FINAL REPORT

Project Title:

Investigations in Experimental and Theoretical High Energy Physics

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Recipient Organization:

Iowa State University
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Contents

Chapter 1

Abstract

We report on the work done under DOE grant DE-FG02-01ER41155. Prior to the establishment of this grant, November 2000, the tasks described had been funded by three independent grants.

The experimental tasks have ongoing efforts at CERN (ATLAS), the Whipple observatory (VERITAS) and R&D work on dual readout calorimetry and neutrino-less double beta decay. The theoretical task emphasizes the weak interaction and in particular CP violation and neutrino physics. The detailed descriptions of the final report on each project are given under the appropriate task section of this report.

Chapter 2

Task A: Particle Astrophysics

Contents

1 Personnel

Senior Staff	Title
D. Carter-Lewis	Professor of Physics (Professor Emeritus since 2011)
F. Krennrich	Professor of Physics
M. Pohl	Associate Professor of Physics (2004 - 2009)
A. Weinstein	Assistant Professor of Physics (since 2010, support by ISU start-up)

Postdoctoral Associates	**Graduate Students**
M. Orr (2009 - 2013)	A. Imran (graduated in 2010)
T. Nagai (2005 - 2009)	T. Stroman (graduated in 2010)
M. Schroedter (2004 - 2010)	A. Madhavan (2009 - present)
Hugh Dickinson (current)	J. Cardenzana (supported via ISU start-up and other support)

Support Staff
R. McKay
L. Shuck

2 Overview

The current generation of atmospheric Cherenkov telescope arrays – which use the Earth's atmosphere as the sensitive volume of an electromagnetic calorimeter – have revolutionized the young field of γ-ray astronomy. The more than 150 TeV γ-ray sources collectively discovered by HESS, MAGIC and VERITAS over the last decade not only cover a wide range of astrophysical phenomena but act as probes of fundamental physics. The field's key goals include: understanding the nature and origin of cosmic particles, including dark matter and cosmic-ray nuclei; addressing the workings of black holes as particle accelerators; and studying the propagation of cosmic particles throughout the universe at all scales.

The VERITAS telescope array is currently the most sensitive TeV telescope in the northern hemisphere, has comparable sensitivity to the HESS observatory in the southern hemisphere, and was upgraded as of September of 2012. The Iowa State University (ISU) group is a founding member of VERITAS and designed, built and delivered the focal plane instruments (camera boxes, light cones and the pixels including preamps and a current monitor system). ISU together with the ANL group also designed and delivered a new camera trigger[1] that uses high-speed FPGAs, which as part of the upgrade was installed in Nov. 2011.

VERITAS has produced spectacular scientific results and is poised to lead the field of TeV γ-ray astrophysics & particle astrophysics in years to come. Recent physics highlights include that occurred in 2009 - 2013 are:

[1] R&D for camera trigger initially developed through a DOE ADR grant to Prof. Krennrich (2007-2009) and LDRD funds to K. Byrum at Argonne National Laboratory, ANL

• the discovery of pulsed emission above 100 GeV from the Crab pulsar. This suggests that the emission originates at least 10 stellar radii from the neutron star's surface (Science, Aliu et al. 2011). No pulsar emission model predicts photon production at these energies. Our then ISU postdoc M. Schroedter was one of three primary authors through his work on the energy spectrum while at ISU.

• the discovery of TeV emission from the starburst galaxy M82, the first of its class, bears directly upon the question of the origin of cosmic rays (Nature, Acciari et al. 2009a). The case for supernova remnants (SNRs) accelerating the bulk of cosmic rays has been substantially reinforced – the predicted cumulative effect of hadronic particles produced by a SNR population in M82 matches the measured γ-ray spectrum. ISU faculty member (2003-2009) M. Pohl provided the theoretical underpinning for interpretation of this paper.

• a growing number of active galaxies at increasingly larger redshifts ($z \sim 0.5$) suggests, either unusually hard TeV spectra, a low cosmological extragalactic background light (EBL) intensity, or new physics for TeV photons traveling cosmological distances (mixing of photons with axion-like particles or interactions of UHE cosmic rays producing pair cascades). Recent ISU graduate A. Imran's PhD thesis work (Acciari et al. 2010a) discusses the discovery of day-scale flux variations in a hard spectrum blazar, ruling out some jet emission models. This work, together with results from other blazars was used to derive limits to the EBL, based on a novel method developed by Prof. Krennrich & postdoc Dr. M. Orr (Orr et al. 2011).

• the discovery of TeV emission from several supernova remnants (SNRs) such as Tycho (Acciari et al. 2011), G54.1+0.3 (Acciari et al. 2010b), G106.3+2.7 (Acciari et al. 2009b), and G78.2+2.1 (VER J2019+407) provides insight not only into particle acceleration processes and properties of SNRs, but also the role they play in the production of cosmic rays. Prof. Weinstein (supported by ISU startup funds) is has been leading the analysis of the latter source, which is associated with a more extended complex of γ-ray emission that may shed light on cosmic-ray escape and propagation; a publication is in preparation.

The ISU group has made significant contributions to the hardware and operations of VERITAS, especially through the following contributions:

• the development of an FPGA-based camera trigger system based on the 400 MHz Xilinx Virtex-Pro chip. This system is a joint ANL/ISU development (Anderson et al. 2008; Krennrich et al. 2009) and the R&D was enabled by a DOE ADR grant to Prof. Krennrich (2007-2009) and by LDRD funds (ANL) to Dr. Byrum, and was chosen by the VERITAS collaboration to be included in the VERITAS upgrade. Th system was installed in November of 2011 and has been working flawlessly. The trigger rates substantially increased and the efficiency of the system is close to 100%.

• the development and installation of a new cooling system to the front-end electronics of the VERITAS cameras using micro fans. This system was installed by Prof. Krennrich and students in summer of 2012 and is working well. The telescope cameras can now be tested during the extremely hot Arizona summer days in May, June and July.

The ISU group led by Prof. Krennrich also included several postdocs, M. Schroedter (2004 - 2010), M. Orr (2009 - 2013), several graduate students, A. Imran (graduated in 2010), A. Madhavan and Josh Cardenzana and several undergraduate students. Co-PI Prof. David Carter-Lewis retired in 2010. Prof. A. Weinstein was hired in 2010 and continues to be

supported from ISU start up funds and NASA support during the last 3 years. Prof. Frank Krennrich is PI of γ-ray and particle astrophysics research at ISU, and he also served as the PI of the ISU HEP umbrella grant. Within VERITAS, he is a member of the VERITAS Executive Committee and chaired the latter in the past. He also served (2009-2011) as an associate member of the C4 commission on Cosmic Rays of the International Union of Pure & Applied Physics. He is active in the CTA-US R&D group, e.g., together with G. Drake and Dr. Byrum (ANL) he is developing a topological array trigger system for CTA-US. He continues to be involved in the VERITAS camera hardware maintenance, and will focus on precision measurements of AGN spectra and their interpretation in the context of propagation and attenuation on cosmological scales (§3.1). He has also been a leader in the development of AGIS (spokesperson), now CTA-US, and he is the chair of the CTA-US executive committee.

In the following we briefly describe the most significant contributions of ISU members to VERITAS science and instrumentation with emphasis on the period of 2009 - 2013.

3 Recent Achievements

3.1 Science Highlight

This section reports the most recent science highlight, the detection of the Crab Pulsar at energies above 100 GeV, and gives a brief status report of the VERITAS upgrade.

In our 2010 report, the work of our then postdoc Dr. Martin Schroedter showed a detection of the Crab pulsar, together with two other independent analyses. While the Crab pulsar was detected at GeV energies by EGRET and now by Fermi and MAGIC up to 25 GeV, the discovery of E > 120 GeV emission stands out, and undoubtedly will force new ideas as to how particle acceleration through a rotating neutron star with a surface magnetic field of a few time 10^{12} G manages to produce sub-TeV photons. The event distribution as a function of the spin phase is shown in Figure 2.1. The most rigorous test statistic (H-test) yields a statistical significance of 6σ.

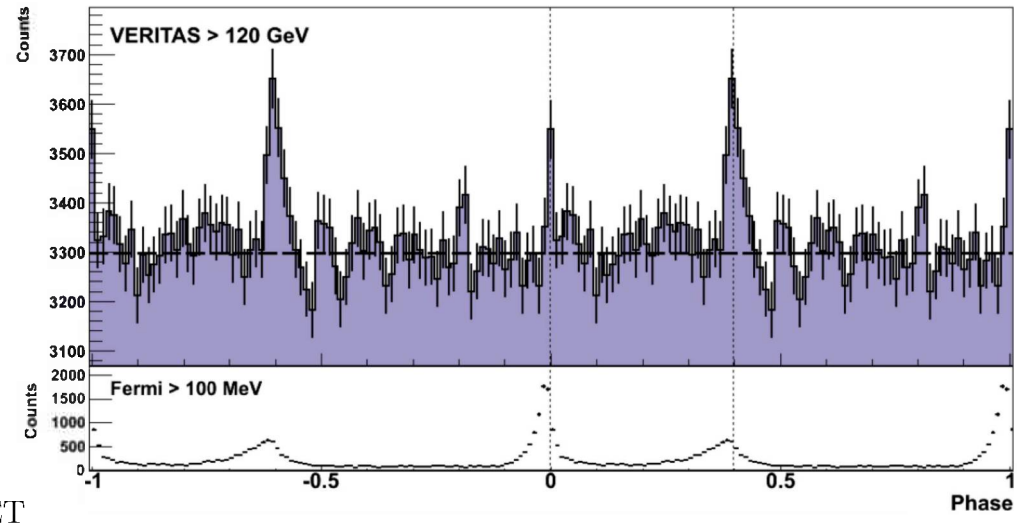

Figure 2.1: - The pulse profile of the Crab pulsar (Science, Aliu et al. 2011) is shown, the shaded histogram shows the VERITAS data.

The energy spectrum of the pulsed emission is shown in Figure 2.2. Based on the Fermi data, a power law with an exponential cut-off was favored, the VERITAS detection at 100 - 400 GeV clearly requires an additional emission component/process.

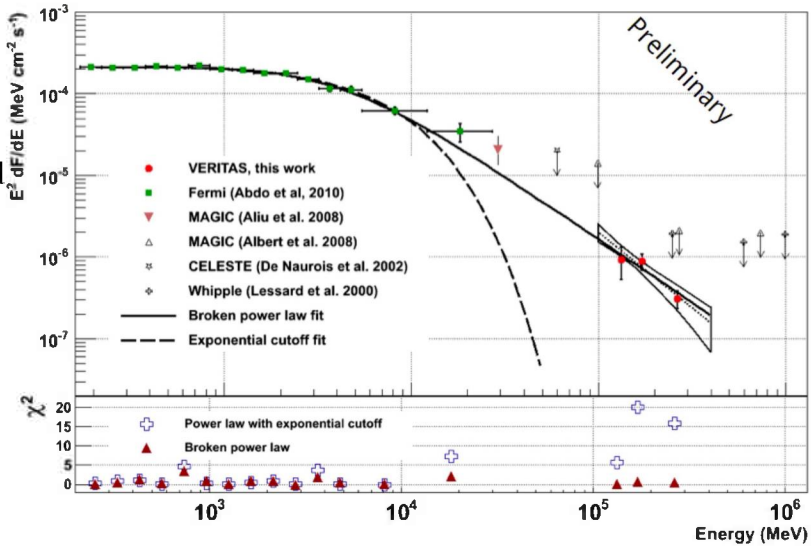

Figure 2.2: - Energy spectrum of the Crab pulsar.

This result challenges the "standard model" of pulsar physics and was unexpected!

3.2 Science Focus: Particle Physics & EBL Cosmology

The diffuse light spanning the UV/optical to the near-far-IR wavelength regime, termed the extragalactic background light (EBL), is second in intensity only to the CMB. The EBL is a source of γ-ray opacity in the Universe, which provides an opportunity for probing fundamental physics involving the nature of weakly interacting massive particles (WIMPs), and their role in early structure formation, as well as the existence of axion-like particles (ALPs), a class of new particles arising within many grand unified theories. The EBL also contains a wealth of cosmological information from processes associated with star/galaxy formation, for example the collapses of massive stars, providing the dominant astrophysical contributions to the EBL (see Hauser & Dwek 2001 and Dwek & Krennrich 2013 for reviews).

In the context of particle physics, contributions to the EBL may come from the earliest stars whose fates were tied to a heavy dark matter particle. In the case of dark stars, their collapse would have been aided significantly by accretion of heavy dark matter particles; WIMPs in turn would have contributed to energy releases via WIMP annihilation and altered the properties of such massive stars significantly, prolonging their lifetimes, resulting in a noticeable (excess) contribution to the EBL in the mid-IR (Maurer et al. 2012). Recent EBL limits from γ-ray observations have ruled out dark

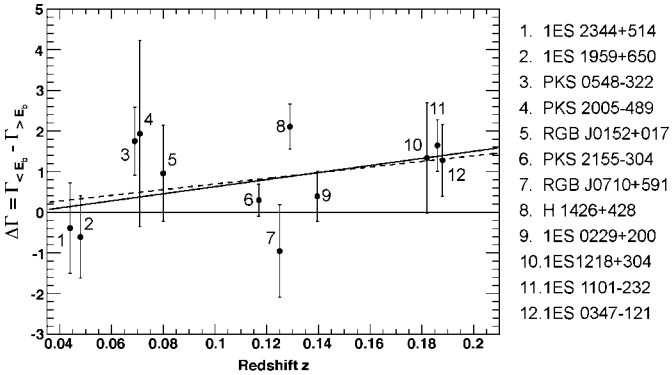

Figure 2.3: - Distribution of spectral break versus redshift is shown. The spectral break is defined as the spectral index below the break energy $E_{\rm b}$ minus the spectral index above the break energy (i.e., $\Delta\Gamma = \Gamma_{<{\rm E_b}} - \Gamma_{>{\rm E_b}}$) The solid line represents the best linear fit given by $\Delta\Gamma(z) = (8.68 \pm 5.37)z - (0.24 \pm 0.71)$ and yields $\chi^2/\nu = 14.10/10$.

stars with of order 100 solar masses, while more massive dark stars are still viable. Another possible contribution to the EBL has been postulated to arise from the decay of exotic particles since the early universe (Bond et al. 1986). Such a contribution would result in a truly diffuse component, whereas radiation components of stellar/galaxy origin would be associated with point sources, that will eventually be resolved with current and/or next generation infrared telescopes.

Furthermore, the EBL offers a unique laboratory for fundamental physics through its ability to absorb γ rays via pair production. Particle physics processes that alleviate the γ-ray opacity of the universe have been proposed. These include the production of ALPs in the intergalactic magnetic field the subsequent mixing of ALPs with photons within the γ-ray horizon of the observer could allow the detection of TeV photons from sources at redshift z $\geq$1 (De Angelis et al. 2007; Sanchez-Conde et al. 2009), similarly to experiments shining laser beams through walls in the presence of a magnetic field.

The **γ-ray technique** can probe the EBL from the UV to the mid-IR and **is unique as it allows one to probe the EBL across cosmic time** (pair production absorption effect can be measured as a function of redshift/epoch), whereas direct measurements with JWST only probe the local cumulative radiation field from all epochs combined. VERITAS has already detected $\approx$ 2 dozen blazars and provided a few precision measurements, such as the spectrum of 1ES 1218+304 (Imran et al. 2009; Acciari et al. 2010a)[2]. Blazar γ-ray spectra provide important constraints (Gould & Schréder 1967) on the intensity of the extragalactic background light (EBL).

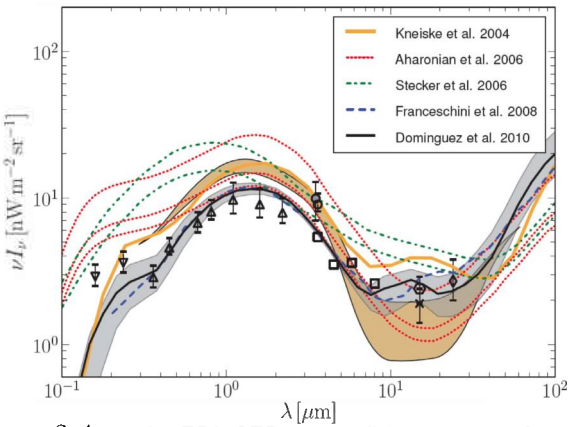

Figure 2.4: - The EBL SED 2σ confidence region from our work (shaded area in orange) is shown along with a range of models. The data points represent lower limits from galaxy counts.

Our recent work on EBL absorption is concerned with three topics: **1) Relativistic jet & black hole physics using EBL lower limits** from galaxy counts (Krennrich, Dwek & Imran 2008), **2) A search for a unique signature from EBL absorption** due to the mid-IR trough (Imran & Krennrich 2007; Orr, Krennrich & Dwek 2011), **3) A measurement of the EBL across cosmic time**. The largest difficulty in extracting the EBL density from blazars is the fact that we do not know the intrinsic spectra *a priori*.

One approach to solve this problem, is to search for features & trends in γ-ray spectra uniquely attributable to EBL absorption. Such feature may arise, from the EBL intensity (see Fig. 2.4) that is expected, on astrophysical grounds; a sharp rise between 0.1-1 micron (star/galaxy formation peak) and a trough towards the mid-IR at 10 micron. This translates into a change in the opacity τ for γ-rays at a characteristic energy of 1 TeV and energy-independent absorption between 1-10 TeV. As a consequence, a spectral feature results with a

[2]this was the work of ISU student Asif Imran, who graduated in Fall 2010. He is now a postdoc on HAWC.

magnitude that scales with redshift[3]. Thus, EBL scenarios with different near/mid-IR ratios can be distinguished when using spectra of blazars that reach up to multi-TeV energies.

Energy spectra at a few GeV from Fermi are most useful for constraining the intrinsic source spectrum in a regime where no EBL absorption takes place (below 10 GeV). Based on these ideas, we have developed new methods to constrain the near- to mid-IR portion of the EBL. Our first method (Method 1) used *Fermi* observations of four hard spectrum blazars as a proxy for the intrinsic source emission in the sub-TeV to TeV regime. A second method (Method 2) involves testing for a spectral break at $\sim 1\,\mathrm{TeV}$ in a sample of 12 blazars using data from Cherenkov telescopes. When combined, these two methods provide strong constraints on the EBL in the near-to-mid IR. The spectral break versus source redshift distribution for a set of 12 TeV blazars (Figure 2.3) was compared with predictions from a range of EBLs applied to a power law γ-ray spectrum, representing a typical blazar spectrum[4], to identify the intensity parameter space consistent with observations.

Our EBL constraints are summarized in Figure 2.4, which shows the 2σ confidence region (brown) for the EBL SED. Our results indicate a low mid-IR EBL, consistent with the most recent lower limit placed on the EBL intensity at $15\,\mu\mathrm{m}$[5]. Most EBL models (see figure) fall outside this 2σ contour and are consequently excluded by our analysis. The complementary nature of the two γ-ray methods applied here results in an absolute constraint on the EBL rather than an upper limit. Method 1 is sensitive to the overall normalization of the EBL intensity while Method 2 is sensitive to the near- to mid-IR ratio. The combination of analyses from both methods yields a closed confidence region for the EBL.

To extend these studies and unambiguously establish a spectral feature from EBL absorption, we have taken two approaches: one is to improve statistics for energy spectra through deep exposures of 120 h each for 4 of the most promising blazars. This will take $\sim$ 4 seasons of VERITAS operation. A second approach is to extend the redshift range of the objects. Two VERITAS detected blazars, 1ES 0414+009 (z=0.28) and PG 1553+113 (z$\geq$0.4) are targeted. An extensive observing campaign of the latter has provided a strong detection (40 σ). A preliminary spectrum is shown in Fig. 2.5. Methods previously developed by Dwek & Krennrich (2005) can be used to constrain the redshift of PG 1553+113 – using a minimal EBL one can exclude large redshifts as those yield an absorption corrected spectrum with an exponential rise with energy (see Fig. 2.5). Dr. Orr is currently preparing a publication.

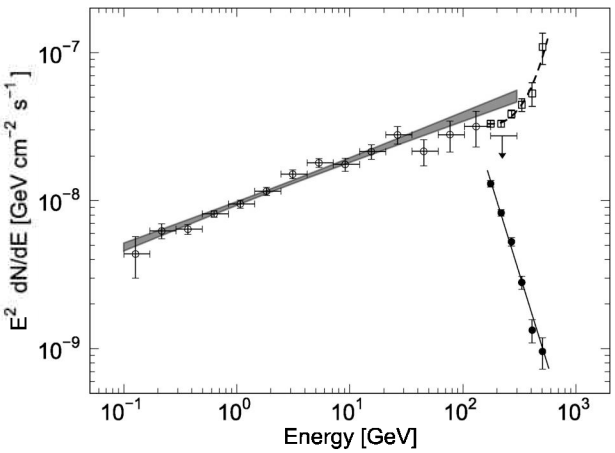

Figure 2.5: - The preliminary energy spectrum of PG 1553+113 is shown (Orr et al. 2012).

[3]Constant τ implies a constant absorption term $e^{-\tau}$ rendering the observed spectral index close to the intrinsic source spectrum, thereby producing an observable break at 1 TeV that scales with redshift

[4]Note that the absolute value of the power law spectrum is immaterial as the spectral break is invariant with the index.

[5]Our results are consistent with previous constraints from galaxy counts, of $2.4 \pm 0.5\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ (Elbaz et al. 2002) to and recent result of $1.9 \pm 0.5\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ (Hopwood et al. 2010).

3.3 New Camera Trigger for the VERITAS upgrade

The aim of the VERITAS upgrade is to substantially improve its performance through a combination of a new camera trigger (L2) system and high quantum efficiency phototubes. The upgrade helps substantially with the next phase of the VERITAS physics program to perform deep observations with improved sensitivity. Compared to the initial VERITAS configuration in 2007, our recent improvements including the upgrade reduces the exposure time by at least a factor of 2 for a given γ-ray flux. After extensive tests including in-situ trigger efficiency measurements, the new VERITAS L2 trigger system was installed in November 2011.

This new system is FPGA-based and provides significantly more control for tuning the trigger to optimize performance. The new system allows one to align the digital pulses from the discriminators to better than 0.2 ns (see Figure 2.7), thus enabling a reduced effective coincidence resolving time, going from 10 ns of the old system, to as short as 3 ns, without significant efficiency loss. Shorter coincidence times reduce the amount of noise triggers from the night sky background fluctuations, thereby stabilizing the L2 rates while enabling a lower energy threshold.

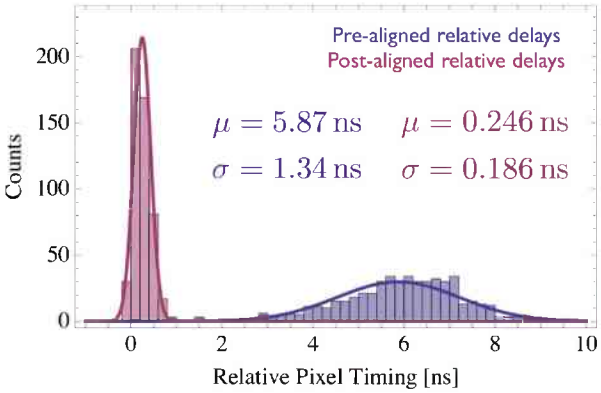

Figure 2.6: - The arrival times of the trigger signals at the FPGAs that form time coincidences are shown before (right) and after (left) the timing calibration.

Besides providing consistent and stable L2 rates, the new trigger system also offers the possibility to measure the efficiency of the system in situ using cosmic-ray and γ-ray events. Since one of the trigger systems uses passive splitters, the digital pulses are routed to a second system and the response of the latter is recorded in the data stream by a VERITAS FADC channel. This setup has allowed us to measure the efficiency[6] of the trigger across the camera showing that the new trigger system operates essentially 100% efficient, even when using a 5 ns coincidence resolving time. The understanding of the camera trigger efficiency at the few percent level, is an important prerequisite for performing deep exposures to limit/estimate systematic uncertainties.

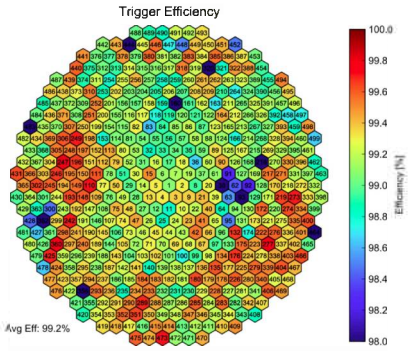

Figure 2.7: - Camera map of the efficiency of the ANL/ISU L2 trigger relative to the previous L2 trigger. These data were taken with a 5 ns coincidence width setting in the ANL/ISU trigger.

The FPGA-based trigger design also allows one to implement real-time image analysis to further reduce background and dead time of the data acquisition system and the ISU groups is currently exploring new trigger schemes, e.g., the implementation of a real-time stereo analysis.

[6] efficiency study is led by Prof. Weinstein.

4 References

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5 Significant contributions by ISU group to Refereed Journal Publications since 2009

2009

1. *Cosmic-ray electron signatures of dark matter*, Pohl, M., Phys. Rev. D 79, 041301, 2009, **Theory paper by Prof. M. Pohl as the sole author.**

2. *A connection between star formation activity and cosmic rays in the starburst galaxy M82* Acciari, V.A., et al. (the VERITAS collaboration), Nature, 462, 770, 2009 **Modeling and Interpretation by Prof. M. Pohl.**

2010

3. *Discovery of Variability in the Very High Energy Gamma-Ray Emission of 1ES 1218+304 with VERITAS*, Acciari, V.A., et al. (the VERITAS collaboration), ApJL, 709, L163, 2010 **Analysis work by graduate student A. Imran, interpretation and guidance by Prof. F. Krennrich**

2011

4. *Design Concepts for the Cherenkov Telescope Array*, Actis, M. et al. (the CTA collaboration), Experimental Astronomy (2011) 32:193-316 (2011) **Conceptual work on array trigger electronics for Schwarzschildt-Couder telescope by Prof. F. Krennrich**

5. *Strong Constraints Strong New Constraints on the Extragalactic Background Light in the Near- to Mid-IR* , Orr, M., Krennrich, F. & Dwek, E., ApJ, 733, 77, 2011 **Analysis work by postdoc Dr. M. Orr, analysis ideas, interpretation and guidance by Prof. F. Krennrich**

6. *Discovery of TeV Gamma Ray Emission from Tycho's Supernova Remnant*, Acciari, V.A., et al. (the VERITAS collaboration), ApJL, 730, L20, 2011 **Modeling and Interpretation by Prof. M. Pohl.**

7. *Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar*, Aliu, E. et al. (the VERITAS collaboration), Science, 334, 6052 2011 **One of three analyses done by postdoc Dr. M. Schroedter.**

2013

8. *Discovery of TeV Gamma-ray Emission Toward Supernova Remnant SNR G78.2+2.1*, Aliu, E., et al. (the VERITAS collaboration), ApJ, in press (2013) **Analysis work by Prof. A. Weinstein**

9. *VERITAS Observations of the BL Lac Object PG 1553+113*, Aliu, E., et al. (the VERITAS collaboration), in preparation (2013) **Analysis work by Dr. M. Orr, science interpretation jointly with Prof. Krennrich**

Chapter 3

Task B: D0 top physics (Tevatron); Dual-readout (CERN)

Contents

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1 Oct 2009 → 30 Sept 2012 → 30 April 2013

1 Outline of Report

This report covers work during this grant period on the D0 experiment at the Fermilab Tevatron Collider, plus work done on dual-readout calorimetry at CERN:

1. production cross section for $t\bar{t}$ production at 1.96 TeV;
2. first test of CP-violation in $t\bar{t}$ production at 1.96 TeV; and,
3. beam tests for dual-readout calorimetry, including new work in measurements of neutrons yield and fluctuations in hadronic calorimetry.

In addition, correlated work incorporating dual-readout calorimeter into an ILC detector, including simulations, are included. Graduate student Sehwook Lee did all of the top quark physics within D0 on both physics measurements; Lee plus several undergraduate physics majors from ISU worked on the neutron counters (and other beam test related work) on the dual-readout RD52 (DREAM) tests at CERN.

1.1 Top quark physics on D0

Measurement of the the top quark pair production cross section

The best D0 measurement on Run2, using over 5 fb^{-1}, with a large fraction fully reconstructed and understood with a stability worthy of a cross section measurement.

Sehwook Lee gave 62 D0 talks and two APS talks on this measurement.

"Measurement of the top quark pair production cross section in the lepton+jets channel in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV"

Phys. Rev. D **84**, 012008 (2011). [18 pages]

This measurement was based on $\mathcal{L} = 5.3$ fb^{-1} of data and resulted in a $t\bar{t}$ cross section measurement of $\sigma = 7.78 + 0.77/-0.64$ pb at a top mass of $M_t = 172.5$ GeV/c^2.

First test of CP violation in top quark pair production.

The distributions of 7 physics observables shown that CP violation is ruled out at the 9% level in all physics observables.

This first test of CP violation in $t\bar{t}$ production is the PhD thesis of Sehwook Lee, and was performed with the formalism developed by German Valencia of this Grant. On 4.3 pb^{-1} of data, the asymmetry induced by CP violation is measured by several kinematic observables, all of which are consistent with zero. The largest deviation is in the observable $\mathcal{O}_2 = 0.106 \pm 0.088/0.091$. The definitive document on this measurement is Lee's thesis

> "CP violating anomalous top-quark coupling in $p\bar{p}$ colliions at $\sqrt{s} = 1.96$ TeV"
> Sehwook Lee, Iowa State University, PhD, 2011

available at

`http://www-d0.fnal.gov/results/publications_talks/thesis/name.html#J-L`

on the D0 website under "Sehwook Lee, Iowa State University, 2011".

This work represents a rare and almost completely unique case of a graduate student defining his own thesis problem, doing all of the physics analysis, and reporting on the results himself. This seldom happens in the large collaborations of high energy physics today. Of course, this work was done within the "double top" group in D0 and rested upon the substantial work done by Sehwook Lee on the top cross section. This measurement has been submitted as a D0 Note, the first step in the publication process in D0. We expect to draft a *PRL* based on this note:

> D0 INTERNAL DOCUMENT NOT FOR PUBLIC DISTRIBUTION
> "CP violating anomalous top-quark coupling in $p\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV
> John Hauptman, Sehwook Lee
> Iowa State University, Ames, IA, USA
> July 11, 2011 (95 pages)

available at http://highenergy.phys.ttu.edu/ swlee/note/cp_ttbar.pdf.

The essential plots of this test for CP violation for Valencia's observables $\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3, \mathcal{O}_4, \mathcal{O}_7, \mathcal{O}_a$, and $\mathcal{O}_b$:

The contributions of the systematic uncertainties are very small compared to the statistical uncertainty. The factors for asymmetry dilution studied in this analysis are related to D0 detector performance. The b-tagging algorithm is used to reduce background contributions significantly. The CP asymmetry measurements for lepton+jet events, including uncertainties due to statistical sample sizes, dilution, and systematics, are:

$O_1 = +0.053 \pm 0.083$ (statistical + dilution + systematic uncertainties)
$O_2 = +0.106 \pm 0.090$ "
$O_3 = -0.049 \pm 0.083$ "
$O_4 = +0.046 \pm 0.087$ "
$O_7 = +0.039 \pm 0.087$ "

where I have averaged the top-side and bottom-side uncertainties for clarity since they differ by only 2-3%. The asymmetry results to measure CP conserving contamination in the CP-odd state are

$O_a = -0.025 \pm 0.087$ (statistical + dilution + systematic uncertainties)
$O_b = -0.053 \pm 0.091$ "

At the Tevatron, such measurements are statistically limited to about 9%.

b quark identification: several improvements, including the 'taggability' processor to include multiple vertices, full study was made in p20 data.

1.2 Dual-readout in the DREAM collaboration

We have developed new techniques in calorimetry within the DREAM collaboration

We have published two papers in Nucl. Instr. Methods Phys. Res., Sect. C (plus two conference papers and numerous talks) on the importance of neutrons in hadronic calorimetry in DREAM.

I gave two talks on neutron measurements at the Pavia CALOR 09 and the Beijing CALOR 10 calorimeter conferences;

I initiated a program to *extrude* the copper shapes needed for the "superDREAM" test module that we expect to be about 5 tonnes. This work was supported by Director's Development Funds at the Ames Laboratory, USDoE (Alex King);

I organized the aluminization of the clear Cerenkov fibers by Eileen Hahn at Fermilab

The ISU Physics majors and I developed a small factory at CERN (in the scintillation lab and shop area, granted to us by Christian Joram) to produce 0.5 tonnes of neutron counters to surround any module in the DREAM tests

We have built miscellaneous counters for the beam test in H8 (a veto counter in the beam, an interaction target counter, and a fiber hodoscope);

I initiated a small program within the Ames Laboratory to roll Cu and Cu alloys into the fine shape needed for superDREAM.

The students worked in the beam tests: cabling, testing, and taking shifts;

Recently, I was invited to a small meeting of Italian principals14 at Villa del Grumello, Lake Como, to talk about a detector for the International Linear Collider, ILC. Of course, I am the leader of the 4th concept detector for the ILC and wrote the Letter of Intent13. This is an international affirmation of my work, in spite of severe opposition in some quarters within the US.

The full Letter of Intent can be accessed at http://www.4thconcept.org. Two Appendices to the LoI contain many internal notes and documents with measurements, calculations, and studies are also available at this website.

2 Outreach to the community and to physics majors

I always support undergraduate physics majors in research with great consequence.

2.1 A physicist writes to the public

10 columns in local and state newspaper.

2.2 A physicist does diplomacy

At the invitation of the Ministry of Education, Nicosia, Cyprus, I gave a series of talks on teaching physics, in addition to talks on dual-readout calorimetry and future high energy colliders and detectors in physics. All expenses paid by the US Embassy, Nicosia, Cyprus. Seven talks.

3 Papers, Talks and Notes

3.1 Papers: top quark, dual-readout, RD52, DREAM

1. "Measurement of the top quark pair production cross section in the lepton+jets channel in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. D* **84**, 012008 (2011).

2. "Optimization of Crystals for Applications in Dual-Readout Calorimetry", Akchurin, N., *et al.*, *NIM* **A621** (2010) 212.

3. "A Comparison of BGO and BSO Crystals Used in the Dual-Readout Mode," *NIM* **A640** (2011) 91.

4. "Polarization as a Tool for Dual-Readout Calorimetry," *NIM* **A638** (2011) 47.

5. "Detection of electron showers in Dual-Readout crystal calorimeters," Akchurin, N. *et al.*, *NIM* **A686** (2012) 125-135.

6. "Particle identification in the longitudinally unsegmented RD52 calorimeter," submitted to *Nucl. Instr. Meths.* (July 2013)

7. "Electromagnetic performance of the RD52 fiber calorimeter," submitted to *Nucl. Instr. Meths.* (July 2013)

D0 Papers We do not list D0 papers which are available on the D0 website `www.d0-fnal.gov`.

4th papers

1. "Dual-readout, Particle Identification, and 4th," *Proc. Technology in Particle Physics*, TIPP09, *Nucl. Instr. Meths.* **A623** (2010) 237.

"Hadron and Jet Detection with a Dual-Readout Calorimeter", *NIM* **A537** (2005) 537-561.

"High Voltage Distribution to the CMS Hadronic Forward (HF) Calorimeters," Atramentov, O., *et al.*, CMS Note, 1 August 2005.

J. Hauptman, "Measurement of the neutron fraction event-by-event in DREAM," *Jour. of Physics* Conf. Series, **293** (2011) 012080, XIV Int'l Conf. on Calorimetry (CALOR10), Beijing, 10-14 May 2010.

J. Hauptman, "Estimate of Neutrons Event-by-event in DREAM," *Jour. of Physics*, Conf. Series, **160** (2009) 012072; XIII Int't Conf. on Calorimetry (CALOR08).

"Measurement of the contribution of neutrons to hadron calorimeter signals," N. Akchurin, *et al.*, *Nucl. Instr. Meth.* **A 581** (2007) 643.

"Neutron signals for dual-readout calorimetry," N. Akchurin, *et al.*, *Nucl. Instr. Meth.* **A 598** (2009) 422-431.

http://www.las.iastate.edu/newsletters/physical-sciences/s2012_students.php

Internal DREAM note on details of the n-counter production and scheduling in the summer 2011.

"The Evolution of Lepton Collider Detectors," Frascati Storage Ring Conference (STOR11), 9-11 October 2011.

"Particle identification in the longitudinally unsegmented RD52 calorimeter," submitted to *Nucl. Instr. Meths.* (July 2013)

"Dual-Readout Calorimetry for High-Quality Energy Measurements,", RD52 Report to SPS Committee, April 2012, R. Wigmans.

"Dual-Readout Calorimetry for High-Quality Energy Measurements," RD52 report, 3 April 2013, G. Gaudio, R. Wigmans.

"Fourth Concept Letter of Intent," Sakue Yamada, 31 March 2009.

"Dual-readout calorimeters in ILC detectors - it's not too late," *ILC & more*, 16-17 May 2013, Villa del Grumello, Lake Como, Italy.

Chapter 4

Task C: Experimental HEP (ATLAS, *BABAR*)

Contents

1 The Energy Frontier

1.1 Personnel

Personnel whose work is described in this task and for whom we are requesting support are listed below.

Senior Staff	Title
C. Chen	Assistant Professor of Physics (supported via ISU start-up)
J. H. Cochran, Jr.	Professor of Physics
S. Prell	Professor of Physics

Postdoctoral Associates	**Graduate Students**
F. de Lorenzi	C. Bieganek
F. Dudziak	L. Cheng (shared with Theory group)
A. Ruiz Martínez	M. Lockner
	A. S. Mete (graduated 2012)
	A. Nelson (graduated 2011)
	D. Pluth
	S. Shrestha
	N. Triplett (graduated 2011)
	K. Yamamoto (graduated 2012)

Support Staff
R. McKay
L. Shuck
C. Zaruba

Other personnel	Title
(not supported via this grant)	
N. Krumnack	Project Scientist
W. T. Meyer	Adjunct Research Professor of Physics (retired)
E. I. Rosenberg	Professor of Physics

1.2 Introduction

Over the course of the last award cycle, our group has focused its efforts on the ATLAS experiment and has concluded its activities on the *BABAR* experiment. During this period we have graduated four students, each of whom successfully obtained a postdoc position. Members of our group have given 12 invited talks/posters and were authors on 22 (ATLAS, *BABAR*, or DØ) internal notes. The following pages summarize our activities. Section 1.7 provides a list of published papers in which the Iowa State group made significant contributions. Section 1.8 provides a list of the positions of responsibility held by members of the group during this period.

1.3 ATLAS

[Chen, Cochran, Prell; de Lorenzi, Dudziak, Ruiz Martínez; Mete, Nelson, Pluth, Shrestha, Yamamoto]

Pixel Detector [Chen, de Lorenzi, Dudziak, Nelson, Prell]

We have continued our work in the Pixel Detector group. Below is a list of tasks where ISU personnel made significant contributions.

- Pixel detector software validation: performing the validation tasks of the ATLAS software validation group and further development of validation software (Prell with two ISU undergraduates)
- Development of pixel occupancy information tool. (Chen)
- Development of a new multivariate clusterization model to improve identification of multi-track clusters. A clear improvement for large clusters is provided by the new algorithm. The tool is now part of the standard ATLAS reconstruction sotware. Calibration of the clustering algorithm for 2012 data and for the IBL upgrade (De Lorenzi).
- Maintenance of pixel geometry database. Study of data-MC discrepancies in pixel material description. Study of material description for IBL module and Service Quarter Panel. (Dudziak)
- Development and maintenance of Readout Driver DSP online monitoring tools. (Nelson)

e/γ Trigger [Ruiz Martínez]

The ATLAS High Level Trigger (HLT), which covers both the Level-2 and Event Filter stages, is a crucial element for any physics analysis in ATLAS. The HLT is responsible for selecting the events for permanent storage in the challenging LHC high-luminosity environment. Postdoctoral associate A. Ruiz Martínez (adviser Chen) has been involved in several HLT activities, contributing in particular to the e/γ trigger signature group. In particular, she served as one of the main responsibles for the e/γ trigger software development and maintenance. In addition, Dr. Ruiz Martínez took expert on-call shifts for the e/γ and τ trigger slices and also served as a TDAQ (Trigger and Data Aquisition) shifter in the ATLAS control room.

As a result of this work, Dr. Ruiz Martínez contributed to the ATLAS Conference Note "Performance of the Electron and Photon Trigger in p-p Collisions at $\sqrt{s} = 7$ TeV" (ATLAS-CONF-2011-114) and gave a talk in the June 2011 ATLAS Week plenary with the title "Performance and Outlook for e/γ and τ triggers".

High Level Trigger Monitoring [Mete]

Crucial tasks necessary for efficient operation of the HLT include monitoring of the data flow, ensuring that consistency of the algorithm executions across all the HLT computing farm is

achieved, and that the prescales are applied correctly for all the items in the current trigger menu. ISU graduate student S. Mete (adviser Cochran) worked with collaborators from UC Irvine, DESY, and U. of Pennsylvania on an implementation of the necessary software packages to accomplish these tasks.

From November 2010 through the end of the 2012 LHC run, these packages were deployed in the online environment and ran automatically for every data taking period. They ran as expected without any reported problems as part of the official software release.

Studies of J/ψ production [Nelson, Prell]

Prof. Prell and Dr. Nelson studied J/ψ production with ATLAS. Theoretical models do not explain all of the measured features of the cross-section and production polarization. We have measured both the J/ψ prompt (J/ψ formed directly in the proton-proton collisions or produced through higher mass charmonium radiative decays) and non-prompt (J/ψ produced through decays of long-lived b hadrons) cross-sections with an integrated luminosity of 2.2 pb^{-1}. The unbinned likelihood fit software that Prof. Prell and Dr. Nelson developed for this analysis has since been used for several other analyses in the ATLAS B Physics Group. While the non-prompt cross-section agrees well with the experimental measurement across the measured range of p_T and rapidity, the prompt cross-section is not reproduced by theoretical predictions. This measurement has been published in Nucl. Phys. B850, 387 (2011). Due to the increased instantaneous luminosity and the need to prescale the muon triggers the measurement of the J/ψ production cross-section is no longer possible at the lower transverse momenta.

Measurement of D^{*+} mesons in jets [Chen, Ruiz Martínez]

The measurement of the production cross section of heavy flavor quarks (c and b quarks) in pp collisions at the LHC provides us with an opportunity to test the relevant predictions of Quantum Chromodynamics (QCD). It is of crucial importance for an understanding of the backgrounds in many searches for NP beyond the SM. After Prof. Chen joined the ATLAS experiment in July 2009, he proposed to study the production of heavy flavor quarks by measuring the rate of $D^{*\pm}$ mesons produced inside jets. Together with Dr. Ruiz Martínez, a postdoctoral research associate from Iowa State University, he performed the first measurement of $D^{*\pm}$ meson production in jets from proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ at the LHC. The results have been recently published in Physical Review D: PRD 85,052005 (2012).

Search for 4th generation up-type quark [Shrestha, Cochran, Krumnack]

The observation of the Higgs boson at 125 GeV puts indirect constraints on the existence of 4^{th} generation quarks, ruling out some extensions of the SM. However, there are a number of models that still allow 4^{th} generation quarks. The ISU group has been active in the search for an up-type 4^{th} generation quark (labeled t') since April of 2011. The model we work under assumes that the t' decays into a W and a light quark. We have focused exclusively on pair produced $t'\bar{t}'$ where one W decays into a lepton and a neutrino, and the other one decays

into two quarks: $pp \to t\bar{t}(t'\bar{t}') \to W^+W^-q\bar{q}' \to \ell\nu qq'q\bar{q}'$. The search is being performed on the 8 TeV 2012 data set (20 fb^{-1}) and is expected to be unblinded mid summmer of 2013. This analysis will be the basis for Suyog's PhD thesis. A publication is targeted for fall.

Studies of Drell-Yan pair and Z boson production [Yamamoto, Prell, Cochran]

Dr. Yamamoto along with Profs. Cochran and Prell and Dr. Begel from BNL have studied the transverse momentum distribution of the lepton pair in Drell-Yan events ($pp \to Z/\gamma^*X \to l^+l^-X$) at $\sqrt{s} = 7$ TeV. The measurement of the lepton pair transverse momentum in Drell-Yan events, $p_T(Z/\gamma^*)$, is a unique way of studying QCD in hadronic collisions. The Drell-Yan p_T distributions have been measured for two different di-muon mass ranges; the Z-mass region is defined from 66 to 116 GeV, and the high-mass range is above 116 GeV. First results on Z production in ATLAS have been published in JHEP 12, 060 (2010) and a journal paper on the differential Z/γ^* cross-section with respect to Z/γ^*-p_T has been published in Phys. Lett. B705, 415 (2011). Dr. Yamamoto's contribution to this analysis was the determination of the shapes and amounts of the various background sources. In addition, Dr. Yamamoto has studied the high-mass range and the sensitivity to a physics beyond the Standard Model Z' for her PhD thesis.

Search for W' [Mete, Cochran]

Graduate student Serhan Mete (adviser Cochran) was a key member of the group involved in the search for high-mass states, such as heavy charged gauge bosons (W'), decaying to a charged lepton (electron or muon) and a neutrino. The possible existence of such heavy charged spin-1 gauge bosons is predicted by many extension of the Standard Model.

The results of this search were based on the analysis of pp collisions at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of 1.04 fb^{-1}. No excess beyond Standard Model expectations was observed. A W' boson with Sequential Standard Model couplings was thus excluded at the 95% confidence level for masses up to 2.15 TeV, a significant improvement over previous limits. These results were published in PLB in late 2011. This work constituted the major component of Mr. Mete's Ph.D. thesis which he successfully defended in February 2012.

Identifying boosted hadronically-decaying particle using jet substructure in its center-of-mass frame [Chen, Cochran, de Lorenzi, Prell, Ruiz Martínez, Yamamoto]

Since the summer of 2011, together with Profs. Cochran and Prell, Prof. Chen has led two postdoctoral research associates from ISU, Dr. De Lorenzi and Dr. Ruiz Martínez, to work on a measurement of the inclusive production cross section of boosted W/Z bosons using current ATLAS data at the center-of-mass energy of $\sqrt{s} = 7$ TeV. The analysis is based on a method proposed by Prof. Chen to identify boosted hadronically-decaying particle (W, Z and t) using jet substructure in its center-of-mass frame. The method has been published in Physical Review D: PRD 85,034007 (2012) and PRD 87,074007 (2013). The analysis is current under internal review by ATLAS collaboration for publication and is expected to be

ready by the end of summer 2013. The ISU group is also working on the application of the method to search for NP:

- Search for new heavy resonance X beyond the SM decaying to di-boson final states, such as $pp \to X \to WW/WZ$.
- Search for possible new heavy neutrino decaying to final states with W bosons.
- Measurement of production cross section of top quarks with high transverse momentum.

All of those analyses are ongoing and will be ready by the end of 2014 or summer 2014.

1.4 DZero [Triplett, Cochran]

Single-top cross section [Triplett, Cochran]

In 2009, due to uncertainties in the LHC schedule, graduate student Nathan Triplett moved from the ATLAS experiment at CERN to the DØ experiment at Fermilab. He continued his work on the observation/measurement of single-top quark production, focusing on b-tagging and multivariate tools and was instrumental in the 2011 DØ single-top cross section measurement and publications. Nathan successfully defended his thesis in March of 2011 and accepted a postdoc position on ATLAS with the BNL group. As part of the arrangement with DZero management concerning Mr. Triplett's move to DØ, Prof. Cochran served on the DØ "Top Properties" Editorial Board until the fall of 2011. Both Prof. Cochran and Mr. Triplett received limited authorship privileges in return for their participation on DØ.

1.5 BABAR [Chen, Prell]

Iowa State personnel have in the past focussed their analyses of BaBar data on searches for physics beyond the Standard Model and measurements of CP violation. Prof. Chen recently completed an analysis on the "Search for CP violation in the decay $D^{\pm} \to K^0_S \pi^{\pm}$." The measured CP-violating decay rate asymmetry is consistent with the standard model prediction and is currently the most precise measurement of this parameter. This work has been published in Phys. Rev. D (RC) 83, 071103 (2011). Dr. Chen has continued to collaborate with Dr. Cenci from University of Maryland on a "Search for time-integrated CP violation in $D^+_s \to K^0_S K^+, D^+_s \to K^0_S \pi^+$ decays." The results have been published in Phys. Rev. D 87, 052012 (2013).

After the end of data taking of the BaBar and Belle experiments, the two collaborations agreed to collaborate on the "Physics of the B Factories Book" (PBF book) project. The book will contain full reviews of all major physics areas that the B factories have studied over the last decade and serve as reference for the scientists that work on the next generation of Super B factories. Prof. Prell wrote the "white paper" for the book and is one of its co-editors. More than 60 contributors from BaBar, Belle and theory are working on the book. At this time, three quarters of the 850-page book have been reviewed by the two collaborations.

Prof. Prell co-organized four PBF book workshops and several editors meetings to organize and review the writing of the book. The book will be submitted for publication to Eur. Phys. Journal C/Springer this fall.

1.6 Papers published

The Iowa State group made significant contributions to the following journal papers published since our last grant proposal:

1. Dr. Nelson was a leading analyzer on the analysis described in the paper "Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at $\sqrt{s} = 7$ TeV," .

2. Prof. Chen and Dr. Ruiz Martinez were the primary analyzers and authors of the paper "Measurement of $D^{*\pm}$ meson production in jets from pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector," .

3. Prof. Chen was the single author of the paper "New approach to identifying boosted hadronically-decaying particles using jet substructure in its center-of-mass frame," .

4. Dr. Yamamoto was a leading analyzer on the analyses described in the papers "Measurement of the $W \to l\nu$ and $Z/\gamma^* \to ll$ production cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector," and "Measurement of the transverse momentum distribution of Z/γ^* bosons in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector," .

5. Dr. Mete was a major contributor (analyzer/editor) to the papers "Search for high-mass states with one lepton plus missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector," and "Search for a heavy gauge boson decaying to a charged lepton and a neutrino in 1 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector," .

6. Prof. Prell and Dr. Dong were principal authors for the paper "Dalitz Plot Analysis of $B^- \to D^+\pi^-\pi^-$," .

7. Prof. Chen was a principal author for the paper "Search for CP violation in the decay $D^+ \to K^0_S\pi^+$" .

8. Prof. Chen was chair of the review committee for the paper "Search for CP violation using T-odd correlations in $D^\pm \to K^+K^0_S\pi^+\pi^-$ and $D^+_s \to K^+K^0_S\pi^+\pi^-$ decays" .

9. Prof. Prell was on the internal *BABAR* review committee for the paper "Evidence for direct CP violation in the measurement of the CKM angle γ with $B^\mp \to D^{(*)}K^{(*)\mp}$ decays" .

10. Dr. Triplett made major contributions to the analysis presented in the papers "Measurements of single top quark production cross sections and $|V_{\rm tb}|$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV," and "Model-independent measurement of t-channel single top quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV" .

11. Prof. Cochran was on the internal DØ review committees for the papers "Measurement of the W boson helicity in top quark decays using 5.4 fb^{-1} of $p\bar{p}$ collision data," "Measurement of Spin Correlation in $t\bar{t}$ Production using a Matrix Element Approach," "Forward-Backward Asymmetry in Top Quark-Antiquark Production," and "Measurement of Color Flow in $t\bar{t}$ Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV" . As per the agreement with DØ management concerning the (re)admission of Prof. Cochran and Dr. Triplett to DØ their authorship privileges are limited only to papers directly related to Dr. Triplett's thesis work on the single-top quark search.

1.7 Positions of Responsibility

Members of the Iowa State group served in the following positions during the period of this award.

1. **U.S. ATLAS Fellowship** - Chen
2. **Pixel Software Validation Coordinator** - Prell
3. **Pixel ACR Shifts** - Nelson, Chen, Yamamoto
4. **Pixel DAQ Expert "On Call" Shifts** - Nelson
5. **e/γ Trigger Expert "On Call" Shifts** - Ruiz Martínez
6. **ATLAS Calorimeter trigger coordinator (deputy)** - Ruiz Martínez
7. **Trigger ACR Shifts** - Mete
8. **DAQ ACR Shifts** - Ruiz Martínez, Shrestha
9. **Convener: ATLAS Standard Model Jet and Photon Physics Working Group** - Ruiz Martínez
10. **ATLAS contact of the Jets subgroup in the LHC Physics Center at CERN (LPCC)** - Ruiz Martínez
11. **Analysis contact for ATLAS Boosted W/Z group** - de Lorenzi
12. **Analysis contact for ATLAS WW/WZ resonance search at 8 TeV group** - Ruiz Martínez
13. **Analysis contact for ATLAS W' group (2011-2012)** - Mete
14. **ATLAS Editorial Board: Top cross section (8 TeV) Chair** - Cochran
15. **ATLAS Editorial Board: Top to dilepton cross section (7 TeV) Chair** - Cochran
16. **ATLAS Editorial Board: Υ production cross section as a function of p_T and η** - Prell

17. **ATLAS Editorial Board: Quark Gluon Tagger 2012** - Ruiz Martínez
18. **Argonne National Laboratory Fellowship: ATLAS TDAQ Upgrade** - Pluth
19. **U.S. ATLAS Deputy Operations Program Manager (Designate)** - Cochran
20. **U.S. ATLAS Analysis Support Manager** - Cochran
21. **U.S. ATLAS Speakers Committee Chair** - Prell
22. **U.S. ATLAS Executive Committee** - Cochran
23. **Editor: Physics of the *B* Factories book** - Prell
24. ***BABAR* Review Committees [Chair]** (see Sec. 1.7) - Chen, Prell
25. **DØ Review Committees** (see Sec. 1.7) - Cochran

Chapter 5

Task D: Theoretical Physics

Contents

Final Report for ISU Theory Task: German Valencia

1 Summary of research activity during 2009-2013

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Topics

1. CP violation in top-quark production and decay
2. Color octet scalars and CP violation in top-quark production at the LHC
3. FCNC and non-universal Z'
4. Extended scalar sectors and a fourth generation
5. Searching for new physics with τ-lepton pairs at LHC
6. Rare Kaon Decay Mini-Review

2 Publications

Publications

1. X. -G. He and G. Valencia, "B decays with τ-leptons in non-universal left-right models," Phys. Rev. D **87**, 014014 (2013) [arXiv:1211.0348 [hep-ph]].
2. H. Potter and G. Valencia, "Probing lepton gluonic couplings at the LHC," Phys. Lett. B **713**, 95 (2012) [arXiv:1202.1780 [hep-ph]].
3. X. -G. He, G. Valencia and H. Yokoya, "Color-octet scalars and potentially large CP violation at the LHC," JHEP **1112**, 030 (2011) [arXiv:1110.2588 [hep-ph]].
4. X. -G. He and G. Valencia, "An extended scalar sector to address the tension between a fourth generation and Higgs searches at the LHC," Phys. Lett. B **707**, 381 (2012)
5. N. G. Deshpande, X. -G. He and G. Valencia, "D0 Dimuon Asymmetry in $B_s - \bar{B}_s$ Mixing and Constraints on New Physics," Phys. Rev. D **82**, 056013 (2010)
6. S. K. Gupta and G. Valencia, "Flavor changing Z' couplings at the LHC," Phys. Rev. D **82**, 035017 (2010) [arXiv:1005.4578 [hep-ph]].
7. X. -G. He and G. Valencia, "Ansatz for small FCNC with a non-universal Z'," Phys. Lett. B **680**, 72 (2009) [arXiv:0907.4034 [hep-ph]].
8. S. K. Gupta, A. S. Mete and G. Valencia, "CP violating anomalous top-quark couplings at the LHC," Phys. Rev. D **80**, 034013 (2009) [arXiv:0905.1074 [hep-ph]].

Conference Talks

1. SSP (Symmetries in Subatomic Physics) 2009 Taipei
2. TOP-2010 International Workshop
3. HQL-2012 Prague
4. SSP 2012 Groningen
5. Tau2012 Nagoya
6. ICHEP 2012 Melbourne

Graduate Students and Postdocs supported by the grant during this period

1. Alper Hayter (2012), Natascia Vignaroli (2011-2012), Sudhir Gupta (2009-2011) postdocs
2. Li Cheng, Han Phoon, graduate students, summer support