DEPARTMENT OF ENERGY

FINAL PROGRESS REPORT

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PROGRESS REPORT

1 INTRODUCTION

This report covers the activities of the NIU high energy physics group as-supported by DOE contract DE-AC02-87ER40368 during the period from July of 1990 to June of 1991 and from February to March 1992. Our group has three main efforts. The first is the D0 experiment at the Fermilab proton-antiproton collider, with major emphasis on its muon system. The second is the involvement of a portion of the group in Fermilab Experiment 789. Finally, we are also members of the SDC collaboration at the SSC.

2 D0-RELATED WORK

The D0 detector is a large, general-purpose detector designed to take full advantage of the 1.8 TeV energy of the Fermilab collider by a collaboration of over 250 physicists from 31 institutions. The primary physics goals of D0 include searching for new phenomena such as the top quark or compositeness and high-precision studies of the W and Z bosons. In addition, the excellent muon identification will allow the study of b -quark production and decay. The design of the experiment emphasizes accurate identification, complete angular acceptance, and precise measurement of the decay products of W and Z bosons: charged leptons (both electrons and muons), quarks and gluons, which emerge as collimated jets of particles, and noninteracting particles, such as neutrinos, which appear as an energy imbalance in the calorimeter. As an example of the detector's performance, D0 will have greater than 80% efficiency (including all particle ID and cleanliness requirements) for the direct, high- p_t muons from top decay and greater than 65% for the electrons.

The D0 detector consists of three major hardware systems, calorimetry, muon, and central tracking, which together allow fairly complete characterization of most proton-antiproton collision events. The tracking system consists of four drift-chamber systems (a microvertex, a central, and two end systems) with delay-line readout to provide measurement of space points and transition radiation detectors for electron identification. This system allows reconstruction both of charged-particle tracks coming from the primary

interaction vertex and of tracks from secondary vertices such as those of K_S and B decays (though the lack of a central magnetic field limits the physics utility of these reconstructed tracks). Surrounding the tracking system is a uranium/liquid-argon calorimeter. The uranium is a dense medium, allowing containment of high-energy hadron showers in a relatively short depth, as well as equal response to electrons and hadrons, while the liquid-argon readout gives ease of calibration, stability, radiation hardness, and the ability to build in fine segmentation in all three coordinates. Finally, surrounding the calorimeter is the muon system, consisting of five magnetized iron toroids and three layers of drift chambers. The magnets deflect the muons and absorb all remnant portions of hadron showers. The drift chambers measure the amount and direction of deflection, allowing determination of each muon's momentum and the sign of its electric charge. The wide-angle muon system (WAMUS) consists of 164 chambers, most 20 feet long by 8 feet wide and consisting of 72 drift cells, which cover more than 90% of the area surrounding the calorimeters in the region greater than 10 degrees. Each drift chamber cell measures positions to an accuracy of about 400 microns along the drift direction (the bend view) and to a few mm along the wire direction. In the small-angle region between 5 and 20 degrees, 6 modules of 2.5 cm drift cells in an X,Y,U configuration are used. The smaller cell size is needed there due to cell occupancy and to increase the p_t threshold of the trigger. The small-angle muon chambers, designated SAMUS, were built by physicists from IHEP-Protvino.

The primary emphasis of the NIU group is the muon system. The muon system (like the rest of D0) was completed in 1991, commissioned in early 1992, and rolled into the collision hall and recommissioned in February and March 1992. Initial data was then collected in April. NIU is involved in all aspects of the D0 muon effort, with particular responsibilities for design and implementation of the data readout and the hardware trigger; calibration of the chambers; and the software, including both development and coordination. We also have a number of global responsibilities including data taking, triggering, and physics analysis.

Although members of the NIU group participated in debugging and repairing the muon

modules and the electronics mounted on the modules, our primary responsibility was for the electronics in the movable counting house: VME crates for data acquisition, fast Level-1 triggering, momentum-finding Level 1.5 triggering, and a supervisor crate. These crates are controlled by 68020-based microprocessors, which may be downloaded from the host VAX computers.

Each of the 24 muon data-acquisition crates contains Module Address Cards (MACs), Analogue to Digital Conversion cards (ADCs), a Fanout module, a crate controller, a VME Buffer Data card (VBD), and a Vertical Interconnect card. There are from five to eleven MACs per crate, and each MAC communicates to one muon module. The MAC receives pad latch information from the modules, and passes that information on to the trigger crates. There are two 24-channel ADC modules per crate. All the analog data from each module are multiplexed onto four ADC channels. The MAC card coordinates this multiplexing. The Fanout module receives various clock signals needed for data acquisition and calibration and puts them onto the VME backplane, where they are picked up by the MAC cards and sent on to the muon modules. The crate controller coordinates all the activity of the data crate. The VBD receives the digitized values from the ADC and puts them onto the data cable to be collected by the Level 2 computers and the host VAX computers. The Vertical Interconnect interfaces with the Fermilab controls system and is the pathway for downloading programs and control signals to the crate controller.

There are two trigger pathways for signals from the MACs. A fast timing path takes coarse trigger patterns through a Coarse Centroid Trigger card (CCT) to the muon Trigger Monitor in the muon supervisor crate. This creates the first-level muon trigger signal for D0 within the 3500 ns interval between crossings. If greater trigger rejection is needed, the Octant Trigger Cards (OTCs), using fine centroid patterns from the MACs, form a trigger in about 5 μ sec. A Trigger Manager Card in the VME trigger crate generates timing and readout signals and also processes the trigger output of the CCTs or OTCs. A "valid-trigger" reply from the trigger framework holds off further event cycles. Timer modules in the trigger supervisor crate generate interrupts to the 68020 microprocessors

in the data crates, thus initiating an event readout cycle.

Fortner has overall responsibility for the muon electronics in the counting house, overseeing production, installation, and debugging. Morphis has particular responsibility for the Fanout cards. Also, a number of NIU students have been involved in designing and testing new electronics, in making design changes to existing modules, and in repairing those which have failed during operation of the detector.

Fortner wrote the programs which run on the VME crate controller microcomputers. The microcomputer program consists of a shell and a set of subprograms which are called depending on how the crate is being operated. There are subprograms for regular data taking, calibration data taking, local testing, and self testing. Green helped write the subprogram for calibration mode.

NIU personnel are also involved with the D0 on-line system. The D0 on-line system consists of hardware and software needed to read data from the VME crates into a "farm" of Level 2 computers and transfer data from them to the host VAX and on to disk and tape. The system also controls and monitors the experimental equipment. In 1991 the D0 group started using the on-line system, first to read out individual detector components, then to read central detector, calorimeter, and muon detectors together for cosmic rays. The resulting data have been invaluable in debugging and calibrating the detector. During the summer, large portions of the on-line system were upgraded. In the fall, we once again started using the on-line system to read individual components. We have now resumed full-scale cosmic-ray running, this time with the complete D0 detector being tested, and with almost final versions of the data acquisition hardware and software.

Fortner and Green are among the cadre (currently about 20) of "global" experts who work shifts to keep the on-line system operating so that others can use it to test their equipment and collect data. These are the people who have the best understanding of how to smoothly operate the detector. D0 plans on having at least one global expert on shift at all times as we move toward final commissioning of the detector and the start of collider operation.

The D0 muon system has over 55,000 channels of read-out electronics including drift times, time divisions, and vernier pads. Each of these channels has an ADC offset (T_0 , DT_0 , or pedestal) and a slope (to convert, for example, ADC charge to time in ns). There are also response functions used to convert the corrected ADC values to positions in space. These response functions may be chamber or time dependent; in particular, the drift velocity in our FDTs is unsaturated and is sensitive to the gas composition. Electronic calibration values are determined first by pulsing the individual channels with signals of known pulse height and (relative) timing. Muon tracks through the chambers are then used to both refine and verify the values and determine the response functions. We also need to determine alignment and magnetic-field parameters. All of these calibration parameters will be stored in the D0 database, which will need continuing updating and validation during the course of data taking and analysis.

The muon calibration effort involves a number physicist primarily from NIU, Hawaii, and Fermilab. Green and Hedin play a major role in this group, Green being responsible for the program which calibrates the wide-angle muon system by pulsing the electronics and for utilization of the muon database. Hedin developed the initial program which uses muon tracks to improve the calibration. The electronics pulsing program had two major changes in 1991. The first allowed calibration of an entire crate's worth of electronics with one run of the program, instead of merely one module's worth of electronics. Since we have 164 modules, calibration by crate is clearly needed. This change required modification of many subroutines which assumed that only one module's worth of data was being handled. The second modification was to incorporate the ability to control the pulsing electronics. This enables the calibration to proceed automatically, instead of having the operator change pulser settings by hand. This change required that the muon calibration program be more tightly integrated with other programs in the on-line system. Green also worked with collaborators from IHEP-Protvino to produce a version of the program which can calibrate the small-angle muon system.

Data collected during the cosmic-ray commissioning run in the spring of 1991 were used

to calibrate those muon chambers involved in that run. The first version of this calibration used code developed by Hedin, and was done during the summer by Hedin and an NIU undergraduate. The initial version had a number of labor-intensive procedures, both in determining calibration values and response functions and in inserting these values into the database. During the fall, a second version of the code was developed which reduces the amount of physicist time needed to determine a set of constants and produces a list of diagnostics which indicate the quality of the calibration set.

The D0 trigger consists of two stages. The first, Level 1, uses specially-designed electronics to make initial trigger decisions, indicating (for example) a muon candidate in a particular region of the detector. Its purpose is to reduce the 500 kHz interaction rate to about 200-400 Hz. After this, a farm of "Level 2" microprocessors running PASCAL and FORTRAN code make more sophisticated decisions to reduce the rate of events permanently stored on tape to about 2 Hz. Both trigger levels are constrained by limited resources. One is the bandwidth of the data cables between levels. There are also limitations on the architecture of the trigger system, which currently allows up to 32 distinct Level 1 triggers (including calibration and monitoring triggers), each made only from an AND of available trigger components.

During 1991, D0 formed a trigger panel to coordinate trigger-related development and decision making. This panel consists of nine people (including Fortner and Hedin) representing both the trigger implementors and the different physics groups. The most important decision that this panel will make is the allocation of trigger resources: how the 32 Level 1 trigger bits are assigned, what thresholds and prescale factors are assigned, etc. We are currently using D0's trigger simulator to develop an initial trigger list for the first run that satisfies resource limitations while maximizing the physics potential of the data collected. Once we begin taking data and start to understand the actual rates, the trigger panel will adjust resource allocations accordingly.

NIU also has a number of specific muon-trigger responsibilities. As part of overseeing the electronics in the movable counting house, Fortner is playing a major role in the

installation and commissioning of the muon trigger. He also is the primary person defining how the muon trigger communicates with the rest of the D0 triggering and data-acquisition system. During 1991, successful runs using the wide-angle muon Level 1 trigger were taken. We are in the process of debugging all the Level 1 trigger cards for the wide-angle chambers and will then proceed to installation of the SAMUS trigger cards and the Level 1.5 trigger; physicists from Arizona, Fermilab, CBPF, and Riverside are also involved in these tasks. Fortner and Willis are among those writing the muon trigger simulation code.

Finally, Hedin is the primary author of the muon Level 2 trigger software. The code for this is almost identical to the trackfinding part of the muon off-line reconstruction and has been relatively stable during the past year. It was used as part of the trigger during the spring 1991 commissioning run. This filter package meets its design goal of using the muon drift-time and time-division information (not used in Level 1) to provide both muon particle identification and momentum resolution approaching off-line performance (for example, Level 2 may have $\Delta p/p$ of 21% compared to the off-line 18%). It also needs to be CPU-efficient, with nominally 250 ms being available per event. For the wide-angle system, a number of minor items need improving, but we are essentially waiting for $p\bar{p}$ data in order to understand the true performance of the trigger.

Significant progress has also been made on the muon reconstruction. This encompasses the muon portions of D0's Monte Carlo, the muon trackfinding algorithm, the association of calorimeter and central tracking information with a muon track, and the complete fit and resultant momentum determination. Hedin continues to coordinate this effort and has the major responsibility for the muon trackfinding in the wide-angle system.

The muon part of D0's GEANT-based Monte Carlo should now be complete. This version includes SAMUS, magnetic field maps, some geometry corrections, a more accurate drift-time to distance relation, and some bug fixes. The wide-angle trackfinding code and the routines which associate a muon with the calorimeter and central tracking have been stable for the past year. Some tuning of parameters to increase the efficiency for low momentum muons was performed. Also, code to see if the found track projects to a muon

chamber but had no hits from that chamber was developed. This aids in rejecting any remnant non-muon-induced tracks.

During the spring and early summer of 1991, D0 had its first cosmic-ray commissioning run. Components of all major detector systems were operated at the same time in an almost-final data-acquisition mode. We attempted to treat this as collider data in the sense that both hardware and software (e.g. data-acquisition and reconstruction programs) were forced to be working for all detector components.

Finally, during the past year, Repond had responsibility for the muon on-line data monitoring program. This program reads data from the on-line system and analyzes the data for purposes of determining how well the hardware is functioning (e.g. determining chamber efficiencies).

While installing and commissioning the detector has been the highest priority during the past year, D0 has continued the organization of physics analysis groups. The purpose of these groups is to develop analysis procedures so that physics results can be extracted in a timely fashion once D0 begins taking data. Four groups have been formed: Top, *B*-physics, Electroweak, and QCD/New Phenomena. There is clear overlap between the groups (for example, $B \rightarrow \mu$ events are important to the Top, *B*, and QCD groups), and NIU is especially interested in those channels involving muons. Currently, Hedin is one of the coordinators of the *B*-physics group (along with D. Green) and is also coordinating the subgroup which will search for top decays into dileptons. Related to this, Hedin is a member of the D0 physics advisory panel, a fourteen-member group charged to advise the D0 spokesperson on physics-related items. Among the items will be: reviewing analysis procedures such as electron identification, assigning priorities to computer resources, and reviewing results before presenting them at conferences or submitting articles.

The first tasks of the physics analysis groups are to define the interesting physics channels and their backgrounds. For each channel, procedures are then developed to isolate the signal using the information produced by the reconstruction program. A critical task is understanding how well the reconstruction program is performing: to identify parameters

which are not being calculated; to understand detector-related biases introduced in the reconstruction; and, at this preliminary stage, to find mistakes in the reconstruction code. As we have yet to collect data, the primary tool in this procedure is a sample of Monte Carlo events generated using a complete (GEANT-based) detector simulation. In addition to Monte Carlo events generated for specific channels, last year we also used a sample of 100,000 “blind” events. These events were a mix of channels including QCD events, W and Z decays, and possibly new physics signals. The identity of these events was known only by their creator (P. Grannis). It was the goal of each physics group to analyze these events and attempt to extract their content.

A analysis workshop was held in September, which included reports from Hedin and Repond on extracting signals from top-like objects decaying to two leptons, on W and Z decays to muons, and on D0’s ability to measure asymmetries in Z decays. Signals from ψ , Υ , and Z are seen. The background for the lower-mass states is much smaller than that expected for real data, but this does demonstrate that the muon reconstruction was working. (It should be noted that similar plots for dielectrons had about 100 times more events but no ψ or Υ signals. This is due to untuned electron identification for lower-energy electrons. A number of members of the B -physics group are currently working on improvements to the lower-energy electron reconstruction.)

The top-to-dilepton group extracted a “signal” of about 10 $e - \mu$ events from new sources in the blind sample. Comparison of the events with what their creator generated showed that the number of signal events passing any given cut and the estimated number of background events agreed with their (now-known) source. The signal turned out to be a mixture of top events with a mass of 60 GeV and lepto-quark events. (We weren’t able to determine this mixture; we could only say that such kinematic distributions as invariant mass and opening angle were not consistent with pure top.) Analyses of background channels indicated that the largest source of backgrounds will be from $b\bar{b}$ decays, often with a hadron misidentified as an electron. This immediately led to a determination of “golden” electron selection criteria (which will be repeated using $Z \rightarrow ee$ events once

we begin collecting data). The backgrounds can also be reduced by requiring the high- p_t electrons and muons to be isolated, by requiring sufficient missing energy, and by requiring jet activity not associated with the electrons and muons. Improvements to the definitions of these quantities are in the process of being added to the D0 reconstruction package.

During 1991 and 1992, D0 developed and submitted a proposal to upgrade our detector. The proposal's initial goal was to maintain the performance of the D0 detector for high- p_t physics at luminosities up to $5 \times 10^{31} \text{cm}^{-2} \text{sec}^{-1}$ and $p\bar{p}$ bunch spacing of 396 ns. The decreased bunch separation and increased trigger rate require changes to the muon and calorimeter data acquisition and improvements to the trigger. Also, at the highest luminosity the inner tracking chambers will need to be replaced. A design using silicon and scintillating fibers plus a superconducting magnet was included in the proposal. This would give electron identification similar to that of the current D0 detector, dramatically improved vertex capability, and reasonable momentum resolution for particles with $p_t < 10$ GeV. For muons, this design would complement the current system, which is based on iron toroids and provides superior triggering and particle identification but momentum resolution limited by multiple scattering. It also increases the muon geometric acceptance for $|\eta| < 3$ from an already good 85% to over 95% by extending coverage to gaps in the current system which are due to supports and services. This design improves the physics capabilities for almost all physics channels, with an especially dramatic increase in D0's capabilities for reconstructing large, clean samples of exclusive B -decays.

The proposal was presented to the Fermilab PAC a number of times, was reviewed by a PAC-appointed panel in April of 1991, and has undergone a number of revisions. During the summer of 1991, essentially all the items except the inner tracking and magnet upgrades were approved. D0 is in the process of exploring alternative tracking designs while still intensively investigating the feasibility of the design in the proposal (in particular, the readout of the scintillating fiber). Results of these studies will be presented to the PAC during the next six months, with decisions on how we will proceed expected during the summer.

NIU has been involved in the upgrade work, and we anticipate that D0 will continue to be our main activity for the next five years, during which the upgrade will be carried out. Fortner was a co-convenor of the hardware trigger group, and Green of the muon group, during the initial D0-upgrade workshop in the summer of 1990, and Fortner, Hedin, and Green all contributed to the initial proposal. Hedin co-coordinated the trigger group, and Fortner the muon group, during a series of mini-workshops held between November 1990 and April 1991, with Hedin and Fortner defending the trigger and muon system aspects of the proposal at the April 1991 review. Following the approval of the muon part of the proposal, Fortner was appointed to coordinate the R&D and construction of the muon system upgrades.

3 E789-RELATED WORK

The E789 collaboration includes physicists from eight institutions: Abilene Christian University, Berkeley, Chicago, Fermilab, Los Alamos, NIU, South Carolina, and the Taiwan Users Group. A sensitive search for rare low-multiplicity decay modes of particles containing c or b quarks, E789 had a test run with partial instrumentation in the spring and summer of 1990, and its first run with all equipment installed has just ended.

The start of E789's data-taking in the 1991 run was delayed relative to that of the other fixed-target experiments due to concerns about radiation safety in our counting rooms. After an extensive series of measurements and considerable shielding work, we received approval on August 24 to run our spectrometer at the charm setting. In order to approve us for the (higher-intensity) beauty running, the Fermilab Research Division first installed a temporary trailer in the parking area to the east of Meson Laboratory to house experiment personnel, so that we no longer needed continuous occupancy of the electronics rooms inside Meson Lab. Beauty running began October 7. The run was divided roughly equally between charm and beauty running (two months each). A total of $\approx 1.5 \times 10^9$ events, collected over a total of $\approx 8 \times 10^4$ beam spills, were recorded on ≈ 1300 8mm tapes.

The charm running was crucial for tuning up our newly installed stereo-view silicon-strip detectors and our vertex trigger processor. Using the information from the silicon detectors to require a decay vertex downstream of our target, we see a clear $D^0 \rightarrow K\pi$ peak in a preliminary analysis of less than 1% of our charm data. The on-line vertex processor, which makes a looser vertex cut than that used off-line, worked successfully and reduced the background trigger rates by a factor of ≈ 10 . The data acquisition upgrade, which replaced the E605 4-megabyte buffer memory with a 64-megabyte buffer, allowed a ten-fold increase in our data acquisition rate. These two factors together permitted data-taking at interaction rates up to 4 MHz, yielding up to $\approx 10^3$ reconstructible $D^0 \rightarrow K\pi$ events per day. The ring-imaging Cherenkov (RICH) counter worked well during a significant fraction of the run.

Our charm measurements are expected to provide some 45,000 D^0 or $\bar{D}^0 \rightarrow K\pi$ events on tape, of which $\approx 7,000$ should survive vertex cuts in the gold-target sample and ≈ 1500 in the beryllium sample, permitting a useful measurement of the D cross section and its nuclear dependence in the small-Feynman- x region at 800-GeV beam energy. In addition, the RICH-identified data should yield a limit on the $D^0/\bar{D}^0$ production asymmetry. (It is possible that a reliable $D^0/\bar{D}^0$ identification can also be made kinematically; if so, the statistics of the entire charm sample will be available to support the results from the RICH analysis.) The gold-target sample should also contain some 400 $D^0 \rightarrow K^+K^-$ events and, by virtue of an acceptance enhancement for $\pi^+\pi^-$, 500 $D^0 \rightarrow \pi^+\pi^-$ events, yielding interesting measurements of the ratios of the three branching ratios; since in E789 we can distinguish $\pi\pi$, KK , and $K\pi$ decays kinematically, our measurement should have reduced systematic errors (as well as superior statistics) compared to that of the E691 collaboration. We can also improve on current knowledge of dileptonic D^0 decays. The 90%-c.l. upper limits for $D^0 \rightarrow$ dileptons should be $\approx 0.5 \times 10^{-5}$ each for e^+e^- , $\mu^+\mu^-$, and $e\mu$.

Beauty data were collected at a spectrometer setting (1500A in the "SM12" analyzing magnet) which simultaneously optimized sensitivity for $B \rightarrow J/\psi$ and for $B^0 \rightarrow$ dihadrons.

We ran at interaction rates up to ≈ 50 MHz, limited by radiation levels in our trailer. The beauty data correspond to a total of 2.5×10^{13} interactions. Using standard assumptions for the size, shape, and A -dependence of the $b\bar{b}$ cross section, this should provide some 100 reconstructible $B \rightarrow J/\psi$ events; over a plausible range of cross-section assumptions, the number of events could well be as small as 40 or as large as 250.

Assuming no dihadronic decays are observed after all cuts, the 90%-c.l. upper limit for each dihadronic B^0 decay mode is estimated at 1.0×10^{-4} (and similar limits for $B \rightarrow e^+e^-$, $\mu^+\mu^-$, and $e\mu$).

NIU personnel contributed to many facets of the E789 effort during the past year. Kaplan is co-spokesman for the E789 collaboration and is also supervising and organizing the work of the NIU E789 group and the collaboration as a whole. Preston continued to refine the field map of the SM12 analyzing magnet. Tanikella worked on software and hardware associated with the RICH, including off-line analysis and on-line monitoring software and Monte Carlo simulation. He was responsible during the run for the day-to-day operation and maintenance of the gas purification system, the photon chambers and their gas system, and the readout electronics. NIU undergraduate W. Luebke developed and maintained an on-line database system used to keep track of the running conditions and data taken during each data run. He also took shift regularly during weekly group meetings and helped with numerous technical tasks. Along with Kaplan, he and graduate student M. Apolinski installed and carried out the first test of a beauty trigger technique proposed by Charpak, Lederman, and Giomataris, which is under consideration for use during a future run. (Graduate student J. Sa completed his Master's thesis, and V. Martin left to undertake doctoral study in physics at Michigan State University after completing her thesis data analysis; her analysis of normalization for the 1990 J/ψ data sample contributed to results presented at the "Quark Matter 1991" conference.)

4 SDC-RELATED WORK

The Solenoidal Detector Collaboration (SDC) has proposed a general-purpose detector

aimed at pursuing a broad range of physics goals at the SSC. The detector has been designed so that all subsystems will be fully functional at the design luminosity of $10^{33} \text{cm}^{-2} \text{s}^{-1}$, and so that it will perform with somewhat reduced functionality at substantially higher luminosity. The detector has central tracking in a solenoid magnetic field, hermetic calorimetry, identification and energy measurement of electrons and muons, and high-resolution vertex detection.

NIU is working on the muon system of the SDC, including the trigger and simulations for both the forward and the barrel systems. The muon system of the SDC detector has been designed to perform several distinct functions: to identify muons; to trigger on high- p_t muons in Level 1; to provide information to the Level 2 and 3 triggers; and to provide an independent measurement of the momentum of muons in physics processes of interest, improving that momentum measurement by linking those muon tracks with tracks measured in the inner tracker.

The SDC barrel muon system consists of three measurement stations of wire chambers. The innermost layer is separated from the two outermost layers by a 1.5-meter iron toroid, energized to 1.8 Tesla. The magnetic field lines are in the ϕ direction; therefore most of the wires measure the θ coordinate most accurately. However, the field of the inner solenoid is in the z direction, so the inner tracker is optimized to measure ϕ ; in order to facilitate track matching, the muon system includes ϕ -measuring wires as well. There are small-angle stereo wires, which associate the two orthogonal views. BW1, the innermost station, contains 4 θ layers and 4 ϕ layers; BW2, just outside the toroid, contains 4 θ layers; and BW3, the outermost station, contains 4 θ layers, 4 ϕ layers, and two small-angle (primarily ϕ) stereo layers. Finally, there are two layers of scintillator, used to identify which beam crossing produced a particular trigger. The trigger relies on the wires having a projective geometry; that is, that a pair of wires will point back to the interaction region.

The forward muon system consists of two identical ends, each of which has two toroids and five measuring stations. In addition, there is a Cherenkov counter used in the trigger: it identifies which crossing a trigger came from and vetos triggers from particles whose

momentum is low or which do not come from the interaction region. The forward region presents a number of unique problems: the rates are much higher than in the central region, and the tracking and calorimetry are less well defined. Therefore, system operation in the absence of inner tracking information is more of a concern here.

A muon is identified in two ways: by penetrating the 9λ calorimeter and the 9λ (at 90°) toroid, and by having its momentum measured in both the inner tracker and the muon system. The momentum measurement is limited by multiple scattering to about 18% in the barrel system and to about 10% in the forward system. At higher momenta, the chamber resolution and misalignment dominate; at sufficiently high momenta, even the sign will be indeterminate.

At NIU, we are doing simulation studies of the effects of electromagnetic showers (bremsstrahlung, delta rays, and pair production) accompanying high-energy muons; experimental and simulation studies of neutron backgrounds in the forward system; and physics simulations of the effects of resolution and misalignment. In addition, Willis is coordinating the muon simulation group's efforts and is a member of the committee which is selecting the muon-chamber technology for the barrel muon system, and Hedin is a member of the Cherenkov counter review committee.

Sirotenko has recently been studying the properties of electromagnetic showers which can accompany muons. Preliminary results show that for 500 GeV/c muons, approximately 5% of muons in BW2, 4% in BW3, and 2% in BW1 have one or more extra tracks accompanying them, where those extra tracks are in the same drift cell (assuming a 4 cm cell); the average multiplicity of extra tracks is about 1 in BW1, 1.7 in BW3, and 2.5 in BW2. The average momentum of these tracks is quite low.

Finally, NIU graduate student E. Mierkiewicz has been involved in the test beam measurements of neutron production in hadronic showers (Fermilab experiment E-821, led by K. Johns of Arizona). The goal of E821 is to measure the flux and energy spectrum of low-energy neutrons produced in hadronic showers. Measurements of the flux and energy spectrum of neutrons after a given number of absorption lengths are needed as input to

design considerations for Level 1 and Level 2 triggering at the SSC.

The E821 detector setup consisted of seven Bonner spheres and four liquid scintillation counters placed in the segmented Fe beam stop at the NWA test beam. Using a segmented beam stop we were able to vary the thickness of iron, and hence the number of absorption lengths, between the beam and our detectors. Over the course of the recent fixed-target run, data were collected at lengths from 4.8-15.7 λ and incident beam energies from 25-150 GeV. Data were also collected behind the D0 test calorimeter. A number of studies were done measuring neutron albedo and side leakage. Calibration data using an Am-Be neutron source and various gamma sources have also been collected; this information will be used as input to FERD (a neutron spectrum unfolding routine). All these data are presently being analyzed, with the goal of producing both energy and angular spectra for the neutrons exiting the absorbers.

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