buras, J. Ellis and M. K. Gaillard, "Aspects of the Grand Unification of Strong, Weak and Electromagnetic Interactions", Nucl. Phys. **B135**, 66 (1977); D. Nanopoulos and D. A. Ross, "Limits on the Number of Flavours in Grand Unified Theories from Higher Order Corrections to Fermion Masses", Nucl. Phys. **B157**, 273 (1979); D. Nanopoulos and D. Ross, " m_b/m_ρ : A Sensitive Flavour-Meter", Phys. Lett. **108B**, 351 (1982); and, D. Nanopoulos and D. A. Ross, " b/m_ρ in Supersymmetric GUTs: Superflavour-Meter", Phys. Lett. **118B**, 99 (1982).
15. D. Nanopoulos and J. Lopez, "Three Generations: A Prediction Fulfilled", Mod. Phys. L. **A5**, 645 (1990).
16. D. Nanopoulos and A. Faraggi, "A Superstring Z' at 0(1 TeV)?", Texas A&M University preprint CTP-TAMU-69/89.
17. D. Nanopoulos and J. Lopez, "New Bounds on the Higgs Sector of Minimal SUSY", Mod. Phys. L. **A5**, 1259 (1990).
18. D. Nanopoulos, J. Ellis, and S. Kelley, "Precision LEP Data, Supersymmetric GUTs and String Unification", Texas A&M University Preprint CTP-TAMU-60/90, ACT-11 and CERN-TH 5773/90. Phys. Lett. in press.
19. D. Nanopoulos, R. Arnowitt and J. Lopez, "The Electric Dipole Moment of the Neutron in Supersymmetric Theories", Phys. Rev. D **42**, (1990), to appear.
20. D. Nanopoulos and J. Lopez, "Primordial Nucleosynthesis Corners the Z'", Phys. Lett. **B241**, 392 (1990).
21. D. Nanopoulos, J. Ellis, L. Roszkowski and D. Schramm, "Dark Matter in the Light of LEP", Phys. Lett. B **245**, 251 (1990).
22. D. Nanopoulos, J. Lopez, L. Roszkowski, and K. Yuan, "Supersymmetric Dark Matter Below the W Mass", Texas A&M University preprint CTP-TAMU-76/90 and ACT-13.
23. D. Nanopoulos, B. Campbell, J. Ellis, S. Kalara and K. Olive, "Phase Transitions in QCD and String Theory", Texas A&M University preprint CTP-TAMU-36/90, ACT-3, and CERH-TH 5833/90.
24. D. Nanopoulos, J. Ellis, J. Hagelin and M. Srednicki, "Search for Violations of Quantum Mechanics", Nucl. Phys. **B241**, 381 (1983); and, D. Nanopoulos, J. Ellis and S. Mohanty, "Quantum Gravity and the Collapse of the Wave Function", Phys. Lett. **221B**, 113 (1989).
25. D. Nanopoulos, J. Ellis, and S. Mohanty, "Wormholes Violate Quantum Mechanics in SQUIDS", Phys. Lett. **235B**, 305 (1990).
26. A.B. Zamolodchikov, Teo. Mat. Fiz. **65** (1985) 347.
27. V.A. Fateev and S. Lukyanov, Int. J. Mod. Phys. **A3** (1988) 507.
28. I. Bakas, Phys. Lett. **228B** (1989) 57.
29. C.N. Pope, L.J. Romans and X. Shen, Phys. Lett. **236B** (1990) 173; Nucl. Phys. **B339** (1990) 191; Phys. Lett. **245B** (1990) 72.
30. C.N. Pope, L.J. Romans and X. Shen, Phys. Lett. **242B** (1990) 401.

31. E. Bergshoeff, C.N. Pope, L.J. Romans, E. Sezgin and X. Shen, Phys. Lett. **245B** (1990) 447.
32. I. Bakas and E. Kiritsis, "Bosonic realisation of a universal W -algebra and Z_∞ parafermions," preprint, UCB-PTH-90/8.
33. K. Yamagishi, " $\widehat{W}_\infty$ algebra is anomaly free at $c = -2$," preprint, LLNL/HEP05 (1990).
34. C.N. Pope, L.J. Romans and X. Shen, "Conditions for anomaly-free W and super- W algebras," preprint, CTP-TAMU-71/90.
35. M.J. Duff and D. Toms, in: *Unification of the fundamental particle interactions II*, Eds. S. Ferrara and J. Ellis (Plenum, New York 1982);
G.W. Gibbons and H. Nicolai, Phys. Lett. **143B** (1984) 108;
T. Inami and K. Yamagishi, Phys Lett. **143B** (1984) 115.
36. E. Witten, "Surprises with topological field theories," preprint, IASSNS-HEP-90/37.
37. Q-H. Park, Phys. Lett. **238B** (1990) 287.
38. H. Ooguri and C. Vafa, "Self duality and $N = 2$ string magic," preprint, HUTP-90/A024.
39. E. Bergshoeff, C.N. Pope, L.J. Romans, E. Sezgin, X. Shen and K.S. Stelle, Phys. Lett. **B243** (1990) 350.
40. E. Bergshoeff, C.N. Pope, L.J. Romans, E. Sezgin and X. Shen, " W_∞ gravity and super- W_∞ gravity," preprint, CERN-TH.5743/90 (1990), to appear in Mod. Phys. Lett. A.
41. A. Abouelsaood, C.N. Pope, E. Sezgin and X. Shen, "Gauged sigma models from 2+1 dimensions and the issue of unitarity," preprint, CTP-TAMU-24/90, to appear in Mod. Phys. Lett. A.
42. E. Bergshoeff, P. Howe, C.N. Pope, E. Sezgin and E. Sokatchev, "Ten-dimensional supegravity from light-like integrability in loop superspace," preprint, CTP-TAMU-45/90.
43. D. Friedan, Z. Qiu and S. Shenker, Phys. Rev. Lett. **52** (1984) 1575.
44. E. Bergshoeff, C.N. Pope and K.S. Stelle, "Covariant w_∞ gravity," preprint, CTP-TAMU-61/90, to appear in Phys. Lett. B.
45. K. Schoutens, A. Sevrin and P. van Nieuwenhuizen, "Covariant w_∞ gravity and its reduction to W_N gravity," preprint, ITP-SB-90-39.
46. K. Li, "Action for topological W gravity," preprint, CALT-68-1635 (1990).

APPENDIX A
Publications and Reports for 1990
Experimental

1. F. Abe et al., "Two-jet Invariant-mass Distribution at $\sqrt{s} = 1.8$ TeV", Physical Review D (Rapid Communications), 41, 1722 (1990).
2. F. Abe et al., "Search for the Top Quark in the Reaction $p\bar{p} \rightarrow$ Electron + Jets Channel at $\sqrt{s} = 1.8$ TeV", Physical Review Letters, 64, 142 (1990).
3. F. Abe et al., "Search for New Heavy Quarks in Electron-Muon Events at the Fermilab Tevatron Collider", Physical Review Letters, 64, 147 (1990).
4. F. Abe et al., "Measurement of the ratio $\sigma(W \rightarrow e\nu)/\sigma(Z \rightarrow ee)$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV", Physical Review Letters, 64, 152 (1990).
5. F. Abe et al., "Two-jet Differential Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV", Physical Review Letters, 64, 157 (1990).
6. F. Abe et al., "Search for a Light Higgs Boson at the Fermilab Tevatron Proton-antiproton Collider", Physical Review D (Rapid Communication), 41, 1717 (1990).
7. F. Abe et al., "Pseudorapidity Distribution of Charged Particles Produced in $p\bar{p}$ Interactions at $\sqrt{s} = 630$ and 1800 GeV", submitted to Physical Review Letters (1990)
8. Shah M. Zaman, "Measurement of the Optical Performance of Liquid Scintillator Filled Teflon-Fiber Tubes," DOE-40039-43 (unpublished).
9. P. P. Altice, "A Study of Liquid Scintillator and Fiber Materials for Use in a Fiber Calorimeter," DOE-40039-45 (unpublished).
10. Antonio W. Chan, "Report on the Performance of the MACRO oil - Glass-clad Coating Detector System," DOE-40039-44, July, 1990 (unpublished).
11. Tim Hessian, "Inclusive Jet Cross Section at $\sqrt{s} = 1.8$ TeV," CDF Contribution to Moriond, 1990.
12. J. Ng, G. Brandenburg, M. Franklin, P. Hurst, E. Kearns, T. Kamon, "Measurement of $\frac{d\sigma}{dp_T^2}$ Using $p\bar{p} \rightarrow Z^0 \rightarrow e^+e^-$," CDF 1269. (unpublished).

END

DATE FILMED

12 / 10 / 90