FINAL REPORT

University of Oklahoma – High Energy Physics (OU-HEP)

Task A: Experimental HEP Physics – P. L. Skubic, PI
and B. Abbott, P. Gutierrez, G. R. Kalbfleisch, M. Strauss, co-PI's

**Experimental Physics Investigations using
Colliding Beam Detectors at Fermilab and the LHC**

Task B: Theoretical HEP Physics – K. A. Milton, PI, C. Kao, co-PI
Nonperturbative Quantum Field Theory

Experimental **Task A** (D-Zero at Fermilab)

Prof. B. Abbott, P. Gutierrez (spokesperson), P. Skubic, and M. Strauss
Dr. S. Jain, M. Kopal, A. Pompos, and H. Severini (RA's)
and Mr. I. Hall and X. Zhang (GS's)

Experimental **Task A** (Magnetic Monopoles E-882 at OU)

Prof. Kalbfleisch (spokesperson), and Prof. Milton and Strauss

Experimental **Task A** (Atlas at LHC)

Prof. Skubic (contact person), Abbott, Gutierrez, Strauss,
and Snow (LU)
Dr. H. Severini (RA) and Mr. G. Boyd (EE)

Theoretical **Task B** (OU-HEP Theory)

Prof. C. Kao, K. A. Milton (spokesperson)

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1 Overview – Recent Progress and Goals

The University of Oklahoma (OU) high energy physics (HEP) group was last reviewed externally in 2000, and we are currently in the third year of our three year grant period. We are submitting this proposal, which contains the status of the current work, to request renewal funding for another 3 year grant period. The OU-HEP group has 5 experimental faculty, including G. Kalbfeisch who recently retired from teaching. Professor Kalbfeisch has completed an in-house magnetic monopole search that he supervised for the past several years. In addition to the experimentalists, there are 3 theorists including C. Kao who was recently hired. This proposal requests funding to continue our work on $D\bar{D}$ and on the ATLAS experiment at the LHC. Currently our base budget supports only 2.5 postdoctoral positions whereas all three positions are filled. It is therefore vital to obtain increased base budget funding so that all three postdoc positions and fully supported or serious disruption of our research program will occur.

The OU-HEP group initiated its experimental task 24 years ago, its theory task 17 years ago, and started the Langston HEP group 14 years ago. It has been funded by the Department of Energy (DOE) under contract DE-AS-05-80ER10629 from 1980-1991, grant DE-FG-05-91ER40636 from 1991-1995, from DE-FG02-95ER40923 for 1995-1997, and DE-FG03-98ER41066 currently. The cumulative funding has been about 9.8 (1.7) million dollars from DOE and 1.4 (0.2) million dollars from other external sources (NSF, SSCL, TNRLC, TAC, URIP) for the experimental (theoretical) Task A (B) to date, respectively, in addition to substantial internal University funding.

Several new initiatives have been started or proposed during the current grant period:

1) An EPSCoR proposal was funded under a DOE Laboratory Partnership Award with Brookhaven National Laboratory. Professor C. Kao is the PI of this grant which supports students and a theory postdoc. An experimental postdoc is also supported as part of the OU match.

2) We have joined with other $D\bar{D}$ institutions in our region to establish the Southern Analysis Region (DØSAR). This consortium is designed to optimize use of computing resources in our region. We have bi-weekly video meetings to discuss software problems and to organize Monte Carlo production and data analysis by the participating institutions. We expect DØSAR institutions to be active users and developers of Grid software tools.

3) We have just submitted a DOE EPSCoR proposal to establish a regional Center of Excellence dedicated to research and education in High Energy Physics (HEP). The Center will consist of a consortium of three universities in Oklahoma: Oklahoma State University (OSU), OU, and Langston University (LU). This EPSCoR funding will enable the initiation of two major programs: (i) Starting of a new experimental HEP research group at OSU, and (ii) Establishment of a Tier 2 Grid Computational Facility at OU as part of the LHC Grid Network. Under the umbrella of the Center the independent research programs in HEP at the three institutions will be integrated into a cohesive unit representing all facets of HEP research - from new theoretical ideas and models, to computer simulation, detector development, data acquisition, analysis and interpretation. This proposal has strong commitments from the institutions to continue support for faculty and researchers after the duration of the grant period.

1.1 Experimental Group – Task A

1.1.1 The DØ Experiment at Fermilab-Task A

During the past three years, the DØ collaboration has gone from a period that has concentrated on the analysis of Run I data and the construction of the Run II detector, to the commissioning of the Run II detector and the start of Run II analysis with $\approx 214 \text{ pb}^{-1}$ of data recorded so far. During the coming years, we expect to collect a factor of 30 to 60 times more data than we did during Run I. This data will be used to test the limits of the standard model (SM), search for new phenomena, and possibly see hints of the Higgs boson.

Our plans during this exciting period are to maintain our involvement with the DØ experiment at least until the LHC starts producing physics. At the present time, the members of the University of Oklahoma (OU) DØ group include 4 OU faculty members (B. Abbott, P. Gutierrez, P. Skubic, M. Strauss), 4 postdocs (M. Kopal, H. Severini, S. Jain, and A. Pompos), and 2 graduate student (X. Zhang and I. Hall). This list includes former members of the OU CLEO group, who transferred their research work to DØ in 2002 (P. Skubic, H. Severini, plus one postdoc position that has now been filled).

Over the years, the OU group has contributed to many areas of the experiment. During Run I we contributed to the trigger simulator, and to a number of physics analysis. We were major contributors to 6 analysis that have been published. We contributed to a number of other analysis either through our involvement in different physics groups or through the editorial board process. For the Run II upgrade, we made major contributions to the development of the Silicon Microstrip Tracker (SMT): We tested a large fraction of the raw silicon wafers using our facilities at OU, participated in beam test of the detectors, made a major contribution to testing and debugging the detector elements, and contributed to the construction of the detector. With the start of Run II, we are helping to commission the level 2 trigger. Our main responsibility was to bring up the Level 2 Central Fiber Tracker (L2CTT) trigger hardware, but are contributing to other areas as well. This work has led to the naming of M. Kopal as the coordinator of Level 2 trigger operations. In addition, we have contributed to data taking, the upgrade of the silicon tracker (because of the recent decision made by the Fermilab management to cancel this project, we are phasing out of this work), Monte Carlo production using the OU farm, DØ grid computing effort, and have started making contributions to the analysis of Run II physics. Up to this point, we have primarily concentrated on b -physics, but we are starting to contribute to top-quark physics. We will concentrate primarily on heavy flavor physics during the early part ($< 2 \text{ fb}^{-1}$) of during Run II.

Run I of the Tevatron collider, which was completed in February of 1996, led to a large number of physics results. During the run, DØ recorded an integrated luminosity of approximately 100 pb^{-1} . This data, some that is still being analyzed, has already produced a large number of physics results in the areas of QCD, electroweak interactions, b quark physics, limits on new particles outside the standard model, the co-discovery, with CDF, of the top quark, and the measurement of some of its parameters. The analysis of this data has so far produced 123 papers published in peer reviewed journals, with 3 of these being published this year. In addition, 1 more has been submitted for publication, and 1 is under collaboration review. The OU group took full advantage of this large data set by contributing to several analyses, being lead authors on 6 publications.

The DØ detector has been upgraded for Run II, and is currently taking data reliably. The primary component of the upgrade is the addition of a magnetic tracking detector. This detector

fills the inner volume of the calorimeter with a silicon vertex detector, a fiber tracker, and a superconducting solenoid magnet that produces a 2 Tesla field.

During the construction phase of the upgrade for Run II, we used our experience in silicon microstrip detectors to contribute to the development of the SMT. Once this period ended, we made the decision to move our resources to the commissioning of the Level 2 trigger. For this we have taken on the responsibility of installing the hardware and making it operational. In addition to this, we are also providing software to do a bit by bit comparison of the Level 2 trigger data with the trigger simulator. This software is meant to provide close to real time monitoring of the trigger to insure that it is functioning correctly. We have also written software to monitor the flow of data through the Level 2 trigger. The program will keep track of buffer occupancies, processing time, and any bottlenecks in the data flow. It keeps track of this information for individual cards, as well as for systems of cards that build the different Level 2 detector components. Finally, we did some studies on methods and developed software to measure the efficiency of the Level 1 track trigger.

We have participated in discussions on upgrading the trigger for the latter part of Run II when the luminosity is expected to increase. Scaling from current numbers, the rate into Level 1 will be too large to effectively trigger. A task force was put together to study this problem and to propose a solution. A limiting factor for the Level 1 trigger is the dead time caused by the silicon readout chip. This limits the Level 1 trigger and will not be improved. The two major areas that were studied to improve the Level 1 trigger are the calorimeter trigger and the tracking trigger.

An area that is of particular interest to us, is the ability to do analysis at OU and generate large numbers of Monte Carlo events. As experiments become larger, the computing resources at the labs will not be sufficient to meet the needs of those resident at the lab and those resident at the universities. In fact, with the increasing size of data sets, it becomes increasingly clear that shared computing resources is the only solution as envisioned by the various grid computing efforts world-wide. We have initiated efforts in this area: We were one of the driving forces behind the creation at OU of the OU Supercomputing Center for Education and Research (OSCER), which gives us the ability to generate Monte Carlo for $D\bar{O}$ and our specific analyses. OU, along with other $D\bar{O}$ universities in our region, has created the $D\bar{O}$ Southern Analysis Region to provide a mechanism for sharing resources. In addition, we have started to participate in grid computing work on $D\bar{O}$.

Our physics interests for Run II will concentrate on heavy flavors, this includes both b and t quarks, during the early portion of the run, with a transitioning during the latter part of the run to new phenomena and Higgs searches. We have taken on a major role in the b -physics group, with 4 members of the OU group contributing. These include B. Abbott who served as co-convenor of the $D\bar{O}$ b -physics group, X. Zhang a graduate student who along with his supervisor P. Gutierrez are attempting the first $D\bar{O}$ measurement of $\sin 2\beta$, and I. Hall another graduate student, who along with his supervisor B. Abbott are studying methods of measurements of B_s mixing.

Our effort on top physics is just beginning. Two members of our group have joined this effort. These are M. Kopal and S. Jain, who are concentrating on the search for single top production.

1.1.2 CLEO

Our group has been a member of the CLEO experiment at the CESR storage ring at Cornell University since 1988. CLEO III completed data taking this summer and CLEOc data running is

beginning. Our work on CLEO is winding down now that we have decided to concentrate our future efforts on DØ. Postdoctoral RA Horst Severini has continued service work on the muon system calibration. He may individually continue his involvement with CLEO if it is mutually beneficial to him and the collaboration. Otherwise he will withdraw from the collaboration after the muon calibration responsibility is passed on to another group.

1.1.3 Magnetic Monopoles and Electric Dipole Moments

A. Magnetic Monopoles. "A Search for Low Mass Monopoles," Fermilab E-882, 1996, has been completed. Three sets of samples were taken; all three are finished. The three sets are: 1) aluminum (and beryllium beam pipe) samples from the central region of the D0 detector (the so-called "extension" cylinders of that support structure), 2) lead samples from the forward/ backward CDF electromagnetic calorimeters, and 3) aluminum samples from the CDF central vertexing detector support cylinder. The results from the first set are published (Phys. Rev. Letters **85**, 5292 (2000)), and from the second set are documented in Dr. Wei Luo's thesis ("Search for Magnetic Monopoles Possibly Produced by pbar-p Collisions at the Tevatron Collider," PhD. thesis, University of Oklahoma, Summer 2002). An overall Phys. Rev. **D** comprehensive paper covering all aspects of the experiment, detector, samples, measurement, analysis and final results of all three sample sets has been submitted; the reviewer's comments are currently being addressed with publication expected shortly.

B. Electric Dipole Moment of the Electron. A proposal "Measurement of the Permanent Electric Dipole Moment of Ultracold PbF Molecules," is being prepared by a small group here at the University of Oklahoma: two atomic/molecular physicists expert in the appropriate techniques, Prof. Neil Shafer-Ray and Eric Abraham with two high energy collaborators, myself (Kalbfleisch, experiment) and K. A. Milton (theory). We have high expectations that our ideas will lead to a measurement of 2 (possibly 3) orders of magnitude improvement on the electric dipole moment of the electron. The current limit is that of Commins of $< 1.6 \times 10^{-27}$ e-cm at 90% C.L. (B. C. Regan, et al, "New Limit on the Electron Electric Dipole Moment," Phys. Rev. Letters **88**, 071805 (2002)). We expect to trap the appropriate cold polar paramagnetic molecules (PbF) in an electrostatic Stark trap (a paper, "Design of a Biased Stark Trap of Molecules Moving Adiabatically in an Electric Field," has been published in Phys. Rev. **A67**, 45401 (2002) by Shafer-Ray, Milton, Brendan Furneaux, Abraham and Kalbfleisch). The trapping lifetime of 100 seconds will allow for a phase change of 45 degrees if the electron's moment is at the Commins limit, making improvement in the limit as stated above relatively easy (or measuring a non-zero value as some super-symmetry advocates predict). We have submitted the proposal to NSF (October, 2003) and will submit to DOE also. We are looking at a three year timetable for the experiment. We will pursue some R and D for the magnetics and traps during the interim period until funded.

1.1.4 ATLAS

Four OUHEP faculty members (B. Abbott, P. Gutierrez, P. Skubic, and M. Strauss) and one adjunct faculty member from Langston University (J. Snow) are working on the ATLAS experiment, one of two general purpose experiments to be done at the Large Hadron Collider (LHC) which is now under construction at CERN. This proposal is for the eighth year of funding for OUHEP involvement on ATLAS. Our group is collaborating on construction of the ATLAS pixel vertex detector. U.S. institutions have the responsibility to build the forward (disk) pixel modules. This year we received

\$227K in supplemental funds from NSF and \$30K in matching funds from OU for work on ATLAS. Funds are requested in this proposal to continue support of Electrical Engineer G. Boyd who is responsible for design and layout of the pixel module interconnection circuit (flex-hybrid).

We were recently awarded infrastructure funds from NSF in the amount of \$284K (including matching funds) as part of a joint MRI proposal with the University of New Mexico and Langston to purchase much needed equipment for construction of the ATLAS pixel detector.

The contribution of OUHEP to the ATLAS pixel detector includes the following projects:

(1) We have taken on responsibility for design, production, and testing of the flex circuit which carries analog and digital signals to and from the module front-end (FE) readout chip and the module clock and control chip (MCC). The collaboration has constructed many pixel modules with prototype flex-hybrids and they have been successfully operated in the CERN test beam. The baseline pixel detector module design has been chosen to be the flex-hybrid technology. Both barrel and disk modules will use flex-hybrids that are being designed by our group. We have completed design and fabrication of four generations of flex-hybrid prototypes. One of the major equipment items we have obtained with the MRI funds is an automatic wire bonder. This will be used to assemble flex-hybrids including placement of the MCC chip and its associated wire bonds. This will allow extensive testing of the flex-hybrids before shipment to institutions responsible for module assembly. We have begun flex-hybrid production with the order of 2253 circuits. All have been received and are being assembled and tested in our lab at OU.

(2) We have completed contributions to development of the pixel readout system. The OU group has contributed to development of the pixel readout electronics by the efforts of OU Electrical Engineering student (Mr. A. Gorthy) who completed his Masters thesis on VLSI design in part on the pixel readout simulations. We also have had a EE Masters student (S. Sivasubramaniyan) resident at LBNL who contributed to the development of the pixel detector data acquisition module called the ReadOut Driver (ROD). He is now working for us at OU on flex-hybrid production.

(3) We have tested irradiated pixel detectors at OU, and have participated on beam tests of pixel sensors and electronics at CERN. We have the capability to do quality assurance tests on ATLAS pixel sensors during production.

(4) During production, we will be able to test assembled disk pixel modules for quality assurance and burn-in at OU and Langston. We have set up a data acquisition system at OU to read out pixel modules. Identical pixel test stations have been set up at other institutions including Albany, UNM, and Langston.

(5) We are contributing to the ATLAS Grid testbed. This year we have used much needed DOE and OU matching funds to expand our Beowulf cluster of Linux PC's and to provide computers for our research personnel at OU and Fermilab. We have set up software utilities to allow remote submission of jobs to our Linux cluster. These utilities include CONDOR, for batch job management, and GLOBUS, for Grid job management. Our cluster was one of the major contributors to the ATLAS Data Challenge 1 (DC1) Monte Carlo production. We are also running ATLAS Monte Carlo jobs on the new 260 processor Pentium-4 Linux cluster that was recently purchased by the OU Supercomputing Center for Education and Research (OSCER).

To successfully carry out the above tasks, it is of vital importance that we receive continued funding for engineering technical support (EE G. Boyd). These funds will be necessary for us to complete the very ambitious flex-hybrid project and to provide technical support for OU, Langston, and Albany. The University provides support for the Department Electronics Shop and for Electronics Technician A. Wade who supervises it.

The State University at Albany is responsible for high voltage testing of the flex-hybrids. This is vital because the flex-hybrid is mounted on the high voltage side of the sensor and must hold off up to 700 V. Albany has the equipment necessary for this test and has been doing an excellent job testing prototypes.

Funds are requested in this proposal to support travel to CERN to attend ATLAS collaboration meetings and to work on the CERN test beam. Project funds were requested in a supplemental proposal to purchase pixel components such as the flex-hybrid. We obtained project funds from NSF through a subcontract from Columbia University during the past five years.

1.1.5 Research Activities at Langston University

The research program in physics at Langston began in 1990 under the direction of Professor George Kalbfleisch of the University of Oklahoma (OU) in a collaborative effort with OU's HEP group. Initial funding for the program was provided by the University of Oklahoma while awaiting Texas National Research Laboratory Commission (TNRLC) funding which was provided in support of the Superconducting Super Collider Laboratory (SSCL). The premise of the collaboration was to bring research opportunities and a research environment to Historically Black Colleges/Universities (HBCU's), which traditionally have had few if any research programs. In 1999 DOE awarded LU HEP direct funding through a grant award for three years, which was renewed in 2002 for an additional three years. LU Professor Joel Snow is the PI for this grant and is also an adjunct faculty member at OU.

During the last several years, a Linux cluster with 17 CPU's has been set up at LU and is being used for DØ and ATLAS computing. LU HEP maintains a close collaboration with OUHEP. Professor Snow serves as DØ code librarian, software maintainer, and co-webmaster for the OU/LU group. Both OU and LU are members of the DØSAR group. This consortium shares resources and knowledge to enhance productivity through economies of scale both intellectual and economic. The DØSAR institutions have become Monte Carlo production farms for the DØ experiment, processing official Monte Carlo set requests and storing the resulting data in the central storage facility at Fermilab.

1.2 Theory Group – Task B

The OUHEP theory group has been in existence for the past seventeen years, and at the present time the DOE grant supports two faculty members, Milton and Kao, and one Graduate Assistant, Cavero-Pelaez. Next year we hope to restore funds to support a postdoc. It is critical to do so: This lack these past two years has had a dampening effect on our productivity. This deficiency this year has been partly offset by the receipt of an EPSCoR State-DOE Laboratory Partnership Award with Brookhaven National Laboratory, with Kao as PI. This allows us to strengthen our resources in the phenomenology area, by allowing us to hire another Graduate Research Assistant (Shankar Sachithanandam), an Undergraduate Research Assistant (Blake Burdett), and a new postdoc, Peter Williams. The receipt of this grant, however, should not be used as an excuse to not fully fund the current proposal, but rather should be seen as a justification for further investment in human capital. Not included on the grant, but a part of the theory group, are Professor Ron Kantowski and graduate student Kuloth Shajesh. Judicious use of non-DOE funds (including substantial OU funds which enabled us to bring Igor and Olga Solovtsov to Oklahoma for the Spring 1998 and Spring 2000 semesters) has enabled us to function effectively in spite of a quite small DOE budget.

It should be noted that external collaborators, such as Carl Bender, Sergei Odintsov, Igor and Olga Solovstov, and Iver Brevik, play a vital role in the group's vitality. A signal of that vitality is the success of the international workshop, Quantum Field Theory Under the Influence of External Conditions (QFEXT03), organized by Milton and hosted by our department, which took place 15–19 September 2003.

The focus of Milton's research continues to be the development of *nonperturbative field theory* which includes various researches into the Casimir effect, magnetic monopole physics, $\mathcal{PT}$ invariant theories, and analytic perturbation theory. Applications to Abelian and non-Abelian gauge theories (QCD), and to quantum cosmology are underway. Moreover, Milton is involved in theoretical aspects of a new experiment at OU to search for a possible electric dipole moment of the electron, or at least set much improved limits.

A major thrust for the past eight years has been based on our experimental project to search for magnetic monopoles produced at Fermilab. Although the experiment has now been concluded, with a final paper submitted to Physical Review D, theoretically much work remains to be done. A proper interpretation of the experimental results requires improved calculations, both relativistic and nonrelativistic, of the binding of monopoles to atomic nuclei through the anomalous magnetic moment interaction. Improved calculations of the production of monopoles through the Drell-Yan process are also being carried out.

Significant research continues on the effect of quantum fluctuations or the Casimir effect in various models (including applications to cosmology and hadrons). Two years ago Milton published a monograph on the status of our understanding of this fundamental, yet surprisingly poorly understood, aspect of quantum field theory. Following the conclusion of QFEXT03, he will be writing an updated review article for Journal of Physics A. Significant improvements in our understanding of important temperature corrections, and of the divergence structure of the theory, topics on which no consensus has emerged, are forthcoming.

The focus of Kao's theoretical research is the phenomenology and model building of electroweak symmetry breaking, supersymmetric grand unification, CP violation, cosmology, and theories with extra dimensions. We are making efforts to investigate physics of fundamental importance in particle theory, such as the mechanism by which particles acquire mass, the reasons why the top quark is so heavy while the neutrinos are so light, signals of supersymmetry, clues for unification of the electroweak and the strong forces, the source of CP violation, and the identity of dark matter.

Recently, we have been investigating direct and indirect signatures of new physics in present and future experiments to search for Higgs bosons and supersymmetric particles or to prove their non-existence, to measure the electric dipole moments of elementary particles and other signals of CP violation, and to identify new physics effects from radiative corrections beyond the Standard Model. In addition, we are employing particle physics to explain astrophysical and cosmological phenomena as well as applying astrophysical and cosmological observations to test and constrain particle theories.

The recently received EPSCoR Award provides support for 3 years (2003–2006) in building a partnership between the University of Oklahoma (OU) and the Brookhaven National Laboratory (BNL). We are confident that the collaboration between Kao (OU) and Sally Dawson (BNL) will make significant contributions to high energy physics and will lead to a long-term partnership between OU and BNL. We hope that our regular DOE program can be suitably funded to strengthen our particle theory and phenomenology program in testing the Standard Model and exploring new physics.