Final Report,
STUDIES OF HADRONIC PHYSICS WITH THE BABAR DETECTOR AT SLAC AND THE ATLAS DETECTOR AT THE LHC

Grant Period: May 1, 2013 – March 31, 2016
Report Period: May 1, 2013 – March 31, 2016

Submitted by:
Dr. David N. Brown, Principal Investigator
Professor of Physics, University of Louisville
david.brown@louisville.edu
502-852-6790

University of Louisville Research Foundation
Research and Graduate Programs, University of Louisville
Louisville, KY 40292
DUNS#: 05-758-8857
EIN: 61-1029626

June 30, 2016

Prepared for

THE U.S. DEPARTMENT OF ENERGY
AWARD NO. DE-SC0009812

ABSTRACT

The University of Louisville High Energy Physics group contributed significantly to the success of the BaBar Experiment at SLAC and the Mu2e Experiment at Fermilab. In particular, they have contributed to understanding hadronic processes in electron-positron annihilation and charged lepton flavor violation in a very rare muon conversion process. Both are high-precision undertakings at the Intensity Frontier of High Energy Physics.

Background

Professor David N. Brown joined the faculty at the University of Louisville in 1996, jumping immediately into the role of Principal Investigator (PI) the High Energy Physics (HEP) group at the University. Brown was funded as PI primarily by the US Department of Energy (DOE) from 1998 to 2013 and again from 2013 to early 2016, the period covered by this report. Under Brown, the UofL HEP group made significant contributions to the *BABAR* Experiment at the SLAC National Accelerator Laboratory (previously Stanford Linear Accelerator Center), the ATLAS Experiment at CERN's LHC in Geneva, Switzerland, and the Mu2e Experiment at Fermilab in Batavia, Illinois. Brown and his students continue to make significant contributions to the Mu2e and *BABAR* experiments.

The physics covered by the *BABAR* Experiment focused on measuring CP Violation in Weak decays of B mesons and constraining the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements. This work has been and continues to be a resounding success. CP Violation in the B system is now firmly established and our knowledge of CP Violation parameters refined so that we can now search for New Physics (NP) signals in our data. The success of the *BABAR* *B* physics program has been noted widely, perhaps most visibly in the press release for the 2008 Nobel Prize in Physics to Kobayashi and Maskawa. Indeed, Kobayashi and Maskawa wrote: *"Please accept our deepest respect for the B-factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize."*

By its design, the *BABAR* detector is suitable for carrying out a broad spectrum of particle physics studies. In addition to B physics, including hadronic, leptonic, semi-leptonic, penguin decays, and others, members of the Collaboration have pursued bottomonium spectroscopy, charm physics including charmonium, Tau physics, particle production via Initial State Radiation (ISR), QCD, two-photon physics, and various searches beyond the Standard Model (SM). The *BABAR* Collaboration has published more than 500 papers in peer-reviewed journals. Highlights of its research include: establishing CP Violation in the *B* meson system in 2001, first observation of direct CP Violation in the B meson system in 2004, discovery of new subatomic particles such as the Y(4260) and D_{sJ}, discovery of the lowest ground state of the bottomonium system in 2008, measurement of branching fractions that may provide hints at New Physics in 2012, and the first direct observation of Time-reversal Violation in 2012. The latter was named a "top ten breakthrough in 2012" by Physics World. Eight years after data-taking stopped, collaborators on *BABAR* continue to utilize the large and high-quality data sets to maintain a brisk pace of publication and conference presentations.

The Mu2e experiment is a search for spontaneous muon to electron conversion, providing one of the most compelling searches for physics beyond the Standard Model (SM) at a precision four orders of magnitude better than existing measurements. The experiment is specifically named as a priority in the Particle Physics Project Prioritization Panel (P5) report. The Mu2e project has completed significant portions of its design, planning, and R&D. With Department of Energy (DOE) approval through CD-3c, endorsement from

P5, and civil construction well underway, Mu2e is making steady progress toward data-taking. The Mu2e Experiment will be an essential part of the Intensity Frontier program for at least the next decade. It will be a sensitive test for New Physics (NP) that complements other experiments in the muon and neutrino efforts.

Goals

The goals of this project were initially to contribute to the research of the BaBar Collaboration at SLAC in Stanford, California, particularly in terms of hadronic physics. During the course of the project, an added goal was to contribute to the development and research of the Mu2e Experiment at Fermilab.

Accomplishments

During the 3 years of this grant, the UofL HEP group made significant contributions to *BABAR*. In December 2014, Brown officially gained membership in Mu2e for the UofL group. Work on Mu2e has been ramping up while work on *BABAR* has slowly ramped down.

The large body of results from BaBar include over 50 peer-reviewed journal publications in the review period and over 400 conference talks with many associated proceedings published. Mu2e is still in its development stage, but has produced several instrumentation papers and a large technical design report. The UofL HEP group's relation to these accomplishments is outlined and detailed below. The full list of BaBar peer-reviewed publications can be found here:
http://www-public.slac.stanford.edu/babar/Publications.aspx
While the Mu2e Technical Design Report is located at:
http://arxiv.org/abs/1501.05241

Brown has contributed to *BABAR* in the following ways during the past three years:

- Worked with students on measurements of inclusive production of hadrons in the decay of Y(nS) resonances below the OZI threshold. This work will be published in the thesis of Jake Berg later this year, and turned into papers. This work will provide important input in the study of Quantum Chromodynamics (QCD).
- He and Ph.D. student Jake Berg have presented 8 conference talks: 1 talk at DPF2013, 1 at the 2013 Indiana-Illinois Fragmentation Function Workshop, 1 at the 2014 Dark Interactions Workshop, 4 at DPF2015, and 1 at Hadron2015. Brown also presented an invited seminar at Brookhaven National Lab in October 2015. Two of his proceedings are:
    - http://arxiv.org/abs/1511.02224
    -
- Served on the Review Committee for more than half a dozen papers, including as committee chair. The Review Committee provides feedback and critique throughout the development of an analysis into a publication, and serves as the primary editorial board for the paper draft.
- Served as Deputy Chair of the *BABAR* Speakers Bureau continuously. In this role, Brown was responsible for assigning chairs for over 400 practice conference talks

since 2013, of which he personally chaired over 135. In this role, he also chairs Speakers Bureau meetings when the Chair is not available. The Speakers Bureau is responsible for rigorous review of the technical and aesthetic elements of presentations on *BABAR* physics results.

- Served as Simulation Production Coordinator continuously, a role he held from 2001 through 2008 and again since 2012. Since 2013, Brown has been the sole producer of simulated data used by *BABAR* analysts for estimating efficiencies, studying cuts, etc. This work has been critical for nearly all of the more than 50 papers published by *BABAR* during the reporting period.
- Served on the *BABAR* Long Term Task Force (LTTF) in 2013, helping to plan out collaboration activities through 2018 and beyond.

Brown has contributed to Mu2e in the past *two* years in the following ways:

- He has been appointed the Mu2e "Geometry Czar." In this role, he is responsible for overseeing design of the software representing the complete experimental geometric model, including detector elements, cryostats, shields, services, etc, out to the dirt surrounding the experiment hall. He introduced software that simplifies the addition and modification of elements to the geometry, thus making it possible to easily test designs in Offline simulation. The software was used to optimize the design of downstream shielding around the critical detector areas. He has worked with students on fleshing out the geometry model in Offline.
- He advocated successfully for the use of Hypernews as a collaborative tool, and has been appointed as Mu2e "Hypernews Czar." He led the effort to create a Mu2e policy document for use of Hypernews. Regularly, he adds and maintains discussion forums and user accounts, and troubleshoots problems that arise.
- He has worked with students on an analysis of pion capture as a potential background to the search for muon to electron conversion. This was critical work leading up to the DOE CD-3c review of the Mu2e project in June 2016.
- He has been elected to the Mu2e Speakers Committee, a body that provides critical technical and aesthetic review to Mu2e speakers.

More detail on recent analysis work and findings on *BABAR*:
We measured charged hadron production and fractions in the four quark continuum at an energy 40 MeV below the Y(4S) peak as a crosscheck for the paper published in Physical Review **D 88**, 032011 (2013). In particular, we are interested in the fraction of protons among the stable charged hadrons production in quark and gluon fragmentation. This analysis is inclusive in that it does not distinguish among production mechanisms. The work is being expanded to include results from Y(2S) and Y(3S) data sets. Specifically, we seek to confirm or eliminate the notion of baryon enhancement, an increase in the average number of baryons produced in the final state per initial state parton in hadronic decays of the Υ resonances, seen by ARGUS over 20 years ago.

Undergraduates have worked with Brown to study proton and Λ fractions as correlated with the number of hadronic jets in the event and as a function of event topology as measured by sphericity and Fox-Wolfram moments. Jets are identified using the JetFinder software package written by Brown and previous students. The software

calculates a metric for pairs of particles based on their momentum-energy four-vectors. The pair with the smallest metric is most likely from a common jet. The four-momenta of the two particles in this pair are combined, creating a mother pseudo-particle which then takes the place of the two daughters in the particle list of the event. This process continues until the smallest metric exceeds a cutoff value. The number of pseudo-particles remaining in the event particle list at this time is then the number of jets. We record the momentum spectra of antiprotons and all stable charged particles in order to determine the proton fraction as a function of momentum. We perform our analysis with three different values of the jet cutoff parameter, to help understand systematics. Preliminary results show that the proton fraction across the full momentum region is greater for 3-jet events than for 2-jet events. While we expect that the absolute number of hadrons will be higher in 3-jet than in 2-jet events, we do not expect the fractions to be affected by the number of jets, *except* that we expect less energy per particle and thus might naively expect a lower fraction of heavy baryons to be produced in 3-jet events.

Similarly, we have investigated proton fraction as a function of sphericity and of the variable *R2*, the ratio of the second to zeroth Fox-Wolfram moments. Roughly speaking, low sphericity and high *R2* are associated with events consistent with fragmentation of a back-to-back light quark-antiquark pair (2-jet events), while high sphericity and low *R2* are associated with events consistent with fragmentation of a quark, antiquark, and radiated gluon (3-jet event). Initially, the investigation centered on the dependence of proton fraction on event shape only for events in the four-quark continuum. With data taken by *BABAR* in early 2008 on the Y(2S) and Y(3S) resonances, we are repeating this study on these data sets. Hadronic decays of these resonances proceed typically through two-gluon jets, providing an interesting comparison with the typical two-quark jets on the continuum.

The most ambitious of the efforts has included contributions from all recent undergraduate students in the group. This is an inclusive hadronic particle spectra study for 15 hadrons in $q\bar{q}$, Y(2S), and Y(3S) data sets. Due to the scope of the work, the results will be split up by particle family and published in 3 to 5 papers. The paper on baryons will be combined with results from *BABAR* Analysis Document 2171. Currently, preliminary measurements exist for many of the particles, and systematics are being studied in detail at this time. The particles being investigated are: $\eta, \eta', \omega^0, \rho^0, \rho^+, D^0$, and D^+ mesons and the Δ^0, Δ^+, $\Delta^{++}, \Sigma^0, \Sigma^+, \Xi^-, \Omega^-$, and Λ_c^+ baryons. Among the most interesting of our preliminary findings is that baryon enhancement is observed for all baryon species investigated.

Publications from *BABAR*, even limiting our attention to the past three years, have been too numerous to attach. However, the complete set of *BABAR* publications can be found here:
http://www-public.slac.stanford.edu/babar/Publications.aspx

More detail on recent Mu2e background studies:
The search for direct muon to electron conversion will be a search for the product – a lone electron with a specific momentum of approximately 105 MeV/c. Any other process

capable of creating an electron of this momentum is then a background. Radiative Pion Capture (RPC) occurs when a negatively charged pion is captured in a nucleus in our experimental target. Absorption of the pion by a proton, and its conversion to a neutron, is accompanied by the emission of a gamma-ray photon which then pair produces an electron and positron. Since the electron can have a momentum as high as 105 MeV/c, this is one such background process. To perform this study, we need a complete geometric model of the Mu2e experiment in GEANT4 and need to separately consider the quantum mechanically independent processes of virtual vs. real photon production. We also need to consider carefully the time distribution of arrival of pions at the target. We find that the potential background due to RPC is strongly dependent on the livegate time of our detectors. With a nominal livegate time selected, we estimate a potential background of less than 0.0153 ± 0.0014 in-time events over the 3-year run period of the experiment.

Training

During the nearly 3 years spanned by this grant, 13 undergraduate and 2 high school have received research training and experience under Dr. Brown's guidance, some of the undergraduates supported as undergraduate research assistants through this grant. Three of the undergraduates have graduated – one is starting the Ph.D. program in Physics at Purdue University and another at Indiana University. One of the students (Conrad Smart) received the prestigious Goldwater Scholarship, Brown's fourth student to do so. Brown also mentored 4 Masters students and 2 Ph.D. students during this period. Three of the four Masters students have been accepted to Ph.D. programs in Physics. Both Ph.D. students have been hired by local industry due to their demonstrated software skills. One of them is finishing up his dissertation as an ABD student.

In the previous 15 years of DOE funding, Brown had mentored almost 60 undergraduate and high school students. Most of those students have gone on to Ph.D. programs in Physics at institutions including the University of Michigan, The Ohio State University, Purdue University, the University of Wisconsin, UCLA, Idaho, UC Davis, Columbia, Harvard, Vanderbilt, University of Birmingham (England) and others. Three of the undergraduates won Goldwater Scholarships, one received a Hertz Scholarship, about a dozen are known to have won fellowships, and three were named the outstanding graduate from the College in their respective years. Another three are known to now be high school physics and mathematics teachers. Brown has also mentored 15 graduate students during the grant period. Most of the students were at the MS level because the Department of Physics did not have a Ph.D. program until 2009, when Brown was Department Chair.

Summary

In summary, the Department of Energy grant has allowed the University of Louisville High Energy Physics group, under Principal Investigator Dr. David N. Brown, to contribute significantly to the widely-recognized *BABAR* and Mu2e research programs, while providing excellent technical training to students. Their research is helping make advances in understanding the Intensity Frontier of High Energy Physics.