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Technical Progress Report
Indiana University
High Energy Physics
Task A

January 1, 1990 to April 15, 1991

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MASTER

Note: This Technical Progress Report describes the activities of our group. Our grant proposal, submitted to the DOE in May, 1991, makes frequent reference to this report. Please read this report in conjunction with that grant proposal. Thank you

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1. Introduction and Overview

1.1 Personnel

The Experimental High energy Physics Group (Task A of the DOE contract) at Indiana University consists of the following:

Faculty : B. Brabson, R. Crittenden, A. Dzierba, G. Hanson, H. J. Martin, H. Ogren and A. Zieminski

Research Physicists : J. Li, X. Lou, T. Marshall, R. Mir, T. Mouthuy, D. Rust, S. Teige and D. Zieminska

Graduate Students: D. Averill, T. Foxford, S. Kartik, R. Li, R. Lindenbusch, W. Murray, J. Schuler, M. Settles, E. Silva and M. Yurko

Technical Staff : R. Foster (Programmer/Designer), F. Luehring (Physicist/Programmer), B. Martin (Technician), I. Najdowski (Technician), P. Smith (Electronic Engineer), T. Sulanke (Applications Programmer/Engineer), E. Wente (Assistant Research Scientist)

Secretary : D. Martin

Accountant : S. Snodgress

1.2 Experiments

During this reporting period the group has been carrying out programs at:

- *Brookhaven National Laboratory (NY)*

where the group is the prime mover in the construction of a major new experiment (E852) in precision meson spectroscopy.

- *Fermi National Accelerator Lab (IL)*

where the group is the prime mover in (E672) a high mass dimuon experiment which will be taking more data and is a collaborator in the D0 collider experiment.

- *Stanford Linear Accelerator Lab (CA)*

where the group was a collaborator in the Mark II experiment at the SLC.

- *CERN (Geneva, Switzerland)*

where the group is a collaborator in the OPAL experiment at LEP and the development of a major offline facility *shift*.

- *SSC (TX)*

where the group is a prime mover in the tracking design of the SDC experiment.

The assignment of personnel to these efforts is shown in Tables 1.1 through 1.4.

1.3 Space and Facilities

The group occupies 3,358 sq. ft. of office space and 8,654 sq. ft. of laboratory space (including a hi-bay area) in Swain Hall. The group also has access to the Physics Department machine shop at no cost.

Construction Facilities

The High Energy Physics Group has extensive facilities for constructing detector apparatus. Computer-aided design software is available for electronics and mechanical design. There is an electronics assembly and test laboratory with tools for building printed circuit or wire-wrap devices. Meters, oscilloscopes, and VAXstation computers with CAMAC and FASTBUS interfaces are available for testing electronics and detectors. There are also CAMAC crates linked by serial lines to the VAX 6340 for low data rate tests. There is a departmental machine shop with 5 full time machinists. Other facilities include two wire winders for proportional chambers and a large flat jig table located in a clean room. Also available for detector testing is a large room with access to a truck loading area.

Computing Facilities

The local computing facilities for the Indiana University High Energy Physics group consists of a VAX cluster, two Unix workstations, and sixteen Macintoshes.

A VAX 6340 and five VAXstations make up the VAXcluster. In December 1990 a 1 Gigabyte disk was added to one of the VAXstations bringing the total disk space available to the whole cluster to 5.5 Gigabytes. A two Exabyte drive tape system was added to the VAX 6340 in February 1990. These two drives are heavily used for processing data from E672, storing Monte Carlo data for D0, and for routine backup. The VAX also has two 9-track tape drives and three laser printers. Through its terminal servers it can be accessed by about 12 terminals, the Macs, and 4 dial-in modems. The VAX can be accessed via internet from the Macs, the workstations, and many external computers or via DECnet from HEPnet.

Two of the VAXstations (IND1 and IND2) are being used for detector hardware development and data acquisition. IND1 is being used by the SDC development group. An additional VAXstation was purchased in August 1990 to free IND1 which was previously used for D0 software development. IND1 has been equipped with a Fastbus interface. The other data acquisition VAXstation, IND2, has a CAMAC interface and its own Exabyte tape drive. It is used with the E852 lead glass detector prototype currently at BNL.

In May 1990, a Silicon Graphics Personal Iris 4D25 workstation was installed. This UNIX workstation is used for running simulations for E852 and will be used for analyzing data for this experiment. This workstation has 16 Megabytes of memory, 760 Megabytes of disk storage, and an Exabyte tape drive.

An IBM RISC System/6000 workstation was delivered in September of 1990. It is being used to run simulations for SDC development. The workstation has 16 Megabytes of memory, 640 Megabytes of disk, an Exabyte tape drive, and a CD reader.

Both UNIX workstations are connected to internet allowing remote logins and file transfers between them and many other systems.

With the addition of three Macs last year, a total of sixteen Macs are used by faculty, staff, and graduate students. These Macs are used to run a variety of analysis and

word processing programs. They also are used as terminal emulators to connect to the other local computers and computers at various laboratories. Two laser printers are networked to these Macs.

SSC Facilities

We have developed a number of facilities for use in our SSC effort at Indiana University.

- We have modified an assembly area with a 3 .5 meter long precision straw tube holder to measure long straw performance.
- For the tests in this assembly area we have put together gas mixing facilities and have purchased two fast oscilloscopes- a Hewlett Packard 54503A digital oscilloscope with 500 MHz bandwidth, and Tektronics 2467B , 400 MHz oscilloscope with enhanced imaging.
- We have also constructed a straw module test stand that will permit simultaneous cosmic ray and high rate source tests. This includes a FASTBUS readout system of up to 64 TDC channels. It is interfaced to a VAX workstation, which is in turn networked to our VAX 6340 mainframe.
- For SSC tracking simulation work we have an IBM 6000 workstation. This is interfaced via Ethernet to the VAX 6340.
- We have a number of software packages that run on the VAX and the IBM to facilitate our interaction with the SDC design and engineering . This includes PRO Engineer, and the finite element analysis program NISA.

Faculty	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
B. Brabson	√			√		√
R. Crittenden	√	√				
A. Dzierba	√	√				√
G. Hanson				√	√	√
H. J. Martin		√	√			
H. Ogren				√	√	√
A. Zieminski		√	√			

Table 1.1

Research Physicists	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
J. Li			√			
X. Lou					√	
T. Marshall		√	√			
R. Mir					√	
T. Mouthuy					√	
D. Rust				√	√	√
S. Teige	√					
D. Zieminska	√		√			

Table 1.2

Graduate Students	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
D. Averill				√		
T. Foxford	√					
S. Kartik		√				
R. Li		√				√
R. Lindenbusch	√					
W. Murray				√		
J. Schuler			√			
M. Settles					√	
E. Silva					√	
M. Yurko				√		

Table 1.3

Technical Staff	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
R. Foster						√
F. Luehring						√
B. Martin						√
I. Najdowski	√					
P. Smith	√	√				
T. Sulanke	√	√	√		√	
E. Wente						√

Table 1.4

2. Searching for Unusual Mesons at BNL

The material in the first two sections of this chapter also appeared in articles on our BNL experiment written by A. Dzierba for the CERN Courier (Dec. 1990) and the BNL AGS Newsletter (Jan. 1991)

2.1 The Physics

In the late 1960's, meson spectroscopy was furnishing crucial evidence for what was to become the naive quark model: mesons are grouped in nonets with $|Q| \leq 1$ and $|\text{strangeness}| \leq 1$ and with J^{PC} (spin, parity and charge conjugation) consistent with mesons being made of a non-relativistic bound state of a spin 1/2 quark and anti-quark. Indeed there were a number of null-result experiments searching for *exotics of the first kind*, doubly-charged mesons or mesons carrying two units of strangeness. Experiments also searched for and found no evidence for *exotics of the second kind*, mesons with J^{PC} inconsistent with the naive quark model (e.g.: $J^{PC} = 0^{- -}, 0^{+ -}, 1^{- +},$ or $2^{+ -}$). There is an intriguing exception which will be discussed below.

After the overwhelming experimental evidence (from both meson and baryon spectroscopy) establishing the quark model, came the notions of color and confinement which explained the colorless systems: $q\bar{q}$ (mesons) and qqq (baryons). But these are the *minimal* colorless systems. One should also expect multiquark states such as $qq\bar{q}\bar{q}$ or *molecules*, bound states of color singlet mesons. Moreover, QCD, with its colored gluons, predicts *glueballs*, gluons bound by the same attractive forces that bind quarks. This prediction inspired a number of experimental searches in the isoscalar, flavorless meson sector. Other combinations are also possible: *hybrid* bound states of quarks and gluons, such as $q\bar{q}g$.

Among the plethora of mesons predicted by QCD we should find exotics of the first kind and exotics of the second kind. Frank Close made a pointed observation, referring to exotics of the second kind: "Had such a state been found in 1968, it would have undermined the naive quark model. If one is found tomorrow, it will be greeted with enthusiasm as *proof* for the quark-gluon theory of hadronic particles. This interesting turnabout is the stuff of theses on the philosophy of science".

A number of experiments were launched in the last decade to look for non- $q\bar{q}$ states in hadronic production, $p\bar{p}$ annihilations and J/ψ radiative decays. What have we learned? There are no completely unambiguous glueball or hybrid states but there are several tantalizing candidates. The GAMS group has observed an as yet unverified $J^{PC} = 1^{-+}$ meson decaying into $\eta\pi^0$ with a mass of 1405 MeV. Since $I=1$ for this state, it cannot be a glueball so it could be a $qq\bar{q}\bar{q}$ or a hybrid. Close and Lipkin have noted that if it is a $qq\bar{q}\bar{q}$ then its decay into $\eta\pi$ should dominate over $\eta'\pi$ while if it is a hybrid, the reverse should be true. The same group has reported a scalar $G(1590)$ decaying into $\eta\eta$ and $\eta\eta'$. The measured branching ratios for the $G(1590)$ into other pseudoscalars are peculiar for a $q\bar{q}$ meson. Others have explored the gluon-rich J/ψ radiative decay for non- $q\bar{q}$ candidate states such as the pseudoscalar $\eta(1440)$ and the $f_2(1750)$ (formerly the $\iota(1440)$ and $\theta(1750)$ respectively).

There is still much work to be done in light meson spectroscopy in carefully mapping out the conventional $q\bar{q}$ sector. For example, one of the problems in unambiguously identifying the $\eta(1440)$ as a glueball candidate is that two radially excited pseudoscalar (2^1S_0) isoscalars are expected to have masses in this region. Another problem is the confusion with an axial vector state in this mass region, the $f_1(1420)$ (formerly the $E(1420)$). A map of the light-meson nonets is needed to provide the template against which we can compare exotic candidates. Moreover, there are still missing nonets, for example the 3D_2 nonet whose isoscalar and isovector members are expected to have dominant decays into $\eta\omega$ and $\pi\omega$ respectively.

In the past decade, there have been a number of experiments in meson spectroscopy at the Brookhaven Alternating Gradient Synchrotron (AGS) using the Multiparticle Spectrometer (MPS). The AGS energy range is ideal for light-quark meson spectroscopy; at higher energies, exclusive cross sections decrease and backgrounds increase while at lower energies one cannot produce the desired states with good acceptance. One of these experiments observed the 2^{++} tensor mesons, g_T , decaying into $\phi\phi$. Another experiment (E771) studied the $E/\iota(1440)$ phenomenon in the $K\bar{K}\pi$ system; it established for the first time the presence of at least one and possibly two pseudoscalars in the 1.40 to 1.48 GeV mass region. A recent experiment (E818) has gathered data to search for hybrid states in the $\pi f_1(1285)$ channel. Analysis is in progress.

The recent advances in light-meson spectroscopy point to the importance of being able to detect *all* the possible pseudoscalar decays of candidate states. It is important to

establish branching ratios. The rich results obtained by GAMS demonstrate the advantage of studying $\eta\pi$, $\eta'\pi$, $\eta\eta$ and $\eta\eta'$ systems. These systems are constrained in their quantum numbers. For example $C = +$ and J^P occur in the sequence $0^+, 1^-, 2^+, \dots$. If $\eta\pi$, $\eta'\pi$ or $\eta\eta'$ resonate in a P-wave we have a $J^{PC} = 1^- +$ exotic with $I = 1$ (not a glueball) for $\eta\pi$ and $\eta'\pi$ and $I = 0$ (possibly a glueball) for $\eta\eta'$. For $\eta\eta$, only even spins are allowed. However limiting the detection to only photons ($\pi^0 \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$, and $\eta' \rightarrow 2\gamma$), as in the case of GAMS, precludes the possibility of seeing charged decay modes. For example if a resonance occurs in $\eta\pi^0$ it should also be seen in $\eta\pi^-$. Excellent photon detection is needed along with charged particle detection and identification.

In order to make the advances needed in light-quark spectroscopy to untangle the experimental problems of identifying possible hybrid, glueball and exotic states, the problem has to be addressed from many fronts. This experiment, E852, complements work in progress or planned at LEAR ($p\bar{p}$), in J/ψ radiative decays, two-photon physics and at Fermilab (Primakoff production of hybrids).

2.2 The E852 Detector

A new experiment, E852 (Brookhaven/Indiana/Louisville/Moscow State/Notre Dame/ Serpukhov/Southeastern Mass), has been approved at the AGS to use the Multiparticle Spectrometer (MPS) with extensive upgrades (see Fig. 2.1). The upgrades are motivated by recent developments in experimental meson spectroscopy and include the addition of a 3000-element lead glass calorimeter, a CsI barrel surrounding the target placed inside the MPS magnet, improved charged-particle tracking and a segmented Cerenkov counter. Initially data will be collected with a 21 GeV/c π^- beam incident on a LH₂ target. The upgrades will provide for the detection of all neutral final states (e.g. $\eta\pi^0n$, $\eta'\pi^0n$ or $\eta\eta n \rightarrow 4\gamma n$) as well as mesons which decay into $\eta\pi^-$, $\eta\pi^+\pi^-$, $K^+K^-\eta$ or $\omega\omega$. The simultaneous detection of neutral and charged modes, with particle identification, will help to establish branching ratios. A key feature of experiment 852 is the ability to reconstruct photons in the trigger and, for example, to require the presence of an $\eta \rightarrow 2\gamma$. The excellent coverage in decay angles, coupled with high statistics, will permit a complete partial-wave analysis, crucial in the search for missing nonets or non- $q\bar{q}$ states.

Target Region

Fig. 2.1 shows the MPS with the planned modifications for E852. The target region is shown in Fig. 2.2. The liquid hydrogen target is located in the middle of the MPS magnet and is surrounded by an array of CsI crystals. The crystal array, shown in more detail in Fig. 2.3, consists of 180 elements, each 4 radiation lengths (7.5 cm) thick and trapezoidal in shape. Since this array resides in a magnetic field, light from the crystals will be read out using photodiodes. The target region also includes an upstream endcap array (UEA) made of CsI elements and a downstream endcap array (DEA in Fig. 2.2) which is a lead/scintillator shower counter. A charged particle veto (CPV) scintillation counter will be used to define all-neutral triggers, such as $\pi^- p \rightarrow \eta \pi^0 n \rightarrow 4\gamma n$.

In the all-neutral triggers, e.g. the $4\gamma n$ final state, it is important to insure, for purposes of the partial wave analysis, that the recoil baryon is a neutron, rather than an excited N^* which decays into a π^0 and n . The missing mass determination, from measuring only the forward-going photons, does not allow for such a distinction. The CsI and the DEA will be used to veto on soft photons (as low as 20 MeV) from the decay of the π^0 from the N^* .

Tracking and Particle Identification

The charged particle tracking consists of an array of drift chambers (already in place in the MPS) and proportional wire chambers (PWC's). The PWC's will be used to provide triggers based on charged particle multiplicity (the first upstream PWC is shown as TPX1 in Fig. 2.2) and on correlations of momentum measurements with information from the downstream Cerenkov counter to require the presence of kaons in the final state. Engineering studies are under way to look into replacing some of the trigger PWC's with drift chambers. The downstream Cerenkov counter will consist of 96 segments, each consisting of two mirrors (see Fig. 2.1) and a photomultiplier.

Lead-Glass Photon Calorimeter

The photon calorimeter is a detector made of lead glass (LGD). The LGD is an array of 3052 elements (see Fig. 2.4). Each element consists of a 4 cm x 4 cm x 45 cm (15 radiation lengths deep) lead glass module. The size of the total array, matched to the

aperture of the MPS magnet, is 2.84 m wide by 1.72 m high. One or more modules in the central region will be removed to allow for passage of the beam.

Each module will be read out using a Soviet FEU-84-3 photomultiplier, which has a diameter of 34 mm. Each photomultiplier base will have a voltage multiplier employing a capacitor/diode array. The photomultiplier signals will be digitized by fast-encoding (within 5 μ s) ADC's. The ADC outputs of modules with a signal (typically 1 to 2 % of the modules will have a signal) will be processed by a trigger processor which will compute diphoton effective masses within about 15 μ s (including ADC digitizing time). This will be used in the trigger, for example, to require the presence of an $\eta \rightarrow 2\gamma$. This ability to trigger on diphoton masses is a unique feature of E852.

Calibration of the LGD will be performed using electrons and straight-through muons. Studies are under way to examine the possibility of moving each module into an electron beam by having the array mounted on a computer-controlled table. We are also studying a scheme for using a charge-exchange trigger and converting the photons from π^0 decays using a thin sheet of lead. Resulting electrons and positrons will be tracked through the spectrometer and into the LGD. A xenon flash lamp will illuminate a bundle of fibers which will then will be channeled into each module. This system will be used to monitor gain changes with time resulting, for example, from any radiation damage.

Detector Acceptance, Resolutions and Event Yields

Monte Carlo simulations of various final states produced with an incident 21 GeV/c π^- beam have been carried out. The acceptances as a function of effective mass are shown in Figs. 2.5 and 2.6 for all-neutral and neutral plus charged particle triggers respectively. The requirements are that all photons enter the LGD, that all photon energies be greater than 500 MeV, all photons be separated by at least 8 cm and that photons be separated from charged particles in the LGD (when present) by at least 20 cm. We are also sensitive to rather complicated decays of possible states. For example, according to Isgur's flux-tube model, the lightest exotic hybrid has a mass of 1.9 GeV with a preferential decay mode into $\pi b_1(1235)$. The b_1 decays into $\pi\omega$. Our acceptance for such a state is 30 %.

Based on GEANT studies of energy and position resolution of the LGD, we expect a resolution (σ) of 40 MeV for a 1400 MeV $\eta\pi^0 \rightarrow 4\gamma$. With kinematic fitting (using η and π^0 mass constraints) the resolution is reduced to 21 MeV. With a 30-cm long LH₂ target,

a beam flux of 2 million pions per AGS pulse, 1200 pulses/hour, and an overall efficiency of 50 % we expect to achieve a sensitivity of 2.8 events/pb in a 2000-hour (the approval) run.

2.3 The Indiana Involvement

Personnel

During the reporting period, the following Indiana personnel have been involved in E852:

Faculty : B. Brabson, R. Crittenden and A. Dzierba

Research Physicists : S. Teige and D. Zieminska

Engineers : P. Smith and T. Sulanke

Technician : I. Najdowski

Graduate Students : T. Foxford and R. Lindenbusch

Indiana physicists also participated in two earlier meson spectroscopy experiments using the MPS which were mentioned above: E771 and E818. In addition to hardware contributions (a 1-mm pitch PWC for E771 and multiplicity trigger electronics for E818), D. Zieminska participated in the PWA leading to the physics results of E771.

Responsibilities

The Indiana group is the leading group in this collaboration. The bulk of the proposal preparation was done at Indiana. A. Dzierba, Co-Spokesman (with S. U. Chung of BNL), made both proposal presentations (in 1988 and 1989) and also presented the experiment to DOE Reviews at BNL in 1990 and 1991 and before the HEPAP subpanel ("Sciulli Committee") in 1990.

The LGD Design and Construction and Associated Electronics

The IU group has responsibility for all hardware and software aspects of the LGD and its associated electronics. In this effort we are working closely with the groups from the USSR: Moscow State (MSU) and Serpukhov (IHEP). MSU physicists are in charge of constructing the HV system while IHEP is providing the lead glass and PM's. MSU physicists (Demianov and Sinev) have been in Bloomington since Oct., 1990.

B. Brabson has been doing extensive work on understanding possible LGD/charged particle triggers and has introduced important changes to the apparatus configuration. He is also working on calibration schemes. In these efforts he is working with T. Sulanke. Brabson is also supervising I. Najdowski in the construction of a PM tester to be used for quality control of PM's as they arrive from IHEP. This device is based on measurements made earlier by Crittenden, Brabson and Foxford.

R. Crittenden, working with P. Smith, is overseeing the electronics of the LGD. The trigger will be based on the successful technique developed by Crittenden, Smith and Sulanke for triggering on dimuons in E672 at FNAL. In order to carry out the diphoton effective mass trigger with sufficient resolution and speed an ADC system needs to be developed. P. Smith has recently tested an ADC prototype shown schematically in Fig. 2.7. The results have exceeded the performance of commercially available, fast-encoding ADC's. The conversion time ($4 \mu\text{s}$) for a 12-bit ADC is faster than achieved by the 10-bit Phillips ADC or the 11-bit LeCroy ADC. Initial tests indicate that the integral non-linearity is better than 0.025 %.

P. Smith has also constructed a device (see Fig. 2.8) to measure lead glass blocks. A stepping motor moves a stage along the long axis of the block. Pneumatically activated probes contact the glass on all four sides. These probes have a resolution of $0.5 \mu\text{m}$. The measuring device has been controlled and read through CAMAC. All blocks will be measured and their dimensions will be archived. The information will be used to optimally stack the array.

S. Teige supervised the construction of a 25-element LGD prototype which is currently in the A2 test line at BNL. Teige is also supervising the tests. The results, to date, have been very promising. The prototype and test results are presented below.

S. Teige also visited IHEP in Nov., 1990 to coordinate the preparation of the lead glass blocks with Soviet physicists and engineers.

2.4 The LGD Prototype

There is nothing like data. A 25-element prototype has been built and, at this writing, is in place in the A2 test beam. The prototype was oriented vertically in Bloomington early in 1991 and used to look at cosmic rays. Our goal is to use the prototype to understand our simulations, gain experience with the lead glass and try out some ideas. The prototype project has been led by S. Teige, who joined the IU group in July, 1990. Working with him are IU graduate students T. Foxford and R. Lindenbusch. A. Demianov and N. Sinev have also contributed to the design and running of the LGD prototype. C. Davis, from UL, has contributed to the software. When the A2 tests are complete we will bring the prototype back to Bloomington and concentrate on long-term tests.

The Design

The prototype consists of a 5 by 5 array of 4 cm x 4 cm x 45 cm lead glass blocks held in an aluminum framework. The blocks and the framework holding them are contained in a 18 in x 18 in x 38 in light-tight, temperature-controlled box. The framework holding the array is made of 1 inch aluminum plate and bars and is fitted with 5/8 inch eyebolts suitable for moving it with a crane.

The blocks are identical to the ones that will be used in the full scale detector. They are wrapped in 1/2 mil mylar aluminized on both sides for optical isolation. Provisions have been made to allow the blocks to be stacked one on top of the other or staggered. Additionally, connectors and space exist to allow the addition of another row of blocks to the array should they become available.

Each phototube is contained in an aluminum canister along with its base and a magnetic shield. The canisters are attached to aluminum plates glued to the back faces of the blocks. The optical fibers for monitoring are attached to connectors on these plates. Signal and HV connections are to feedthroughs on the back plane of the temperature controlled box. The photocathode is optically coupled to the block by a 0.7 inch thick

cylindrical "cookie" made of Sylgard 184 optical gel. The signals are sent to LeCroy FERA ADC's.

Phototube gain is monitored by a Laser Science Inc. model number VSL-337ND nitrogen laser. Its maximum average power is 6 mW, maximum pulse energy 400 μ J and its emission at 337 nm. The output pulse is directed into an optical fiber attached to the laser. The other end of the fiber is connected permanently to the prototype and illuminates a photodiode. A portion of the light from the primary fiber illuminates the end of a bundle of 32 fibers that fans out the pulse to the individual modules. Gain is monitored by the response of the individual modules normalized to the photodiode response plotted versus time.

The temperature-controlled box is made from 1/32 inch thick aluminum sheet on a 3/4 inch "skeleton". The box is insulated with 3/4 inch thick Styrofoam on its interior. The temperature in the interior of this box is controlled by a solid state refrigerator/heater made by TECA Inc. to within $\pm 1^\circ$ F. The front face of this box presents 1 % of a radiation length of material to the beam.

Results of Energy Resolution Measurements

Earlier this year, a meeting of the E852 Technical Review Committee (appointed by the BNL management) with the E852 collaboration was scheduled for April 5. The first electron beam was delivered through the A2 line on April 2. We were able to present first results of the energy resolution at the Technical Review meeting on April 5 (see Fig. 2.9). The distribution shown is the sum of the 25 ADC outputs when a 2.5 GeV/c electron beam was centered on the center module of the 5 x 5 array. The σ /centroid corresponds to 6 %. More recent measurements of an energy scan indicate that our resolution corresponds to:

$$\frac{\sigma}{E} = \left(1.5 + \frac{6}{\sqrt{E(\text{GeV})}} \right) \%$$

Further tests are underway including tests in which electrons strike the prototype obliquely and the effect on resolution of having material upstream of the LGD.

We have been getting requests from others to use our readout and DAQ system. The plan is to have the Notre Dame use the setup in May, 1991 to test a 9-element CsI

array. Our system will also be used by C. Woody of BNL in May to test a 25-element CsI array.

2.5 Technical Review of E852

As mentioned above, the BNL management appointed a Technical Review Committee (TRC) to oversee the progress of our experiment as it proceeds through the design and construction phase. The chair of this committee is Sam Aronson and the other members are Gerry Bunce, Rick Fernow, Mark Sakitt and Craig Woody, all members of the BNL staff. Our experiment met with the committee in September of 1989 and more recently on April 5, 1991. The TRC reported to Associate Director Mel Schwartz:

In general the review went very well and produced a favorable snapshot of the status and plans of the experiment. The committee felt that the collaboration has shown good judgement in setting priorities among the early design and testing tasks. They appear to have put most effort into those elements which deserve it by reason of lead time, complexity or cost.

Regarding the progress on the LGD the TRC had this to say:

A test of 25 lead-glass blocks is underway in the A2 line. We saw impressive results on energy resolution after only a few days of data taking. The specification, procurement and testing of components for the LGD seem to be getting off to a good start and the design of the housing is getting appropriate attention.

Regarding the need for custom-built ADC's:

It appears that custom-built ADC's are required and the committee felt it was important that this decision be made carefully and with high priority.

2.6 Timetable

The timetable for LGD project is shown in Fig. 2.10.

Figure 2.1 - The E852 Apparatus

Figure 2.2 - Target Region of E852

Figure 2.3 - The CsI Veto for E852

Figure 2.4: - The Lead Glass Detector (LGD)

Figure 2.5: - Acceptance for several all-neutral final states

Figure 2.6 Acceptance for several photon plus charged particle final states

Figure 2.7 – Schematic of the proposed ADC system for E852

Figure 2.8 – Device for measuring lead glass block dimensions

Figure 2.9 – Response of the LGD prototype (in ADC counts) to a 2.5 GeV electron beam

Activities	1991												1992												1993											
	A	M	J	J	A	S	O	N	D				J	F	M	A	M	J	J	A	S	O	N	D				J	F	M	A	M				
Quality tests																																				
Shields																																				
Module assembly																																				
Electronics																																				
HV/bases																																				
ADC's																																				
Trigger processor																																				
Monitoring																																				
Laser/Fibers																																				
Table																																				
Software																																				
Calibration																																				
Monitoring																																				
Online analysis																																				
Beam tests of full LGD																																				
Data																																				

Figure 2.10 – Timetable for the LGD project

3a. Fermilab Experiment E672: Hadronic States Produced in Association with High-mass Dimuons

3.1 Overview of the Experiment

Collaboration

Caltech-Fermilab-UIC-Indiana-Louisville-Michigan(Flint)-Serpukhov
Spokesperson: A. Zieminski

E672 Indiana participants in 1990

PhD physicists: R. Crittenden, A. Dzierba, T. Marshall, J. Martin, A. Zieminski
Visitors from the Moscow State U. A. Gribushin, A. Ostrovidov
Tech. experts: P. Smith, T. Sulanke
Grad. Stud. S. Kartik, R. Li, S. Markham (until July 1990)
Summer Students: M. Knudsen, J. Schuler

Physics goals

This is an open-geometry dimuon experiment, the aim of which is to study hadronic processes yielding high-mass dimuons (the trigger) and associated particles using proton and pion beams on nuclear targets at beam energies up to 800 GeV/c. The specific goals, which all are related to experimental tests of Quantum Chromodynamics, include:

- general properties of the production of vector mesons (ρ/ω , ϕ and J/ψ)
 - total and differential cross sections
 - production of associated charged and neutral particles
 - dependence on the inelasticity of the collision
 - the A-dependence
- the hadronic production of χ states by observing their radiative decay into $J/\psi + \gamma$
- a search for b-quark decays to J/ψ and double semileptonic $B\bar{B}$ decays to dimuons.

Apparatus

The layout of the combined E672 and E706 experiment is shown in Fig 3.1. The E706 detector contains a liquid argon calorimeter (LAC), a charged particle spectrometer including silicon-strip detectors (SSDs - 13 planes), proportional wire chambers (PWCs),

straw drift tubes, and a forward calorimeter. The E672 dimuon detector, shown in detail in Fig.3.2, consists of a toroid magnet, proportional wire chambers downstream and upstream of the magnet, scintillator hodoscopes, pretrigger and trigger processor modules. The output of all detectors are available to both experiments.

The E672 apparatus has been gradually assembled since 1982. All components of the system were designed and built at Indiana under the supervision of Prof. R. Crittenden. The 1990 additions (installed and commissioned in the Spring) included:

- two PWC stations (8 planes, 3mm wire spacing, 3500 wires) located upstream of the toroid
- a new pretrigger processor allowing clustering of the scintillator hodoscope signals
- an additional TRIGGER PROCESSOR module to verify hits along muon tracks projections in the upstream PWCs.

Both processors were constructed by R. Crittenden, P. Smith and T. Sulanke.

Data taken (anticipated)

1987/8: Test/Physics Run

This run was used primarily to bring up and test the E672/E706 spectrometer. However, we were also able to collect enough data to do some physics analysis. (a) First, we recorded data from the E672 spectrometer alone. We used 530 GeV/c π^- beam incident on thick nuclear targets of C, Al, Cu and Pb. Approximately 1,300 J/ψ events were reconstructed. (b) For the second part of the run, full E672/E706 spectrometer was operational. We took data with π^- and p beams at 530 GeV/c incident on Be and Cu targets. Two million E672 triggers were recorded, corresponding to integrated luminosities of 0.8 pb^{-1} and 0.7 pb^{-1} for the p and π^- data, respectively. The total sample of reconstructed J/ψ 's consists of 700 events.

1990: First Physics Run

We ran with 530 GeV/c π^- beam incident on Be and Cu targets and accumulated data corresponding to the integrated luminosity of 10 pb^{-1} . In total 5.5 M events were recorded, which yielded 400 K fully reconstructed dimuon events. This sample includes 9,500 J/ψ events.

1991: Second Physics Run

The second part of the 1990 run was originally scheduled to start in December and to last for 5 months. The reevaluation of safety issues at Fermilab postponed the startup until July 1991 at the earliest. The run plan includes taking data with 530 GeV/c and 800 GeV/c protons incident on H, Be and Cu targets.

3.2 The 1990 Fixed Target run at Fermilab

The timetable of the run was as follows

February 20	First beam available at Meson West.
Early March	E672 detector fully tested and ready for data taking
March - May	Data taking in a self mode, while the E706 spectrometer was commissioned.
June - August	Data taking. In August the primary beam intensity allocated to Meson West increased from 1.5×10^{12} ppp to $4-5 \times 10^{12}$ ppp.

The run required an enormous effort from the entire group. A. Ziemiński was relieved from teaching in the Spring of 1990 and spent extended periods of time at Fermilab, supervising recommissioning of the E672 apparatus and running the experiment. A graduate student, R. Li, moved permanently to Fermilab. P. Smith regularly commuted to Fermilab to install and check fast trigger electronics. J. Martin provided a monitoring and tracking software packages. He also commuted weekly to Fermilab to monitor the quality of the data and to address offline software needs of the experiment.

1990 running conditions

Beam : 530 GeV/c π of intensity less than 10 MHz
Targets: Cu (1.5% interaction length) followed by Be (8%)

Pretrigger:

We required at least two hits in each of two scintillating hodoscopes located downstream of the toroid magnet. We also vetoed against halo muons identified by signals

from three scintillating hodoscopes located upstream of the targets. The measured pretrigger rate was 2×10^{-4} per interaction.

Trigger:

The trigger processor reconstructs muon tracks downstream of the toroid and measures their momenta assuming that they originate from the target. In addition, the trigger processor verifies the existence of a track upstream of the toroid by requiring the presence of hits around projected muon trajectories in 6 out of 8 planes upstream of the toroid magnet. Finally, an event is accepted when the invariant mass of the dimuon pair exceeds a preselected threshold. It takes 5-10 μ sec per event to make the final decision. The trigger rate was 1.5×10^{-5} per interaction for 0.7 GeV mass threshold.

Data collected:

Events selected by the E672 and E706 triggers, containing information from the entire E672/E706 spectrometer, were written onto joint EXABYTE tapes. Our 5.5 M triggers represented 17% of the total number of triggers recorded on over 550 EXABYTE tapes.

1990 Data processing and analysis

Data processing was done on the IU VAX 6340 computer. First, we extracted E672 events from the common E672/E706 EXABYTE tapes. Secondly, we processed them through the muon reconstruction program. From the original 5.5M dimuon triggers we accepted on the DST 400K events with two muons linked through MUON-PWC-SSD systems. The program to reconstruct muons from the combined E672/E706 spectrometer was written by H.J. Martin (Indiana). These stages of the data processing required 5,000h of CPU (4.4 Mips). The DST contains information on muons and all remaining charged particles.

All 400K of good dimuon events were extracted from the original data tapes and stored on 15 EXABYTE tapes. These data will be the subject of further processing, which includes:

- multivertex search (algorithm designed and implemented by H.J.Martin)
- photon reconstruction (E706 group software)
- hadronic calorimeters reconstruction.

This processing should be completed by July 1991.

The opposite charge dimuon mass spectra for the entire mass range and in the J/ψ region are shown in Figs. 3.3 and 3.4, respectively. Clear peaks corresponding to the production of vector mesons ρ/ω , ϕ and J/ψ are seen. There are 27K ρ/ω 's, 4.5K π 's and 9.3K J/ψ 's in the data sample. The J/ψ mass resolution is 65 MeV. The analysis of the data is in progress (see below).

3.3 Analysis of data taken during the 1987/88 run

We have published two papers based on our limited statistics 1987/8 data. The third paper is being prepared.

- (a) The A-dependence of J/ψ production (PRD 141, 1(1990).)

We have studied the production of J/ψ by 530 GeV/c negative pions incident on targets of carbon, aluminum, copper and lead. In the forward region ($0.1 < x_F < 0.8$), using the parametrization $\sigma = A^\alpha$, we obtain $\alpha = 0.85 \pm 0.06$. A number of mechanisms have been proposed for the A-dependence of J/ψ production and nuclear suppression at large x_F . Our data provide new constraints for these explanations. They are also relevant for studies of quark-gluon plasma.

- (b) Properties of J/ψ production in π -Be and p-Be collisions. (Fermilab preprint PUB 91/62-E)

This paper covers the following results:

- total and differential J/ψ cross sections (Fig.3.5). We observe more central J/ψ production with increasing energy. Comparison of the pion and proton data provides constraints on the pion gluon structure function.
- comparison of forward multiplicities and charge flows from proton and pion data. The symmetry of the distributions for pions and protons indicates that the gluon fusion mechanism is dominant for both types of incoming particles.
- relative J/ψ and Drell-Yan pair production as a function of transverse energy or charged multiplicity observed in the event. We do not observe a statistically significant J/ψ

suppression for high transverse energy events, contrary to the observations made for heavy ion collisions.

(c) Inclusive production of vector mesons.

The aim is to understand differences between strange and non-strange quark production. The physics topics covered are similar to those of the J/ψ paper. There are indications for an increase of relative ϕ production with respect to ρ/ω for high transverse energy events.

The remaining topics (d)-(g) have been extensively studied. However, due to limited statistics, no publications are expected on the 1987/8 data on these subjects. On the other hand, we will get definite answers from the 1990/91 data.

(d) Production of χ states

The measurement of the fraction of J/ψ 's produced indirectly via radiative decays represents an important test of QCD models. A large amount of effort was spent in an attempt to extract a χ signal in our data. We have found approximately 30 χ candidates (as expected). The collected 1990 data have 20 times better statistics and improved LAC energy resolution for low energy γ 's (no zero suppression threshold set for the LAC readout).

(e) Search for secondary vertices

The aim was to find J/ψ events coming from secondary vertices (a tag for beauty production). We expect one beauty decay per 1500 J/ψ events. Several algorithms were developed to search for secondary vertices and several interesting events were closely investigated. No single event could be uniquely identified as a beauty decay candidate. We expect to collect half a dozen of $B \rightarrow J/\psi$ decays in 1990/1991.

(f) Production of like-sign dimuons and three-muon events.

We applied kinematic cuts to the like-sign dimuon events to enhance the signal from two semileptonic decays of a $B\bar{B}$ pair. The extraction of the signal is Monte Carlo dependent. We expect only 5 such events in the 1987/8 data sample and approximately 100 in the 1990 data.

(g) Search for exotic states decaying into $\phi\gamma$ final state.

A relatively clean ϕ signal and availability of information on associated charged and neutral particles enables us to study $\phi\pi$ and $\phi\gamma$ spectroscopy.

3.4 Analysis of data taken during the 1990 run

Analysis of the new data has just started. The 20-fold increase in statistics combined with improved data quality enables us to address all physics topics as outlined in the previous section and even expand the list. The activities in the Spring of 1991 concentrated on:

- reconstruction of the $(\pm)$ dimuon spectrum (see Figs. 5.3,5.4)
- development and testing of a multivertex finder for the $B \rightarrow J/\psi +$ decays. Monte Carlo analysis indicates that the present algorithm is 65% efficient in reconstructing secondary vertices due to B decays. A sample of B decay candidates has been selected and subjected of kinematic fits.
- search for a Ψ' signal in the $\mu^+ \mu^-$ and $J/\psi \pi^- \pi^+$ decay modes. More than a hundred Ψ' events have been observed (see Figs 5.8,5.9.)
- dependence of the vector meson production on the inelasticity of the event. The new data, shown in Fig. 5.10, confirmed our previous results: we observe a relative enhancement of π production with respect to ρ/ω for more inelastic collisions. On the other hand, inelasticity of the event does not change the ratio of the Ψ production with respect to the underlying continuum. (Fig. 5.11).

3.5 Summary of Indiana participation

The Indiana Group is the dominant group within the collaboration. We proposed the experiment, provided spokespersonship, built the entire muon detector, organized runs, wrote the offline reconstruction program and many online monitoring programs, prepared entirely two publications and wrote the third one.

Soviet Visitors at Indiana University

Three physicists from the Moscow State University spent extended periods of time at Indiana University and at Fermilab participating in the run. They are N. Sinev, A.

Ostrovidov and A. Gribushin. The first two were supported by the American-Soviet exchange program, whereas IU was paying per diems for the third one. They were involved in several projects: χ analysis (NS), Monte Carlo for double electron and single muon triggers (AO), data processing (AO), MACRO DAQ (AO), scalers monitoring/analysis program (AG), and data processing monitoring (AG). AG actively participated in the 1990 run. They worked under A. Zieminski's supervision.

3.6 Publications and Theses

Published papers

1. R. Crittenden, A. Sambamurti and P. Smith "16 Channel Camac Multiplicity Unit", Nucl.Instr.Meth. A270 (1988) 99.
2. S. Kartik et al., "A-dependence of forward J/ψ production in π -A interactions at 530 GeV/c", Phys. Rev. D141, 1 (1990).
3. V. Abramov et al., "Properties of J/ψ production in π -Be and p-Be collisions at 530 GeV/c", Fermilab PUB-91/62-E.

Invited and review talks published in the Conference proceedings

1. A. Zieminski; QCD Workshop, St. Croix; Oct. 1987 Proceedings - p. 379.
2. R. Crittenden and A. Dzierba, B-physics Workshop, Fermilab, Nov. 1987 Proceedings - p.427.
3. T. Marshall et al.; Intersections between Particle and Nuclear Physics Rockport, ME; May 1988; Proceedings p.624.
4. L. Dauwe et al.; DPF Meeting, Storrs; Aug. 1988; Proceedings; K. Haller et al. editors, World Scientific p.613.
5. K. De et al.; XXV Rencontre de Moriond; Mar. 1989; Proceedings - Fermilab preprint, Fermilab-Conf-89/151-E.

MS and PhD Theses

1. S. Markham (Indiana, A. Zieminski) 1990 (MS - only).
2. S. Kartik (Indiana, A. Dzierba) - in progress (1987 data)
3. R. Li (Indiana, H. Martin) - in progress (1990 data)
4. R. Jesik (UIC, S. Margulies) - in progress (1990 data)

3b. Fermilab Experiment E557: Hadronic Production of Jets

Collaboration

Caltech-Fermilab-Florida State-UIC-Indiana-Maryland-George Mason-Serpukhov

Spokespersons: E. Malamud, A. Zieminski (1982, after 1984)

E557 Indiana participants

PhD physicists: R. Crittenden, A. Dzierba, T. Marshall, J. Martin, A. Zieminski

Tech. experts: J. Krider, P. Smith, T. Sulanke

Grad. Stud. S. Blessing, P. Draper, A. Sambamurti, C. Stewart

In May of 1990 we have concluded a decade long involvement in the Fermilab experiment E557. Two final papers were published in 1990 and A. Zieminski gave several invited talks, including a minirapporteur's talk at the XXVth High Energy Conference in Singapore.

Summary of the results published in 1990

We have shown that production of jets off-nuclei is consistent with the cross section being proportional to the atomic weight. Therefore nuclear matter is transparent for propagation of color objects: an essential piece of information for nuclear chromodynamics. Our analysis of highly inelastic hadron-nucleus collisions provides a yardstick for quark-gluon plasma searches. We have shown that transverse energy represents a good measure of the inelasticity of the interaction. At a fixed E_t event structure in the central and forward region is to a good approximation independent of the target nucleus.

The analysis is completed. All together we published 9 papers and 7 students based their PhD theses on the data from the experiment (3 from Indiana). Six papers were prepared and written by Indiana physicists.

Papers published in 1990

A. Sambamurti et al. "The A-dependence of highly-inelastic p-nucleus collisions",
Phys.Rev. D41(1990)1371.

C. Stewart et al. "Production of jets in hadron-nucleus interactions" Phys. Rev.
D42(1990)1385.

Invited and review talks in 1990

- A. Zieminski, "Fermilab jet experiments", mini-rapporteur's talk at the XXV th Inter. Conf. On High Energy Physics Singapore, August 1990
- A. Zieminski, High Energy Seminar, University of Warsaw, Poland
- C. Stewart, High Energy Seminar, Northwestern University
- A. Zieminski, Nuclear Physics Seminar, University of Washington, Seattle
- A. Zieminski, Nuclear Physics Seminar, Michigan State University, Lansing
- to be given before July 1991
- A. Zieminski, High Energy Seminar, Brookhaven National Lab
- A. Zieminski, Invited speaker at the Gordon Conf. on Nuclear QCD

The E672/E706 Apparatus

Figure 3.1

Figure 3.2

Figure 3.5

Figure 3.6

Figure 3.7

Figure 3.8

Figure 3.9

Figure 3.10

Figure 3.11

4. THE D0 EXPERIMENT AT FNAL

4.1 Overview of the D0 Detector and Physics

D0 is a second generation detector facility being assembled at the Fermilab Collider. The experiment is scheduled to roll in towards the end of 1991. It is expected to complement the existing CDF detector with superior coverage and energy resolution for studying jets and leptons emerging from $p\bar{p}$ collisions. The physics goals of the D0 experiment include the search for the top quark and other new particles and phenomena, and will include precision studies of the W and Z bosons to look for possible deviations from the Standard Model predictions.

The D0 detector is now in the final stages of assembly and testing, and involves more than 200 physicists from the US and abroad. The effort is divided among six major areas of detector instrumentation: central detector, calorimetry, muon detector, electronics, data acquisition and online and offline software. Indiana University has been a member of the collaboration since the Fall of 1985. Our efforts have concentrated on various aspects of software design and development and on activities within the muon group. Below we summarize our contributions to the offline software, Monte Carlo studies and muon group hardware projects.

Indiana physicists involved in D0 during FY 1991 include:

Faculty: H. J. Martin and A. Zieminski (IU Contact Person)

Research Physicists: T. Marshall and D. Zieminska

Postdoc: Jia Li (since November, 1990)

Graduate Student: J. Schuler

4.2 Offline Software

Daria Zieminska is working on the Central Detector (CD) part of the offline reconstruction program and on some aspects of muon reconstruction. As one of the people responsible for the Central Detector offline reconstruction package, she closely collaborates with physicists from Berkeley, Northwestern, Stony Brook University and Saclay. The CD reconstruction program involves finding the primary vertex and finding central detector

tracks. Tracking can be called under two different circumstances: (a) tracking in selected volumes around lepton candidates, (b) full tracking for special events. The package includes finding the z coordinate of primary vertices (allowing for multiple interactions), finding tracks in the three drift chambers, Vertex Drift Chamber, Central Drift Chamber, Forward Drift Chamber, linking the VTX tracks with those found in outer chambers, and adding the information from the Transition Radiation Detector. Reconstructed hits, tracks and vertices are stored in Zebra banks. Central Detector event displays are available as part of the D0 event display package. A separate package for reconstructing secondary decays is being prepared by Daria. Progress on Central Detector software is documented in two D0 notes^{1,2}.

Work on the muon reconstruction is done in collaboration with the group from Northern Illinois University and from Serpukhov, USSR. The two groups are responsible for the muon reconstruction in the main D0 muon detector and in SAMUS (Small Angle Muon System), respectively. We have undertaken the reconstruction of muon tracks in the overlapping region. We are also involved in linking of the muon track found in the muon detector with its CD part.

The full event reconstruction program, DORECO, is now extensively tested on simulated Monte Carlo events and in the cosmic ray commissioning run in progress.

4.3 Monte Carlo Studies

"Double Blind" test

The Indiana group was one of six collaborating institutions which participated in processing of 100,000 "Double Blind" Monte Carlo events through the chain of DOGEANT and DORECO programs. The data sample, the contents of which are known only to the spokesman of D0, has been analyzed by the collaboration as part of the test of the performance of the event reconstruction program. Results were discussed at the D0 Monte Carlo Mini Conference in LBL, in January 1991. The exercise will be repeated using a refined reconstruction program and new analysis programs. Another Monte Carlo Mini Conference is planned for July 1991.

Level 1 trigger studies

The aim of Level 1 trigger studies has been fourfold:

- to verify the Level 1 trigger simulator code
- to verify the validity of the shower library approximation for the large statistics trigger studies
- to tabulate different trigger rates expected for the forthcoming D0 run
- to combine muon and calorimeter information in order to reduce muon trigger rates without much loss to the b-quark production signal.

We ran several thousand of selected GEANT events using the full GEANT simulator as well as the CPU-time-efficient shower libraries. We found that the calorimeter resolution assumed in the Monte Carlo simulations was a factor of two worse than expected. There are indications that a missing E_t requirement could enhance the b signal over background by a factor of 1.5 with only less than 20% loss for the signal. This work is still in progress.

4.4 Top Physics Studies

The Indiana group also takes part in the work of the top physics group. Andrzej Zieminski and John Schuler are doing Level 1 trigger studies³ and Daria has been working on prospects for finding "top to all jets" events⁴ and, most recently, on the possibility of finding (or ruling out) the 4th generation quark in the mass range accessible at the Tevatron.

Daria designed a method of defining the "top to all jets" signature using a maximum likelihood function. Although this is the most probable decay mode, there is an overwhelming QCD background even after imposing severe requirements on the multiplicity of high- p_t jets. To distinguish between the two processes we have compared the event "shape" using such variables as planarity and Fox-Wolfram moments. We also used the information from the tracking system on the presence of particles with high impact parameter coming from b decays. We calculated a top likelihood function taking into account the distributions of the lowest Fox-Wolfram moments, the number of

"secondaries" and the presence of two W bosons for a sample of $t\bar{t}$ events ($m_t=140$ GeV) and for QCD events. We obtained an enhancement factor of 30:1, which still leaves the signal to background ratio at the level of 1:50. However, the method is useful generally and can be used in dealing with background in other top decay channels and in the search for 4th generation quark signals.

4.5 Muon Detection System

The muon detection system for D0 will have better detection performance than those for other existing hadron collider detectors, with respect to both hadron attenuation length and position resolution⁵. The muon detection system consists of three shells of drift tube chambers completely surrounding the tracking and calorimeter modules of the detector. The tubes have a rectangular cross section (2 in x 4 in) and are between 10 and 20 feet in length. The first shell (A) consists of four planes of drift tubes. The A shell is enclosed by large steel central end toroids. The next shells, B and C, each consist of 3 layers and cover the outside of the steel. These shells are separated by about one meter. The three shells and toroids provide a spectrometer for detecting and measuring the momentum of muons produced in the collision. There are a total of 164 chambers consisting of 12,000 drift cells in this part of the wide angle muon system (WAMUS).

Muons passing through the three shells in the very forward directions (from 12 degrees down to 3 degrees from the beams) are detected and measured with the small angle muon system (SAMUS). The 6 SAMUS chambers each consist of 3 crossed planes of 1 inch diameter drift tubes. There is a total of 6000 tubes in the forward region.

Tom Marshall and Jia Li have been involved in all aspects of constructing and commissioning of the muon detector⁵⁻⁷. In particular, they contributed to the projects described below.

Chamber commissioning

Tom was in charge of the certification of the muon proportional drift tube chambers of D0 before their installment in the detector. A certified chamber is one that has all cells working at or nearly at 100-% efficiency for some chosen threshold of sensitivity, has all monitoring devices working and calibrated, and is capable of communicating at all levels

with the triggering and data acquisition systems. This task was completed in early October, 1990. He is now working on commissioning the 164 chambers as they are installed in the detector. So far, about 120 chambers have been commissioned, and the last 44 chambers will be installed and ready to commission in mid-May 1991.

MAC boards

Jia Li has been testing the MAC boards (the circuit boards which communicate with the chambers and the local processors) and the muon VME backplanes, and evaluating the upgrades to these circuits.

Cosmic ray scintillator readout.

Indiana took over the evaluation and testing of the cosmic scintillator boards. These circuits will reside with the muon chamber electronics and will handle all signals and logic for the cosmic ceiling hodoscope. Input and output for these circuits will be done through the muon system. The board will also provide latches, analog signals and times of arrival for every photomultiplier input. It must be sensitive to signals only 3 mV in amplitude and 5 nanoseconds wide. Jia has deciphered the circuit and written VME-based programs to read and write to this board through the muon circuit boards. A number of problems were found and corrected, and the board is now going into production. These boards will be added to all outside chambers for the D0 upgrade when all sides of the detector will be surrounded by scintillator.

Cosmic ray run

Last summer the D0 collaboration decided to push for a cosmic ray commissioning run. Its declared purpose was to unite all the individual detector systems and the online and offline software and to flag problems and fix them before the detector is moved into the collision hall.

Tom was responsible for providing a cosmic ray trigger for several regions of the detector. He supervised the assembly and testing of four hodoscope walls and debugged a new manually controlled version of the D0 cosmic scintillator board. Each board replaces about one NIM Crate of electronics. He used these boards with the scintillators covering the entire central detector to provide a general trigger. This trigger can also be set in

coincidence with a scintillator placed in the beam pipe passing through the vertex chambers to simulate muon events coming from a collision. The wall scintillators will be mounted on either side of the end toroids to provide triggers for the forward detectors.

The cosmic ray commissioning run is now in progress and muons have been tracked through the entire central detector. Tom and Jia are actively participating in this run either taking shifts, being on call or evaluating data from the muon system.

Other activities

Tom has spent a non-negligible fraction of his time complying with safety issues and reviews requested by Fermilab in preparation of the Tiger Team safety review of the muon system.

4.6 Summer students - 1990

Two IU students, John Schuler (graduate) and Martin Knudsen (undergraduate) spent 3 months at Fermilab during the summer of 1990 participating in various D0 projects. John Schuler worked on calorimeter electronics, primarily under the supervision of Marvin Johnson. He performed measurements of the noise resolution of the BLS and pre-amp motherboards. These measurements were done with a new fanout on the pulser calibration setup, and encompassed varying cable delays and impedances. He found the expected precision of the calorimeter gain control to be better than 0.4%. John's results are summarized in a D0 Note⁸. John also was involved in the GEANT processing and Trigger Level 1 studies, projects which he has continued working on during the academic 1990/91 year.

Martin Knudsen actively participated in the calorimeter test beam run. In addition to regular shifts, he completed several independent projects. Martin investigated sources of the electronic noise in the experimental hall, contributed to the offline data monitoring and built several mechanical devices in the D0 machine shop.

Both students helped with cabling in the D0 counting house and of the detector itself and with testing power supplies for the muon detector. The summer experience

convinced John to join D0 as a graduate student and Martin to choose a career as a high-energy experimentalist.

4.7 D0 Upgrade

A major goal for the Fermilab Tevatron collider program in the 1990's is the discovery of the top quark. To help reach this goal there will be an upgrade of the collider to higher luminosities, which will require an increased number of beam bunches in the ring resulting in a reduced time between beam crossings. This new environment will require major upgrades of the D0 detector, which are planned for 1995. The upgrade proposal⁹ includes the addition of a central field surrounding improved tracking which consists of scintillating fibers and a silicon vertex detector. These improvements will allow the study of B-physics to be an important added ingredient to the D0 physics program. A large fraction (50%) of muons from B decays is expected to go through the SAMUS detector. All of this puts strong demands on the SAMUS trigger to sort out forward-going muons with a high efficiency.

SAMUS will use two triggering schemes. The first will use narrow one-dimensional strips in the x and y projections to give momentum information at the Level 1 trigger. A second trigger requires coarser x-y-u coincidences. But both triggers will often be fooled by the large background rate of low energy hadrons. Then the Level 2 trigger will be overwhelmed trying to sort through all the x-y-u combinations. What is needed is another trigger element to locate the true muon location in 3 dimensions.

A conclusion of the D0 upgrade proposal is that in order to cope with the expected high occupancies in the SAMUS chambers, additional wire proportional chambers with cathode pad readout must be added between the B and C layers to provide space points to aid in triggering. The geometric arrangement of the pad matrix will be determined by the granularity used in the SAMUS trigger scheme and the occupancy of each region.

We propose to work on the design, testing and production of the new SAMUS system pad chambers. Tom and Jia have begun studies for the design of a pad chamber to supplement the SAMUS forward muon trigger. Tom was involved in budgeting of the muon upgrade proposal which was presented as part of the D0 upgrade to the PAC and

Fermilab in early April 1991. Jia is working on simulating pad chamber geometries using D0 Monte Carlo packages. These studies will determine the granularity required for the pads for different backgrounds, luminosities and physics triggers.

4.8 Plans for 1991/1992

The present schedule for the D0 experiment calls for

Summer - Fall 1991

Commissioning of the apparatus, cosmic ray run.

Late Fall 1991 - June 1992

Detector roll-in, first test/physics run (up to $L=25 \text{ pb}^{-1}$)

June 1992 - October 1992

Linac upgrade at FNAL, analysis of first data, detector corrections

Late 1992

Start a long physics run, collecting the integrated luminosity of 50 pb^{-1}

During this period Tom, Jia and John will remain based at Fermilab. The rest of the group will travel frequently to participate in shifts and data analysis.

Much of the effort of Tom, Jia, and John for the next year will be dedicated to commissioning the D0 muon detection system in preparation for the first physics run. There will be another cosmic ray commissioning run this Fall, at which time the entire detector should be assembled. We are responsible for the commissioning of the scintillator ceiling using the scintillator board electronics. John will take part in all of these activities. He will also arrive in time to take shifts during the end of the first commissioning run and will join Tom in the analysis of the muon detector data. The anticipated topic of his thesis is "Study of $J/\psi \rightarrow \mu\mu$ at D0".

As mentioned earlier, we propose to work on the design, testing and production of the new SAMUS system pad chambers to supplement the SAMUS forward muon trigger.

The Indiana group will continue to run Monte Carlo simulations of the SAMUS detector response to expected background and physics events. Our plan is to determine which combination of triggering algorithm and pad arrangement would best serve the level 1 trigger in being efficient for triggering on interesting physics while reducing background triggers to an acceptable rate.

Simultaneously, we propose to build a small prototype chamber with a variety of pad layouts and wire spacings in order to determine what the physical and time constraints are for various mechanical configurations. We estimate the cost for constructing this chamber and for its onboard hardware to be about \$13000. It is important to duplicate the real electronics environment. Therefore, we would operate and read out this chamber through a standard D0 data acquisition system.

The final chamber design would depend on experience gained from the first data run of D0, which is scheduled to begin within one year, and from the results of our experience with the prototype chamber. To this effect we will do two things. The first will be to process actual minimum bias events recorded in D0 through our Level 1 trigger simulator. The second will be to install the test chamber in the D0 collision hall during the regular collider run as close as possible to the proposed location behind the SAMUS B layer. These two tests should be enough to optimize the chamber design. Once the project is finalized, we intend to participate in the construction of the pad chambers. The whole IU D0 group will participate in this work.

References

- [1] D.Zieminska, "Tutorial on Offline Tracking Packages" D0 Note #1006 (available also on a video tape).
- [2] D0 Notes #948,1025, 1079, 1081, 1096.
- [3] D0 Note #1079.
- [4] D0 Notes #1058, 1082.
- [5] C. Brown *et al.* (T.Marshall), Nucl. Instr. & Methods **A279**, 331(1989).
- [6] "Study of Fast Gases, Resolutions, and Contaminants in the D0 Muon System." J.M. Butler, et al. (T.Marshall), Nucl. Inst. and Meth. **A290**, 122 (1990).
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5. Mark II at the SLC at and PEP

5.1 The Mark II Collaboration

LBL-Berkeley-Santa Cruz-Indiana-SLAC-Caltech-Johns Hopkins-Michigan-Hawaii-Colorado.

Indiana Participants

Graduate Students: Mike Yurko, Doris Averill, Bill Murray

PhD Physicists: David Blockus, Bennet Brabson, Jean-Marie Brom (visiting Physicist from Strasbourg, France), Gail Hanson, Xinchou Lou, Harold Ogren, David Rust and Arthur Snyder.

5.2 Mark II Physics

Mass and Width of the Z^0

The Stanford Linear Collider (SLC) provides electron-positron colliding beams with a center-of-mass energy in the region of the Z^0 resonance (91 GeV). In 1989 approximately 500 Z^0 's were produced in the center of mass energy range from 89.2 to 93.0 GeV. The first observations were made of the hadronic decays of the Z^0 . From these data precise measurements of the mass and width of the Z^0 were made and, with the Standard Model partial widths, an upper limit on the number of light neutrino species was found to be three. Several specific decays of the Z^0 were observed including its decay to pairs of leptons, and pairs of bottom quarks.

Quantum chromodynamics

QCD predictions of event shapes, particle inclusive distributions, and numbers of jets were tested at the Z^0 . The results of several direct comparisons between QCD and these Z events were done and are listed below.

Searches

Several searches for new particles were done using the extended kinematic range available at the Z^0 . Specifically, searches were done for the Higgs, for t and b' quarks,

for supersymmetric particles, and for neutral heavy leptons, both stable and unstable. These searches are also listed below.

5.3 Detector Upgrades and Improvements

The Mark II detector was the first detector to take data at the SLC. The detector was an upgraded version of the device previously used successfully at the PEP and SPEAR storage rings. The upgrade included a new central drift chamber (Gail Hanson was in charge of construction of the new central drift chamber before moving to Indiana University), a new time-of flight system, a new coil, new endcap electromagnetic calorimeters, and a new **muon facade** extending the coverage for muon detection. In the fall of 1989 both the Silicon Strip Vertex Detector (SSVD) and the Drift Chamber Vertex Detector (DCVD) were installed and contributed to the final Mark II runs of 1990. The SSVD achieved a track resolution of better than 10 μm .

Muon Facade Physics

Indiana's major hardware contribution to the detector was the **muon facade** system. This system was a drift tube system sandwiched behind absorber layers of lead and iron. It was completed in the spring of 1989 (including its TDC electronics built by the Michigan group) and by July, 1989 was fully operational. With the muon facade system the angular coverage of the Mark II system was extended from $|\cos \theta| < 0.55$ to $|\cos \theta| < 0.85$. The increased muon coverage improved certain areas of physics accessible to Mark II. The particle searches were improved from added muon coverage. For instance, light quark backgrounds to heavy quark searches using high- p_T leptons were reduced by applying isolation criteria to the leptons. Also, the forward-backward asymmetry of muon tagged quarks provided a method of distinguishing charge-2/3 quarks from charge -1/3 quarks. The added muon coverage in the forward direction made this a more sensitive measurement.

Muon Facade Hardware

In January of 1990 lead shielding for the facades was added to reduce the few MeV photon background. Lead screens proved effective in protecting the upper facades from photons produced along the beam line. Backgrounds were sufficiently reduced to allow the reconstruction of muons reliably. The resolution achieved was 900 μm in the drift tubes.

Muon Facade Software

Indiana physicists created the data acquisition software for the muon facade drift tube system. Doris Averill and Mike Yurko in collaboration with Gail Hanson and Art Snyder were responsible for this data acquisition and calibration software. Bill Murray and Art Snyder developed the alignment software for muon drift tube system.

5.4 The SLC Operation and Mark II Data Collection

The first Z^0 event was recorded in April of 1989. The first 500 Z^0 's were collected during the following 6 month period. The final Mark II runs took data at the Z^0 in January 1990 and in the period from July through November 1990. Both the silicon strip vertex detector (SSVD) and the drift chamber vertex detector (DCVD) were operational during these runs, and therefore, for the 300 Z^0 's collected in 1990.

5.5 Experimental Results from Mark II at SLC

We divide the Mark II physics results from the Z^0 running into three sections: the Z^0 parameters, the manifestations of QCD in the hadronic physics, and the particle searches performed.

A. Standard Model Physics

Z^0 Mass and Width. A measurement of the Z boson mass of (91.14 ± 0.12) GeV/c² and a width of $(2.42^{+0.45}_{-0.35})$ GeV was based on approximately 450 Z^0 's or a total of 19 nb⁻¹ of data recorded at center-of-mass energies between 89.2 and 93.0 GeV. Constraining the visible width to its Standard Model value, we found the partial width to invisible decay modes to be 0.46 ± 0.10 GeV, corresponding to 2.8 ± 0.6 neutrino species, with a 95% confidence level upper limit of 3.9. Thus, our observations excluded the presence of a fourth Standard Model massless neutrino species at a confidence level of 95%. These results are presented in Refs.2 and 3 in the publications list below.

Z^0 Decays into Lepton Pairs. As the first experiment to observe the hadronic decays of the Z, we were able to measure the ratios of leptonic partial widths to hadronic partial widths. The measured ratios were: $\Gamma_{ee}/\Gamma_{\text{had}} = 0.037^{+0.016}_{-0.012}$, $\Gamma_{\mu\mu}/\Gamma_{\text{had}} = 0.053^{+0.020}_{-0.015}$, $\Gamma_{\tau\tau}/\Gamma_{\text{had}} = 0.066^{+0.021}_{-0.017}$. These are in good agreement with the Standard Model prediction of 0.048. These measurements also give the vector coupling constants for the leptons as presented in Ref.4 below.

$b\bar{b}$ Fraction in Hadronic Z Decays. Isolated electrons and muons were used to tag $b\bar{b}$ events in Z decays. The measured fraction, $\Gamma_{b\bar{b}}/\Gamma_{\text{had}} = 0.23^{+0.11}_{-0.09}$, is in good agreement

with the Standard Model prediction of 0.22. From this ratio we were able to extract a value for the vector coupling constant, v_b , as is given in Ref.5 below.

B. Quantum chromodynamics Physics

Hadronic Decays of the Z Boson. The shape parameters, sphericity, thrust, aplanarity and the number of jets were measured for the hadronic decays of the Z. Several Monte Carlo fragmentation models, including Lund Shower, Lund Matrix Element, Webber, and Caltech II, tuned to the Mark II data at 29 GeV, were then used to predict these event parameters at the Z mass. Ref.6 below discusses the comparisons of these models to our data. Each of the fragmentation models follows the features of these shape parameters remarkably well considering the factor of 3 difference in center-of-mass energy.

Charged Particle Inclusive Spectra. Charged particle multiplicity, scaled momentum, and transverse momentum (to the sphericity axis) were measured and compared with our Mark II data at 29 GeV and with the Lund Shower, Webber, and Caltech II Monte Carlo models. As with the shape parameters above, our measured inclusive particle distributions agreed well with these models even though the extrapolation was a factor of three in energy.

Jet Multiplicity and α_s . By comparing the jet multiplicity distributions at the Z mass with our 29 GeV data we examined the running of α_s with energy. Ref.8 below uses this comparison to extract a value of $\alpha_s = 0.123 \pm 0.009 \pm 0.005$ at $E_{cm} = M_Z c^2$. The two competing effects were the increase in number of jets due to the enlarged phase space available at 91 GeV and the decrease in number of jets due to the reduced value of α_s at the higher energy.

C. Particle Searches

Despite the success of the present three generation Standard Model, there is immense interest in looking for new physics beyond this model. A series of searches were conducted using the Mark II data.

New Quarks and Leptons in Z Decays.

Three event topologies were examined to identify potential Z decays to a pair of t quarks, a pair of b' quarks or a pair of unstable heavy leptons. First, isolated charged tracks would occur in semileptonic decays of a t or b' quark. Second, isolated gammas would come from the radiative decay of a b' quark. Third, the decay of two heavy objects

produces a high sphericity event. A t or b quark or a heavy unstable lepton can produce such a topology. Using these techniques, we established 95% confidence level upper limits of $40.7 \text{ GeV}/c^2$ for the top quark mass, $44.7 \text{ GeV}/c^2$ for the b' quark, and $41.3 \text{ GeV}/c^2$ for the unstable neutral lepton.

Long-lived Massive Neutrinos in Z Decays.

Long lived neutral particles would produce a secondary vertex removed from the small and stable primary SLC $e^+ e^-$ collision vertex. A search was made for events with a number of tracks coming from such a displaced secondary vertex. No such events were found, giving a 95% confidence level limit on the production of a pair of fourth generation neutrinos between the masses of $10 \text{ GeV}/c^2$ and $43 \text{ GeV}/c^2$. This result is given in Ref.10 below.

Low Mass Unstable Neutral Leptons.

The expected branching fraction of an unstable fourth generation neutrino to two charged particles is large, typically greater than $1/3$. A search for such two prong decays in the Mark II Z^0 data is described in Ref.11 listed below. Such neutral unstable leptons were excluded at the 95% confidence level between masses of 2.5 and $22 \text{ GeV}/c^2$.

Heavy Stable Charged Particle Pair.

A stable fourth generation charged lepton pair would appear in the Mark II apparatus as a back-to-back charged pair of tracks each with half of the center-of-mass energy. The mass of each track must be consistent not only with the measured momentum of each track but also with the time-of-flight and dE/dx measurements of each track. An analysis of the two charged particle events is given in Ref.12 and found no events consistent with a high mass interpretation. A 95% confidence limit was placed on the existence of such a stable lepton between the muon mass and $36.3 \text{ GeV}/c^2$.

Non-minimal Neutral Higgs.

For two doublet models, which are the minimum extension of the minimal Higgs sector, there are two physical neutral scalar (CP even) Higgs bosons H_s^0 and one neutral pseudoscalar (CP odd) Higgs boson H_p^0 . Ref.13 considers the possible decay $Z \rightarrow H_s^0 H_p^0$ where the lighter of the two Higgs is relatively light ($< 10 \text{ GeV}/c^2$). Limits on the coupling of the Z to such a pair of Higgs bosons were set by examining the Mark II Z decay events.

Doubly Charged Higgs Scalars.

Doubly charged Higgs bosons are expected to decay into a pair of like-sign leptons. In a Mark II sample of 528 Z^0 events no candidates were found for such a four lepton final state. For a Higgs coupling to a pair of like sign leptons of ($g_{ll} > 3 \times 10^{-7}$), the mass region excluded was $6.5 \text{ GeV}/c^2$ to $36.5 \text{ GeV}/c^2$ at the 95% confidence level.

Supersymmetric Particles.

The acoplanarity angle is defined as the angle between the projections of the thrust axes of each hemisphere onto the plane perpendicular to the beam axis. Events with a large acoplanarity angle are consistent with unobserved momentum which can be attributed to a non-interacting supersymmetric particle. Using this technique 95% confidence lower mass limits were placed on a variety of supersymmetric particles including degenerate squarks, non-degenerate up-type squarks, non-degenerate down-type squarks, charginos, pair-produced unstable neutralinos, and associated-produced neutralinos. This study is reported in Ref.15 below.

5.6 Physics Analysis at Indiana

The three Indiana graduate students are carrying out analyses of both Z^0 data from SLC and 29 GeV data from PEP. All three will have completed their analyses and theses by Fall, 1991. We give a brief summary of the three projects here.

b and c Fraction: Doris Averill is studying the fraction of hadronic Z decays which contain bottom and charm hadrons by searching for isolated leptons. Electrons are identified using both the liquid argon calorimeter and the dE/dx in the central drift chamber of the Mark II detector. Muons are detected by both the central muon system and by the muon facade system.

Intermittency: Bill Murray is studying intermittency, the fractal-like behavior in rapidity, which has recently been investigated in data from several other experiments (Delphi at the Z^0 , HRS and TASSO at $\sim 30 \text{ GeV}$). He is in a position to compare data at these two energies in the same detector, and to compare these results with existing Monte Carlo models.

Energy-energy Correlations: Mike Yurko has completed an energy-energy correlation (EEC) analysis on both SLC and PEP data. The measured EEC is influenced

both by the underlying QCD shower structure and by the hadronic fragmentation processes. By comparing data at the two energies with each other and with Monte Carlo models, he can critically examine these models and is able to extract values of the strong coupling constant, α_s , at each energy.

5.7 Summary

The final Mark II data was taken in November, 1990. The total data sample, some 800 Z^0 s, was disappointingly small. We therefore anticipate that the majority of Mark II data analysis will have been completed by the end of the current year (December, 1991) and are not requesting further research support for this project. A number of papers will result from on-going analysis by physicists both at Indiana and at collaborating institutions.

5.8 Published papers from SLC work

The Mark II Detector

1. THE MARK II DETECTOR FOR THE SLC, G.S. Abrams, et al., Nucl. Instr. Meth. **A281**,55(1989).

Standard Model Physics papers

2. INITIAL MEASUREMENTS OF Z BOSON RESONANCE PARAMETERS IN $e^+ e^-$ ANNIHILATION, G.S. Abrams, et al., Phys. Rev. Lett. **63**;724,1989.
3. MEASUREMENTS OF Z BOSON RESONANCE PARAMETERS IN $e^+ e^-$ ANNIHILATION, G.S. Abrams, et al., Phys. Rev. Lett. **63**;2173,1989.
4. MEASUREMENT OF Z DECAYS INTO LEPTON PAIRS, G.S. Abrams, Phys. Rev. Lett. **63**; 2780,1989.
5. MEASUREMENT OF THE B ANTI-B FRACTION IN HADRONIC Z DECAYS, J.F. Kral, Phys. Rev. Lett. **64**;1211,1990.

QCD related papers

6. FIRST MEASUREMENTS OF HADRONIC DECAYS OF THE Z BOSON, G.S. Abrams, et al., Phys. Rev. Lett. **63**;1558,1989.
7. MEASUREMENTS OF CHARGED PARTICLE INCLUSIVE DISTRIBUTIONS IN HADRONIC DECAYS OF THE Z BOSON, G.S. Abrams, et al., Phys. Rev. Lett. **64**;1334,1990.
8. DETERMINATION OF α_s FROM A DIFFERENTIAL JET MULTIPLICITY DISTRIBUTION AT SLC AND PEP., S. Komamiya, et al., Phys. Rev. Lett. **64**;987,1990.

Searches

9. SEARCHES FOR NEW QUARKS AND LEPTONS PRODUCED IN Z BOSON DECAY, G.S. Abrams, Phys. Rev. Lett. **63**;2447,1989.
10. SEARCH FOR LONG-LIVED MASSIVE NEUTRINOS IN Z DECAYS, C. Jung, et al., Phys. Rev. Lett. **64**;1091,1990.
11. A SEARCH FOR DECAYS OF THE Z TO UNSTABLE NEUTRAL LEPTONS WITH MASS BETWEEN 2.5 AND 22 GeV, P.R. Burchat, et al., Phys. Rev. **D41**, 3542, 1990.
12. A SEARCH FOR PAIR PRODUCTION OF HEAVY STABLE CHARGED PARTICLES IN Z DECAYS, E. Soderstrom, et al., Phys. Rev. Lett. **64**, 2980, 1990.
13. SEARCH FOR NON-MINIMAL NEUTRAL HIGGS BOSONS FROM Z BOSON DECAYS, S. Komamiya, et al., Phys. Rev. Lett. **64**, 2881, 1990.
14. A SEARCH FOR DOUBLY CHARGED HIGGS SCALERS IN Z DECAY, M. Swartz, et al., Phys. Rev. Lett. **64**, 2877, 1990.
15. SEARCHES FOR SUPERSYMMETRIC PARTICLES PRODUCED IN Z BOSON DECAY, T. Barklow, et al., Phys. Rev. Lett. **64**, 2984, 1990.

5.9 Mark II Invited Talks by Indiana Physicists

REPORT ON THE 12TH NORDIC MEETING ON PARTICLE PHYSICS, G. G. Hanson, High Energy Physics Seminar, Indiana University, January 30, 1990.

RESULTS FROM THE MARK II AT SLC, G. G. Hanson, invited talk at the 12th Nordic Meeting on Particle Physics, Spatind Mountain Hotel, Dokka, Norway, January 6-10, 1990.

NEW RESULTS FROM MARK II, H. Ogren and G. G. Hanson, High Energy Physics Seminar, Indiana University, November 14, 1989.

SLC PHYSICS: LIMIT ON NUMBER OF GENERATIONS FROM Z DECAYS, G. G. Hanson, Seminar at Indiana University Cyclotron Facility, November 9, 1989.

LATEST RESULTS FROM MARK II AT SLAC, H. Ogren University of Cincinnati, October 24, 1989.

PRODUCTION AND DECAY OF Z BOSONS: RESULTS FROM THE STANFORD LINEAR COLLIDER, B. Brabson, Colloquium, Indiana University, February 21, 1990.

PRODUCTION AND DECAY OF Z BOSONS, B. Brabson, High Energy Physics Seminar, University of Virginia, April 25, 1990.

THE Z^0 BOSON: RESULTS FROM THE STANFORD LINEAR COLLIDER, B. Brabson, Sigma Xi Chapter at University of Virginia, April 25, 1990.

THE Z^0 BOSON, B. Brabson, Indiana University Purdue University at Indianapolis,
October, 1990.

PhD Theses

1. Doris Averill - in progress.
2. Mike Yurko - in progress.
3. Bill Murray - in progress.

5.10 Electron-Positron Collisions at 29 GeV

Experimental Results from Mark II at PEP

In the past 18 months several new analyses have been performed on Mark II data taken at 29 GeV at PEP. Part of these data were collected with the upgraded detector. Ten papers have been published or submitted during this time period and are listed below as Refs. 16 - 25. Indiana physicists have contributed to several of these papers. Art Snyder did the analysis and wrote the paper on the search for B decay to Higgs bosons, cited as Ref. 18 below.

Experimental Results from the HRS at PEP

The Indiana high energy group in collaboration with Michigan, Purdue and Argonne carried out the High Resolution Spectrometer (HRS) experiment at the PEP collider from 1981 to 1986. More than 50 publications come from this work, including 3 publications during the last year, cited below as Ref. 26 - 28.

5.11 Published papers from PEP work

Mark II Physics at PEP

16. SEARCHES FOR NON-MINIMAL HIGGS BOSONS FROM A VIRTUAL Z DECAYING INTO A MUON PAIR AT PEP, S. Komamiya, et al., Phys. Rev. D40;721,1989.
17. STUDIES OF JET PRODUCTION RATES IN $e^+ e^-$ ANNIHILATION AT $E_{cm} = 29$ GEV, S. Bethke, et al., Z. Phys. C43;325,1989.
18. SEARCH FOR B DECAY TO HIGGS BOSONS FOR HIGGS BOSON MASSES BETWEEN 50 MEV/C² AND 210 MEV/C², A. Snyder, et al., Phys. Lett. B229;169,1989.
19. UPPER LIMITS ON $D^\pm$ AND $B^\pm$ DECAYS TO TWO LEPTONS PLUS $p^\pm$ OR $K^\pm$, A. Weir, et al., Phys. Rev. D41;1384,1990.
20. MEASUREMENT OF THE B^0 LIFETIME, S. R. Wagner, et al., Phys. Rev. Lett. 64;1095,1990.
21. REANALYSIS OF B^0 ANTI- B^0 MIXING IN $e^+ e^-$ ANNIHILATION AT 29 GEV, A. Weir, et al., Phys. Lett. B240, 289, 1990.
22. MEASUREMENT OF THE TOTAL HADRONIC CROSS SECTION IN $e^+ e^-$ ANNIHILATION AT $E_{cm} = 29$ GeV, C. von Zanthier, et al., Phys. Rev. D43, 34, 1991.

23. FOUR LEPTON FINAL STATES IN e^+e^- INTERACTIONS AT 29 GEV, M. Petradza et al. (Submitted to Phys. Rev. D)
 24. A SEARCH FOR ELASTIC NON-DIAGONAL LEPTON PAIR PRODUCTION IN e^+e^- ANNIHILATION AT 29 GEV, J. J. Gomez Cadenas et al, Phys. Rev. Lett. **66**, 1007, 1991.
 25. PRECISE MEASUREMENT OF THE τ LIFETIME, R. Harr et al., (Submitted to Phys. Rev. D)
- HRS Physics at PEP*
26. STUDY OF INTERMITTENCY IN e^+e^- ANNIHILATIONS AT 29 GEV, S. Abachi et al., (submitted to Phys. Rev. B)
 27. MEASUREMENT OF THE BRANCHING RATIO FOR $\tau \rightarrow e^- \nu_e \nu_\tau$, S. Abachi et al., Phys. Lett **B226**, 405, 1989 and Phys. Rev. **D41**, 1414, 1990.
 28. QUARK HADRONIZATION PROBED BY K_0 MESONS, S. Abachi et al., Phys. Rev. **D41**, 2045, 1990.

Cavendish Laboratory, Cambridge, UK
 Carleton University
 Centre for Research in Particle Physics, Carleton University
 CERN
 University of Chicago
 Albert Ludwigs Universität, Freiburg
 Universität Heidelberg
 Indiana University
 Queen Mary and Westfield College, University of London
 Birkbeck College, London
 University College London
 The University, Manchester
 University of Maryland
 Université de Montréal
 Herzberg Institute of Astrophysics, Ottawa
 Rutherford Appleton Laboratory
 CEN Saclay
 Technion - Israel Institute of Technology
 Tel Aviv University
 International Centre for Elementary Particle Physics and Dept. of Physics,
 University of Tokyo and Kobe University
 Brunel University, UK
 Weizmann Institute of Science
 University of British Columbia
 University of Victoria

Indiana University joined OPAL in June, 1990, at about the same time as the University of British Columbia and the University of Victoria.

The OPAL Detector

The OPAL detector is a general purpose detector designed for e^+e^- physics at the Z boson resonance. The detector is shown schematically in Fig. 6.1. The detector consists of a central tracking detector in a solenoidal magnet, surrounded by a time-of-flight counter array, a lead-glass electromagnetic calorimeter with a presampler, an instrumented magnet

6. OPAL Experiment at CERN

6.1 Overview of OPAL Detector and Physics

The OPAL detector has been running at LEP at CERN since August, 1989. About 180,000 events have been recorded at energies at or near the Z^0 resonance peak. The OPAL collaboration has published or submitted about 30 papers reporting results on Z^0 mass and width, electroweak physics, QCD physics, B physics, and new particle searches. A list of OPAL publications is included. The OPAL detector has been upgraded with a new silicon microvertex detector for the 1991 LEP run, which is just beginning. We expect to collect at least 500,000 Z^0 events during this run.

Physics at LEP

In the energy range accessible at LEP, the mechanisms by which symmetries are broken at present energies should manifest themselves. Among the central physics issues are the study of the Z and W , the determination of their exact masses and widths, and couplings to leptons and quarks. With the energy upgrade of LEP 2 an even richer physics region above W^+W^- threshold will open up. It is clear that the focus of the highest energy e^+e^- physics will remain in Europe for many years.

The addition of a silicon microvertex detector to OPAL, with a new beam pipe of radius 5.5 cm, will improve the impact parameter resolution by about a factor of four, to a high-momentum plateau value of about 10 μm . There are about 140K $b\bar{b}$ events per 10^6 Z^0 events. With the microvertex detector, we will be able to tag $b\bar{b}$ events with high efficiency and purity. We will be able to study and measure branching ratios for B meson decays and eventually to measure $B^0 \bar{B}^0$ mixing.

The OPAL Collaboration

The institutions participating in the OPAL experiment are:

University of Birmingham, UK

Università di Bologna and INFN

Universität Bonn

University of California, Riverside

A two-layer silicon microvertex detector, described in more detail in Section 6.3, along with a new 5.5 cm beam pipe, has been installed inside the OPAL detector for the run beginning in April, 1991. The addition of the silicon microvertex detector will give an impact parameter resolution of about 10 μm for high-momentum particles.

6.2 Recent Results from OPAL

The results from the OPAL 1990 run center around four major topics:

- Measurements of Electroweak Parameters
- QCD Physics
- Heavy Flavor Physics
- The Search for New Particles.

OPAL has analyzed numerous topics. Below we shall concentrate only on some highlights of the analyses. Further information can be obtained from the reference list of the OPAL publications.

Measurements of Electroweak Parameters

During 1990 an energy scan around the Z^0 mass was performed. The mass and the width of the Z^0 were measured to be:

$$M_Z = 91.156 \pm 0.009 (\text{exp}) \pm 0.020 (\text{LEP}) \text{ GeV}/c^2$$

$$\Gamma_Z = 2.492 \pm 0.0166 (\text{exp}) \pm 0.0049 (\text{LEP}) \text{ GeV}.$$

The error on the mass of the Z^0 comes from the experimental uncertainty and from the error on the LEP energy measurement.

The number of light neutrino generations was measured to be:

$$N_V = 3.046 \pm 0.068 (\text{exp}) \pm 0.004(M_t, M_H),$$

return yoke serving as a hadron calorimeter, four layers of outer muon chambers, and an endcap system that includes a small-angle forward detector.

The central detector consists of a system of tracking chambers inside a 0.435 Tesla solenoidal magnetic volume. The central tracking detector consists of a precision vertex chamber, a large volume "jet" chamber, and a chamber for tracking in the $r - \theta$ dimension (the coordinate system is defined with z along the beam axis, and θ and ϕ the polar and azimuthal angles). The main tracking is done with the jet chamber, a drift chamber of approximately four meters length and two meters radius with 159 layers of sense wires and having 24 sectors in ϕ . The region of tracking registering a minimum of 40 wires covers approximately $|\cos\theta| \leq 0.94$. Integrated charges are measured at both ends of the wires and used for determining the position along the wire and for energy loss dE/dx for particle identification.

The electromagnetic calorimeter consists of an array of lead glass elements for detection of electrons and photons and is mounted around the solenoid, covering nearly the full solid angle. The electromagnetic calorimeter consists of a cylindrical array of 9,440 lead glass blocks of 24.6 radiation lengths thickness covering the range $|\cos\theta| \leq 0.82$, and 2,264 lead glass blocks of 20 radiation lengths thickness in the endcaps covering the region between $0.81 < |\cos\theta| \leq 0.98$. Each block subtends a solid angle of approximately 40×40 mrad² and projects towards a point near the interaction point in the barrel region and along the beam direction in the endcaps. The two sections of the electromagnetic calorimeter together cover 98% of the solid angle.

Located radially outside the presampler chamber of the electromagnetic calorimeter, the time-of-flight system covers the barrel region of $|\cos\theta| \leq 0.82$. It consists of 160 scintillator bars, 6.8 m long and 45 mm thick, located at a radius of 2.4 m. The hadron calorimeter is of the iron-scintillator sandwich type, with the iron of the calorimeter serving as the return yoke for the magnet. A system of drift chambers for the detection and identification of muons covers the full solid angle outside the return yoke.

The forward detector includes a luminosity monitor and an electromagnetic calorimeter system for the study of 2γ processes.

$$N_V = 3.0 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.)}.$$

QCD Physics

Global event shapes of hadronic final states are largely determined by the jet structure of the events. The comparison of measured event shape distributions with QCD plus hadronization models tests both QCD and the different hadronization models. From the various models studied by OPAL, the JETSET QCD shower plus string hadronization model agrees best with the experimental data.

The determination of α_s is one of the key analyses of hadronic final states. $\alpha_s(M_{Z^0})$ is determined from the hadronic partial width of the Z^0 , from jet production rates, from energy-energy (as well as asymmetric-energy-energy) correlations, and from global event shape distributions. The results are summarized in Fig. 6.3.

The specific spin structure of the triple gluon vertex within 4-jet events is an excellent test for the non-abelian nature of QCD. The Feynman diagrams in Fig. 6.4 can occur only if the gluon spin is 1. The distribution most sensitive to this effect is of the angle between two planes, each plane being defined by two jet directions. This distribution is shown in Fig. 6.5, together with several theoretical predictions. The data are in good agreement with QCD, and significantly rule out the abelian hypothesis.

Heavy Flavor Physics

OPAL has observed D^* production in jets. The selection of the D^* candidate events from the reaction $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ K^- \pi^+$ makes use of the excellent dE/dx measurements obtained with the OPAL jet chamber. The mass difference $M(D^*) - M(D^0)$ is shown in Fig. 6.6 for events with $x_{D^*} > 0.2$, where $x_{D^*} = E_{D^*} / E_{cm}$. Fixing the yield and fragmentation function of bottom quarks to the values obtained at LEP from lepton tags, we obtained:

$$\Gamma_{Z^0 \rightarrow c\tau} = 0.292 \pm 0.082 \pm 0.050 \text{ GeV},$$

where the first error is the combined statistical and systematic error of OPAL, and the second one is the total error from other sources.

where the second error comes from varying the top quark mass between 50 and 230 GeV/c², the Higgs mass between 50 and 1000 GeV/c², and α_s by ± 0.008 .

The weak mixing angle was measured to be:

$$\sin^2 \theta_W = 0.238 \begin{array}{c} + 0.03 \\ - 0.006 \end{array}$$

The partial widths of the Z^0 were measured to be:

$$\Gamma_{had} = 1.838 \pm 0.046 \text{ (exp)} \pm 0.030 \text{ (LEP)} \text{ GeV}$$

$$\Gamma_{l+l-} = 83.1 \pm 1.9 \text{ MeV}$$

$$\Gamma_{e+e-} = 82.9 \pm 1.0 \text{ MeV}$$

$$\Gamma_{\mu+\mu-} = 83.2 \pm 1.5 \text{ MeV}$$

$$\Gamma_{\tau+\tau-} = 82.7 \pm 1.9 \text{ MeV.}$$

Assuming that the only invisible decay mode of the Z^0 is to light neutrinos, we define:

$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3 \Gamma_{l+l-} = 0.504 \pm 0.015 \text{ GeV.}$$

An independent measurement of the branching ratio of the Z^0 into invisible particles was performed by measuring the cross section of single photon events in e^+e^- collisions near the Z^0 resonance. The single photon originates from initial state radiation. We observed 73 events with single photons depositing more than 1.5 GeV in the electromagnetic calorimeter, with an expected background of 8 ± 2 events. The cross sections at each center-of-mass energy point for the reaction is shown in Fig. 6.2. The overlaid curves show the expectation for three (solid curve), two and four (dashed curves) light neutrino generations. The invisible width was measured to be:

$$\Gamma_{inv} = 0.50 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.) GeV.}$$

Assuming the Standard Model coupling to neutrinos, this corresponds to:

No positive signals were seen. Mass limits are at the kinematic limit of the center-of-mass energy.

6.3 Indiana University Participation in OPAL

Indiana University Personnel

The Indiana University group has had many years of experience in e^+e^- physics at SLAC, including the Mark II experiment at the SLC, which ended in the fall of 1990. We chose to continue research in e^+e^- physics at LEP by joining the OPAL experiment.

Members of the Indiana University group at OPAL are:

Faculty: Gail Hanson, Harold Ogren, Ben Brabson

Research Physicists: Ronen Mir, David Rust

Postdocs: Xin Chou Lou, Thierry Mouthuy

Graduate students: Michael Settles, Eduardo Silva, plus one more

Software engineer: Thom Sulanke

The Indiana University Group officially joined OPAL in June, 1990, when Xin Chou Lou moved from SLAC to CERN. During the summer of 1990, Gail Hanson and David Rust worked with OPAL for long periods. Michael Settles arrived in September. Two new members of the group, Ronen Mir and Thierry Mouthuy, began work there in October, 1990, and January, 1991, respectively. Indiana University is listed on OPAL papers beginning with those submitted in January, 1991.

Indiana University currently has four physicists in residence at CERN: Ronen Mir, Xin Chou Lou, Thierry Mouthuy, and Michael Settles. During the summer of 1991, a new graduate student in the high energy group, Eduardo Silva, will be resident at CERN for a year. Settles will return to Indiana University in August. We may have a third graduate

The production of J/ψ in hadronic Z^0 decays is observed in the di-muon channel. The $\mu^+\mu^-$ mass distribution is shown in Fig. 6.7. A clear J/ψ signal is seen. The inclusive branching fraction is measured to be:

$$B(Z^0 \rightarrow J/\psi + X) = (5.2 \pm 1.1 \pm 0.6 \pm 0.7) \times 10^{-3},$$

where the first error is statistical, the second systematic, and the third is due to the uncertainty in $B(J/\psi \rightarrow \mu^+\mu^-)$. The scaled momentum distribution of the J/ψ is consistent with the distribution expected from B decays.

The Search for New Particles

OPAL has searched for the currently undiscovered particles predicted by the Standard Model, and for most particles predicted by theories beyond the Standard Model. No positive signals were observed. Mass limits are typically at the kinematic limit of the center-of-mass energy:

- A stable heavy neutrino has been excluded up to 44 GeV/c², at the 95% C.L.
- The top quark has been excluded up to 45.1 GeV/c², at the 95% C.L.
- The b' quark has been excluded up to 45.5 GeV/c², at the 95% C.L.
- A Standard Model Higgs has been excluded from 0 to 44.0 GeV/c², at the 95% C.L.

Other searches have been performed to look for:

Heavy leptons
 Excited leptons
 Neutralinos
 Technipions
 Charged Higgs
 Other SUSY particles

of CPU server, disk servers, about 30 Gbytes of SCSI disks, a Cisco IP router, and the UltraNet backplane and network.¹ The pilot *shift* configuration is shown in Fig. 6.8. The CERN Cray X-MP/48 is used as the tape server. Indiana University purchased a Silicon Graphics 340S for the CPU server and 20 Gbytes of Wren VII SCSI disks. CN purchased the UltraNet hardware and the disk server(s). The equipment was in place by late December, 1990. Existing Apollo DN10000 CPUs from the HOPE project can also be used, although the Apollo UltraNet interface is just beginning to work. Indiana University physicists are setting up the OPAL analysis codes on the different CPUs (Silicon Graphics and Apollo DN10000) of the *shift* project. They have written procedures (in UNIX) that take care of the different environments of the different CPUs and ease the submission of jobs by the OPAL physicists. They are writing documentation² and are assisting other OPAL physicists to run their analysis jobs on the new system. The project is making excellent progress and will be able to receive all the data taken in 1991, allowing OPAL physicists to run their analysis programs quickly and reliably.

Silicon Microvertex Detector

A two-layer silicon microvertex detector, along with a new 1.5 mm thick and 5.5 cm radius beryllium beam pipe, has been installed inside the OPAL detector for the 1991 LEP run, which is just beginning. The silicon microvertex detector is shown schematically in Fig. 6.9. This device consists of 75 sensitive single-sided silicon strip wafers. The silicon strip wafers are of 300 μm thickness and 25 μm pitch. Three silicon wafers each 6.0 cm long are bonded together to form a ladder. The first layer contains 11 ladders and is positioned at radius 6.0 cm. The second layer lies at a radius of 7.5 cm and consists of 14 ladders. The silicon microvertex detector covers the area $30^\circ \leq |\theta| \leq 150^\circ$, where θ is the polar angle relative to the beam direction. The silicon is AC- coupled to the readout. The signal is read out every other strip using MX5 microplex chips, developed at the Rutherford Laboratory. Test beam measurements gave a signal-to-noise ratio about 20/1 and a point precision of about 5 μm . Noise measurements made so far with the detector installed in OPAL and with the magnet on give similar results. The Fastbus data

¹ SHIFT, The Scalable Heterogeneous Integrated Facility for HEP Computing, J.-P. Baud *et al.*, presented at Computing in High Energy Physics 91, Tsukuba, Japan, March, 1991.

² OPAL User's Guide for the SHIFT Project, Version 1.01, Xinchou Lou, Ronen Mir, Thierry Mouthuy, Steve O'Neale, Michael Settles, and Igor Zacharov, March 6, 1991, OPAL/16-OFFL/0478.

student from the entering class at CERN during the summer. Harold Ogren, David Rust, and Gail Hanson will continue to spend several periods at CERN during the academic year with longer stays in the summer.

We are contributing to the OPAL experiment in the following areas:

- Offline Analysis Computing Upgrade
- Silicon Microvertex Detector
- Data Analysis
- Manpower for Running Shifts
- OPAL Common Maintenance and Operation Funds

Offline Analysis Computing Upgrade

CERN provides only enough computing capability to analyze about 10 percent of the data at the LEP design luminosity. Therefore, the LEP experiments have had to provide their own computing. During the upcoming runs, we expect one million Z 's. Two aspects must be addressed: data storage and computing power. With the present size of OPAL events, 100 Gbytes of mass storage are required for one million Z 's. In addition, the physicists must be able to run analysis jobs on this data in a timely manner. To meet this need, in early 1990 OPAL set up an offline analysis facility based on a VAXstation cluster. However, by summer it was recognized that such a system was CPU-limited and a better solution could be found given the technology currently available.

Under the leadership of physicists from Indiana University, the OPAL Collaboration is implementing an offline analysis computing upgrade based on RISC processors and access to the data via a high-speed (1 Gbit/s) UltraNet network. RISC computers from various vendors can be used, as long as they have a UNIX operating system and an UltraNet interface. We have formed a joint project with the CERN CN (Computing and Networking) Division to carry this out (the project is called *shift*, for Scalable Heterogeneous Integrated Facility). The pilot project consists of about 100 MIPS

physics. The goal is to isolate a B_S^0 signal and further to study $B_S^0 \bar{B}_S^0$ mixing. We have looked into two final states of the D_S^+ meson: $D_S^+ \rightarrow \phi \pi$ and $\bar{K}^0 K$. We used the dE/dx information and a secondary vertex constraint for the analysis. Our preliminary work reveals high background for these modes. The statistics are also low. We expect that more data and better impact parameter measurement will help increase the statistical significance of a signal and reduce the background, leading to the observation of D_S^+ and ultimately the isolation of a convincing B_S signal, which will allow for the study of the $B_S^0 \bar{B}_S^0$ mixing.

We also searched for charmed baryon Λ_c and bottom baryon Λ_b signals in the OPAL data. The backgrounds are quite high, and no clear signals are observed at the moment. We will perform the same analysis with the full 1991 data sample when it becomes available.

The dE/dx resolution of the charged tracks in the central jet chamber is 3.5% for tracks with more than 40 valid dE/dx hits. Meanwhile the single track r - ϕ resolution of the OPAL vertex chamber is 40 μm . These are the best among all the LEP experiments, which puts us in a unique position to study heavy flavor physics. The addition of a new silicon microvertex detector brings in the possibility of vertex constraint on the B decays. We are investigating B tagging techniques making use of the improved r - ϕ resolution and the dE/dx particle identification. Preliminary Monte Carlo study shows that the signal-to-noise ratio improves by up to a factor of four for charmed meson D^+ decaying into $K^+ \pi^+ \pi^-$. More detailed study will be carried out with the new OPAL Monte Carlo program which has just recently been rewritten to include more realistic simulation of the silicon microvertex detector.

acquisition system and Siroccos are all installed and working. We hope for delivery of all power supplies at the end of April. Meanwhile, we are recording events with the detector partially powered.

The addition of the silicon microvertex detector will improve the impact parameter resolution from $45\text{ }\mu\text{m}$ to an expected value of $10\text{ }\mu\text{m}$. This improvement will give us the capability to do excellent heavy flavor physics with the data from the coming run. Monte Carlo studies show that with the silicon microvertex detector the decay length technique for tagging B 's will select $Z \rightarrow b\bar{b}$ events with a purity of 80% at about 20% efficiency. The purity and the efficiency obtained with the silicon microvertex detector are significantly superior to the high p_T lepton B tagging technique and tagging B 's by decay length using only the existing OPAL vertex chamber. Furthermore, secondary charm vertex reconstruction, which we are studying now, is expected to be significantly improved.

The physics topics we can study with the 1991 data include: $\Gamma_{b\bar{b}}$, independent of $b \rightarrow cl\bar{\nu}$ and less sensitive to the fragmentation models than other methods; b lifetimes for individual b -flavored mesons; b semileptonic decay branching ratio $B(b \rightarrow cl\bar{\nu})$ for $Z \rightarrow b\bar{b}$ events; $B^0\bar{B}^0$ mixing; search for the B_S^0 meson and study of B_S^0 decays and $B_S^0\bar{B}_S^0$ mixing. In addition, we can also study heavy flavor fragmentation at around $91\text{ GeV}/c^2$; measurement of the strong coupling constant α_S in $Z \rightarrow b\bar{b}$ events; and the string effect in $b\bar{b}$ events. Future high luminosity runs will allow for the study of the heavy flavor spectroscopy and inclusive and exclusive decays of b -flavored particles.

We plan to gain experience with the silicon microvertex detector just installed, use it for 1991 physics analysis, and then replace it with a double-sided device during the 1991/92 winter shutdown. The new device will provide z information close to the b, c decay vertex and improve the momentum resolution. Development of a double-sided silicon detector is now beginning. Ronen Mir is working on the double-sided silicon prototypes. Xin Chou Lou is participating in alignment of the installed detector using data from the 1991 run.

Data Analysis Activities

The Indiana group is just beginning to work on data analysis since we have been in the collaboration for less than a year and our major commitment has been the upgrade of offline analysis computing. We are working on analysis of data and Monte Carlo studies without and with the new microvertex detector on topics in the area of heavy flavor

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Fig. 6.1. Schematic view of the OPAL Detector.

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MEASUREMENT OF THE Z^0 MASS AND WIDTH WITH THE OPAL DETECTOR AT
LEP, OPAL Collaboration, CERN-EP/89-133, Phys. Lett. **231B**, 530 (1989).

Fig. 6.4. Generic Feynman diagrams for the process $e^+e^- \rightarrow Z^0 \rightarrow 4 \text{ jets}$.

Fig. 6.5. Measured distribution of χ_{BZ} together with the predictions of QCD and abelian vector gluon models.

Fig. 6.2. The corrected cross sections (pb) at each centre-of-mass energy point for single photons above 1.5 GeV in the angular range $|\cos\theta| < 0.7$ from the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. The solid curve shows the result corresponding to 3.0 light neutrino generations. The expectations from two and four light neutrino generations are shown by the lower and upper dashed curves respectively.

Fig. 6.3. Summary of OPAL measurements of $\alpha_s(M_{Z^0})$.

the *shift* configuration at CERN - (8 Mar. 1991).

Fig. 6.8. Configuration of the *shift* pilot project.

Fig. 6.9. Schematic view of the OPAL microvertex detector.

Fig. 6.6. The measured mass difference $M(D^*) - M(D^0)$.

Fig. 6.7. Measured $\mu^+ \mu^-$ mass distribution and fit.

7. Superconducting Super Collider

7.1 Solenoidal Detector Collaboration

Introduction

On December 16, 1990, the Program Advisory Committee at the SSC Laboratory approved the Solenoidal Detector Collaboration (SDC) to proceed to the detector design stage. So far, the SDC detector is the only one so approved. Our group at Indiana University participated in writing the Expression of Interest and the Letter of Intent for the Solenoidal Detector Collaboration (SDC) and helped defend the proposal to the PAC. Members of our group are on the Executive Board, the Institutional Board, and several steering committees. We have been very active in the research and development of straw tube drift chambers for use in the SDC. The major part of this detector work and a substantial tracking simulation effort are ongoing as part of the SSC Wire Tracking Subsystem.

Personnel

The members of Indiana High Energy Physics Group who are in the SDC collaboration are:

Gail Hanson- member of the Executive Board of the SDC

Harold Ogren- Institutional Board member and the Indiana contact for the collaboration

Alex Dzierba, faculty

Ben Brabson, faculty

David Rust, Senior Scientist

Fred Luehring, Physicist/Programmer

Ellsworth Wente, Assistant research scientist

Bryan Martin, Technician

Randy Foster, Programmer- designer

The SDC Collaboration

SDC grew out of several initially independent efforts centered at the Lawrence Berkeley Laboratory, Argonne National Laboratory, Fermilab, and the KEK National Laboratory in Japan, with strong participation from university groups. These efforts were all aimed at a solenoidal detector for high- p_T physics at the SSC. At a workshop at Fermilab in September 1989, the various groups decided to combine their activities and develop a joint Expression of Interest for an SSC detector. An interim steering committee was set up to prepare a governance document and determine the membership of the collaboration. The collaboration was formally formed at the first collaboration meeting at Fermilab in December 1989. Presently the SDC consists of about 600 physicists from 11 different countries. In the Spring of 1990 the collaboration prepared and submitted an Expression of Interest (EOI) which outlined many of the details of the detector and areas of particle physics that could be explored. In June, 1990, the Program Advisory Committee at the SSC Laboratory indicated their approval of the SDC Expression of Interest and directed the collaboration to proceed to the writing of the Letter of Intent. This Letter of Intent (LOI) was reviewed by the PAC in November 1990. In December of 1990 the PAC approved the SDC experiment to proceed to the design stage. SDC was the only detector at that time to be given approval. Our group at Indiana is now working on the many details that must be addressed in the design report, which must be submitted April 1, 1992. We are also part of the core effort to develop a simulation of the SDC tracking system. Our group is designing the outer wire tracker component of the SDC tracking system. Much of the engineering work is being done in conjunction with Westinghouse Science and Technology Center (WSTC), Oak Ridge National Laboratory (ORNL) and the SSC laboratory. We have been active in working with the technical board, the tracking task force, and the facilities task force in the preparation for the design report.

The SDC Detector

One of the reasons for proposing a general-purpose detector for the SSC is provided by the great success of existing large detectors at electron-positron and proton-antiproton colliders. Many of the possible physics signals of interest at the SSC produce leptons and hadron jets at large angles and with large transverse momenta. It is thus natural to consider a detector that combines a large solenoidal magnet for determining the momenta of charged particles with a hermetic calorimeter to measure jet and electron energies and

missing transverse energy. The measurement of momenta with a magnetic field has the outstanding advantage of providing an absolute stable energy scale. This is not easily achieved with calorimetric techniques. Moreover, the signs of charged particles can be determined, a capability that is essential for a number of physics topics such as charge asymmetries and like-sign dilepton production. A solenoid field configuration provides azimuthal symmetry and simplifies detector construction and event analysis. The detector envisioned for SSC, shown in Fig. 7.1, consists therefore of a solenoidal spectrometer surrounded by electromagnetic shower counters, hadronic calorimeters, and systems for detecting muons.

It is the goal of the SDC to build a tracking system that will provide momentum measurements of all charged particles with p_T above a few GeV/c for $|\eta| < 2.5$. The tracking system will also provide a fast trigger for such particles. These goals can best be realized by several different types of tracking technology. The tracking detector will use a combination of silicon devices with wire chambers and/or scintillating fibers. For the region with radii greater than 60 cm the wire chamber tracking technology that will probably be used is a small-cell chamber with continuous cathodes called straw tubes. These can provide a fast trigger for particles above some minimum p_T by the simple requirement that the reconstructed track segment near the outer radius point back to the interaction point within some appropriate uncertainty. They also provide significant pattern recognition and momentum measurement capability.

SDC Related Activities

1) Tracking Task Force

As one of the principle proponents of a wire tracking scheme using straw drift chambers, our group at Indiana has been a primary focus of the SDC Tracking Task force. We are now attempting to finish a baseline design for tracking that will be the basis of an engineering and cost study for the final design report. There are a multitude of areas that need to be optimized in the tracking design, such as material in the tracking region, pattern recognition with a mixed system, alignment and precision for components, electronics capabilities, safety concerns, and assembly and access requirements. Many of these topics require professional engineering studies and large systems experience. For this reason, some of this work is being coordinated through the Westinghouse Science and Technology Center and Oak Ridge National Laboratory.

2) Simulation group

The SDC tracking system will probably involve several types of detectors- silicon strips and pixels, scintillating fibers, straw tubes and gas microstrip detectors. There are many parameters that define the tracking system such as track position measurement resolution, track separation capability, the average number of hit cells per event, the amount of material along a typical track, radial position of the layers, etc. A detailed simulation effort is required to optimize the tracking system. This is now proceeding for the wire system as a joint effort between Indiana University, University Colorado, and LBL. The scintillating fiber and the silicon groups also have simulation efforts well under way. Members of our group are working with them to form a unified simulation group to be able to understand the entire SDC tracking system. The Indiana group has also been active in promoting the unified "shell " for a complete detector simulation. Recently the group has incorporated the stereo straw modules and the silicon strip system in this simulation. The goal is to begin to operate with a unified system in the summer of 1991.

3) Electronics

Electronic readout is a key element in all the tracking devices. It is in large part the cost of electronics that sets the cost of the tracking system. The major design effort for the straw chamber electronics is being carried out at University of Pennsylvania. The layout work for the on- chamber electronics will be coordinated by University of Colorado and Oak Ridge National Laboratory. A small number of channels are now available and have been used in several chamber tests at Indiana. We anticipate that by Fall of 1991 we can begin to test this electronics on the prototype modules we are developing at Indiana. This will include preamplifiers, shapers, and time-to-voltage convertors on each module. These tests will measure resolution, noise, power consumption, and high rate capabilities.

There will be a fast trigger for high momentum particles mounted directly on the chambers. The basic design has been developed at University of Michigan. It will soon be tested on one of our prototype modules. As participants with the electronics group, we have also been working on power, trigger, high voltage, and signal cabling specifications for the tracker.

4) Facilities

Members of our group are also part of the facilities task force. This group will specify the above-ground and below-ground facilities for the SDC. This work also includes specification of the assembly areas and the procedures for assembling straw chambers at the SSCL site.

5) Costing

Members of our group are on the costing task force. We have worked with Westinghouse and Oak Ridge to determine the costs of the modules. This includes the assembly sequence, quality control, and construction of superlayers. In addition we have worked with Westinghouse on the support structure fabrication and assembly costs. This is part of a collaboration effort to have a new cost review this summer.

6) Mechanical and Engineering Task force

We have also been collaborating on the mechanical engineering research and development plan for the 1992 period. This will be the most intense period for mechanical research and development since the final designs for most of the tracking components must be near completion by 1993 to meet a 1996 deadline for shipping the tracker to SSCL. This M&E work will involve engineering studies of the support and superlayer structures, support of the intermediate tracker and the silicon system, and studies of the modules themselves.

7) Integration group

Much of the tracking integration development is taking place at Westinghouse. We have been assisting in the integration planning. This includes assembly operations, time scheduling, interaction hall requirements, support facilities, and SSC assembly structures, to name a few.

In addition to the above activities with the SDC collaboration our group has participated in a number of national and international meetings on SSC detectors.

Vancouver meeting on Tracking Systems for the SSC

Members of the Indiana Group played major roles in the Workshop on Tracking Systems for the Superconducting Supercollider, held at the TRIUMF Laboratory, Vancouver, Canada, July 24-28, 1989. G. Hanson was a member of the international organizing committee and was scientific program coordinator with Bill Frisken, York University. G. Hanson, H. Ogren, and D. Rust were participants in the workshop. H. Ogren and G. Hanson were leaders of the group that studied wire chamber tracking, gave three plenary session talks, listed in the Reference section, and many more informal talks in the working group meetings.

Arizona Workshop on SSC detectors Feb. 18-23, 1990.

This was an international workshop on SSC detectors. Our group was active in the simulation, straw chamber development, electronics, and engineering sessions. G. Hanson gave a review talk on tracking simulation and H. Ogren reviewed progress on straw drift chambers.

KEK Workshop on Solenoidal detectors April 23-25, 1990.

The KEK meeting combined an international workshop on solenoidal detectors with an SDC collaboration meeting. The Indiana group participated in both activities. G. Hanson presented a talk on a combined wire and silicon tracking system and H. Ogren reviewed developments on the straw chambers.

Symposium on Detector Research and Development for SSC. Fort Worth, Texas. October 15-18, 1990.

This was a major review of the technologies being considered for SSC detectors. H. Ogren presented a review of straw chamber development and progress in the various LOI detectors, and G. Hanson discussed the design considerations for a wire tracking system at SDC.

In addition to the national and international meetings, the SDC collaboration had an intense schedule of meetings to coordinate the EOI and LOI writing and to prepare for the final design report. The following is a list of the collaboration meetings. Indiana representatives have been present at all meetings.

March 21-23,1991	ANL (Argonne National Laboratory)
Feb.11-14,1991	ORNL (Oak Ridge National Laboratory)
Jan. 22-24,1991	SSCL (Superconducting Supercollider Laboratory)
Dec 13-15,1990	PAC meeting at SSCL
Nov. 7-9,1990	LBL (Lawrence Berkeley Laboratory)
Sept 19 -23,1990	SSCL
July 2-7,1990	Snowmass Conference Center
June 7-8 ,1990	EOI presentation to PAC - SSCL
May 10 -12,1990	SSCL
April 23-26,1990	KEK (High Energy Physics Laboratory in Japan)
March 10-13,1990	SSCL
Feb 18-23,1990	University of Arizona, Tucson
Dec 18-20, 1989	Fermilab - Organizational Meeting

7.2 SSC Wire Tracking Subsystem

Introduction

The goal of the wire tracking subsystem R&D project is to carry out a detailed study and design of a complete wire chamber tracking system for the SSC. The system includes central tracking with straw tube chambers and intermediate angle tracking with wires transverse to the beam direction. The system should provide identification of charged particles over $|\eta| \leq 3$ and momentum measurement over $|\eta| \leq 2.5$.

Personnel

This subsystem is a collaborative effort of Indiana University, University of Colorado, University of Pennsylvania, KEK National Laboratory, Lawrence Berkeley Laboratory, University of Michigan, Rutherford Appleton Laboratory, University of

Liverpool, University of Glasgow, Westinghouse Science and Technology Center, Oak Ridge National Laboratory, Los Alamos National Laboratory, and Stanford Linear Accelerator Center.

The contact person for the subsystem is Gail Hanson.

Other members from Indiana University are:

R. Foster, Programmer- designer

E. Wente, assistant research scientist

H. Ogren, faculty

D. Rust, senior scientist

X. Luo, graduate student

F. Luehring, physicist/programmer

Organization

The wire tracking subsystem group is developing an optimized tracking system for the SDC detector. Meetings are held about once every 6 weeks to coordinate the effort, and electronic mail, fax, and the telephone are also used extensively.

This is a list of meetings held by the Wire Tracking Subsystem group:

Mar. 21, 1991 at Argonne National Lab (during Collaboration meeting)

Feb. 11, 1991 at Oak Ridge National Lab (during Tracking Workshop)

Jan. 23-24, 1991 at Indiana University

Jan. 10, 1991 at SSC Lab (during Collaboration meeting)

Nov. 7, 1990 at LBL (during Collaboration meeting)

Oct. 2, 1990 at Indiana University

Sept. 22, 1990 at SSC Lab (during Collaboration meeting)

Other important meetings were the Fort Worth meeting Oct. 16-19, 1990, on technology associated with the SSC, in which several of our results were presented, and earlier Collaboration meetings and workshops where many discussions were held:

July 1990 at Snowmass
Apr. 23-25, 1990 at KEK in Japan
Mar. 11-13, 1990 at SSC Lab
Feb. 18-23, 1990 at University of Arizona.

SDC Wire Chamber Tracking

The efforts of our group at Indiana have been in developing continuous cathode drift chambers. To meet the constraints imposed by radiation damage, current draw, chamber lifetime, gain reduction from large particle flux, hit rate, loss of data because of high occupancy, and pattern recognition in complex events, the cylindrical drift cells are made as small as practical. Acceptable current draw and lifetime can be obtained with a 4 mm diameter straw tube chamber about 50 cm from the beam line; the other operating limits are somewhat less restrictive. This is also the practical lower limit on the tube diameter from considerations of track ionization density and electrostatic stability. Occupancy is minimized by use of a fast gas such as a mixture containing CF₄.

The straw tubes have to be as long as 3 or 4 meters and this means they must be supported to keep them straight and in a precise and stable position. We have proposed that this can be accomplished by packing them in thin but rigid shells made from carbon fiber epoxy composite material. These modules would maintain the alignment of one tube with respect to its neighbors in the module. The modules would then be aligned with respect to each other. The alignment of the 240 tubes in each module would be automatic due to the precise construction technique and the total alignment task consequently reduced.

We have been working together with several other groups who have been contributing in several areas. The group from the University of Pennsylvania has developed a preamplifier and shaper circuit and has studied various triggering schemes. The preamplifier-shaper circuit is being adapted to larger scale integration. It may also be integrated with a discriminator circuit. This is a very important part of a wire chamber system because of the severe requirements dictated by the high rate, the needs for low noise and operation at low gain, low power consumption and also by the limited space.

Part of our 1990 proposal included justification for development of techniques for a gaseous charged track detector to cover the non-central (intermediate) rapidity range $1.4 <$

$|\eta| < 2.4$ of a hadron supercollider experiment. Coverage of this rapidity range is extremely important for the best possible acceptance for new physics, and it is not easily accessible with sense wires oriented as in a conventional central track detector, i.e., parallel to the beam axis. Called the Intermediate Track Detector (ITD), it would possibly also include enhanced electron identification by means of simultaneous detection of transition radiation (TR) X-rays. This area of development was assumed by some groups from the UK - University of Liverpool, University of Glasgow, and the Rutherford Appleton Laboratory.

Simulation effort

Computer simulation work at Indiana University has focused on several topics: simulation of the detector geometry, evaluating the performance of the detectors, pattern recognition and track fitting studies, and simulation of our detectors within a simulation of the entire SDC detector. This work is a continuation of work started on the IBM 3081 at SLAC by G. Hanson. The code was transported to the VAX 6340 at Indiana and then to our new IBM RS/6000 RISC-based UNIX workstation.

The simulation program uses ISAJET to generate signal events, PYTHIA to generate background events, and GEANT to simulate the detector. Introducing the use of PYTHIA version 5.4 to simulate the background ("minimum bias") events led to a more accurate modeling of the the charge multiplicity per unit rapidity for these background events. The GEANT version used in making the simulation has been updated to version 3.14 from the previous version, 3.13. The simulation code was altered to take advantage of enhancements that became available with GEANT 3.14. In particular, GEANT 3.14 provides a much better model for a stereo tracking geometry. In converting to GEANT 3.14, the simulated tracking system geometry was altered to agree with the most current SDC design.

The simulation is now running under a UNIX operating system on our IBM RS/6000 workstation. This system executes the simulation code approximately a factor of five times faster than the VAX 6340. The RS/6000 also has an extremely powerful graphics capability which greatly reduces (compared to the VAX 6430) the amount of time needed to display events with thousands of simulated tracks. Since the RS/6000 is a very recently introduced system, work continues to optimize system performance for this workstation and to update the CERN supplied software to take advantage of the most current operating system release for this computer.

Both the VAX 6340 and RS/6000 computer systems now have installed on them the SDC collaboration shell program which is a GEANT-based model of the entire SDC

detector. The shell program has options built into it to allow comparison of the various detector design options. We are contributing to the collaboration-wide job of developing the shell program by writing command procedures that install it automatically on VAX-type computers. The shell will be used to investigate the effects of secondary particles produced in material in the SDC detector between our subsystem (the straw tube central tracking system) and the interaction point. In Fig. 7.4 we show an event simulation in the central tracker and silicon system.

Work continues on the pattern recognition procedure that matches track segments in azimuth and curvature. Since the full simulation of the geometry includes stereo superlayers, we are able to study the resolution of the tracking system in the coordinate along the wire direction. Our current pattern recognition algorithm finds stiff tracks well for ISAJET-generated Higgs events. We are also considering the possibility of using a neural network algorithm to do the track finding. Work is beginning to investigate the effect of luminosity on pattern recognition and also to link the strawtube tracks to tracks found in other parts of the system. Eventually, the SDC collaboration envisions developing a global, detector-wide track finding algorithm within the shell program.

Engineering Effort

The Indiana group has been working with the Westinghouse Science and Technology Center (D. T. Hackworth and R. L. Swensrud and their support personnel) to develop engineering concepts for the outer wire tracker. Westinghouse has provided extensive engineering help calculating stresses, strains, deformation, etc. Our goal is to design a practical structure for supporting the straw tube modules. Engineering studies form a large part of the wire chamber tracking group effort because of the large scale of the detector and the requirements of a minimum of mass and very high stability of the structure which hold the drift cells.

The engineering work on the carbon fiber shells with which we are proposing to hold the straw tubes is being done largely at Oak Ridge National Laboratory. They have completed a number of finite element analyses on prototype test modules and on the proposed 4 meter modules required for the final tracking system. This work will continue as the prototype development progresses.

The Westinghouse Science and Technology Center and Oak Ridge National Laboratory have also been working under our direction on some detailed studies of several proposed concepts for mounting and supporting the chamber modules in a precise way. This has included a system which allows the modules to be removed and realigned as well

as concepts that bond the modules to a rigid support frame early in the construction phase. We hope to be able to decide on a concept by this summer. Both institutions are also examining structures for supporting the straw modules. This include concepts involving precision cylinders (that could also be used for scintillating fibers), and ringed structures for holding modules.

Los Alamos National Laboratory has been assisting our Indiana group with prototype design and precision measurements. They are also helping to design a conducting termination.

Electronics

The group from the University of Pennsylvania (F.M. Newcomer, R. Van Berg and H. H. Williams) have developed a low level, low power, high speed, low noise preamplifier shaper circuit which is at present implemented in semi-custom ASIC technology. The integration scale is one channel per chip, but that will soon be changed to four channels per chip. A discriminator has also been developed which could be integrated together with the preamp or kept as a separate package. We have operated the two units together with the straw tube at gas gains of less than 2×10^4 with good pulse shapes and low noise.

The group from the University of Colorado (W. T. Ford, *et al.*) have provided us with a circuit board without amplifiers but with passive components for a 64 straw module.

The trigger electronics, which finds track segments using a circuit mounted on the detector, is being developed at the University of Michigan by a group led by Jay Chapman.

Basic Drift Chamber Research

One of the aims of our SSC R&D was to study the drift chamber parameters of a straw system. This includes drift gas velocities, efficiencies, gas gain and reconstruction resolution. To begin these studies we constructed a 6-straw module. A number of gases were studied with this system. A full report is given in an internal report listed later. We found that a gas mixture of CF₄ and 20% Isobutane had many desirable parameters. The maximum drift time for a 4 mm diameter straw is about 19 ns. This is comparable to the crossing time of the SSC. It also had a very high efficiency, and plateaued above 1900 volts, well within the acceptable limit for wire stability at 50 grams tension. We also measured the gas gain, and found that operation at 1900 volts corresponds to a gain of about 5×10^4 , which is consistent with the SSC requirements for current draw and

occupancy. Using cosmic rays we have tracked in the system and found a resolution of 100 microns, again consistent with our SSC tracking requirements. We have extended the straw tube concept towards longer lengths and and larger arrays.

One of the limitations on tube length was the attenuation of the electrical pulse in its transmission along the straw. The old straws were made of stocks of material which the manufacturer had on hand. We had material made with a thicker layer of aluminum and consequently a surface resistivity of less than one third of the surface resistivity of the old material. The attenuation due to the cathode was therefore reduced to the point that it was considerably less than the attenuation due to the anode (a 25 mm gold plated tungsten wire). The attenuation length thus was increased from 4 m to 5.5 m.

One of the important considerations in the construction of a long straw tube chamber is the electrostatic stability of the wire. We completed a number of calculations and measurements of these effects. The results of the studies are given in an internal publication by our group. The conclusion is that wire centering is required at 80 cm intervals in a 4 mm diameter straw for tensions about 50 grams. The design of the centering device is an on-going effort. We designed a spacer known as the double-vee which is not bonded to the wire. It is a cylindrical shell which has endcaps with vee-shaped cutouts. The vees on the opposite ends are pointing in opposite radial directions. The wire can be led through the spacer either on an air current or just by letting it fall through. It is shown in Figure 7.2. As part of our studies of straw construction we have built a 3.5 m straw system. The system was built in order to understand the problems that we would encounter for SSC chambers. These include wire stringing, assembly of multi- straw systems, alignment, and signal attenuation. We have completed two 6-straw modules. It appeared that they both work very well and do not have any electrical or mechanical problems.

Our next major project was to construct short modules of 64 straws each which could be used not only to evaluate straw tube designs but also to provide a source of data and signals for electronic development and hardware track trigger evaluation. The design addressed some of the problems of packing a large number of cells into a small space. The tubes are enclosed in a carbon fiber epoxy shell with a rhombus-shaped cross-section. (Fig. 7.3) We used the double-vee spacers one on each end of each tube to center the wires. The wire tension was borne by end plugs which fit into the end of the carbon fiber shells but did not touch the tubes. The wires were strung from one plug through the double-vees and the tube to the plug on the other end. The wires were soldered to bronze clips anchored in holes in the plugs. Finally, a cap with signal feedthroughs and mechanical

spring contacts to the bronze clips fit over the end of the plug. This also provided a gas manifold.

Four out of six planned units of this type have been built and are available for use. One is being used at the University of Colorado and another at the University of Michigan. We have been studying resolution, efficiency and cross-talk. The resolution is limited partly by the capabilities of the gas, partly by the capabilities of the electronics and partly by mechanical tolerances on the placement of the wires.

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Fig. 7.1 Quadrant view of the SDC detector

Fig. 7.2 Detail of endplate and connection of the anode wires in the 64 tube prototype module.

Double-V wire support

Identical pieces are snapped together to make a double-V wire collar.

Scale: 20X inches

Revised: 8-JUN-90

VC L5

Fig. 7.3 The double-vee wire spacer

Figure 7.4a. Simulated hits in a straw-tube tracking system for a $400 \text{ GeV}/c^2$ Higgs event. The Higgs particle decays to $Z^0 Z^0$ and each Z^0 decays to e^+e^- or $\mu^+\mu^-$.

Figure 7.4b. Hits lying on found tracks for event shown in Fig. 7.4.a. Only hits lying on tracks with a momentum $> 1.0 \text{ GeV}/c$ are shown.

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