University of Arizona

29 July 2013

Final Report

for DOE Grant from 1 Feb 2004 to 30 Apr 2013

University of Arizona

High Energy Physics Program

DOE/HEP Grant - Final Report **Submitted 29 July 2013**

Project Title:	University of Arizona High Energy Physics Program
DOE/HEP Contact:	Dr. David Boehnlein
DOE Award Number:	DE-FG02-04ER41298
Lead Principal Investigator:	John Rutherfoord, rutherfo@physics.arizona.edu Physics Department 1118 E 4th St University of Arizona Tucson, AZ 85721 (520)621-2657
Recipient Organization:	Arizona Board of Regents PO Box 3308 Vice President for Research Dr. Leslie P. Tolbert Tucson, AZ 85722-3308 (520)626-6000
Period of this grant:	1 February 2004 to 30 April 2013
Report covers the period:	1 February 2010 to 30 April 2013
Co-Principal Investigators:	Task A - Theory
	Keith Dienes dienes@physics.arizona.edu
	Shufang Su shufang@physics.arizona.edu
	Doug Toussaint doug@physics.arizona.edu
	Task B - Experiment
	Elliott Cheu elliott@physics.arizona.edu
	Kenneth Johns johns@physics.arizona.edu
	John Rutherfoord rutherfo@physics.arizona.edu
	Michael Shupe shupe@physics.arizona.edu
	Erich Varnes varnes@physics.arizona.edu
	Task C - Theory
	Ina Sarcevic ina@physics.arizona.edu

Table of Contents

Introduction …… 1

Individual Project Reports .....……... 2

Task A Theory ....…… 2

Keith Dienes …… 3

Shufang Su …….. 8

Doug Toussaint …… 13

Task B Experiment ATLAS/D0 ……. 17

Elliott Cheu ……. 18

Kenneth Johns ……. 23

John Rutherfoord ……. 28

Michael Shupe ……. 33

Erich Varnes …… 38

Task C Theory ……. 43

Ina Sarcevic …….. 44

Appendix 1: Graduate Student PhDs …….. 49

Appendix 2: References cited in the Individual Project Reports …… 50

Appendix 3: Publications during the last renewal period ...…… 56

UNIVERSITY OF ARIZONA HIGH ENERGY PHYSICS – FINAL REPORT

DOE Grant No. DE-FG02-04ER41298 1 Feb 2004 to 30 Apr 2013

Introduction:

The High Energy Physics Group at the University of Arizona has conducted forefront research in elementary particle physics. Our theorists have developed new ideas in lattice QCD, SUSY phenomenology, string theory phenomenology, extra spatial dimensions, dark matter, and neutrino astrophysics. The experimentalists produced significant physics results on the ATLAS experiment at CERN's Large Hadron Collider and on the D0 experiment at the Fermilab Tevatron. In addition, the experimentalists were leaders in detector development and construction, and on service roles in these experiments.

The most recent focus of the experimental faculty was the search for new physics at the Energy Frontier on the ATLAS experiment. They pursued searches for new physics and new particles in a variety of decay channels including dijets and top-antitop quark pairs. They also studied Standard Model QCD processes (jets) which helped better understand many of the backgrounds. Three Arizona graduate students have received PhDs on ATLAS physics topics.

In addition to physics, it is worth noting that the University of Arizona joined ATLAS early on and led the Liquid Argon Forward Calorimeter design and construction. The group also had a modest participation in the Cathode Strip Chamber electronics. Most recently the group has become involved in the high luminosity detector upgrades for the Liquid Argon Calorimeter and the Muon system.

In the past several years the experimental faculty have provided many significant physics analyses, detector electronics, and leadership roles on the D0 experiment. These include a Higgs search using the full Tevatron data set and writing up the publications.

This Final Report marks the end of this grant. A new DOE/HEP grant started immediately thereafter with many exciting projects on-going.

The following will describe the accomplishments of each faculty member with emphasis on the reporting period of the latest 3-year renewal.

UNIVERSITY OF ARIZONA HIGH ENERGY PHYSICS PROGRAM

FINAL REPORT FOR DOE GRANT DE-FG02-04ER41298

INDIVIDUAL PROJECT REPORTS

TASK A: THEORY

Professors Keith Dienes, Shufang Su, and Doug Toussaint

The theorists supported by this task are working on cutting edge physics topics. For those projects completed during the last renewal period of this DOE grant the following people also participated and were fully or partially supported by grant funds: Postdoctoral Researchers Brooks Thomas, Vikram Rentala, and Barath Coleppa; also Graduate Students Walter Freeman, Jonathan Eckel, Xinyu Miao, and Menika Sharma.

KEITH DIENES

During the past three years (2009 through the present), my research has resulted in fifteen publications: these include eleven research articles published in peer-reviewed journals, one additional research article currently under review, one long overview Chapter published in a retrospective volume on supersymmetry, and two conference proceedings. Several additional research articles are also due to appear shortly (to be discussed below). During this period, I also graduated two Ph.D. students, one of whom accepted a postdoctoral position at IISc Bangalore, and the other of whom accepted a postdoctoral position in the Boston area working to apply ideas from high-energy physics in biophysics. I continue to guide an additional Ph.D. graduate student (soon to be entering his third year of graduate school), and I have collaborated with and partially supported one postdoc (Brooks Thomas, Ph.D. 2007 from the University of Michigan) and partially supported another (Vikram Rentala, Ph.D. 2010 from UC Berkeley). A new postdoc Barath Coleppa (Ph.D. 2010 from Michigan State) joined our group in Arizona in Fall 2012. I have also given plenary talks at literally dozens of major international conferences (e.g., SUSY, String Pheno, *etc.*), and have given numerous research seminars and colloquia at institutions worldwide.

During the most recent period funded by our current DOE grant, my research has focused broadly on four themes: string phenomenology, SUSY field theories, extra spacetime dimensions, and dark matter, with several papers completed in each category. Dark matter, in particular, represents a major new research direction for me over the past year, and has been my focus almost exclusively since that time.

String phenomenology: During the most grant period, I have completed three papers concerning various aspects of string phenomenology.[1]

- In Ref. [S81] (in collaboration with my former Ph.D. student M. Lennek), we addressed a critical question for string phenomenology: In light of recent discussions of the string landscape, to what extent is string theory predictive? We argued that it is unlikely that the landscape as a whole will exhibit unique correlations amongst low-energy observables, but rather that different regions of the landscape will exhibit different overlapping sets of correlations. We then provided a statistical method for quantifying this degree of predictivity, and for extracting statistical information concerning the relative sizes and overlaps of the regions corresponding to these different correlation classes.

- In another paper (Ref. [S94], in collaboration with my former Ph.D. students M. Lennek and M. Sharma), we continued our long-standing investigation into certain unusual properties of strings at finite temperature. According to the standard prescriptions, zero-temperature string theories can be extended to finite temperature by compactifying their time directions on a so-called "thermal circle" and implementing certain orbifold twists. However, the existence of a topologically non-trivial thermal circle leaves open the possibility that a gauge flux can pierce this circle — *i.e.*, that a non-trivial Wilson line (or equivalently a non-zero chemical potential) might be involved in the finite-temperature extension. In Ref. [S94], we concentrated on the zero-temperature heterotic and Type I strings in ten dimensions and surveyed the possible Wilson lines which might be introduced in their finite-temperature extensions. We found a rich

[1] Due to limitations of space, I will refer to papers on which I am (co-)author using a format such that Ref. [S38] indicates paper #38 in the INSPIRE-HEP database at `inspirehep.net` when a publication list is generated via the search command "*find author dienes,k*" and then subsequently re-ordered by changing the output format to *'CV format (html)'* and the sort option from *'desc'* to *'asc'* (with all other options unchanged).

structure of possible thermal string theories, some of which even have non-traditional Hagedorn temperatures, and we demonstrated that these new thermal string theories can be interpreted as extrema of a continuous *thermal* free-energy landscape. Our analysis also uncovered a unique finite-temperature extension of the heterotic $SO(32)$ and $E_8 \times E_8$ strings which involves a non-trivial Wilson line but which — like the traditional finite-temperature extension without Wilson lines — is metastable in this thermal landscape.

- Finally, in a third paper (currently under review at *Phys. Rev.* **D**, to appear on the arXiv upon acceptance), we continued our investigation into string thermodynamics by investigating the extent to which strong/weak coupling S-duality relations hold at finite temperature. This work is particularly subtle for several reasons. First, thermal effects necessarily break SUSY, which removes most of the standard tools for analyzing string theories at strong coupling. Second, the critical role played by non-trivial Wilson lines (as discussed above) implies that the S-duality map is not one-to-one, a feature which is also known to affect certain supersymmetric S-duality maps at zero temperature. Finally, the Jeans instability (the tendency towards gravitational collapse for such systems) presents an increasingly severe obstruction as the string coupling is increased. Nevertheless, partly based on former work [S31-S33,S35,S36], we developed several methods for addressing these issues and charting their ranges of validity.

Supersymmetry and Supersymmetric Field Theories: During the most recent grant period, I also continued my work in collaboration with my former postdoc B. Thomas concerning the vacuum structures and properties of supersymmetric field theories.

- In Refs. [S82,S83], we were able to present a series of supersymmetric models exhibiting an entirely new vacuum structure: infinite towers of metastable vacua with higher and higher energies. As the number of vacua grows towards infinity, the energy of the highest vacuum remains fixed while the energy of the true ground state tends towards zero. We studied the instanton-induced tunneling dynamics associated with such vacuum towers, and found that many distinct decay patterns along the tower are possible. We also discussed several potential phenomenological applications of this setup. This work was featured on the APS website *Physics: Spotlighting Exceptional Research*, `http://physics.aps.org`.

- In Ref. [S84], we then turned our attention to a somewhat different question: to what extent can supersymmetric theories with non-zero Fayet-Iliopoulos (FI) terms be consistently coupled to supergravity? Our work in this area was stimulated by an important paper by Z. Komargodski and N. Seiberg (arXiv:0904.1159) in which an explanation was proposed for many of the historical difficulties that arise when attempting to achieve such a coupling. In their paper, it was shown that globally supersymmetric theories with non-zero FI terms give rise to supercurrents which are not $U(1)_{\rm FI}$ invariant. Even more dramatically, they showed that in the full SUGRA theory, the presence of FI terms spawns additional global symmetries, thereby contradicting commonly held beliefs about additional global symmetries in supergravity. If these results are true, they would explain the apparent impossibility of coupling theories with non-zero FI terms to supergravity.

  Yet these results seemed to leave room for suspicion. For example, it was claimed that the supercurrents of theories with FI terms do not respect $U(1)_{\rm FI}$ gauge symmetry. But how can this happen, given that FI terms, in and of themselves, preserve $U(1)_{\rm FI}$ gauge symmetries?

Likewise, these results also break R-symmetry. How can this happen, given that FI terms, in and of themselves, preserve R-symmetries?

Our work [S84] was motivated, in part, to answer these questions. Specifically, we revisited the issue of whether globally supersymmetric theories with non-zero FI terms may be consistently coupled to supergravity. We examined claims that a fundamental inconsistency arises due to the conflicting requirements which are imposed on the R-symmetry properties of the theory by the supergravity framework. We also proved that certain kinds of Fayet-Iliopoulos contributions to the supercurrent supermultiplets of theories with non-zero FI terms fail to exist. A key feature of our discussion was an explicit comparison between results from the chiral (or "old minimal") and linear (or "new minimal") formulations of supergravity, and the effects within each of these formalisms that are induced by the presence of non-zero FI terms. In all cases, our results confirmed those of Seiberg and Komargodski and perhaps help to provide an added perspective on their results.

- I also co-authored a reprinted overview Chapter on open questions in supersymmetric theories for a retrospective volume on supersymmetry [S88].

Extra Spacetime Dimensions:

- In collaboration with my former Ph.D. student S. Bauman (currently a postdoc at the University of Wisconsin, Madison), we also completed a study of radiative corrections in Kaluza-Klein theories. In general, the most direct experimental signature of a compactified extra dimension is the appearance of towers of Kaluza-Klein particles obeying specific mass and coupling relations. However, such masses and couplings are subject to radiative corrections. Indeed, while there has been a large literature investigating the KK-induced radiative corrections for the zero modes, there has been relatively little discussion of the KK-induced radiative corrections to the spectrum of the excited KK states themselves. (For a notable exception, see work by Cheng, Matchev and Schmaltz, hep-ph/0204342.)

  In Ref. [S91], using specialized regulators that we previously developed for this purpose in Refs. [S77,S78], we investigated the extent to which such radiative corrections deform the expected tree-level relations between Kaluza-Klein masses and couplings. As toy models for our analysis, we investigated two theories which are relevant to the Higgs model: a flat five-dimensional scalar $\lambda\phi^4$ model as well as a flat five-dimensional Yukawa model involving both scalars and fermions. In each case, we identified the conditions under which the tree-level relations are stable to one-loop order, and those in which radiative corrections modify the algebraic forms of these relations. Although small, such corrections to the KK spectra are relevant because they have the potential to distort the apparent geometry of a large extra dimension, and may be observable at future colliders.

- In a completely different vein, I also investigated some features that arise due to "compactification" in two common condensed-matter systems: carbon nanotubes and nanotori. This work was motivated in part by the considerable recent interest in the properties of carbon nanotori within the condensed-matter community. As is well known, carbon nanotori can be parametrized according to their radii, their chiralities, and the twists that occur upon joining opposite ends of the nanotubes from which they are derived. In Ref. [S87], however, my former postdoc B. Thomas and I demonstrated that many physically distinct nanotori with wildly

different parameters nevertheless share identical band structures, energy spectra, and electrical conductivities. This surprising isospectrality occurs as a result of certain hitherto-unnoticed geometric symmetries (including modular invariance) which are direct consequences of the properties of the compactified graphene sheet. We have recently learned that several experimental groups are now seeking to test these isospectralities in the laboratory, and to exploit this property in the fabrication of new graphene-related materials.

String Vacuum Project (SVP): Much of my string phenomenology research described above is part of a broader initiative called the String Vacuum Project (SVP). Established approximately four years ago, the SVP is a large, multi-year, multi-institution, interdisciplinary collaboration dedicated to exploring the space of string models (string vacua) and their low-energy phenomenological implications. Given that relatively large numbers of string vacua exist, it is imperative that string phenomenologists confront this issue head-on by learning about these vacua and the space of resulting possibilities. The SVP has a strong interdisciplinary component, combining research in particle physics, mathematics, and computer science. On the particle-physics side, the SVP collaboration in the U.S. includes nearly twenty string phenomenologists from many of the leading institutions across the United States. I was the host and primary organizer of the Kickoff Meeting for the United States SVP collaboration which was held in Arizona in April 2008, and we have had annual or semi-annual meetings every year since then. I also served as the original PI for this project.

Dynamical Dark Matter (DDM): Finally, a major thrust of my research over the past year concerns the development of a new framework for dark-matter physics which we call "dynamical dark matter" [S89,S90,S92,S93,S95].

Over the past year, in collaboration with our former postdoc B. Thomas, I have opened an entirely new line of research: a new framework for dark-matter physics which we call "dynamical dark matter (DDM)". This has already resulted in five papers [S89,S90,S92,S93,S95] (all either published or accepted for publication in *Phys. Rev.* **D**), with further papers on the way. Moreover, during the past few months, this project has expanded to include additional collaborations with my Arizona colleague Shufang Su, with Prof. Tony Gherghetta of the University of Melbourne (Australia), with Prof. Jason Kumar of the University of Hawaii, and also with my Arizona colleague John Rutherfoord (an experimentalist working on ATLAS). Indeed, as we continue to give talks on this work, additional collaborations are developing almost daily. For these reasons, further investigations into DDM will likely be a major thrust of my upcoming research.

The basic idea behind DDM is relatively simple [S89]. Rather than focus on one or more stable dark-matter particles, we instead consider a multi-component framework in which the dark matter of the universe comprises a vast ensemble of interacting fields with a variety of different masses, mixings, and abundances. However, rather than impose stability for each field individually, we ensure the phenomenological viability of such a scenario by requiring that those states with larger masses and SM decay widths have correspondingly smaller relic abundances, and vice versa. *In other words, dark-matter stability is not an absolute requirement in such a framework, but is balanced against cosmological abundance across the entire ensemble.* This leads to a highly dynamical scenario in which cosmological quantities such as $\Omega_{\rm CDM}$ experience non-trivial time-dependences beyond those normally associated with cosmological expansion.

Although it might initially seem difficult to arrange an ensemble of states which have the required decay widths and relic abundances, one particular example in which this balancing act occurs naturally consists of an infinite tower of Kaluza-Klein (KK) states living in the bulk of large extra spacetime dimensions. Remarkably, this remains true even if the stability of the KK tower itself is entirely

unprotected! Thus theories with large extra dimensions — and by extension, certain limits of string theory — naturally give rise to dynamical dark matter. However, DDM also arises naturally in other contexts as well, such as the axiverse or theories with large hidden sectors. Thus, the DDM framework is a very broad one, and represents in some sense the most general dark sector that can possibly be envisioned. Moreover, because the dark-matter "candidate" in the DDM framework consists of a carefully balanced ensemble which cannot be characterized in terms of a single well-defined mass, decay width, or interaction cross section, the DDM framework generically gives rise to a rich set of collider, astrophysical, and direct-detection phenomena which transcend those usually associated with dark matter and which ultimately reflect the collective behavior of the entire DDM ensemble.

In Ref. [S89] we introduced the DDM framework and surveyed its theoretical aspects, while in Refs. [S90, S92] we constructed an explicit DDM model and demonstrated that this model satisfies all known collider, astrophysical, and cosmological constraints. The results of Refs. [S90,S92] therefore constitute an "existence proof" of the phenomenological viability of the overall DDM framework.

As might be imagined, this new framework for dark-matter physics is pregnant with numerous possibilities for exploration, extension, and generalization. For example, in Ref. [S93], in collaboration with my Arizona colleague Shufang Su, we investigated the prospects for identifying a DDM ensemble at the LHC and for distinguishing such a dark-matter candidate from the candidates characteristic of traditional dark-matter models. For this study, we focused on DDM scenarios in which the component fields of the DDM ensemble are produced at colliders alongside some number of SM particles via the decays of additional heavy fields. We then demonstrated that in many situations it is possible to differentiate between a DDM ensemble and a traditional dark-matter candidate on the basis of the invariant-mass distributions of those SM particles. Likewise, in Ref. [S95] with Prof. Jason Kumar of the University of Hawaii, we studied the prospects for observing DDM at the next generation of direct-detection experiments, focusing primarily on the case in which elastic scattering via spin-independent interactions dominates the interaction rate between the particular atomic nuclei relevant for these experiments and the constituent particles of the DDM ensemble.

SHUFANG SU

Shufang Su's research interest is new physics beyond the Standard Model (SM), and interplay between particle physics and cosmology. Su has conducted research in many areas of particle phenomenology, including direct and indirect searches for new physics and dark matter studies.

This section covers Su's research accomplishments and activities over the past three years, which were focused on collider searches at the Large Hadron Collider (LHC) and dark matter related topics.

Higgs physics

MSSM Higgs bosons at the LHC (publication 9)
The recent results on Higgs boson searches from LHC experiments provide significant guidance in exploring the Minimal Supersymmetric (SUSY) Standard Model (MSSM) Higgs sector. Unlike the SM, which only have one neutral physical Higgs boson, there are five Higgses in the MSSM, two CP-even neutral Higgses, h^0 and H^0, one CP-odd Higgs A^0 and a pair of charged ones $H^\pm$. With my collaborators T. Han and N. Christensen, we studied the implication of Higgs search results on the MSSM. If we accept the existence of a SM-like Higgs boson in the mass window of 123 GeV$-$127 GeV as indicated by the observed $\gamma\gamma$ events, there are two distinct mass regions (in m_A) left in the MSSM Higgs sector: (a) the lighter CP-even Higgs boson being SM-like and the non-SM-like Higgs bosons all heavy and nearly degenerate above 300 GeV (an extended decoupling region); (b) the heavier CP-even Higgs boson being SM-like and the neutral non-SM-like Higgs bosons all nearly degenerate around 100 GeV (a small non-decoupling region). We also found strong correlation between the Higgs decays to W^+W^- and to $\gamma\gamma$ predicted in the MSSM. A similar correlation exists between the W^+W^- and $\tau^+\tau^-$ channels: a reduced W^+W^- channel would force the $\tau^+\tau^-$ channel to be larger. Future searches for the SM-like Higgs boson at the LHC will provide critical tests for the MSSM prediction. We studied the signals predicted for the non-SM-like Higgs bosons and emphasized the potential importance of the electroweak processes $pp \to H^+H^-,\ H^\pm A^0$, which are independent of the SUSY parameters except for their masses. In addition, there may be sizable contributions from $pp \to H^\pm h^0,\ A^0h^0$ and $W^\pm H^0,\ ZH^0$ in the low-mass non-decoupling region, which may serve to discriminate the model parameters. We allowed variations of the relevant SUSY parameters in a broad range and demonstrated the correlations and constraints on these parameters and associated SUSY particles.

Low-mass Higgs bosons in the NMSSM and their LHC implications (publication 11)
With my collaborators T. Han, Z. Liu and N. Christensen, we studied the Higgs sector of the Next to Minimal Supersymmetric Standard Model (NMSSM) in light of the discovery of the SM-like Higgs boson at the LHC. We performed a broad scan over the NMSSM parameter space and identify the regions that are consistent with current Higgs search results at colliders. In contrast to the commonly studied "decoupling" scenario in the literature where the Minimal Supersymmetric Standard Model CP-odd Higgs boson mass is large $m_A \gg m_Z$, we paid particular attention to the light Higgs states in the case when $m_A \lesssim 2m_Z$. The Higgs bosons in the NMSSM, namely three CP-even states, two CP-odd states, and two charged Higgs states, could all be rather light, near or below the electroweak scale, although the singlet-like states can be heavier. The SM-like Higgs boson could be either the lightest CP-even scalar or the second lightest CP-even scalar, but is unlikely to be the heaviest scalar. These NMSSM parameter regions have unique properties and offer rich phenomenology. The decay branching fractions for the SM-like Higgs boson may be modified appreciably. The correlations of $\gamma\gamma/VV$ and $VV/b\bar{b}$ can be substantially altered. The new Higgs bosons may be readily produced at

the LHC and may decay to non-standard distinctive final states, most notably a pair of Higgs bosons when kinematically accessible. We evaluated the production and decay of the Higgs bosons and comment on further searches at the LHC to probe the Higgs sector of the NMSSM.

Constraining Type II 2HDM in light of LHC Higgs searches (publication 13)
With my collaborators B. Coleppa and F. Kling, we studied the implication of the LHC Higgs search results on the Type II Two Higgs-Doublet Model. In particular, we explored the scenarios in which the observed 126 GeV Higgs signal is interpreted as either the light CP-even Higgs h^0 or the heavy CP-even Higgs H^0. Imposing both theoretical and experimental constraints, we analyzed the surviving parameter regions in m_H (m_h), m_A, $m_{H^\pm}$, $\tan\beta$ and $\sin(\beta-\alpha)$. We further identified the regions that could accommodate a 126 GeV Higgs with cross sections consistent with the observed Higgs signal. We found that in the h_0-126 case, we are restricted to narrow regions of $\sin(\beta-\alpha)\sim\pm1$ with $\tan\beta$ up to 4, or extended regions in $\sin(\beta-\alpha)$ with $\tan\beta<1$. The values of m_H, m_A and $m_{H^\pm}$, however, are relatively unconstrained. In the H_0-126 case, we are restricted to a narrow region of $\sin(\beta-\alpha)\sim 0$ with $\tan\beta$ up to about 7, or an extended region of $\sin(\beta-\alpha)$ between -0.6 to -0.1, with $\tan\beta$ extended to 30 or higher. m_A and $m_{H^\pm}$ are nearly degenerate due to $\Delta\rho$ constraints. Imposing flavor constraints shrinks the surviving parameter space significantly. We also investigated the correlation between $\gamma\gamma$, VV and $bb/\tau\tau$ channels. $\gamma\gamma$ and VV channels are most likely to be highly correlated with $\gamma\gamma:VV\sim 1$ for the normalized cross sections.

Non-decoupling MSSM Higgs sector and light superpartners (publication 14)
In the "non-decoupling" region of the Higgs sector in MSSM, the heavier CP-even Higgs boson (H^0) is Standard-Model-like and close to the charged Higgs bosons ($H^\pm$) in mass, while other neutral Higgs bosons ($h^0,\ A^0$) are lighter and near the Z mass. This scenario is consistent with the current Higgs search limits. With my collaborators T. Han, T. Li and L. Wang, we demonstrated that it can pass the stringent flavor constraints, provided there are other light supersymmetric particles to contribute in the loop induced processes. In turn, the non-decoupling Higgs sector implies the existence of light (left-handed) stop, sbottom and Wino-like gauginos, with mass all below 250 GeV. These light superpartners can still escape the current supersymmetry searches at the LHC. Dedicated searches for soft decay products should be devised for the LHC experiments to improve the searching sensitivity. The International Linear Collider would be able to cover the full spectrum region. The solutions for the viable SUSY parameters result from subtle cancellations and are often missed by the generic multiple dimensional scans, highlighting the importance of theoretical guidance in search for such special cases.

Dark matter at colliders

Dark matter-motivated searches for exotic 4th generation quarks in Tevatron and early LHC data (publications 2 and 7)
With my collaborators J. Alwall, J. Feng and J. Kumar, we determined the prospects for finding dark matter at the Tevatron and LHC through the production of exotic 4th generation quarks T' that decay through $T'\to tX$, where X is dark matter. The resulting signal of $t\bar{t}+\not{E}_T$ has not previously been considered in searches for 4th generation quarks, but there are both general and specific dark matter motivations for this signal, and with slight modifications, this analysis applies to any scenario where invisible particles are produced in association with top quarks. Current direct and indirect bounds on such exotic quarks restrict their masses to be between 300 and 600 GeV, and the dark

matter's mass may be anywhere below $m_{T'}$. We simulated the signal and main backgrounds with MadGraph/MadEvent-Pythia-PGS4. For the Tevatron, we found that an integrated luminosity of 20 fb^{-1} will allow 3σ discovery up to $m_{T'} = 400$ GeV and 95% exclusion up to $m_{T'} = 455$ GeV. For the 10 TeV LHC with 300 pb^{-1}, the discovery and exclusion sensitivities rise to 490 GeV and 600 GeV. These scenarios are therefore among the most promising for dark matter at colliders. Perhaps most interestingly, we found that dark matter models that can explain results from the DAMA, CDMS and CoGeNT Collaborations can be tested with high statistical significance using data already collected at the Tevatron and have extraordinarily promising implications for early runs of the LHC. Motivated by our study, both CDF and ATLAS[1] performed their analyses on final states of $t\bar{t} + \not{E}_T$ and obtained current best limits on the mass of heavy top quark T'.

We also explored the discovery prospects for $B'\bar{B}'$ pair production followed by direct decays $B' \to bX$, where B' is a new quark and X is a long-lived neutral particle. We develop optimized cuts in the $(m_{B'}, m_X)$ plane and show that the 7 TeV LHC with an integrated luminosity of $1\ (10)\ \mathrm{fb}^{-1}$ may exclude masses up to $m_{B'} \sim 620\ (800)$ GeV, completely covering the mass range allowed for new quarks that get mass from electroweak symmetry breaking. This analysis is applicable to other models with $b\bar{b}+ \not{E}_T$ signals, including supersymmetric models with bottom squarks decaying directly to neutralinos, and models with exotic quarks decaying directly to GeV-scale dark matter. To accommodate these and other interpretations, we also present model-independent results for the $b\bar{b} + \not{E}_T$ cross section required for exclusion and discovery.

Distinguishing dynamical dark matter at the LHC (publication 10)
Dynamical dark matter (DDM) is a new framework for dark-matter physics in which the dark sector comprises an ensemble of individual component fields which collectively conspire to act in ways that transcend those normally associated with dark matter. Because of its non-trivial structure, this DDM ensemble $-$ unlike most traditional dark matter candidates $-$ cannot be characterized in terms of a single mass, decay width, or set of scattering cross-sections, but must instead be described by parameters which describe the collective behavior of its constituents. Likewise, the components of such an ensemble need not be stable so long as lifetimes are balanced against cosmological abundances across the ensemble as a whole. With my collaborators K. Dienes and B. Thomas, we investigated the prospects for identifying a DDM ensemble at the LHC and for distinguishing such a dark matter candidate from the candidates characteristic of traditional single particle dark matter models. In particular, we focus on DDM scenarios in which the component fields of the ensemble are produced at colliders alongside some number of SM particles via the decays of additional heavy fields. The invariant-mass distributions of these SM particles turn out to possess several unique features that cannot be replicated in most traditional dark matter models. We demonstrate that in many situations it is possible to differentiate between a DDM ensemble and a traditional dark matter candidate on the basis of such distributions. Moreover, many of our results also apply more generally to a variety of other extensions of the SM which involve multiple stable or metastable neutral particles.

Early LHC discovery and simplified model approach

Many existing LHC searches are model-dependent and often optimized for specific parameterizations of models. The CMS and ATLAS collaborations have formulated a request to the theory community to expand the scope of their new physics searches. I attended the Workshop on *Topologies for Early LHC Searches*, which was held at SLAC in September, 2010. In that workshop, we discussed simplified model approach to possible early LHC discovery signals. A simplified model is characterized

by a short list of new particles together with a minimal Lagrangian that allows one to calculate the production and decay modes. While simplified models are not model independent, having a broad class of simplified models greatly reduces the adverse effects of model dependence. I was involved in the working group of lepton signatures and the working group of resonance signatures. With A. Freitas, we worked on $\tau^+\tau^-$ resonance. With V. Rentala, we worked on same sign dilepton resonance, as well as $W^\pm W^\pm$ resonance. Our work was combined with contributions from other working group members and was presented in the working group report arXiv:1105.2838 (publication 6).

A simplified model approach to same-sign dilepton resonances (publication 5)
With student W. Shepherd and postdoc V. Rentala, we discussed same-sign dilepton resonances in the simplified model approach. The relevant $\mathrm{SU}(3)_Q^J$ quantum numbers are $\mathbf{1}_2^{0,1,2}$. For simplicity, we only considered a spin 0 scalar, which is typically referred to as a doubly charged Higgs in the literature. We considered the three simplest cases where the doubly charged Higgs resides in a singlet, doublet or triplet $\mathrm{SU}(2)_L$ representation. We discussed production and decay of such a doubly charged Higgs, summarized the current direct search limits, and obtained mass limits in the cases of singlet and doublet for the first time. We also presented a complete set of updated indirect search limits. We studied the discovery potential at the LHC with center of mass energies 7 and 14 TeV for the dominant Drell-Yan pair production with $H^{\pm\pm}$ decay in ee and $\mu\mu$ channels. We found that at 7 TeV, the LHC with 10 fb^{-1} luminosity can probe mass of the doubly charged Higgs up to 380 GeV assuming 100% decay to leptons. At 14 TeV, the LHC with 100 fb^{-1} luminosity can reach a mass of up to 800 GeV.

Direct search for new physics at the LHC

Sbottom signature of supersymmetric golden region (publication 4)
With Z. Si and graduate students H. Li and W. Parker, we studied sbottom signature of supersymmetric golden region. The experimental search limit on the Higgs boson mass points to a "golden region" in the MSSM parameter space in which the fine-tuning in the electroweak sector is minimized. One of the sbottoms is relatively light since its mass parameter is related to that of the stop. The decay products of the light sbottom typically include a W boson and a b jet. We studied the pair production of the light sbottoms at the LHC and examined its discovery potential via collider signature of 4 jets + 1 lepton + $\not{E}_T$. We analyzed the SM backgrounds for this channel and developed a set of cuts to identify the signal and suppress the backgrounds. We showed that with 100 fb^{-1} integrated luminosity, a significant level of 5σ could be reached for the light sbottom discovery at the LHC.

$M_{\ell\ell}$ **triangle in cascade decay** (publication 8)
The LHC studies on the slepton sector have mostly been focused on the direct slepton Drell-Yan pair production. With students J. Eckel and W. Shepherd, we analyzed the case when the left-handed sleptons are lighter than winos and can appear in the on-shell decay of those particles. The invariant mass of the lepton pairs, $M_{\ell\ell}$, from the neutralino decay has a distinctive triangle shape with a sharp cutoff. We discussed the utilization of the triangle shape in $M_{\ell\ell}$ distribution to identify the slepton signal. We studied the trilepton signal and obtained the $\sigma \times \mathrm{BR} \times \mathrm{acceptance}$ that is needed for a 5 σ discovery as a function of the cutoff mass for the LHC with center of mass energy 14 TeV and 100 fb^{-1} integrated luminosity. Our results are model independent such that they could be applied to other models with similar decay topology. When applied to the MSSM, it is found that with 30 (100) fb^{-1} integrated luminosity, a reach in the left-handed slepton mass of about 500 (600) GeV could be reached, which extends far beyond the slepton mass reach in the usual Drell-Yan study.

Searching for charginos and neutralinos at the LHC (work in progress)
Given the current results on searches for supersymmetric particles at the LHC, the absence of the spectacular events of large hadronic activities plus substantial missing energy implies that new colored supersymmetric particles may not have been copiously produced. In anticipation of much heavier colored supersymmetric partners, we are thus led to consider a less ambitious search strategy, namely the SUSY signals only from the electroweak sector, the charginos and neutralinos. On the other hand, the direct production of electroweak supersymmetric particles at the LHC suffers from relatively small rates. With T. Han and S. Padhi, we explore these scenarios in some detail. We address the question that to what extent in the parameter space, the SUSY signals are observable at the LHC. In particular, we do wish to take advantage of the existence of a 125 GeV Higgs boson (h) in the hope of seeking for signals from $h \to b\bar{b}, WW^*$. The answer to this question is important not only for the current LHC experiments, but also for the planning of future collider programs.

Collider signatures of the inert doublet model at the LHC (publications 1 and 3)
With students E. Dolle, X. Miao and previous postdoc B. Thomas, we examined the prospects for detecting the additional fields of the inert doublet model at the LHC in the dilepton channel. We investigated a wide variety of theoretically- and phenomenologically-motivated benchmark scenarios, and showed that within regions of model parameter space in which the dark-matter candidate is relatively light (between 40 and 80 GeV) and the mass splitting between the neutral scalars is also roughly $40 - 80$ GeV, a signal at the 3 σ to 12 σ significance level can be observed with 100 fb^{-1} of integrated luminosity. In addition, even if the mass splitting between the neutral scalars is larger than m_Z, a signal of more than 3 σ can be observed as long as the mass of the dark matter candidate is around 40 GeV. We also investigated the prospects for detecting the inert doublet model via the trilepton channel at the LHC. Our studies showed that in some of these scenarios, it is possible to obtain a signal at the 5 σ significance level or better with integrated luminosity of 300 fb^{-1}.

Indirect searches for new physics beyond the SM

The weak neutral current (publication 12)
With my collaborator J. Erler, we wrote a review article on electroweak precision physics with particular emphasis on low-energy precision measurements in the neutral current sector of the electroweak theory and includes future experimental prospects and the theoretical challenges one faces to interpret these observables. Within the minimal Standard Model they serve as determinations of the weak mixing angle which are competitive with and complementary to those obtained near the Z-resonance. In the context of new physics beyond the Standard Model these measurements are crucial to discriminate between models and to reduce the allowed parameter space within a given model. We illustrate this for the minimal supersymmetric Standard Model with or without R-parity.

DOUG TOUSSAINT

Doug Toussaint does research in lattice gauge theory, computing properties of strongly interacting particles and strongly interacting matter in extreme conditions. This work is done in the MILC collaboration, consisting of fourteen physicists at nine institutions. Also, Toussaint is part of a joint MILC-Fermilab collaboration to study heavy-light meson physics. Finally, Toussaint is a member of the HotQCD collaboration, which is doing lattice calculations of the phase diagram and equation of state of high temperature QCD. These collaborations are part of the lattice gauge theory component of the USQCD program.

Generation of lattices with highly improved actions

We are generating ensembles of lattices with the "highly improved staggered quark" (HISQ) action invented by the HPQCD collaboration. These lattices include the effects of four dynamical flavors: up, down, strange and charm, and include ensembles with light quark mass equal to the physical value. These lattices also have larger physical volume than our previous generation of simulations, which used the Asqtad quark action. We found that lattice artifacts for the HISQ action are reduced by approximately a factor of 2.5 from those of the asqtad action for the same lattice spacing, and taste splittings in the pion masses are reduced by approximately a factor of three [2], which is sufficient to enable us to undertake simulations with the mass of the Goldstone pion at or near the physical pion mass. Moreover, the improvement in the quark dispersion relation enables us to include charm sea quarks in the simulations. Given the successes of the HISQ action, we began a project to generate ensembles of gauge configurations using it along with a one-loop Symanzik improved gauge action [3]. We are working at four different lattices spacings, $a \approx 0.06$, 0.09, 0.12 and 0.15 fm, in order to control extrapolations to the continuum limit. (We plan to begin the generation of an ensemble with $a \approx 0.045$ fm and $m_l = m_s/5$ in the coming year). We include up, down, strange and charm sea quarks. We are generating configurations with three values of the light quark mass: $m_l = m_s/5$, $m_s/10$, and the value such that the Goldstone pion mass is as close as possible to the physical pion mass, which is approximately $m_s/27$. We have also generated three ensembles with $a \approx 0.12$ fm and $m_l = m_s/10$ that differ only in their spatial volumes to test finite size effects, and we have generated ensembles with the strange quark mass lighter than its physical value, because such ensembles have proven very useful in controlling chiral extrapolations of physical quantities.

During the past year we have completed the two ensembles with physical light quark mass $m_l = m_s/27$ and lattice spacings $a \approx 0.15$ and 0.12 fm, the $m_l = m_s/5$, $a \approx 0.06$ fm ensemble, and the $m_l = m_s/10$, $a \approx 0.12$ fm ensemble with a large spatial volume $40^3 \times 64$. We have also made progress on the $m_l = m_s/27$, $a \approx 0.09$ fm, and $m_l = m_s/10$, $a \approx 0.06$ fm ensembles. The $m_l = m_s/27$, $a \approx 0.06$ fm ensemble, which we expect to play a critical role in continuum extrapolations, has been equilibrated, and 560 configurations generated. Another physical quark mass ensemble with a lattice spacing of about 0.04 fm is being equilibrated. This ensemble exceeds the capability of current resources, but it is important to equilibrate a lattice for it so that we will be ready to begin production work on new machines as they become available.

Toussaint is responsible for running the generation of several of these ensembles, including the $a = 0.06$ fm physical quark mass ensemble, and has primary responsibility for dharacterizing and archiving these lattices for the subsequent analysis runs.

Physics of heavy-light mesons

The MILC and Fermilab lattice collaborations have been working together for some time to study the physics of heavy-light mesons, particles containing one light and one heavy quark. The goals of this activity are to calculate the QCD effects that can be used determine the parameters of the

standard model of high energy physics. The spectrum of heavy-light particles can be used to determine the charm and bottom quark masses. The leptonic decay constants and semi-leptonic form factors that describe the weak decays of heavy-light mesons, and the bag parameters that characterize the mixing between neutral B and B_s mesons with their anti-particles, can be used extract the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements from the experimental observations.

Over the past four years we have carried out measurements of the above quantities on our asqtad gauge configurations, studying a wide variety heavy-light decays and mixings. Recently completed projects include calculations of the leptonic decay constants in the D and B meson systems using asqtad light quarks and Fermilab heavy quarks [4], calculation of the SU(3) violating ratio of the form factor f_0 in the semileptonic decays $\bar{B}^0 \to D^+\ell^-\bar{\nu}$ and $\bar{B}^0_s \to D^+_s\ell^-\bar{\nu}$ [6], and a study of neutral B mixing, and in particular a determination of the quantity $\xi \equiv f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}}$ that governs the standard model ratio of the mass differences $\Delta M_{s(d)}$ in the B_s and B_d channels[10].

Last summer the BaBar Collaboration released the first measurement of the exclusive semi-leptonic decay $B \to D\tau^-\bar{\nu}$, finding $R(D) \equiv \mathrm{BR}(B \to D\tau\nu)/\mathrm{BR}(B \to D\ell\nu) = 0.440(58)(42)$ [8], which is about two standard deviations away from previous theoretical expectations. Using lattice matrix elements already computed for other projects, we were able to evaluate the combination of form factors relevant to this decay, resulting in the first calculation in full QCD of the branching ratio $R(D)$ [9]. We find $R(D) = 0.316(12)(7)$, where the errors are statistical and total systematic, respectively. This result is slightly closer to the experimental result, about 1.7 standard deviations away, but still in some tension with the standard model.

In addition to the improved versions of the calculations of leptonic decay constants and mixing matrix elements, we are well along on a wide range of calculations of semileptonic heavy-light meson decays. Examples include form factors for $B \to K\ell\ell$ and $B \to K\gamma$ [12], for $B \to D\ell\nu$ at nonzero recoil [13], for $B \to D^*\ell\nu$ [14], and for $D \to K$ and $D \to \pi$ [15]. The $B \to K$ project will aid the search for new physics in these rare decays, while the $B \to D$ and $B \to D^*$ projects will improve the determination of the key CKM matrix element V_{cb}, as well as providing reduced errors for the $f_0^{(s)}/f_0^{(d)}$ calculation discussed above.

Toussaint is involved in the data fitting for the heavy-light decay constants with the Asqtad sea quarks and Wilson/Fermilab heavy quarks, and in the parameter tuning for the new generation projects using the HISQ ensembles.

Meson physics with HISQ quarks

We continue to measure the properties of light pseudoscalar mesons on the HISQ gauge configurations as they are generated. The new feature of these calculations is that they include charm quarks on the same footing as up, down and strange ones. As a result, we obtain high precision results for the masses and leptonic decay constants of the D and D_s mesons, as well as for the π and K mesons, and the up, down, strange and charm quark masses and their ratios. In addition to the phenomenologically important leptonic decay constants, these calculations provide precise determinations of the lattice spacing and quark masses.

The decay $K \to \pi\ell\nu$ provides an alternative approach to f_K/f_π for extracting the CKM element V_{us}. We are well along in the calculation of the needed form factor $f_+(q^2 = 0)$ [16]. We use twisted boundary conditions to adjust the meson momenta to the point where the four-momentum transfer q satisfies $q^2 = 0$. In the first phase of the project, which is nearly complete, we have employed asqtad ensembles, but with the HISQ valence quarks to reduce discretization effects. The second phase uses the HISQ ensembles, as well as HISQ valence quarks, and is in an early stage of development, with two HISQ ensembles at $a \approx 0.12$ fm partially completed.

Toussaint takes the lead role in the computations of charmed meson masses and decay constants in this project, and is setting up the software for the 0.06 fm physical quark mass ensemble.

Strange and charm content of the nucleon

Toussaint and Freeman have used the archived MILC lattices to compute the strangeness content of the nucleon[17, 18], $\langle N|\bar{s}s|N\rangle$. This is important to searches for dark matter, since some of the leading candidates for dark matter couple to the nucleon through Higgs particle interactions with the strange quark loops. Previous lattice studies of this quantity gave wildly varying results[19]. Using correlations of stochastic estimates of $\bar{s}s$ with the archives of nucleon correlators, we get good statistical errors on this quantity. We include study of the extrapolation to the physical light quark masses and to the continuum limit, leading to the result $\langle N|\bar{s}s|N\rangle = 0.69 \pm 0.07_{\text{statistical}} \pm 0.09_{\text{systematic}}$, in the $\overline{ms}(2\ GeV)$ regularization. Since this original paper we have used improved techniques to get more accurate measurements from the Asqtad lattices, and have also done these calculations on some of the new HISQ action lattice ensembles.[20, 18]. The main result of our work, and of a number of other works which have appeared in the same time frame, is that a previously claimed large enhancement of the strange quark content does not exist, so that scattering off of strange quark pairs in the nucleon does not dominate the scattering of dark matter through higgs exchange. Instead, the contribution of the strange quark is of similar size to the contributions of each of the other flavors.

QCD at high temperature and density

The MILC collaboration has extended its study of QCD thermodynamics with four flavors of HISQ quarks. The calculation of the equation of state requires that we generate both high temperature and zero-temperature gauge configurations along a line of constant physics (LCP), which in the first phase of this work we take to be $m_l = m_s/5$. We have generated the ensembles for this project, and presented preliminary result for the equation of state at the Lattice 12 conference.

The HotQCD Collaboration, of which we are members, is studying the equation of state and other thermodynamic properties with three flavors of HISQ quarks. WE have completed calculations of the transition temperature T_C [22] and of the fluctuations of various conserved charges [23]. Both quantities are of considerable phenomenological interest for modeling the quark-gluon plasma created in heavy-ion collisions.

Toussaint is involved in generating and maintaining lattices for this project, and in the calculations of the quark masses and lattice spacings needed to determine the parameters.

Measuring the length scales and quark masses

Since lattice calculations necessarily produce results in units of the lattice spacing, every calculation we do depends on knowing this spacing. This is done by calculating some quantity which can be determined accurately on the lattice and is accurately known experimentally. We are using two such quantities, r_1 obtained from the static quark potential, and f_{p4s}, obtained from the decay constant of a meson with unphysical quark masses.

Toussaint takes the lead role in calculating and analyzing these quantities in both the Asqtad and HISQ action lattice programs.

Isospin breaking and electromagnetic effects

The difference in masses of the up and down quark and the electromagnetic interactions have roughly equal effects on strong interaction quantities, and some of our lattice calculations are reaching the level of accuracy where these effects must be considered. The up-down quark mass difference can be determined from our pseudoscalar meson analysis, by finding the change in light quark mass needed to match the experimental $K_0 - K^+$ mass difference. However, the K masses must first

be adjusted for electromagnetic effects. A subset of the MILC collaboration has been computing these effects by adding a quenched electromagnetic gauge field to the QCD fields in our ensembles. This gave preliminary results for the correction to Dashen's theorem reported at at Lattice 2012. : $\Delta_{EM} = 0.65(17)$ where the error is purely statistical. This result can be combined with the HISQ pseudoscalar analysis to find the light quark mass difference. At the Lattice2012 conference we reported the result $m_u/m_d = 0.508(10)(22)$, a significant improvement on our previous results.

Toussaint is responsible for the calculations of meson masses and amplitudes needed here, in particular the dependence of these masses on the mass of the light quark in the meson.

Code development for new machines

The new machines being used for lattice gauge calculations require developments of specialized codes. In particular, many groups including us are using clusters of GPU's, or graphics cards, for these calculations. Several of the applications in the MILC code suite have been ported to GPU clusters and some production running is being done there. The porting of the HISQ lattice generation is nearly complete. Also, the development of processors that include many (maybe even hundreds) or cores is a challenge for these simulations. For many-core processors it is expected that a hybrid programming model using MPI for internode communication and OpenMP for communication among the cores within a node (or a subset of these cores) will eventually become preferable. We are developing MPI/OpenMP variants of some of our most computationally intensive routines to see whether (or when) these become more efficient than the existing MPI codes.

Toussaint did the OpenMP/MPI code port for the staggered sparse matrix inversion routines, which are the most important part of the staggered fermion applications, and tested them on the Cray XE6 at NERSC (hopper).

Algorithm studies for large simulations

Our collaboration continues to investigate better algorithms both for our lattice generation and for the subsequent analysis codes. These analysis codes are dominated by the sparse matrix inversion algorithms which, for staggered quarks, are variations of the conjugate gradient algorithm. We have developed, tested, and put into production modifications of the conjugate gradient that use fewer global reductions, and modifications that do a preliminary inversion in single precision with later refining in double precision. For the lattice generation steps, we have done some testing of using different numbers of pseudofermion fields and different masses for the "regulator fields".

INDIVIDUAL PROJECT REPORTS

TASK B: EXPERIMENT

Professory Elliott Cheu, Kenneth Johns, John Rutherfoord, Michael Shupe, and Erich Varnes

The experimentalists supported by this task are playing key roles in the ATLAS experiment at CERN's Large Hadron Collider and on the D0 experiment at Fermilab's Tevatron. Accomplishments during the last renewal period of this grant are described in the following pages. The postdocs and graduate students who worked with the group are named and their efforts described.

ELLIOTT CHEU
Beyond the Standard Model Physics at ATLAS

The group of Elliott Cheu, Prolay Mal, Caleb Lampen and Matt Leone concentrated on Beyond the Standard Model (BSM) physics analyses and on the ATLAS Cathode Strip Chambers (CSC). With the onset of large data sets, the group was active in a number of important analyses while performing critical service work. In particular, we performed the first analysis of charged Higgs to chargino neutralino decays. We played key roles in light charged Higgs decays and searches for SUSY using multilepton decay channels. Leone worked jointly with this group and the UA top group on final states containing $t\bar{t}$ pairs. For our service work, we made significant contributions to the performance of the CSCs in the area of alignment and data quality.

Physics Analyses

Our group led the effort to search for a charged Higgs boson decaying to a chargino and a neutralino. We played an active role in the related decay of a light charged Higgs boson to a tau and a neutrino, and on multilepton SUSY searches. At the end of the grant period, we joined efforts with Johns' group on $t\bar{t}$ final states.

Charged Higgs to Chargino + Neutralino (C. Lampen and E. Cheu)

The decay of a charged Higgs to a chargino plus neutralino final state accesses a region of SUSY parameter space in the $\tan\beta$ /m_{H+} plane that is inaccessible to charged Higgs decays to Standard Model particles. This region is referred to as the LHC wedge area. The signature for this decay channel is three leptons, large missing transverse energy, and three hard jets. Our study of the charged Higgs decays involved collaboration between the Higgs and SUSY working groups at ATLAS.

One did not expect to observe this charged Higgs decay with early data, as its cross section is only ~5-10 fb in our region of phase space. Nevertheless, because this decay probes a region of parameter space inaccessible to other charged Higgs searches, we chose to search for evidence of this decay. This effort was pursued in conjunction with the multilepton SUSY physics group at ATLAS, since the topologies are very similar and we could share analysis flows and background studies (see below). From our analysis, we were able to set the first ATLAS limit on this channel using the early 2010 ATLAS dataset. This limit was documented as part of an ATLAS internal note on SUSY multilepton studies in March 2011, [1].

Multilepton SUSY Searches (C. Lampen and E. Cheu)

While pursuing the charged Higgs study above, Lampen and Cheu also joined the multilepton group's SUSY search using a decay channel consisting of a minimum of three leptons, missing transverse energy, and jets. There is very little Standard Model contamination in this channel, the primary backgrounds being Z+jets or $t\bar{t}$ decays with a faked third lepton.

Participating in an ATLAS study using 34 pb^{-1}, Lampen assisted in validating systematics studies for the ATLAS multilepton SUSY group. These were subsequently used to provide new limits

on SUSY parameter space from [2], competitive with the Tevatron results at the time. After analysis of the early ATLAS data, we increased our participation in the SUSY multilepton group. In the resulting analysis we utilized simplified models that highlight the salient features of a three lepton signal from direct weak production. Such models allowed for associated production of the lightest chargino and second-lightest neutralino, in which both are wino-like, and the lightest neutralino is the LSP.

We were responsible for the electron trigger studies for the analysis and in the data driven background estimation, focusing on electron fake rates. We also had significant participation in cross-validation of the analysis. The analysis utilized an integrated luminosity of approximately 2 fb^{-1} and showed significant improvement upon the previous limits on direct chargino and neutralino production, [3]. These results were published in 2012, [4]. Results of this analysis are shown in Figure 2-1, which indicates improved lower bounds on the neutralino and chargino masses. Lampen used the results of this analysis as the basis of his Ph.D. thesis. He implemented a multivariate analysis of the multilepton final state, and graduated in December 2013.

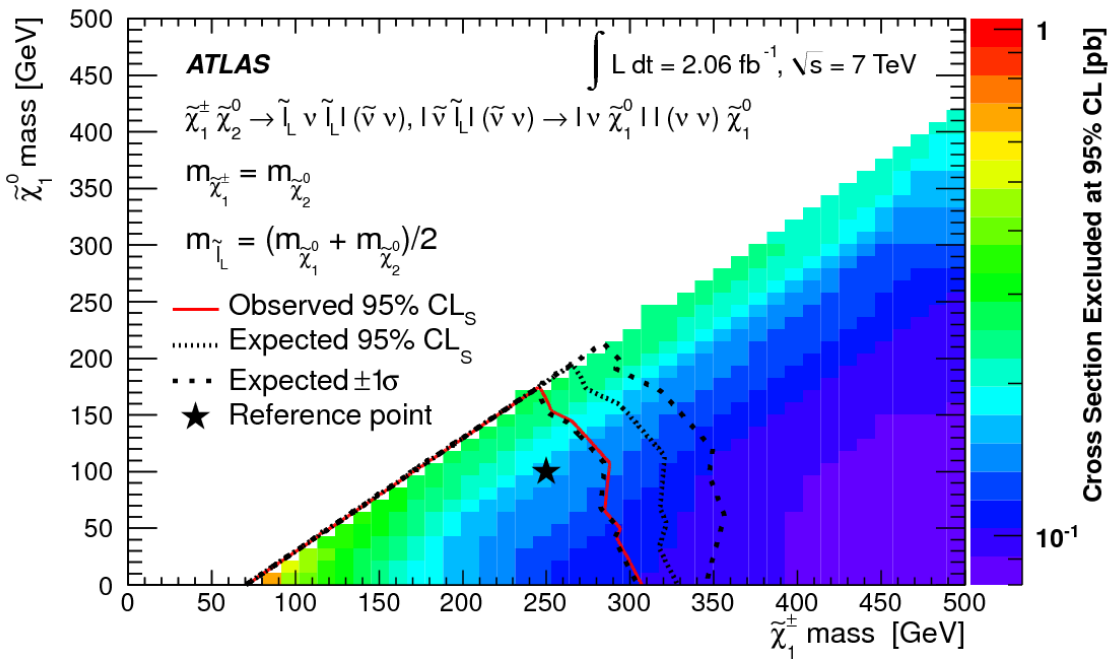

Figure 2-1: Observed and expected 95% CL limit contours for direct chargino and neutralino production in simplified model scenarios. For simplified models, the 95% CL upper limit on the production cross-section is also shown.

Light Charged Higgs Decays (P. Mal and E. Cheu)

In the Minimal Supersymmetric extension of the Standard Model (MSSM), the predicted charged Higgs boson ($H^{\pm}$) can be lighter than the top quark. In such a scenario ($m_{H+}<m_{top}$), the top quark can decay through a light charged Higgs boson ($t\rightarrow H^{+}\, b$) with non-zero branching ratio. The decay of charged Higgs bosons is dependent on the value of tanβ. For tanβ>1, the $t\bar{t}$ events can decay through a charged Higgs boson to produce a dilepton final state: $t\bar{t}\rightarrow H^{+}bW^{-}$ $bbar \rightarrow \tau\, \nu_{\tau}\, b\, l\, \nu_{l}$ $bbar\rightarrow l\, \nu_{l}$ $\nu_{\tau}\, \nu_{\tau}\, b\, l\, \nu_{l}$ $bbar$ (where $l=e$, mu).

The preliminary ATLAS sensitivity studies assuming 200 pb^{-1} pp collision data at $\sqrt{s}$ =10 TeV, indicated a $t \rightarrow H^{+}b$ branching ratio exclusion up to 10% at 95% CL. We played a major role in scaling these sensitivity results for 1 fb^{-1} pp data at $\sqrt{s}$ =7 TeV, which has similar sensitivity in terms of BR($t \rightarrow H^{+}b$) exclusion limits [5]. With data collected in 2010, we provided [6] a good comparison for the variables useful for the light charged Higgs searches. In 2012 we contributed to the background estimates from leptons as well as other systematic studies using 1 fb^{-1} of 2011 data **"** [7], [8]**.** We were able to exclude the branching ratio of $t \rightarrow H^{+}b$ to below approximately 10% over the mass range from 90-160 GeV/c^2. For certain regions of phase space, we also excluded values of tanβ larger than 30–56 for charged Higgs masses between 90-140 GeV/c^2.

Top Physics (M. Leone, E. Cheu in conjunction with the Johns Group)

In many BSM models, heavy resonances are produced that couple to top quarks. Such resonances include topcolor *Z'* bosons and Kaluza-Klein gluons. At higher masses, these massive particles will produce "boosted tops" whose decay products will be highly collimated. Leone concentrated on studies to improve sensitivity to such boosted top decays in the lepton plus jets final states.

As a result of these studies, we:

- Addressed problems with electron isolation requirements in the boosted regime.
- Reduced leptonic top-hadronic top confusion by reconstructing the leptonic top first.
- Increased *Z'* and *KK* gluon acceptance by requiring DPhi(hadtop,leptop)>2.9.
- Suggested ways to improve the triggering on boosted events by utilizing the fatjet trigger.
- Optimized the use of fatjets to reconstruct the leptonic top and study fatjet reconstruction.
- Recommended the use of b-tagging in the boosted top semileptonic study.

These results were incorporated into an ATLAS note [9] on the search for $t\bar{t}$ resonances from the 2011 data set.

In 2012 Leone and Cheu began conducting an analysis of vector-like quarks (VLQs) within the ATLAS exotics collaboration. High mass VLQs are predicted in many BSM models (for example, SUSY, Compositeness and Extra Dimensions), and have only recently become accessible to searches at the LHC. Vector-like top quarks are predicted to decay through the channels W+b, Z+t, and H+t. With the high center-of-mass energy and luminosity of the LHC, pair production of VLTs is the favored signal for discovery. Early searches for pair production of VLTs at the LHC examined the TT->Wb+Wb and TT->Zt+Zt channels, but were done at only 1 fb^{-1} and assumed 100% branching ratios. Our contributions allowed for the investigation of realistic branching ratios, and the simultaneous study of several models predicting VLTs.

Each of the three VLT decay paths (Zt, Wb, ht) provides an interesting signature, but the Zt path provides a distinctive Z-tag accompanied by top decay products, which will allow superior detection above background noise. Thus for pair production of the VLTs, the channel TT->Zt+X where X={Zt, Wb, or ht} was focus of our investigations.

Cathode Strip Chambers

Alignment (P. Mal and E. Cheu)

The Cathode Strip Chambers (CSC) are some of the more important components in the ATLAS Endcap Muon system as they provide 2D position measurements for the muon trajectories before deflection by the toroidal magnetic field. The alignment of these detectors has been particularly challenging due to the large amount of multiple scattering, and the curvature of tracks in the toroidal magnet field.

Our group took a leadership role in providing track-based alignment constants for the CSC detectors using a global χ^2 minimization. Using this technique on a small sample of the collision data, we first demonstrated that the track-based alignment for the CSC detectors had the potential to provide alignment constants with better precision than those obtained from the optical alignment system. In 2010 ATLAS recorded approximately 10 pb^{-1} of data, with the toroidal magnetic field switched off. In this configuration the muons have straight line trajectories except for multiple scattering effects in the muon system. To quantify the alignment for such straight line tracks in the muon system, a convenient observable called "sagitta" was chosen. Our group performed the track-based alignment for the CSC detectors using the standard tracking software, which provided a good crosscheck to the results obtained through using standalone tracking software. The results provided by our group have slightly worse precision mostly due to the differences in tracking algorithms. However, the results from our group are particularly important as they provide a direct cross check using "in-situ" tracking software used globally in ATLAS. In addition, the data quality group will use our software to track the alignment precision over time.

CSC Conditions Database (C. Lampen, M. Leone and E. Cheu)

Our group developed the database that stores the conditions data for the CSC system. This conditions data includes calibration constants and status flags (dead, noisy, etc) for each channel. Lampen was the primary person in the ATLAS collaboration responsible for the CSC conditions database. He developed the database schema, and also wrote the I/O interface wrapper used during reconstruction. The wrapper intelligently caches data for rapid access, and shields the user from the complex inner database format.

Our group was responsible for revisions to the code to maintain compatibility with the latest ATLAS software. We oversaw several large database updates, as well as small, routine updates. Lampen rigorously validated the stored data and monitored the long-term behavior of the CSC chambers. As Lampen was nearing graduation, Leone assumed this key role. In addition to maintenance of the current database, Leone expanded the functionality of the database software to provide timing information, requiring a new internal storage strategy, and developed improved long-term CSC monitoring software.

Calibration (C. Lampen, M. Leone and E. Cheu)

Between ATLAS data runs, a calibration is run on the CSCs which measure the noise, pedestal levels, and thresholds for the chambers. Lampen was the author of the code to do this, and had

been responsible for its continued maintenance. In 2012 Leone assumed this role for the UA. In 2012 he and Lampen oversaw the day-to-day calibration runs. They have also worked together to update the code to be compatible with the latest ATLAS software.

KENNETH JOHNS
Search for Beyond the Standard Model Physics using Top Quarks, DQ Assessment and Phase 1 Upgrades at ATLAS

Summary of Personnel and Progress

This report summarizes the project accomplishments by the Johns group during the last three year grant period. The Johns group currently consists of faculty Kenneth Johns and graduate students Sarah Jones, Fionnbarr O'Grady and Jason Veatch.

Johns supervised the first ATLAS Ph.D. student at the University of Arizona (UA). Under his supervision, graduate student Xiaowen Lei successfully defended her Ph.D. thesis on "Measurement of the $t\bar{t}$ Production Cross Section Using the Semileptonic Final States in Proton-Proton Collisions at Center of Mass Energy = 7 TeV with 35.3 pb^{-1} of ATLAS Data" in May 2011. O'Grady and Veatch are pursuing new physics searches related to top quarks as described below using the full 2012 data set of 20 fb^{-1} at 8 TeV center of mass energy. Sarah Jones is working on developing front-end electronics for Micromegas detectors.

During the last three year grant period we also had substantial support from postdoc Venkat Kaushik. Kaushik is now a software engineer at Unitrends, a company specializing in unified data protection. Development of electronics and firmware is supported by electrical engineers Bill Hart and Dan Tompkins and software engineer Charlie Armijo.

Our group's top priority during the last year was ATLAS physics. We contributed to a variety of analysis tasks, often leading them, for several physics analyses that have resulted in publications. These publications are listed in the Appendix and referenced in this report. Our main results are on searches for $t\bar{t}$ resonances predicted by several Beyond the Standard Model (BSM) theories. We set ever more stringent mass limits on $t\bar{t}$ resonance production predicted in two benchmark models using 0.2 fb^{-1}, 2 fb^{-1} and 5 fb^{-1} of data at 7 TeV and 14.3 fb^{-1} of data at 8 TeV. Additionally we contributed to the measurements of the $t\bar{t}$ differential cross sections and the $t\bar{t}$ production cross section using 2 fb^{-1} and 35 pb^{-1} of data respectively collected at 7 TeV. More recently, we set mass limits on the production of isospin singlet vector-like B and T quarks using 14.3 fb^{-1} of 8 TeV data.

In running the ATLAS experiment, our group successfully completed responsibilities described below for DQA (Data Quality Assessment) of the CSC (Cathode Strip Chamber) detector and HLT (High Level Trigger) Jet and MET (Missing Et) slices. The Phase 1 ATLAS detector upgrades are intended to keep pace with the expected doubling of the nominal luminosity of the LHC after 2018. We are developing electronics and firmware for two Phase 1 ATLAS upgrade projects. We are designing and testing the front-end electronics to be used with Micromegas detectors for the New Small Wheel of the Muon Spectrometer. We are also developing firmware for the LAr Digital Processing Blade that is an integral part of the L1 Calorimeter Trigger upgrade. This challenging work is described below.

Beyond the Standard Model (BSM) Physics using Top Quarks

Our strategy for ATLAS physics was to make the first measurement of the $t\bar{t}$ production cross section at 7 TeV and then to proceed to search for BSM physics using top quarks. We

successfully followed this strategy. New physics using top quarks is interesting because of the top quark's heavy mass and because a number of BSM models predict new particles that decay into high mass $t\bar{t}$ states or predominantly into third generation quarks.

Our first analysis was the measurement of the $t\bar{t}$ production cross section using 35 pb^{-1} of data at 7 TeV in the leptons plus jets channel. This work became the Ph.D. thesis of Lei. In order to separate the $t\bar{t}$ signal from the W plus jets background, a top likelihood discriminant using kinematic and event shape variables was constructed. The $t\bar{t}$ cross section was then extracted via a binned maximum likelihood fit to the top likelihood distribution using templates for signal and background. All backgrounds were evaluated using Monte Carlo simulation, except for QCD multijets, which was estimated using the data-driven matrix method. The first measurement of the $t\bar{t}$ production cross section was published in Physics Letters B [10]. We made strong contributions to this publication by participating in cut flow validation challenges, producing expected signal and background yields, optimizing variables for the top likelihood discriminant and evaluating many sources of systematic errors including the uncertainties associated with the jet energy scale, initial and final state radiation and pileup.

We (Johns, Kaushik) next began work on searches for $t\bar{t}$ resonances using the lepton plus jets decay channel. Two particular models serve as benchmarks since there are associated Monte Carlo generators and cross section predictions. These are a leptophobic topcolor Z' boson [11] and a Kaluza-Klein (KK) gluon that is found in Randall-Sundrum models [12]. We made a variety of contributions to a wide range of analysis tasks in $t\bar{t}$ resonance searches using 0.2 fb^{-1}, 2 fb^{-1} and 5 fb^{-1} of 7 TeV data and 14.3 fb^{-1} of data at 8 TeV. Beginning with the 2 fb^{-1} analysis, we utilized both resolved and boosted $t\bar{t}$ reconstruction techniques. In the resolved analysis, the hadronically decaying top is reconstructed using two or three small radius (R=0.4) anti-kt jets, whereas in the boosted analysis, the hadronically decaying top is reconstructed as a large radius (R=1.0) anti-kt jet with substructure. Such large radius jets are expected for larger values of $m(t\bar{t})$ because of the boost received by the energetic top quarks.

One of our (Johns, Kaushik) contributions to the 200 fb^{-1} search was participation in cut flow validation challenges. This involves ensuring the correct object definitions are used, the correct scale factors adjusting Monte Carlo to data are employed, the correct pile-up reweighting is applied and the correct procedures for determining systematic errors are adopted. In addition, we (Kaushik) pushed the use of a kinematic fitter called KLFitter to reconstruct the $t\bar{t}$ invariant mass. While we did not develop KLFitter (from Erdmann *et al.* at the University of Gottingen) [13] we helped validate its reconstruction algorithm and provided several bug-fixes in the core software and user interface. The results were summarized in a Conference Note [14] rather than a paper because of the steadily increasing integrated luminosity available for analysis.

We (Johns, Kaushik) made substantially more contributions to the resolved and boosted $t\bar{t}$ resonance searches using 2 fb^{-1} of data. These were two separate analyses. We (Kaushik) participated in the cut flow validation challenges and produced the expected signal and background yields for both resolved and boosted reconstruction selection criteria. We generated a large number of data/Monte Carlo comparison plots. We contributed many $m(t\bar{t})$ spectra with systematic variations that were included for limit setting. We (Johns) also set mass limits using Bayesian, *CLs* (LEP) and *CLs* (profile likelihood) methods using RooStats. While the group

decided to use a different Bayesian limit setting machinery (TopStat Bayes), our methods provided a consistency check for the published results and highlighted the effects of profiling on limit setting. Mass limits from both resolved and boosted reconstruction analyses using 2 fb^{-1} were published in EPJC [15] and JHEP [16] respectively.

We continued to make significant contributions to the $t\bar{t}$ resonance search with 5 fb^{-1} of data at 7 TeV. For this round, both resolved and boosted samples are combined into one analysis. We (Johns, Kaushik) did early studies of applying b-tagging in the boosted analysis to reduce the *W* plus jets background. We (Kaushik, Veatch) showed how to increase efficiency by adopting a large-radius jet trigger (as opposed to isolated lepton triggers) in the event selection. We (Kaushik) estimated the trigger efficiency in data and simulation that led to an optimal selection of the large-radius jet in the boosted analysis. Kaushik also produced data-driven scale factors for *W* plus jets events passing the boosted selection criteria in order to reduce the normalization uncertainty of this background. We (Johns, O'Grady) carried out a variety of limit calculations in support of the final result. Johns was co-editor of this paper which was recently accepted by Physical Review D [17]. This analysis was repeated implementing modest improvements using 14.3 fb^{-1} of 8 TeV data. Johns was co-editor of a recent Conference Note documenting these results [18]. An optimized analysis for 20 fb^{-1} of 8 TeV data is currently underway.

Before focusing completely on $t\bar{t}$ resonance searches, Kaushik made significant contributions to a related analysis, measurement of the $t\bar{t}$ differential cross sections with respect to $m(t\bar{t})$, $Pt(t\bar{t})$ and $y(t\bar{t})$. These measurements provide stringent constraints on the inclusive production cross section for many new physics scenarios that predict enhancement in the cross section. In this analysis, Kaushik carried out studies to determine an optimal response matrix that maps the binned true $t\bar{t}$ events to the binned reconstructed events and a binning strategy for unfolding to reduce bin-by-bin migration. The bias and unfolding errors using different unfolding methods were also studied. He compared the $m(t\bar{t})$ spectrum for different reconstruction methods including KLFitter and produced the final measured $m(t\bar{t})$ spectrum for unfolding. These results were published in EPJC [19].

In order to expand the physics reach at Arizona as well as to quickly integrate faculty Erich Varnes and postdocs Xiaowen Lei and Ruchika Nayyar into ATLAS data analysis, we identified several new top-related exotics physics searches to pursue using 8 TeV data. The discovery of the Higgs boson rules out chiral fourth generation quarks. However some Beyond the Standard Model theories require the existence vector-like quarks (VLQ) [20]. Our search for these particles is motivated by naturalness arguments that infer VLQ decay predominantly into third generation quarks. Varnes and Johns are co-supervising a search by O'Grady for vector-like B or T quarks that decay with a final state signature of a pair of same-sign dileptons, at least one b-jet, large missing transverse momentum and large scalar sum jet and lepton transverse momentum (H_T). An ATLAS conference note was produced that set exclusion limits on the production of isospin singlet B (T) vector-like quarks with mass > 0.59 (0.54) TeV using 14.3 fb^{-1} of data collected at 8 TeV [21]. O'Grady's contributions to this note were to produce the expected yields for VLQ signals and to set CLs mass limits for a particular VLQ isospin singlet model [20]. A paper is planned for the results of an analysis optimized for the full 20 fb^{-1} data set at 8 TeV.

CSC DQA (Data Quality Assessment)

In running the ATLAS experiment, one of our main responsibilities is online and offline Data Quality Assessment (DQA) software for the CSC (Cathode Strip Chamber) system. The software and procedures for these US-produced detectors were originally developed by Johns, Kaushik and Lei. O'Grady is now responsible for the online monitoring and Veatch for the offline monitoring. Histograms produced by the online CSC DQA software are used by control room shifters to quickly detect problems. Histograms produced by the offline CSC DQA software are used by the Muon DQ shifter in order to set a CSC DQ flag for each run, which may later be used to include or exclude the run for a given physics analysis. In the last year we (O'Grady, Veatch) continued to improve the monitoring for both online and offline CSC DQA. For example, to increase the probability that we are monitoring distributions from muons produced in proton-proton collisions (as opposed to hits from background photon or neutron interactions) both online and offline monitoring software only use CSC charge clusters that lie on quality track segments. Also, chamber occupancies and segment efficiencies are now monitored as a function of luminosity block (roughly 2 minute intervals) to more quickly identify changes. We (Johns, Jones, Leone) also have an ongoing effort to extract CSC calibration constants using data, which may improve the momentum resolution of forward muons with very high transverse momenta.

HLT Jet and MET Trigger Slice DQA

In running the ATLAS experiment, we held responsibility for HLT Jet and MET (Missing Et) DQA. These are two completely independent tasks that are combined into one here for the sake of brevity. HLT means High Level Trigger and refers to both the L2 (Level 2) and EF (Event Filter) stages. Johns concentrates on the online monitoring software while Kaushik focuses on the offline monitoring software. In the last year, we continued to develop and maintain DQA software for both online and offline shifters for HLT Jet and MET slices. Histograms are used by both general trigger shifters as well as by Jet and MET slice trigger shifters to quickly detect problems in the data. There is also an automatic DQA, which is carried out using various DQ flag algorithms implemented in the data quality software. Both the online and offline monitoring software was updated and improved for 2012 data-taking. An additional responsibility we have is maintaining macros for the online and offline display software.

Micromegas Front-End Electronics for the New Small Wheel (NSW)

We (Hart, Johns, Jones, Tompkins) are developing front-end electronics for Micromegas detectors used in the New Small Wheel, a Phase 1 ATLAS upgrade. The main goal of the NSW is to reduce the L1 Muon trigger rate, which currently is dominated by photon and neutron induced backgrounds. We have been a member of the MAMMA (Muon ATLAS MicroMegas Activity) Collaboration since 2007 and helped develop Micromegas technology for ATLAS through numerous test beam campaigns and subsequent data analysis. The test beam campaigns were used to evolve Micromegas technology for colliding beam use. Studies included evaluating different detector designs and operating conditions (TPC mode, different gases, resistive strips, 2D readout, …). Some results are documented in [22].

In the last year, the development of front-end and readout electronics for Micromegas, rather

than improvements in chamber design and capability, became our focus. The front-end electronics we are designing and testing is built around a peak-finding (amplitude and time) ASIC (Application Specific Integrated Circuit) developed by BNL. For 2012, an analog-only ASIC (called the VMM1) designed to operate with Micromegas was produced by BNL and evaluated by us in test beam runs at CERN. Preliminary results show the chip to be performing as expected in both its precision tracking and trigger capabilities.

For beam tests using Micromegas and sTGC detectors, we designed and built a front-end board using one 64-channel VMM1 ASIC. We also designed several adapter boards that were used to construct a digitization and readout system in collaboration with BNL and Harvard. A fully digital ASIC called VMM2 will be produced by BNL in 2013. For future beam tests with small Micromegas chambers we are designing a front-end board using two 64-channel VMM2 ASIC's. At the same time we are designing a front-end board for use with full-size Micromegas detectors that uses eight VMM2 ASICs. We are also playing a leading role in specifying the L1 trigger data and readout data paths for the Micromegas system. Johns is the Level 3 Manager in US ATLAS for Micromegas electronics. Arizona is presently responsible for the design and fabrication of approximately 4700 Micromegas front-end boards, a significant US contribution to the ATLAS Phase 1 upgrade.

Backend Electronics for the L1 Calorimeter Trigger Upgrade

Another area of responsibility for our group (Armijo, Hart, Johns) is the development of back-end electronics for the Phase 1 upgrade of the L1 Calorimeter Trigger. To keep pace with the increase in LHC luminosity beyond 2018, the L1 trigger rates for electrons and jets must be reduced by improving the resolution of these objects. A new electronics chain will be used. LAr Trigger Digitizer Boards (LTDB) at the front-end will receive finer granularity calorimeter signals, digitize them at 40 MHz and send the digitized data via high-speed optical links to the LAr Digital Processing Blades (LDPB) at the back-end [23]. The LDPB will deserialize the high-speed data from the LTDB and perform digital signal processing to determine the transverse energy of the calorimeter signals. The calculated energies are subsequently sent to the Feature Extractor for use in the L1 Calorimeter trigger. The LDPB physically consists of an ATCA (Advanced Telecommunications Computing Architecture) carrier card with four AMC (Advanced Mezzanine Cards) cards. Large FPGA's on the AMC cards perform the digital signal processing and data handling functions.

We are making significant contributions to the backend electronics in several areas. Our main focus in the last year was to begin to develop firmware with full functionality for the AMC cards. The functionality includes implementation of multi-Gbps serial transceivers, digital signal processing to calculate the energy and bunch crossing number, data buffering pending L1 Accepts and monitoring. In the last year we implemented much of this functionality for a single optical fiber and tested it using a Xilinx Virtex-7 evaluation board. We have begun to expand our firmware chain to use ten optical fiber channels and plan to test and exercise it using a Xilinx-based AMC card being built by BNL and Stony Brook.

Two other areas for which we carry responsibility are firmware development for the ATCA carrier card and participation in the testing and integration of AMC and carrier cards.

JOHN RUTHERFOORD
The challenge and promise of the ATLAS experiment at the Energy Frontier

The following describes the work of Professor John Rutherfoord, Dr. Peter Loch, Dr. Alexandre Savine, Dr. Walter Lampl, Mr. Robert Walker, Mr. Ruben Dominguez, and Graduate Student Chiara Paleari. (Paleari completed her Ph.D. at the end of May 2012 and is now a visitor at LBL.) Some of this work is in collaboration with Professor Michael Shupe, Professor Erich Varnes, Professor Keith Dienes, and Professor Shufang Su.

Brief history

Rutherfoord, Shupe, Loch, Savine, and others who have now moved on, developed a calorimeter concept suitable for the region of a hadron collider detector with the highest rates and the harshest radiation environment, i.e. in the forward region closest to the beam line. Liquid argon ionization sampling calorimetry is a well-established technology which can be made quite radiation hard and impressively stable. The one remaining limitation at high rates is due to the slowly drifting positive argon ions in the liquid argon gaps which can build up enough to screen the electric field near the anode and degrade the signal pulse. We worked out the theory [24] and recognized the most straight-forward approach to avoid these space-charge limitations. For the LHC design luminosity we needed liquid argon gaps much narrower than the norm, of order 0.25 mm. (The rest of the ATLAS liquid argon calorimeter uses gaps of order 2 mm width.) Our concept was accepted and Rutherfoord led the construction project, while building the EM modules and "cold electronics" in our physics department. Rutherfoord and Loch led several test beam campaigns to test and energy-calibrate the FCal modules.

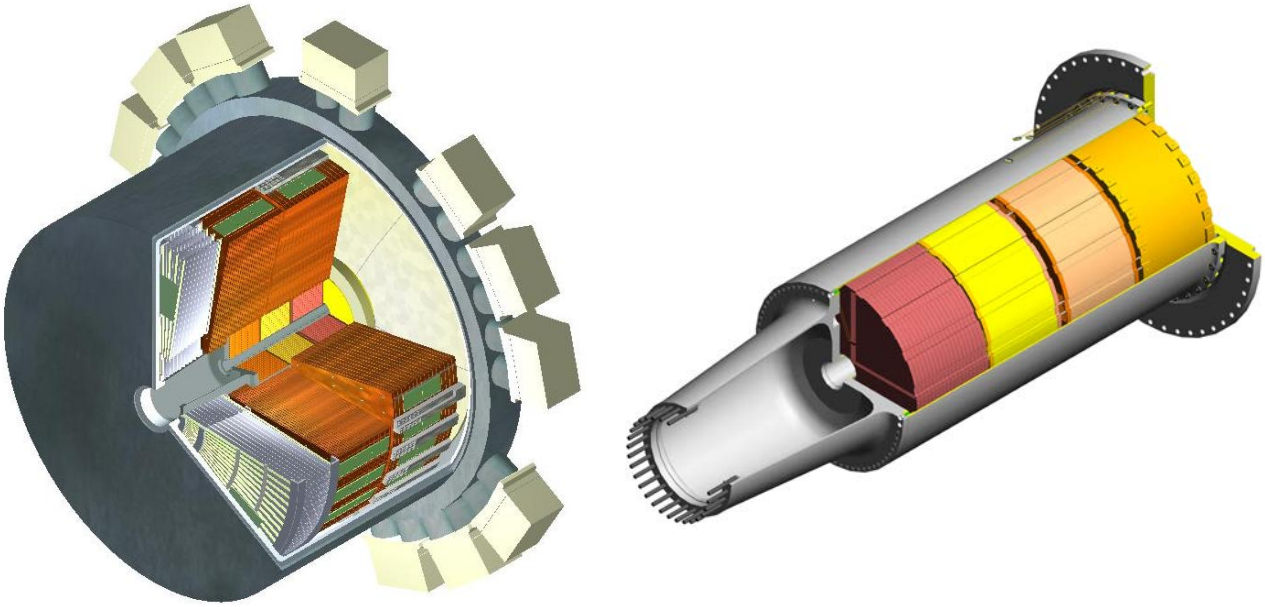

Fig 4-1. Left: The ATLAS End-Cap Cryostat, at ~3.5 m from the IP, contains the EMEC (electromagnetic end-cap calorimeter) (silver colored), the HEC (hadronic end-cap calorimeter) (copper colored), and, closest to the beam, the FCal (multi-colored). Right: The FCal consists of three modules in depth. The FCal1 is intended as an EM calorimeter and is composed of mostly copper. The FCal2 and FCal3 modules are considered hadronic calorimeters and are composed mostly of tungsten. The FCal modules are drawn within their support tube.

The ATLAS Forward Calorimeters

Each of the two ATLAS Forward Calorimeters (FCal for short) [25] is composed of three modules, one behind the other, providing depth segmentation. Fig. 4-1 shows one of the two FCals in its liquid argon cryostat along with the adjacent liquid argon calorimeters on the left and the FCal assembly in more detail on the right. The first module facing the interaction point (IP) contains 12,260 unit cells, one of which is shown in the left panel of Fig. 4-2. With the rod/tube structure it is relatively easy to maintain the precision of the gap width, thus minimizing one contribution to the energy resolution. The small gap allows the positive argon ions to drift out fast enough that they don't accumulate in the gap and distort the electric field and thereby degrade the electrical pulse. But not enough is known about the electrical properties of liquid argon to be certain that the liquid argon technology would work well at HL-LHC luminosities.

The Positive Ion Buildup (PIB) R&D project

This is a University of Arizona effort but recognized by the ATLAS collaboration. In the last three years Rutherfoord, Walker, and students have been involved. The original initiative is due to Shupe. Two FCal-style electrode rods were outfitted with Strontium-90 beta sources embedded in cavities within the rod. The betas penetrate the walls of the cavity and enter the liquid argon gap, ionizing the argon much as showers ionize the argon in the ATLAS experiment. The activity of the hotter of the two sources is such as to match the ionization rate at twice the full LHC design luminosity at $|\eta|=4.7$ at EM shower max. This is approximately the worst location in the FCal and, hence, in the ATLAS detector.

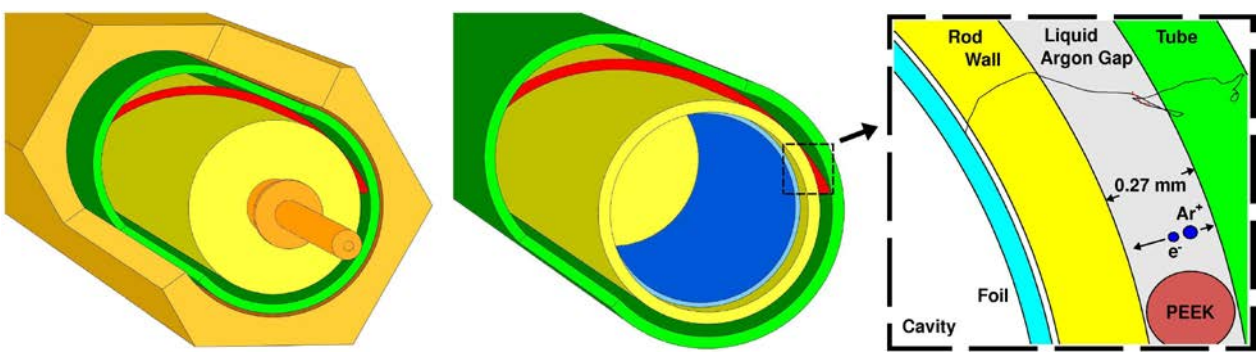

Fig. 4-2. Left: A unit cell within the ATLAS Forward Calorimeter EM module. The axis of each unit cell is parallel to the nominal proton beam and makes a small angle to the collision products. A solid copper (tungsten) rod forms part of the absorber material but is also the anode of the ionization gap. A thin-walled copper tube forms the cathode. An insulating PEEK fiber, helically wound around the rod, centers the rod within the tube. The gap between the rod and tube fills with liquid argon. A positive potential is applied to the rod so that electrons, from ionized argon atoms, drift to the rod producing a negative electrical signal at the signal pin. A copper (tungsten) matrix surrounds this electrode system. Middle: Scheme to replicate the radiation environment in ATLAS. A cylindrical cavity has been machined out of a copper rod. A thin foil (blue), coated on the outer surface with a strong beta source, is sealed within this cavity. Right: Close-up of a cross-section of the electrode structure. Superimposed is a simulated beta track, emitted by the radioactive source material. It penetrates the wall of the cavity and passes through the liquid argon gap, creating ionization.

This second R&D project includes institutes from Canada, Germany, Russia, and Slovakia. Each of the liquid argon calorimeter types (the EMEC, the HEC, and the FCal) is represented. The goal is to find the limits of operation of each calorimeter type as a function of the rate of energy deposit and of the integrated energy deposit. For this we use the U70 proton synchrotron at IHEP in Protvino, Russia. Arizona is the intellectual leader. A proton beam is directed onto three small cryostats, one behind the other, in an external beam line in a well-shielded concrete cave. Each cryostat holds one of the calorimeter types in the order of FCal, EMEC, and HEC from front to back. Before and between these cryostats are iron absorbers to adjust the energy flux in the hadronic showers.

The proton beam intensity can be varied over an exceptionally wide range from about 1 up to 10^6 protons per RF bunch. The upper limit gets us well above the equivalent HL-LHC luminosity. The focus of the project is to see how the pulses from each calorimeter type vary in amplitude and in pulse shape as a function of the beam intensity. These measurements will be compared to predictions [24]. See [26] for earlier results. This project differs from the PIB project in several ways. The PIB experiment has far better control over the systematics but does not measure pulses, only time-averaged currents. The pulse shapes seen in the HiLum project are sensitive to different features of liquid argon at high ionization rates so that these two projects nicely complement each other. The very modest results from our earlier runs at Protvino have now been published [27]. Savine and Rutherfoord do most of the analysis.

Physics Justification

These two R&D projects (PIB and HiLum) are aimed at determining how the performance of the FCal (and of the other calorimeters in the EndCap cryostat) might degrade at HL-LHC luminosities. Once the degradation is determined the next step is to see how this degradation might affect the physics. The FCal plays an important role in physics with missing E_T. A poorly performing FCal will affect the physics signal only slightly but the backgrounds which fake this signal are another matter. Rutherfoord has written a fast simulation which necessarily treats only the very general features of the detector in order to get statistically relevant results on the tails of the distributions. To start this study he has been able to generate 10^9 phojet min-bias events. This preliminary study shows that the rate of min-bias events with fake missing E_T above about 100 GeV rises by orders of magnitude as parts of the FCal degrade so much as to be useless. See Varnes' section for improved simulations.

FCal Upgrade

We anticipate that ATLAS will need a new FCal for the Phase 2 HL-LHC luminosity upgrade. We are presently writing those sections of the Liquid Argon Calorimeter Phase 2 Upgrade Letter of Intent (LoI) which deal with forward calorimetry. The new FCal (dubbed the sFCal) will have gap widths which are smaller than the present FCal to ensure we avoid space-charge effects at the highest luminosities. A prototype with such smaller gap widths is now in the Protvino test beam and is working very well. A description of our two R&D projects appears in that LoI. This should evolve into a large construction project starting in 2015 with Arizona at the lead.

Before the phase 2 upgrade there will be an intermediate (phase 1) upgrade of the FCal trigger electronics to allow improved trigger thresholds. The present Level 1 (hardware) trigger takes FCal signals in rather coarse η-ϕ bins. The upgrade will provide to the trigger values of E_T in

finer bins. We have worked out some of the changes required in the signal routing on the baseplane for the front end boards on the cryostat and for the daughter boards which sum the analog signals and convert them to E_T. This is leading to a modest role for our group in the phase 1 upgrade construction starting in 2014.

HEC Spikes

The Hadronic EndCap Calorimeter (HEC) in ATLAS (see Fig. 4-1 left) displays a peculiar anomaly. Of order half of the readout channels have random pulses consistent with delta functions at the electrodes at a troubling rate. These pulses can be quite large, equivalent to hundreds of GeV of deposited energy. The institutes responsible for the construction of the HEC have tried to diagnose the problem in situ but are thwarted by two factors: 1) many of their tests require special triggers which interfere with the physics triggers and 2) there are very few tests possible with the HEC permanently in the cryostat. Arizona is now the only ATLAS institute with a fully functioning cryostat and cryogenics system (used for our R&D studies). Furthermore we developed an "electronics test bench" consisting of four channels of the standard Liquid Argon front end electronics (preamp and shaper), and a custom ADC, digital pipeline, and computer readout. And we had access to the HEC-style electrodes which were developed for the HiLum project. So we volunteered to study these so-called "HEC Spikes". For the past year this has been an almost full-time project for Rob Walker with substantial help from an undergraduate. They are taking most of the data and reducing that data for summary conclusions. We are finding evidence that the cause is the humidity between the time of production and of installation into the cryostat. Polyimide, a major ingredient of the HEC electrodes, is hygroscopic. For instance, it is known that the dielectric constant of polyimide changes with humidity.

Incidentally, none of these problems show up in our FCal modules. They are relatively trouble-free, so far. The current drawn from the HV supplies by the FCal1 modules so accurately tracks the LHC luminosity at the ATLAS interaction point that the FCals have now been adopted as a major input to the luminosity determination. As the luminosity continues to rise we expect the dedicated luminosity monitor to become non-linear so the FCal1 may become the sole luminosity monitor for the rest of the 2012 run.

Leadership positions in ATLAS

Rutherfoord is serving his second term as Chair of the Group Representatives of the Liquid Argon unit. He is also a member of the Liquid Argon Management Group, the Liquid Argon Steering Committee, and the Liquid Argon Upgrade Advisory Group. He chairs several search committees which find candidates to fill various positions within the Liquid Argon unit. Rutherfoord was also chair of the Search Committee which recommended candidates to replace US ATLAS leaders Howard Gordon and Mike Tuts. As an outcome of Rutherfoord's committee, Brookhaven appointed Srini Rajagopalan to replace Howard this September and Jim Cochran to replace Mike in September of 2013.

Loch is presently serving as Convener of the ATLAS Monte Carlo Physics Group. This is perhaps the most prestigious appointment held by an Arizona person. There are only eight Physics Groups in ATLAS and these convenerships are highly sought after. Loch also served as the level 2 manager of the US ATLAS software contribution to ATLAS, a position he had to

give up last year to take on the ATLAS physics group convenership which requires residency at CERN. Loch has also held leadership positions on a large number of other committees related to hadronic calorimetry. And he has organized and run a very large number of workshops and conferences, either as session organizer or on the organizing committee, often as chair. A number have been in Tucson so many of our European ATLAS collaborators have visited us on our campus.

ATLAS Physics

The Arizona group has been involved in all aspects of the hadronic final state reconstruction in ATLAS, including the reconstruction of jets, missing transverse energy, and even event shapes in the soft part of the proton-proton collisions at LHC. Peter Loch and graduate student Chiara Paleari have made significant contributions to the improvement of the reconstruction performance. Paleari wrote her PhD thesis on her studies of the underlying event shapes, including very original work on energy flow correlations. These studies will have significant impact on the modeling of these collisions, especially with respect to backgrounds for discovery physics.

Rutherfoord has pioneered and Erich Varnes and Peter Loch have recently focused on pile-up suppression in jets and in missing transverse energy reconstruction by making use of the correlations over η-ϕ space. In this work, Loch works in close collaboration with the ATLAS teams at SLAC and at INFN Milan in Italy. This field requires attention for the foreseeable future, due to the ever changing beam conditions at the LHC, in particular with the challenges introduced by the systematically increasing luminosity. Loch developed the method (now validated) using single event features for this task. In addition, in his position as Monte Carlo Physics Group Convener, Loch continued to support and provide consultation for all ATLAS physics analyses, in addition to managing the large scale Monte Carlo production configurations and scripts, and the maintenance of the specific interfaces to all relevant generator software provided by the theory community.

Also, Loch has been a member of the ATLAS simulation steering group since March 1, 2011. This is expected to be a two-year assignment but will likely be extended even further. In the recent past he provided leadership in US ATLAS (software program manager from January 1, 2009 through February 28, 2011) and still helps with committee and (physics) programming work in US ATLAS (SLAC Tier 2 Physics Advisory Group) and ATLAS (organization of the hadronic calibration workshops, most recently at SLAC in September 2011). In addition, he led three editorial boards for early ATLAS publications in 2010, and contributed to four others in the same year, including the one for the very first jet cross section paper from ATLAS. Most recently he was a member of the editorial board for the paper on the first structure function measurement in ATLAS.

In addition, Loch holds a sub-contract issued by the US ATLAS Program Office for software coordination and support for the seventh year now, under which Walter Lampl is employed. Lampl has an excellent track record in all software and production related activities in ATLAS. Until early 2011 he coordinated the prompt data reconstruction effort (a one year assignment), while also managing the fast event display effort for quick access to interesting collision events. He was the electronic calibration co-coordinator for the ATLAS liquid argon calorimeter, and has now taken over the deputy coordinator role for the whole experiment earlier this year.

MICHAEL SHUPE

Physics Research on ATLAS

Michael Shupe's research interests lie in the domain of the hardest parton-parton collisions, with particular focus on the issue of quark/lepton compositeness. Since 2009, he has dedicated his physics research efforts on ATLAS to the Exotics subgroup that searches for new phenomena in dijet final states. Shupe's personal interests and experience in quark/lepton compositeness date from 1979, when he wrote one of the first papers on this subject: "A Composite Model of Leptons and Quarks", M. Shupe, Phys. Letters 86B, 87-92 (1979). A homework problem in the first chapter of "Introduction to Elementary Particles", by David Griffiths, refers to this paper and asks the students to work through the model. This paper also appears as the first reference in the cover article of the November, 2012, issue of Scientific American. This model is conventionally referred to as the Harari-Shupe preon model

The steady operation of the LHC, beginning in 2010, and followed by rapid increases in luminosity, have yielded *pp* collision data sets that continue to extend our knowledge of the short-distance frontier. The growing sample of high p_T collisions extends the kinematic reach for studies exploring the highest energy scales, and the increase in LHC energy, from 7 TeV in 2011 to 8 TeV in 2012, creates a further increase in sensitivity due to the rapid rise in parton luminosity as a function of energy.

The two most sensitive methods to test for quark compositeness are to search for (1) resonance bumps in the dijet mass spectrum due to excited quarks (q*), and for (2) excesses of dijets at large scattering angles that would signal the onset of new interactions at preon level. Traditionally, these two analysis methods have been used separately. But in 2010, our postdoctoral appointee, Dr. Frederik Ruehr, introduced a new observable, $F_\chi(m_{jj})$, to explore the combined two-dimensional phase space of dijet mass and angular distributions at fine granularity in dijet mass.

Ruehr received his Ph.D. from the University of Heidelberg in 2009, and joined the Arizona group in February, 2010, just as ATLAS collision data were beginning to appear. He has been stationed at CERN throughout this period, and has been at the center of analysis development in a number of areas. The multijet eta-intercalibration method that he introduced to ATLAS is now one of the standard *in situ* techniques used to establish the jet energy scale and its uncertainties. In mid-2010, Ruehr was appointed to be the Convenor of the ATLAS Jet+X subgroup, which includes both Standard Model physics and the search for new physics; in dijet distributions, in inclusive jet spectra, and in a number of other jet+X channels. When Ruehr was appointed to convene the Jet+X group, the Exotics group Convenors asked Shupe to be an author for exotic dijets publications and conference notes, has continued to the present day. In 2013, Ruehr has been promoted to Co-Convenor of the group responsible for establishing the calibration and resolution for jets, and for the missing E_T due to jets, and he is Chair of the Editorial Board for a $l\nu jj$ resonance search. At the same time, he continues to be a strong contributor to exotic dijet analyses.

Shupe's main activity from 2009 to the present is as the primary author for most of the conference notes and refereed publications emerging from the ATLAS Exotic Dijets group. The following table lists the physics results coming from these dijet analyses: the 95% C.L. exclusion limits established for a number of new phenomena. The right-most column indicates the authors: Andreas Warburton (AW), Pekka Sinervo (PS), and Michael Shupe (MS). (Citations appear in the left column and the references to these documents appear in Appendix 2.)

95% C.L. [TeV]	sqrt(s) lumin	Λ_{CI} χ	Λ_{CI} $F\chi$	q^* m_{jj}	s8 m_{jj}	W' m_{jj}	SR m_{jj}	axig m_{jj}	QBH χ	QBH $F\chi$	Prim Auth
ICHEP 2010 [28]	7 TeV 61/nb	**.875**									MS
PRL105 2010 [29]	7 TeV 315/nb			**1.26**							AW
PLB694 2011 [30]	7 TeV 3.1/pb	**3.4**									MS
NJP13 2011 [31]	7 TeV 36/pb	**6.6**	**6.8**	**2.15**				**2.10**	**3.49**	**3.78**	PS MS
PLHC 2011 [32]	7 TeV 163/pb			**2.49**				**2.67**			MS
EPS 2011 [33]	7 TeV 810/pb			**2.91**	**1.91**			**3.21**			MS
PLB708 2012 [34]	7 TeV 1/fb			**2.99**	**1.92**			**3.32**			MS
Moriond 2012 [35]	7 TeV 4.8/fb	**7.6**	**7.8**	**3.35**	**1.94**				**3.96**	**4.11**	MS
JHEP1301 2013 [36]	7 TeV 4.8/fb	**7.6**	**7.6**	**2.83**	**1.86**	**1.68**	**3.61**		**4.11**	**4.03**	MS
ICHEP 2012 [37]	8 TeV 5.8/fb			**3.66**							MS
HCP 2012 [38]	8 TeV 13/fb			**3.84**							MS

Exclusion limits at 95% C.L. have been set for the following new-physics hypotheses: the quark contact interaction scale (Λ_{CI}), and the mass scale for excited quarks (q^*), color octet scalars (s8), heavy W bosons (W'), string resonances (SR), axigluons (axig), and quantum black holes (QBH). These results have drawn considerable attention from the theoretical HEP community, and the New Journal of Physics paper was chosen for NJP's exclusive "Highlights of 2011" collection.

All analyses have employed binned distributions of one or more of three observables: the dijet invariant mass (m_{jj}), the χ angular variable binned coarsely in m_{jj}, and the "new" $F_\chi(m_{jj})$ variable – a ratio of χ distributions fine-binned in m_{jj}. The character of these

distributions can be seen from the following plots, taken from the JHEP 2013 article, which presents dijet results from the full 2011 *pp* collision data set, collected at 7 TeV.

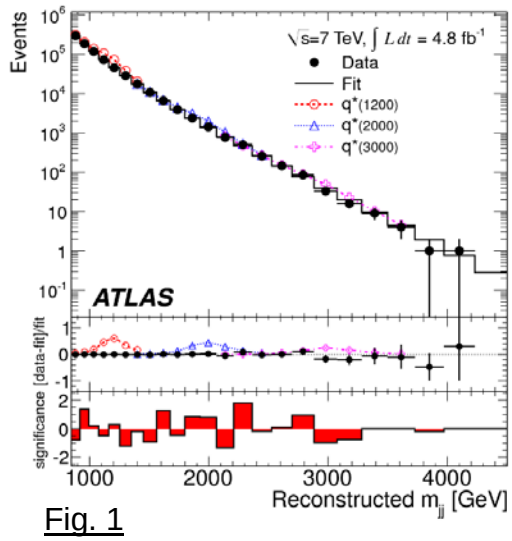

Fig. 1

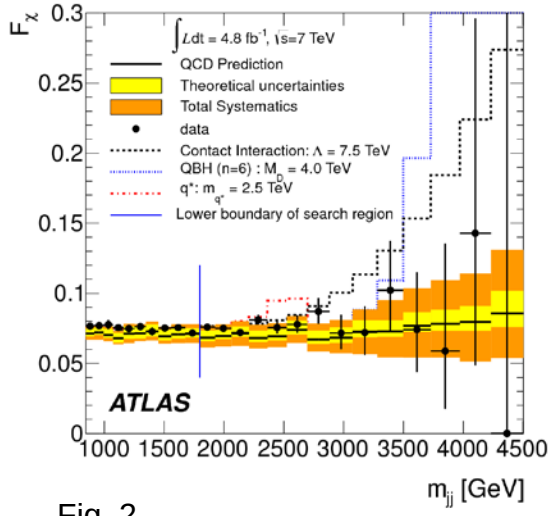

Fig. 2

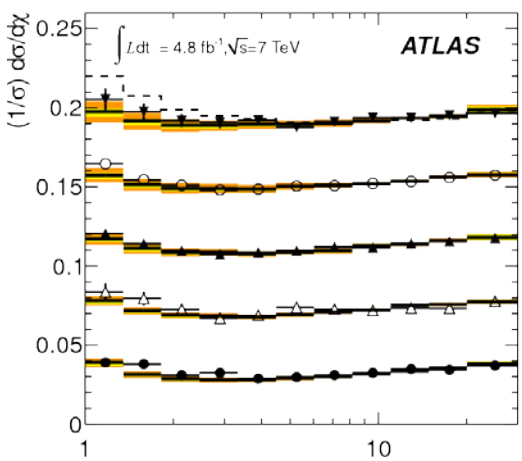

Fig. 3

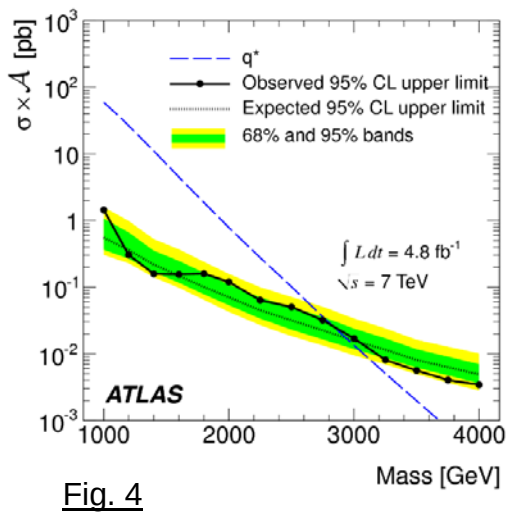

Fig. 4

Figure 1 shows the dijet mass distribution for all 2011 data, along with templates for the excited quark model for three *q** masses. The analysis looks for resonances ("bumps") in this distribution, which would indicate the presence of signals due to new phenomena.

In dijet angular analysis, instead of studying distributions of the scattering angle in the dijet CM, the χ variable is used. The χ variable (used in Fig. 3), is a function of the rapidity difference between the two leading jets, $\exp|y_1-y_2|$, and yields distributions which are relatively flat for leading order QCD. If events at low χ exceed the QCD prediction (which is corrected to NLO in these studies), such an excess could indicate the appearance of new physics since many BSM models lead to angular distributions considerably more isotropic than those of QCD. As shown in Fig. 3, the data are divided

into coarse bins in dijet mass (m_{jj}), with χ distributions accumulated for each mass range. Since new resonances or slow-onset phenomena are expected to appear at high p_T, the highest one or two mass bins are "search" bins, and the lower ones, "control" bins. To indicate what such a signal might look like, the model prediction for a 3 TeV quantum black hole (QBH) is shown as the dotted line in the plot. Similar shapes would appear for quark contact interactions and other new physics hypotheses.

Figure 2 shows the distribution of events in the $F_\chi(m_{jj})$ variable, created by Ruehr, appearing for the first time in the NJP publication. In this distribution there are many bins in m_{jj}, matched approximately to the detector resolution. In each m_{jj} bin the ratio of central events to the total is calculated from $F_\chi = N(|y^*| < 0.6)/N(\text{total})$ in that bin, where $y^* = ½(y_1 - y_2)$, calculated from the leading (1) and subleading (2) jets, is related to the scattering angle of these jets in the dijet CM. If $F_\chi(m_{jj})$ rises above the QCD prediction, it indicates the presence of excess central events. This distribution is complementary to the χ distributions since it is fine-binned in m_{jj} and coarse-binned in the angular space. Figure 2 shows the signal expected for several new physics hypotheses.

Since no significant discrepancies between data and QCD are observed in any ATLAS dijet data, exclusion limits at 95% C.L. have been established for the chosen new physics hypotheses, with a typical analysis shown in Fig. 4. Some models are analyzed using more than one method – as shown in the table above. The table also show the factors that cause the observed limits to evolve. In early running at 7 TeV, the limits rose rapidly as the integrated luminosity increased, due to more events at high dijet mass. This trend slowed as the fractional increases became smaller, and as the highest mass events began to approach the kinematic limit, where parton luminosity is reduced by the drop in PDF's at high *x*. The early results from 8 TeV data accumulated in 2012 show that the attendant rise in parton luminosity increases the sensitivity substantially. This effect will be greatly magnified following the LHC shutdown, as the energy is raised to 13 or more TeV.

The data analysis in 2011 and 2012 has become more challenging due to increasing in-time and out-of-time pileup on the JES and its uncertainty. The rise in instantaneous luminosity has made the need for *in situ* calibration more critical. At the same time, the statistics needed for jet corrections are always lowest in the kinematic region where we look for signal – the domain of the highest p_T jets, so that the JES and jet response must be extrapolated to the region of interest. Peter Loch and Frederik Ruehr have been working throughout this period to optimize the jet calibration, and to reduce its uncertainties. (This activity was discussed in detail in the DOE 2012 narrative.)

As for future activities in the areas of ATLAS jet calibration, Loch, Ruehr, and Shupe will continue working in tandem with the Jet/Etmiss group to achieve the best possible jet calibration for 2012, and the fullest knowledge of its uncertainties. In dijet analysis, Shupe will be continuing, along with the other members of the exotic dijet team, to see the 2012 data analysis to completion, and will serve as primary author for upcoming papers. The current plans are to produce a short publication on resonance analyses, followed by a longer publication combining resonance and angular analyses. Shupe will also continue to provide parallel studies to optimize dijet analyses. His current work is

on the simulation of NNLO k-factors for contact interactions, a correction which is becoming critical as more events are collected at high dijet masses.

Service and Upgrade Projects in ATLAS

Shupe has been providing service and upgrade work steadily in past years in the following areas, and will be continuing with these efforts:

- Providing ATLAS radiation background maps using the Geant3/GCalor simulation system for both the existing geometry and for future upgrade geometries. As an example, in the Fall months of 2012, the Arizona geometry description of the EMEC calorimeter was rendered in more detail to attain greater accuracy for prediction of the highest backgrounds in the HEC electronics region. The results were helpful in understanding the radiation doses that have already occurred in this region, and for predicting future doses.
- Providing more information on observed backgrounds through more detailed analysis of the data taken by the Arizona radiation background monitors during the first years of running.
- Providing any radiation background studies needed for future upgrades of the ATLAS beamline system and for any proposed upgrades to the ATLAS radiation shield.
- Continuing to serve on editorial boards, or in any similar capacities as needed.

ERICH W. VARNES

In the past three years the focus of Varnes' effort has been on the DØ experiment, where he carried out physics analyses and served as one of the top-level managers. Others in the Arizona group who worked on DØ in this period are Amitabha Das, who was a postdoc in the group from 2007 to 2011, Xiaowen Lei and Ruchika Nayyar. Students Matt Leone and Fionnbarr O'Grady were also briefly involved in DØ before choosing to pursue theses on ATLAS.

With Tevatron operations ended, and our DØ physics analysis efforts coming to a close, Varnes became active in ATLAS. Nayyar and Lei are directing their efforts towards ATLAS as well. This redirection is being done in a way that capitalizes on (and therefore amplifies) the existing strengths of our ATLAS group. We are pursuing studies of a potential upgrade of the FCal, investigating improvements to the jet trigger algorithm, and analyzing the data to search for exotic particles that decay into top quarks and *W* bosons.

Activities on DØ

Algorithms and Computing Coordinator

For most of the past three years Varnes served, alongside Fermilab staff scientist Qizhong Li, as coordinator of computing and offline algorithms for DØ. During data-taking this was a highly active responsibility, as Varnes was charged with ensuring that the Monte Carlo simulation kept pace with the changing accelerator and detector conditions (while also integrating improvements to the detector simulation derived from understanding gained over the course of the run), and overseeing the development of new methods for identifying jets, leptons, and *b* quarks.

With data taking complete, the intensity of activity diminished, and the nature of the activity also shifted. One major effort was to direct a reprocessing of part of the DØ data set, so that our premier analyses (such as Higgs boson searches) could make use of the best version of our reconstruction code across their entire sample.

Varnes stepped down as algorithms and computing coordinator in July 2012, to allow a greater fraction of his time to be devoted toward ATLAS.

Deputy Institutional Board Chair

Varnes was recently elected by the collaboration as Deputy Chair of the Institutional Board. After one year as deputy, he will be appointed as chair of the IB in summer 2013. In this role he will help to direct DØ's continuing transition from an active to an archival experiment.

Other Service Activities

Since DØ records relatively few measurements per track, "fake tracks" formed from a random overlap of hits from noise and/or different particles are found frequently during reconstruction. Das developed a multivariate discriminant between tracks from a single charged particle ("real" tracks) and these fake tracks. He found that by combining several features of the track into a

boosted decision tree, one could effectively separate the fake and real tracks. The use of this tool became widespread in DØ. Incorporation of this tool in the vertex algorithm increased the efficiency for selecting the correct primary vertex in $Z \to \ell\ell$ events by about 10%.

The identification of *b* quark jets is critical to many analyses at DØ, and in particular to the top quark measurements and Higgs boson searches that the Arizona group focuses on (and for every search for $H \to b\bar{b}$). Lei devoted her DØ service work largely to the *b* ID effort, and was appointed as co-convener of the *b* ID group in summer 2012.

Nayyar attained substantial expertise in electron identification in the course of her thesis analysis in the $H \to WW \to ee\nu\nu$ channel, and was appointed as co-convener of the EM identification group in summer 2012. Her main tasks in this role will be to oversee the calculation of the relative efficiency for EM identification (with various quality criteria) between Monte Carlo and the reprocessed data.

Miscellaneous DØ Activities

In addition to the service tasks described above, Varnes also chaired task forces looking into the capabilities of DØ under a proposed extension of the Tevatron run through 2014 and into the issues of preserving DØ's data analysis capability in the years after the shutdown, served on the program committee for several of DØ's annual off-site workshops, and served on the editorial boards that review searches for new phenomena in dilepton final states and measurements of electroweak single top production. Varnes also took control room shifts operating the calorimeter and muon systems. Das served as one of the on-call experts for the L1Muon trigger system, contributed to maintenance of the electronics, and took control room shifts.

Physics Analysis

At the beginning of the grant period, our main analysis effort was the measurement of the helicity fractions of the W bosons that originate from top quark decay. In the Standard Model (SM), 70% of these W bosons are expected to have longitudinal helicity and 30% are expected to be left-handed. A significant deviation from these values would be a strong indication of the presence of new physics.

Our measurement is based upon selecting $t\bar{t}$ candidate events in five decay channels (*ee*, $e\mu$, $\mu\mu$, *e*+jets, and μ+jets) using a multivariate discriminant. We optimize both the set of variables to use in the discriminant and the cut value using a novel approach that takes into account both the discriminating power of each variable and the accuracy with which the variable is modeled by our simulation.

For each selected event, we fully reconstruct the $t\bar{t}$ final state to calculate the cosines of the helicity angles θ^* between the top quark and down-type fermion directions in the rest frames of the *W* bosons from each top quark decay. We use a binned Poisson maximum likelihood fit to compare the distribution of $\cos\theta^*$ in data to that for linear combinations of the three *W* helicity states to determine the helicity fractions from the data, with the result

$$f_o = 0.669 \pm 0.102 \left[\pm 0.078 \text{ (stat.)} \pm 0.065 \text{ (syst.)} \right]$$
$$f_+ = 0.023 \pm 0.053 \left[\pm 0.041 \text{ (stat.)} \pm 0.034 \text{ (syst.)} \right],$$

consistent with the standard model.

The above result was published in Phys. Rev. D in 2011 [6-1]. Subsequently, Varnes led an effort with our counterparts at CDF to combine the W helicity results from the two experiments. The result of the combination is

$$f_o = 0.722 \pm 0.081 \left[\pm 0.062 \text{ (stat.)} \pm 0.052 \text{ (syst.)} \right]$$
$$f_+ = -0.033 \pm 0.046 \left[\pm 0.034 \text{ (stat.)} \pm 0.031 \text{ (syst.)} \right].$$

This result was published in Phys. Rev. D-Rap. Comm. in 2012 [6-2].

We have also combined the information from our measurement with information from the rate and kinematic distributions of single top events to place constraints on the values of non-SM coupling form factors in the *tWb* vertex. The results of this combination are shown in Fig. 6-2, and were published in Phys. Lett. B in 2012 [6-3].

In late 2010 we turned our attention to the search for the Higgs boson at low masses where the dominant decay is to $b\bar{b}$, considering the case where the *Z* decays to neutrinos. Among the Arizona group's contributions to this search were identifying a way to increase the acceptance for $WH \to \ell \nu b\bar{b}$ (such events in which the lepton escapes detection contribute to the Higgs signal in our channel) by about 10%, improving the modeling of the multijets background and measuring the diboson production cross section using the same analysis procedure and tools as for the Higgs boson search (thereby helping to validate the performance of the procedure and tools).

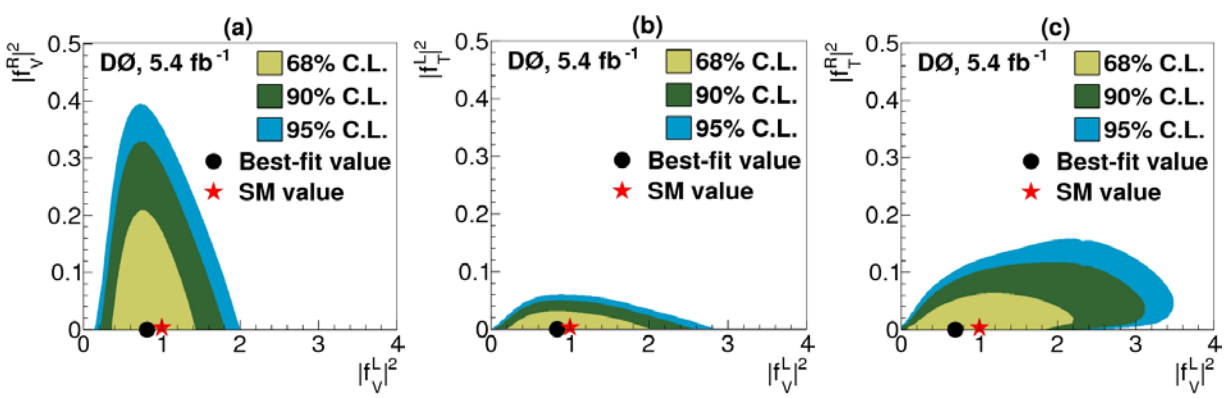

Figure 6-2: Constraints on anomalous *tWb* couplings from single top quark and W helicity measurements. Each plots shows a two-dimensional likelihood, with the SM left-handed vector coupling strength on the *x* axis and one of the three possible anomalous coupling strengths on the *y* axis. The data is consistent with the SM expectation for the *tWb* coupling.

The Higgs production cross section limits obtained in this analysis are shown in Fig. 6-3(a). While we do not have sufficient sensitivity in this channel alone to detect a SM Higgs boson, combination of our results with searches in the $ZH \to \ell^+\ell^- bb$ and $WH \to \ell \nu bb$, and with similar searches from CDF, results in the limits shown in Fig. 6-3(b). This work has been published in Phys. Lett. B [6-4], and contributes to two additional papers, one on the combination of all DØ searches for $H \to b\bar{b}$ (accepted by Phys. Rev. Lett. [6-5]) and one on the combination of such searches at CDF and DØ (submitted to Phys. Rev. Lett. [6-6]). The publication of these papers marked the end of our physics analyses using DØ data.

Activities on ATLAS

Forward Calorimeter Upgrade Studies

The ATLAS forward calorimeter (FCal), for which the Arizona group led the design and construction effort, has performed excellently so far. However, at a high-luminosity LHC that may reach luminosities of 10^{35} cm^{-2}s^{-1} it is likely that the performance of the existing calorimeter will be substantially compromised by a buildup of space charge in the LAr gaps. To operate successfully at these luminosities, a new design with the gap width reduced from 250 to 100 μm is under consideration.

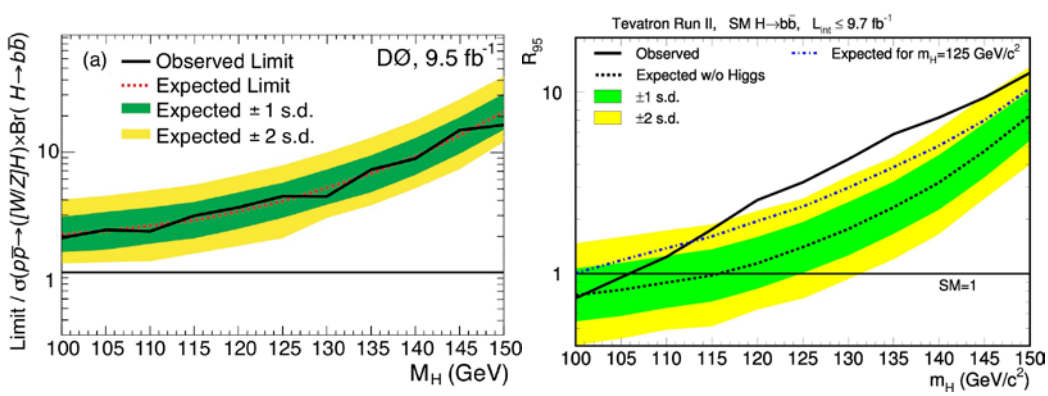

Figure 6-3: 95% C.L. upper limit on the Higgs boson production cross section, relative to the standard model expectation, as a function of assumed Higgs boson mass from (left plot) DØ's search in the $ZH \to \nu\nu b\bar{b}$ channel and (right plot) from a combination of all DØ and CDF searches for $H \to b\bar{b}$. In each plot, the solid line is the measured upper limit, the dashed line is the limit we would expect to observe in the background-only hypothesis, and the green and yellow bands show the one and two standard deviation variations about the expected limit.

To assess the impact of the FCal on the missing E_T resolution, we need to understand the effects on background sources (such as multijet production) where missing E_T arises due to imperfect measurement of particle energies. To simulate the impact of such events that have large production cross section but a very small chance of resulting in large missing E_T, one must generate billions of events, so we are using the fast detector simulation tool PGS for this study. Varnes interfaced the PHOJET generator of minimum-bias collisions to PGS to allow the maximal efficiency for generating events. The simulated missing E_T values are histogrammed.

Then to assess the missing E_T that would arise in the presence of N pileup events we sample the histogram N times to represent each pileup event, generate a random phi direction for each (allowing the calculation of the x and y components of the missing E_T) and sum these components. The result of a simulation of 10^9 beam crossings (with an average of ~60 interactions per crossing) is shown in Fig. 6-4. These studies will be further enhanced and extended to make a quantitative estimate of the impact of the FCal on ATLAS' sensitivity to various new physics scenarios.

Trigger Studies

Due to the rapidly increasing luminosity of the LHC, dealing with pileup has become a pressing issue at analysis level, and also at trigger level. Energy deposition from pileup events can artificially increase a jet's energy, and thus cause triggers based on jet E_T to fire at an elevated rate. To mitigate this, Varnes, Lei, and Nayyar are exploring the optimal use of information from the calorimeter and tracking system to calibrate jets at the trigger level on a per-event basis.

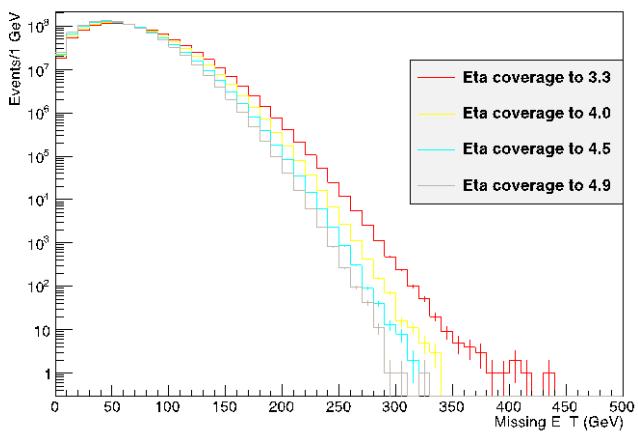

Figure 6-4: Simulated missing E_T distribution for minimum bias events in ATLAS at a center of mass energy of 14 TeV and an average of 63 interactions per beam crossing, under different assumptions about the η coverage of the calorimeter

Physics Analysis

So far the LHC experiments have not yielded evidence for physics beyond the standard model. However, the case for the existence of new physics is still strong, so we must search for violations of the standard model everywhere possible. Varnes' group has embarked on such a search, looking for the pair production of particles that decay to a tW final state (such particles, including vector-like top quarks with charge 5/3, are predicted in several extensions to the SM). Since this analysis uses many of the same tools as a top quark physics analysis, this effort fits well with the analyses undertaken by Johns and the graduate students in our group. With our strong team of faculty, postdocs, and students, we will be one of the leading groups in the analysis of the 2012 data. We started on this path by validating the MC simulation of some of the key background sources, and will continue by investigating data-driven methods to estimate the backgrounds from fake leptons and from electrons with mismeasured charge.

INDIVIDUAL PROJECT REPORTS

TASK C: THEORY

Professor Ina Sarcevic

Professor Sarcevic works on theory topics in both particle physics and astro-particle physics. She supervised Postdoctoral Researchers Tolga Guver and Anastasios Taliotis and Graduate Students Arif Erkoca and William Striegl on topics related to her research.

THEORETICAL ELEMENTARY PARTICLE PHYSICS

.

INA SARCEVIC

TASK C

In the past three years the group consisted of Professor Ina Sarcevic, postdoctoral fellows Dr. Tolga Guver and Dr. Anastasios Taliotis and two graduate students. Dr. Taliotis moved to a postdoctoral position at University of Crete, Greece and Dr. Tolga Guver has moved to a fellowship position at Sabanci University in Istanbul, Turkey. Graduate student Arif Emre Erkoca got his Ph.D. degree in 2011 and he has taken position of a managing director of BUPAT USA company. In the past three years, the main focus of Prof. Ina Sarcevic's research supported by this grant has been on probing new physics with neutrino interactions via radio Cherenkov radiation from the Moon, neutrinos as signals of dark matter annihilation in the Galactic Center, probing dark matter models with neutrinos, investigating the role of charm in astrophysical neutrinos and exploring the constraints on the nature of dark matter and its interactions from observation of old neutron stars. Below we briefly summarize accomplishments in the past three years.

Dark Matter and its Detection

There is an overwhelming evidence of the dark matter existence in the Universe, from the observation of missing mass in galaxy clusters to the precise measurements of the cosmological baryonic fraction performed by the WMAP and BOSS. The possibility that the standard gravitation law needs to be modified to explain the observations with the ordinary visible baryonic matter has recently been ruled out by the Bullet Cluster data. The particle physics interpretation of dark matter requires dark matter particle to be weakly interacting and in thermal equilibrium until the Universe expansion becomes such that particles cannot find each other and their interactions freeze-out. Large-scale structure formations indicate that dark matter particles need to be non-relativistic at the time of the freeze-out, i.e. dark matter needs to be "cold". Measurement of the matter density and its baryonic component implies that dark matter density contribution is about 25%.

There are no viable candidates for dark matter within the standard model of elementary particles, but many in proposed extensions of the standard model. Indirect dark matter searches look for WIMP annihilation (or sometimes decay) products, either photons or anomalous cosmic rays, such as positrons and antiprotons, or neutrinos. For some years, observations of an excess in the positron fraction $e^+/(e^+ + e^-)$ by HEAT, a bright 511 keV gamma-ray line from the Galactic Center by INTEGRAL and a possible unaccounted-for component of the foreground of WMAP around the galactic center, the "WMAP Haze" (among others) have been considered possible hints of WIMP dark matter annihilations.

More recently, the PAMELA satellite reported an excess in the positron fraction in the energy range of 10-100 GeV with respect to what is expected from cosmic rays secondaries, which confirmed the HEAT excess. Also ATIC and PPB-BETS observed a bump in the e^++e^- flux from 200 to 800 GeV, but this was not confirmed HESS or by Fermi/LAT. Fermi found a slight excess in the e^++e^- flux between 200 GeV and 1 TeV.

The positron excess observed by PAMELA may be explained by the presence of particular astrophysical sources (e.g., pulsars), or by the annihilation (leptophilic models) or decay of dark matter particles. If the observed anomalies in the PAMELA and FERMI data are due to dark matter annihilation, a larger annihilation rate than expected for typical thermal relics must be assumed. This enhancement may happen due to either large inhomogeneities

in the dark matter distribution near Earth (subhalos) and/or a larger annihilation cross section of the dark matter particles. The later may happen if the dark matter particles are not thermal relics, in which case they can have larger annihilation cross sections in the early Universe, or due to an enhancement of the annihilation cross section only at very low velocities, which would not affect their annihilation in the early Universe.

Neutrinos from Dark Matter Annihilation

Arif Emre Erkoca, Graciela Gelmini, Mary Hall Reno and Ina Sarcevic
Phys. Rev. **D81**, 096007 (2010)

Dark matter models explaining the PAMELA positron excess must be peculiar in several aspects. To avoid overproduction of antiprotons, the dark matter annihilation or decay must proceed dominantly to leptons. These leptophilic dark matter candidates would copiously produce neutrinos whose fluxes are constrained by the observations of Super Kamiokande (SK) toward the direction of the Galactic Center. Neutrinos with energies of the order of the dark matter mass, $E_\nu \leq m_\chi$, would propagate without being deflected towards the Earth. Some fraction of the arriving muon neutrinos would be converted into muons via charged current interactions in the Earth which can be detected in Earth based neutrino telescopes.

We have shown that muons and showers produced by neutrino interactions, when neutrinos are produced directly in dark matter annihilation, could be used to detect a dark matter signal from the Galactic Center. In the case of direct neutrino production, the signal is above the atmospheric background for both contained and upward events, assuming that the annihilation rate is enhanced by boost factor of 200 and that the branching ratio of dark mater annihilation into neutrinos is one. We have shown that the shape of the muon flux depends on the specific dark matter decay mode, and that the dominant flux comes from tau decay at low muon energies, and from W-decay for muon energies above 200 GeV. Electromagnetic showers have much smaller background, from atmospheric electron neutrinos, than the hadronic showers. We have determined the required dependence of the annihilation cross section on the dark matter mass in order to observe a fixed number of event rates. We have shown that after one year IceCube+DeepCore detector could potentially observe a 5σ signal effect by measuring contained muons (for direct neutrino production), or a 2σ effect with hadronic showers even in the case when they are due to secondary neutrinos.

IceCube+DeepCore will be able to identify track-like events due to the charged current interactions of muon neutrinos, the showers due to neutral current interactions of all the neutrino flavors and the charged current interactions of electron and tau neutrinos. In particular, above the neutrino energy of 40 GeV the signal to background ratio for showers is further enhanced since the atmospheric tau and electron neutrino fluxes are suppressed relative to the atmospheric muon neutrino flux. Thus, the main background is the neutral current interaction whose cross section is about a factor of three less than the charged current cross section of the atmospheric muon neutrinos. The measurement of the ratio of track-like muon and shower events eliminates the dependence on some parameters of the theory (e.g., boost factor, the dark matter density profile, etc) which only determine the overall normalization for the energy dependent differential muon fluxes, so the physical properties of the dark matter particle can better be determined.

Due to its location in the northern hemisphere, the future KM3NeT experiment will be complementary to IceCube+DeepCore in searching for neutrino signals from dark matter annihilation in the Galactic Center through the observation of upward muon events. The

atmospheric muon background at the KM3NeT will be suppressed significantly since the Earth will act as a shield to those muons. Independent searches of the upward muon events by KM3NeT and the contained muon and shower events by IceCube+DeepCore look promising for the discovery of the mysterious dark matter particle or for setting stringent constraints on its properties.

Probing Dark Matter Models with Neutrinos from the Galactic Center

Arif Emre Erkoca, Mary Hall Reno and Ina Sarcevic

Phys. Rev. **D82**, 113006 (2010)

Indirect searches for dark matter annihilations via neutrinos and neutrinos from dark matter decays, with experiments such as AMANDA and IceCube could provide valuable information about the nature of dark matter. For example, neutrino signals from DM annihilation and decay in the Galactic center, when DM particle is a gravitino, a Kaluza-Klein particle and a particle in a leptophilic model may produce detectable signal in neutrino telescopes. We have considered both the case of decaying and annihilating DM. For a gravitino, we have taken into account both two-body and three-body decay channels. For each DM model, we have calculated contained and upward muons and showers using the model parameters that were obtained by fitting the excesses in γ-ray and in the positron or electron plus positron data from the observations of HESS, PAMELA and FERMI/LAT. We have used a cone half angle of 1° (50°) for the muon (shower) events.

With the model parameters that we considered, muon signal (upward or contained) is above the atmospheric background. The muon flux from the decaying DM would be comparable to those for the annihilating DM models only if the decay times were of the order $\sim 10^{25}$ sec and $\sim 10^{24}$ sec for contained muon and upward muon events, respectively. In contrast to the muon case, we find that for a wide range of shower energies, the shower flux for decaying leptophilic particle is larger than for annihilating Kaluza-Klein particle.

We have found the optimum cone half angles for all types of events in order to reach 2σ detection level. For the annihilating DM models, we have found the optimum angle to be a few degree for the muon events and about 10° for the shower events. In both cases, we have shown that there is a good chance of detecting both leptophilic and Kaluza-Klein particles in less than ten years for some DM masses.

Our results can be used to predict neutrino signals for any other values for the parameters of the models we consider. For example, in the literature, the HESS data is also explained by a hypothetical Kaluza-Klein particle with mass $m_\chi = 10$ TeV. The boost factor that is required, in this case, is $B = 1000$. We have found that the observation times become less than a year for the upward muons in order to reach 2σ detection significance. Similar to the decaying leptophilic model, the gravitino model ($\psi_{3/2} \to l^+ l^- \nu$) with a gravitino mass of 3.3 TeV and decay time $\tau = 5 \times 10^{25}$ sec can also account for the FERMI data. We have found that the 2σ detection significance can be reached in 2.6 years via upward muons and in less than a year via the hadronic showers.

Radio Cherenkov Signals from the Moon: Neutrinos and Cosmic Rays

Y. S. Jeong, M. H. Reno and I. Sarcevic

Astropart. Phys. **35**, 383 (2012)

Ultrahigh energy cosmogenic neutrinos originate from cosmic ray interactions with the background radiation. Another source of ultrahigh energy neutrinos may be Active Galactic

Nuclei (AGNs) or Gamma-Ray Bursts (GRBs). Because cosmic rays have been observed up to energies of 10^{19} eV, high energy neutrino flux from cosmic ray interactions with photons producing charged pions which decay into neutrinos is a "guaranteed" neutrino flux.

In contrast to cosmic rays and photons, neutrinos have weak interaction cross sections so neutrino fluxes are not attenuated over cosmic distances. Observational efforts include looking for neutrino-induced radio emission from the Moon, where the Moon is the target, and the signal is the radio Cherenkov emission. Neutrinos, when they interact with nucleons and nuclei, generate hadronic showers. Cosmic ray interactions in the lunar regolith produce hadronic showers as well. The cosmic ray flux is quite large at low energy, but it falls off rapidly with increasing energy. We have considered fluxes that come from the initial assumption of cosmic rays being primarily protons. Enhanced neutrino-nucleon cross sections can arise in a variety of extensions of the standard model. For example, in theoretical models with large extra dimensions and low scale gravity there is a possibility of creating a microscopic black hole in neutrino-nucleon interactions at very high energies. The neutrino-nucleon cross section for black hole production exceeds standard model cross section for neutrino energies above 10^6 GeV and is about two orders of magnitude larger than the standard model cross section at $E_\nu \sim 10^{11}$ GeV. In addition to the cosmogenic neutrino flux, there is a possibility that astrophysical sources produce larger neutrino fluxes via Fermi shock acceleration of the charged particles such as protons which collide with other protons or photons in a disk or a jet producing mesons which decay into neutrinos.

We have shown that the cosmic ray induced event rate always dominates the standard model neutrino event rate for several cosmogenic models for $\varepsilon = 10^{-8} - 10^{-11}$ V/m/MHz. Current capabilities for the electric field threshold are on the order of $\varepsilon_{\rm min} \sim 10^{-8}$ V/m/MHz. The radio Cherenkov technique can be exploited for lunar observations if the neutrino nucleon cross section is increased. We showed that for the choice of $M_D = 1$ TeV and $N_D = 7$ for BH production, an observable neutrino signal from the Moon is induced and it is larger than the cosmic ray induced background. For $\nu = 150$ MHz, this would require an instrumental improvement to reach $\varepsilon_{\rm min} \sim 10^{-10}$ V/m/MHz for the high cosmogenic flux. We have shown that if both the neutrino cross section and the neutrino flux are enhanced, lunar radio Cherenkov techniques can make observations rather than set limits, even for $\varepsilon_{\rm min} \sim 10^{-8}$ V/m/MHz.

Several radio telescopes are looking for very high energy neutrinos using the Moon as a target. The Westebork Synthesis Radio Telescope (WSRT) operates in the frequency range of $115 - 180$ MHz and has reported limit on neutrino flux of $E^2\Phi_\nu \sim 10^{-6}$ GeV/cm^2/s/sr. At ultra-high energies ($E_\nu > 10^{14}$ GeV), NuMoon which uses the WSRT, one of the most sensitive low-frequency experiment ($\nu = 113-175$ MHz), will be able to place more stringent limit on the neutrino flux. LOFAR (Low Frequency Array), is expected to lower their energy threshold down to 10^{11} GeV and with 30 days of data taking will be probing the neutrino flux down to $E^2\Phi_\nu \sim 3 \times 10^{-9}$ GeV/cm^2/s/sr assuming standard model neutrino interactions. For neutrino fluxes lower than $E^2\Phi_\nu \sim 3\times10^{-9}$ GeV/cm^2/s/sr, LOFAR provides an excellent probe of physics beyond the Standard Model.

High Energy Neutrinos from Astrophysical Sources

Rikard Enberg, Mary Hall Reno and Ina Sarcevic

Large underground or underwater experiments like IceCube and KM3NeT are designed with the goal of observing high energy neutrinos produced in astrophysical sources. We have

considered astrophysical sources driven by a relativistic jet outflow, accelerated by a central engine such as a black hole. Shock accelerated protons in the jet outflow may give rise to a high-energy neutrino flux. These neutrinos are potentially produced in hadronic interactions: proton–proton interactions produce charged pions and kaons which subsequently decay into muons and neutrinos.

High energy pions and kaons are relatively long-lived and therefore subject to both hadronic and radiative cooling before they decay, which downgrades the neutrino energies. We have focused on charm production and decay in astrophysical jets as a source of neutrinos, which dominate at high energy over neutrinos from pion and kaon decays.

We have shown that production of charmed mesons in *pp* collisions gives a large contribution to the neutrino flux at the highest energies, since high energy charmed hadrons ($D^{\pm}, D^0$) have short lifetimes and therefore predominantly decay before they interact. The neutrino flux from charm is therefore less suppressed up to higher energies. Even though the production cross section is orders of magnitude smaller than for pions and kaons, neutrinos from charm decays become the dominant contribution at high energies.

Neutron Star Capture of Self-Interacting Asymmetric Dark Matter

Tolga Guver, Arif Emre Erkoca, Mary Hall Reno and Ina Sarcevic

arXiv:1201.2400, submitted to *Phys. Rev.* **D**

As an astronomical object in the Galaxy rotates around the center in its orbit, it will sweep through the Galactic dark matter halo and eventually capture some of the particles on its way. In time, dark matter particles that are captured may have effects on the observational properties of the astronomical object, which may then be used to constrain the nature of the dark matter. In that respect, neutron stars provide a natural laboratory to constrain the properties of dark matter. Large baryonic density inside a neutron star provides a natural area where it is likely that dark matter particles will interact and lose energy.

The capture of dark matter can have significant effects if dark matter does not annihilate. Depending on dark matter density, its mass and interactions, the number of particles may reach the limit necessary for self-gravitating effects to take place. Once a dark matter inside a neutron star becomes self-gravitating, depending on the self-interaction properties it may collapse into a black-hole, thus destroying the neutron star. In such a case even the very existence of neutron stars at certain ages can be used to constrain the properties of dark matter.

The self-capture mechanism depends on the number of particles, therefore in time as more and more dark matter particles are captured self-interaction becomes very important in the capture process. For small DM-nucleon cross-section, the thermalization time may be long enough for the self-capture to make significant contribution to the capture of dark matter particles. We have calculated the time evolution of the number of dark matter particles for a various different dark matter self-interaction and DM-nucleon interaction cross sections and for a range of dark matter masses. We have extended our work on capture of dark matter by the neutron star to include the fact that the size of dark matter star, as it is captured, changes in time, thus resulting in different dark matter density at each step in time. This affects the geometrical limit for the capture and provides tighter parameter space for the asymmetric dark matter that is excluded by the existence of the neutron star. We have evaluated the parameter space that is excluded due to the existence of old neutron stars, which has strong dependence on the assumed dark matter density.

APPENDIX 1: ARIZONA GROUP GRADUATE STUDENTS RECEIVING PhDs WITHIN THE LAST DOE GRANT RENEWAL PERIOD

Student	Date	Advisor
Menika Sharma	Jun 2010	Keith Dienes
Arif Erkoca	Dec 2010	Ina Sarcevic
Xiaowen Lei	May 2011	Kenneth Johns
Walter Freeman	Aug 2011	Doug Toussaint
Xinyu Miao	Jan 2012	Shufang Su
Chiara Paleari	May 2012	John Rutherfoord/Peter Loch
Caleb Lampen	Feb 2013	Elliott Cheu

APPENDIX 2: REFERENCES CITED IN THE INDIVIDUAL PROJECT REPORTS

References to citations in some of the project reports are listed in this appendix. They are divided into Task A and Task B. Task C didn't have citations which required references.

References Cited in the Task A Section

[1] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **106**, 191801 (2011)l Phys. Rev. Lett. **108**, 201802 (2012); Phys. Rev. Lett. **107**, 191803 (2011); G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **108**, 041805 (2012).

[2] The MILC Collaboration: A. Bazavov *al.*, arXiv:1004.0342 [hep-lat], Phys. Rev. D **82**, 074501 (2010).

[3] K. Symanzik, In: Recent Developments in Gauge Theories, edited by G. 't Hooft et al. (Plenum Press, New York, 1980), p. 313, (1980); K. Symanzik, Nucl. Phys. **B226**, 187 (1983); M. Lüscher and P. Weisz, Phys. Lett. **B158**, 250 (1985); M. Lüscher and P. Weisz, Commun. Math. Phys. **97**, 59 (1985); M.G. Alford *et al.*, Phys. Lett. **B361**, 87 (1995).

[4] The Fermilab Lattice and MILC Collaborations, A. Bazavov, *et al.*, arXiv:1112.3051 [hep-lat], to be published in Phys. Rev. D.

[5] The Fermilab Lattice and MILC Collaborations, E. Neil, *et al.*, "B- and D-meson decay constants from 2+1 improved staggered simulations, [arXiv:1112.3978], and E. Neil, talk presented at *Lattice 2012*, Cairns, Australia, June 25-29, 2012.

[6] The Fermilab Lattice and MILC Collaborations, Jon A. Bailey, *et al.*, arXiv:1202.6346, to be published in Phys. Rev. D.

[7] P. Blasi, P. Colangelo, G. Nardulli and N. Paver, Phys. Rev. D **49**, 238 (1994) [hep-ph/9307290].

[8] J.P. Lees *et al.*, (BaBar Collaboration) (2012), arXiv:1205.5442 [hep-ex].

[9] The Fermilab Lattice and MILC Collaborations, J.A. Bailey *et al.*, arXiv:1206.4992, submitted to Phys. Rev. Lett.

[10] The Fermilab Lattice and MILC Collaborations, A. Bazavov, *et al.*, arXiv:1205.7013.

[11] The Fermilab Lattice and MILC Collaborations, C. Bernard, *et al.*, Proceeding of the 19th Particles and Nuclei International Conference (PANIC11), Cambridge, MA, July 2011 [arXiv:1111.2968], and PoS LATTICE **2011** 274 (2011) [arXiv:1112.5642].

[12] R. Zhou *et al.* [Fermilab Lattice and MILC Collaborations], PoS LATTICE **2011** 298 (2011) [arXiv:1111.0981].

[13] S. -W. Qiu, *et al.*, [Fermilab Lattice and MILC Collaborations], PoS LATTICE **2011** 289 (2011) [arXiv:1111.0677].

[14] J. A. Bailey, *et al.*, [Fermilab Lattice and MILC Collaboration], PoS LATTICE **2010**, 311 (2010) [arXiv:1011.2166].

[15] J. A. Bailey, *et al.*, [Fermilab and Lattice and MILC Collaborations], PoS LATTICE **2011** 270 (2011) [arXiv:1111.5471].

[16] E. Gamiz, *et al.*, for The Fermilab Lattice and MILC Collaborations, PoS LATTICE **2011** 281 (2011) [arXiv:1111.2021].

[17] D. Toussaint and W. Freeman, [arXiv:0905.2432], Phys. Rev. Lett. **103**, 2009, 122002.

[18] W. Freeman and D. Toussaint, [arXiv:1204.3866], submitted to Phys. Rev. D.

[19] M. Fukugita, Y. Kuramashi, M. Okawa, A. Ukawa, [arXiv:hep-lat/9408002], Phys. Rev. D **51**, 5319 (1995); S.J. Dong, J.-F. Lagaë, K.F. Liu, [arXiv:hep-ph/960225], Phys. Rev. D **54**, 5496 (1996); SESAM-Collaboration: S. Güsken *et al.*, [arXiv:hep-lat/9809066], Phys. Rev. D **59** (1999) 054504; C. Michael, C. McNeile and D. Hepburn (UKQCD collaboration), hep-lat/010902, Nucl. Phys. Proc. Suppl. **106**, 293 (2002); H. Ohki *et al.*, [arXiv:0810.4223], PoS(LATTICE 2008) 126; [arXiv:0806.4744], Phys. Rev. D **78** (2008) 054502; G. Bali, S. Collins and A. Schafer, arxiv 0811.0807, PoS(LATTICE2008) 161, 2008; R.D. Young and A.W. Thomas, arXiv:0901.3310.

[20] W. Freeman and D. Toussaint, PoS(Lattice 2010), 138 (2010), [arXiv:1011.5271], proceedings of Lattice11, to appear in PoS.
[21] M.A. Shifman, A.I. Vainstein and V.I. Zakharov, Phys. Lett. **B78**, (1978) 443; A. Kryjevski, hep-ph/0305173, Phys. Rev. **D** 70 (2004) 094028.
[22] The HotQCD Collaboration, A. Bazavov, *et al.*, Phys. Rev. D **85**, 054503 (2012) [arXiv:1111.1710].
[23] The HotQCD Collaboration, A. Bazavov, *et al.*, arXiv:1203.0784, submitted to Phys. Rev. D.
[24] The HPQCD Collaboration: C.T.H. Davies, *et al.*, Phys. Rev, D**81**, 034506, (2010) [arXiv:0910.1229].
[25] The MILC collaboration: A. Bazavov *et al.*, PoS(LAT2009)079, [arXiv:0910.3618]; PoS CD09, 007 (2009), [arXiv:0910.2966]
[26] HPQCD, MILC, and UKQCD collaborations: C. Aubin, *et al.*, Phys. Rev. D **70** 031504(R) (2004).
[27] H. Leutwyler, arXiv:hep-ph/0612112, and references contained therein.
[28] The Fermilab lattice and MILC Collaborations: A. Bazavov *et al.*, [arXiv:0912.5221], PoS **LAT2009**,249, (2009); C. Bernard *et al.*, [arXiv:0808.2519], Phys. Rev. D. **79** 014506. C. Bernard *et al.*; [arXiv:0811.3640], Phys. Rev. D **79**, 054507 (2009).

References Cited in the Task B Section

[1] "SUSY Searches at ATLAS in Multilepton Final States with Jets and Missing Transverse Energy", ATL-PHYS-INT-2011-027.

[2] "SUSY Searches at ATLAS in Multilepton Final States with Jets and Missing Transverse Energy", ATLAS-CONF-2011-039.

[3] **"**SUSY Searches in the Final States with Three Leptons and Missing Transverse Momentum at ATLAS", ATL-COM-PHYS-2011-1561.

[4] "Search for supersymmetry in events with three leptons and missing transverse momentum in sqrt{s} = 7 TeV pp collisions with the ATLAS detector", Phys. Rev. Lett. **108** (2012) 261804

[5] "ATLAS Sensitivity Prospects for Light Charged Higgs Bosons in the H+ to csbar and H+ to tau+nu Decay Channels with Simulated LHC Data at 7 TeV**",** ATL-PHYS-INT-2010-060.

[6] **"**Study of discriminating variables for charged Higgs boson searches in ttbar events with leptons, using 35.3~pb−**1** of data from the ATLAS detector**",** ATL-COM-PHYS-2011-187.

[7] "Search for a charged Higgs boson H+ decaying via to tau(lep)+nu in ttbar events with one or two light leptons in the final state using 1.03/fb of pp collision data recorded at sqrt(s) = 7 TeV with the ATLAS detector**",** ATL-COM-PHYS-2011-532.

[8] "MSSM Charged Higgs->Tau(lepton)+nu for HCP 2011", ATLAS-CONF-2011-151.

[9] "Object selection and calibration, background estimations and MC samples for the Winter 2012 Top Quark analyses with 2011 data", ATL-COM-PHYS-2012-224.

[10] *"Measurement of the Top Quark Pair Production Cross-section with ATLAS in the Single Lepton Channel"*, ATLAS Collaboration, G.Aad *et al*., Phys. Lett. B **711** (2012) 244.

[11] "*Topcolor Assisted Technicolor*", C. Hill, Phys. Lett. B **345** (1995) 483.

[12] "*The Bulk RS KK-gluon at the LHC*", B. Lillie *et al*., JHEP **0709** (2007) 74.

[13] *"Kinematic Fitting of $t\bar{t}$ Events Using a Likelihood Approach – The KLFitter Package"* J.Erdmann *et al*., ATLAS Collaboration Internal Note ATL-COM-PHYS-2009-551.

[14] *"A Search for $t\bar{t}$ Resonances in the Lepton Plus Jets Channel using 200 pb^{-1} of pp Collisions at $\sqrt{s}$ =7 TeV"*, ATLAS Collaboration Conference Note ATLAS-CONF-2011-087 (2011).

[15] *"A Search for $t\bar{t}$ Resonances with the ATLAS Detector in 2.05 fb^{-1} of Proton-Proton Collisions at $\sqrt{s}$ =7 TeV"*, ATLAS Collaboration, G.Aad *et al*, EPJC **72** (2012) 2083.

[16] *"A Search for $t\bar{t}$ Resonances in Lepton+Jets Events with Highly Boosted Top Quarks Collected in pp Collisions at $\sqrt{s}$ = 7 TeV with the ATLAS Detector"*, ATLAS Collaboration, G.Aad *et al*., JHEP **1209** (2012) 041.

[17] *"A Search for $t\bar{t}$ Resonances in the Lepton+Jets Final State with ATLAS using 4.7 fb^{-1} of pp Collisions at $\sqrt{s}$ = 7 TeV"*, ATLAS Collaboration, G.Aad *et al*., accepted by Phys. Rev. D and arXiv:1307.4568 [hep-ex].

[18] *"A Search for $t\bar{t}$ Resonances in Lepton+Jets Events with ATLAS using 14 fb^{-1} of proton-proton Collisions at $\sqrt{s}$ =8 TeV"*, ATLAS Collaboration Conference Note ATLAS-CONF-2013-052 (2013).

[19] *"Measurements of the Top Quark Pair Relative Differential Cross-Sections with ATLAS in pp Collisions at $\sqrt{s}$ =7 TeV"*, ATLAS Collaboration, G.Aad *et al*., EPJC **73** (2013) 2261.

[20] *"Identifying Top Partners at the LHC"*, J.A. Aguilar-Saavedra, arXiv:0907.3155v2 [hep-ph].

[21] *"Search for Anomalous Production of Events with Same-sign Dileptons and b-Jets in 14.3 fb^{-1} of pp Collisions at $\sqrt{s}$ =8 TeV with the ATLAS Detector"*, ATLAS Collaboration Conference Note ATLAS-CONF-2013-051 (2013).

[22] *"Development of Large Size Micromegas Detectors for the Upgrade of the ATLAS Muon System"*, T. Alexopoulos *et al*., Nucl.Instrum.Meth. **A617** (2010) 161.

[23] *"Upgraded Readout Electronics for the ATLAS LAr Calorimeter at the Phase 1 of LHC"* S. Starz *et al*., ATLAS Liquid Argon Calorimeter Group, Nucl. Instrum. Meth. **A718** (2013) 115.

[24] John P. Rutherfoord, "Signal degradation due to charge buildup in noble liquid ionization calorimeters", Nucl. Instr. and Meth. A 482 (2002) 156.

[25] A. Artamonov *et al.*, "The ATLAS Forward Calorimeter", JINST 3 (2008) P02010.

[26] B. Toggerson, A. Newcomer, J. Rutherfoord, R.B. Walker, "Onset of space charge effects in liquid argon ionization chambers", Nucl. Instr. and Meth. A 608 (2009) 238.

[27] A. Glatte *et al.*, "Liquid argon calorimeter performance at high rates", Nucl. Instr. and Meth. A 669 (2012) 47.

[28] ICHEP 2010: ATLAS-CONF-2010-074, July 20, 2010.

[29] "Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC", The ATLAS Collaboration, Phys. Rev. Lett.

105, (2010) 161801

[30] “Search for Quark Contact Interactions in Dijet Angular Distributions in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC”, The ATLAS Collaboration, Phys. Lett. B694 (2011) 327-345

[31] “Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at sqrt{s} = 7 TeV Measured with the ATLAS Detector”, The ATLAS Collaboration, New J. Phys. 13 (2011) 053044

[32] PLHC 2011: ATLAS-CONF-2011-81

[33] EPS 2011: ATLAS-CONF-2011-095

[34] “Search for New Physics in the Dijet Mass Distribution using 1 fb^{-1} of pp Collision Data at sqrt{s} = 7 TeV collected by the ATLAS Detector”, The ATLAS Collaboration, Phys. Lett. B708 (2012) 37-54

[35] Moriond 2012: ATLAS-CONF-2012-038, March 14, 2012

[36] “ATLAS Search for New Phenomena in Dijet Mass and Angular Distributions using pp collisions at sqrt{s} = 7 TeV”, The ATLAS Collaboration, JHEP 1301 029 (2013)

[37] ICHEP 2012: ATLAS-CONF-2012-088, July 1, 2012

[38] HCP 2012: ATLAS-CONF-2012-148, November, 2012

APPENDIX 3: PUBLICATIONS IN THE LAST RENEWAL PERIOD

Publications by members of this DOE grant which appeared in the most recent renewal period are listed here. In the case of the experimentalists only publications are listed to which there were significant contributions to the paper.

TASK A PUBLICATIONS IN LAST THREE YEARS:

1. K.R. Dienes and M. Lennek, *Correlation Classes on the String Landscsape: To What Extent is String Theory Predictive?*, *Phys. Rev.* **D80** (2009) 106003.

2. K.R. Dienes and B. Thomas, *Cascades and Collapses, Great Walls and Forbidden Cities: Infinite Towers of Metastable Vacua in Supersymmetric Field Theories*, *Phys. Rev.* **D79** (2009) 045001. This article was selected by the PRD Editors to be featured on the American Physical Society's website *Physics: Spotlighting Exceptional Research*, `http://physics.aps.org`.

3. K.R. Dienes and B. Thomas, *New Non-Trivial Vacuum Structures for Supersymmetric Field Theories*, *AIP Conf. Proc.* **1116** (2009) 391–396.

4. K.R. Dienes and B. Thomas, *Classical Metastable Supersymmetry Breaking with D-Terms: Tree-Level Nests and Vacuum Towers*, *AIP Conf. Proc.* **1200** (2010) 185–193.

5. K.R. Dienes and B. Thomas, *On the Inconsistency of Fayet-Iliopoulos Terms in Supergravity Theories*, `arXiv:0911.0677`, *Phys. Rev.* **D81** (2010) 065023.

6. K.R. Dienes and B. Thomas, *Isospectral But Physically Distinct: Modular Symmetries and their Implications for Carbon Nanotori*, `arXiv:1005.4413`, *Phys. Rev.* **B84** (2011) 085444.

7. K.R. Dienes and C. Kolda, *Twenty Open Questions and a Postscript: Supersymmetry Enters the Era of the LHC* (November 2010), reprinted as an invited Overview Chapter in the the review volume "Perspectives on Supersymmetry II," [a reprint of the original volume "Perspectives on Supersymmetry"], ed. G. Kane (World Scientific, 2010).

8. K.R. Dienes and B. Thomas, *Dynamical Dark Matter: I. Theoretical Overview*, `arXiv:1106.4546`, *Phys. Rev.* **D85** (2012) 083523.

9. K.R. Dienes and B. Thomas, *Dynamical Dark Matter: II. An Explicit Model*, `arXiv:1107.0721`, *Phys. Rev.* **D85** (2012) 083524.

10. S. Bauman and K.R. Dienes, *Kaluza-Klein Masses and Couplings: Radiative corrections to Tree-Level Relations*, `arXiv:1112.5631`, *Phys. Rev.* **D85** (2012) 125011.

11. K.R. Dienes and B. Thomas, *Phenomenological Constraints on Axion Models of Dynamical Dark Matter*, `arXiv:1203.1923`, *Phys. Rev.* **D86** (2012) 055013.

12. K.R. Dienes, S. Su, and B. Thomas, *Distinguishing Dynamical Dark Matter at the LHC* `arXiv:1204.4183`, *Phys. Rev.* **D86** (2012) 054008.

13. K.R. Dienes, M. Lennek, and M. Sharma, *Strings at Finite Temperature: Wilson Lines, Free Energies, and the Thermal Landscape*, `arXiv:1205.5752`, *Phys. Rev.* **D86** (2012) 066007.

14. K.R. Dienes and M. Sharma, *S-Duality at Finite Temperature* (submitted for publication to *Phys. Rev.* **D**, currently under review).

15. K.R. Dienes, J. Kumar, and B. Thomas, *Direct Detection of Dynamical Dark Matter* `arXiv:1208.0336`, *Phys. Rev.* **D86** (2012) 055016.

16. "Dilepton Signals in the Inert Doublet Model", E. M. Dolle, X. Miao, S. Su, B. Thomas, *Phys. Rev.* **D81** (2010) 035003.

17. "Dark Matter-Motivated Searches for Exotic 4th Generation Quarks in Tevatron and Early LHC Data", J. Alwall, J.L. Feng, J. Kumar, S. Su, *Phys. Rev.* **D81** (2010) 114027.

18. "Trilepton Signals in the Inert Doublet Model", X. Miao, S. Su, B. Thomas, *Phys. Rev.* **D82** (2010) 035009.

19. "Sbottom Signature of the Supersymmetric Golden Region",H. Li, W. Parker, Z. Si, S. Su, *Eur. Phys. J.* **C71** (2011) 1584.

20. "A Simplified Model Approach to Same-sign Dilepton Resonances",V. Rentala, W. Shepherd, S. Su, *Phys. Rev.* **D84** (2011) 035004.

21. "Simplified Models for LHC New Physics Searches",D. Alves *et al.*, arXiv:1105.2838 [hep-ph], workshop report for "Workshop on Topologies for Early LHC Searches, SLAC, California, September, 2010.

22. "B's with Direct Decays: Tevatron and LHC Discovery Prospects in the $b\bar{b}$ + MET Channel",J. Alwall, J.L. Feng, J. Kumar, S. Su, *Phys. Rev.* **D84** (2011) 074010.

23. "Slepton Discovery in Electroweak Cascade Decay",J. Eckel, W. Shepherd, S. Su, *JHEP* 1205 (2012) 081.

24. "MSSM Higgs Bosons at The LHC",N. Christensen, T. Han, S. Su, *Phys. Rev.* **D85** (2012) 115018.

25. "Distinguishing Dynamical Dark Matter at the LHC",K. R. Dienes, S. Su and B. Thomas, *Phys. Rev.* **D86** (2012) 054008.

26. "Low-Mass Higgs Bosons in the NMSSM and Their LHC Implications",N. Christensen, T. Han, Z. Liu, S. Su, arXiv:1303.2113 [hep-ph], accepted by JHEP.

27. "The Weak Neutral Current",J. Erler, S. Su, arXiv:1303.5522 [hep-ph], *Progress in Particle and Nuclear Physics* **71** (2013) 1.

28. "Constraining Type II 2HDM in Light of LHC Higgs Searches",B. Coleppa, F. Kling, S. Su, arXiv:1305.0002 [hep-ph], submitted to JHEP.

29. "Non-Decoupling MSSM Higgs Sector and Light Superpartners",T. Han, T. Li, S. Su, L. Wang, arXiv:1306.3229 [hep-ph], submitted to JHEP.

30. *Full nonperturbative QCD simulations with 2+1 flavors of improved staggered quarks*, A. Bazavov, C. Bernard, C. DeTar, Steven Gottlieb, U.M. Heller, J.E. Hetrick, J. Laiho, L. Levkova, P.B. Mackenzie, M.B. Oktay, R. Sugar, D. Toussaint, R.S. Van de Water, Rev. Mod. Phys. **82**, 1349-1417 (2010), [arXiv:0903.3598].

31. *Equation of state and QCD transition at finite temperature,* A. Bazavov, T. Bhattacharya, M. Cheng, N.H. Christ, C. DeTar, S. Ejiri, Steven Gottlieb, R. Gupta, U.M. Heller, K. Huebner, C. Jung, F. Karsch, E. Laermann, L. Levkova, C. Miao, R.D. Mawhinney, P. Petreczky, C. Schmidt, R.A. Soltz, W. Soeldner, R. Sugar, D. Toussaint, P. Vranas, Phys. Rev. D **80**, 104504 (2009), [arXiv:0903.4379].

32. *The strange quark condensate in the nucleon in 2+1 flavor QCD,* D. Toussaint and W. Freeman [MILC collaboration], Phys. Rev. Lett. **103**, 122002 (2009), [arXiv:0905.2432].

33. *Visualization of semileptonic form factors from lattice QCD* C. Bernard, C. DeTar, M. Di Pierro, A.X. El-Khadra, R.T. Evans, E.D. Freeland, E. Gamiz, Steven Gottlieb, U.M. Heller, J.E. Hetrick, A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, M. Okamoto, M.B. Oktay, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, Phys. Rev. D **80**, 2009, 034026, [arXiv:0906.2498].

34. *Topological susceptibility with the asqtad action,* MILC collaboration: A. Bazavov, C. Bernard, B. Billeter, C. DeTar, Steven Gottlieb, U.M. Heller, J.E. Hetrick, J. Laiho, L. Levkova, B. Oktay, J. Osborn, R.L. Sugar, D. Toussaint, R.S. Van de Water, Phys. Rev. D **82**, 114501 (2010), [arXiv:1003.5695].

35. *QCD thermodynamics with nonzero chemical potential at $N_t = 6$ and effects from heavy quarks,* C. DeTar, L. Levkova, Steven Gottlieb, U.M. Heller, J.E. Hetrick, R. Sugar, D. Toussaint, Phys. Rev. D **81**, 114504 (2010), [arXiv:1003.5682].

36. *Scaling studies of QCD with the dynamical HISQ action,* MILC collaboration: A. Bazavov, C. Bernard, C. DeTar, W. Freeman, Steven Gottlieb, U.M. Heller, J.E. Hetrick, J. Laiho, L. Levkova, M. Oktay, J. Osborn, R.L. Sugar, D. Toussaint, R.S. Van de Water, Phys. Rev. D **82**, 074501 (2010), [arXiv:1004.0342].

37. *Tuning Fermilab Heavy Quarks in 2+1 Flavor Lattice QCD with Application to Hyperfine Splittings,* C. Bernard, C. DeTar, M. Di Pierro, A.X. El-Khadra, R.T. Evans, E.D. Freeland, E. Gmiz, Steven Gottlieb, U.M. Heller, J.E. Hetrick, A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, (the Fermilab Lattice Collaboration and the MILC Collaboration), Phys .Rev. **D83**, 034503 (2011), [arXiv:1003.1937].

38. *B- and D-meson decay constants from three-flavor lattice QCD,* A. Bazavov, C. Bernard, C.M. Bouchard, C. DeTar, M. Di Pierro, A.X. El-Khadra, R.T. Evans, E.D. Freeland, E. Gamiz, Steven Gottlieb, U.M. Heller, J.E. Hetrick, R. Jain, A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, E.T. Neil, M.B. Oktay, J.N. Simone, R. Sugar, D. Toussaint, R. S. Van de Water, Phys. Rev. D **85**, 114506 (2012), [arXiv:1112.3051].

39. *The chiral and deconfinement aspects of the QCD transition,* A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H.-T. Ding, Steven Gottlieb, R. Gupta, P. Hegde, U.M. Heller, F. Karsch, E. Laermann, L. Levkova, S. Mukherjee, P. Petreczky, C. Schmidt, R.A. Soltz, W. Soeldner, R. Sugar, D. Toussaint, W. Unger, P. Vranas, Phys. Rev. **D85**, 054503 (2012), [arXiv:1111.1710].

40. *$B_s \to D_s/B \to D$ Semileptonic Form-Factor Ratios and Their Application to BR($B_s^0 \to \mu^+\mu^-$),* Jon A. Bailey, A. Bazavov, C. Bernard, C.M. Bouchard, C. DeTar, Daping Du, A.X. El-Khadra, J. Foley, E.D. Freeland, E. Gamiz, Steven Gottlieb, U.M. Heller, Jongjeong Kim,

A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, Y. Meurice, E. Neil, M.B. Oktay, Si-Wei Qiu, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, Ran Zhou, Phys. Rev. D **85**, 114502 (2012), [arXiv:1202.6346].

41. *The intrinsic strangeness and charm of the nucleon using improved staggered fermions,* W. Freeman and D. Toussaint, submitted to Phys. Rev. D, [arXiv:1204.3866].

42. *Neutral B-meson mixing from three-flavor lattice QCD: Determination of the SU(3)-breaking ratio ξ,* A. Bazavov, C. Bernard, C.M. Bouchard, C. DeTar, M. Di Pierro, A.X. El-Khadra, R.T. Evans, E.D. Freeland, E. Gamiz, Steven Gottlieb, U.M. Heller, J.E. Hetrick, R. Jain, A.S. Kronfeld, J. Laiho, L. Levkova, P. B. Mackenzie, E.T. Neil, M.B. Oktay, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, Phys. Rev. D **86**, 234503 (2012), [arXiv:1205.7013].

43. *Refining new-physics searches in $B \to D\tau\nu$ decay with lattice QCD,* Jon A. Bailey, A. Bazavov, C. Bernard, C.M. Bouchard, C. DeTar, Daping Du, A.X. El-Khadra, J. Foley, E.D. Freeland, E. Gamiz, Steven Gottlieb, U.M. Heller, Jongjeong Kim, A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, Y. Meurice, E.T. Neil, M.B. Oktay, Si-Wei Qiu, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, Ran Zhou, Phys. Rev. Lett. **109**, 071802 (2012), (editors' suggestion), [arXiv:1206.4992].

44. Lattice QCD ensembles with four flavors of highly improved staggered quarks, The MILC Collaboration: A. Bazavov, C. Bernard, C. DeTar, W. Freeman, Steven Gottlieb, U. M. Heller, J. E. Hetrick, J. Komijani, J. Laiho, L. Levkova, J. Osborn, R. L. Sugar, D. Toussaint and R. S. Van de Water, Ran Zhou, Phys. Rev. **D87**, 054505 (2013), [arXiv:1212.4768].

45. Kaon semileptonic vector form factor and determination of $|V_{us}|$ using staggered fermions, A. Bazavov, C. Bernard, C.M. Bouchard, C. DeTar, Daping Du, A.X. El-Khadra, J. Foley, E.D. Freeland, E. Gámiz, Steven Gottlieb, U.M. Heller, Jongjeong Kim, A.S. Kronfeld, J. Laiho, L. Levkova, P.B. Mackenzie, E.T. Neil, M.B. Oktay, Si-Wei Qiu, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, Ran Zhou, Phys. Rev. D **87**, 073012 (2012), [arXiv:1212.4993].

46. Leptonic decay-constant ratio f_{K^+}/f_{pi^+} from lattice QCD with physical light quarks, A. Bazavov, C. Bernard, C. DeTar, J. Foley, W. Freeman, Steven Gottlieb, U. M. Heller, J. E. Hetrick, J. Kim, J. Laiho, L. Levkova, M. Lightman, J. Osborn, S. Qiu, R. L. Sugar, D. Toussaint, R. S. Van de Water, R. Zhou, Phys. Rev. Lett. **110**, 172003 (2013), [arXiv:1301.5855].

Publications to which Elliott Cheu made significant contributions

"A search for ttbar resonances in lepton+jets events with highly boosted top quarks collected in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector", JHEP 1209 (2012) 041

"Search for supersymmetry in events with three leptons and missing transverse momentum in sqrt{s} = 7 TeV pp collisions with the ATLAS detector", Phys. Rev. Lett. 108 (2012) 261804

"Precise Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System," E. Abouzaid *et al.*, *Physical Review* D83, 092001 (2011).

"Search for charged Higgs bosons decaying via H+ -> tau nu in top quark pair events using pp collision data at sqrt(s) = 7 TeV with the ATLAS detector", JHEP 1206 (2012) 039.

Publications to which Kenneth Johns made significant contributions

"Measurement of the Top Quark Pair Production Cross-section with ATLAS in the Single Lepton Channel", ATLAS Collaboration, G.Aad *et al*., Phys. Lett. B **711** (2012) 244.

"A Search for $t\bar{t}$ Resonances in the Lepton Plus Jets Channel using 200 pb^{-1} of pp Collisions at $\sqrt{s}$ =7 TeV", ATLAS Collaboration Conference Note ATLAS-CONF-2011-087 (2011).

"A Search for $t\bar{t}$ Resonances with the ATLAS Detector in 2.05 fb^{-1} of Proton-Proton Collisions at $\sqrt{s}$ =7 TeV", ATLAS Collaboration, G.Aad *et al*, EPJC **72** (2012) 2083.

"A Search for $t\bar{t}$ Resonances in Lepton+Jets Events with Highly Boosted Top Quarks Collected in pp Collisions at $\sqrt{s}$ = 7 TeV with the ATLAS Detector", ATLAS Collaboration, G.Aad *et al*., JHEP **1209** (2012) 041.

"A Search for $t\bar{t}$ Resonances in the Lepton+Jets Final State with ATLAS using 4.7 fb^{-1} of pp Collisions at $\sqrt{s}$ = 7 TeV", ATLAS Collaboration, G.Aad *et al*., accepted by Phys. Rev. D and arXiv:1307.4568 [hep-ex].

"*Measurements of the Top Quark Pair Relative Differential Cross-Sections with ATLAS in pp Collisions at $\sqrt{s}$ =7 TeV"*, ATLAS Collaboration, G.Aad *et al*., EPJC **73** (2013) 2261.

"*Development of Large Size Micromegas Detectors for the Upgrade of the ATLAS Muon System"*, T. Alexopoulos *et al*., Nucl.Instrum.Meth. **A617** (2010) 161.

"Upgraded Readout Electronics for the ATLAS LAr Calorimeter at the Phase 1 of LHC"
S. Starz *et al*., ATLAS Liquid Argon Calorimeter Group, Nucl. Instrum. Meth. **A718** (2013) 115.

Publications to which John Rutherfoord made significant contributions

“Performance of the ATLAS liquid argon forward calorimeter in beam tests”, J.P.Archambault et al., 2013 JINST 8 P05006; http://dx.doi.org/10.1088/1748-0221/8/05/P05006

“Evaluation of the local hadronic calibration with combined beam-test data for the endcap and forward calorimeters of ATLAS in the pseudorapidity region $2.5 < |\eta| < 4.0$”, J. Pinfold *et al*., Nucl. Instr. and Meth. A 693 (2012) 74; http://dx.doi.org/10.1016/j.nima.2012.06.039

“Liquid argon calorimeter performance at high rates”, A. Glatte *et al*., Nucl. Instr. and Meth. A 669 (2012) 47.

“Performance of the electronic readout of the ATLAS liquid argon calorimeters”, H. Abreu et al., 2010 JINST 5 P09003.

“Relative luminosity measurement of the LHC with the ATLAS forward calorimeter”, A. Afonin *et al.*, 2010 JINST 5 P05005.

“Onset of space charge effects in liquid argon ionization chambers”, B. Toggerson, A. Newcomer, J. Rutherfoord, and R.B. Walker, Nucl. Instr. and Meth. A 608 (2009) 238.

Publications to which Michael Shupe made significant contributions

“Search for Quark Contact Interactions in Dijet Angular Distributions in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC”, The ATLAS Collaboration, Phys. Lett. B694 (2011) 327-345

“Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at sqrt{s} = 7 TeV Measured with the ATLAS Detector”, The ATLAS Collaboration, New J. Phys. 13 (2011) 053044

“Search for New Physics in the Dijet Mass Distribution using 1 fb^{-1} of pp Collision Data at sqrt{s} = 7 TeV collected by the ATLAS Detector”, The ATLAS Collaboration, Phys. Lett. B708 (2012) 37-54

“ATLAS Search for New Phenomena in Dijet Mass and Angular Distributions using pp collisions at sqrt{s} = 7 TeV”, The ATLAS Collaboration, JHEP 1301 029 (2013)

“A Search for Prompt Lepton-Jets in pp Collisions at sqrt{s} = 7 TeV with the ATLAS Detector”, The ATLAS Collaboration, Phys. Lett. B 719 (2013)

Publications to which Erich Varnes made significant contributions

V.M. Abazov et. al. (DØ Collaboration) “Measurement of the W Boson Helicity in Top Quark Decays using 5.4 fb^{-1} of $p\bar{p}$ Collision Data”, Phys. Rev. D **83** (2011) 032009.

T. Aaltonen et. al. (CDF and DØ Collaborations) "Combination of CDF and DØ Measurements of the W Boson Helicity in Top Quark Decays", Phys. Rev. D **85** (2012) 071106.

V.M. Abazov et. al. (DØ Collaboration) "Combination of Searches for Anomalous Top Quark Couplings with 5.4 fb^{-1} of $p\bar{p}$ Collisions", Phys. Lett. B **713** (2012) 165 .

V.M. Abazov et. al. (DØ Collaboration) "Search for the standard model Higgs boson in the $ZH \rightarrow \nu\nu bb$ channel in 9.5 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", to be published in Phys. Lett. B; arXiv:1207.5689.

V.M. Abazov et. al. (DØ Collaboration) "Combined search for the standard model Higgs boson decaying to $b\bar{b}$ using the D0 Run II data", to be published in Phys. Rev. Lett; arXiv:1207.6631.

T. Aaltonen et. al. (CDF and DØ Collaborations) "Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron", Phys. Rev. Lett. **109** (2012) 071804.

INA SARCEVIC

Refereed Publications (2009-2012)

1. "High Energy Neutrinos from Charm in Astrophysical Sources", (with R. Enberg and M. H. Reno), *Phys. Rev.* **D 79**, 053006 (2009).

2. "Higgs Production and Decay from TeV Scale Black Holes at the LHC", (with A. E. Erkoca and G. Nayak), *Phys. Rev.* **D 79**, 094011 (2009).

3. "Muon Flux from Dark Matter Annihilation", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D 80**, 043514 (2009).

4. "Neutrino Fluxes from Astrophysical Sources, the role of Neutrinos from Charmed Meson Production and Decay", *Nucl.Instrum. Meth. in Phys. Research* **A 604**, 588 (2009).

5. "Muon and Shower Flux from Dark Matter Annihilation in the Galactic Center", (with A. E. Erkoca, G. Gelmini and M. H. Reno), *Phys. Rev.* **D81**, 096007 (2010).

6. "String-Gauge Dual Description of Deep Inelastic Scattering at Small-x", (with R. C. Brower, M. Djuric, and C-I Tan), **JHEP 11**, 051 (2010).

7. "Probing Dark Matter Models with Neutrinos from the Galactic Center", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D82**, 113006 (2010).

8. "Radio Cherenkov Signals from the Moon: Neutrinos and Cosmic Rays", (with Y. S. Jeong and M. H. Reno), *Astropart. Phys.* **35**, 383 (2012).

9. "On Neutron Star Capture of Dark Matter", (with T. Guver, A. E. Erkoca and M. H. Reno), arXiv:1201.2400, submitted to *Phys. Rev.* **D**.

Invited talks in the last three years

1. "Neutrinos as Signature of Dark Matter", invited talk presented at Aspen Winter Conference on *The Revolution in Particle Physics is Here*, Aspen, Colorado, January 15-21, 2010.

2. "Dark Matter Signals with Neutrinos", talk at American Physical Society Annual April Meeting, Washington, DC, February 13-16, 2010.

3. "Neutrinos as Signature of Dark Matter", invited talk presented at workshop on *Dark Matter 2010*, Marina del Ray, California, February 23-27, 2010.

4. "Neutrinos as Signature of Dark Matter", invited talk, *Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)*, Snowbird, Utah, March 23-30, 2010.

5. "Neutrinos as Probes of Particle Physics", invited seminar, Physics Department, University of Iowa, Iowa City, Iowa, April 27, 2010.

6. "Neutrinos as Signature of Dark Matter", invited seminar, Department of Physics, University of Maryland, College Park, Maryland, May 2010 (cancelled).

7. "Small x Parton Distributions and Ultrahigh Energy Neutrino Cross Sections", Workshop on *Small x Parton Distributions*, Kavala, Greece, June 23-27, 2010.

8. "Probing Dark Matter with Neutrinos", invited seminar, Physics Department, Arizona State University, Phoenix, Arizona, November 10, 2010.

9. "Probing Dark Matter with Neutrinos", invited talk presented at Conference on *Elementary Particle Physics, Astrophysics and Cosmology (Miami 2010)* , Lago Mar Resort, Ft. Lauderdale, Florida, December 14-19, 2010.

10. "Probing Dark Matter with Neutrinos", invited talk presented at Aspen Winter Conference on *Indirect and Direct Detection of Dark Matter*, Aspen, Colorado, February 6-12, 2011.

11. "Probing Dark Matter with Neutrinos", invited talk presented at "Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)", Snowbird, Utah, January 31- February 6, 2011.

12. "Probing Particle Physics with Neutrinos", invited seminar, Physics Division, Argonne National Laboratory, Argonne, Illinois, April 20, 2011.

13. "Probing Particle Physics with Neutrinos", invited seminar, Physics Department, University of Wisconsin, Madison, Wisconsin, April 21, 2011.

14. "Probing Dark Matter with Neutrinos", invited talk, workshop on *Dark Matter: Its Origin, Models and Detection*, New Mexico Center for Particle Physics at the University of New Mexico, Albuquerque, New Mexico, May 26-28, 2011.

15. "Probing Dark Matter with Neutrinos", invited talk, *XXIIIrd Recontres de Blois, Particle Physics and Cosmology*, Chateau de Blois, France, May 29 - June 3, 2011.

16. "Ultrahigh Energy Neutrino Cross Sections", invited talk presented at Eleventh Workshop on *Non-Perturbative Quantum Chromodynamics*, l'Institut d'Astrophysique de Paris, Paris, France, June 6-10, 2011.

17. "Probing Dark Matter with Neutrinos", invited talk, *Looking at the Neutrino Sky* (NUSKY), Workshop on Cosmic Rays and Cosmic Neutrinos, ICTP, Trieste, Italy, June 20-24, 2011.

18. "Probing Dark Matter with Neutrinos", invited talk, *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2011), Moorea, French Polynesia, September 8-13, 2011.

19. "Ultrahigh Energy Neutrinos", invited seminar, Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

20. "Neutrinos as Probes of Physics Beyond the Standard Model", invited seminar, University of New Mexico, Albuquerque, New Mexico.

21. "Probing Dark Matter with Neutrinos", invited seminar, Department of Physics and Astronomy, University of Wisconsin, Madison, Wisconsin, September 28, 2011.

22. "Probing Dark Matter with Neutrinos", invited High Energy Division seminar, Argonne National Laboratory, Argonne, Illinois, September 27, 2011.

23. "QCD in Astrophysics: Atmospheric Neutrinos", invited talk, Workshop on *Frontiers in QCD*, INT, University of Washington, Seattle, Washington, October 18, 2011.

24. "Neutrino Astronomy", invited series of lectures, *International Workshop on Neutrino Physics, Dark Matter and Gamma Rays*, Taiwan National Center for Theoretical Studies, National Taiwan University, November 8-10, 2011.

25. "Probing Dark Matter with Neutrinos", invited talk presented at Conference on Elementary Particle Physics, Astrophysics and Cosmology (Miami 2011) , Lago Mar Resort, Ft. Lauderdale, Florida, December 15-20, 2011.

26. "Limits on Self-interacting Dark Matter", invited talk presented at *Dark Matter 2012*, Marina del Rey, California, February 22-26, 2012.

27. "QCD in Astrophysics: Atmospheric Neutrinos from Charm", invited talk presented at *47th Recontres de Moriond, QCD and High Energy Interactions*, La Thuille, Italy, March 10-17, 2012.

28. "Probing Dark Matter with Neutrinos", invited AstroParticule et Cosmologie Theory seminar, Universite de Paris VII, Paris, France, March 20, 2012.

29. "Constraints on Dark Matter from Neutron Star", invited talk presented at mini-workshop on *Neutron Stars and Neutrinos*, Arizona State University, Tempe, Arizona, Macrh 26, 2012.

30. "Probing Dark Matter with Neutrinos", invited seminar, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, April 17, 2012.

31. "Neutrinos as probes of Physics Beyond the Standard Model", invited talk, 24the Recontres de Blois, Particle Physics and Cosmology, Chateau Royal de Blois, France, May 27-June 1, 2012.

32. "Dark Matter and Neutron Stars", invited talk to be presented at *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2012), Moorea, French Polynesia, September 6-11, 2012.

33. "Probing Dark Matter with Neutrinos", invited talk, Conference on *Elementary Particle Physics, Astrophysics and Cosmology (Miami 2010)* , Lago Mar Resort, Ft. Lauderdale, Florida, December 16-22, 2012.

34. "Probing Dark Matter with Neutrinos", invited talk presented at Aspen Center for Physics Winter Conference on "New Directions in Neutrino Physics", Aspen Center for Physics. Aspen, Colorado, February 3-9, 2013.

35. “Neutron Star Constraints on Dark Matter”, invited talk, SnowDARK 2013 conference on Dark Matter, Snowbird, Utah, March 22-25, 2013.

36. “Dark Matter and Neutrinos”, invited talk. Conference on “Light Dark Matter: Asymmetric, Thermal and Non-thermal Dark Matter and its Detection”, University of Michigan, Ann Arbor, Michigan, April 14-18, 2013.

37. ”Atmospheric Neutrino Fluxes”, invited talk, “IceCube Particle Astrophysics (IPA) Symposium”, Madison, Wisconsin, May 13-15 2013.

38. “Limits on Dark Matter Self-Interactions”, invited talk to be presented at *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2013), Moorea, French Polynesia, September 4019, 2013.