Final Report,
CONTRIBUTIONS TO STUDIES OF CP VIOLATION AND HADRONIC PHYSICS WITH THE BABAR COLLABORATION

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ABSTRACT

The University of Louisville High Energy Physics group has undertaken a long-term effort in understanding baryon production in elementary particle processes in the 10 GeV energy region. We have contributed significantly to the broad program of the BaBar Collaboration, particularly in support of computing, data visualization, and simulation. We report here on progress in the areas of service to the Collaboration and understanding of baryon production via measurement of inclusive hadronic particle spectra.

During the grant period September 1998 through April 2013, the High Energy Physics group at the University of Louisville, under Principal Investigator (PI) David N. Brown, made significant contributions to the BaBar Experiment at the SLAC National Accelerator Laboratory (previously Stanford Linear Accelerator Center). Contributions were also made to the ATLAS Experiment at CERN in Geneva.

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. Five 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.

ATLAS has a similarly broad physics program, including heavy flavor physics, jet-based QCD, searches beyond the Standard Model, and, in particular, Higgs physics. Though still early in their data-taking, ATLAS and its fellow Large Hadron Collider (LHC) experiments announced the discovery of a "Higgs-like" boson on July 4, 2012. As measurements have continued, the identity of the particle as the Higgs Boson has become firmer.

During the 15 years spanned by this grant, nearly 60 undergraduate and high school students have received research training and experience under Dr. Brown's guidance, many of the undergraduates supported as undergraduate research assistants through this grant. Most of the 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. Since 2009, Brown has had two Ph.D. students join him. They will produce dissertations in 2014 and 2015, respectively.

During the 15 years of this grant, the UofL HEP group has made significant contributions to BaBar.

Brown quickly became head of the BaBar Graphics Group and introduced the first BaBar offline single-event display. Programming much himself and managing contributions from each detector and analysis group and his students, a number of features were added to the display under Brown's guidance, including representation of detector elements and most data quantities, and numerous helpful specialized projection modes. With undergraduates, Brown was able to speed up the display considerably, allowing it to become an online event display as well. Brown also oversaw the transition to using the "Wired" Java display client to allow faster remote event displays. The event display proved useful to many of the hardware groups during early debugging of detector performance. It later served analysts in visualizing events and presenting them in talks.

Brown and students also performed early work on the BaBar Particle Identification software and performed a study of the feasibility of using beam-gas and beam-pipe events to provide a calibration sample of protons. An offshoot of the study was improved triggering to remove such "noise" events from our data.

The University of Louisville was one of the first University sites outside SLAC to run the complete BaBar software on its own computing system, and also one of the first to produce simulated data in production mode. The site has continued to be active in production of simulated data through today. In the last two years, UofL has been one of the 4 top-producing sites. Because of his success in running simulation production at UofL, Brown has also served as the manager for simulation production at SLAC nearly continuously since 2001. He has been overall coordinator of all BaBar simulation production 2007-2008 and continuously since 2010. The UofL HEP group has thus been directly or indirectly responsible for the vast majority of simulated data used in BaBar analyses throughout the experiment's lifetime.

Brown served as BaBar's Physics Software Manager in 2001. While making improvements to code, he also managed the input of collaborators into the code repository, oversaw builds, and handled quality assurance. At one point he was package coordinator for 45 separate software packages within the BaBar software system.

During BaBar data-taking, from 1999 to early 2008, the UofL HEP group satisfied more than its required allotment of data-taking shifts, maintaining a positive balance of shifts in each year of running, except 2008. Brown took the lion's share of these shifts. Brown was scheduled to serve as BaBar Run Coordinator in summer 2008. This plan evaporated when the final data-taking run was shortened due to the federal budget situation.

Brown took a major role in several major code migrations for the BaBar software releases. He was the first person to run the BaBar software on Digital Unix 4.0 and developed scripts used to migrate the code away from propriety Roguewave libraries to Standard C++ Libraries.

Brown has been involved with the Inclusive Hadronic Production and Spectra (IHPS) Analysis Working Group (AWG). Through this association, Brown has served on the review committee for most of BaBar's searches for pentaquarks, hypothetical particles containing 5 quarks rather than the usual two (mesons) or three (baryons). Since the beginning of his current grant period in 2005, he has worked with students on several analyses related to this AWG.

Brown served as Deputy Chair of the BaBar Speakers Bureau for 2009 and 2010 and is currently reprising that role for the foreseeable future. In this role, he coordinates practice talks for BaBar conference presentations. In 2012 alone, more than 130 BaBar talks were given. Likewise, the UofL HEP group has consistently reviewed its share of papers being prepared for publication.

Brown was elected to the BaBar Long Term Task Force in January 2013. The group will work through 2013 to plan for changes needed in policy and procedure as activity in the BaBar Collaboration begins to wane.

Jamie Bougher serves BaBar in the Documentation Working Group (DWG), performing a major overhaul of BaBar documentation that will serve the collaboration in its longterm data analysis period. Among other things, she revamped the public web pages for the collaboration, and updated the Users Workbook. According to Matt Bellis, convenor of the working group, "Jamie has done a huge amount of service work for the DWG."

Dr. Chris Davis has recently accepted the position of Physics Data Quality Manager and will ensure the integrity of Physics computed quantities in new software releases.

Starting in 2009, Brown and Bougher performed work on ATLAS as affiliates (or 'visitors') in the SLAC ATLAS group. We contributed to a new effort in understanding cavern background radiation. We developed a new software package and contributed substantially to two other packages. We helped develop and validate the software, create simplified geometry descriptions of the detector and surroundings appropriate to background studies, and compare the simulation with data. The tools developed have already been used for studying proposed upgrades in the beampipe and endcap detectors, and promises to be very useful in planning for major upgrades as the LHC intensity continues to ramp up. Three internal papers were produced based on this work.

In 2011, Brown ran nearly 50 shifts on ATLAS, including Data Quality Monitoring for ATLAS and, separately, for the Tile Calorimeter subsystems.

Our analysis work has primarily been in two areas: inclusive hadronic particle production spectra and rare charmless baryonic decays of the *B* meson. These analyses are currently encapsulated in several supporting BaBar Analysis Documents - #175, 2169, 2171, 2185, and 2426, and the BaBar Analysis Information System entry ChmlsQ2B-12/01.

We measured charged hadron production and fractions in the four quark continuum at an energy 40 MeV below the Y(4S) peak. This reproduces work already reported in BaBar Analysis Document 610, which is in submission to Physical Review **D**, provides a useful crosscheck to this existing analysis, and establishes a basis for related analyses within our own group. 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. Included in the document is a report on a parallel analysis completed by Brown on the fractions of π^0, K_s^0, and Λ in the same data. The work is being expanded to include results from $\Upsilon(2S)$ and $\Upsilon(3S)$ data sets. Specifically, we seek to confirm 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. An Undergraduate Research Assistant presented this work at the April 2011 APS meeting in Los Angeles.

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 $q\overline{q}$, $\Upsilon(2S)$, and $\Upsilon(3S)$ data sets, and possibly in events with *B* meson decays. Due to the scope of the work, the results will be split up by particle family and published in 3 to 5 papers over the next year and a half. The paper on baryons will be combined with results from BaBar Analysis Document 2171, mentioned above. Preliminary work on this project was presented by another Undergraduate Research Assistant at the 2011 April APS meeting in Los Angeles. 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.

Work is well underway by Ph.D. student Jamie Bougher searching for rare 2-body charmless baryonic *B* decay modes based on theoretical predictions that they should have branching fractions that make them readily observable at BaBar. The modes are rare enough by Standard Model predictions, however, to have not yet been seen and to potentially be sensitive to New Physics. Their observation would be help fill a gap in our knowledge of *B* decays. Work is progressing on this analysis and we expect Bougher to graduate in 2014.

Publications from BaBar and ATLAS, 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

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 ATLAS research programs. Their research is helping make advances in understanding production of baryons.