Final Report: High Energy Physics Research at the University of Pennsylvania

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1 ATLAS Introduction

1.1 Personnel

The ATLAS group at the University of Pennsylvania consists of four faculty: Joseph Kroll, Elliot Lipeles, Evelyn Thomson and Brig Williams, and one senior researcher, Joel Heinrich. Our group benefits greatly from working together synergistically as much as possible, with postdoctoral fellows and graduate students welcoming ideas and advice from all of the faculty. There are five postdoctoral fellows: Tae Min Hong and Rustem Ospanov (Lipeles); James Degenhardt and Saša Fratina (Thomson); and Peter Wagner (Williams). There are thirteen graduate students: John Alison, Chris Lester, and Kurt Brendlinger (Kroll); Josh Kunkle, Doug Schaefer, and Rami Vanguri (Lipeles); Dominick Olivito, Elizabeth Hines, and Brett Jackson (Thomson); Ryan Reece, Jon Stahlman, Jamie Saxon, and Alex Tuna (Williams). Three of the graduate students (Brendlinger, Saxon, Tuna) are currently in their second year but are already very involved in research. Currently four of five postdoctoral fellows and nine of thirteen graduate students are based at CERN.

Our first ATLAS graduate student, Mike Hance (Williams), graduated in July 2011 and began a Chamberlain Fellowship at LBNL in August. Two postdoctoral fellows departed recently: Franck Martin (Williams) in August 2010 for a teaching position in France, and Mauro Donegà (Kroll) in April 2011 for the equivalent of a tenure-track assistant professorship at ETH, Zurich.

Personnel from the Engineering and Instrumentation group that have been actively involved in ATLAS are Rick Van Berg, Mitch Newcomer, Nandor Dressnandt, Paul Keener, Mike Reilly, Godwin Mayers, and Walter Kononenko.

1.2 Overview

The Penn ATLAS program is very broad, encompassing: physics analysis and publication; physics objects development; online event selection (trigger); detector construction, maintenance, operations, performance, and calibration; and research and development of future detector upgrades. This section is intended to give a complete and coherent overview of the Penn ATLAS group, its impact on the ATLAS experiment, and the valuable synergy between the efforts of the faculty, graduate students, postdoctoral fellows, and instrumentation group. This is followed by sections detailing each faculty members research activities.

1.2.1 Leadership & Shifts

The Penn ATLAS group has leadership roles in online and offline detector operations, trigger, physics objects, and national and international committees, as listed below.

- ATLAS Run Manager - Degenhardt (2011)
- TRT Deputy Run Coordinator - Degenhart (2010)
- TRT Software Coordinator - Fratina (July 2009 - June 2010)
- TRT Software Deputy Coordinator - Fratina (January 2009 - June 2009)
- TRT DAQ & Electronics Coordinator - Olivito (Aug 2008 - present)

- TRT DAQ & Electronics Coordinator - Hance (July 2005 - Aug 2008)
- TRT Particle Identification working group contact - Hines (July 2010 - present)
- Trigger Rate Coordinator - Lipeles (2010 - present)
- e/gamma Group Co-coordinator - Donegà (Sept 2009 - March 2011)
- Appointed Member, USATLAS Speakers Committee, Thomson (July 2009 - present)
- Elected Member, USATLAS Executive Board, Williams (July 2010 - present)
- Elected Member, ATLAS Publications Committee, Kroll (March 2011 - March 2013)

Publication Penn personnel have been, or are, editors of four publications and five conference notes. We currently serve on six editorial boards (internal review committees for publications and conference notes).

ATLAS Service Penn is one of only two US institutions that has fulfilled all of its Class 1, Class 2, and Class 3 shift obligations in 2011 (134%, 113%, 165% respectively). We expect to complete a similar number of shifts in 2012. In addition to our TRT responsibilities, our group also supports many different aspects of the ATLAS operation, including Shift Leader (Degenhardt), Trigger Shifter (Hong, Ospanov), Global Online Data Quality Shifter (Kroll, Degenhardt), and Run Control Shifter (Wagner, Lester, Olivito).

1.2.2 Physics Analysis and Publication

Our physics analysis interests include searches for new particles, especially a low-mass Higgs boson and exotic massive gauge bosons. Our major contributions are in the following areas:

- Standard model physics including W and Z physics (Kroll), inclusive direct photon production and $Z \to \tau\tau$ (Williams), and WW production (Lipeles, Kroll). Hance was the editor of the first article on direct photons; Lipeles was the editor of the first PRL on WW.
- Higgs boson searches in two channels that are particularly important at low mass: $H \to \gamma\gamma$ (Williams), and $H \to WW$ (Kroll, Lipeles). Lipeles is the editor of the WW PRL with 2.0 fb^{-1}, and Ospanov is an editor of the 5.0 fb^{-1} long paper expected to be published in early 2012.
- Exotic massive gauge bosons searches: W', Z' (Thomson, Williams). Williams was the editor of the first PRL on Z'. Degenhardt is the analysis contact of the 5.0 fb^{-1} W' search.
- Exotics and SUSY searches in the dilepton channel (Thomson).

To support our physics analysis, we have established a Tier 3 Computing Center with ~ 150 cores and 90 Terabytes of storage (maintained by Keener).

1.2.3 Contributions to the e/gamma Combined Performance Group

The Penn ATLAS group plays a central role in the group responsible for electron and photon identification. This includes defining of the selection criteria both for offline analysis and online selection (trigger), and determining of the corresponding selection efficiencies. Donegà served as one of the e/gamma group co-conveners from October 2009 to March 2011, first with Laurent Serin (LAL-Orsay) and then with Fabrice Hubaut (CPPM). Our contributions include:

- Development of the conversion reconstruction algorithm and its application to the extraction of the amount of material in the inner detector (Donegà).
- Development of an algorithm combining tracking and calorimetry information to separate converted photons from prompt electron candidates (Martin).
- Reoptimization of the offline and online electron selection criteria for initial running in 2010 and for higher instantaneous luminosities in 2011 (Alison, Lester).
- Calorimeter isolation for electron and photon identification at high-p_{T} (Hance, Olivito).

- Studies of transition radiation in electron and converted photon identification (Hines).
- Development of tools to extract the photon purity based on calorimeter isolation and their application to the measurement of the direct photon spectrum in early data (Hance).

1.2.4 Trigger

Since joining the Penn faculty in 2008, Lipeles has built up a substantial involvement in the trigger. We now provide a number of the most important tools that monitor online trigger rates, determine the resource "cost" of each trigger chain (CPU, data band-width, etc.), and predict trigger rates as the luminosity increases.

- Software framework for online cost and trigger rate prediction (Ospanov)
- Grid framework and cost ntuple production system (Kunkle)
- Validation of MC and data-based trigger rate predictions (Lipeles, Kunkle)
- CPU and bandwidth predictions (Schaefer)
- Online monitoring (Schaefer)
- Offline rate tools, and trigger cross-section monitor (Lipeles, Hong)

1.2.5 Transition Radiation Tracker (TRT) [1]

For the ATLAS detector, our primary initial contribution was the design, prototyping, production, and installation of all of the front end electronics for the ATLAS Transition Radiation Tracker (TRT). The TRT is both an integral part of the ATLAS tracking system and also a transition radiation detector which greatly enhances electron identification. Our group played a large role in commissioning all of the TRT electronics, including the off-detector systems, and in the area of TRT software. We continue to play a critical role in the operation and data acquisition of the TRT and are making major contributions in understanding and improving the performance of the TRT in terms of alignment, position resolution, time resolution, and identification of electrons based on transition radiation.

Synopsis of the TRT Electronics and Data Acquisition. To appreciate the responsibilities of the Penn ATLAS group for TRT Data Acquisition and Electronics, as well as the group's past contributions, it is necessary to have some knowledge of the scale of the TRT electronics and its design and construction.

The TRT is composed of $\sim$ 350,000 proportional tubes (straws) with 4 mm diameter. The "front end electronics", which are mounted directly on the detector, include $\sim$ 44,000 "ASDBLR" integrated circuits and $\sim$ 22,000 "DTMROC" integrated circuits. The ASDBLR provides amplification, shaping, base-line restoration, and two discriminators: low-threshold for the track position measurement and high-threshold for the detection of transition radiation photons. The DTMROC provides a digital time measurement of the leading and trailing edges, as well as a pipeline buffer, readout control, threshold setting, and testing of the ASDBLR. Penn provided all of the design, prototyping, production, and testing of the ASDBLRs and all of the analog blocks, and testing, of the DTMROCs.

The Penn ATLAS group also designed two custom packages for these integrated circuits, played a major role in the design and prototyping of the printed circuit boards for the barrel TRT (384 boards total of 12 slightly different designs), collaborating with Yale and Lund Universities,

[1] For an independent assessment of the role of the Penn group in the TRT activities, one could contact the TRT Project Leader, Christoph Rembser (Christoph.Rembser@cern.ch) or the TRT Run Coordinator, Anatoli Romaniouk (Anatoli.Romaniouk@cern.ch), both at CERN.

and shared the design and prototyping of the two different boards (3984 copies of each) for the TRT Endcaps, collaborating with CERN.

The "Backend Electronics" for the TRT consists of 48 Timing and Trigger Control boards (TTC) which provide clock, trigger, and parametric control to the front end electronics; 96 "Read Out Driver" boards (ROD) which receive the data from the front end, reformat, and transmit to the ATLAS DAQ system; 128 "TTC Patch Panel" boards which are located at the PP2 locations deep within the muon system and receive/retransmit signals from the TTC to the front end; and 192 "ROD Patch Panel" boards, also located at PP2, which receive/retransmit the signals from the front end electronics. These sets of boards were designed, fabricated, and bench tested by other institutions (Niels Bohr, Yale/UBC, and CERN). However, for various reasons, the installation into the detector, commissioning, operation, and repair when necessary of these boards has become almost entirely the responsibility of the Penn ATLAS group.

Although the low voltage system is largely designed and maintained by the Krakow group, Penn personnel make significant contributions as discussed in more detail below. All of the Data Acquisition software for the TRT, with the exception of the firmware in the TTC and ROD boards, has been provided by the Penn ATLAS group.

An oversimplification of the participation of the engineering and instrumentation personnel in this 15 year enterprise is as follows: System Design – Van Berg, Newcomer, Keener; Integrated Circuits – Newcomer, Dressnandt, Keener; Chip Packaging – Newcomer, Dressnandt; Chip Testing – Newcomer, Reilly, Van Berg; Printed Circuit Board (PCB) Design & Fabrication – Newcomer, Dressnandt, Van Berg; PCB Assembly & Testing – Mayers, Reilly; PCB Installation at CERN – Mayers, Reilly, Newcomer, Van Berg; Data Acquisition – Keener.

TRT Data Acquisition. Penn has most of the responsibility for the installation, commissioning, operation, and maintenance of the full TRT readout chain. Paul Keener, a long standing DAQ specialist in our Instrumentation and Engineering Group, developed the initial TRT DAQ system over many years and still maintains and develops the low level software. Peter Wagner, Dominick Olivito, and Jon Stahlman, currently based at CERN, have led much of the recent DAQ evolution. We support ATLAS physics runs by serving as on-call experts (Wagner, Olivito, Stahlman, Reece, Saxon). Josh Kunkle and Liz Hines made substantial contributions to the installation of off-detector electronics and are still experts for their replacement. A very condensed list of some of the tasks and responsibilities follows:

- Development of automatic readout recovery tools for TRT, which were then adopted by all subsystems, greatly improving ATLAS operational efficiency (Olivito, Stahlman)
- Timing adjustment of Clock Signals to front end to ~ 2 ns (Olivito, Stahlman)
- Investigation of low voltage problems, whether from front end boards, patch panels, or bulk supplies (Wagner, with support from Krakow)
- Development of online Data Quality monitoring for TRT (Degenhardt)
- Development of "Fast-Or" trigger from TRT, which was primary trigger for cosmic rays through the Inner Detector (Wagner, Hance)
- Tuning and monitoring of high and low thresholds (Reece, Fratina, Hines, others)
- Training of TRT shifters (Degenhardt)
- Support of test stands in Buildings 104 and SR1 (Olivito, Stahlman, Wagner, Saxon)

TRT Software and Performance. The Penn group has played a significant role in all areas of the TRT software (TRT SW) group. Fratina served as the TRT SW convener during the time when first collision data were recorded by ATLAS (January 2009 - June 2010) and is co-editor of three conference notes on calibration, particle identification, and performance. The contributions from Fratina and graduate students (Hines, Jackson, Reece, Stahlman) are summarized below:

- Determination of off-line timing calibrations to ~ 1 ns prior to collisions (Fratina)
- Determination of TRT hit-efficiency to ~ 1 % as a function of R, ϕ, and z (Reece)
- Optimization of TRT time resolution to ~ 0.6 ns per track (Fratina, Jackson)
- Coordination of R-t calibration (Fratina, with Niels Bohr Institute)
- Optimization of position resolution, yielding $\sim 118\,\mu$m in barrel and $\sim 122\mu$m in endcap including effects of our alignment effort as well (Stahlman)
- Optimization of high threshold hit efficiency for electron/pion discrimination (Hines, Fratina)

TRT and Inner Detector Alignment. Since Summer 2007, the Penn group has taken on a major role in the Inner Detector (ID) alignment effort when Kroll and Alison assumed responsibility for the TRT Alignment. Since then the Penn effort has expanded into a major contribution to the entire Inner Detector alignment with significant contributions by Brendlinger and Stahlman. Our contributions include:

- Overall alignment (Level 1) of the TRT Barrel and TRT Endcaps and the module alignment (Level 2) of the individual TRT modules (Alison).
- Substantial contributions to the Inner Detector alignment, including integration of the pixel and SCT into the same framework as is used for the TRT (Alison).
- Independent alignment (Level 3) of all 300,000 wires (Alison, Brendlinger).
- Identification of z-offsets in TRT Endcap wheels, observed only when observing residuals for positive and negative tracks separately (Stahlman).
- Identification of remaining systematic misalignments by looking at charge asymmetries in the Z mass as a function of the η and ϕ of the positive and negative muons (Stahlman).

1.2.6 ATLAS Upgrade

We have an extensive and active program on upgrades to the ATLAS detector with involvement in a new inner-detector tracking system, upgrades to the Liquid-Argon electronics, and a proposed new trigger scheme by Lipeles to deal with the very high first-level trigger rates that will occur with luminosities of 5×10^{34} cm^{-2} s^{-1}. Current activities include:

- Strips readout: Hybrid Controller Chip (HCC) and Serial Powering (Newcomer, Dressnandt)
- Liquid-Argon preamp and shaper (Newcomer, Dressnandt), and radiation hardness measurements (Kononenko)
- Development of a multipurpose wide dynamic-range programmable gain, shaping, and delay ASIC useful for the L1 calorimeter trigger (Newcomer, Dressnandt)
- Region of Interest based L1-trigger architecture for the SCT (Lipeles, Newcomer)

2 Research Program of Elliot Lipeles

Elliot Lipeles joined Penn in 2008 as an assistant professor and launched two new activities in the Penn group: trigger operations and design, and multilepton physics. These efforts built on his previous experience in trigger and DAQ on the CLEO-III and CMS experiments and multilepton physics on CDF. Both efforts are now well established on ATLAS. Lipeles also provided partial support from his start-up funding at Penn and his Alfred P. Sloan Research Fellowship for his group of two postdocs, Rustem Osapanov (2008) and Tae Min Hong (2009), and three graduate students, Josh Kunkle, Doug Schaefer (supported by NSF graduate fellowship) and Rami Vanguri. The trigger efforts are described in Sections 2.1 through 2.3, and the multilepton physics is described in Section 2.4.

2.1 Trigger Monitoring and Operations

Overview The trigger cost group at Penn focused on building tools to monitor and predict the loads placed on various trigger subsystems. Lipeles led the ATLAS trigger rate group which included Ospanov, Kunkle, Schaefer, and Hong from Penn. There were additional collaborators in the group from CERN (Monica Dunford), SMU (Aidan Randle-Conde and Steve Sekula), and NIKEF (Pieter van der Deijl). This group provided tools which played a critical role in the development of the trigger menus[2]. The trigger is a three level system with a variety of complex constraints which any configuration must work within. We monitored and predicted these loads to support data-taking and the optimization of the trigger configuration for scientific output in 2011 and 2011.

The Penn group has made several additional contributions to the trigger group to support commissioning and operations described in Section 2.2.

Cost Monitoring Infrastructure The constraints or "costs" related to the trigger menu begin with the trigger first level (L1), implemented in hardware, which cannot accept at a larger rate than the ATLAS subsystems can readout. The data are then buffered in Readout Subsystems (ROSs), from which a level-2 (L2) CPU farm extracts the relevant subset of data useful for refining the selection made at L1. This calculation is limited by the CPU time available, the maximum rate at which data can be requested from the ROSs, and in its total output rate. The final level, called the Event Filter (EF), builds the full events and further processes the data in a second CPU farm which is also limited in its available CPU. Ultimately, the ATLAS EF output rate is limited by the availability of offline computing.

In order to monitor these loads, Ospanov has written a detailed framework for efficiently recording trigger decisions, ROSs requests, and CPU consumption. This system runs online as monitor and is used offline to make cost predictions. An example of its use as a monitor occurred when the ROS systems first reached the request rate limits: the online ntuples were used to identify a problem in the menu that caused an event to request the same data multiple times.

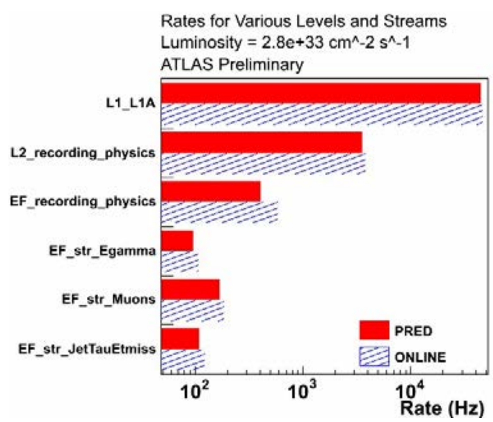

Figure 1: *Comparison of data-based predictions with online rates*

Trigger Rate Prediction Tool One of most important applications of this tool is the prediction of trigger rates from online data. These rate prediction tools are used on a daily basis by approximately a dozen trigger menu experts and trigger slice (egamma, muon, tau, ...) coordinators to implement ATLAS physics priorities. The procedure works by taking an "enhanced-bias" sample of triggers which is a simplified level-1 only trigger menu whose selections can be inverted by an offline calculation to get an unbiased sample which has enhanced statistics for the events of greatest interest (most likely to be selected by a full menu). This data sample is then processed offline with new or modified L2 and EF algorithms to produce ntuples from which one can calculate detailed trigger rate predictions for each selection, combination of selections, or levels of the menu as a whole. These predictions take 5-10 minutes, meaning that menu experts can iterate frequently to formulate a menu. Figure 1 shows the high quality of the current predictions.

[2] A trigger menu is the list of specific event selections used online.

This data-based procedure has several advantages over the Monte-Carlo-based procedure used before data taking began. First, using actual data assures greater reliability. A second key issue is that the LHC has a 40 MHz beam crossing rate, so it is not practical to simulate even a full second of operations. The MC-based procedures are still supported and studied, both to improve the understanding of the trigger system and to simulate environments that the LHC has yet to produce. The primary coding for the rate predictions was done by Ospanov, with Dunford (CERN) contributing several important parts of the "enhanced-bias" predictions and their validation.

Kunkle has developed a grid infrastructure to produce the cost monitoring ntuples for proposed trigger menus. These ntuples have to be produced every time the algorithms in a trigger menu change or a new enhanced-bias run is taken and is effectively part of the algorithm validation. Schaefer continued support of this operational task until the end of the 2012 data-taking.

Some trigger rates scale non-linearly with the number of collisions (pile-up) in a beam crossing. To model this effect in the predictions, we are implemented a system to use the number of reconstructed vertices in an event (beam crossing) as a measure of the in-time pile-up. Lipeles and Ospanov worked closely with Randle-Conde (SMU) to develop these predictions.

Trigger Rate Access Infrastructure In validating the prediction code described above, we found that it was extremely difficult to access the trigger rates observed online after data-taking had stopped. In order to rectify this problem, Lipeles and Ospanov wrote an infrastructure to access these rates in detail and make comparisons between different runs and predictions. This tool is in regular use on ATLAS and has been maintained and developed by Hong.

A second project, along the same line of allowing experts to monitor the long term behavior of triggers, is called "XMon" for trigger cross-section monitor. This a web-based tool developed by Hong to allow users to dynamically request a plot of the observed trigger rates and cross-sections, plotting them as a function of luminosity or time. Figure 2 shows a snap shot of the web page. The first version of the tool was made available in 2010. We maintained this tool on an on-going basis, including implementing new features requested by the trigger group.

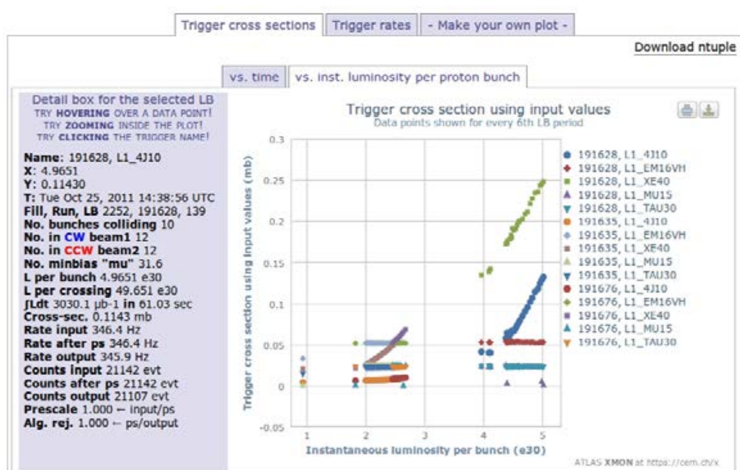

Figure 2: *XMon: Cross-section monitor page*

Hong also worked with an undergraduate to make fits to the scaling of the trigger rates with the luminosity and pile-up. These fits can be used for planning and to make live rate predictions which would allow shifters to identify changes in the operation of the trigger during data-taking (unexpected changes would be an indication of a problem).

ROS/CPU Monitoring and Predictions In addition to trigger rate limitations, the L2 and EF systems are also limited by CPU and data (ROS) requests. Schaefer has developed monitoring and predictions for CPU and ROS request rates based on the cost monitoring infrastructure. The monitoring work consists of condensing the raw information in the online monitoring ntuples into

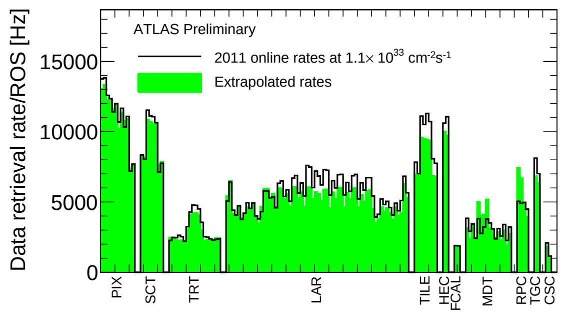

Figure 3: *Readout Subsystem (ROS) request rate predictions*

web pages that allow users to see which algorithms are requesting data and using CPU. These procedures were used to evaluate a plan to recable the pixel detector ROS system to balance the load across the system. Figure 3 shows a validation comparing a prediction to the actual rates observed online. This effort allows ATLAS to operate within 10% of the hardware limits. It is also used to study the scaling of the CPU and ROS request rate requirements with instantaneous luminosity and pile-up. We received requests on a weekly to monthly basis to support menu group and hardware planning activities.

2.2 Additional Contributions to the ATLAS Trigger Group

Ospanov served as a online trigger menu expert and contributed to the core trigger software development. Hong developed an online monitor of the prescale configuration that assures that the L2 and EF are actually implementing the prescales as defined in the trigger menu. The menu expert is a complex position requiring significant control room presence as well as being on call approximately one week out of six. The task involves maintaining the specific trigger menus used each day, diagnosing problems, and implementing fixes and improvements. Our involvement in this effort was strongly synergistic with our tool development effort since we were able to identify needed tools and provide them.

2.3 Trigger Upgrade

Lipeles has proposed a strategy for the addition of tracking information to the L1 trigger for the HL-LHC[3]. The strategy builds on the concept of a region of interest in the current system. The first level of the trigger is split into two levels: L0 and L1. The beam synchronous L0 resembles the current L1. After an L0, all the front-end chips move the data into a new asynchronous second buffer. Because the second buffer is only filled at the L0 rate, the time a given size buffer corresponds to is much longer than a buffer being filled at the beam crossing rate. This means we can support a long ($\approx 256\mu s$) L1-latency. During this time, the data in a region of interest defined by the L0 is extracted from the front-ends, and track finding and fitting algorithms are run. The Penn instrumentation group and the ATLAS strip readout working group have implemented a prototype of the required buffering and communication scheme in the strip readout front-end chip under development, described in Section 6.2.

[3] Lipeles presented a review of the track trigger motivation and possible methods at the TWEPP11 conference [1].

2.4 Multilepton Physics

Lipeles has established a multilepton physics program in collaboration with Kroll. The focus is on developing expertise in detector and modeling issues that directly impact the sensitivity of the $H \to WW$ analysis, particularly at low mass, while putting the infrastructure into place to address other physics issues. Multilepton physics includes final states with three or more electron, muon, or missing transverse-energy ($\not{E}_T$) objects in an event. This includes final states like $ll\nu\nu$, $lll\nu$, and $llll$, which in the standard model come from the heavy-diboson (WW, WZ, and ZZ) and $t\bar{t}$ processes. This class of physics provides access to real and virtual W and Z bosons which must couple to the mechanism of electroweak-symmetry breaking by definition. Furthermore, the decay chains of many possible new physics processes are likely to involve leptons (SUSY, extra-dimension, ...).

The students and postdocs most closely associated with Lipeles in this effort were graduate students Kunkle, Schaefer, and Vanguri and postdocs Ospanov and Hong. Working with Kroll were graduate students Lester, Alison, and Brendlinger.

This effort required both low- and high-level tools. The low-level tools take selected lepton candidates and turn them into calibrated objects for which the identification efficiencies, trigger efficiencies, jet and photon misidentification rates, resolutions, and fake $\not{E}_T$ distributions are known. Of particular relevance are the lepton and $\not{E}_T$ fake rates as these are what distinguish these final states from the much more common multijet, W, and Z final states. The high-level part of the framework is a systematic assembly of the final states, including the appropriate weighting of the Monte Carlo and data events based on the luminosity, expected cross-sections, and calibrations. We have implemented the core of this framework and exploited it to study the detector performance and derive physics results.

The core infrastructure, primarily developed by Kunkle and Ospanov, is designed to be independent of input format. We primarily used the AOD (analysis object data) format which contains more information and allows a broader range of studies than the more commonly used D3PD. These tools were synergistically being used for several other Penn efforts described in other sections: electron id studies (optimization and B-layer hit efficiency) in Section 3.3, and same-sign dileptons in Section 4.2.

Analysis Projects:

Standard Model *WW* Lipeles served as the editor of the PRL on the first measurement of the WW cross-section by ATLAS [2]. This work was performed by a group of about 39 scientists. Our main contributions were the modeling and understanding of fake leptons and fake $\not{E}_T$.

Higgs decaying to *WW* Lipeles served as the editor of the 1.7 fb^{-1} conference note for Lepton-Photon 2011[3] and was an editor of the 2 fb^{-1} PRL. Ospanov was an editor of the 5 fb^{-1} long paper expected to be published in early 2012. This is a key early physics goal of ATLAS with 66 official internal authors. We ae one of the main groups involved, currently contributing many studies on fake leptons and fake $\not{E}_T$. In addition, we spend significant effort in investigating data anomalies. Kunkle in particular has done a lot to rule out possible sources of the moderate excess in $\mu\mu$ events, which is ultimately degrading the current limits.

Standard Model $ZZ \to ll\nu\nu$ Kunkle applied his understanding of $\not{E}_T$ to the $ZZ \to ll\nu\nu$ process, which can be modified by new physics processes such as resonances decaying to ZZ, anomalous triple gauge couplings, and other Z plus invisible processes. This final-state has ≈ 60 times larger branching fraction than the cleaner $ZZ \to 4l$ final-state. To avoid the dominant WW background, we only look at large Z p_T. Although this loses a large part of the acceptance gain over $ZZ \to 4l$, the region at high p_{T} is of particular interest for new physics. A specific challenge is that the fake $\not{E}_{\mathrm{T}}$ control regions used in the SM WW and $H \to WW$ analyses are the signal region. We in the middle of investigating using γ+jet events to constrain the background in-situ.

Technique Development Specific techniques we are developing to improve these important analyses are:

Fake Lepton Modeling We are developing more sophisticated methods for the modeling of fake leptons. This is a key issue for the $ll\nu\nu$ final-state because a single $W \to l\nu$ with an additional jet misidentified as an electron or muon is otherwise indistinguishable from an $ll\nu\nu$ event. The main work on this is by Alison (electrons), and Schaefer and Ospanov (muons). We continue to develop new procedures to improve the reliability of our modeling, such as the new method for handling the differences between fakes from heavy and light jets described in Section 3.4, which is a collaboration with Olivito. This addresses a long standing issue with the modeling procedures that even predates the LHC experiments.

Fake Missing Energy Drell-Yan events, $Z/\gamma^* \to ll$, can be misidentified as $ll\nu\nu$ if large missing energy is reconstructed even though there were no neutrinos present. Kunkle is developing methods to understand the sources of fake $\not{E}_{\mathrm{T}}$ and estimate the uncertainty on this background. In particular, we use the peak region, $|m_{ll} - m_Z|$, which is excluded from the SM WW and $H \to WW$ signal regions, to quantify the quality of the modeling. We then use this either to define the systematic uncertainty (SM WW) or validate the simulation driven estimate ($H \to WW$).

Track $\not{E}_{\mathrm{T}}$ With increasing pile-up, we expect the quality of the calorimeter-based $\not{E}_{\mathrm{T}}$ calculations to degrade. This has already be seen significantly in the current data. One handle to improve this situation is to use a missing energy quantity based on the tracking system. Because the tracking system provides precision vertex information, we can calculate the missing energy for the specific vertex we are interested in (i.e. containing other leptons or jets in a signature). Vanguri did initial work delivering a workable track $\not{E}_{\mathrm{T}}$.

Multivariate Analysis Techniques (MVA) and Limit Setting Procedures Ospanov implemented a k-nearest neighbors, kNN, algorithm for use in discrimination $H \to WW$ from WW in a Higgs search. The results were compared in detail with other options in a workshop organized by Hong. Along with Schaefer, Ospanov and Hong established the procedures for making the comparisons. The performance was comparable to the more complex boosted-decision tree and matrix element methods. We also applyied our understanding of limit setting procedures from these efforts to studies of the impacts of systematics on the $H \to WW$ analysis. Ospanov is a leader in the $H \to WW$ MVA effort.

Optimization of Low-p_{T} Lepton Selections $H \to WW$ is well known as a potential discovery channel for an intermediate mass $135 < m_H < 200$ GeV Higgs, but it could also be used in the low mass region ($115 < m_H < 135$ GeV). The current limits from ATLAS and CMS differ greatly in this region because ATLAS only uses $p_{\mathrm{T}} > 15(\mu), 20(e)$ leptons while CMS uses down to 10 GeV in both electron and muons. ATLAS lepton selections below 20 GeV have not yet been studied in detail. We are currently doing so and believe that there are several avenues for improvement, including more detailed understanding of the impact on pile-up on isolation and how to suppress its effects. We are investigating track vertexing, the correlation of tracking and calorimetry, and track and cluster energy thresholds as possible handles to improve background rejection as the pile-up continues to increase. We believe that this effort will allow use to place limits with the $H \to WW$ down to 115 GeV and will also have a range of applications in new physics searches.

3 Research Program of Joseph Kroll

My entire career has been at the energy frontier: I was a Harvard graduate student on UA1 at the CERN Sp$\bar{p}$S (1984-89), a post-doc at EFI/Chicago on OPAL at LEP (89-93) and then a Fermilab Wilson Fellow (93-97) and Penn faculty (97-present) on CDF. I began working on ATLAS in 2007, qualifying for authorship in June 2008. During the past three years, the members of my research team have been post-doc Mauro Donegà (now an assistant professor at ETH/Zurich) and graduate students John Alison (6th year), Chris Lester (4th year, funded by a DOE SCGF) and Kurt Brendlinger (2nd year). Their contributions to ATLAS include co-leading the e/gamma combined performance group (Donegà), mapping the inner detector material with photon conversions (Donegà, Lester), leading the alignment of the TRT (Alison, Brendlinger), leading the reoptimizing of electron identification for both online event selection (trigger) and data analysis (Lester, Alison) and developing a neural-network-based electron identification (Brendlinger, Lester, Alison).

In physics we have contributed to the first observation of W and Z bosons by ATLAS, and we have made major contributions to the first measurement of the W^+W^- cross section and the search for the standard model Higgs boson in the WW final state. The WW work is carried out in collaboration with my colleague Elliot Lipeles and his research team.

In addition to my participation in the above activities through my post-doc and graduate students, I contribute to ATLAS by taking data quality shifts in the ATLAS control room (ACR), and I am serving (from March 2011 to March 2013) as an elected-member of the twelve-member ATLAS Publications Committee. In my capacity as a member of this committee, I serve on three editorial boards, resulting in three preliminary conference results [4–6] and two publications [7, 8]

3.1 Map of Inner Detector Material with Photon Conversions

When Mauro Donegà joined the Penn group in 2008, he had already initiated (as a CERN Fellow on ATLAS) the research program to measure the material in the ATLAS Inner Detector (ID) using reconstructed photon conversions in the ID material with the goal of comparing these measurements to the material included in the ATLAS GEANT detector description. This work came to fruition in the past three-year period.

The material in the ID is equivalent to 0.4 radiation lengths (X_0) at $\eta = 0$, increasing to 2.5 X_0 in the inner detector services at larger η. Electrons radiate between 20% and 50% of their energy (depending on their pseudorapidity) before leaving the SemiConductor Tracker (SCT) and, in the same region, between 10% and 50% of photons convert into an electron-positron pair. The material has a detrimental impact on the reconstruction of electrons and photons, and the precise measurement of the material in the ID is critical for modelling their resolution, *e.g.*, for $H \to \gamma\gamma$.

In order to obtain sufficient statistics for this precise measurement, a major portion of this project was developing algorithms tuned for efficient reconstruction of low-momentum photon conversions. These algorithms exploit the TRT particle identification capabilities. The first proton-proton collisions at the LHC were used to test these tools, validate the simulation of conversions and extract the first material distributions as documented in a paper [9] co-authored by Donegá. This study revealed misplaced material (pixel support structures) in the simulation and showed that the total amount of material in the ID up to the radius of the first layer of the SCT was correctly described to within 10%.

In Spring 2010, Chris Lester began studying conversions occurring in the outer layers of the SCT, which could only be reconstructed using tracks using TRT information alone. As part of this work, Lester found that events with high-occupancy in the TRT were the result of rare bursts of noise in the TRT electronics and recommended a criteria to reject events with these noise bursts in collision data. Lester substantially improved the efforts in material mapping by suggesting the use of conversions originating close to the primary interaction point and by suggesting a redefinition of the size of the normalization region used in the measurement (beam-pipe).

3.2 Inner Detector Alignment

Since Summer 2007, the Penn group has played a major role in the alignment [10, 11] of the ATLAS Inner Detector (ID), with graduate student John Alison leading the effort for the TRT Alignment. In Summer 2010, incoming graduate student Kurt Brendlinger joined the effort. This responsibility includes both performing the TRT alignment within the ATLAS ID Alignment group and validating the alignment performance.

The TRT alignment takes place in three stages [11] or "levels," with each higher level corresponding to an increased number of degrees of freedom (DoF). In the first stage (Level-1), the TRT barrel and each TRT endcap are moved as three independent rigid bodies with three translational DoF[4] and three rotational DoF. In the second stage (Level-2), 96 barrel modules and each set of 40 endcap modules are translated and rotated. Finally at the third stage (Level-3), individual straws are moved. Important milestones in the TRT alignment include using cosmic-ray data to perform the first barrel Level-1 alignment (summer 2007), the first barrel Level-2 alignment (summer 2008) and the first endcap Level-1 and Level-2 alignments (fall 2008). As part of this initial work, Alison developed a method for splitting trajectories from cosmic rays into two independent parts, allowing comparison of track parameters; this method was adapted by the pixel and SCT alignment groups as well.

In summer 2009, Alison made substantial extensions to the TRT alignment algorithm [12] and software including adding the capability of moving individual straws (Level-3). The pixel and SCT used separate stand-alone alignment algorithms. Daniel Kollar (CERN) adapted the TRT algorithm to perform the alignment for the entire ID. Alison played a key role in facilitating this transition and, with the experience gained from developing and maintaining the TRT software, became involved in the initial alignment of all three ID subsystems.

The Level-1 and Level-2 alignments of the barrel and endcap TRT using 900 GeV (fall 2009) and 7 TeV (spring 2010) collision data [10] confirmed the alignment parameters in the barrel that were determined using cosmic-ray data and resulted in a substantial improvement in the endcaps. A Level-3 alignment was not practical until sufficient statistics of tracks became available in summer 2010 from 7 TeV collision data; the major focus of the alignment since then has been this straw-by-straw alignment. This work [11] was carried out by Brendlinger with guidance from Alison.

The Level-3 alignment has over 700,000 dof—three orders of magnitude more than Level-2—resulting in a significant increase in complexity, which poses challenges both in terms of solving for the large number of parameters and interpreting the results.

The wire-by-wire alignment has brought a substantial improvement [11] in the ID tracking performance and represents a significant gain in our understanding of the detector geometry. Systematic misalignments of order millimeters in the TRT have been corrected, removing biases

[4] There are only two translational dof in the barrel, since no measurement in the z coordinate along the beamline is made in the barrel.

in the track residuals [5] and improving the overall residual resolution by $\sim 20(10)$ microns in the endcaps (barrel).

3.3 Optimization of Electron Identification

My group has been integrally involved in supporting and optimizing the official offline and online electron identification criteria for ATLAS over the past year. Electron identification at ATLAS is accomplished through a cut-based approach using calorimeter-based and tracking-based identification variables. Three operating points—loose, medium, and tight—are defined, which provide increasing rejection against prompt electron backgrounds from hadrons and photon conversions. These operating points are used both offline, for electron selection in physics analysis, and online, in the high level trigger (HLT) used to collect data. In fall 2010, one of the primary ATLAS triggers, critical for almost every analysis using high-E_T electrons, was e20_medium, which requires an electron with $E_T > 20\,\mathrm{GeV}$ satisfying the medium identification criteria. With increasing instantaneous luminosity, the output rate of the e20_medium was approaching allocation limits dictated by the overall HLT output bandwidth. The conveners of the e/gamma combined performance group, Mauro Donegà (Penn) and Fabrice Hubaut (CPPM), charged John Alison and Chris Lester with improving the e20_medium rejection, reducing the output rate to fall within the allocated bandwidth, while keeping high signal efficiency, crucial for the the large number of physics analyses using the trigger. This work is being carried out in stages, which are described below. In all cases, the offline selection criteria must follow any changes in the online selection criteria (menu), so, for example, if the medium criteria is made more restrictive in the trigger, the corresponding offline selection must be tightened in a similar way.

The Penn group gained responsibility for the electron identification based on the work by Alison and Donega in the detector commissioning associated with the first W and Z measurements. In summer 2010, the initial electron selection, which was optimized on simulation, cut too harshly on mis-modeled shower-shape variables, leading to a poor electron signal efficiency. In this first stage, Alison proposed the "robust" electron identification, which was tuned on the initial data, leading to increased signal efficiency. The robust selection was adopted by the eγ performance group, incorporated online in the trigger, and used for all 2010 physics analyses using electrons.

With the start of the 2011 data taking and the increase in luminosity provided by the LHC, the output rate of the e20_medium trigger, using the robust selection, became unsustainable. The eγ performance group tasked Alison and Lester with the second stage of optimizing the electron selection to achieve an output rate sustainable up to integrated luminosities of $5 \times 10^{32} cm^{-2} s^{-1}$. Using control samples in 2010 data for both signal and backgrounds, they achieved electron optimization that brought a 30% improvement in rejection at no cost in signal efficiency. The new criteria were delivered in January 2011; they became standard for all analyses using electrons and were used for the primary electron trigger until May 2011.

To re-optimize the electron identification criteria, Alison and Lester developed a novel method to correct for mismodeled selection quantities in the Monte Carlo samples based on Z boson tag-and-probe sample from data. This method was used to develop corrected Monte Carlo signal samples for lower E_T (10–20 GeV) electrons, making the simulation reliable for optimization where data from W and Z decays are statistics-poor.

Alison and Lester performed a third re-optimization of electron identification in May 2011 designed to sustain the e20_medium trigger rate for LHC collisions at $10^{33} cm^{-2} s^{-1}$. They developed an entirely new menu—loose++, medium++, and tight++—to be used both online and

[5] The TRT track residual is the difference between the particle position predicted by the fitted trajectory and the measured position from the wire.

offline. Loose++ provides similar efficiency ($\sim 95\%$) compared to the previous loose selection with background rejections three to four times better. The Medium++ operating point was driven by the bandwidth limitations of the HLT and offers efficiencies close to the previous medium selection with rejections similar to the old tight selection. Tight++ improves both the efficiency and rejection over the previous tight definition.

The ++-menu has become the standard electron identification at ATLAS since the migration of the trigger from e20_medium to e22_medium1 (based on medium++) in August 2011. The menu is currently integrally important to the sensitivity of ATLAS Higgs searches, including $H \to WW$ and $H \to ZZ \to 4l$, as well as a number of SUSY and exotic searches.

Currently, the Penn group is leading a number of projects toward improving electron identification. Recently high luminosity runs have indicated that a number of electron identification variables are sensitive to pile-up. Alison and Lester are currently investigating strategies for correcting these sensitive variables and providing a robust cut-based electron identification for the start of running in February 2012. At the same time, Alison, Brendlinger and Lester are developing multi-variate electron identification on the same time scale. This is done in conjunction with Penn efforts in multivariate photon identification, conducted by Jamie Saxon and Brig Williams. Preliminary studies suggest substantial improvements can be made in background rejection over cut-based identification, while maintaining high efficiency.

Anticipating the need for further rejection to maintain a low-E_T single electron trigger, Alison and Lester are currently developing and testing a further improvement to the trigger by adding isolation. Their recommendations will allow the operation of the single electron trigger unprescaled at 25 GeV (the corresponding unprescaled electron trigger at CMS is currently above 50 GeV). Alison has also developed a set of low-E_T multi-lepton triggers for signal as well as control triggers for background samples to maintain the sensitivity of many SUSY, Higgs and standard-model analyses as low-E_T single electron triggers become increasingly untenable. These triggers are currently collecting data as part of the ATLAS standard model trigger menu.

To support the work and plans in developing electron identification, Alison and Lester have invested considerable effort in improving electron identification efficiency measurements, especially at lower energies (10-20 GeV). For instance, their recommendations for isolation-template-fitting in background subtraction and improved selection in the W tag-and-probe analysis have eliminated a 15% systematic discrepancy with respect to the efficiencies measured with Z electrons. They are also developing a technique for cross-checking these efficiencies using Z decays to tau leptons (which subsequently decay to electrons).

3.4 Standard Model WW and $H \to WW$

I collaborate with Professor Elliot Lipeles in a physics program described in section 2.4 that addresses signatures with two oppositely-charged leptons (ee, $\mu\mu$, $e\mu$) and missing transverse energy from neutrinos. We have made major contributions to the first measurement of the standard model $W^+W^- \to \ell\ell\nu\nu$ cross-section [2] and the current search for the Higgs decaying to the same WW final state [3]. We have prepared an analysis framework that enables us to reproduce all aspects of these two analyses, and we have chosen to focus on pieces of the analysis that are particularly challenging. One of these areas is the determination of the background due to the production of a W boson with associated QCD jets: the leptonic W decay produces a high transverse momentum lepton and a significant momentum imbalance, and a jet mimics the signature of a second charged lepton, leading to the apparent same final state as the signature.

At the suggestion of Lipeles, John Alison began work on understanding how to determine this background in 2009. The rate at which jets are misidentified as leptons is not expected to be accurately described in the simulation because the misidentification is due to rare fragmentation processes or interactions with the detector. This background is modeled from a control sample dominated by W+jets events. This sample is constructed by requiring one fully-identified lepton and one lepton-like jet that resembles an electron, but fails the full electron-identification criteria. The W+jets background is then estimated by scaling the control sample by a p_T-dependent fake factor f. The factor f is the ratio of fully-identified leptons to lepton-like jets measured in QCD jet events.

In order for this procedure to produce an accurate estimate of this background, the factor f must be independent of event environment, which is achieved by careful definition of the lepton-like jet selection (referred to as a denominator object as it is the denominator of the fake factor). This denominator definition was studied to minimize the dependence on the p_T of the other jets in the event, but maintain a large enough rate that the statistical uncertainty on the predicted W+jets backgrounds was not too large.

Alison has developed a detailed model for jets that are misidentified as electrons. The procedures he derived were merged with those of Tatsuya Masubuchi (Tokyo) to make an overall more robust estimate, both for the measurement of the standard model WW cross-section as well as in the search for $H \to WW$. Alison's contributions include understanding the importance of the impact of isolation on the denominator definition, including prescaled triggers to achieve statistically more precise measurements of f and, most recently, evaluating the possible variation in f due to differences in heavy flavor content of the various data samples used to measure this factor. This latter work was especially important for determining this background in same-sign dilepton searches (see Sec. 4.2). The procedure for the W+jets background estimate is checked using a data sample with the similar selection criteria as the signal selection except that the two charged leptons are required to have the same charge.

4 Research Program of Evelyn Thomson

The physics interests of the Thomson group are searches for exotic massive gauge bosons and searches for supersymmetry. The group has made and is making significant contributions to the successful operation of the Transition Radiation Tracker and its use in electron identification. There is interest in future hardware research with the Instrumentation group on ATLAS upgrade projects, described elsewhere in this report, starting during the 2013-2014 shutdown.

Thomson started her group on ATLAS in 2007, after working in Top Quark Physics on CDF and serving as convener from 2004-2006. With the expectation that LHC collisions were imminent in 2008, Thomson recruited two postdocs to work on commissioning the TRT, understanding the performance of the TRT, and physics analysis with the first data. She supported both postdocs from 2007 through 2010 from her OJI award, an Alfred P. Sloan Research Fellowship, and start-up funding from the University of Pennsylvania. Thomson served on the department graduate student recruitment committee for several years and helped recruit eight graduate students to Penn's current ATLAS group. Thomson earned tenure at Penn in summer 2010.

Her research group currently consists of the two original postdoctoral fellows (Dr. James Degenhardt, Dr. Saša Fratina) and three graduate students (Dominick Olivito, Elizabeth Hines, Brett Jackson), who finished the first of two years of graduate classes in spring 2007, 2008, and 2009.

- Postdoc Degenhardt has made extensive contributions to the operations of ATLAS and the TRT and is leading the search for an exotic massive W' boson in the full 2011 dataset.

- Postdoc Fratina has studied the performance of the TRT and is working on searches for supersymmetry.
- Graduate student Olivito is expected to defend his thesis by the end of 2012 on a search for anomalous inclusive production of same-sign dileptons with the full 2011 dataset. Olivito also worked on the first search for a Z' boson with the 2010 dataset. Olivito is a DAQ expert for the TRT and made enormous contributions to the commissioning and operation of the TRT from 2007 through 2010. Funding is requested for Olivito for the period June-December 2012.
- Graduate students Hines and Jackson are expected to defend their theses on searches for supersymmetry using the full 2012 dataset. For TRT performance, Hines has studied electron identification with transition radiation, and Jackson has improved the measurement of a charged particle's time of passage through the detector.

4.1 Searches for exotic massive gauge bosons.

Many models predict new massive resonances such as Z' or W' bosons [13]. The main experimental challenges are optimizing the efficiency for identification of high p_{T} leptons, understanding the resolution on the muon momentum at the highest momenta, understanding the $\not{E}_{\mathrm{T}}$ resolution, and estimating in a robust manner the relatively small backgrounds from standard model processes.

James Degenhardt is now the contact person for the search for an exotic W' boson with the full 5 fb^{-1} of the 2011 dataset, expected to be presented at winter conferences in 2012 and published shortly thereafter. This is a group of about 10 scientists, mainly graduate students from other universities. James contributed significantly to the summer 2011 search with 1 fb^{-1}, now published in PLB [14]. James is studying the $\not{E}_{\mathrm{T}}$ resolution, which affects the transverse mass distribution that is critical to this search. He presented his recent studies at the ATLAS Jet/Etmiss hadronic calibration workshop in Stanford in September 2011. He is also estimating several of the systematics on signal acceptance and background estimates in the electron channel, including the effects of the isolation and $\not{E}_{\mathrm{T}}/\ E_{\mathrm{T}}$ selection requirements.

Dominick Olivito contributed significantly to the first search with ATLAS data for a Z' boson, published in PLB [15]. He studied several additional electron identification requirements in order to reduce the QCD background, including calorimeter isolation and the requirement of a pixel B-layer hit to reduce background from photon conversions. He performed a fit to the calorimeter isolation in order to estimate the level of the QCD background. The background distribution was taken from a control sample of data with some of the identification cuts reversed. The signal distribution was taken from data, using electrons from W and Z boson decays. Dominick studied corrections to the isolation, working with Penn graduate student Mike Hance. The corrections account for leakage from very high energy electrons, necessary in order for these relatively low energy electrons to model the isolation distribution around the much higher energy electrons from a possible Z'.

With the 2011 dataset, Dominick has continued his studies of calorimeter isolation for electrons in the context of the electron/photon combined performance group. Note that the corrected calorimeter isolation variable is very important for the efficient selection of high p_{T} electrons in the searches for W' and Z' bosons, as well as all other ATLAS searches for high p_{T} electrons. In particular, he has studied the effects of pile-up and has developed corrections for the extra energy associated with pile-up. He chaired the session on isolation at the e-gamma workshop in October 2011.

James Degenhardt and Brett Jackson also have contributed to the Z' search in the muon channel and the muon combined performance group's high p_{T} muon task force. James studied the energy loss and charge misidentification rate of very high p_T muons for the first Z' search. He also cross-checked several studies of the momentum resolution and offsets between postively and negatively charged muon, which are essential for systematics on the transverse mass and the dimuon mass. One of the main goals of the high p_T task force is to expand the acceptance for the muon channel (currently only 40% compared to 70% for electrons) by adding muons with hits in only 2 detector stations. James has studied a method to compare the amount of $\not\!\!E_T$ in events with two muons in order to identify poorly-measured muons and thus reduce long tails in dimuon mass. Brett has studied calorimeter and track isolation for muons, including the effects of pile-up. Brett developed a fit to the track isolation in order to estimate in data the level of the QCD background. He found that the QCD background is also very small (0.5%) for 2-station muons.

Of future interest is a model with a B-L symmetry, from the intersection of recent work by Penn theorist Burt Ovrut [16] and Wisconsin theorists Barger, Spinner, and Perez [17].

4.2 Searches for exotics and supersymmetry

We are beginning a new effort to search for evidence of Exotic and SUSY physics in the dilepton channel. We have already made substantial progress in the exotics search for same-sign di-electron production. In SUSY, we plan to contribute to the central result on direct gaugino production, starting with the 2011 dataset for winter conferences 2012, and to develop searches for gluino-mediated stop production and compressed spectra. Note that the November 2011 re-organization of the SUSY group has created working groups dedicated to each of these areas, indicating the high level of interest in these searches.

We are starting to contribute to the direct gaugino search with comparisons of muons (Jackson) and electrons (Hines) between releases 16 and 17. Jackson has recently implemented the current SUSY dilepton cut-flow in an SFrame-based analysis framework from Olivito. This framework is shared with Thomson, Fratina, and Hines. The sensitivity could be increased by lowering the electron E_T threshold from the current threshold of 20 GeV to 10 GeV. In order to achieve this, the fake rate and efficiency for identifying electrons in this p_T range needs to be well understood. Olivito has further developed a fake estimate, as described below. Fratina, with ATLAS collaborators from the e/γ working group, is studying a sample of $J/\psi \to e^+e^-$ candidates. One idea is to use the TRT performance work of Hines and Fratina to estimate the background contamination in the J/ψ, W, and Z samples in this p_T range, where the TRT provides excellent discrimination. This work complements the $H \to WW$ search by the Penn groups of Lipeles and Kroll.

Search for same-sign dileptons. Dominick Olivito is the main contributor to the inclusive search for anomalous production of same-sign leptons in the dielectron channel. The same-sign lepton scenario has very small backgrounds from standard model processes, mainly from fakes or charge mis-identification of Z/γ. This search is well-motivated by several models, including SUSY chargino-neutralino production, heavy Majorana neutrino decays, and doubly-charged Higgs decays. Therefore, the search is designed as an inclusive search and is not limited to a particular number of jets or amount of $\not\!\!E_T$. The plan is to set a limit on production cross section times branching fraction as a function of the invariant mass of the dilepton pair, as well as limits on specific models.

Dominick's research takes place in an Exotics working group led by Else Lytken (Lund). A first pass (internal to ATLAS) of the entire analysis has been performed with 1 fb^{-1} of data in October 2011. The next steps are to perform comparisons between reconstruction versions (release 16 and release 17) for this data, and then to perform the analysis for the full 2011 dataset for winter conferences in 2012, with a publication shortly afterwards.

Dominick has developed an improved estimation of the fake background. This background has two main sources: fluctuations in jet fragmentation and detector response that result in a jet of hadrons being misidentified as an electron; semileptonic decays of heavy flavor hadrons that produce electrons inside a jet of a hadrons. Dominick has extended the fake factor technique developed by Alison and Lipeles for $H \to WW$ search to evaluate these two sources. A denominator sample that is dominated by light flavor is obtained by reversing some of the electron identification requirements. A separate denominator sample that is enriched in heavy flavor is obtained by reversing the isolation requirement. The solution of a set of simultaneous equations gives separate fake factors for light flavor and heavy flavor. These fake factors are then applied to data sampes with one fully identified electron and one denominator object of the appropriate type. The method has been tested in simulation and in several control data samples, with satisfactory agreement reached.

Searches for compressed spectrum signatures. Elizabeth Hines will investigate searches for compressed spectra, and contribute to the new SUSY working group on this topic. Compressed spectrum models assume that the lightest neutralino is relatively close in mass (within a few hundred GeV) to the heavier particles in the model, rather than being very light at around 60 GeV. In this scenario the visible jets and leptons are much softer than in models with a light neutralino, which makes the limits on this kind of model poorer as seen in the recent ATLAS paper based on 2010 data [18]. Another experimental challenge is small observed $\not{E}_{\mathrm{T}}$ as the heavy LSP has less momentum. Further, in pair production and cascade decays, it is likely that the two heavy LSPs carry off their undetected energy in opposite directions, leaving little imbalance. A theoretical approach [19] was shown to improve limits for the $\not{E}_{\mathrm{T}}$+jets channel search at the Tevatron. This approach requires a hard ISR jet, against which the hard scatter recoils. This provides large visible energy for a trigger and a “Y-shaped” event topology where there is now large $\not{E}_{\mathrm{T}}$ from the LSPs. The proposed work here starts with a simulation case-study to investigate the potential number of signal events and the discrimination between signal and standard model backgrounds.

4.3 TRT Operation

James Degenhardt and Dominick Olivito have made significant contributions to the operation of the TRT. During 2009-2010, James Degenhardt was TRT Deputy Run Coordinator. James shared the duties of TRT Run Coordinator with long time Run Coordinator Anatoli Romaniouk (MEPhi). In addition to normal coordination duties, James also headed the shifter organization and training effort for over 60 TRT shifters. James was chosen in 2011 to represent the TRT in a task force to merge the three Inner Detector ATLAS control room shifts (Pixel, SCT, TRT). James’s efforts were essential to organize the new shift structure and training regimen, which has started in fall 2011. James is also an ATLAS Run Manager in 2011, where he reports the daily issues of ATLAS operations to the Daily ATLAS Run Meeting, and manages the day to day of the ATLAS detector. This role is a week long task shared among ten other individuals who are experienced in ATLAS operations.

James was the lead developer of the data quality monitoring software for the TRT from 2007 through 2009. The histograms are automatically produced for online shifters in the ATLAS control room, and after offline reconstruction for daily checks by offline shifters. This allows the rapid detection of a range of problems from noisy electronics channels to changing beam conditions to incorrect configurations of the offline reconstruction. The TRT Data Quality shifts can be taken remotely, indeed Evelyn Thomson has taken 4 weeks of shifts in 2011 while at Penn.

Dominick is a DAQ expert for the TRT readout electronics and DAQ system. During 2007-2009, he developed many of the DAQ features that have enabled the TRT to run with 100% operational efficiency. He has helped train Jon Stahlman to become the next expert, as well as several other Penn students.

4.4 TRT Performance

Saša Fratina has performed and led many studies that have improved the understanding and performance of the TRT. Saša served as TRT SW convener during the time when first collision data were recorded by ATLAS (January 2009 - June 2010). She has made crucial contributions to the timing-in of the 350,000 channels of the TRT with her studies of cosmic-ray, beam-splash, and collision data. These have been crucial in fine-tuning the hardware settings and calibration constants in order to achieve the best performance. Under her leadership, several Penn students have performed the following studies: investigation of effect of clock-noise on tracking residuals, found to be negligible, by Olivito; measurement of low threshold hit efficiency on reconstructed tracks by Reece; study of electron identification and TRT high threshold settings by Hines; improved algorithm for determining time of passage of a charged particle by Jackson; improved position resolution from time-walk corrections by Stahlman. The work of Hines and Jackson is described in more detail below.

The detector performance is being documented in three ATLAS conference notes, edited by Saša and Fido Dittus (CERN). The notes describing calibration [20] and particle identification [21] are publicly available, while the third note on performance is in the final stages of preparation.

Transition Radiation and Electron Identification The electron identification performance by detection of the TR has been studied by Elizabeth Hines. She is the main author of the ATLAS conference note in August 2011 [21]. She has been one of the two TRT PID contacts since July 2010 and has helped coordinate related work.

Transition radiation (TR) is emitted when a highly relativistic charged particle with a Lorentz factor $\gamma > 10^3$ traverses boundaries between materials of different dielectric constants. The space between the straws is filled with such a radiator material. In order to detect a higher signal due to the absorption of the TR photons (soft X-rays) in the gas inside the straws, the read-out electronics is able to discriminate the signal size against a second, high threshold (HT).

Elizabeth Hines has been studying the 7 TeV data using electron candidates from photon conversions and hadrons. One of the important studies that she designed and conducted in 2010 was the validation of the hardware HT setting. For this purpose, a small amount of data was taken with the high threshold shifted uniformly across the entire detector. The figure of merit was the pion misidentification probability for the selection criteria that has 90% electron efficiency. As the pion misidentification probability was shown to increase for higher threshold, a decision was made to lower the threshold by 8 DAC counts for 2011 running.

Elizabeth is currently studying the HT requirements for electron identification with 2011 data. She has shown that the default electron selection criteria could be improved based on our improved understanding of the detector performance. She recently reported on this work at the $e\ \gamma$ workshop in October 2011 and is working with Chris Lester on the release 17 definition of tight electrons, important for many electron-based analyses with the full 2011 dataset.

Measurement of track time Brett Jackson has studied the track and event times in data from collisions and cosmic rays and has documented this work in two internal ATLAS notes [22, 23]. The time measurements can be used to monitor the read-out and trigger timing of ATLAS and the TRT, as well as to evaluate and reject cosmic-ray background in physics analyses.

The TRT has a single hit time resolution of about 3 ns. Time measurements in the TRT can be used to determine the time of a charged particle passing through the detector, or, by averaging the results for all reconstructed tracks, the event time. Brett measured the track and event time resolution to be 1.1 ns and 0.29 ns respectively.

Cosmic-ray muons pass through the detector at any time, unlike charged particles from collision events that pass through the ATLAS detector at a fixed time relative to that of the bunch-crossing. The arrival time of cosmic-ray muons was initially measured with the Transition Radiation Tracker to have a mean accuracy of 0.97 ± 0.01 ns. With an improved understanding of this measurement, Brett achieved a time resolution of 0.58 ± 0.01 ns.

5 Research Program of H.H. Williams

Brig Williams has been working on ATLAS since 1994. Prior to that he worked on tracking electronics for the SDC collaboration at SSC for about six years. In parallel, he has been an active member of the CDF experiment, playing a major role in the top quark discovery and subsequently pursuing a number of SUSY searches. He led the team from Penn involved in the design, construction, and commissioning of electronics for the TRT. A list of his other responsibilities for ATLAS may be found in his biography. His research group most recently included postdoctoral fellow Peter Wagner and graduate students Ryan Reece (5th year), Jon Stahlman (4th year), James Saxon (2nd year) and Alex Tuna (2nd year). His first ATLAS graduate student, Michael Hance, recently graduated and received a Chamberlain Fellowship a LBNL. Williams' recent focus is on maintenance and operation of the TRT, improving the performance of the TRT, photon and tau identification, and a range of physics topics. The latter includes the first ATLAS measurement of direct photon production (Hance), searches for the Higgs boson in the $\gamma\gamma$ and $\tau\tau$ channels (Hance, Saxon, and Reece) and Z' (Wagner, Reece, Stahlman, Tuna).

5.1 TRT Operation and Data Acquisition

Students and postdoctoral fellows working with Williams (aided by others in the Penn group) have generally taken responsibility for the operation and maintenance of the full TRT readout chain. This includes taking all of the TRT DAQ On-Call Expert shifts. While problems are infrequent, they include everything from loss of readout or excessive noise on individual integrated circuits or front end boards to temporary loss of larger fractions of the tracker (typically 1 - 2 %). Penn personnel are generally responsible for both diagnosing the specific problem and for replacing the failed off-detector electronics, whether it is the Readout Drivers (ROD's), Timing and Trigger Control Boards (TTC's, or one of the power supply cards or receiver-drivers boards at the PP2 locations deep within the muon system. Penn personnel play a large role in maintaining, via repair and testing, an adequate supply of spares for the PP2 receiver-driver cards (the power supply cards are maintained by Krakow). Other "routine maintenance" of the DAQ system includes adapting to changes in the central ATLAS Trigger/DAQ system.

The above DAQ/electronics responsibilities have been borne primarily by postdoctoral fellow Peter Wagner and graduate students Dominick Olivito and Jon Stahlman, all of whom are based at CERN. Ryan Reece, also based at CERN, also has taken DAQ Expert shifts regularly. Jamie Saxon, a 2nd year student, has significant experience with the electronics and data acquisition and is likely to develop into a "TRT DAQ and electronics experts".

While the TRT DAQ system has operated stably with little downtime, we have prepared for a number of challenges that may arise, driven primarily by the increasingly high luminosity of the LHC.

- Increasing luminosity will lead to both higher occupancy in the TRT and a higher Level 1 trigger rate for ATLAS. These combined effects may stress our readout bandwidth beyond conditions we've been able to replicate in tests.
- At luminosities much above 10^{33}, we expect there will be some evidence of single event upsets (SEU's) in the electronics (although the most important registers and counters were triplicated).
- At the full design luminosity of 10^{34}, both the SCT and TRT amplifier circuits begin to accumulate measurable radiation effects over the period of a few years. We do not expect to observe much effect with a year's running at 5×10^{33}.
- At full luminosity, heating of the TRT simply due to the ion current in the straws amounts to a significant (∼20 %) fraction of the heat generated by the front end electronics. The temperatures in both the detector and on the front end boards will need to be monitored.

To maintain a high efficiency of operation, and to keep a large fraction of the detector operational, a number of tools and procedures were developed by Penn personnel.

Readout Recovery Tools These generate automatic responses to rare problems that currently require shifter action.

Front-end Electronics Polling This functionality allows continuous monitoring of the status of the front-end electronics during data-taking, enabling checks for single event upsets and other deviations from the nominal configuration, as well as monitoring of the temperature and the digital supply voltage at the front-end electronics.

Long Term Detector Monitoring This encompasses tools for actively monitoring various TRT detector performance metrics (timings, thresholds, occupancies, etc.) and for chronicling that information in a database.

Low Voltage Together with the Krakow group, we have monitored the low voltage supply system, at the bulk power supplies, patch panels, and the front-end, to ensure stability.

TRT Fast-OR Trigger The TRT "Fast-OR" trigger has been utilized for cosmics runs during brief LHC shutdown periods and especially during the "recommissioning" phase of ATLAS following the 2013-2014 shutdown.

Test Bench Support We have provided support for the TRT electronics test stand in building 104 and the full TRT detector test stand in the SR1 assembly building.

5.2 TRT and Inner Detector Performance

Here we present a very brief summary of the work of Ryan Reece on TRT efficiency and of Jon Stahlman on TRT position resolution, TRT and Inner Detector alignment, and muon momentum resolution and scale uncertainties.

TRT Straw Efficiency Studies Ryan Reece studied the hit efficiency as a function of a number of geometric variables, e.g. radius R, ϕ z, and distance of the track from the wire, both in data and Monte Carlo samples. In collaboration with Esben Klinkby (Duke / NBI), he compared the results for different assumptions in the simulation/digitization package, thereby improving the accuracy of the simulation. Knowledge of the known dead-channels is taken into account. The result of these studies is a very accurate, about $1 - 2\%$, measurement of the TRT hit efficiency which is modeled well by the simulation. The same tool was adopted to give accurate on-line efficiency measurements.

TRT Position Residuals and Alignment The dramatic improvement in the position residuals over the last year owes a great deal to the work of Jonathan Stahlman in addition to the alignment work of Alison, Brendlinger, and Kroll. One of the first big advances was determining the position residual as a function of R, ϕ and z using high statistics samples of high p_{T} tracks. This enabled one to uncover, and in most cases address, a range of subtle effects: variation along the wire length due to propagation delay and charge division, time-offsets between parts of the detector, effect of increased material and the error in track extrapolation, off-sets of the endcap wheels in z (previously not well constrained), and individual wire offsets that could not be removed by simply aligning the individual modules.

Another major contribution by Stahlman was to use the time-over-threshold measurement for a given hit to correct the signal start time, thereby improving the position resolution by $\sim 10\,\mu$m, in both data and Monte Carlo samples. Combined with an improved alignment and smaller improvements in the calibration procedure, we achieve a position resolution of about 118 μm in the barrel and 122 μm in the end-caps. This observed resolution far exceeds the TDR design performance of 170 μm and approximately matches that expected from the simulation with perfect alignment and that observed in the 2004 test beam.

In the process of determining the mean, as well as the sigma, of the position residuals, Stahlman's studies clearly pointed to two things which had not been fully realized: a significant z offset in the position of the endcap wheels (which showed up only when looking at positive and negative tracks separately) and the necessity of aligning each of the 300,000 wires individually. The actual realignment task was carried out by Alison and Brendlinger

Inner Detector Alignment and Muon Momentum Resolution The decay of the Z boson to two muons provides a powerful tool for finding systematic effects in the tracking of charged particles at higher momentum. Charge asymmetries in the measured track parameters are indicative of systematic effects which can be the results of misalignments. Stahlman studied the invariant mass of di-muon pairs from the Z boson in various regions of the detector in order to check for charge asymmetries and systematic momentum biases. Evidence for such biases were clearly observable in the ID endcaps when the mean Z mass was plotted as a function of η and ϕ of the positive or negative muon (separately).(Anthony Morley-CERN observed almost coincidentally a similar charge asymmetric bias in the e/p of electrons from W bosons). After the alignment was redone using a constraint on the track momentum derived from the e/p, Stahlman showed that the bias was largely removed. Stahlman's work also highlighted some misalignments between the ID and the muon system. He has also investigated time dependent effects, establishing limits on the "scale-error" for muons (as measured in the ID) as a function of η and ϕ, and determining the momentum resolution of the ID in the several hundred GeV regime.

5.3 Physics: Analyses

5.3.1 Photons and Direct Photon Cross Section

Many signatures for new physics at the LHC have energetic photons in the final state; hence a measurement of the prompt photon cross section serves as a stepping-stone to searches for new physics. Furthermore, photons produced in proton collisions provide a color- and flavor-less probe of the hard scattering process. The Penn group, in particular postdoctoral fellows Donega and Martin and graduate student Mike Hance, spent several years working on photon reconstruction and identification. Much of our focus has been on measuring and reducing background using a calorimeter isolation variable, the transverse energy, $E_{\mathrm{T}}^{\mathrm{iso}}$, in a cone around the direction of the photon candidate. Prompt photons should have low values of $E_{\mathrm{T}}^{\mathrm{iso}}$ as they are usually well separated from other significant hadronic activity. Mike Hance made important advances in the use of this variable by (a) developing corrections that remove leakage of the photon shower into the isolation cone, (b)subtracting the effects of both underlying event and pileup by measuring the "ambient energy density" in the event, (c) determining the isolation distribution for background processes from data by reversing photon ID cuts, and (d) determining the signal template for photons from data using $Z \to ee$ events (correcting for the small expected difference between electrons and photons). These corrections were adopted quickly by the photon group and have since become standard within ATLAS for measuring $E_{\mathrm{T}}^{\mathrm{iso}}$ for both photons and electrons.

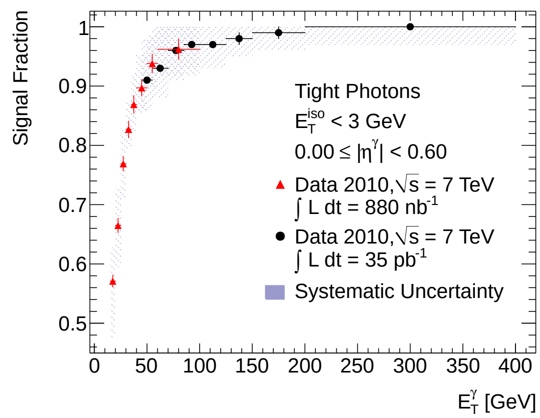

Figure 4: *The purity of the photon candidate sample, after tight identification criteria and a cut on the calorimeter isolation, for the pseudorapidity range* $0 \leq |\eta| < 0.6$.

The $E_{\mathrm{T}}^{\mathrm{iso}}$ distributions from background control samples and from the signal template are used to determine the fraction of background in the signal sample, i.e. the purity for a given isolation cut, e.g. $E_{\mathrm{T}}^{\mathrm{iso}} < 3$ GeV as shown in Figure 4.

ATLAS performed two measurements of the inclusive isolated prompt photon cross section with data recorded in 2010, both of which relied heavily on measurements of $E_{\mathrm{T}}^{\mathrm{iso}}$. The first was published in Physics Review D [24] and used 880 nb^{-1} of data collected between April and August of 2010. Mike Hance played a central role in this analysis and was editor of the paper.

5.3.2 $H \to \gamma\gamma$

Production of a Higgs boson, followed by the decay $H \to \gamma\gamma$, remains one of the most promising processes by which one can observe a low mass (< 130 GeV) Higgs boson. While evidence for the Higgs may show up first in the WW final state, observation of a signal $H \to \gamma\gamma$ is likely to be important for an unequivocal discovery.

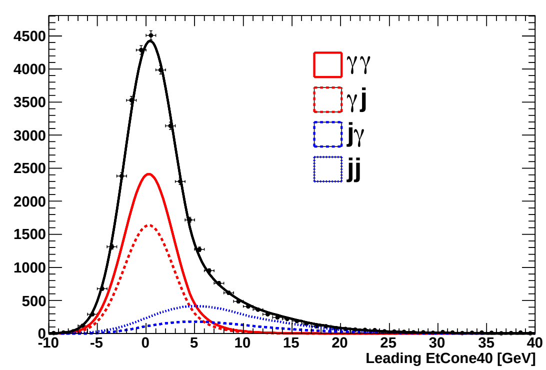

Figure 5: *Fit of signal and background isolation templates for the leading photon. (ATLAS work in progress)*

Rejection of background and determination of signal purity using the isolation variable described above has formed the basis for both a measurement of inclusive diphoton production and for the Higgs search. By simultaneously fitting the background and signal isolation templates to the observed distributions for both leading and subleading photons, one can determine the signal composition. Figure 5 shows the results of such fits to the sample of diphoton events passing the Higgs selection criteria: $p_{\mathrm{T}} > 40$ GeV for the leading photon, $p_{\mathrm{T}} > 25$ GeV for the subleading photon and $|\eta| < 2.37$, excluding the region $1.37 < |\eta| < 1.52$ which includes the crack between the barrel and endcap calorimeters. For these plots we have also imposed a cut on the $\gamma\gamma$ invariant mass, $110 GeV < M_{\gamma\gamma} < 150 GeV$. For the single photon analysis of the 2010 data, the "signal region" was defined to have isolation energy < 3 GeV. For 2011 data, because of the increased pileup and also because of the desire to increase the acceptance for the Higgs process, it was important to re-examine the optimal cut on isolation energy. James Saxon and Mike Hance were the first persons to do this quantitatively; they showed that raising the cut to 5 GeV increased the expected Higgs signal rate by 25–30% and resulted in an improved signal/background.

The technique of fitting the isolation distributions may be applied to individual bins in $M_{\gamma\gamma}$ yielding a breakdown of the different processes, true diphoton final state, photon + jet, and jet-jet, as a function of mass. (Due to space limitations, we are not able to show the nice results determined.)

5.3.3 Tau Identification and Searching for $H \to \tau\tau$

Tau Identification and $Z \to \tau\tau$ Ryan Reece has worked extensively on taus over the last several years. His primary contributions to date on tau identification have included: (a) development of the set of variables for the initial "cut-based" analysis with emphasis on the importance of scaling the cuts with p_{T}, (b) use of these variables in the tau trigger, (c) comparison of data and Monte Carlo to support use of these variables in multi-variate tau selection, and (d) editor for the ATLAS 2011 conference note documenting the tau reconstruction, identification, and energy calibration [25].

Reece also contributed heavily to the first ATLAS observation and cross section measurement of $Z \to \tau\tau$ (in the final state where one tau decays leptonically and the other to hadrons). Here his contributions included (a)reducing the QCD background by tightening the cut on muon isolation, (b) providing one of the first data-driven determinations of the QCD background, (c) introducing a new variable to separate W + jets from the $Z \to \tau\tau$ signal, (d) being a lead developer of the analysis framework and cutflow, and (e) overall being one of the main contributors to the first ATLAS publications on this process.

Searching for $H \to \tau\tau$ Penn has applied the expertise we have developed in taus to the search for $H \to \tau\tau$. We have been especially interested in searches related to possible Minimal Supersymmetric extensions to the Standard Model (MSSM) as the production of Higgs bosons and their decay to taus can both be enhanced in large regions of the MSSM parameter space [26, 27].

Our primary focus has been on improving isolation requirements on both the lepton and the hadronic tau decays in light of the increasing pile-up conditions at the LHC. Reece has developed a redefinition of the tau identification variables most sensitive to the effects of pile-up and has also introduced a new pile-up corrected calorimeter isolation variable [28]. Currently the cut-based identification is being used as a testbed for these new variables, which will likely be included in the Boosted Decision Tree identification method.

5.3.4 SUSY and Exotics Searches

Search for $Z' \to ee, \mu\mu$ Many models predict new massive resonances such as Z' or W' bosons [13], and Penn has had a significant involvement in searches for such particles. For the first ATLAS analysis and publication, Williams focused mostly on the electron channel, motivating changes in the electron selection and providing a data-driven estimate of the background from di-jets (with Dominick Olivito). He also worked with Peter Wagner on an estimate of the background from cosmic rays for the muon final state and on a data-driven estimate of the background from ttbar and W^+W^-. Finally, Williams was an editor of the first Z' publication. More details of past work in this area are presented in the section of Evelyn Thomson.

Searches in Diphoton + MET Brig Williams and an undergraduate, Jack Bradmiller-Feld, have made preliminary investigations of this final state which is interesting for Gauge Mediated SUSY. We have suggested a number of changes to the analysis that should improve the sensitivity significantly.

6 ATLAS Upgrades

6.1 Overview

ATLAS is planning a series of upgrades with timescales aligned approximately with the LHC shutdowns planned for 2013-2014, 2018, and 2022. With the exception of the insertable pixel b-layer, most projects in the 2013 shutdown are related to fixing weak links in the existing detector. For upgrades aimed at installation in 2018, we are already involved in the plan for a higher-granularity level-1 trigger via the work on an analog delay line to be used in upgraded tower builder boards. Replacement of the small muon wheels with micromegas-based detectors is an area we find attractive, although we do not yet have any direct involvement. The bulk of our present effort is focused on a replacement for the Inner Detector (ID) and an upgrade of the electronics for the liquid Argon calorimeter. In a recent presentation, Abe Seiden, the USATLAS Upgrade R & D coordinator, listed eight integrated circuits under development in the US for ATLAS upgrades: Penn is involved in five of the eight, often taking a lead role.

Our large effort on a replacement tracker is motivated by several factors. First, while the upgrade of the tracking system is often motivated by the large increase in luminosity at an HL-LHC, we expect it may be *necessary* to replace the ID on the time scale of ten years due to radiation damage. The ID electronics are designed to withstand seven years of running at high design luminosity. The luminosity, however, could exceed the design luminosity during the current decade. In addition, while extensive tests of the SCT and TRT front-end chips were done with MeV-equivalent neutrons, the bipolar process utilized is also sensitive to thermal neutrons, and the flux of these neutrons is known much more poorly. Second, while some regard 2022 as a long way off, *the schedule is already tight.* For installation in 2022, macro-assembly is planned to begin in 2019. The current date for submission of a Letter of Intent and presentation to the CERN RRB is Fall 2012. It took close to 12 years to build, install and commission the ID; the outstanding issues for a new tracker are at least as challenging as those being faced in 1995. Finally, personnel in the Penn HEP Instrumentation group have a combination of knowledge, skills, and experience that is particularly well suited to solving some of the issues related to a new tracking system and that is rarely found in universities (and not so common in the national laboratories). The associated faculty also have extensive experience in designing, providing, and commissioning large electronics and data acquisition systems for tracking detectors.

The desirability of replacement of the front-end electronics for the liquid argon calorimeter also can be decoupled, at least partly, from the time scale for ultimate upgrades to the LHC. In order to improve granularity and selectivity in the trigger system, which is already a “hot-topic”, it will be necessary to replace the front-end boards. Again, our expertise in analog integrated circuits is highly valued for the development of a new preamplifier-shaper (in collaboration with BNL).

In summary, while detailed plans for funding US participation in the major upgrades of ATLAS have not yet been formulated, the technical time scale demands a continuing active participation. An early, and sustained, focus on R & D is also likely to significantly decrease the ultimate project cost.

6.2 Inner Detector Upgrade: Silicon Tracker

The ATLAS ID must be upgraded for the high-luminosity running of the LHC currently planned to start in 2022. The current ID will be replaced: the 10cm silicon strips in the SCT will be replaced with 2.5cm strips, and the TRT will be replaced by additional silicon-strip layers in the barrel and endcap. With these changes, the silicon-strip tracker will increase its channel count to from 6M to 42M strips. A lesson learned from the current ATLAS detector is that without a comprehensive plan encompassing the detector and all its services from the beginning, the non-active material in the inner detector can easily grow beyond the target value as the final design of each element is completed. For the ATLAS upgrade, the number of channels to readout is significantly larger than what we have in the current ID, but the ID volume and the access for power, readout and cooling services is the same, so our attention needs to extend well beyond the sensor and analog front end from the outset. Historically, Penn has looked at the whole system and applied our expertise to everywhere we found it could help to complete a detector system that meets its design goals. Our involvement in the SCT upgrade includes the areas of Technology, Architecture, and Power Services.

Technology Going from 6M channels of SCT readout and 340k TRT channels to an upgraded 42M channel silicon-only tracker implies a potentially significant increase in power dissipation if we simply scale up the existing system. Higher occupancy implies increased total dose radiation tolerance—from 5MRad to 25MRad and similarly from 1 to $5 \times 10^{15}\,\mathrm{N/cm^2}$—in the inner SCT barrel layers. Deep sub-micron CMOS technologies address both of these issues. Radiation studies have shown that native devices in deep sub-micron CMOS technology with a gate thickness of 2.2nm or smaller offer suitable radiation tolerance requiring little or no mitigation due to effects of total ionizing dose or bulk damage. The least exotic (expensive) technology to satisfy this gate thickness requirement is 130nm CMOS, although single event effects will require some special considerations with this technology. In summer 2008, we studied the requirements for clocked digital functions in various CMOS technologies. We concluded that the 130nm technology would deliver six to eight times lower power for the same functionality than that of the less expensive 250nm technology, taking into consideration the enclosed drain layout required for 250nm technologies to achieve the appropriate level of radiation tolerance. Either of these technologies would be significantly lower in power than the 800nm-feature-size DMILL technology used for the ABCD chip presently in the SCT. One striking advantage of the 130nm process is that the number of channels on the FEIC can be doubled from 128 to 256, thus reducing the infrastructure required and halving the number of front-end chips in the detector. Our conclusion that 130nm technology offers an excellent tradeoff between cost, radiation hardness and power has been supported by the rest of the SCT ASIC community. We have been acquiring experience with IBM's CMOS8RF since 2009 through simulations, layout and the submission of two ASICs for serial powering.

Architecture Penn has participated in the Strips Readout Working group and subsequently the SCT Upgrade Architecture group since 2008. This provided the opportunity to significantly influence the design of the SCT front-end architecture. Our previous work with the design of the TRT DTMROC enabled us to join in the design of the ABC next (ABCn) chip in 2008 using the same 250nm CMOS process used for the DTMROC. Several of the blocks developed for the DTMROC were used in the ABCn. In addition to participating in minor modifications of its LHC-compatible architecture, we supplied the bi-directional I/O used for serial data transfer between chips and an externally-controlled current shunt that forms the basis of our distributed-shunt serial-power design. Elliot Lipeles and Nikos Konstantinidis (UCL) suggested that providing multi-level trigger signaling and a second beam-crossing-asynchronous data buffer on the front-end chip would offer a way to move the level-2 trigger readout decision from the ROD to the front-end electronics thus eliminating the need to deliver data to USA15 at the 500KHz low-level trigger rate projected for HL-LHC. Additional information required from the tracker to provide sufficient information for the level-2 trigger would be acquired by reading data from a few percent of the ID, a so-called Region of Interest. The implications of this plan, discussed in Sec. 2.3, is that the number of fibers required for a full detector readout can be reduced by an order of magnitude when compared to simply scaling up the present readout on level-1 trigger system. Since April 2011, we have been heavily engaged in implementation of this approach. The system includes a synchronous low-level trigger requiring the traditional pipeline with a maximum retention of $\sim 6\,\mu$sec, a highly selective Regional Readout Request, R3, addressable at the module level, and a level-2 trigger that initiates readout of the whole detector.

Hybrid Controller Chip As part of the front-end design, we proposed including a special chip, recently renamed the Hybrid Controller Chip (HCC), in the SCT architecture as an interface between front-end chips (2560 strip readout) and the control and data bus that links 24 hybrids together on a stave. We are now writing a detailed specification of the HCC, and we intend to follow this with implementation of the analog blocks and many of the digital blocks. These blocks include a voltage and temperature monitor, ac-coupled LVDS drivers and receivers compatible with either serial power or standard DC powering, bi-directional 160MHz transceivers for chip-to-chip data communication, and the adaptation of the PLL used in the GBT chip for the HCC. Given the tight submission schedule, we will need to complete this work by summer 2012.

Powering Services Although a DC-DC powering scheme is being tested, serial powering remains the default powering approach for the barrel SCT. Penn has assumed primary responsibility for the design, development and modeling of testable serial-power systems for the SCT upgrade. In serial powering, the voltage increases as current, sufficient for one hybrid, is passed from one hybrid to the next. We proposed a distributed-shunt serial-power approach (now the baseline for the upgraded barrel SCT) and implemented a first version in the ABCn, the current SCT prototyping workhorse. In this approach, each ABCn has an external reference controlled block capable of shunting more current than the chip consumes. One master control ASIC (SPP chip for Serial Power and Protection) per hybrid sets the shunt reference based on feedback from the voltage measured across the hybrid. This distributed-shunt approach ensures a nearly constant power dissipation from each chip over a wide range of trigger conditions. There are no hot spots under normal or fault conditions, and a high level of redundancy is provided in the event of an ASIC shunt failure. In July we submitted a SPP ASIC in IBM's 8RF process to complete the serial-power design. Its purpose is to provide a remotely addressable, independently powered, hybrid voltage regulation loop with an autonomous shut down mode activated when an over voltage condition sensed. It contains shunting transistors connected in parallel with the hybrid's serial power lines to cover the case of an open in hybrid power connection. The SPP requires one additional line used for power (8 mA per chip) and pulse-width modulated external communication. Assuming this design proves successful, we will test its radiation sensitivity and revise the layout using radiation-tolerant layout on the I/O transistors with the thicker oxide as necessary. We will then decide on the full command set required for the final design and will submit a production ready version.

6.3 ATLAS Liquid Argon Front End Electronics

We joined the Atlas Liquid Argon (LAr) upgrade electronics effort in 2007 as participants in the measurement of the radiation hardness of a new technology, Silicon Germanium (SiGe), along with members of the SCT group interested in its potential for low-power analog front ends. IBM's 8WL SiGe BICMOS process was identified as having a high potential benefit because of its compatibility with standard CMOS digital design tools. A requisite test for the qualification of the technology was the development and test of a system-appropriate circuit block. For the LAr, BNL implemented a version of the LAr preamp, and we developed a fully differential CR-$(RC)^2$ shaper. Penn assembled a 4-channel preamplifier and shaper into an ASIC dubbed the LAPAS chip, which we submitted in December 2008. This work was reported by us at the Paris TWEPP09 conference. Our two-stage shaper was demonstrated to have the requisite 16 bits of dynamic range with an input noise of $2.2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and an integral nonlinearity of less than 0.05%. Measuring the latter was itself a significant undertaking. When the SCT group decided not to pursue SiGe technology, the high cost of IBM's 8WL BiCMOS technology became an issue since the LAr requirement alone is too small to amortize the high NRE costs. We therefore decided to turn to one of the other SiGe processes examined by our measurement group: IHP's SG25H3P process. When we contacted IHP in 2009, they expressed an interest in tests of the radiation hardness of their process devices at cold temperatures as well as a willingness to work with us on costs in the prototyping phase of our LHC upgrade work.

IHPPSD ASIC In September 2011, we submitted an SG25H3P-based prototyping ASIC that contains two preamps, a shaper—based on our LAPAS chip design mentioned above—and a wide-dynamic-range analog delay line. We also included a bank of devices, subsidized by IHP, that will allow us to make parametric measurements of the process transistors over operational ranges of interest for our LAr designs in addition to measurements of interest to IHP. The prototype will help answer some technical questions about the operating range of the pnp transistors. In particular the foundry has not characterized the noise behavior at the operating point (V_{CE} = 3V) required by our design. Our simulations show that the target 90nA-equivalent input noise current for the preamp could be compromised by leakage current in these pnp transistors.

By exploiting IHP's SiGe technology, we were able to design an analog delay block that could provide the Tower Builder Board's (TBB) delay functionality in 7% of the present board area in order to allow greatly increased digital circuitry for enhanced trigger functionality. To form the level-1 trigger, the TBB must normalize the amplitude, shape and delay of the incoming layer sums prior to summing them. While programmable shape and gain circuits are relatively common, an ASIC-based wide-dynamic-range programmable analog delay is unusual in our field. Building on an earlier design for SNO, where we delayed the analog integrator signal by 8ns, we came up with a design that meets the specifications of the current TBB tapped delay line: eight 2.2 ns delays (totaling $\sim$18 ns) with a dynamic range of 12 bits.

In an attempt to limit the costs of prototyping, we negotiated an agreement with IHP whereby Penn will measure the radiation hardness of their pnp transistors at cold temperatures at their request. In return for providing these measurements, the foundry will allow us to submit the preamp prototype at $\sim$ 50% of normal cost and they will fully cover the costs of fabrication of a $2.5\,\mathrm{mm}^2$ test-structure array. The IHPPSD will provide a significant test bed for the SG25H3P process. Assuming a mostly successful prototype, we expect to fast track the design of the TBB's programmable delay, shape and amplitude circuitry over the next 18 months so that we can be ready with an initial LHC legacy analog sum for installation on a few TBB's at the end of 2013.

Part II
Experimental Research at the Intensity Frontier

7 Intensity Frontier: Neutrinos

The neutrino group at Penn is involved in two separate efforts: the Long Baseline Neutrino Experiment (LBNE) and the SNO+ multipurpose neutrino experiment. LBNE will use a neutrino beam from Fermilab and a detector located in the Homestake mine in South Dakota to provide precision measurements of the neutrino mixing parameters, with a focus on a search for CP violation in the lepton sector. SNO+ uses the existing Sudbury Neutrino Observatory (SNO), but with the heavy water replaced with 780 tonnes of liquid scintillator (linear alkyl benzene or LAB). SNO+ will perform a sensitive search for neutrinoless double beta decay with the isotope ^{150}Nd, measure the low-energy fluxes of solar neutrinos including the poorly measured *pep* neutrinos, and investigate other physics such as the flux of geoneutrinos. Over the past three years, the group also spent substantial time on the completion of analyses of data from SNO.

The majority of funding for these efforts comes from support from the Department of Energy's Office of Nuclear Physics (SNO+), an NSF S4 grant (LBNE), and startup and other University funds. Department of Energy Office of High Energy Physics project funds have also been used as partial support for project management activities and R&D work related to LBNE. The NSF S4 grant for LBNE, which has provided support for post-docs Stan Seibert and Rob Knapik, expires at the beginning of the first fiscal year of this grant. We are requesting here support for summer salary for the PI, post-doctoral support for work on LBNE which includes funding to replace the expired NSF S4 grant, and partial salary support for members of Penn's instrumentation group who are involved in both LBNE and SNO+ efforts.

We are quite proud of the group's track record, in particular when it comes to the subsequent success of the young people who have been group members. Over the past 15 years, a period that spans most of the work done on SNO, nearly every post-doc with the group has gone on to receive an offer of a tenure-track faculty position or equivalent (in one case, the offer was turned down for a position in the financial industry). Graduate students who have done their PhD theses during this time have gone on to Fermi Fellowships (two cases), a Los Alamos Director's Fellowship, a Wilson Fellowship, a CERN Fellowship, and faculty positions at prestigious universities.

The members of the current neutrino group include faculty members Josh Klein and Gene Beier; Visiting Scholar Bill Heintzelman who has been with the group for more than a decade; post-doctoral fellows Gabriel Orebi Gann, Rob Knapik, and Stan Seibert; graduate students Tim Shokair, Richie Bonventre, Andy Mastbaum, and Tom Caldwell; and significant contributions from 'post-graduate' Tony LaTorre and undergraduates Kevin Shapiro, Logan Ware, and Brian Delgado. Members of our group (Klein, Seibert, and Caldwell) are also involved in the MiniCLEAN dark matter experiment, which is part of the broader DEAP/CLEAN program of single-phase dark matter detectors. That effort is described in the Cosmic Frontier section of this proposal.

Although we are involved in three different experiments (four, counting the small continuing effort on SNO), we play significant and leading roles in all of them, with a focus on our traditional strengths of electronics instrumentation and data analysis and simulation. On SNO+, Klein is the US spokesperson, outgoing chair of the SNO+ Science Board (the SNO+ 'executive committee'), and the Level 2 project leader for the SNO+ electronics upgrade. Post-doc Gabriel Orebi Gann is the Deputy Physics Analysis Coordinator for SNO+, as well as convenor of the solar neutrino working group and the PMT calibrations working group. Both post-doc Rob Knapik and Orebi Gann serve as 'young members' of the SNO+ Science Board, and Orebi Gann was recently voted on as a permanent member of the Board, the only post-doc to hold such a position. The SNO+ collaboration's simulation and analysis software package (RAT) was written by Seibert, and second-year graduate student Andrew Mastbaum serves as the chair of the 'code integrity committee' that has developed (and enforces) code quality criteria for SNO+ RAT. Third-year graduate student Richie Bonventre is the coordinator for the first SNO+ commissioning runs ('air fill') that will begin Winter 2012.

Beier continues as US co-spokesman for SNO, and of the four physics papers published by SNO in the past three years three were efforts lead by the Penn group. The recent low energy threshold analysis (LETA), which pushed the analysis threshold down to 3.5 MeV and halved the uncertainties on the total flux of ^{8}B neutrinos from the Sun, was lead by Klein, with analyses by Seibert and Orebi Gann providing the final, published numbers. Orebi Gann was also the primary editor of the final ~50-page Physical Review article.

On LBNE, Klein is a member of the Executive Committee, is the Level 4 project leader for photomultiplier tube characterization, and was the co-editor of the 'case study' report that presented the conceptual design and physics reach of the 200 kton water Cherenkov option for the LBNE far detector, presented to the recent DOE 'Marx Committee'. Rick Van Berg, as part of Penn's instrumentation group, is the deputy Level 3 project manager for LBNE water Cherenkov electronics.

One of the reasons we have been able to manage such involvement in all of these experiments is the large degree of technical overlap between them, which has allowed us to leverage the effort on one to enhance our effort on another. For example, as has been mentioned above, the use of the RAT package for both MiniCLEAN and SNO+ (and the fact that Seibert is at Penn) has allowed graduate students and post-docs (and faculty) focusing on different experiments to assist and learn from one another, trade macros, etc. As part of the SNO+ electronics upgrade, we chose waveform digitizers for recording trigger signals that are also being used for the MiniCLEAN data acquisition electronics, thus increasing our expertise on both experiments. Photomultiplier tube characterization tests being done for LBNE have also been applied to SNO PMTs, thus providing the LBNE PMTs with a 'standard candle' and the SNO+ experiment with additional data for a more precise PMT simulation model. And, of course, the intellectual infrastructure and experience that exists within the group on these kinds of rare process/low background experiments is a benefit to all of our efforts.

We focus in the next sections on our Intensity Frontier LBNE and SNO/SNO+ efforts, for which we are requesting support from this sector of the grant.

8 Long Baseline Neutrino Experiment

8.1 Long Baseline Neutrino Experiment

8.1.1 Scientific Motivation

The Long Baseline Neutrino Experiment (LBNE) is focused on the areas of neutrino mixing that are least known. The primary physics is aimed at ν_e appearance measurements, with the highest priority being a search for a Standard Model-like CP-violating asymmetry in the oscillation $\nu_\mu \rightarrow \nu_e$, with a beam originating at Fermi National Accelerator Laboratory. Other beam-related

LBNE ν_e appearance measurements include a resolution of the neutrino mass hierarchy, precision measurement of θ_{13}, and observation of the matter effect. In five years of running with a 700 kW beam in neutrino mode, and five years of running in antineutrino mode, LBNE will be able to make a 3σ measurement of CP violation, for 50% of all δ_{CP} values, for values of $\sin^2 2\theta_{13} > 0.03$.

The Penn group has been involved in this effort for at least a decade—both Klein and Rick Van Berg, along with Professor Ken Lande and Emeritus Professor Alfred Mann, were co-authors of some of the original papers describing the physics that could be done with a very long baseline neutrino experiment [29]. While LBNE has evolved since then, the basic principles set out have remained: a very large, underground detector, a broadband on-axis beam, and a focus on ν_e appearance along with a broader program of non-accelerator physics.

Our effort was focused on the design of a 200 kt water Cherenkov far detector. In addition to the leadership and project management roles described in the previous section, we had three primary efforts associated with LBNE: photomultiplier R&D and evaluation, simulation and reconstruction development, and front-end electronics design.

8.1.2 Accomplishments Over Previous Three Years

Our effort on LBNE included work by the PI (Klein) on PMT characterization and project management, staff scientist Rick Van Berg on project management and electronics design, post-doctoral fellow Rob Knapik on PMT testing, post-doc Stan Seibert on simulation and reconstruction, as well a significant effort by post-graduate Anthony LaTorre on both PMT characterization and our analysis/simulation work. We also received significant support from Penn's instrumentation group, for designs and fabrication of PMT bases and the construction of our PMT testing facility, and have had several undergraduates working with us on the PMT tests.

PMT Evaluation and Characterization: For a water Cherenkov detector, the total number of photons detected, their times of arrival, and the angular positions relative to a hypothesized Cherenkov cone (or cones) determine energy and position resolution, particle identification efficiency and ultimately background rejection. While the PMTs are not the primary cost driver for LBNE, to accomplish the beam-related measurements will still likely require roughly \$100 M, and for the broader physics program, as much as twice that.

There is a clear need for such a detector, therefore, for a careful evaluation of the possible photomultiplier tubes, and a program of characterization of those tubes. As Level 4 manager for PMT characterization, Klein coordinated the collaboration's PMT effort into three 'phases': an Evaluation Phase which would make the measurements most needed to decide which of several PMT models from different vendors would be optimal for LBNE; an Optimization Phase which would work with the selected model to determine its best running conditions, such as voltage distribution in the base, gain, and effects of light enhancement devices like wavelength shifter plates or Winston cones; and a Characterization Phase which was intended to provide a complete electrical and optical model of the PMTs that could be used in simulation and reconstruction work.

At Penn, our effort was focused on measurements of relative PMT efficiencies between different PMT models, using single-photoelectron Cherenkov light (which is ultimately what LBNE will be interested in), tests of various PMT base designs and precision measurements of PMT timing and charge response, including position-dependence along the PMT photocathode. Along the way we uncovered some unexpected (if not new) PMT behaviors, which have implications for future PMT manufacturing as well as LBNE's electronics design, detector simulation, and reconstruction. We worked directly with the phototube manufacturers on improving their designs to suit LBNE's needs (as well as any future experiments that might use the same PMTs).

We examined PMTs made by two vendors: Hamamatsu and ADIT/ETL. The sampled tubes included 8" PMTs made by ADIT/ETL, and Hamamatsu's 10" high quantum efficiency (HQE) PMTs and 12" standard quantum efficiency PMTs. The 12" PMT, shown in Figure 6, was developed specifically for LBNE, and we received two sets of higher-quantum efficiency versions of the 12" PMTs.

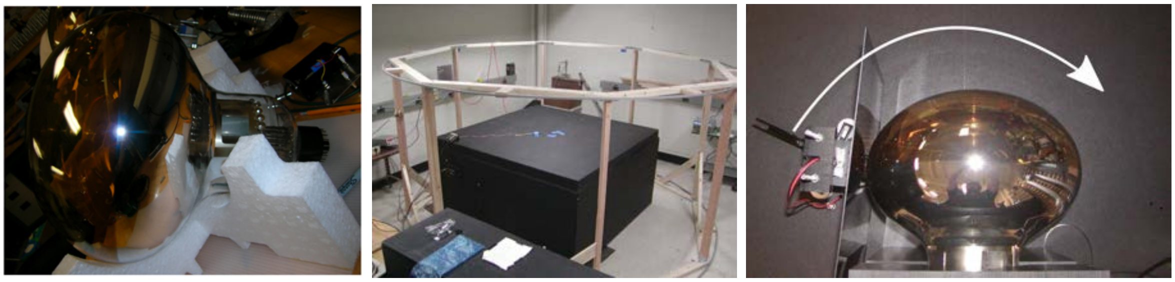

Figure 6: *Hamamatsu R11781 12" PMT, designed for LBNE (left), Penn PMT testing darkbox and magnetic compensation coils (center) and LaTorre's automated scanning arm with opaque pinhole mask viewed from the top (right).*

For our work at Penn, we tested the PMTs using a triggered Cherenkov source made from a piece of SNO acrylic with ^{90}Sr embedded within. A fast ($\sim$ 250 ps) 1" PMT was optically coupled to the acrylic source, and provided a trigger. All timing information for the PMT tested was done relative to the trigger PMT, with corrections made for pulse risetime and slewing. The Cherenkov source provided a wavelength spectrum very similar to what would be seen in a water Cherenkov detector, as well as very fast timing, at a far lower cost than a fast laser system would.

Post-graduate Anthony LaTorre constructed a large ($\sim$ 2 m on each side) darkbox (Figure 6) along with very large Helmholtz coils that enclose the entire volume, cancelling the vertical component of the Earth's magnetic field. The data acquisition system was a LeCroy Waverunner scope, running software that Mr. LaTorre developed. Mr. LaTorre's code controls the scope as well as taking full digitized waveform data over an ethernet connection at kilohertz rates, exploiting a previously undocumented listening port on the scope. The code ('LeCrunch') is still available to anyone with a LeCroy scope at `http://www.bitbucket.org/tlatorre/lecrunch`. The analysis software for our various tests was written by Dr. Knapik, Mr. LaTorre, and undergraduate Kevin Shapiro. The source, darkbox, and coils (including power supplies), as well as a handheld digital magnetometer built by LaTorre and Seibert, all together cost less than \$3k. The box is large enough that three PMTs can be tested at one time, with plenty of space to vary the relative source-to-PMT position inside.

Figure 7 shows the charge and time-residual spectra taken with a 12" standard quantum efficiency Hamamatsu PMT. As is clear from the figure, the response of these tubes is excellent. In our tests of a sample of ten of these PMTs, we found that the peak/valley ratio of the single photoelectron charge spectrum for these tubes is on average nearly 3. The width (σ) of the transit time spread of the single photoelectron prompt light is roughly 1.4 ns at a gain of 1×10^7, and better at higher gains. The other PMT candidate models we have examined have also had very good to excellent characteristics.

The good peak/valley ratio of the PMTs also means that we could to run the electronics for a detector using these PMTs at thresholds lower than the canonical 1/4 of a photoelectron of charge. Mr. Shapiro showed that lowering the threshold to 1/8 of a photoelectron of charge improved the photon detection efficiency above the noise level by nearly 10%.

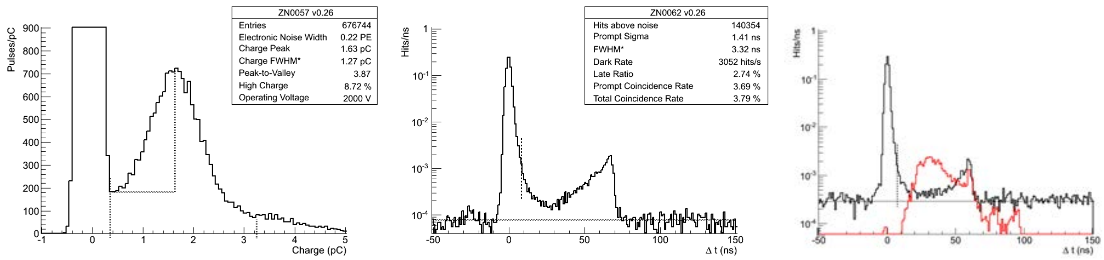

Figure 7: *Dr. Knapik and Mr. Shapiro's measurements of the single photoelectron charge spectrum (left) and transit time residuals (middle) for a Hamamatsu R11781 12' PMT. On the right the black curve shows the time residual for single pulses, and the red curve shows the time for the second pulse in all double-pulse events. There is a clear association between these second pulses and the latepulsing phenomenon.*

As can be seen in the time residual spectrum, the PMT exhibits a typical 'latepulsing' phenomenon, with about 3% of all recorded coincidences having a time that ranges from 20-70 ns later than the prompt peak. Such latepulsing effectively acts as a loss of photons, particularly since energy and position reconstruction algorithms typically cut hard on PMT times to avoid scattered and reflected light. Thus understanding the phenomenon can recover these hits for analysis: 3% more photons is the equivalent of an additional 1000 PMTs for a 200kt water Cherenkov detector, therefore potentially worth $2-3M. While it has been known for a long time that at least some types of latepulsing are caused by elastic scattering of photoelectrons off of the first dynode, what Knapik discovered was that much of the breadth of the latepulsing 'plateau' was in fact caused by *inelastic* scatters off of the dynode, in which an initial pulse is created in-time and a second pulse appears late. Because the scatter is inelastic, the second of the two pulses occurs earlier than a typical latepulse, as shown in Figure 7.

In addition to being able to test several PMTs at once, the large darkbox also allows precision scans of the PMT response across the photocathode. For this purpose, Mr. LaTorre invented an articulating arm that uses a stepper motor to position the illumination from the Cherenkov source along the face of the PMT. To accommodate differently-shaped PMTs, Latorre's mechanism uses two nylon nubs to 'sense' the PMT shape and thus maintain the relative source-PMT position. Figure 6 shows a close-up of the source positioning, including the opaque pinhole mask which is used to keep only a small part of the photocathode illuminated at normal incidence. By using normally incident light, we effectively measure the relative collection efficiency for the photoelectrons point to point, under the (yet to be proven) assumption that the photocathode is reasonably uniform.

Figure 8 shows two-dimensional contour plots of the efficiency across the face of a 12" PMT relative to the center, and the relative transit time relative to the time at the center. We see that even in the region near the edge there is still significant sensitivity. This additional sensitivity contributes in an important way to the overall photon detection efficiency—as much as 14%—because the area near the PMT edge is quite large. The asymmetry apparent in the contour is caused by the asymmetry in the first dynode of the PMT.

What came as something of a surprise is what is shown in the right half of Figure 8: the relative position of the prompt time residual peak as a function of position along the photocathode. We see dramatic (and asymmetric) shifts in time as one nears the edge of the tube. Such shifts could lead to biases in position reconstruction, and thus make the outer region of the PMTs much less useful. We showed these plots to the Hamamatsu engineers, who verified this behavior in their own electron optics simulations. They then re-designed the dynode stack so as to make the timing more uniform across the PMT. Clearly, the total number of PMTs needed for an experiment like

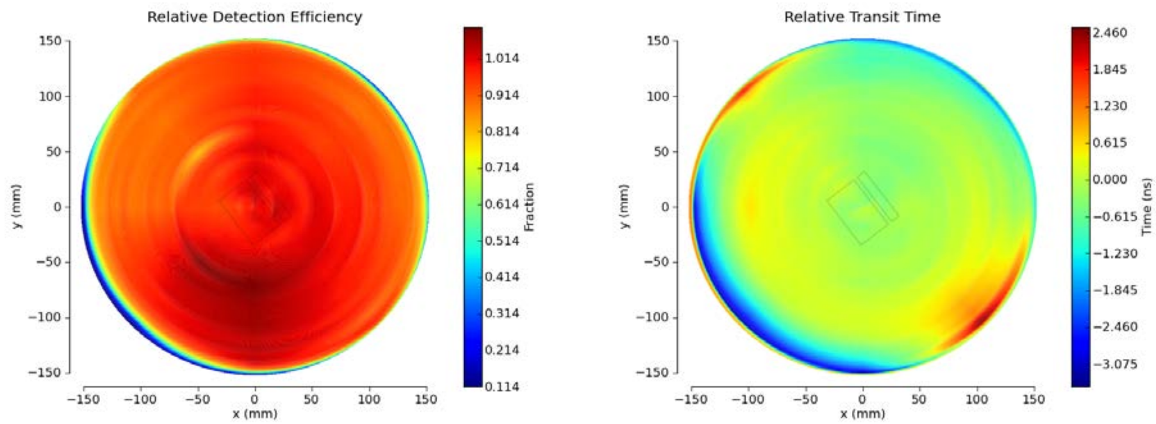

Figure 8: *Position-dependent collection efficiency (left) and shifts in the median transit time (right) for a Hamamatsu 12" R11781. The color indices are relative to measurements made at the center of the PMT. Orientation of the dynode stack also shown for reference.*

LBNE was a critical question both for the physics, and its cost. The operating assumption for LBNE was that it woudl accomplish its physics goals if it had the same photon detection efficiency as Super-Kamiokande II. To determine what number of PMTs this corresponds to, Dr. Knapik and Mr. Latorre developed a fast, parameterized detector model that models the Cherenkov wavelength distribution, the known optical properties of water (based on SNO measurements) and the wavelength-dependent quantum efficiency of the PMTs. Their calculation predicted a need for roughly 37,000 12" HQE PMTs, assuming no additional passive light collectors are included in the design.

Simulation and Reconstruction Mr. LaTorre and Dr. Seibert developed a dramatically new way to simulate and reconstruct events in photon-based detectors. The new approach, called *Chroma*, performs complete physical photon ray-tracing on graphics cards (GPUs), and does it *200 times faster than GEANT4.* The huge improvement in speed was necessary because *Chroma* was designed as a way of reconstructing events by generating Monte Carlo-based likelihoods.

The most general reconstruction and particle ID algorithm for a water Cherenkov detector is to maximize the likelihood $\mathcal{L}(\vec{r}, t, \vec{p}, \mathrm{ID}) \sim \prod_{i=0}^{N_{\mathrm{PMT}}} p_i(\vec{r}, t, \vec{p}, \mathrm{ID}|Q_i, t_i)$ where $\vec{r}$ is the position of the event, t is its time, $\vec{p}$ the event momentum (or, equivalently, energy and direction), and ID is the particle species, which can be a single particle such as an electron, muon, or π^0, or can be many charged particles each creating its own Cherenkov cone. The p_i are the normalized probability densities for each PMT to observe charge Q_i at time t_i, given the hypothesized event position, momentum, etc. The Q_i and t_i are our only observables. Thus the entire challenge to reconstruction is to first, accurately generate the p_i, and second, to efficiently find the maximum likelihood by varying the fitted parameters like position, momentum, and particle ID. The probability that a particular PMT sees charge Q at time t (the p_i) depends on an enormous number of physical effects: the Cherenkov process, the absorption, scattering, and dispersion of the water, the reflectivity and efficiency of the PMTs, including position-dependent effects like those shown in Fig. 8. Typically, the p_i are created via analytic approximations, often ignoring out-of-time light from scattering, or in some cases (like SNO) generated statically from a simulation. What Seibert and

LaTorre did was to replace these analytic or static PDFs with *dynamic* PDFs created in realtime with a complete simulation model. In other words, each time they evaluated the likelihood shown above, they ran a complete simulation for a particle of type ID with position $\vec{r}$, momentum $\vec{p}$ at time t. This approach therefore includes the greatest amount of information possible and is probably the best reconstruction that can be done.

There are obvious problems: running a simulation for every likelihood evaluation is bound to be very slow, and using a simulation means the likelihood space has statistical variations that make finding a minimum (of $-log\mathcal{L}$) very difficult. Seibert and LaTorre solved the first problem by completely re-inventing the way photons are propagated in detector simulations, and running their simulation on graphics cards (GPUs). They succeeded in being able to simulate all the optics of photon propagation through a detector (including complete, three-dimensional models of the PMTs) at speeds in excess of *200 times faster than GEANT4*. Along the way—as a collateral benefit—they created realtime visualizations of detectors that allow a user to move throughout the detector in three dimensions at will. Figure 9 show two screen shots from *Chroma*'s visualization

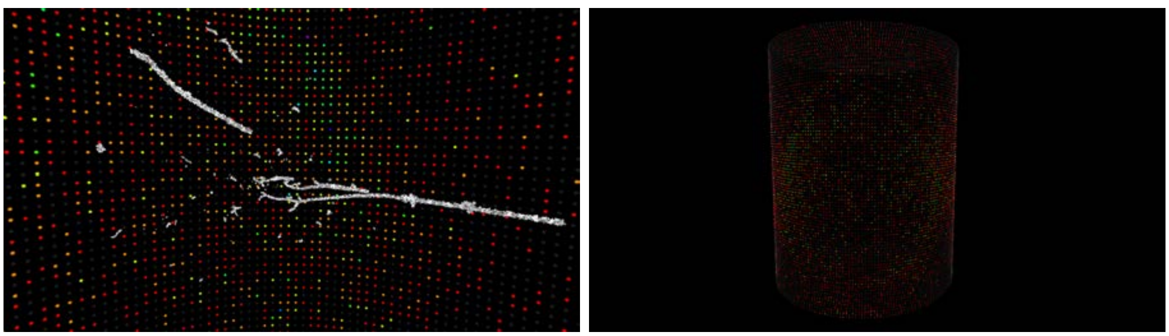

Figure 9: *A 1.5 GeV electron track shown in the LBNE detector, rendered using the Chroma photon propagation code (left) and the associated Cherenkov ring viewed from outside the detector (right).*

of a 1.5 GeV electron event in the LBNE detector but a more dramatic demonstration is in the video that can be found at `https://www.physics.upenn.edu/~jrk/chroma`. The video is just a recording of a user moving through the SNO detector and thus shows what one can do in realtime.

To fix the minimization problem, Seibert created a stochastic gradient descent method (a 'fuzzy fitter') that is able to handle the variations in the likelihood space, and is now able to fully reconstruct events. The whole point here is that *Chroma*, plus the fuzzy fitter, turns reconstruction and particle ID into a simulation problem—the more detailed and accurate the simulation, the better particle ID will be. To test whether a given event is an electron created by a ν_e or a π^0 decaying to collinear γs is as easy as changing a simulation switch and re-fitting the event.

Electronics: The Penn electronics effort for LBNE focused on developing reasonable cost and schedule estimates, some new conceptual ideas (like the possibility of a time-over-threshold measurement on each channel, rather than just integral charges and 'first-hit' times), as well as the design and construction of PMT bases for our characterization effort.

Case Study: Klein was co-editor of the the final version of the Cherenkov 'case study' document, which was used to help make the far-detector technology decision. On the basis of this study, the LBNE Executive Board voted to build a Water Cherenkov detector, although Project Management eventually overruled this decision. Klein also wrote the PMT section of the LBNE CDR, including budgets and schedules for the PMT characterization WBS element.

9 SNO/SNO+

9.1 SNO/SNO+

9.1.1 Scientific Motivation

SNO+ will replace the heavy water used in the SNO detector with liquid scintillator. With a double beta decay isotope dissolvedin the liquid scintillator, SNO+ will perform a search for the neutrinoless double beta decay, with a sensitivity to the neutrino mass parameter $\langle m_{\beta\beta} \rangle$ of 100 meV upper limit at 90% C.L. As a very rare process search aimed at understanding the nature of neutrinos, SNO+ fits squarely within the DOE's intensity frontier.

SNO+ will make sensitive measurements of the solar *pep* neutrinos as well as possible sensitivity to the as-yet-unobserved CNO neutrinos. At Penn we are also studying the possibility of measuring the high intensity, but very low energy, *pp* solar neutrinos. The experiment will also be sensitive to geo-neutrinos, supernova neutrinos, and reactor anti-neutrinos. Due to a fortuitous baseline, SNO+ may be able to make reactor antineutrino measurements with roughly the same precision as KamLAND, despite our lower reactor flux.

In the following sections we discuss work performed on this grant on the SNO+ project during the past three years. Our effort at Penn included remaining work on SNO, most notably the completion of graduate student Tim Shokair's PhD thesis analysis. Mr. Shokair searched for antineutrino events in all three phases of the SNO data set, which provided limits on the reactor antineutrino flux in Sudbury that can then be used as a guideline for the SNO+ reactor antineutrino program.

9.1.2 Accomplishments in the Past Three Years

Penn's effort on the SNO+ experiment has two components. The higher data rates obtained using scintillator light relative to Cherenkov light can be handled by the existing front-end electronics, but require an upgrade in the readout electronics. Klein is the SNO+ group leader for electronics, and provided the conceptual designs for the upgrade. Postdoc Rob Knapik and graduate students Richard Bonventre and Timothy Shokair designed, manufactured and tested boards that read out each of the nineteen electronics crates over 100 times faster than the original SNO electronics. An additional set of boards that makes the trigger more robust for the larger light output of scintillator have been designed by Klein, grad student Andrew Mastbaum, and instrumentation physicists Rick Van Berg and Mitch Newcomer. The boards were fabricated and stuffed by technicians Godwin Mayers and Mike Reilly and are now installed and running underground.

The second major effort of the Penn group is the development of offline simulation and analysis software migrating the function of the SNO Fortran based code to a new C++ architecture (RAT) developed by Penn postdoc Stan Seibert. Postdoc Gabriel Orebi Gann was co-coordinator of the analysis effort and charged with assuring that all software systems are ready for data as the data appears. Grad student Andrew Mastbaum chairs the Code Integrity Committee, making him effectively the 'code czar' of SNO+, an unusual position for a grad student to hold. Visiting Scholar William Heintzelman and Professor Eugene Beier worked on code verification issues including choices of low energy electromagnetic physics models and the choice of parameters within those models while Klein and Dr. Orebi Gann produced a detailed simulation of the data acquisition system. Klein is also the US spokesperson for SNO+, and was outgoing chair of the SNO+ Science Board.

Part III
Experimental Research at the Cosmic Frontier

10 Cosmic Frontier: Dark Energy Overview

The University of Pennsylvania is an institutional member of two large dark energy surveys with substantial DOE involvement: the *Dark Energy Survey (DES)* and the *Large Synoptic Survey Telescope (LSST)*. We have played a major role in developing the scientific and software capabilities of DES, and in the lensing science and camera electronics design for LSST, and in defining the methods and capabilities of the observational tests that are common to all dark-energy experiments. Our group also had a large role in the design and optimization of the now-defunct *Supernova Acceleration Probe (SNAP)* and *Joint Dark Energy Mission (JDEM)* space dark energy missions.

Penn's Cosmic Frontier research is undergoing a shift in emphasis from theory and forecasting to analysis of data from DES. The 500-megapixel *Dark Energy Camera* and new prime-focus optics for the existing 4-meter Blanco Telescope in Chile saw first light in September 2012, with survey operations beginning September 2013. Using 525 nights of observing time over the following 5 years, the DES will conduct a visible/NIR survey of 5000 deg^2 of the Southern sky. The scale of the DES will be a dramatic step forward, with 15–20 times the statistical power of any preceding weak gravitational lensing survey, for example. In the 2009-2012 period we developed and tested much of our software for this data analysis challenge.

10.1 Personnel

Penn faculty contributing to the dark energy projects under the DOE aegis are:

- Professor Gary Bernstein: weak lensing theory and methodology, systematic-error analysis, and DES data quality testing. Service to DOE projects and planning over the previous grant period includes membership on several JDEM advisory panels, the selection committee for DES Director, and the Particle Astrophysics Science Advisory Group (PASAG).
- Professor Larry Gladney: member of PASAG; co-chair of the SNAP simulation group; co-implementation of SNAPsim design; co-leader of physics studies using SNAPsim and ground-based supernovae (SNe) simulations. Penn representative on the LSST management council.
- Professor Bhuvnesh Jain: co-coordinator of the DES weak lensing working group, co-chair of the LSST weak lensing science collaboration, Penn representative on the DES management council. His primary expertise is in weak lensing theory and methodology, techniques for systematic-error analysis, and tests of modified gravity.

Other researchers working on dark energy with DOE support during the recent past are:

- Dr. Michael Jarvis (research staff) is writing the gravitational lensing DES pipeline. His other contributions to the project include techniques for using the shapes of stars to diagnose telescope alignment problems. He has also begun contributing to the lensing-relevant parts of the LSST pipeline development effort.
- Dr. Yan-Chuan Cai started a DOE-funded postdoctoral position in October 2009 and moved to NASA funding in August 2011. Dr. Cai is studying the stochasticity in the distribution of dark matter halos and galaxies within the large-scale fluctuations of the Universe, which

has important consequences for the design and performance of baryon-oscillation surveys and joint lensing-galaxy surveys for constraint of dark energy.

- Dr. Robert Armstrong assumed Dr. Cai's postdoctoral position in August 2011, as part of our shift to a data-analysis emphasis. Dr. Armstrong obtained his PhD on the MINOS project, comes to us via the DES Data Management group at Illinois, and is concentrating on processing and analysis pipelines for the DES.
- Dr. Anna Cabre was a postdoc from October 2009-August 2012. Dr. Cabre has worked on galaxy-shear measurement from DES, including tests of the method on mock catalogs. She is also working on tests of gravity using lensing and dynamical properties of galaxies and clusters.
- Dr. Brian Connolly (postdoc, DOE supported) worked on defining the techniques and requirements for Type Ia (SNIa) measurements on JDEM and researching general techniques for extracting physics information from SNIa images and classifying supernovae (SNe) using photometric data for any of a number of dark energy surveys
- Graduate student Joseph Clampitt (DOE supported) has worked on testing lensing correlation function estimators with DES mock catalogs and on predictions of observable properties of galaxy and cluster halos in gravity theories.
- Rick Van Berg, Mitch Newcomer, and Nandor Dressnandt of the instrumentation group are playing a major role in the front-end electronics for the LSST camera.

There are, in addition, members of the Penn community who contribute to the projects and topics of interest to the dark energy task of the DOE grant, but do not receive support from this grant. These people are named in the sections of this narrative that are relevant to their activities. Particularly relevant is the work of Assistant Professor Masao Sako, who is co-chair of the DES Supernova Working Group.

11 Supernovae Investigations

Personnel: Gladney; Connolly; graduate student (TBD)

11.1 Project Objectives

The main goal of Supernovae Ia (SNIa) measurements for the determination of the properties of dark energy is to make use of these "standard candles" of known intrinsic luminosity to measure distances at different redshifts. The determination of distance and redshift in a Hubble diagram relates directly to the geometrical evolution of the Universe—its expansion history—from which the effect of dark energy over time is inferred. The Dark Energy Task Force (DETF) [30] developed a widely-accepted figure of merit for evaluating the scientific gain of dark energy experiments for the foreseeable future. These are classed as Stage I through Stage IV depending on their figure of merit reach.

A Stage III experiment like DES is expected to improve the figure of merit for SNIa studies over those of Stage II surveys (e.g. SNLS, Essence, etc.) by a factor of at least two. This will require advances in color calibration, our understanding of heterogeneity in SNIa behavior, and the ability to more quantifiably identify systematic uncertainties. These, in turn, necessitate the identification of more supernovae, deeper redshift reach, better signal-to-noise for photometry, and broader restframe wavelength coverage. A new feature of Stage III and IV ground-based surveys will be the necessity of including in the Hubble diagram a substantial fraction of SNIa with no spectroscopic identification. Speaking specifically about DES, it will be essential to also have a set of the SNIa followed up by other telescopes.

A major objective is to produce well-understood tools that can be used to "trigger" spectroscopic follow-up with scarce telescope resources with high efficiency for SNIa and a low fraction of false positives; the quantification of systematic uncertainties in cosmological parameter determination from SNe identified and measured with photometry only; and the determination of systematic uncertainties in these same parameters (if any) due to SNIa heterogeneity.

11.1.1 Accomplishments - SNIa Surveys

Starting in the summer of 2007, Professor Gladney co-headed the simulation study to determine the science performance of various JDEM mission designs for finding and following Type Ia SNe as a function of primary mirror aperture diameter and image spot size on the focal plane. With the addition of post-doctoral fellow Brian Connolly to the Penn dark energy efforts, we expanded our responsibilities for the SNe studies used for setting SNAP mission requirements for optimizing the measurement of dark energy parameters using Type Ia supernovae, in particular with regard to "triggering". Code written by Gladney for the SNAP simulation package was used to evaluate the optimal cadence and sky coverage for a large number of focal plane layouts of optical and near-infrared detectors for various JDEM designs. Comparisons to both ground-based and other space-based designs were performed by Gladney as part of the JDEM studies. These included reasonable variations in photometric measurements of SNIa due to cosmology, magnification due to gravitational lensing, extinction due to host galaxy and Galactic dust, and background from zodiacal light. This work was further generalized to include generic optimization of and figure of merit determination for a number of ground-based observational dark energy missions. The work of Gladney, Connolly and collaborators has resulted in four publications with regard to future SNIa surveys [31–34].

Our recent efforts have been focussed on optimizing the SNIa identification for the Dark Energy Survey (DES). DES will discover a large number of supernovae (SNe) candidates. Due to the sheer number of detected candidates, it will not be possible to spectroscopically confirm the type of each candidate (*e.g.*, type Ia, Ib/c, IIn, etc.). Therefore, it is crucial to have robust techniques for identifying SNe of the desired kind photometrically (using broadband filters). DES, for example, will want to select a subset of SNe for spectroscopic follow-up. A common scenario would be photometrically identifying a number of SNIa that have not yet reached their maximum, then requesting their spectroscopic identification using either the DES telescope or another available instrument.

In the following sections we discuss methods developed to classify SNe offline and allow for near-automatic selection for those needing spectroscopic follow-up. We then discuss how these methods are employed in the *psnid* package that will be used in the DES pipeline. Finally, we discuss various studies relevant for DES SNe analyses.

11.1.2 SNe Typing

Modern large SNe data sets seem to increasingly indicate a degree of diversity among SNIa that is rather striking. In order to fully understand which subset of SNIa is particularly suited for cosmological applications, it is important to identify SNIa candidates such that an unbiased spectroscopic sample of SNIa can be obtained. Experiments such as the DES are in a prime position to do this, as long as they use fairly light constraints on the photometric identification of SNe. The reverse side of this requirement is that one must employ increasingly sophisticated strategies to identify SNe candidates. We have developed the following methods to address these issues:

- A sequential-analysis-based trigger that will allow one to identify a supernova satisfying given criteria with a minimum number of photometric measurements.
- A color-based SNe trigger capable of discriminating between SNe of a given kind and any other transient object, well-modeled or not.
- A novel non-parametric Bayesian order-restricted method to find rising flux transients in a sequence of images.

We discuss each method in more detail below.

Sequential Analysis Technique While photometrically identifying SNe candidates, it will be important to select sub-samples of light curves that satisfy certain criteria for further follow-up. For example, one might select only the candidates that appear to be SNIa *and* have not yet reached their maximum brightness. It is therefore important to develop a scheme whereby one can not only accurately classify SNe using as few photometric measurements as possible, but also select SNe that satisfy any additional constraints a given survey might wish to impose on its desired sample. Ideally, such a scheme should also allow for the purity and efficiency of the SNe selection to be set *a priori*. We have developed a sequential analysis technique for selecting SNe candidates that satisfies all of these requirements. The technique requires the computation of the so-called Bayes factor, which quantifies the belief that a given SNe candidate is consistent with being a desired type (*e.g.*, Type Ia); the belief that the supernova candidate has not yet reached its maximum brightness can be trivially included. As photometric data are accumulated, the Bayes factor provides a natural ranking for candidates for spectroscopic follow-up, if desired, and thus provides the flexibility to stop the selection process and turn the list of candidates over to the instrument that will be taking the spectra at any time, depending on the survey's and the external telescopes' timing constraints. Results from our studies on photometric typing of SNIa candidates from the SDSS-II SNe survey are now published [34].

Color-based Classification The realization that most upcoming SNe surveys will have to rely on spectroscopy to identify their supernova candidates is not new. Over the past several years, a number of supernova identification schemes have been proposed that rely solely on photometric data. Some of these schemes use color-color or color-magnitude diagrams; others simply fit supernova data to various models. Both of these approaches suffer from a number of drawbacks, most of which are at least partially remedied in the so-called Bayesian-based SNe classification techniques. However, Bayesian techniques typically require that the supernova candidate be one of a known set of supernova types. The most obvious problem with this requirement is that, in large SNe samples, there are bound to be objects that do not conform to any presently known models. We address this problem by developing a new photometric classification scheme that uses a Bayes factor based on the supernova candidate's color. This method is free from the assumption that the candidate be one of a known set of possible objects that could mimic a supernova signal.

Rising Light Curves Many surveys (including the DES) will want to select a subset of SNIa that have not yet reached their maximum brightness. Traditionally, the time of maximum is estimated using simple fits of the available supernova light curves to various supernova type models, or templates. We have developed a more general approach to characterizing supernova light curves. This method, based on calculating the posterior probability that a light curve is rising, is not only applicable to supernova light curve data, but to any data that require an immediate identification of a transient with certain characteristics (*i.e.*, the transient's light curve is rising, falling, leveling off, etc.). This method is work in progress, but is already a part of the publicly available *psnid* package described below.

We use a time sequence of images to calculate a Bayes factor statistic, R, defined as the ratio of the probability that a light curve is rising (*i.e.*, every mean flux is larger than the previous flux within statistical uncertainties) to the probability that it is not. Figure 10 shows that the ratio, R, behaves reasonably: rising light curves systematically have an $R > 1$, while those that are non-rising have an $R < 1$. Also shown is the difference between the estimated and true time of explosion (T_{exp}), defined as that time (in days) where the light curve begins to rise. This estimate is helpful in determining whether or not the candidate is in fact a supernova and whether or not it is worthwhile to follow it up. The estimated T_{exp} is typically within a couple of days of the actual time of explosion. On time scales of order weeks, which is the rise time of a typical SNIa at redshift ~ 1, such an estimate is sufficient.

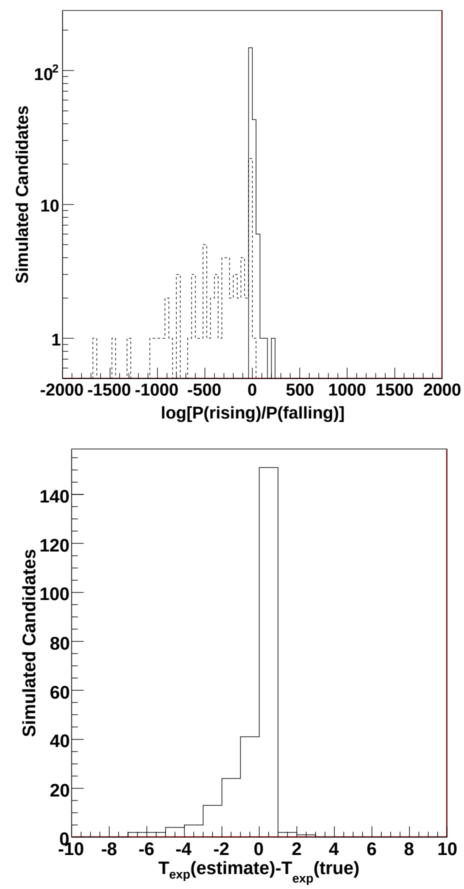

Figure 10: *Top: the distribution of $\log R$ (defined in the text) for rising (solid line) and non-rising (dashed line) light curves. Bottom: the difference between the estimated and true time of explosion.*

psnid **Supernova Typing Package** We have a developed a package that implements the techniques described above to be used within the DES pipeline. Although the package was designed specifically for DES, it can be used by the general public, thus facilitating comparisons of DES results with those from other experiments.

The toolkit, named *psnid*, has been built on top of a package used by the Sloan Digital Sky Survey (SDSS) to perform photometric identification of SNe [35] based on traditional Bayesian classification techniques with their associated drawbacks, such as the assumption that a supernova candidate is one of a known set of empirical models (*e.g.*, those found in [31, 35–37]). In *psnid*, we have expanded on and added to such techniques to make supernova identification more robust. The package is meant to serve three purposes: (1) to provide a way to photometrically classify SNe by type in the DES pipeline, (2) to evaluate various possible spectroscopic follow-up strategies, and (3) to provide a general analysis package that can be easily used by the SNe community.

psnid has the following features:

- Classifies SNe using a traditional Bayesian approach assuming the supernova candidate is one of a known set of modeled SNe.
- Outputs χ^2's and corresponding best fitting light curves along with ROOT[6] routines to plot them.
- Classifies SNe using color only.
- Selects SNe (of a given type) that have not yet reached their maximum brightness, defined within some (user-specified) time window.
- Provides model-independent identification of rising light curves.
- Provides a way to read in light curve templates using a number of different formats, thus allowing for an easy comparison of any supernova light curve models.
- Comes with an extensive manual with examples.

[6] http://root.cern.ch

12 Weak Gravitational Lensing Statistics & Methods

Weak lensing (WL) is a primary goal of the DES, plus two other contemporary large international collaborative surveys on the Subaru and VLT Survey Telescopes. WL projects in the proposal stage for the next decade include even larger ground-based surveys—the Large Synoptic Survey Telescope (*LSST*)—plus space-based surveys: the *Euclid* project approved for a 2019 launch by the European Space Agency, and the *WFIRST* mission planned as NASA's next large astrophysics mission for launch in the 2020's.

Gravitational lensing is uniquely powerful as a direct and unambiguous measure of the gravitational potential field(s) that define the deflection of light. Since the advent of the dark matter paradigm c. 1980, it has been clear that lensing offers the cleanest "view" of the dark components of the Universe, since they must deflect light even if they neither absorb nor emit any. The effect of lensing is subtle, detectable primarily by slight elongations ("shear") of the images of background objects, except along rare strongly-lensed lines of sight. The resultant coherent pattern of galaxy alignments was first detected around rich clusters of galaxies in 1990 [38], dramatically confirming the dominance of dark matter over baryons. It was quickly realized that the power spectrum of the galaxy shape distribution across the full sky is a direct measure of the power spectrum of matter fluctuations, and hence a cosmological probe independent of the ambiguous relation between luminous objects and dark matter. With the discovery of accelerated expansion of the universe in 1998, WL was also recognized as a clean and direct probe of dark energy and the expansion history.

WL observations are challenging, not just because astronomical techniques had previously emphasized positions and fluxes, not precision galaxy shape measurements. The shear on a typical line of sight is only $\approx 2\%$, below the level of coherent distortion typically induced by telescope optics—a very careful correction for the instrumental effect must be applied. The ultimate limitation is that the random shapes and orientations of background galaxies set a "shape noise" floor on shear measurements—hence WL surveys are enabled by wide-field imaging instruments that can harvest huge number of galaxy shapes: $\sim 10^7$ in the best present-day surveys, and 10^8–10^9 in DES and future surveys.

The Penn group has been responsible for developing many of the concepts and techniques for extracting cosmological information from weak gravitational lensing surveys. These span the range from purely theoretical, to the invention of statistics and analysis methods that could guide and enhance the design dark energy experiments, to practical methods for processing pixelized data and measuring weak lensing without systematic error. In this section we give an overview of recent and planned work that is generally applicable to all WL surveys and drives designs for future projects. Specific work for DES is described in section 13.

12.1 Weak lensing theory and methodology

Personnel: Jain, Bernstein, Armstrong, Clampitt

Over the past decade, we have realized that WL offers much richer statistics than the simple power spectra originally explored in the early 1990s. There is much information in the detailed redshift dependence of the lensing shear [39], in the nonlinear power regime [40], and in the cross-correlation of lensing signals with foreground galaxy concentrations [41–44]; in 3-point functions [45]; in counts of lensing peaks (related to galaxy clusters) [46–49]; in the combination of lensing data with galaxy-redshift survey data that offer improved accuracy[50, 51] and focused tests of General Relativity (GR)[52–54].

At the same time we have realized that interpretation of shear data is complicated by intrinsic alignments of galaxies [55, 56], photometric redshift (photo-z) errors, limitations to theoretical predictions of nonlinear growth [57], and magnification bias [51, 58]. As a consequence, the reduction of *DES* and other high-precision lensing data into cosmological constraints will be significantly more complex than in previous cosmological tests.

We describe in section 13.3 our efforts to develop a comprehensive data-analysis scheme for lensing and (angular) galaxy-clustering data. Theoretical understanding of WL signals in a Universe obeying GR is at a mature state, but the search for observational signatures of departures from GR is relatively new. Section 15.2 describes our work on modified gravity and astrophysical tests of gravity.

12.2 Weak lensing measurement techniques

Personnel: Bernstein, Armstrong

While successful WL measurements have already been made, there remains much work to do in developing measurement and analysis techniques for WL. The much larger data samples from DES and other future experiments will demand lower systematic errors in galaxy shape measurements than are currently achieved in order to reach the full statistical potential of the survey data. Future WL surveys like LSST, Euclid, or WFIRST will need to measure weak lensing shear with systematic errors smaller than 1 part in 1000 to reach their full potential. DES requirements are $\approx 3\times$ looser; yet to date no method for shear measurement has demonstrated accuracy better than ≈ 1 part in 100 on realistic galaxy images.

In [59] Bernstein presents a new approach to measuring the shapes of galaxies and inferring the lensing shear imparted on the galaxies: "Fourier-domain null tests," or FDNT. This work recognizes that biases arise from attempts to use information that is destroyed by the telescope/atmosphere point spread function (PSF), and some fundamental errors in treating galaxies whose shape varies with radius. The new method fixes these biases and is the first method that is rigorously correct without any *a priori* assumptions about the shapes of galaxies and PSFs.

Figure 11 illustrates that FDNT is able to achieve < 1 part in 1000 errors for a wide range of galaxy types, in the case where the PSF is perfectly known and the image S/N is high. In particular we are the first to demonstrate an algorithm that attains required accuracy on the community-wide blind GREAT08 challenge [60], attaining a "Q value" of 3000, six times better than any competitor in the GREAT08 competition, and consistent with the fundamental noise floor of the challenge data.

The next milestone is to achieve this superb performance on data with realistic noise levels without incurring various noise-induced biases that typically appear at $O(S/N)^{-2}$. Bernstein and Armstrong have devised a rigorous Bayesian formalism for evaluating shear from noisy data that should be immune to such biases if an accurate prior for the *noise-free* galaxy shape distribution can be found. This approach has been published and work on implementation and testing continues.

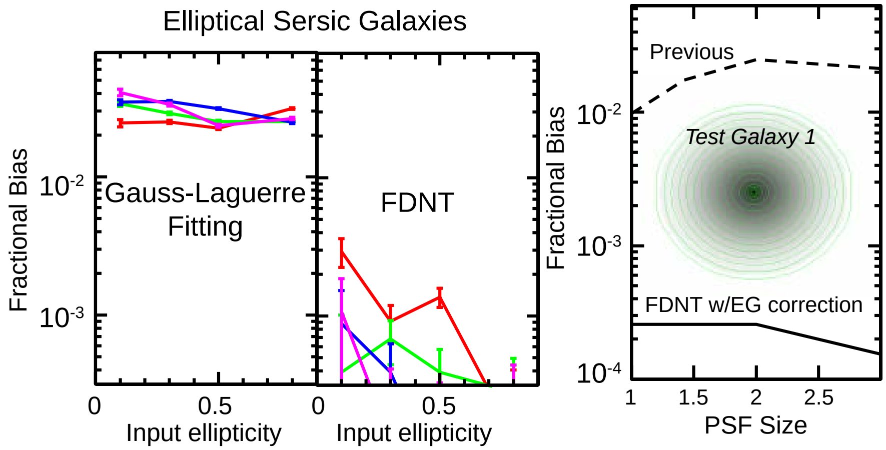

Figure 11: *Performance of the FDNT shear measurement method compared to previous methods (from [59]): the left two panels show the multiplicative shape measurement errors vs the ellipticity of an input Sersic-profile galaxy. Colors are for Sersic indices $n = 0.5, 1, 2, 4$. The left side shows few-percent errors from previous Gauss-Laguerre fitting software, the center panel shows the much-reduced errors from the model-free FDNT method. The right-hand panel shows the $\approx 2\%$ shear errors on a simple bulge+disk galaxy model using previous methods (dashed), compared to $< 10^{-3}$ errors with the FDNT method after applying the required ellipticity gradient correction (solid).*

13 The Dark Energy Survey

The DES will be a dramatic step forward, with 15–20 times the statistical power of any preceding weak gravitational lensing survey. Given that existing WL surveys are already systematic-error limited, harnessing the full statistical power of DES will be a significant and exciting challenge.

Penn scientists have developed many of the techniques that will be central to meeting this challenge in the DES WL analysis. Gary Bernstein co-leads Science Verification phase of DES. Bhuvnesh Jain is co-chair of the DES WL Working Group and Penn leads the development of the WL analysis pipeline. Michael Jarvis leads the shear measurement pipeline development and testing subgroup; Jain leads the galaxy-shear cross-correlation subgroup. We have (with S. Bridle at UC London) planned and worked on all aspects of WL studies with DES, from the proposal stage to the software development and testing underway currently. We have a deep involvement in all phases of the processing of pixel data into dark energy constraints, as detailed below.

The DES WLWG hopes to change the paradigm of WL observations, which have typically processed data through to cosmological constraints, afterwards going back to hunt for signs of systematic errors and root them out retroactively. Instead we are being proactive, testing each component of the pipeline on simulated data in advance, and *starting* the analysis with validation of the instrument and software performance. Here we detail our contributions, from the initial validation steps through the cosmological analysis.

13.1 Instrument and software validation and monitoring

Personnel: Bernstein, Armstrong, Jarvis

Successful WL shear measurement depends upon a deep understanding of the instrumental signatures in the data. Bernstein is leading a group of 5–10 scientists charged with validating that models of the astrometric mapping and the point spread function (PSF) for every exposure of the

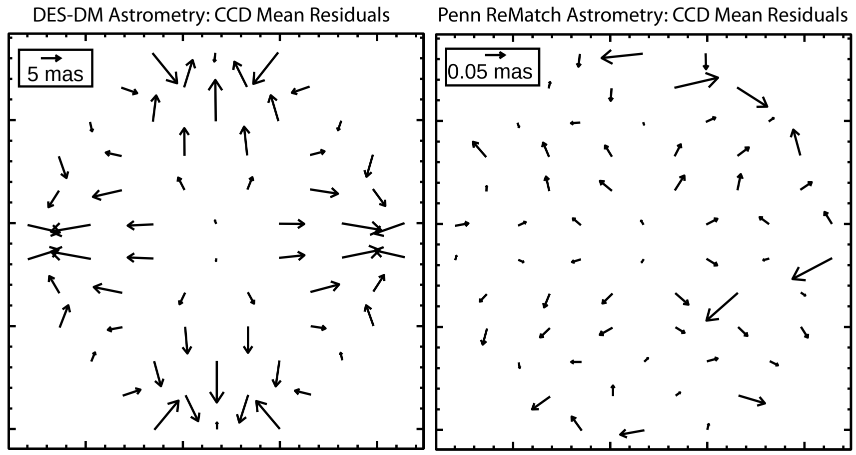

Figure 12: *Example of astrometric validation test, run on DES DC6B3 simulation. Arrows plot the mean astrometric error on each CCD of the DECam array. At left are mean residuals of astrometric solutions from the DES-DM pipeline software. At right are mean residuals per CCD using new astrometric solutions generated by UPenn* `ReMatch` *program. Note the scale change on the right-hand side—the new solution is more than 100 times better, with these residuals reduced to micro-arcsecond level.*

survey meet DES requirements. We have defined a suite of validation tests to be applied to data from simulations, from commissioning data, and from routine survey data. Results of these tests will feed back into hardware systems (e.g. the telescope alignment system), DES DM software pipeline, and the WL-specific pipeline.

The DES astrometry requirement is that distinct images be properly aligned on the sky to < 15 milliarcsec RMS in each axis—larger misalignments mimic an unacceptably large stretch from cosmic shear. Bernstein has produced a code that re-fits the astrometric solutions and reduces the residuals to 12 mas on early SV data. Figure 12 illustrates the level of improvement on a sample astrometric validation test using simulated data. We have also successfully detected subtle image distortions due to electric field bending near the edges of the CCDs ("glowing edges") that were placed in the simulations. This demonstrates the ability of our validation suite to detect unanticipated effects in the real data.

The PSF ellipticity and size must be known at any location in any DES exposure to about 3 parts in 10^3. Any color dependence must also be known to similar accuracy. We have developed several distinct PSF modelling methods, and the validation group is coding tests to check any of them against the requirements. Jarvis already has code in the DES DM pipeline which models PSFs with Gauss-Laguerre decompositions, with each coefficient having polynomial dependence on pixel position in the array. Jarvis and Armstrong are implementing a suggestion by Jarvis & Jain [61] to determine principal components of the PSF variation patterns, using sparse-sampling algorithms. This has the advantage of identifying the recurring PSF variations presumably associated with degrees of freedom in the optical structure. A third PSF model using pixellized representations is part of the DESDM pipeline created by Emmanuel Bertin (IAP Paris) and has been interfaced to the WL codes by visiting UPenn grad student D. Gruen (now returned to Munich).

Postdoc Bob Armstrong retains responsibility for other aspects of the DES DM pipeline: propagation of photometric solutions to the object catalogs; insuring that the WL code runs properly in the DESDM computing environment; and maintaining lists of securely identified stars.

Bernstein served on an internal DES review of focus and alignment mechanisms for the camera and continues to work with a focus & alignment group (headed by Steve Kent at FNAL) charged with tying together diverse elements of the DES project for an effective system of maintaining image quality. The weak lensing science has the most to gain from maintaining excellent and stable optical quality, and we will insure that PSF diagnostics generated in the WL analysis are fed back to improve the focus & alignment control system.

13.2 Shear measurement pipeline(s)

Personnel: Jarvis, Bernstein, Armstrong

Once the models for astrometric and PSF instrumental signatures are in hand, the WL analysis pipeline faces its greatest challenge in the determination of galaxy shapes and lensing shear from the pixel data.

Jarvis is leading the testing effort for all of the DES weak lensing code: ≈ 20 collaborators world-wide are testing various aspects of the software using the DES Data Challenges, as well as our own more specialized simulations, to test the accuracy of the WL software.

The Jarvis pipeline uses the Gauss-Laguerre decomposition method developed in [62] and [63]. Bernstein is supervising (NSF-funded) graduate student Andrés Plazas, who has created a testing suite for shear measurements that has been run repeatedly on Jarvis's DES lensing pipeline. For the past year we have identified bugs and refined the algorithms to reduce biases in shape measurement revealed by these tests. The effort is approaching its goal of demonstrating shear recovery with biases of $< 1\%$ for DES observing conditions, which we believe is the requirement for the first round of DES lensing science. Note that part of the testing regime is determining a set of cuts and weights on size, flux, etc., which can be applied to the galaxy shape catalog to yield accurate shear measurements without inducing selection biases in the shear.

13.3 Correlation functions and cosmology

Personnel: Jain, Bernstein, Armstrong, Clampitt, Jarvis

A major task is to *create a data-analysis pipeline that implements a comprehensive lensing modeling framework.* This pipeline must take shear and density catalogs as input, and produce a likelihood distribution of the cosmological expansion history and growth histories as output. The halo model and N-body simulation work described above will be part of the covariance estimation and model predictions. Many "nuisance" parameters—galaxy biases, intrinsic alignments, baryonic physics—that are fit will be of interest to the galaxy-formation community, while others—shear calibration errors, photo-z miscalibrations—are uninteresting, but must be included in the data analysis anyway.

13.3.1 Correlation functions and their covariances

Starting with the catalog of galaxy positions, shears and redshifts, the next step towards cosmological analysis is the measurement of shear and galaxy correlation functions. We have implemented multiple estimators of 2- and 3-point correlations of the lensing shear. These have been applied to data from a 75 square degree survey in the past [64]. A more comprehensive set of estimators has been applied more recently on mock catalogs as part of the DES data challenges. The estimators include shear-shear correlations, galaxy-shear correlations, the shear power spectrum and mass aperture moments. The testing with mock shear catalogs was successful at the level of statistical errors in the mock catalogs.

Using a halo model approach, we demonstrated the ability of all two-point correlations to provide cosmological information while marginalizing over uncertainties in galaxy bias parameters [42]. The inclusion of several key sources of systematic errors for weak lensing was formulated by us in [65], where the resulting degradation in dark energy parameters was estimated as well. In [51] we outlined a scheme of forecasting and data analysis for joint weak-lensing and galaxy-structure surveys that incorporates all of the information available in 2-point statistics while for the first time considering the major systematic errors: intrinsic galaxy alignments, redshift errors, shear-measurement errors, and uncertainties in theoretical predictions of non-linear physics. [66] quantifies the cosmological biases caused by gross errors in photometric redshift assignment, and derive the size of spectroscopic calibration survey that is required to calibrate the photo-z error rate to needed accuracy. These methods are key to planning the DES photo-z calibration effort.

A major source of complexity in analyzing lensing measurements is the covariance in the signal at different length scales due to its non-Gaussian features. In a series of papers, most recently [67], we developed a halo-model based prediction for higher order correlations and used it to estimate non-Gaussian contributions to covariances in the power spectrum. We found that a non-Gaussian contribution related to finite survey size, not previously included in the lensing literature, can contribute significantly to the off-diagonal elements in the power spectrum covariance matrix. The impact on cosmological parameter estimation is not severe provided care is taken in excluding strongly nonlinear scales (also needed to prevent being biased by the effect of baryonic physics on small scales).

There are at least two essential follow-up steps needed in the non-Gaussian calculations. One is the joint covariance of the power spectrum and bispectrum. The bispectrum includes complementary information from the lensing signal and is likely to improve our knowledge of cosmological parameters, especially in the presence of systematics [45, 65]. However, its covariance with the power spectrum must be estimated carefully. This complex calculation is well underway but still requires effort, especially to test it against N-body and ray tracing simulations (which are also in place). Jain and Clampitt are carrying this out in collaboration with Krause (Caltech) and Takada (Tokyo). Second, we need to develop the methodology and software to calculate these covariances from survey data. As described below, this is a significant computational challenge requiring new approaches to parameter estimation.

The comprehensive cosmological analysis will likely create substantial computational challenges. The WMAP analysis required fitting $O(10)$ cosmological parameters to $O(100)$ observables (the power spectra). A comprehensive WL analysis will require fitting up to $O(1000)$ parameters from a larger number of observables. Creating a useful Monte-Carlo Markov Chain over this many dimensions will be a challenge.

The parameter count is high because there are many nuisance quantities that may be functions of redshift (*e.g.* shear calibration) and/or angular scale (*e.g.* intrinsic alignments). Characterizing these free functions requires substantial numbers of parameters.

There are many observables, even at the 2-point level, since we will be cross-correlating up to $O(100)$ pairs of redshift bins, in $O(10)$ different bins of angular scale, and creating 3 different kinds of two-point functions in each bin. Thus, for 2-point statistics alone, we can expect $O(1000)$ observables; the number is significantly larger for three-point statistics. Thus extracting cosmological information from upcoming lensing surveys poses a huge computational challenge (one that has yet to be tackled in the literature). Progress will require some hands-on experimentation and carefully tested approximation schemes. We began work on the comprehensive cosmology analysis with colleagues at Michigan, Fermilab, OSU and UC London.

13.3.2 Shear peaks, galaxy clusters and mass mapping

Personnel: Bernstein and Jain

Galaxy clusters are the most massive objects for which gravitational collapse has overtaken the Hubble expansion and are therefore a sensitive measure of the Hubble acceleration and gravitational growth. Many surveys plan to detect and count clusters to measure dark energy, but success depends critically on assigning accurate masses to clusters detected through proxy measures such as galaxy counts, x-ray emission, or Sunyaev-Zeldovich effect. A principal goal of DES is to use WL to calibrate the mass proxies. With visiting student Daniel Gruen, Bernstein derived the optimal methods and ultimate limitations for calibrating cluster masses with weak lensing [69]. This was the first study to take into account the variety of internal structures of galaxy clusters and their environs. The method will be applied to the DES data in collaboration with the cluster working group.

Weak lensing in principle allows us to make mass maps of the observed universe, unbiased by the emission of radiation from baryonic structures like galaxies. In practice, the nonlocal relation of the observed shear to the underlying mass distribution, coupled with the inevitable complications of noise and masks in realistic survey data, makes mass mapping a challenge. Jain has worked with with Professor A. Connolly and graduate student J. VanderPlas at U. Washington on techniques for making 2- and 3-dimensional maps of the dark matter distribution from weak lensing data [54, 68]. We have placed mapmaking on a rigorous footing by using signal-to-noise eigenmodes, specifically the Karhunen-Loeve (KL) orthonormal eigenfunctions, that allow for smoothing and masked survey geometry. In addition, we have developed an algorithm that performs the inversion of 2-D lensing data with photo-z's to obtain 3-D maps sufficiently rapidly that it can be applied to DES and LSST scale surveys. Figure 13 shows at a simple visual level the signal and noise in the mass reconstruction [68].

We have also used the 2-D mass peaks to test the effects of noise and masking on the fidelity of the maps and on shear peak statistics, including E/B mode decomposition in our analysis. Our work extends the statistics of massive clusters to more typical peaks, associated with galaxy groups, that are detected at lower signal-to-noise. The KL expansion of the observed shear maps can be used for cosmological parameter estimation as well.

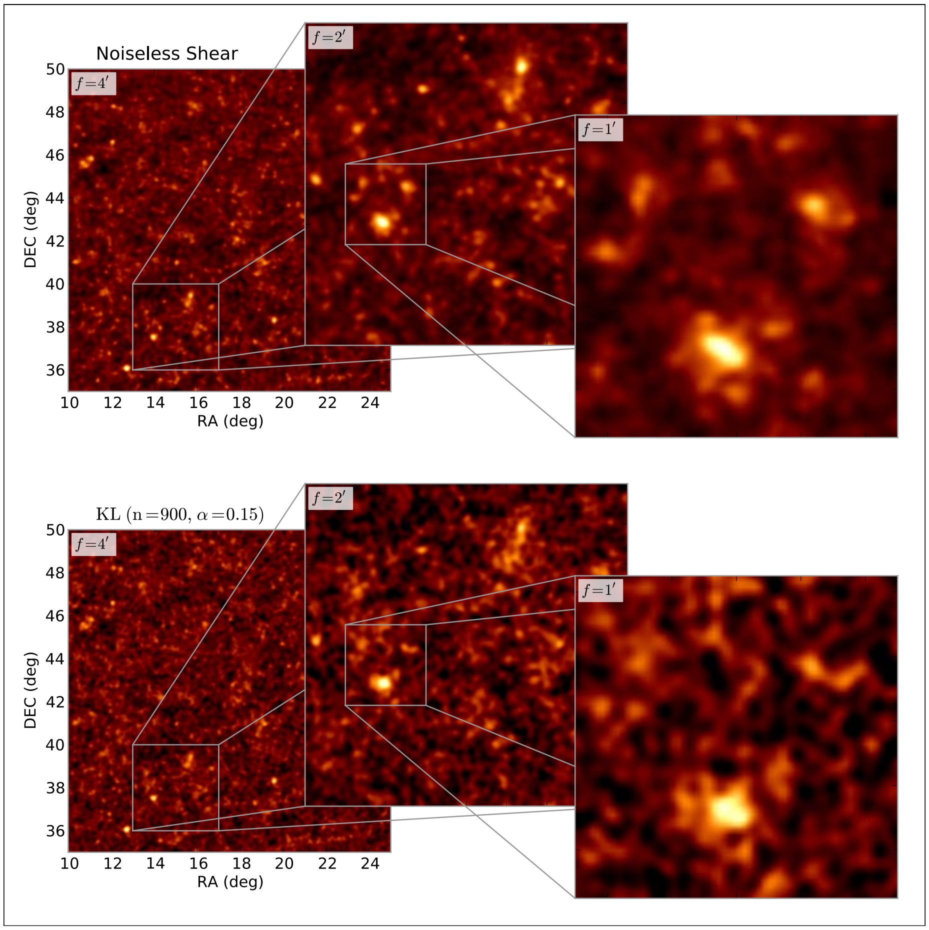

Figure 13: *The reconstruction of the density field from lensing data that has noise and masks as expected in a realistic survey [54, 68]. The KL technique is used to construct orthonormal signal-to-noise eigenmodes even for masked fields and thus reconstruct the density field with desired resolution. The upper panels shows a ray traced convergence field* 15 *degrees on a side, with two levels of zooming to show individual galaxy clusters and groups more clearly. The lower panels show the same field reconstructed from noisy shear data, with over 10% of the area masked out to mimic realistic survey conditions – the effects of noise are evident by comparison with the upper panels. We demonstrate how statistical measures such as lensing peak counts from such a reconstruction can be used for cosmological inferences.*

14 The Large Synoptic Survey Telescope

LSST proposes to use an 8.4-meter telescope and a camera with a 9.6 deg^2 field of view to image half the sky in six filters and at significantly greater depth than DES and other precursor surveys. It will provide an enormous dataset for dark energy measurements via gravitational lensing, supernovae and other methods. LSST is currently finalizing the instrument design; weak lensing places the most stringent requirements on its image quality specifications.

14.1 Weak Lensing

Personnel: Jain, Jarvis

Much of the Penn lensing effort for LSST follows naturally from the work on methodology and for DES described above. The main topics are: (1) Theoretical predictions at a percent level for lensing power spectra and several other statistics. (2) PSF-related systematic errors: framework for analyzing them, estimation of contributing effects via detailed simulations, and algorithm development for correction of galaxy shapes. (3) Development and implementation of software to measure lensing power spectra and other statistics. (4) Estimation of cosmological parameters via a joint analysis of measured statistics and marginalization over systematics. In this work we have anticipated the higher-precision needs of LSST and the scaling of computational effort for its significantly larger data size.

Jain co-chairs the LSST weak lensing science collaboration with Dave Wittman at UC Davis. We set up a series of studies to be carried out to prepare for lensing measurements with LSST. We wrote and edited the weak lensing chapter of the LSST science book [70]. Jain led the development of the weak lensing planning document for LSST—it will be expanded and formalized as LSST establishes its dark energy collaboration. Jain presented the weak lensing talk and responses to several technical issues at the CD1 review for LSST in early November 2011.

Jarvis worked on the LSST pipeline in addition to contributing to the overall lensing agenda. He worked with the LSST data management team to include weak lensing modules in the LSST software pipeline. The software is at a much earlier stage than the DES pipeline, since there is more time until the observations begin. The first two components of the pipeline, bright star identification and PSF measurement using those stars, have been delivered to the LSST data management team. The full incorporation of these modules into their software stack is still ongoing as other modules within LSST begin to use this PSF code.

There are other activities from the past not described above, as well as plans for the future that will be developed as the project matures. Bernstein has been involved at several key steps of the weak lensing planning and will continue to contribute as a member of its science collaboration, as well as to time-domain astronomy enabled by LSST. Jain and Jarvis have helped formulate the science requirements for the design of the LSST instruments. With M. Takada and others we have calculated the forecasts for dark energy measurements and tests of gravity on large-scales with LSST. Jarvis and Jain have examined the scaling of the PCA method of PSF correction to the enormous survey size of LSST. The computational issues in carrying out a global image analysis of the LSST dataset are challenging; we have made analytical estimates and begun the adaptation of the software for testing with LSST simulations. We have also studied the connection of photometric redshifts and lensing science goals; this effort is in collaboration with A. Connolly (U. Washington) and others.

14.2 Camera and electronics development

Personnel: Newcomer, Dressnandt, Reilly, Mayers, Van Berg

The three gigapixel LSST CCD camera requires over 3000 separate electronics channels to be able to achieve the 15 second exposure / 2 second read cadence specified for the survey. To reduce capacitance on the CCD readout lines and simplify the passage of signal and control connections through the vacuum jacket of the camera cryostat, the LSST design calls for placing all of the front end and digitizing electronics inside the cryostat – unlike almost all previous astronomical camera designs. In order to meet the stringent requirements for noise (a few e^- rms), cross talk (10,000:1 after correction) and dynamic range (100,000:2 e^-) within the tight space constraint of the camera cryostat, the LSST will place two custom integrated circuits (a CMOS correlated double sampler and a high voltage CMOS clock driver, both designed by IN2P3, Paris) and commercial high-speed analog-to-digital converters on a high-density circuit board kept at a temperature of around -40 C. The ADC data are sent to the external data farms over multi-gigabit-per-second links. Successful first prototypes of the custom integrated circuits were produced and tested two years ago and the second-round devices are presently under test or, in the case of the clock driver, redesign.

The LSST Camera Project received CD1 approval from DOE in early 2012 and an NSF Final Design Review is scheduled for this year. The project has received enthusiastic support from the agencies and the science community - support that lends impetus to ourwork on the hardware to accomplish the scientific goals.

During 2012 the original conceptual design of an analog Front End Board carrying the custom circuits and held at the CCD temperature of about -100 C and a second Back End Board with commercial components kept at about -40 C was replaced by this much higher density combined design, the Raft Electronics Board (REB). This change was initially driven by realization that it was going to be very difficult to get the necessary refrigeration capapcity to hold the FEB at -100C, but we immediately realized that there were many *electronics* advantages to running all the devices in a single temperature zone. The biggest win is eliminating cables between front and back so that there is no artificial limitation on the number of conductors - this enabled us to double the board density (now three REBs handle the nine sensors in a raft while previously six FEBs plus six BEBs plus an FPGA board were required) and to have more individual control of each sensor, to guarantee identical potential rails for a given CCD and to include a wide array of diagnostic and verification tools in this single design. In addition, the power and space requirements were reduced and, we expect, the system reliability improved. The first discussions of this change occurred in the beginning of calendar 2012 and a completed REB is now available for initial testing.

Raft Electronics Board Penn had been responsible for the design, testing and production of the FEB but with the change in baseline design and redirection of the Harvard team's efforts Penn is now responsible for the full REB which includes all the analog and digital elements of the Camera focal plane electronics system. A major accomplishment for the past year was taking this significant design change from concept to realization. The REB (Figure14) is a quite complex 12 layer printed circuit with dense (almost 3,000) component mounting on both the front and rear of the 100 x 400 mm board. The board includes full readout of three LSST CCDs at 550 kpixels/sec with an expected noise electronics contribution of less than 2 electrons. The output of the REB is a digitized data stream in excess of 1 Gb/s. The board includes temperature, voltage and current monitoring, raft heater control, test pulse generation and the ability to do realtime measurements of most of the signals on the board including all the CCD clocks via a pair of high speed twelve bit digitizers - the equivalent of a dual channel 50 MHz oscilloscope on each board.

Vertical Slice Test This test program (the Vertical Slice Test - VST) is a three-phase effort with the present first phase planned to culminate in the readout of an LSST prototype CCD but

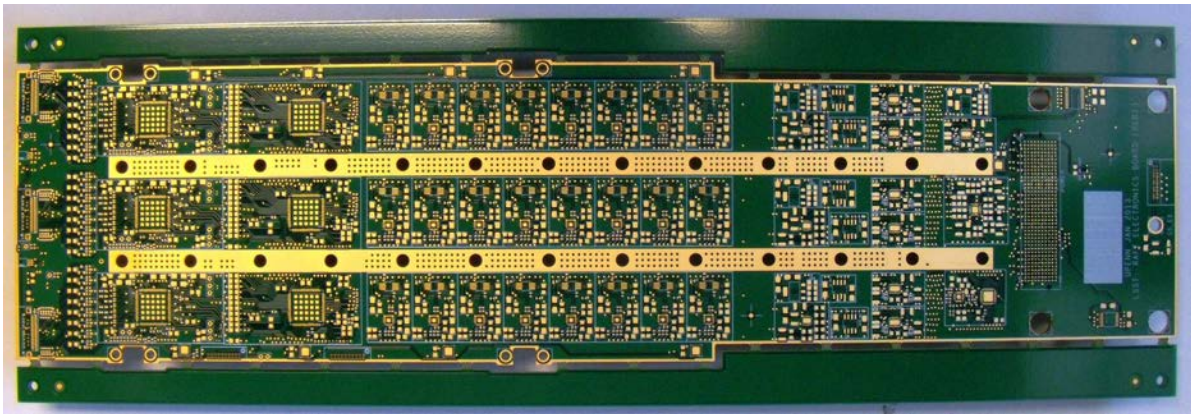

Figure 14: *Photo of an unstuffed REB - connectors for three 4cm square 16 Mpixel CCDs on left, connector for high speed FPGA interface to the LSST DAQ on the right.*

with warm electronics. The next phase of the VST will exercise a second generation analog chip and a second generation clock driver chip. The third phase of the VST will verify the final (third generation) designs of chips and boards in realistic mountings with real pre-production CCDs and verify all of the cleanliness issues required to maintain a very low contamination environment for the CCDs.

The first phase of the VST is now nearing a successful conclusion with the readout of an engineering grade sensor using the previous generation FEB + BEB as shown in Figure15).

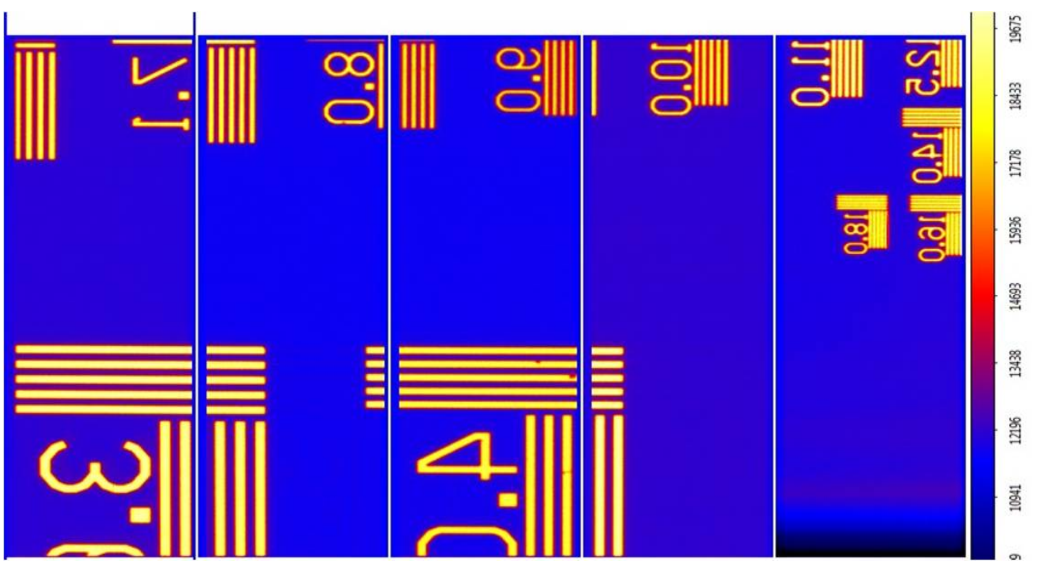

Figure 15: *Readout of five (of 16) segments of an e2v engineering grade sensor at Brookhaven. This readout used the full LSST readout chain - FEB+BEB+prototype DAQ and is the first demonstration of the readout of an astronomical grade CCD using custom designed integrated circuits.*

System Engineering Rick Van Berg has been serving as the LSST Camera Electronics System Engineer for the past four years and has managed some progress in organizing and rationalizing the baseline design of the camera and in encouraging the multiple groups toward a common goal and vision for all the electronics on the Camera. In addition to leading the effort on the science electronics (IC developments in IN2P3, back end at Harvard and front end at Penn plus testing at all three locations), there are more general electrical and electronic issues that encompass all of the electrical and electronic devices, sensors and controls in the Camera including additional groups at Arizona, Illinois and SLAC. Many of these issues have resulted in design and policy documents that cover both the Camera and the entire Project - Grounding and Shielding, Electromagnetic Interference, Design for Reliability are among the issues raised in the past two years and Project and Camera policies have been produced to cover most of these areas.

15 Beyond Lensing: Cosmological Surveys and Tests of Gravity

15.1 Multiple tracers of large-scale structure

Personnel: Bernstein, Cai

Most of the experimental probes of dark energy are derived from measurements of the large-scale structure (LSS) of the Universe—weak gravitational lensing (WL), baryon acoustic oscillations (BAO), redshift space distortions (RSD), and galaxy cluster counts are all, in essence, using the LSS as a window into the expansion history of the universe and the rate of gravitational collapse of structures. Since dark energy (or modification of gravity) alters the balance between the Hubble expansion and the gravitational collapse instability, the history of LSS becomes a primary diagnostic of the origin of the Hubble acceleration. Uncertainties from baryonic physics become less important on scales $\gg 10$ Mpc, so the largest scales and volumes accessible in the Universe are highly favored for precise tests of cosmic acceleration.

Multiple tracers of LSS are accessible to observation, each with its own merits and problems. WL is the purest tracer since it measures the gravitational potential directly, requiring no baryonic physics for interpretation. It is, however, a weak effect and hence a noisy probe; furthermore it has almost no line-of-sight resolution and hence loses statistical power. Galaxy or cluster density maps from imaging surveys have higher S/N, but interpretation is severely hampered by the unknown "bias factor" b between galaxy fluctuations and total mass fluctuations. Spectroscopic galaxy redshift surveys resolve line-of-sight structure and hence have even more statistical power, but they are "contaminated" by the Doppler shifts from galaxy velocities—a contamination that is a valuable tracer itself, although difficult to disentangle from density information, and still subject to degeneracies from galaxy bias.

A major recent project has been to understand how to enhance the power of LSS cosmology by *combining* these multiple tracers, particularly if they can be obtained over a common volume of the Universe. In [71] we show that the combination of weak lensing surveys with galaxy redshift surveys provides much better measure of large-scale gravity than can be obtained with the standard RSD method alone, as illustrated in Figure 16—a gain equivalent to a factor-10 increase in RSD survey size. In essence, the WL survey calibrates the bias of the galaxies, turning the spectroscopic galaxy survey into an accurate and precise mass tracer, and further breaking the degeneracy between density and velocity tracers. In [72] we investigate the critical issue of just how precisely (or stochastically) the galaxies map the dark matter, showing that the optimal galaxy-based mass estimator is up to $15\times$ better than standard Poisson statistics would suggest.

15.2 Gravity theories and tests with survey data

Personnel: Jain, Cabre, Clampitt

We have worked on methods to carry out astrophysical tests of gravity theories using lensing and a variety of other observables. These tests are motivated by recent theoretical developments in which the dark sector includes new (light) degrees of freedom (generally scalar fields) so that the scenarios of interest reduce to scalar-tensor gravity theories in the observationally-relevant regime. They mediate additional long range forces, thereby directly impacting the dynamics of galaxies and the growth of structure.

In a recent review article [73], we laid out an approach to testing gravity based on the screening mechanism deployed by the gravity theory, namely, the physical basis by which it recovers general relativity in the solar system. Our approach is distinct from the standard linear-regime based approach: it has the advantage that any future gravity model must rely on screening mechanisms

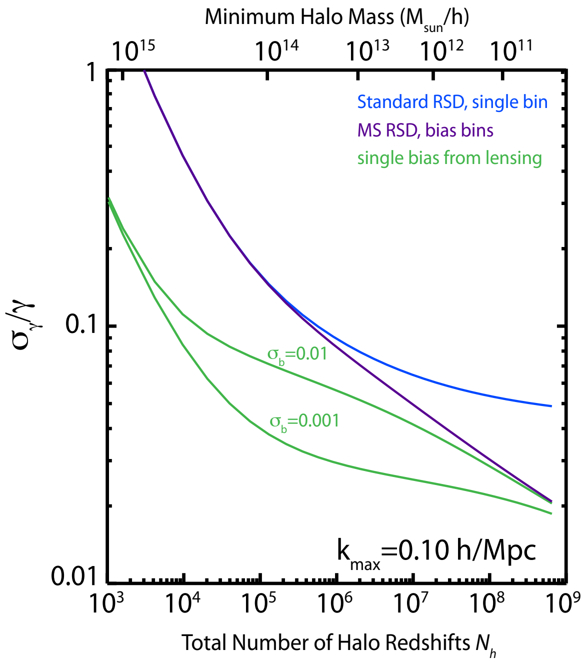

Figure 16: *¿From [71], the constraint on modification to General Relativity obtained from redshift-space distortions (RSD) in a survey of* $\frac{1}{2}$ *of the sky at* $0.45 < z < 0.55$ *is plotted vs the number of spectroscopic redshifts obtained. We assume that all halos above some mass are targeted in the spectroscopic survey, and the top axis gives the required mass threshold. The growth rate is assumed to be* $d\ln G/d\ln a = \Omega_m^\gamma$*, with* $\gamma = 0.55$ *for General Relativity. The blue (top) curve is for standard RSD analyses; the purple curve below implements a split of targets by their bias, as suggested by McDonald & Seljak. The lower 2 (green) curves show that combining the redshift survey with a weak gravitational lensing survey that measures the bias factor of the galaxies to 1% (or 0.1%) accuracy yields much stronger constraints on* γ *for fixed number of spectra. A lensing+galaxy survey of* 10^6 *targets performs better than a standard RSD survey with* 10^9 *spectra.*

(there are generically only a few such mechanisms) with characteristic signatures with length scale and environment.

We emphasized that new tests of gravity using galaxies in the local universe (within 100-200 Mpc) can be as powerful in discriminating MG theories as conventional cosmological tests [74], following the work of [75]. The density/potential fields generically couple to the additional scalar fields inherent in the theories of interest. This regime is therefore the hardest to describe in any general way as the nature of the coupling to scalar fields is theory specific. However, the predicted deviations from GR are generically large, e.g., for models studies so far, the predicted deviation of the gravitational force is a factor of 1/3. Thus, while this regime has largely been neglected in probes of quintessence-like dark energy, it can provide powerful tests of gravity and novel phenomena in the dark sector.

With graduate student VanderPlas at U. Washington, Jain proposed a set of observable properties of the stellar disks of dwarf galaxies [76] that can significantly improve constraints on cosmologically motivated gravity theories. The key idea underling these tests is that in dwarf galaxies the dark matter and neutral Hydrogen (HI) gas (observable with radio telescopes via its emission at 21cm wavelength) respond to a "fifth" force due to a scalar field, while stars are dense enough to self-screen and therefore differ in their dynamics. Figure 17 shows the expected deviation in rotation curves of stellar and HI disks—even with a sample of dozens of dwarf galaxies, useful constraints can be obtained by averaging suitably scaled measurements. Jain has begun a program of tests of gravity using disk galaxies in the local universe by implementing the theoretical ideas proposed in [76] and [75]. Screening mechanisms for different models of gravity can be distinguished based on these tests (e.g. [77]). He has also begun a collaborative project on pulsating stars, such as Cepheids whose properties are very well studied observationally. Tests of gravity theories in the nearby universe probe a region of parameter space that is distinct from cosmological tests. We developed new methods of testing gravity in the local universe with collaborators at Columbia (L. Hui) and Cambridge (J. Sakstein and others).

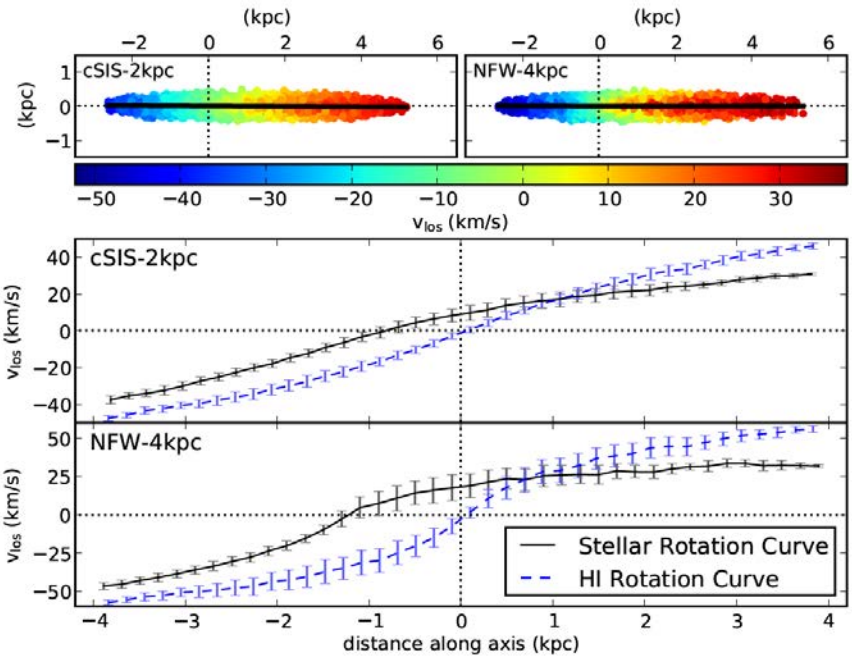

Figure 17: *Upper panels: A near edge-on view of the an infalling disk galaxy in chameleon or symmetron gravity theories. We show two halo profiles, an NFW form and a cored Isothermal sphere. Stars are color-coded by their radial velocity in km/s. Black lines denote the principal axis of the stellar distribution used to define the rotation curves. Lower panels: The HI and stellar rotation curves along the major axis of each galaxy. Two effects are apparent. First, because the HI disk is not dense enough to be self-shielded, it feels a stronger gravitational attraction to the dark matter and has a faster overall rotation. Second, the self-screened stellar disk lags the halo, leading to asymmetric distortions in the rotation curve of the disk.*

16 Dark Matter and DEAP/CLEAN (MiniCLEAN)

16.1 Introduction

The Penn group working on direct dark matter detection was made up of members of the larger Penn neutrino group (described in the 'Intensity Frontier' section of this proposal) which works on LBNE and SNO+, and has a successful history with SNO. Our dark matter effort over the previous three years included Joshua Klein (the PI), post-doc Stan Seibert, and graduate student Tom Caldwell. We were able to make great contributions here by leveraging our expertise and resources from our neutrino efforts, and by taking advantage of the large amount of technical overlap between the neutrino experiments and our approach to dark matter. In fact, we were drawn to the DEAP/CLEAN effort for exactly this reason: the great neutrino experiments like SNO, Super-Kamiokande, and others, have all had in common detectors which can be made very large inexpensively and which are simple to model and operate.

The DEAP/CLEAN program seeks to detect dark matter directly using interchangeable targets of liquid argon (LAr) and liquid neon (LNe). Unlike most other noble liquid dark matter detectors, DEAP/CLEAN will operate as a liquid-only 'single-phase' detector, observing just the scintillation light produced by WIMP scatters. The basis for our background rejection is three-fold: external backgrounds from radioactivity in the photomultiplier tubes (PMTs) and detector structure are reduced by self-shielding and removed by fiducial volume restriction, neutrons scattering within the volume are removed by a delayed-coincidence tag, and internal (electron-like) backgrounds from radioactivity inside the target liquid are reduced using pulse-shape discrimination. Pulse-shape discrimination is made extremely effective in our detectors because of the remarkable difference in the time profile of the scintillation light produced by WIMP-like nuclear recoils and electron-like backgrounds in Ar and Ne, and the superior light collection achievable in a single-phase detector. In argon, the electron/nuclear recoil separation is remarkably good but also necessary to reject the dominant background of ^{39}Ar decays, at a level of 10^{-10} or better.

We are currently constructing the next stage of our program, a 150 kg fiducial mass detector called MiniCLEAN. With two years of operation, MiniCLEAN will achieve a sensitivity to the WIMP-nucleon scattering cross-section of 2×10^{-45} cm^2 for a 100 GeV WIMP mass. Should an apparent signal be seen, MiniCLEAN has the great advantage of being able to verify the signal directly in two ways. The first is to introduce a 'spike' of ^{39}Ar, to increase the nominal background rate by up to a factor of 10. Should the signal not increase, we will know it is not leakage from ^{39}Ar events. The second is the target swap from argon to neon, which will allow us to look for the expected A^2 cross-section dependence of the WIMP-nucleon cross-section. Our colleagues in Canada are currently designing the next step in the DEAP/CLEAN program, a 1-ton fiducial volume, argon-only single phase detector, called DEAP-3600.

Figure 18 shows an engineering drawing of the MiniCLEAN detector. The central target of liquid cryogen will be contained in a low-background stainless steel vessel (the Inner Vessel - IV). The IV contains ports to accompany PMT optical modules that will view the inner liquid via lightguides. The front faces of the lightguides are coated with a wavelength shifter (tetra-phenyl butadiene or 'TPB') that shifts the extreme ultraviolet scintillation light into the blue. The lightguides transport the blue light to PMTs immersed in the cryogen.

Substantial progress was been made over the past few years on both the construction of the detector and on the underground location at the 6800 ft level of SNOLab. Figure 18 also shows the assembled outer vessel (OV) and the progress on the assembly of the IV and the water tank for MiniCLEAN's veto shield assembled underground, with SNOLab diretor Nigel Smith standing in front. The last major piece of construction will be the PMT optical modules or 'cassettes'

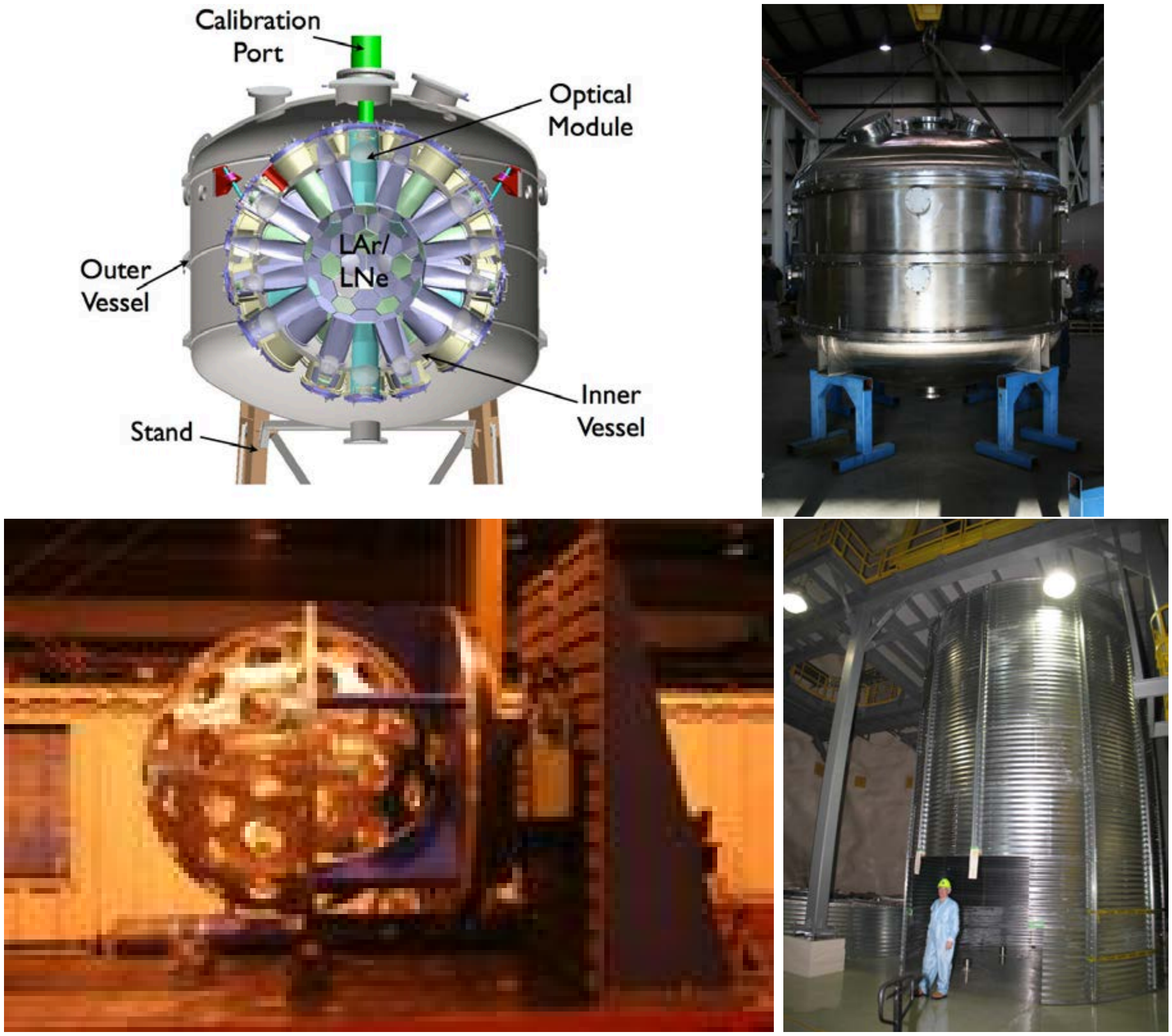

Figure 18: *Engineering drawing of MiniCLEAN detector (top left) and assembled outer vessel (top right). Finished spherical inner vessel with ports of optical cassettes (bottom left) and veto water tank underground at SNOLab (bottom right).*

which include the photomultiplier tube support and lightguide. Once assembled, the cassettes are inserted into the holes of the IV.

Our effort on MiniCLEAN received substantial funding from Penn, through Klein's startup and through a University Research Foundation grant.

The work by the Penn group on MiniCLEAN over the past three years focused on DAQ electronics and software, and simulation and analysis. Our effort increased substantially with the arrival of post-doctoral fellow Stan Seibert in Fall 2010. Dr. Seibert was the Physics Analysis Coordinator for MiniCLEAN and the author of the RAT simulation and analysis package used by the MiniCLEAN collaboration (and also used by the SNO+ collaboration). In addition to Klein, Seibert, and Caldwell, we had important contributions from Anthony LaTorre, who worked with us on MiniCLEAN as an undergraduate. Seibert's effort on MiniCLEAN was funded entirely from start-up funds. Caldwell and Klein received support from this grant from the Office of High

Energy Physics.

16.2 DAQ and Electronics

The PMT signals from MiniCLEAN will be read out using CAEN V1720 waveform digitizers (WFDs), which operate at a bandwidth of 125 MHz. We purchased four of these modules with Klein's grant from Penn's University Research Foundation. In collaboration with colleagues at Boston University, Mr. Caldwell has set up a multi-board system here, to optimize the boards' configuration and to help stress-test them under various realistic running scenarios. Mr. Caldwell also constructed a multi-channel pulser capable of feeding signals of various delays into multiple boards at once.

To optimize MiniCLEAN's sensitivity, we would like to run at as low a hardware trigger threshold as possible—the kinematics of elastic scattering by WIMPs produces very low-energy nuclear recoils. While the hardware can handle our expected data rates (~ 500 Hz), the costs of storing, maintaining, and analyzing the resultant 70 TB/year would be beyond the MiniCLEAN collaboration's resources.

The majority of the 500 Hz comes from ^{39}Ar decays, and thus a large fraction of these backgrounds can be removed with reasonably loose cuts on the scintillation timing profile or event energy. Mr. Caldwell thus developed a 'Level 2' software trigger for MiniCLEAN that will apply several loose filters to the online data stream, before events get written to disk. Caldwell's software trigger is designed to make fast decisions by using time offsets and integrals of the DAQ's zero-suppressed waveforms, rather than the entire waveform. His trigger does fast estimation of energy, position, and the prompt-time fraction of the light ('f_{prompt}') which distinguishes electrons due to ^{39}Ar decays from WIMP-like nuclear recoils. Caldwell's trigger tags the events depending on which cuts they pass, and then writes to disk different levels of information on this basis. WIMP-like events (and a pre-scaled sample of all others) will be written out with full zero-suppressed waveforms; events that are rejected are kept in a reduced form that contains only a summary of prompt and total scintillation light.

Caldwell developed the Level 2 software trigger entirely within our RAT simulation and analysis package; thus we can run it offline as well as online in an identical way to check its efficiencies and rejection levels. For the simplest rejection level, the Level 2 trigger accepts more than 99.9% of all WIMP events, and reduces ^{39}Ar backgrounds (and hence the data rate) by a factor of seven.

16.2.1 Simulation and Analysis

The RAT simulation and analysis package was written by Seibert. In addition to being adopted by MiniCLEAN and SNO+, RAT has seen use in other experiments and was considered by LBNE as a possibility for its offline package. RAT provides event-level simulation of particle propagation, energy loss, and photon-level optics using a combination of GEANT4 and custom code. In addition, RAT contains a full simulation of the data acquisition system and several reconstruction algorithms. Finally, RAT also defines a standard ROOT-based file format allowing events to be easily plotted interactively, analyzed, reprocessed, and shared between users.

One of the great advantages of the DEAP/CLEAN approach is that the detector is so simple to model—much like the large-scale neutrino scintillation experiments like KamLAND, SNO+, and BOREXINO. Philosophically, RAT follows SNO's FORTRAN-based 'SNOMAN' simulation, which emphasizes physically-motivated detector models as opposed to empirical or phenomenological measurements. It thus requires detailed calibrations as input, particularly when it comes to the optics of surfaces such as the wavelength-shifting TPB layer. Comparisons of RAT to data taken with a prototype detector at Yale ('MicroCLEAN') have shown very good agreement, and as our understanding of the PMTs and detector optics improves, we expect the agreement to continue to get better.

Penn led an effort to completely re-write the DAQ simulation so that it is more flexible and better mimics the real CAEN V1720 modules. A majority of this re-write was done by Caldwell based on his hands-on experience with the digitizers. A collateral win is that Caldwell's code is more than 20 times faster than the old DAQ simulation, removing a major bottleneck to the generation of high-statistics ^{39}Ar events. With the new DAQ code, Caldwell was able to tune up the software trigger in great detail. The identical code will be used on-line as part of the DAQ.

In a low-energy experiment based on photon detection, the ability to resolve single photons in individual PMTs is critical to improving position reconstruction and particle identification. One solution to this problem is to divide the integral charge observed from each PMT by the mean of the charge distribution. While simple, this approach has poor resolution due to the large variance in PMT pulse amplitudes. Alternatively, one can use a peak-finding technique that ignores pulse amplitude. While this method has much better resolution for counting photons separated in time, pileup of photons will always bias it low. Mr. LaTorre developed a hybrid approach that combines the best attributes of both charge integration and peak-finding into a robust Bayesian photon counting algorithm. The key input to the algorithm is a model for the time distribution of photon production in order to determine the probability of pileup photons at different times in the event. Figure 19 shows the improvement in bias and resolution of the LaTorre algorithm compared to charge integration and peak-finding.

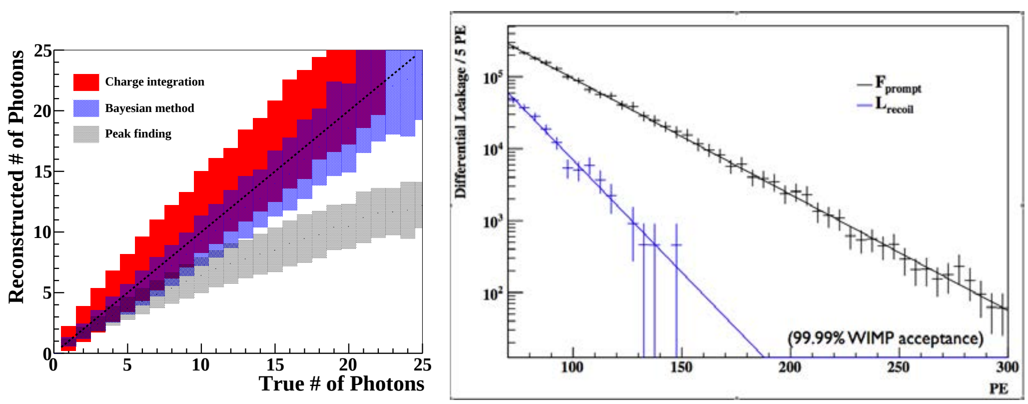

Figure 19: *Improvement in bias and resolution of photon count from waveforms using LaTorre's Bayesian photoelectron counting algorithm (left) and the reduction in background leakage from* ^{39}*Ar events as a function of the detected number of photoelectrons (PE) using Seibert's* L_{recoil} *compared to the canonical* F_{prompt} *parameter.*

The most important background rejection tool that a single-phase detector like MiniCLEAN has is pulse-shape discrimination. The simplest way to reject events is to use a ratio of 'prompt' to 'total' light in an event (f_{prompt}). But Seibert has developed a more sophisticated likelihood-based rejection approach, using LaTorre's Bayesian pulse-counting method. His approach has now been tested in detail by Caldwell. Figure 19 shows the great reduction in leakage of ^{39}Ar events using Seibert's 'L_{recoil}' likelihood-based parameter as compared to the simple F_{prompt}. With this reduction, we expect to significantly improve MiniCLEAN's sensitivity to WIMP events.

The most complex (and least-understood) optical component in MiniCLEAN is the TPB wavelength-shifting layer. A detailed understanding of the TPB re-emission spectrum, angular distribution, and efficiency is crucial to making reliable predictions of signal acceptances and background leakage. Working with collaborators at Los Alamos, Seibert published a paper in April 2011 to NIM A (Ref. [78]) on the fluorescence efficiency and re-emission spectrum of TPB. Contrary to some previously published measurements, but in agreement with others, the work found that the re-emission spectrum of TPB has a short wavelength cutoff at 400 nm, as shown in Figure 20. By confirming this spectral behavior, we were able to optimize our choice of acrylic for the lightguides in the optical cassettes. The work done on TPB is also relevant for LBNE:

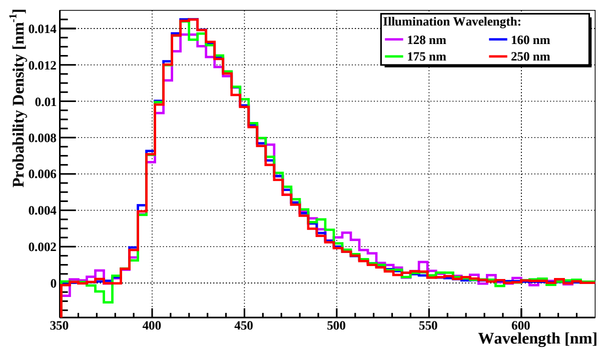

Figure 20: *Re-emission spectrum from a 1.5 micron layer of TPB for various incident wavelengths of UV light.*

plans for a 'photon trigger' in the liquid argon far detector will use TPB as the wavelength shifter for the argon scintillation light, very similar to MiniCLEAN.

Part IV
Theoretical High Energy Physics Research

17 Overview

The theory group at Penn is a productive and influential center for the study of the fundamental forces of nature, early universe cosmology and mathematical physics. Activities span the range of these fields: from model building, formal field theory and string theory, to new paradigms for cosmology and the interface of string theory with mathematics. Thus, the Penn theory group is one of the few in the world where extensive development of the formal aspects of string theory has been united with a focus on real phenomena in particle physics, cosmology and gravity. The faculty in the group at present are Vijay Balasubramanian, Mirjam Cvetič, Justin Khoury, Burt Ovrut and Mark Trodden. The group trains postdoctoral researchers and PhD students, supported by the DOE, the NSF funded String Vacuum Project, expiring start-up funds, and the University. The group is an integral part of the new Center for Particle Cosmology and runs a very active Visitor Program supported partly by the University. The group continues an active effort within the Math-Physics program, with the strong involvement of the post-docs and theory students. In this introductory section we will provide a snapshot of the range of research carried out in our group.

Brief history of research in the Penn Theory group

We summarize here the research of the faculty. The range of expertise lends itself naturally to significant internal collaboration. We benefit significantly from cross-pollination between the formal and phenomenological aspects of the work of different group members. In recent years particularly, a number of jointly-authored papers have emerged from these discussions, and more are expected as our interactions increase within the Center for Particle Cosmology, discussed later.

• **Vijay Balasubramanian** has made fundamental contributions to the study of gravity and gauge theory. He wrote some of the foundational papers that defined the dualities between gauge theories and gravity and has used these to study many aspects of quantum gravity and of strongly coupled quantum field theory. In recent years he has written a number of papers on understanding black hole thermodynamics, the information loss paradox and the emergence of spacetime from the dynamics of strongly coupled gauge theories. He also wrote a key paper on moduli stabilization in Type II string theories, which has become one of the two standard scenarios (the so-called LARGE volume scenario) for moduli stabilization in string model building. He has recently turned his attention to using the AdS/CFT correspondence to understand properties of hot nuclear matter and strongly interacting systems in condensed matter physics. These efforts have also led him to think about quantum entanglement in strongly interacting field theories and the role of this in quantum gravity.

• **Mirjam Cvetič** has made key contributions in the gravitational aspects of string theory and to constructing string vacua with realistic low energy physics. Her work on topological defects in gravity gave some of the first examples of supergravity domain walls, and of multi-charged, rotating black holes, important for counting black hole microstates. She constructed new spaces with special curvature (Spin(7) holonomy and L^{abc} Einstein-Sasaki spaces) and comprehensively studied consistent non-linear Kaluza-Klein flux compactifications of string and M-theory. Contributions to string phenomenology include constructing globally consistent compactifications of

Type II string theory on Calabi-Yau orientifolds with intersecting D-branes which resulted in the first supersymmetric, 3-family Standard-like models, and constructing Standard-like and GUT-like models. Her efforts also led to stringy non-perturbative effects due to D-instantons which can modify couplings for charged matter and introduce new hierarchical scales with phenomenological implications. Most recently, she has focused on: studies of microscopic interpretation of near- and non-extreme multi-charged rotating black holes in terms of dual conformal field theory; classifications of multi-stack D-brane quivers with realistic particle spectrum and couplings; extensive study of D-instantons, both within particle physics and formal developments, focusing on Type IIB and F-theory.

Burt Ovrut helped to introduce supersymmetry and supergravity into particle physics. He gave the supergraph Feynman rules for spontaneously broken supersymmetry and constructed the first supergravity theories of inflation. Some of his contributions were the introduction of Wilson lines in string vacua to break gauge symmetry to the standard model; a five-dimensional superspace called heterotic M-theory that serves as a string vacuum for realistic particle physics; the development of algebraic geometric methods necessary for the construction of gauge connections; explicit evaluation of the low energy spectrum; and the calculation of non-perturbative superpotentials. Using this, Ovrut constructed heterotic vacua with exactly the particle spectrum of the minimal supersymmetric standard model with right-handed neutrinos. He applied these theories to cosmology and was co-inventor of the ekpyrotic theory of cosmology. More recently, Ovrut has given renormalization group analyses of realistic superstring particle theories, studying phase transitions in the gauge group and has explored their low energy predictions for the LHC. He has also considered aspects of late-time cosmology, including gauge domain walls, dark matter and baryogenesis.

Justin Khoury's research interests lie at the interface of particle physics and cosmology. Over the last few years, Khoury's efforts have focused on devising novel theories of the dark sector involving new degrees of freedom coupling to matter and developing their observational implications. To ensure consistency with laboratory and solar system tests of gravity, some screening mechanism is necessary to "hide" these degrees of freedom locally. Khoury has introduced both the chameleon and symmetron screening mechanisms, in which the properties of light scalar fields vary according to their environment, leading to striking predictions for near-future tests of gravity both in the laboratory and in space. Khoury has also worked extensively on theories of the very early universe and their observational predictions, such as non-gaussianities. Khoury has proposed novel cosmological scenarios, such as Ekpyrotic theory (partly with Ovrut), in which the observed flatness, homogeneity and isotropy of our present universe, as well as nearly scale invariant and gaussian primordial density perturbations, are generated in a phase of slow contraction before the big bang.

Mark Trodden has worked broadly in both cosmology and particle physics, including the development of one of the most-studied modified gravity approaches to cosmic acceleration, models of dark energy and dark matter, extra dimensional models of particle physics and cosmology, and the matter-antimatter asymmetry of the universe. He has focused on several areas in recent years, most prominently in investigating and constructing new examples of four-dimensional theories of scalar fields and gravity arising from higher-dimensional induced gravity models. He has also worked on constraining couplings between dark energy and dark matter and on theoretical issues of stability and consistence of dark energy and modified gravity models.

Programmatic initiatives

In addition to the strong overlapping interests existing within the group, our research benefits greatly from connecting to other researchers at Penn and beyond through three key initiatives.

• **The Center for Particle Cosmology** was established in 2009 to facilitate interactions between the disciplines of particle physics and astrophysics to address questions about the origin and evolution of the universe and fundamental theories of matter and energy. The Center (www.physics.upenn.edu/particlecosmo/) is directed by Trodden and Bhuvnesh Jain (Penn astrophysics), and builds on our existing strengths in particle physics and cosmology. The Center is seeded through startup funds to Profs. Trodden and Khoury, and a significant renovation has just been completed to provide a common space for the different groups, to allow their free interaction within the Center. While certainly benefiting faculty, this also increases the opportunities available to, and intellectual breadth of, our postdocs, graduate students and undergraduates. Our joint journal club is an example of this that has been running uninterrupted for two years.

The Center has hosted and taken part in a large number of workshops and symposia, including regular series with NYU and Columbia. Furthermore, the Center has a significant outreach program, with an endowed public lecture, panel discussions, science cafe talks, and alumni lectures. We are seeking private funding to help continue these activities and fund those parts of the intellectual mission of the center unsupported through our regular DOE funds.

• **The Visitors Program** is a key component of our activities. Many articles have resulted from the interactions between visitors and members of the Penn group, thus significantly increasing the overall productivity and visibility of the high energy group. We have received uniformly positive feedback from physicists who have found their visits to Penn scientifically productive and invigorating. The visitor program is partly supported by the DOE and partly by matching funds from the University. The matching funds recognize both the success of the visitor program and the continued strength of DOE grant support. Recent activities in the group can be found at http://www.sas.upenn.edu/heptheory.

• **The Math/Physics program** encompasses a highly productive collaboration between the theorists in the high energy group and Penn mathematicians with primary expertise in algebraic geometry. Many well-known results were achieved in this collaboration, such as the theory of vector bundles and its application to realistic heterotic vacua. This program has also trained numerous students and postdocs, and run several courses, conferences and seminar series (see the website http://www.physics.upenn.edu/mprg/). The program was partially supported by an NSF Focussed Research grant, with Ovrut (and Ron Donagi–Penn Math) as principal investigator, and is currently supported by an NSF Research Training Grant. Most recent activities include the Seminar Series on Toric Varieties and the Working Group on F-Theory (Cvetič and Donagi) as well as String-Math 2011 Inaugural Conference http://www.math.upenn.edu/StringMath2011/ .

Personnel

Healthy postdoctoral and student support forms the backbone of our group, and has been essential to our historical success. The group has an outstanding training record, with almost all postdocs in the last decade holding faculty positions around the world. Recently, for example: Inaki Etxebarria (CERN fellow), Lara Anderson (Harvard postdoctoral fellow) Timo Weigend (Assoc. Prof., Heidelberg), Volker Braun (Schrodinger Fellow, Trinity College, Dublin), Joan Simon (Reader, Edinburgh, UK), Yang-Hui He (Reader, City University of London), Brent Nelson

(Asst. Prof., Northeastern), Michael Schulz (Asst. Prof., Bryn Mawr), Gary Shiu (Assoc. Prof., Wisconsin), Finn Larsen (Prof., Michigan), Alex Kusenko (Prof., UCLA), Andre Lukas (Prof., Oxford), Dan Waldram (Prof., Imperial College, UK), Jaemo Park (Prof., POSTECH, S. Korea), Jens Erler (Prof., UNAM, Mexico), Tianjun Li (Prof., ITP, Chinese Acad. Sci.). Furthermore, our students also obtain excellent postdocs. Recent students have gone to positions at Chicago and UCSB (Tao Liu, McCormick Fellow); U. Rome and DESY (Robert Richter, INFN Fellow); U. Toronto and Simons Institute (Peng Gao); UBC (Bartolomiej Czech); NYU and UBC (Tom Levi), Wisconsin, CERN and IPM (Minxin Huang); IAS, Perimeter Institute and Imperial College (Evgeny Buchbinder); Rutgers and Harvard (Rene Reinbacher). Lisa Everett is an Assoc. Prof. at Wisconsin and Justin Vazquez-Poritz is an Asst. Prof. at CUNY. Furthermore, Profs. Khoury and Trodden have demonstrated similar successes training and placing students before their arrival at Penn.

Our postdocs and graduate students encounter an exciting and nurturing research environment. While we choose postdocs broadly to help cover the research interests of the entire group, they are free to pursue collaborations with any members of the group and to develop as independent researchers in their own right. Our historical successes mean that we already know how to do this well, making full use of the visitor program and the math-physics program to improve and broaden the training experience. With the new addition of the Center for Particle Cosmology, the intellectual environment and available collaborative opportunities makes Penn an extremely attractive environment for postdocs and graduate students.

18 Understanding space and time (V. Balasubramanian)

During the present grant cycle my research had three main themes: (a) using the AdS/CFT correspondence to understanding strongly coupled field theories (e.g. non-Fermi liquids, and thermalization of the quark-gluon plasma), (b) understanding how space-time "emerges" in the gauge-gravity dualities, (c) understanding the landscape of vacua that arise from string and consequences for model-building and cosmology. I will summarize progress on each of these fronts below.

18.1 Understanding strongly coupled field theories

Thermalization in strongly coupled theories: Non-equilibrium dynamics and thermalization of quantum field theories is very difficult to study, especially in the strongly coupled conditions relevant for the heavy-ion collisions. We recognized that the gauge-gravity dualities provide a potentially tractable approach to this problem in a simplified setting and our work [79, 80] has since generated a substantial. amount of activity in the field. Specifically, in [79, 80], we used the AdS/CFT correspondence, to probe the scale-dependence of thermalization in strongly coupled field theories following a quench, via calculations of two-point functions, Wilson loops and entanglement entropy in $d = 2, 3, 4$. In the saddlepoint approximation these probes are computed in AdS space in terms of invariant geometric objects - geodesics, minimal surfaces and minimal volumes. Our calculations for two-dimensional field theories are analytical. In our strongly coupled setting, all probes in all dimensions share certain universal features in their thermalization: (1) a slight delay in the onset of thermalization, (2) an apparent non-analyticity at the endpoint of thermalization, (3) top-down thermalization where the UV thermalizes first. For homogeneous initial conditions the entanglement entropy thermalizes slowest, and sets a timescale for equilibration that saturates a causality bound over the range of scales studied. The growth rate of entanglement entropy density is nearly volume-independent for small volumes, but slows for larger volumes. These results, obtained in collaboration with nuclear theorists Berndt Mueller (Duke University) and Andreas Schafer (Regensburg Univsersity, Germany) are strikingly different from results obtained in perturbative gauge theory. In [81] we probed the thermalization of more sophisticated information theoretic quantities – the mutual information and tripartite information – following a quench. Such quantities provide sensitive nonlocal probes of thermalization, and in the AdS/CFT correspondence are far easier to compute than apparently simpler quantities such as correlation functions.

Non-fermi liquids: In [82] we studied cold interacting fermions in two dimensions which form exactly solvable Luttinger liquids, whose characteristic scaling exponents differ from those of conventional Fermi liquids. Specifically we use the AdS/CFT correspondence to discuss an equivalence between a class of helical, strongly coupled Luttinger liquids and fermions propagating in the background of a 3D black hole. The microscopic Lagrangian is explicitly known and the construction is fully embeddable in string theory. The retarded Green function at low temperature and energy arises from the self-dual orbifold geometry very near the black hole horizon. This structure is universal for all cold, charged liquids with a dual description in gravity.

18.2 Foundations of gravity and gauge theory

Black hole entropy arises in string theory via coarse graining over an underlying space of microstates. In [83] we address the question of how the classical black hole geometry itself can arise as an effective or approximate description of a pure state, in a closed string theory, which semiclassical observers are unable to distinguish from the "naive" geometry. A precise account is given for several extremal black holes in Type II string theories. In addition to having an entropy, black holes can evaporate into apparently thermal radiation that threatens naively to destroy the unitarity of quantum mechanics. A quantitative resolution of the information loss paradox could involve: (a) a precise argument that the underlying quantum theory is unitary, and that information loss must be an artifact of approximations in the derivation of black hole evaporation, (b) an explicit construction showing how information can be recovered by the asymptotic observer, (c) a demonstration that the causal disconnection of the black hole interior from infinity is an artifact of the semiclassical approximation. In [84] we summarize progress on all these fronts.

Most of the progress in understanding black hole thermodynamics has been achieved by applying the AdS/CFT correspondence to extremal or near-extremal black holes. A universal feature of such black holes is the presence of a near-horizon region with the geometry of AdS_2 with a constant electric field. Since this part of the geometry controls the low energy physics of the dual field theory it is of great interest to understand this essentially universal low energy sector of theories with a gravitational dual. In [85, 86] we set out to do this by studying extremal black holes in three dimensions. We found that the near-horizon geometry could be described in terms of a "self-dual orbifold" of AdS_3 or as the universal AdS_2 described above. This allowed us to show that this universal sector has a dual description as a chiral, Discrete Light Cone Quantized (DLCQ) two dimensional conformal field theory (CFT). Our considerations clarified aspects of the chiral CFTs appearing in proposed dual descriptions of the near-horizon degrees of freedom of extremal black holes, e.g. in the proposed Kerr-CFT correspondence. In particular we showed how the entropy of the original black hole is encoded in the states of the chiral infrared CFT.

In quantum mechanics, one way in which a system A can acquire an entropy is by being entangled with another system B which is un-measured and thus integrated out. Now consider the Wilsonian approach to the renormalization group, in which we integrate out momenta above a particular scale. If the wavefunction of the system has entanglement between degrees of freedom below and above this scale then the low-energy system should be in a density matrix with a non-zero entropy! For theories which enjoy decoupling, like the standard model of particle physics, this must be a small effect. But for theories that do not have UV-IR decoupling (e.g. non-commutative gauge theories, or any theory that contains gravity), there is a potentially large effect. In [87] we demonstrated this effect, and described how to compute it for scalar field theories. In ongoing work I consider how such entanglement may lead to the emergence of dual spacetime descriptions of strongly coupled field theories (e.g. the AdS/CFT correspondence).

Finally, I wrote an invited article on *What we don't know about time* for a special issue of Foundations of Physics commemorating "Forty Years of String Theory" [88]. The article laid out a series of questions, some of which I return to in the Research Plan below.

18.3 Explorations of the landscape of string vacua

Consistent coupling of effective field theories with a quantum theory of gravity appears to require bounds on the rank of the gauge group and the amount of matter. In [89] we argue that appropriately "coarse-grained" aspects of the randomly chosen field theory in such bounded landscapes, such as the fraction of gauge groups with ranks in a given range, can be statistically predictable. A basic insight from these works is that the typical theory emerging from the string landscape will have a complex architecture of gauge groups and matter, particularly in the dark sector. Given a particular string theoretic landscape, this sort of argument can give the likely structure of the quantum field theory describing the world just below the Planck scale. To get low energy predictions we must carry out the RG flow of such theories. Thus we examined certain classes quiver gauge theories (gauge factors interacting through bifundamental matter) and developed efficient methods for determining their infrared fixed points [90]. With such complex models in mind, in the context of local type IIB models arising from branes at toric Calabi-Yau singularities, we presented a systematic way of joining any number of desired sectors into a consistent theory [91]. In this "Toric Lego" construction, the different sectors interact via massive messengers with masses controlled by tunable parameters. We applied this method to a toy minimal supersymmetric standard model interacting via gauge mediation with a supersymmetry breaking sector and an interacting dark matter sector.

In [92] we describe how local toric singularities, including the Toric Lego construction, can be embedded in compact Calabi-Yau manifolds. We study in detail the addition of D-branes, including non-compact flavor branes as typically used in semi-realistic model building. The global geometry provides constraints on allowable local models. As an illustration of our discussion we focus on D3 and D7-branes on (the partially resolved) $(dP0)^3$ singularity, its embedding in a specific Calabi-Yau manifold as a hypersurface in a toric variety, the related type IIB orientifold compactification, as well as the corresponding F-theory uplift. Our techniques generalize naturally to complete intersections, and to a large class of F-theory backgrounds with singularities. Thus our paper now provides a new systematic tool for investigating realistic low-energy models arising from string theory.

Finally, the sort of landscape of vacua that motivates the studies described above would lead to a characteristic cosmological feature – regions of the universe can be trapped in false vacua and periodically tunnel towards the true vacuum. This sort of process has been mostly studied in the context of an effective potential in a one-dimensional field space, whereas the stringy landscape represents an extremely high dimensional field space. Thus, in [93], we study tunneling between vacua in multi-dimensional field spaces in the thin wall approximation, and show the existence of novel non-spherical saddlepoints of the action. We also showed that some vacuum decays are "blocked" or "enhanced" by the presence of other local minima in the field potential.

19 Physics From Basic Theory (M. Cvetič)

Cvetič's efforts encompass broad thrusts in fundamental theory, ranging from non-perturbative gravitational physics in M-theory and work at the interface with differential and algebraic geometry, to leading efforts in constructions of String/F-theory vacua and the study of their physics implications.

The gravitational physics program stems from seminal works on topological defects in effective string theories such as first examples of supergravity domain walls and multi-charged black holes which are prototypes for studies of black hole microscopics. It further led to new constructions of spaces with special curvatures (G_2 and $Spin(7)$ holonomy spaces, and L^{abc} Einstein-Sasaki spaces), and comprehensive studies of consistent non-linear Kaluza-Klein as well as flux compactifications in effective string and M-theory. In recent years the program focused on constructions of new multi-charged rotating charged black holes in asymptotically anti-deSitter space-times and studies of their microscopics, such as microscopic interpretation of near-extremal multi-charged rotating black holes in terms of dual conformal field theory (Kerr/CFT correspondence) and subsequent microscopic studies of grey-body factors.

The program on four-dimensional string theory solutions encompasses: globally consistent compactifications of Type II string theory on Calabi-Yau orientifolds with intersecting D-branes which resulted in the first supersymmetric, three-family Standard-like models and subsequent systematic constructions of Standard-like and GUT-like models; the discovery of stringy non-perturbative effects due to so-called D-instantons which can modify couplings for charged matter and introduce new hierarchical scales with important phenomenological implications. Recent efforts have focused on: systematic classifications of multi-stack D-brane configurations with the spectrum of the realistic particle spectrum and couplings, such as the minimal supersymmetric standard model (MSSM) and its singlet extensions; extensive study of D-instantons, both within particle physics framework and formal developments, focusing on Type IIB and F-theory employing conformal field theory and advanced algebraic geometry techniques.

The gravitational physics efforts involved a long-standing *collaboration* between UPenn, Texas A&M (Chris Pope) and Cambridge (Gary Gibbons), as well as U. Michigan (Finn Larsen) . The program on string vacuum constructions involves Jim Halverson (UPenn student, String Vacuum Project Fellow and DOE Theory Fellow), P. Langacker (IAS, Princeton) and Robert Richter (former UPenn student, INFN Fellow in Rome). Formal studies of non-perturbative effects in Type II/F-theory involve Jim Halverson, Iñaki Garcia-Etxebarria (former post-doc at Penn, now CERN fellow) as well as Timo Weigand (former post-doc at UPenn, Associate Professor at Univ. of Heidelberg), R. Blumenhagen (Max Planck Institute, Munich) and Dieter Lüst (Maximilian Ludwig Univ. Munich). There are strong scientific ties with R. Donagi and T. Pantev (Mathematics Dept. at UPenn), including a co-organization of "String-Math 2011" conference, the Seminar Series on Toric Varieties (2010/11) and the Working Group on F-Theory. Cvetič's collaborators frequently visit Penn, recently supported in part by the visitor program, UPenn Distinguished International Scholar Program Award (Gary Gibbons, Fall 2009), Turkish Funding Agency (Tolga Birkandan, Fall 2010), the NSF Research Training Grant (PI, T. Pantev) and Fay R. and Eugene L.Langberg Chair.

19.1 Recent Research

A summary of the research results since January 2008 will be given.

19.1.1 Non-perturbative Gravitational Physics

Black Holes in String Theory

The work on black holes stems from Cvetič's seminal work in the mid/late nineties, which resulted in general charged multi-charge rotating black holes in asymptotically Minkowski space-times and the subsequent study of their dynamics and microscopics. In the past years the focus was on new constructions of general charged rotating black holes in asymptotically anti-de Sitter (AdS) space times, study of their thermodynamics and global space-time structure, as well as for dual strongly coupled field theories. Based on earlier works on rotating charged black holes with zero cosmological constant (with Youm, Nucl. Phys. **B476**, 118 (1996)) and static AdS black holes (with Behrndt, and Sabra, Nucl. Phys. **B553**, 317 (1999)), new AdS charged rotating solutions with *equal* and unequal angular momenta in five dimensions (with Lü and Pope, Phys. Lett. **B 598**, 273-278 (2004); Phys. Rev. **D70**, 081502 (2004) and with Chong, Lü and Pope, Phys. Rev. Lett. **95**, 161301 (2005), respectively) as well as in four and seven dimensions were constructed. These works represent the state of the art for general charged rotating solutions in asymptotically anti-deSitter space-times.

In [94], a new investigation of microscopics for extreme rotating black holes was carried out. The Kerr/CFT correspondence asserts that the quantum states in the near-horizon region of an extremal rotating black hole are holographically dual to a two-dimensional chiral conformal theory. By considering a general canonical class of near-horizon geometries in arbitrary dimension D, it was shown that in any such metric, a microscopic entropy that agrees with the Bekenstein-Hawking entropy of the associated extreme rotating black hole.

In subsequent work [95], an analytic computation of the greybody factors for general charged rotating charged black holes in four and five dimensions was presented in the so-called super-radiant limit. The concrete CFT interpretation of the emission amplitudes was given, including the overall frequency dependence and the dependence on all black hole parameters. The results provide new insights into Kerr/CFT correspondence for more general rotating black holes. Recent study [96] of the wave equation in the background of charged rotating black holes with cosmological constant established the conformal invariance for the near-extremal limit of such black holes.

In a related context, intriguing results [97] were obtained for the product of all horizon areas for general rotating multi-charge black holes, both in asymptotically flat and asymptotically anti-de Sitter spacetimes in four and higher dimensions. These expressions are universal, and depend only on the quantized charges, quantized angular momenta and the cosmological constant. If the latter is also quantized, these universal results may provide a "looking glass" into microscopics of such general black holes.

Furthermore, new explicit black holes of anti-de Sitter Einstein-Yang-Mills gravity were obtained [98] as solutions of a consistent truncation of five-dimensional maximal gauged supergravity. This is one of a very few analytic black hole solutions with non-Abelian charges.

Most recently, in [99], the so-called Thorn's Hoop conjecture was studied. The conjecture was recently precisely formulated in four spacetime dimensions: the Birkhoff invariant β (the least maximal length of any sweepout or foliation by circles) of an apparent horizon of energy E and area A should satisfy $\beta \leq 4\pi E$. This conjecture was verified in [99] to hold on the horizons of general four-charged rotating black holes both of ungauged and gauged supergravity theories. Generalizations of the conjecture to five spacetime and higher dimensions were formulated and verified for large classes of known black hole solutions there.

[In another work [100] an analytic study of gravity trapping thick domain walls was performed, and a quantitative study of Kaluza-Klein resonances which can drastically modify gravitational interactions on the wall was addressed.]

Cvetič has been invited to lecture on black hole physics in string theory at a number of schools (Series of Lectures on Black holes in String Theory at Univ. of Bremen, September 2008; School on Atractor Methods at INFN Frascati, July 2009; First Brazilian School on Methods in Gauge Theory and Gravitational Physics, June 2010).

19.1.2 Four-dimensional String Vacua

The second program on the exploration of string vacua on Calabi Yau spaces with D-branes was initiated in the early 2000's (with G. Shiu and A. Uranga, Phys.Rev.Lett. **87**, 201801 (2001)), and resulted in the first examples of four-dimensional supersymmetric solutions of Type II theory with intersecting D-branes that yield three-family Standard-like model as well as grand unified models (GUT's). Lifts of these constructions on a circle provide a description of M-theory on a compact singular G_2 holonomy space which connects to Cvetič's program on new constructions of $Spin(7)$ and G_2 special holonomy spaces and new $L^{a,b,c}$ Einstein-Sasaki spaces (with H. Lü, D.Page and C. Pope, Phys. Rev. Lett. **95**, 071101 (2005)). [In a related context in [101], the supergravity solutions describing a stack of D3-branes localized at a point on the blown-up cycle of a resolved $L^{a,b,c}$ cone were obtained and a dual field theory analysis given.]

Non-perturbative D-instanton effects in Type II and F-theory

An advance in the study of string theory compactifications with D-branes was the discovery of new stringy non-perturbative effects due to D-instantons which can modify couplings for charged matter and introduce new hierarchical scales with important phenomenological implications (with Blumenhagen and Weigand, Nucl. Phys. **B771**, 113 (2007)). This work has generated much activity with a large number of follow-up papers addressing both phenomenological and formal implications of these string instanton effects.

Recent efforts focused on a broad program that explores both formal and phenomenological aspects of these effects in Type II and more recently in F-theory, by employing both conformal field theory as well as algebraic geometry techniques.

Further Phenomenological Implications of D-instantons

In [102] it was explicitly shown how D-brane instantons can generate perturbatively absent $\langle \mathbf{10}\,\mathbf{10}\,\mathbf{5}_H \rangle$ couplings in (flipped) SU(5) Grand Unified models, thus elucidating the non-perturbative origin of this coupling in the Type IIA context. Further developments involve specific constructions [103] where the small Dirac neutrino masses are generated via D-instantons.

The explorations of D-instantons on compact Calabi Yau spaces resulted in the first globally consistent semi-realistic constructions [104] of Type I string theory on globally defined Calabi Yau spaces which can realize non-perturbative Majorana masses as well as the Polonyi-type non-perturbative superpotential terms. Further analysis of globally defined models with Polonyi-type couplings and hierarchical supersymmetry breaking via gauge-mediation was given in [105].

Formal Aspects of D-instantons in Type II and F-theory

A detailed study [106] of so-called U(1) instantons, which do not intersect with orientifold planes, revealed that such configurations do not contribute to the the charged sector superpotential, contrary to an earlier proposal (within F-theory context).

A subsequent program focused on exploration of the D-instanton in F-theory. The so-called O(1) instantons were studied in [107], by exploring the SL(2,Z) monodromy action on them, and demonstrating that a set of zero fermionic modes, present for the U(1) instantons, are projected out, and thus, O(1) instantons can contribute to the superpotential. In [108] a new construction of compact F-theory GUT models (on Calabi-Yau four-folds which complete intersections in toric varieties) were presented. New aspects of F-theory strong gauge dynamics, absent in the Type II limit, were demonstrated and the calculation of instanton zero modes was performed by implementing an algorithm for computing cohomology of line bundles on arbitrary toric varieties. The code has been made publicly available and it should be of general use for studying the physics of global Type IIB and F-theory models.

In a recent project [109] the computability of non-perturbative potentials in string theory was addressed. Specifically, the problem of finding the low-energy non-perturbative F-terms in generic Type IIB compactifications implies finding solutions to certain quartic diophantine equations, and thus, in analogy to powerful results in number theory, specifically the negative solution to Hilbert's 10^{th} problem, it was conjectured that there exists no algorithm which can answer such questions across the entire landscape of string vacua. This suggests that, algorithmically, the landscape is "patchy". Nevertheless, an algorithm, which allows for the determination of *all* instanton contributions to the uncharged superpotential for a class of Type IIB compactifications on a Calabi-Yau manifold was presented. As part of the study of the required systematics, a new mathematical result for an efficient computation of the so-called Z_2 equivariant line bundle cohomology on toric varieties was developed.

In an invited review [110] the progress in determining the effects of D-brane instantons were summarized. The D-brane instanton calculus for couplings in the effective action was presented, and the concrete consequences of stringy D-brane instantons for the construction of semi-realistic models of particle physics in compact and non-compact geometries was summarized.

New algebraic geometry results for toric varieties, obtained in above works, led to a Seminar Series on Toric Varieties (Fall 2010), organized by Cvetič and Donagi. These works have been presented at schools (D-Instanton lectures at the Galileo Galilei Institute in Florence, June 2009; Lectures on "Perturbative and non-perturbative D-brane Vacua", TASI'10 School, June 2010) and numerous conferences and workshops (String Phenomenology Workshop at CERN, July 2008; opening lecture at Clay Institute Workshop on Stringy Reflections on LHC, October 2008; String Workshop in Buenos Aires, December 2008; Strings'09, Rome, June 2009; Simons Institute on String Theory, August 2009; 'Strings'10, Texas A&M, March 2010; Harvard-Brandeis Workshop on "Generalized Geometries", Boston, March 2010; Great Lakes String Conference, Cincinnati, March 2010, etc.). Cvetič was a key physics organizer of the "Strings-Math 2011" conference (June 2011, UPenn), the inaugural meeting of the new conference series, devoted to wide-ranging aspects of mathematics and physics of string theory.

Quiver Classification of Realistic String Landscapes

In addition to formal works on D-instantons, a series of papers [111–113] focused on systematic classifications of landscapes of realistic Minimal Supersymmetric Standard Models (MSSM's) for Type II string theory quivers which are compatible with the global constraints. The analysis explored conditions under which D-brane instantons induce missing couplings, including small neutrino masses without generating other phenomenological drawbacks. It was shown that a small fraction of such models exhibits phenomenology compatible with experiments. A sophisticated computer code implemented both perturbative and non-perturbative (D-Instanton) contributions to obtain realistic fermion textures and other couplings of the MSSM's and to systematically classify them [111, 112]. Further detailed study of constraints for the absence of dimension-five proton decay operators was given in [113]; exploration of MSSM quivers with neutrino masses due to stringy Weinberg operators was studied in [114], leading to examples with lower string scale; study of MSSM quivers with additional Standard Model singlets was done in [115].

Based on a series of lectures on String Phenomenology at TASI'10, a comprehensive review [116] addressed broad aspects of semi-realistic particle physics models by employing both perturbative and non-perturbative techniques of Type II orientifold compactifications with D-branes.

These works were presented at a number of conferences (DESY Workshop, February 2009;

SUSY'09,Boston, May 2009; String Phenomenology '09, Warsaw, June 2009; plenary talk at DPF'09, July 2009; Winter Aspen Conference "Revolution in Particle Physics is here", January 2010; LMU Workshop on "GUT's and Strings 2010", Munich, February 2010; String Phenomenology'10, Paris, July 2010; String Phenomenology"11, Madison, August 2011; SUSY'11, Fermilab, August 2011, etc.). Cvetič was a key coordinator of the KITP program " Strings at the LHC and in the early Universe " (March-May 2010).

20 Heterotic String Theory, Particle Physics, Cosmology (B. Ovrut)

20.1 Research Overview:

Burt Ovrut is a high energy particle theorist with research interests in 1) supersymmetry and supergravity–specifically, the application of *supersymmetry* to particle physics models and their phenomenology, 2) *superstring theory*–in particular, the compactification of these theories to realistic models of particle physics, 3) *mathematical physics*–specifically, the development of algebraic geometry methods required for the analysis of superstring compactifications, and 4) *cosmology*–the application of supersymmetry and superstrings to create new ideas in cosmology, both of the early and late Universe. Those contributions Ovrut views as the most important are the following.

Supersymmetry–

• The development of supergraph Feynman rules for supersymmetric particle physics theories where the internal gauge symmetry is spontaneously broken. Presented in "Supersymmetric R(xi) Gauge and Radiative Symmetry Breaking", Burt A. Ovrut and Julius Wess, Phys.Rev. D25 (1982) 409.

• Construction of one of the first $N = 1$ supersymmetric theories of the standard model–that is, the MSSM. This paper introduced "gauge mediated" supersymmetry breaking into the literature and appeared in "Supersymmetric Extension of the $SU(3) \times SU(2) \times U(1)$ Model", Chiara R. Nappi and Burt Ovrut, Phys.Lett. B113 (1982) 175.

Superstrings–

• Introduced "Wilson Lines" into superstring theory as a method to spontaneously break gauge symmetry in the absence of Higgs scalars. Presented in "E(6) Symmetry Breaking in the Superstring Theory", J.D. Breit, Burt A. Ovrut, Gino C. Segre, Phys.Lett. B158 (1985) 33.

• The construction of five-dimensional "heterotic M-theory" and the first string realization of our observable Universe as a brane in higher-dimensional space-time. Appeared in "The Universe as a Domain Wall", Andre Lukas, Burt A. Ovrut and Daniel Waldram, Phys.Rev. D59 (1999) 086001 and "Heterotic M-Theory in Five Dimensions", Andre Lukas, Burt A. Ovrut, K.S. Stelle, Daniel Waldram, Nuc.Phys. B552 (1999) 246-290.

• Results from the Penn Math/Physics collaboration were used to find a vacuum of smooth heterotic string theory which has exactly the spectrum of the MSSM with three right handed neutrinos. Appeared in "The Exact MSSM Spectrum from String Theory", Volker Braun, Yang-Hui He, Burt A. Ovrut, Tony Pantev, JHEP 0605 (2006) 043.

Mathematical Physics–

• The theory of holomorphic vector bundles constructed using "spectral covers" was applied to elliptically fibered Calabi-Yau threefolds to produce three family MSSM-like spectra in heterotic M-theory. Published in "Standard Models from Heterotic M-Theory", Ron Donagi, Tony Pantev, Burt A. Ovrut, Daniel Waldram, Adv.Theor.Math.Phys. 5 (2002) 93-137.

•The theory for calculating the massless spectrum in heterotic compactifications using the "sheaf cohomology" of the bundle was presented in "The Particle Spectrum of Heterotic Compactifica-

tions", Ron Donagi, Yang-Hui He, Burt A. Ovrut, Rene Reinbacher, JHEP 0412 (2004) 054.
Cosmology–
• The first supergravitational theory of Inflation. Published in "Supersymmetry and Inflation: A New Approach", Burt A. Ovrut, Paul Steinhardt, Phys.Lett. B133 (1983) 161.
• The collision of a five-brane with our observable wall in heterotic M-theory was shown to lead to a "scale-invariant" two-point function in the early Universe and was identified with the "Big Bang". Presented in "The Ekpyrotic Universe: Colliding Branes and the Origin of the Hot Big Bang", Justin Khoury, Burt A. Ovrut, Paul Steinhardt, Neil Turok, Phys.Rev. D64 (2001) 123522 and extended in "From Big Bang to Big Crunch", Justin Khoury, Burt A. Ovrut, Nathan Seiberg, Paul Steinhardt, Neil Turok, Phys.Rev. D65 (2002) 086007.
• Ekpyrotic cosmology was constructed within the context of four-dimensional field theory using ghost condensation to induce the requisite "bounce" from contraction to the expanding phase. This greatly simplified theory appeared in "New Ekpyrotic Cosmology", Evgeny I. Buchbinder, Justin Khoury, Burt A. Ovrut, Phys.Rev. D76 (2007) 123503.
• New Ekpyrotic cosmology was shown to lead to large "non-Gaussianity" in the three- and higher-point functions in the CMB. Published in "Non-Gaussianities in New Ekpyrotic Cosmology", Evgeny I. Buchbinder, Justin Khoury, Burt A. Ovrut, Phys.Rev.Lett. 100 (2008) 171302.

20.2 Recent Research:

In the three years between May, 2009 and April, 2012, Ovrut was very active in research–publishing 18 research papers and gaving 20 invited conference talks on his work. This research can broadly be placed into five categories: 1) algebraic and numerical computation of string parameters, 2) the analysis of realistic low energy superstring models, 3) the algebraic geometry of heterotic vector bundles and their physical implications, 4) the cosmological consequences of realistic string theories and 5) supersymmetric ghost condensation and galileons. Specifically, Ovrut's research was the following.
Algebraic and Numerical Computation–
• It was shown in Ovrut's previous work with the Penn Math/Physics group that the massless modes of heterotic superstring compactifications arise as elements of the "sheaf cohomology" of the slope-stable holomorphic vector bundle containing the E_8 gauge connection. Any such class has a "harmonic" representative which satisfies the gauge twisted Laplaces equation on the Calabi-Yau threefold. Solving this equation gives a "wavefunction" for that specific field. Given the wavefunctions, one can take their cubic product and, by integrating over the Calabi-Yau manifold, obtain a direct computation of the associated Yukawa couplings. To compute the Laplacian it is essential to know both the metric and the gauge connection on the Calabi-Yau space. By employing algorithms by Yau and Donaldson, it is possible to obtain numerical approximations for the metric and the gauge connection. Ovrut was able to extend and numerically solve the Yau/Donalson algorithhm to compute the metric on a variety of Calabi-Yau manifolds. This work appeared in [117] and was applied to compute the eigenvalues and wavefunctions for gauge scalars in [118]. The numerical computation of the gauge connection is harder. However, Ovrut was able to present new algorithms to enable these calculations and numerically computed the gauge connections for a variety of Calabi-Yau manifolds, vector bundles and regions of moduli space. This work was published in [119]. This was further extended in [120], where it was used to check the slope-stability structure of the bundle as a function of the Kahler moduli.
Realistic Low Energy Models–
• The discovery of neutrino mass strongly implies the existence of right-handed neutrinos in super-

symmetric realistic particle models. In smooth heterotic compactifications, right handed neutrino multiplets appear most naturally in vacua with an $SU(4)$ gauge connection. When broken by Wilson lines, the low energy particle spectrum in such theories can be exactly that of the MSSM, as was shown by Ovrut's research group in "The Exact MSSM Spectrum from String Theory", Volker Braun, Yang-Hui He, Burt A. Ovrut, Tony Pantev, JHEP 0605 (2006) 043. Furthermore, the gauge group is that of the standard model with, however, an additional gauged U(1) group factor that can be identified with B-L symmetry. We will refer to this class of theories as the B-L MSSM.

Since it contains matter parity as a finite subgroup, this additional symmetry prohibits dimension four proton decay, as well as lepton violating processes. However, it is essential to show that this gauged B-L symmetry is spontaneously broken above, but not too far above, the electroweak scale. The requisite renormalization group calculation was carried out first using quasi-analytic approximations in an appropriate region of moduli space and presented in [121]. Second, a more precise numerical calculation, valid for a wider range of initial parameters, was published in [122]. The results showed that for a wide range of initial parameters, the gauged B-L symmetry was indeed broken by right handed sneutrinos acquiring vacuum expectation values (VEVs) of $\mathcal{O}(1-10\ TeV)$. Furthermore, the Higgs fields also get a non-zero VEV of order the electroweak scale. Having established this radiative hierarchy, constraints were imposed on the theory arising from the most recent LEP data. Using these constraints, it was shown that a wide range of initial parameters lead to realistic low energy spectra and particle physics. The breaking of B-L symmetry allows dimension four lepton number violating operators and higher dimensional suppressed baryon number violating operators to be regenerated. These lead to proton decay, which was analyzed and shown to be sufficiently suppressed for small neutrino Yukawa couplings. This can lead to an inverted hierarchy of neutrino masses, as well as other low energy phenomenological predictions. These were presented in [16].

• Ovrut and collaborators explored the phenomenology of other, less minimal, heterotic models that have, in addition to the matter content of the MSSM, two pairs of Higgs/Higgs conjugate superfields. It was shown that the tree level Yukawa couplings to the second Higgs pair vanish by a cohomological selection rule. Such couplings and, hence, flavor changing neutral currents, do arise from stringy effects, specifically the coupling of light fields to heavy Kaluza-Klein modes. However, it was shown that these induced couplings are naturally small and, hence, flavor changing neutral currents are smaller than the present experimental bounds. This work was published in [123].

The Algebraic Geometry of Vector Bundles–

• To preserve $N = 1$ supersymmetry, the gauge connection on the Calabi-Yai manifold must satisfy the three hermitian Yang-Mills equations. The trace equation was shown by Uhlenbeck and Yau to be identical to the requirement that the associated vector bundle be "slope-stable". It was proven in [124, 125] that a given vector bundle can be stable in one region of Kahler moduli space, not stable in another, with the two regions being separated by a co-dimension one "stability wall". The massless spectrum is enhanced on the stability wall where at least one additional anomalous $U(1)$ gauge factor appears. In [124, 125] slope stability was proven to be equivalent to the vanishing of the associated D-term in the effective theory. This D-term has a Fayet-Iliopoulos (FI) term which is dependent on the slope and, hence, on the Kahler moduli. It was used to find the Kahler regions of stability of a large number of realistic vector bundles.

Many of the matter fields and vector bundle moduli acquire a non-zero charge under the anomalous $U(1)$ symmetry on the stability wall. Hence, the superpotential is constrained by this additional symmetry. Although this symmetry is spontaneously broken as one moves in Kahler moduli space away from the stability wall and into the supersymmetric region, the $U(1)$ induced texture persists due to the holomorphicity of the superpotential. This manifests itself in a number of ways, the most important being that the Yukawa terms giving mass to quarks/leptons, as well as the mass matrix of vector-like pairs of matter, are constrained. This has important phenomenological significance and was presented in [126].

• Given a vector bundle with a supersymmetric and non-supersymmetric branch in Kahler moduli space, it was shown in [127] that at a second, inequivalent bundle of the same rank can exist with precisely the reverse supersymmetry structure. These two bundles coincide only on the stability wall. Furthermore, using the D-terms associated with each bundle, one can show that there is no obstruction to making a transition from the supersymmetric branch of one bundle to the supersymmetric branch of the other. Indeed, the second bundle can make a transition to a third inequivalent bundle, and so. These results were applied to several explicit examples in [127].

• One of the most important problems in any superstring compactification is to show that the associated moduli are all stabilized to fixed values. This has been particularly difficult for the complex structure moduli in smooth heterotic theories since the introduction of non-trivial form-flux–as used to fix these moduli in Type II theories– also deforms the compactification space away from being Calabi-Yau. It would, therefore, be important to stabilize the complex structure moduli without flux. It was shown in [128] that this is, indeed, possible. Specifically, it was proven that the holomorphicity of the vector bundle itself can constrain the complex structure. This was worked out and applied to several examples in [128, 129]. It was shown that a subset of complex structure moduli can be stabilized in this way. Using these results, and previously derived formulas for both perturbative and non-perturbative potentials, Ovrut and collaborators exhibited several simple heterotic vacua in which all geometric moduli, that is, the complex structure and Kahler moduli and the dilaton, were stabilized. Furthermore, it was shown that vacua of this type can be embedded as the hidden sector of M-theory compactifications. These results were presented in [130].

Cosmology of Realistic Strings–

• The B-L MSSM theories introduced by Ovrut and discussed above, have several important predictions for late time cosmology. The first arises from the radiative spontaneous breaking of $U(1)_{B-L}$ symmetry at a scale of $1-10\ TeV$. Associated with this will be the formation of "cosmic strings". The low energy density of these specific strings is sufficiently small to make them difficult to detect through lensing and other gravitational effects. A careful study of superconductivity in B-L MSSM cosmic strings was carried out in [131]. It was shown that for a simplest set of initial parameters, neither bosonic nor fermionic superconductivity can occur. However, large bound state fermion currents do occur and can potentially be detectable.

• Using the RG running of the B-L MSSM discussed above, the masses of all sparticles can be computed. It was shown explicitly in [16], for differing values of the initial parameters, that the breaking of B-L symmetry via VEVs of right handed sneutrinos does not erase the baryon asymmetry produced in the early Universe. Furthermore, generically, the gravitino is the lightest superpartner (LSP) while a neutralino is the next lightest superparticle (NLSP). We find that the lifetimes of the LSP and the NLSP are much longer and much shorter respectively than the age of the Universe. Hence, the B-L MSSM models naturally have gravitino dark matter.

Supersymmetric Ghost Condensates/Galileons–

• Ekpyrotic cosmology requires that the universe "bounce" from a contracting to an expanding phase. This was realized in the New Ekpyrotic cosmology discuss above by allowing the associated scalar field to develop a "ghost condensate". This violates the null energy condition (NEC) of relativity, enabling the bounce. However, cosmology associated with supergravity or string theory should be $N = 1$ supersymmetric. Therefore ghost condensation, originally derived for a single real non-supersymmetric scalar, must be generalized to a chiral supermultiplet. This was carried out in [132]. Around the supersymmetry breaking ghost condensate, both scalars and the associated Weyl fermion are ghost-free. The fermion has a non-canonical, but physically acceptable, "wrong sign" spatial gradient in the kinetic energy.

• In [133], Ovrut and collaborators asked whether this supersymmetric ghost condensate theory could be minimally modified so that the fermion gradient energy was canonical. It was shown that this is possible and that the canonical supersymmetric ghost condensate theory was precisely the supersymmetric extension of the so-called Galileon theories–originally derived in non-supersymmetric higher-derivative gravity theories. Thus, [133] contains a new and completely different derivation of Galileons, as well a giving the first supersymmetric extension of these theories.

Training for Post-Doctoral Fellows and Graduate Students: During the three year period under consideration, Ovrut interacted closely with one of the high energy theoretical post-docs and one graduate student. He also interacted to a lesser extent with remaining post-docs and one other graduate student.

21 Research in Particle Physics and Cosmology (Mark Trodden)

I describe DOE-supported research carried out and published over the 3-year period of this grant.

21.1 Extra Dimensions, Cosmology, and Low Energy Effective Field Theories

The possibility that the universe may contain large, and possibly infinite, spatial dimensions beyond the three we perceive has opened up new avenues to address fundamental questions posed by particle physics and by cosmology [134–144]. The manner in which the dynamics of the higher-dimensional space manifests itself in the 4D world depends on the geometry and topology of the extra-dimensional manifold, and the matter content and action. At low enough energies, the relevant physics is captured by a 4D EFT with properties inherited from the higher-dimensional model under consideration. Although the simplest example is the Kaluza-Klein tower, there are much more exotic possibilities. Many of these describe viable theories, while others are merely mathematical tools with which to construct interesting 4D EFTs.

A particularly interesting and well studied example is the Dvali-Gabadadze-Porrati (DGP) model [145], consisting of a flat 5d spacetime in which a Minkowski 3-brane floats, subject to an action consisting of two separate Einstein Hilbert terms – one in 5D, and the other on the brane, constructed from the induced metric. In an appropriate limit, the resulting 4D EFT describes gravity plus a scalar degree of freedom parametrizing the bending of the brane [146, 147]. The specific form of the 4D action inherits a symmetry from a combination of 5d Poincaré invariance and brane reparametrization invariance. In the small field limit, this symmetry takes a simple form — the *Galilean* symmetry — with the associated scalar becoming the *Galileon* [148].

Abstracting from DGP, a 4D field theory with this Galilean symmetry is interesting in its own right. It turns out that there is a finite number of terms, the *Galileon terms*, that have fewer numbers of derivatives per field than the infinity of competing terms with the same symmetries. These terms have the surprising property that, despite higher derivatives in the actions, the equations of motion are second order, so that no extra degrees of freedom propagate around any background. Much has been revealed about the Galileons, including a non-renormalization theorem [146, 149], and applications in cosmology [150–158]. The Galileons have been covariantized [159–161], extended to p-forms [162], and supersymmetrized [163].

I have extended these general ideas, with the goals of mapping the space of novel 4D EFTs that may arise, and investigating their implications for particle physics and cosmology. With postdocs Hinterbichler and Wesley, I have studied [149] a generalization to co-dimension greater than one. We showed that the resulting 4D effective theory is invariant under a generalized symmetry, in which the Poincaré group $p(1, D-1)$ is broken to $p(1, d-1) \times so(N)$. We were then able to obtain the multi-field actions invariant under this symmetry. In 4D there are only two possible terms; the kinetic term and a fourth order interaction term. This is an intriguing scalar field theory with a single interaction term, and thus a single coupling constant. There exist regimes in which the quartic term is the only one which is important. Furthermore we were able to extend previous arguments to prove that Galileon terms are not renormalized to any order in perturbation theory, in any dimension, so that classical calculations in these regimes are exact.

We studied how to treat the multi-field Galileons as arising from a probe-brane prescription, following the construction in [164], addressing the technical question of identifying the ingredients from which to construct the action; i.e. the geometric quantities associated with a higher co-dimension brane. We demonstrated that what are required are higher co-dimension Lovelock invariants [165] and their boundary terms [166]. This highly constrained structure is the origin of the specific form of the multi-field Galileon.

Working with graduate student Melinda Andrews, Hinterbichler and Justin Khoury, I then studied [167] spherical solutions and showed that avoiding superluminal propagation requires nontrivial couplings to matter. In work with graduate student Garrett Goon and Hinterbichler, we performed [168] a similar analysis for the single field Dirac-Born-Infeld (DBI) Galileons.

With Goon and Hinterbichler, I have extended the general probe-brane construction [164] to its most general form, leading to a general class of 4D EFTs [169, 170]. The symmetries inherited by scalar fields in the 4D theory are determined by isometries of the bulk. The manner in which the symmetries are realized is determined by the choice of gauge against which brane fluctuations are measured. We derived the symmetries of these field theories, and classified the maximally-symmetric examples. These are new theories living on curved space but with the same number of non-linear symmetries as the flat-space Galileons or DBI theories. These theories have unique properties; e.g., in curved space, the field acquires a potential which is fixed by the symmetries – unlike the flat space Galileons. In particular, the scalars acquire a mass of order the inverse radius of the background, with value fixed by the nonlinear symmetries. Further, we have extended this construction [171] to describe a class of Galileons propagating on cosmological backgrounds. I have recently written a brief invited review on these topics [172].

The clear particle physics connections of these theories are drawn out in my papers with Goon, Joyce (student), and Hinterbichler on how one may construct Galileons with gauge symmetries from the embedded brane construction [173], and in our lengthy description [174], involving both the physics and mathematics, of how Galileons may be seen as Wess-Zumino terms, categorized by certain cohomology groups.

If our universe really is a brane world, then theories of this sort are generic, since they share, in a limit, the symmetries of the DBI action, which encodes the lowest order dynamics of a brane embedded in higher dimensions, and provides an important arena within which to study a variety of cosmological and particle physics phenomena. The Galileon terms can be thought of as a subset of the higher order terms expected to exist in any EFT of the brane, suppressed by powers of some cutoff scale. The Galileons are a special subset of these terms because they have fewer derivatives per field than competing terms with the same symmetries and because they yield second order equations. Crucially, there can exist regimes in which only a finite number of Galileon terms are important, and the infinity of other possible EFT terms are not.

Cosmological Implications of New Effective Field Theories

A question related to the above is that of the behavior of cosmological perturbations, the stability of the solutions and the speed of propagation of fluctuations in these models.

One way to extend the models discussed above is to consider higher-dimensional models in which branes of lower co-dimension are successively embedded within multiple branes of increasing dimensionality. Such *cascading gravity* models [175] provide a rich framework for exploring new phenomena associated with infrared-modified gravity. Since the induced propagator is free of divergences, the theory is perturbatively ghost-free, and adding a small tension on the $4D$ brane yields a bulk solution which is nowhere singular and everywhere perturbative. Due to its higher-dimensional nature, however, extracting cosmological predictions presents a daunting challenge.

In papers [150, 176] with Rachel Bean and Nishant Agarwal (Cornell) and Khoury, I considered the more tractable problem of a $5D$ effective brane-world set-up, obtained through the decoupling limit. Our effective action describes $5D$ DGP gravity with a bulk scalar field, coupled to a $4D$ brane with intrinsic gravity. In our first paper [176] we supplemented the $5D$ action with boundary terms and obtained covariant junction conditions across the brane. In order to study cosmology on the brane, we then considered a scenario in which a dynamic brane moves across a static bulk. We derived analytical solutions for the induced cosmology at early and late times and confirmed these expectations with a complete numerical analysis. Our results hint at self-accelerating possibilities, which we are now pursuing.

In [150] we attempted to obtain flat brane solutions to this theory. Our analysis uncovered an intriguing screening mechanism that can shield bulk gravity from a large tension on the brane, resulting in a small brane extrinsic curvature. The brane remains flat for *arbitrarily large* tension, while the bulk is non-singular. However, the stability analysis imposes stringent constraints. The bulk solution is perturbatively unstable for positive brane tension, while it is possible to find stable solutions for sufficiently small negative brane tension.

Particle Physics Implications of New Effective Field Theories

It is possible that the braneworld model is a field-theoretic construction, in which the brane is a topological defect [177, 178]. In that case, the extended nature of the brane may have important implications. In work [179] with Volkas and George, I have studied the cosmology of field-theoretic braneworld models, and in related work [180] with Andrews, Lewandowski (undergraduate) and Wesley, I have studied defects in theories with non-canonical kinetic terms, obtaining results that also constrain certain families of DBI instanton solutions. Further, with Manuel Toharia (Maryland) and graduate student Eric West, I studied [181] the existence and stability of kink-like configurations of a 5D scalar field. I will build on this experience to perform a comprehensive study of how the particle physics and cosmology implications of braneworld models constructed from field theories differ from those in fundamental brane models.

With Ray Volkas and Kalliopi Petraki (Melbourne) I have investigated [182] the idea that he similar cosmological abundances observed for visible and dark matter suggest a common origin for both. By viewing the dark matter density as a dark-sector asymmetry, mirroring the situation in the visible sector, we showed that the visible and dark matter asymmetries may have arisen simultaneously through a first-order phase transition in t he early universe. The dark asymmetry can then be equal and opposite to the usual visible matter asymmetry, leading to a universe that is symmetric with respect to a generalised baryon number. Testable consequences for colliders include a Z' boson that couples through the B-L charge to the visible sector, but also decays invisibly to dark sector particles. The additional scalar particles in the theory can mix with the standard Higgs boson and provide other striking signatures.

Gravitational Tests of New Effective Field Theories

21.2 Stability of and Constraints on Models of Cosmic Acceleration

There now exist many proposed models of cosmic acceleration, some of which I have developed, and some of which fall into the category discussed in the previous section. I have emphasized the constraints that stability imposes on general extra dimensional models. It is just as important to investigate the stability of models of cosmic acceleration. Ghost instabilities are an example of an issue of this type: Phantom theories [183] are subject to catastrophic decay of the vacuum [184, 185], and related problems appear in higher dimensional models, sometimes in subtle ways. For example, the DGP model exhibits a ghost around the accelerating branch [186, 187]. Models also sometimes contain superluminally-propagating modes, which, although worrying, require a careful analysis to establish whether they pose a measurable causality problem in the theory.

While ways around the ghost problem have been suggested, it is difficult to make them work in general. For example, with Fontanini, I explored [188] a Euclidean path integral alternative [189] to the EFT formalism to deal with higher-derivative ghosts. We explored whether this approach can be extended to apply generally and showed that this is highly-dependent on the background.

In general I have also investigated the stability of modified gravity and dark energy models. These include models in which the couplings between dark energy and dark matter arise from compactifying down from a higher dimensional model; models with non-minimal lagrangians, such as k-essence models; and models which seek to explain cosmic acceleration by postulating a separate sector with multiple components.

The possibility of distinguishing between different models by comparing the expansion history of the universe to the growth rate of cosmological perturbations has been emphasized in a variety of approaches [190–204], and it is important to understand the ways in which this distinction can manifest itself. As an example, prior to this grant, I considered [205] constraints on theories with a nontrivial coupling between the dark matter sector and the sector responsible for the acceleration of the universe. I discussed this work as part of a Scientific American cover article [206] and in an invited review article [207] on cosmic acceleration.

21.3 Important Other Work

I co-Direct the Center for Particle Cosmology. I am an editor for *Physics Letters B*, *JCAP*, *New Journal of Physics*, and of the Springer *Multiversal Journeys* Series. I regularly review proposals and serve on panels for the Department of Energy, the National Science Foundation and N.A.S.A. I serve on the international advisory boards for several conferences, and routinely deliver ten to fifteen invited lectures at international conferences and at colloquia and seminars each year.

21.4 Educational Development, Mentoring and Outreach

I have taught large lecture courses, small undergraduate courses, and specialized graduate classes. I have also supervised six undergraduate students performing research over the summer months.

Public Science education is a particular interest. I have delivered numerous public lectures; I have mentored five high-school students; I organized a public lecture series - *Saturday Morning Physics*; I have helped construct exhibits on modern cosmology for display in the Rubenstein

Museum of Science and Technology; and I co-founded and organized a *Café Scientifique*, where scientists and non-scientists meet informally.

I am research advisor to three graduate students. Melinda Andrews is a fifth year student who has published three papers and is now working on tow more that will complete the work required for her thesis. Garrett Goon is a fourth year student who has published seven papers, has one more in preparation and is also now working on his thesis topic. James Stokes is a very promising third year student who has written four papers and is working on two more. Michele Fontanini graduated in 2011 and is a postdoctoral research associate at the University of Sao Paulo. Eric West graduated in 2010 and is a Visiting Assistant Professor at Rochester Institute of Technology. Alessandra Silvestri graduated in 2008 and is a postdoc at MIT.

Previous postdocs have gone on to successful positions. Kurt Hinterbichler is a Research Associate at the Perimeter Institute, Levon Pogosian is an assistant professor at Simon Fraser University; Laura Mersini is an Associate Professor at the University of North Carolina; and Damien Easson is an Assistant Professor at the Arizona State University.

Part V
Advanced Technology Research and Development

22 Introduction and Overview

The Penn High Energy Physics Instrumentation & Engineering group has been involved in the design, development, and implementation of large scale high energy physics experiments for four decades. We have concentrated on electronics for new experiments, although we have also worked on detector development, and have significant effort devoted to developing new ideas that are useful to the HEP community and often see application in a wide variety of epxeriments. While the group is especially interested in front end signal processing, for example for the CDF and ATLAS inner tracking detectors, we have also delivered complete electronic systems. Penn provided nearly the entire system of electronics for the BNL νe elastic scattering experiment, for the Kamiokande-II experiment, for the SNO experiment and for the CDF Time-of-Flight system. In the past two decades, the group has added a specialization in the design of custom integrated circuits and has developed seven complete integrated circuits for experiments, as well as numerous test and demonstration chips. Foremost among these are SNOINT and SNOD developed for SNO, the ASD8 developed for the SSC, the ASDQ developed for CDF, and the ASDBLR and DTMROC (in collaboration with CERN) developed for ATLAS.

In our tradition of sharing the technology we develop, the ASDBLR designed for the ATLAS TRT is also was also used in the LHCb outer tracker. Our ASIC tester, purchased to test ASDBLR and DTMROC ASICs, has been made available to several groups for testing their own ASICs, and recently we have helped other instrumentation groups such as BNL and CERN's Microelectronics group exploit free SPICE (analog simulation software) programs by providing detailed implementation examples of our use of this very unencumbered software.

The Instrumentation group includes four professional and three technical people, with a broad and highly integrated set of skills and experience of two to four decades. It is led by Mitch Newcomer. Rick Van Berg, who led the group for ~ 40 years, recently retired but is still active. The Advanced detector projects we have worked on included participation by five faculty members: Josh Klein, who played a large role in the design, prototyping, and commissioning of electronics for the SNO detector; Joseph Kroll, who oversaw development of the electroncs for the CDF Time-of-Flight system; Elliot Lipeles, who suggested the multi-level strips readout trigger we have designed and developed for the ATLAS upgrade ; Evelyn Thomson, who played a lead role in the development and commissioning of the XFT tracker for CDF; and H. H. Williams, who was responsible for leading the design, prototyping, production, and commissioning of the front end electronics for the Transition Radiation Tracker (TRT) in ATLAS.

23 Advanced R&D Projects

23.1 Serial Powering for High Channel Count, High Density Detectors

We submitted a prototype version of the serial power and protection ASIC (SPP chip) in the fall of 2011 that was fabbed in IBM's 130nm CMOS8RF process. The operation of this chip was validated by tests using a test board designed by us for stand alone tests during the winter of 2012. The SPP chip was shown to respond to all pulse width modulated commands. It regulates voltage bshunting up to 2 Amps of current as necessary between the input and output, maintaing the input at the resistor programmed voltage to within a few millivolts of the expected value. The control voltage for distributed shunt current has been shown to work as expected as well as the "trip" mode that causes an input to output short in the event of an over voltage.

23.2 LAr Front End and Wide Dynamic Range Analog Delay Line

Analog signals in high channel count HEP detectors are often manipulated to achieve appropriate amplitude or signal shape using post fabrication handles such as CMOS switches or current summing multiplier circuits. Another important capability is to be able to delay the signal arrival time. We are aggregating this functionality into one or two ASICs that will minimize the use of high value board area. The Tower Builder Board (TBB) in the ATLAS Liquid Argon detector, requires time alignment of wide dynamic range signals from various regions in the first level trigger. One of the options we explored for the Phase I ATLAS upgrade was to rebuild the tower builder board with components that significantly reduced the amount of board real estate required for the trigger sum time alignment. Based on our SNO experience, we incorporated multiple stages of complementary current mirrors using a combination of RC based delays between stages to add a programmable analog delay. A prototype programmable analog delay with 8 steps of 2.2ns was developed by us for the ATLAS TBB and submitted to the German IHP foundry in the fall of 2011 using their SG25H3P rad tolerant process. The die area of the delay block is $\sim 200X300$um, leaving plenty of room in a follow-on design for programmable gain and possibly shape control. For comparison, a commercial part with 8 individual tapped outputs (not programmable) would require a board area of 1200 X 750um, 15 times larger.

23.3 Autonomous Analog monitoring Block for HEP detectors

In a high density HEP detector readout, the overhead required to develop an on-detector system separate from the front end electronics to monitor temperatures and voltages—including extra cables and a rad tolerant readout—is significant. This translates directly into an increase in cost for development, installation and material. In 2010-12 we developed several parts of a self contained IP block in IBM's CMOS8RF process that can be adapted for any front end ASIC with an internal clock and register read back protocol. One particularly important part was a an integrating dac intended for use with a 10 bit counter sensitive from 0V to 1V using the ASIC's 1.2V supply. The comparator and its layout along with much of the logic for the autonomous monitor was completed by April 2012.

The autonomous monitor function works by using a local clock to increment a counter and ten bit staircase reference generatot (integrating DAC). Monitored quantities are voltages with a dependence on the monitored current, temperature or supply voltage. Each monitored quantity is presented to one input of a comparator. The counter linked staircase reference voltage goes to the other input. When the staircase reference exceeds the monitored voltage, the counter value is stored in a register and compared with programmable upper and lower window limits for the quantity. If it is out of range, a flag is set to generate a readout request. Each time the counter rolls over, the system is reset and a fresh measurement is taken. The clock rate can be scaled to control power.

The ideas for this block were evolved from experience with a crude version of this kind of monitoring in the TRT's DTMROC that has been used quite successfully in the TRT system for front end chip level monitoring.

23.4 PMT Measurements

As part of our work on characterizing photomultiplier tubes for the proposed LBNE water Cherenkov detector, the Penn group assembled a sophisticated single photo-electron measurement system for large hemispherical PMTs. The detailed point-by-point two dimensional measurements of photon sensitivity (relative measures of quantum efficiency times electron collection efficiency) and transit time that were made on several candidate PMTs (shown in Figure 8 in the Intensity Frontier section of this proposal) were of interest not only to LBNE collaborators, but also to the PMT manufacturers.

Our finding was that the offset in the transit time shifted dramatically (from -2 to +3 ns) across the face of the PMT. This led the manufacturer to re-run their electro-optical simulations. They found good agreement with our measurements and now have a new dynode design that will reduce the position-dependent shifts to about $\pm$1ns. The fast timing of our PMT measurement system has also allowed us to understand in detail the "latepulsing" behavior seen in large-area PMTs.

23.5 Large Synoptic Survey Telescope

Since being invited to join in 2005, Penn has played a significant role in determining the design of the LSST CDD camera readout. We designed a commercial part version of the Correlated Double Sample (CDS) readout to get started and went on to help pinpoint the cause of excess noise in the first multi-channel CCD readout ASIC designed by IN2P3 (Paris). ASIC designs were already being done elsewhere, so we therefore chose to design the next most critical part of the camera readout, the Front End Board (FEB). The first version of a 3CCD readout FEB was completed in 2012. Rick Van Berg has been the electronics coordinator for the camera readout since 2010.

23.6 Micromegas Detectors

Having spent years in the development of proportional drift tube based tracking systems, we are encouraged by recent developments at CERN that seem to have solved the breakdown problem for micromegas detectors. They appear to be capable of operation at very high rates and may be suitable for tracking detectors. In 2011 and 2012 we worked with Professor Bob Hollebeek to develop a 3D micromegas based monitor intended to cross check the dose administered at Penn's Proton therapy machine. The monitor consists of many sensing planes with the approximate density of human flesh. Each plane has $\approx$ 500 5x5 mm pixels that are read out in current sensing mode. The micromegas substrate was fabricated by the CERN PCB shop and we have developed the current-sensitive readout electronics. We used this opportunity to develop expertise in the design, development and readout of micromegas chambers that could be back to the HEP detector community to explore the possibilities and limits for a PCB or kapton based tracking layer using short strips or pixels. This may be useful for both collider detectors and large volume underground detectors where a fast readout would enable a high quality background reduction and thus allow construction closer to the surface, thus reducing cost.

Part VI
Appendix

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